John Gibbon and His Heart-Lung Machine

Ada Romaine-Davis

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This work is dedicated to my husband
JOHN F. DAVIS,
editor extraordinaire,

our children
KEVIN, KAREN, AND BILL,
scholars in their own fields,
and

FRANK F. ALLBRITTEN, JR., M.D.
and
GEORGE J. HAUPT, M.D.,
consultants extraordinaires
who helped to make this book a reality

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Mary Gibbon Clarke—daughter

John Gibbon, Ph.D.—son

Alice Gibbon Saltzman, Ph.D.—daughter

Marjorie Gibbon Masek—daughter

Marjorie Gibbon Battles—sister

Robert H. Gibbon, M.D.—nephew

Virginia Gibbon—sister-in-law

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Preface

In the address presented at the time of his election as president of the Southern Surgical Association, Dr. Hiram C. Polk, Jr.—citing the general perception of the last decade or so that surgeons have been excluded from major research on new technologies in medicine—concluded that "We need to go back to the innately innovative era of Gibbon and the pump oxygenator."[33]

Having spent two years collecting information about John Heysham Gibbon, Jr. from his articles, family members, colleagues, and other sources, I was particularly startled by those words "era of Gibbon." Gibbon was the first surgeon to perform successfully heart-and-lung bypass surgery using his own invention, the heart-lung machine. Yet I had not previously considered his life and work as comprising a specific era. Therefore, I returned to my materials and considered them from this and other perspectives. Questions formed in my mind: What were the forces that provided the motivation for Gibbon to pursue his work on the oxygenator? What vision did he hold? What factors affected his work? What support did he have or not have? What were the economic, social, and political milieux at the time? What personal characteristics distinguished him from others and resulted in his ultimate success? Who among his parents (particularly his father), his professional colleagues, his wife, his teachers, and his mentors influenced him most in his work? What values and beliefs did he hold that sustained him through the years of repetitive experiments and failures?

I looked anew to find JHG as a person, to discover him through the meager evidence left by him about himself. He rarely wrote letters to his family or friends; most of his correspondence relates to perfunctory requests for information or materials, or responses to inquiries about his work or about the oxygenator. He reveals little about himself in his writings, with the exception of *The Inquiring Mind, The Education of a Surgeon, A Trip to Europe*, and *An Army Doctor Comes Home and Looks at Civilian Practice*. These reveal something of the man beyond his professional life and work. His penchant for "scribbling" poetry from time to time showed not only his love for literature but revealed attempts to articulate deeper feel-

ings that he found difficult to express outwardly. One of his closest friends, Dr. Rudolph C. Camishion, caught glimpses of the complex, sensitive, deeply caring person that he was—glimpses that others, even those apparently closest to him, were unable to see, primarily because these facets of his personality were so deeply hidden from causal view.

In writing this account, I have tried to keep in mind the observation of Mark Twain that "biographies are but the clothes and buttons of the man—the biography of the man itself cannot be written."[36] This biography, nevertheless, attempts to reveal JHG as physician, surgeon, husband, father, educator, and inventor—a simple yet profoundly complex man, with the hope that future historians and biographers will be able to gather more information and, adding to this work, create a more complete portrait of a fascinating man, the man who made the "era of Gibbon."

Birth and Early Years

When John Heysham Gibbon, Jr. was born in 1903, Philadelphia was a rapidly growing, bustling, exciting city of almost 1.3 million people, with large neighborhoods of ethnic groups—Germans, Swedes, Italians, Poles, and Jews. Bounded by the Delaware River on the east and the Schuylkill River on the west, Philadelphia's position at the head of Delaware Bay afforded easy access from the larger Atlantic seaports of New York and Baltimore and, following the Civil War, promoted the city's development as a financial, manufacturing, trading, and railroading center. In 1854 the city merged with the county of Philadelphia, a move that enlarged not only its area and population, but also its economic and political base. In the post—Civil War decades, large retail stores established by Strawbridge and Clothier, John Wanamaker, and others in center city allowed people for the first time to buy inexpensive, mass-produced goods and clothing of all kinds. More important, the stores provided jobs. In 1911 President William Howard Taft gave the dedication speech for the opening of the main Wanamaker store at its present location. His presence gave additional credence to the fact that Philadelphia was a major American commercial center.[38]

People from other states and newcomers from other countries flooded into the city, drawn by its burgeoning activities in the arts and sciences and by its many and varied educational and health- and safety-related institutions, among them the country's first hospital, the Pennsylvania Hospital; its first fire insurance companies; and the University of Pennsylvania, the first American institution officially to be designated a university.

Other outstanding educational institutions, most of which were established during the nineteenth century, attracted prospective students—with their families—from all parts of the United States and from abroad: Temple University, Drexel University, St. Joseph's University and, within the metropolitan area, distinguished colleges such as Bryn Mawr, Swarthmore, Haverford, and Villanova, before Villanova became a university.

Philadelphia's medical schools added to the city's growing reputation

as a medical center: Hahnemann Medical College, Temple, University of Pennsylvania, Philadelphia College of Osteopathic Medicine, and Women's Medical College. Jefferson Medical College, established in 1825, was the alma mater of many members of the Gibbon family over many generations.

Early in the twentieth century visitors could find quiet, well-kept, picturesque streets, tree-shaded parks, and architecturally pleasing residences. Along Pine and Spruce streets were rows of plain but beautiful old brick "town" houses with dormer windows and white shutters.[38]

With the rapidly expanding population came the problem of transportation. In 1905 there were fewer than 500 automobiles registered in the city, but by 1918 there were more than 100,000. A further indication of Philadelphia's growth was the opening of the two-mile Market Street Subway in 1907. Another section of the Subway east of 15th Street to the Delaware River was completed in 1908.[38]

Philadelphia was JHG's home for most of his life. He devoted many volunteer hours to its organizations, particularly those that fostered good health care for its people. He was especially pleased and honored to receive the Philadelphia Award in 1964 for his work on the oxygenator and for his years of service to the city.

In the past, the world often seemed to be divided between two views about what makes the individual—those who claimed that genetics is the only basis for intelligence, motives, behavior, and personality, and those who said that environment is the true basis for all that we are and do. John Heysham Gibbon, Jr. was fortunate both in his ancestors and in his environment. He was gifted in many ways and to such an extent that one might be tempted to say that he was destined to accomplish great things.

Father and Mother

JHG's parents were married at the Presidio in San Francisco on September 2, 1901, with many distinguished government and military representatives and private citizens present. Following their honeymoon trip, they settled into the home that Dr. Gibbon had bought for his bride at 1608 Spruce Street, Philadelphia. Close to both Jefferson Medical College and the Pennsylvania Hospital, where he was to practice for many years, this red-brick, four-story "townhouse" was home to the Gibbon family for almost fifty years.

Born September 29, 1903, JHG was the first son of this famous surgeon and his wife, Marjorie Young. Marjorie was fourth of the "five beautiful Young sisters," daughters of Samuel Baldwin Marks Young, who

was a major general of volunteers in the army (1898), commanded a brigade in the Santiago campaign in the war with Spain (1889) and in the Philippine insurrection of 1899-1901. He became the first president of the Army War College in July 1902. General Young was the only grandparent JHG and his siblings ever knew.[4]

Great-Uncle John

Another of JHG's family members was his great-uncle, General John Gibbon, an 1847 graduate of West Point who later fought in many of the major Civil War battles. While an instructor at West Point, he wrote *The Artillerist's Manual*,[17] a book used for many years in teaching cadets and soldiers about arms, ballistics, and battle tactics. After Lee's surrender for the Confederacy, General Gibbon was the senior of three Union officers who developed the materials and arrangements for the meeting between Lee and General Grant during which terms of the surrender were considered, and implemented the surrender terms.

After the war, General Gibbon served in the West as an Indian fighter. In 1876 he commanded one arm of the Little Big Horn expedition against the Sioux and, after Custer's disastrous battle, rescued the survivors and buried the dead. In 1885 he wrote *Personal Recollections of the Civil War*,[18] which was not published until 1928, after his daughter Frances discovered and edited the handwritten manuscript and submitted it for publication. His style of writing, like that of his great-nephew, was clear and straightforward, with impeccable syntax.

"General John" was not mentioned in Civil War histories until the 1950s, when Bruce Catton included him in several of his later works.[6, 7, 8, 9] Other historians then came to know of him, and his military activities are mentioned in Shelby Foote's three-volume work *The Civil War: A Narrative*,[16] *The American Heritage Picture History of the Civil War*,[24] Pfanz's *Gettysburg: The Second Day*,[31] and the Time-Life series on the Civil War,[1, 2, 10, 11, 22, 23, 25, 29] among others. Currently, three biographers are researching his life. In 1987 a statue of General John Gibbon was erected at Gettysburg and is situated in a place of prominence near the beginning of the tour of the battlefields. Like JHG's, the General's reputation has grown over time, long after his death, for accomplishments that were not fully recognized during his lifetime. A descriptive phrase on the metal plaque on the pedestal of the statue is: "He has a keen eye, and is as bold as a lion." On his gravestone at Arlington National Cemetery is inscribed, "The Iron Brigade rears this block of granite to the memory of a loved commander."

Inherited Talents

JHG was the fifth generation physician (third generation surgeon) in the Gibbon family. JHG, Sr. was born in Charlotte, North Carolina on March 16, 1871, the son of Dr. Robert and Mary Amelia (Rogers) Gibbon. He was educated at Macon School and admitted to Jefferson Medical College in 1888 at the age of seventeen. He remained in the Philadelphia area for the rest of his life, except for service in the Army Medical Corps during the Spanish-American War and World War I. Although JHG, Sr. was born in the South, his father, grandfather, great-grandfather, and great-great-grandfather were all born in Philadelphia. His father had moved to Charlotte when several of his children were still young; the younger children, including JHG, Sr., were born in North Carolina. The family's roots, however, were deeply imbedded in Philadelphia.

Geneticists have speculated that talents in such disciplines as music, the visual arts, and writing are transmitted by means of DNA structures.[26] If so, JHG, then, would have been a likely recipient of genes related to writing ability from his parents, his maternal grandfather, and his great-uncle. His father, besides contributing extensively to the medical literature, wrote several biographies of famous physicians such as Thomas Dent Mütter.[20] This fact suggests that he was interested not only in reporting medical and surgical practice, but also in conveying his enjoyment of other facets of medicine and medical history.

Paternal Example

JHG, Sr. graduated from Jefferson Medical College in 1891, and was professor of surgery and clincial surgery there from 1907 to 1931. In 1898, during the Spanish-American War, he was a surgeon in the U.S. Volunteer Engineers, and a colonel in the Army Medical Corps and Consulting Surgeon with the American Expeditionary Forces in World War I. After the war, at various times in his career, he was elected Fellow and was president of the American Surgical Association, the College of Physicians of Philadelphia, and the Philadelphia Academy of Surgery. He was also a member of the American Medical Association, the Medical Society of the State of Pennsylvania, the Pediatric Society, and the National Society for the Study and Prevention of Tuberculosis. Among his publications were contributions to the *Reference Hand-Book of Medical Sciences* and to Keen's *System of Surgery*, and many articles in medical journals.

People remember JHG's father as a robust, charismatic, handsome, and highly intellectual man, who also loved doing things with his hands—carpentry, woodworking, farm work. He loved horses and riding and

became Master of the Hunt at the Rose Tree Fox Hunt Club. He was usually accompanied by JHG's sister Marjorie, and continued to ride almost until his death.

JHG, Sr. had a cold water shower installed outdoors at the Gibbon home, Lynfield Farm. His year-round habit was to use this shower after working on the farm or after riding. He believed bathing in cold water to be good for one's health. This stoic belief exemplified Dr. Gibbon's principles of conduct for himself. He taught his children, by example, to have the same standards. His racist attitude toward blacks, which was perhaps a vestige of his years in the South, was a prejudice that his children and grandchildren abhorred. In every other respect, he was totally without bias and treated every person with equal respect. For example, he evidenced no anti-Semitic feelings, nor other ethnic, religious or political antipathy.

JHG's father was particularly fond of playing chess and taught his three boys to play. JHG became the most skilled player, and regularly challenged his father to a game whenever they were together throughout his father's lifetime. This early competitiveness in chess between father and son perhaps engendered a subconscious desire in JHG to equal or surpass his father. Indeed, their professional careers are nearly parallel. The major difference between them, and the factor that was to allow JHG to excel, was his early and abiding interest in research. Although JHG, Sr. carried out some surgical research studies and fostered research interest in his students, his primary activities focused on clinical practice rather than research.

JHG's Persistence

JHG's apparently innate persistence was seen early, as evidenced by his willingness to play chess for hours, even through meals. His mother would serve Sunday dinner while JHG and his father were absorbed in a chess game. They would sit at the table, but JHG's mind would be busily constructing possible countermoves. Sometimes, he would jump up abruptly, go to the chessboard in the library, complete his move, then return to the table to finish his dinner. When the meal was over, he and his father would return to the game for the rest of the afternoon.

This personality trait of persistence was displayed in many instances throughout his professional life, as several of his former colleagues recalled. His care in editing an article that he and one or more of his residents had written was almost painfully meticulous. He reviewed every paragraph, sentence, phrase, and word, suggesting changes to increase clarity and completeness. Sometimes the editing and rewriting process took several

weeks, which in some cases delayed submission for a particular targeted issue of a journal. His residents said that they could write and complete an article on a surgical topic with other faculty members in half the time or less. However, they also knew that when JHG worked with them on an article, it was more likely to be accepted with no requested revisions, and therefore published quickly.

JHG was assisting a colleague with a paper that was to be presented the next day with the stipulation that the manuscript be in pristine publishable condition at the time of presentation so that it could be sent to the journal immediately following the talk. The effort became a minor nightmare for the colleague, whose anxiety level was rapidly rising at the thought of presenting the still incomplete paper the next morning. JHG became fixated on whether it was proper for the abbreviation of "cubic centimeter" to be "c.c.," which he considered the correct form, or "cc." He went to medical style manuals, called one or two editors whom he knew personally at the nearby publishing houses, and held up the paper for hours while he tried to obtain an opinion that agreed with his. They finally elected, using a one-sided decision, to go with "c.c." The entire paper had to be retyped—this was before word processors—further delaying the finished manuscript. By this time, the dinner hour was long past, and the harassed secretary who was staying to complete the typing was fervently wishing that she hadn't volunteered, despite the overtime pay. When the paper was published, the editor had changed to "cc." Even then, JHG wrote to a prominent medical writer/editorialist to seek his opinion; his answer was "cc." JHG, undeterred, clung to his preference. His colleague was not certain that JHG ever relinquished his choice.[5]

Once decided on a course of action, JHG maintained his commitment, sometimes beyond all reason, as was considered to be true in the case of his work on the oxygenator (heart-lung machine). Only one of his mentors offered him the slightest encouragement, and that was simply to say that if JHG thought that the idea had merit, then he should go ahead with it. The encouragement did not indicate that the mentor had the slightest hope of its success; he was merely affirming JHG's right to make the decision.

For most of the 22 years that JHG worked on the oxygenator, his colleagues thought him foolish, if not downright insane, for pursuing what they called a hopeless goal. Such an apparatus could not possibly work, they thought; the human body was not capable of having its heart and lung functions sustained by a machine. In 1947, when Dr. Clarence Dennis[12] from the University of Minnesota, who had been asked to explore how to go about developing an oxygenator, went to Gibbon at Jefferson, JHG

greeted him with, "It's great to know that now there are two of us whom our colleagues will call 'crazy!'"

This statement illustrates that JHG was well aware of how his colleagues viewed his work with respect to the oxygenator. His persistence further indicates that, although he was aware of others' attitudes, he chose to pursue the dream that he had had since 1930. In a very real sense, JHG's pump oxygenator was the direct result of his persistence. Without that character trait, he would not have succeeded.

That same characteristic—his bulldog determination and strength of commitment—also made him a loyal friend, a deeply responsible physician and surgeon, and a dependable colleague. His friends knew that they could count on him. His employers recognized that he carried out his duties fully and to his best capabilities. His family knew that he upheld the family honor and integrity. JHG personified Aristotle's "Ideal Man," in fact:

> He does not expose himself needlessly to danger, since there are few things for which he cares sufficiently; but he is willing, in great crises, to give even his life,—knowing that under certain conditions it is not worth while to live. He is of a disposition to do men service, though he is ashamed to have a service done to him. To confer a kindness is a mark of superiority; to receive one is a mark of subordination . . . He does not take part in public displays . . . He is open in his dislikes and preferences . . . He is never fired with admiration, since there is nothing great in his eyes. He cannot live in complaisance with others, except it be a friend; complaisance is the characteristic of a slave. . . He never feels malice, and always forgets and passes over injuries . . . He is not fond of talking . . . It is no concern of his that he should be praised, or that others should be blamed. He does not speak evil of others, even of his enemies, unless it be to themselves. His carriage is sedate, his voice deep, his speech measured. He is not given to hurry, for he is concerned about only a few things. He is not prone to vehemence, for he thinks nothing very important. A shrill voice and hasty steps come to a man through care . . . He bears the accidents of life with dignity and grace, making the best of his circumstances, like a skilful general who marshals his limited forces with all the strategy of war . . . He is his own best friend, and takes delight in privacy whereas the of no virtue or ability is his own worst enemy, and is afraid of solitude.[14, 27]

Maternal Influence

JHG's mother was reared as an "Army brat," and benefited from these circumstances by receiving most of her formal education from army personnel. At that time, education provided to army dependents was superior to that found in most private schools. She was, like her husband, an intellectual, fond of literature and poetry. She wrote prodigiously as a diarist and avid letter-writer. She was said to be both quick-witted and quick-

tempered, possessing a sharp tongue that could bite when necessary.[4] She encouraged her daughter to attend Dana Hall, a private finishing school in Wellesley, Massachusetts, to prevent her from becoming a "hide-bound Philadelphian." Her quick wit was matched by her husband's; their home was stimulating, as well as warm and affectionate. She and Dr. Gibbon were exceptionally hospitable, offering their home to many family members, friends, or casual acquaintances met in their travels. At any one time, the Gibbon house might have several visitors who often stayed weeks: Army cousins waiting to hear about admission to West Point, Southern cousins up for sessions with their Philadelphia dentist, a refugee White Russian, a homesick Louisiana bride met on a commuting train. Marjorie Young Gibbon was described as outgoing and energetic, but also shy. Her influence on all her children, and particularly on JHG, was great; she and JHG were devoted to one another.

Siblings

JHG was one of four children, all born in the house on Spruce Street. Marjorie, the oldest, was born in 1902, and JHG, the first son, the following year. Then came two more sons: Samuel Young in 1905 and Robert in 1909. All but Sam had black hair and blue eyes; Sam's hair was red, although he, too, had their father's blue eyes.

The children had a governess whom they called Mamu—Mademoiselle Louise Fillitier—who lived on the fourth floor at the back of the house. She remained with the family for many years, greatly loved by all.

JHG got along well with his sister and brothers. Marjorie, as the oldest, would often try to dominate her brothers during play. She would be the "mother" and JHG the "father." Young Sam would be their child whom they pushed about in an old baby carriage. However, JHG would soon be absorbed in his own play activities, leaving Marjorie and Sam to their own devices. Always the pacifist who hated arguments or hard feelings, JHG would continue to wear the "father" hat and to keep a toy pipe clamped between his teeth, as though still part of the "mother-father" game, but would drift off to another part of the yard to engage in his own make-believe.

As the children got older, Marjorie tended to play with her own friends, while JHG and Sam continued to play together. A strong bond developed between them which continued throughout their lives. Sam did not follow JHG into medicine; he was drawn to the business world. However, the brothers' professional lives crossed in the early 1950s. At that time Sam managed and owned stock in the Air-Shields Company, which

manufactured Isolettes, the innovative infant incubator that had "portholes" in the Plexiglas top through which the baby could be fed and cared for without leaving its protective, climate-controlled environment. At Jefferson, George J. Haupt, one of JHG's surgical residents, developed an effective ventilator for use with patients undergoing thoracic surgery. Gibbon encouraged Haupt to patent the invention, and suggested that a possible manufacturer might be his brother. Although Haupt later transferred the patent to Jefferson, the ventilator continued to be manufactured by Air-Shields.

The family went abroad in 1910, from June to October, and traveled mainly in England and France. JHG, Sr., then a professor at Jefferson and with sufficient financial resources, was able to be away during some summers. They rode in a pony cart in the English countryside, explored art galleries, and attended Shakespeare plays in London.

In the fall, the two older boys, Jack and Sam, because of their excellent early education under Mamu, were a year ahead of others of the same age when they were enrolled in the Delancey School—which later merged with the Episcopal Academy, a private boys' school.

The Farm

During the summer of 1911, the family rented a farm in Devon, Pennsylvania. It was probably this experience, as well as encouragement from Dr. James Hutchison, who owned a farm on the outskirts of Philadelphia, that motivated JHG, Sr. to buy Lynfield Farm in 1912. The 150-acre farm bordered Crum Creek three miles outside Media, a small town southwest of Philadelphia. The farm was a mile from the Rose Tree Fox Hunting Club and only a few miles from Dr. Hutchison's farm. The house itself was built of fieldstone in the seventeenth century, and originally had two stories with one room on each floor. A large fireplace in the main living room could accommodate eight-foot-long logs. Two doors, on opposite sides of the room, were large enough to allow a horse, pulling a load of logs, to come in one door and go out the other. A large oven was built into the back wall near the fireplace with a small area intended for smoking meats. Somewhat later, the house was enlarged and divided into a living room, dining room, and, upstairs, three bedrooms. When the family bought it, JHG, Sr. had a wing added that increased the size of the dining room where he also had windows built all along one wall and french doors at one end that opened onto an herb garden, the creation and love of Mrs. Gibbon. Eventually, Dr. Gibbon built a brick serpentine wall around the herb garden. A master bedroom and bath were added on the second floor.

The barn had stalls for horses and cows, and two tremendous haymows on the upper level. A carriage house was attached to a tack room containing harnesses, saddles, and bridles. Dr. Gibbon had a pigpen and two chicken houses built, and repaired an old corncrib. At first, water was pumped from a spring at the bottom of a small hill to wooden cisterns at various locations around the property.

In the early years, because of the distance from Philadelphia, the family spent only summers at Lynfield Farm and continued to live on Spruce Street during the winters. Renovations were completed in 1914, and the family moved in for the first of many summers.

The Farm became a haven of happiness and a source of new learning experiences. JHG was 11 years old in 1914 and more than ready to absorb everything he could about his new surroundings. He had already displayed a highly developed "inquiring mind." When he was about five, he and his mother were returning from an errand in Philadelphia. His mother held his hand as she tried to hurry him along, but JHG kept hanging back and "dawdling." Finally, in exasperation, his mother said, "*Will* you come along, Jack! What's the matter?" She stopped to hear whatever explanation he had for his slowness. JHG said, "Mother, if God is everywhere, but we can't hear Him or see Him, why can't we *feel* Him?"[3] He was interested in and curious about everything. The Farm offered him a much broader scope in which to expand his interests. Here, he was able to learn about and handle tools, materials, and machinery. Like his father, JHG loved working with his hands. He was also highly competitive, always trying physical exploits that he felt Sam would be unable to copy such as walking along the rafters of the big barn—and Pennsylvania barns were often exceptionally high—or swinging from a rope tied over the rafters and jumping into the haymows. They also learned a great deal about farm living and farm work. Dr. Gibbon had hired a couple to do much of the farm work and installed them in a separate small house on the property; he also employed other household help. Nevertheless, each of the children was expected to do his or her own share of chores, whether it was gardening, haying, caring for the animals, or whitewashing fences, a task that JHG was frequently called upon to do. They had a small herd of Holstein cows that had to be milked twice a day, and at one time they owned five horses and a Welsh pony. Two of the horses were used in the farm work, and the other three were hunters—two geldings and a mare. Grandfather Young contributed a great Standardbred sorrel horse as well as some young walnut trees and the bull for the beginning herd of Holsteins.[3]

On almost any day during the summer, JHG could be found working

with his father or with the hired farmer as they repaired equipment or tools. The family car was a long-lived fascination. JHG learned every facet of how the motor operated. He changed the tires when new ones were needed. He learned about batteries—how they were built and how they worked. He watched and helped with planting and harvest chores. He seemed to love the smell and feel of the rich, warm earth, the fragrance of fresh-cut hay, the feel and shape of tools in his hands, and the sounds of birds and insects throughout the long summers. When the farm work was over for the day, he found equal pleasure in reading. His mother encouraged him to read everything that interested him. Topics covered history, biography, science, medicine, poetry, and both English and American literature.

At the end of a long, busy day, JHG invariably went for a walk on the grounds, in order to "put the stars to bed."[34]

JHG grew to love the Farm. After his parents died in 1956, he bought his sister's and brothers' shares in this property that had been willed equally to all of them. As soon as was feasible, he moved his family to Lynfield Farm, where they lived for the rest of his life, amidst the warm memories of an enchanted childhood, where he could swim and play tennis as often as he found time, and where he and his wife Maly entertained frequently. Family, friends, and world-renowned physicians and scientists were among those who often visited the Farm.

World War I

War in Europe broke out soon after the Gibbons moved to the Farm. Dr. Gibbon had kept his status as reserve officer in the Army Medical Corps and was among the first to go when Base Hospital #10 went to France in 1917. His first post was at a casualty clearing station close to the front lines. Surgery was performed in tents, and personnel were frequently under direct fire. He started out in the French-American sector, but was soon promoted to colonel and made Liaison Medical Officer for all the Allied medical forces. For the duration of the war, he coordinated British, French, and American medical operations of the casualty clearing stations, from which the wounded were sent to base hospitals and then back to their home countries.

During this time Dr. Gibbon noted that the German prisoners seemed to have a better record of recovery without infection than did the Allied wounded. This observation was made at surgical stations behind the lines where major procedures were performed before the wounded were evacuated to base hospitals. After careful investigation, he and the other officers found that the Germans, while awaiting definitive surgery for their wounded, applied maggots to grossly infected wounds. The maggots de-

brided the wounds of infected material. Later, he used this information in his own work at Jefferson Medical College Hospital.

In April 1917, when America entered the war and joined the Allied forces, Marshal Jacques-Joseph-Césaire Joffre came to the United States with ex-Premier René Viviani of Italy to promote the Allied cause and the sale of war bonds. Marshal Joffre had been commander-in-chief of the Allied forces that won the first battle of the Marne in 1914. Pennsylvania senator George Wharton Pepper and the University of Pennsylvania arranged to award honorary degrees to both men. Senator Pepper, a close friend of the Gibbon family, arranged for Jack and Sam to attend the ceremony and to stand, in their boy Scout uniforms, just below the podium where the president of the university was to stand. The boys were able to witness the ceremony at close quarters and to meet the two famous honorees.

In 1917 while their father was overseas, Jack (fourteen years old) and Sam (twelve years old) were placed in charge of the two-acre asparagus patch. They had to cut the asparagus when it was ready, chop off the ends, tie it in bundles with raffia, and take it to be sold at the grocery store in town, as previously arranged by Dr. Gibbon. They drove the old family car, loaded with asparagus, from the Farm to Media and back throughout the summer—three miles each way—with no major mishaps.

Similarly, Mrs. Gibbon, with her husband in France, was faced with four children to support on a greatly reduced income. She, with several other ladies, set up an antique and tea shop where they sold Lynfield Farm produce—butter, eggs, and vegetables. At the same time, she managed the Surgical Dressings Department of the Philadelphia Red Cross.[3]

After completing the required number of years at the Episcopal Academy, Jack and Sam entered the William Penn Charter School, where they acted in school plays. In George Randolph Chester's play *Get Rich Quick Wallingford*, Jack played a male part and, for lack of an alternative at the all-boys' school, Sam played a female secretary. When the play was presented at the Bellevue-Stratford Hotel on December 20, 1918, Jack was fifteen and Sam was thirteen and a half.

One of the school requirements was to attend Quaker Meeting for worship on Wednesday evenings for an hour. Both boys were naturally boisterous and physically unable to stay still for very long; they found the hour-long meetings difficult. Sam said that this kind of discipline was a help in forging their personalities, but that the appreciation of its effect came only much later.[21]

On entering the Penn Charter School, the boys were advanced another year. This accounts for the fact that Jack was only sixteen when he entered

Princeton University in 1919 and Sam was only fifteen and a half when he entered Princeton a year later.

The Princeton Years

A former student, F. Scott Fitzgerald, attended Princeton from 1913 to 1917 but, because of consistently low academic achievement, did not graduate and, instead, left in the fall of 1917 to accept a commission as second lieutenant in the regular Army. Later, he described Princeton in his first novel, *This Side of Paradise*, in which he used the university as the backdrop: "Princeton . . . filtered slowly into his [Amory Blaine's] consciousness—West and Reunion, redolent of the sixties, Seventy-nine Hall, brick-red and arrogant [JHG's dormitory during his junior and senior years], Upper and Lower Pyne, aristocratic Elizabethan ladies not quite content to live among shopkeepers and, topping all, climbing with clear blue aspiration, the great dreaming spires of Holder and Cleveland towers."[15a]

In the days before World War I, athletics—primarily football—was the highroad to undergraduate prestige.[35a] Varsity football players were looked upon as demi-gods.[35b] Life for most lowly freshmen, however, was far more mundane, consisting of wrestling matches, pillow fights, interminable games of red-dog and poker, and bicker sessions during which the problems of the universe were settled to everyone's satisfaction.[35c]

When JHG entered Princeton in the fall of 1919, he, along with the other freshmen, was quickly oriented to the network of traditions that kept freshmen strictly in their places. They were expected to be in their rooms after the nine o'clock curfew, were forbidden to walk on the grass or to smoke pipes around the campus, and had to wear the accepted items of clothing: cuffless trousers, stiff collars, black ties, shoes *and* garters—everyone wore garters then—and black skullcaps known as "dinkies" or "beanies."[35d] The rules of dress, however, were gradually relaxed following World War I; JHG happened upon the Princeton scene at a time when many of these long-held traditions were less rigid, but nevertheless in place.

Summer in Europe

At the end of his freshman year at Princeton, JHG had the opportunity to travel to Europe with a Scottish family who saw him safely to his sister Marjorie's small apartment in Paris. She was then at the Sorbonne studying French history. He and Marjorie spent most of the summer touring the

Continent. While Marjorie delved deeper into history, JHG avidly read philosophy and comparative religion, and thought about his own values and place in the world, trying to determine who and what he was as a person—what the younger generation of today call "finding themselves." He seemed to know instinctively that "science gives us knowledge, but only philosophy can give us wisdom."[13]

JHG seemed to blossom as his self-understanding grew. It was an enriching period, not only because of the travel but because of his exploration of his inner self. During their long conversations, JHG apparently impressed Marjorie a great deal and influenced her to break away from the traditional manner of thinking regarding religion.[3]

Dorms and Clubs

No record of the Princeton years exists from JHG. University records and the *Yearbook* of 1924, however, show that in his freshman year JHG roomed alone. In 1920–21, when Jack was a sophomore, he and a classmate rented rooms off campus at 19 Edwards Place. Sam, then a freshman, rented a ground-floor room at the same house. JHG roomed with Sam in Seventy-nine Hall during his last two years.[30]

While at Princeton as students, the brothers and their classmates occasionally acquired bootleg whiskey. Prohibition had become law in 1921. These small drinking parties occurred sporadically throughout their college years. The Twenties had already been identified as "the Jazz Age," and F. Scott Fitzgerald's 1920 novel, *This Side of Paradise*, connected him in many people's minds with the period, so that he was for them both the historian—"the laureate"—of the postwar generation, and its exemplar.[28a]

During students' sophomore year, the "eating clubs" of Princeton (similar to fraternities) chose their new members. Mizener[28b] indicates that the function of the Princeton clubs was to provide a system of grading people according to social distinction. Fitzgerald's protagonist[15b] identified the members of the various clubs: Ivy as detached and breathlessly aristocratic; Cottage as an impressive mélange of brilliant adventurers and well-dressed philanderers; Tiger Inn as broad-shouldered and athletic, vitalized by an honest elaboration of prep-school standards; Cap and Gown as anti-alcohol, faintly religious and politically powerful; Colonial as flambuoyant; Quadrangle as literary. In all, there were about twelve or more in addition to these. JHG and Sam considered Cap and Gown the "nicest" of the snob clubs. The Gibbon brothers were selected for the Cloister Inn Club (not otherwise identified or characterized). JHG was also a member of the Cliosophist Club, a debating society that provided opportunities for

platform, on-topic, off-topic, humorous, extemporaneous, and individual debates.[30] In 1923 the Cliosophic Society merged with the Whig Society. Now known as the American Whig-Cliosophic Society, it is the oldest undergraduate political and debating society in the country. In his senior year, JHG was also a member of the Princeton Medical Club.[31, 37]

Walking to Philadelphia

A few weeks before Easter vacation in 1922, JHG and Sam were hard up for cash, and were trying to figure out how to buy transportation home to Philadelphia for the holiday. They talked it over with a group of their mutual friends, and they came up with the idea of walking. The distance from the dorm to their home at 1608 Spruce Street was 41 miles. They thought that they could walk the distance in twenty-four hours, perhaps less. One of the people who became interested in the project was the editor of the *Daily Princetonian*, who felt that he might be able to get a feature into the *Philadelphia Inquirer*. He decided to follow up on the story, and observed the boys' every move from the time they got up on the day selected for the walk, through breakfast at the Baltimore Dairy Lunch, to the start of the hike. They stopped at midday for lunch at a sandwich shop, and Sam took a twenty-minute nap.

They reached the intersection of Route 1 and North Broad Street, ten miles from their house, where they were greeted by about a dozen boys who showed them a copy of the *Philadelphia Evening Bulletin*, which carried a full story on this unusual undertaking. They arrived home in triumph, went to bed for an hour's rest before dinner, and then attended a debutante ball that evening, where they were the center of attention. In addition, the brothers collected eighty dollars from classmates who had bet on the time it would take them to make the walk.

Driving to New Haven

In the fall of 1922, Jack and Sam borrowed the family car, a Dodge touring car, to attend the Yale-Princeton football game in New Haven. On the way to Connecticut, the car developed a burned-out bearing. They were obliged to leave it at a garage, where the mechanic said that he would do the best he could to repair it while they were at the game. They managed to get to the stadium by hitching a ride with some Princeton friends whom they met. After making several bets at the game, which Princeton lost by a wide margin, they had only a few dollars left with which to pay for the car repairs. However, an understanding Yale student offered to pay the garage bill and they promised to send him the money.

However, as they drove on, they quickly found that the damage had not been repaired. Not only did they have to stop frequently to add water and oil, but the car also lost its muffler and the headlights went out. They stopped in Manhattan after several grueling hours on the road from Connecticut, and paid a visit to a family friend, Haridell Hallmark, fashion editor for the *New York Times*. She was out for the evening, but the doorman let the boys stay in the lobby of the apartment building until "Uncle Harry" arrived home. She was delighted to see them, and fixed them scrambled eggs, bacon, toast, and even offered to put them up overnight. They declined, however, and got back on the road. As they were passing through Hoboken, *sans* lights and muffler, a policeman stopped them. When he learned of their troubles, he simply advised them to get back to Philadelphia as quickly as possible, in their crippled car. They did.

Everyone for Tennis

In spring 1923 John Eager Howard, who later became a distinguished internist in his native Baltimore, was captain of the Princeton tennis team. Both Jack and Sam were excellent players and had many opportunities to play with him. The three of them devised a plan to have one of the U.S. Doubles champions, Vincent Richards, come to Princeton for an exhibition match. This event, and other experiences, intensified the brothers' love for tennis during their college years.

Summers in Maine

That same year, Dr. Gibbon acquired a ten-acre parcel of land on the western shore of Mt. Desert Island in Maine. Part of the property divided the estuary called Squid Cove from Goosemarsh Pond at a narrow stretch of water where there once was a mill. The property was secluded and beautiful, with pine, spruce, fir, cedar, and birch trees, and groundcover of blueberries, moss, and ferns. At low tide, the family found beds of mussels and littleneck clams. Flounder and mackerel were plentiful.

The next summer, 1924, following JHG's graduation from Princeton, the family went there to camp for the first of many summers. One main cabin had a living and dining area, a bedroom, and a bath for Dr. and Mrs. Gibbon. Built-in bunk beds were in two additional "dormitory" buildings for the Gibbon children and, later, grandchildren. All the buildings were connected by covered walkways.

The family treasured these years, when cooking was done on kerosene stoves and lavatory facilities were somewhat primitive, but there was plenty of time for reading, hiking, fishing, boating and telling stories in front of

the fireplace in the main living room in the evenings. Shopping was done at nearby Bar Harbor.

The three boys and Marjorie learned a great deal about "roughing it" in the wild, with limited resources. The boys learned carpentry, woodcutting, fire building, boat building, and other similar skills. Majorie and some of her friends joined in these activities as much as possible, but also perfected their cooking skills under the tutelage of Mrs. Gibbon, an expert cook. Dr. Gibbon continued teaching chess to the boys, and maintained the same standards of conduct during vacation times as were expected at all other times.

Death of Grandfather Young

In 1924, Mrs. Gibbon received word that her father had died December 1 in Helena, Montana at the age of 84. An entry in her diary on that date was:

> 12/1/24- ". . . and lo! a certain moment shuts the daylight off, calls the glory from the grey." At sunset came the news that my blessed Father had died peacefully at six this morning, December 1st, the 63rd anniversary year of his marriage to my dear Mother.

The family traveled to Washington, D.C. for the funeral services and the burial at Arlington Cemetery. They rode in the cortège which moved slowly from the chapel to the burial site, preceded by a troop of cavalry, the coffin, and a horse with all the military trappings. The cavalry officer's boots were placed in the stirrups with the toes pointed to the rear. During the procession, a canon was fired once a minute. At the grave, a squad of riflemen fired three salvos over the coffin and a bugler sounded Taps. It was a funeral befitting a man who had enlisted during the Civil War, had held every rank except that of first lieutenant, and was the first Lieutenant General, the first Chief of Staff, and the first Head of the War College.[21]

Medical Education

Following his first year at Jefferson Medical College, JHG went to his father and said that he didn't want to finish medical school—he really wanted to become a writer. As always, Dr. Gibbon listened attentively to what Jack had to say, then tactfully persuaded him to complete his medical education and, at the same time or in connection with his medical profession, develop his writing skills so that he could share with other members of his profession events of importance occurring in the medical world. Jefferson was,

from its inception in 1825, a center for medical education in the United States. Much was happening there and at other medical institutions in Philadelphia; Jack would not have difficulty in finding things to write about regarding medicine. JHG graduated in 1927. For the next two years he had an internship at the Pennsylvania Hospital.

While at the Pennsylvania Hospital, JHG came under the influence of Joseph M. Hayman, Jr., a physician-researcher who at that time was in charge of the medical wards under Dr. Thomas McCrae.[19] Dr. Hayman was studying the effects of potassium chloride versus sodium chloride in the diet of patients with hypertension. The realization that controlled research studies could add substantive knowledge to the medical literature and thus increase the efficacy of medical treatment of diseases initiated JHG's lifelong interest in and devotion to meticulous clinical research.

This beginning interest in research led him to seek a year-long research fellowship with Edward D. Churchill at Harvard. This opportunity suggested to him by Dr. John B. Flick, a surgical resident at the Pennsylvania Hospital under JHG's father, who was chief surgical resident. At that time, there were no medical or surgical "residents," as the term is understood today (a physician still in training in a particular specialty). A "chief resident" was a jack-of-all-trades who arranged schedules, clinical rotations, vacation time, and some details of hospital care of patients.[19]

JHG knew that his father wanted him to begin his professional career by joining him at the Pennsylvania Hospital, where JHG, Sr. had spent much of his professional life. However, JHG had become entranced by research, which Dr. Hayman had encouraged because he saw in JHG those qualities necessary for a researcher: an inquiring mind, the ability to indefatigably pursue small details, the determination to persevere even in the face of apparent failure, an analytical approach to problem solving. His father accepted his decision, at the same time urging him not to neglect the practice side of surgery, but to combine the two. This suggestion made sense to JHG, who later promulgated this attitude in his own residents, believing that clinical practice forms the basis for the best research.

JHG left for Boston, not realizing that the next year would change his life and set him on the course that would eventually lead to the development of his pump oxygenator.

The 1930s—Sigificant Years

Enter Maly

JHG began his fellowship year early in February 1930. Soon after arriving at Massachusetts General Hospital, JHG met Dr. Churchill's research assistant, Mary Hopkinson—known to her family and friends as Maly.

The daughter of a well-known portraitist, Charles S. Hopkinson, and Elinor Curtis Hopkinson, Maly was born on September 23, 1905 in Manchester, Massachusetts, the second of five daughters. She described her family as well-to-do. She attended the Buckingham School and Miss Winsor's School, in Cambridge and in Brookline, Massachusetts respectively. For two years she attended Bryn Mawr College near Philadelphia. Maly then decided that continuing college was not as important as travel and left Bryn Mawr to study music in Paris. By arrangement, she was to stay with a cousin who, with her physician husband, was living in Paris at the time. Over the next year she worked hard at her studies, installing a small, rented upright piano for her use in a tiny cellar room of the apartment on the Left Bank.

Her cousin was Frances Eliot, granddaughter of the late Charles Eliot, a former president of Harvard University. Frances had married a young doctor, Frank Fremont-Smith (who later would be associated with the Josiah Macy, Jr. Foundation and instrumental in helping JHG to obtain research funding). The couple with their two small sons were studying in Europe that year. They had first lived in Germany, then moved to Paris, where Maly joined them. Maly and the Fremont-Smiths were paying guests in the large apartment of a Russian émigré, near the Champs de Mars. Here, night after night, Frank talked with Maly about medicine in all its aspects, and especially about related research activities going on both in Europe and in America. During those winter evenings, as she listened to Frank, Maly decided that, when she returned to Boston in the summer, she would apply to Harvard Medical School for a job as a laboratory assistant.

Soon after returning home, she introduced herself to Dean Edsall at Harvard to say that she was interested in laboratory work, and then en-

rolled in a summer course being offered by the medical school that covered laboratory procedures. Dean Edsall's secretary called her a few days later to say that Dr. Churchill needed a laboratory technician at Massachusetts General. She met him the next day and he offered her the job. Gratefully, she accepted. The year was 1927.

By the time JHG arrived in the laboratory at Massachusetts General, Maly had been there for three years. She had become quite knowledgeable about laboratory procedures involving animal research. Conscientious and eager to learn, she was an asset to JHG's laboratory work done under the supervision of Dr. Churchill and reported in the medical literature.[22] This research was most relevant to JHG's later work on the pump oxygenator.

The 1931 Animal Experiments

In the experiments performed under the direction and supervision of Dr. Churchill, cats were used as the experimental animals. The study involved observing effects on the animals of partial and complete obstruction of the pulmonary artery, thus simulating a pulmonary embolism. JHG was able to show that, as the pulmonary artery was compressed with a clamp that could be closed by very small increments (0.079 mm), there was a corresponding gradual decrease in the animal's arterial pressure and a gradual rise in venous pressure.

The decrease in arterial blood pressure was caused by diminished cardiac output resulting from forced accumulation of the blood on the venous side of the circulation as the pulmonary artery was closed.

Occlusion of the pulmonary artery sufficient to cause a drop in systemic blood pressure of more than 10 mm Hg was accompanied by a decrease in cardiac output varying between 31% and 66%. As expected, the amount of decrease in blood pressure and the amount of decrease in cardiac output were directly related to the degree of occlusion of the artery.

In fourteen experiments JHG and Maly made determinations of the cross-sectional areas of the pulmonary artery as compression occurred. They found that the systemic blood pressure was not significantly lowered until 61% to 86% of the artery was occluded, and that compression was not fatal until 84% to 96% of the artery was occluded. They concluded from these experiments that only a clamp capable of very fine increments would be suitable for this type of work so that subtle effects that occurred during a slow, gradual compression could be observed and recorded. As JHG's results showed, cardiac failure occurs only when at least 81% of the artery is occluded.

This early work was a necessary prelude to the work still to come, for it

planted the first seed in JHG's mind about the link between the physiological events surrounding pulmonary embolism, and the use of a pump oxygenator to temporarily take the place of the compromised heart and lungs. JHG, however, was unaware of the connection until he was a participant in a clinical event that took place soon after—an event that was to prove critical to JHG's furture.

Patient with Pulmonary Embolus

At 2:45 on the afternoon of October 3, 1930, Dr. Churchill and Dr. James White were called in consultation to the bedside of a middle-aged, rather obese woman who was lying in bed in a semiconscious condition, with pale, clammy skin and breathing with difficulty. Only five minutes earlier this patient had been well, recovering uneventfully from an operation two weeks before in which her gallbladder had been removed. At that time, the care of all postoperative and postpartum patients required at least two weeks in bed. She had been wheeled to the lavatory at 2:30 and had just returned to her bed, when she had a queer feeling in her right chest "like a lump" that immediately developed into a sharp pain. As the doctors examined her, she became paler, apprehensive, and nauseous. Dr. Churchill made a diagnosis of massive pulmonary embolus, a large blood clot lodged in the pulmonary artery—the artery that carries blood from the right side of the heart to the lungs to be oxygenated. He ordered her to be moved at once, in her bed, to the operating room and made the necessary arrangements for an emergency operation if it were needed.

He assigned Jack Gibbon the task of recording the patient's blood pressure, pulse, and respirations every 15 minutes. The surgical procedure that Dr. Churchill intended to perform was the Trendelenburg operation, named for the German surgeon who first described pulmonary embolectomy. The outcome of such surgery at that time was usually death of the patient. There had been no successful attempt in the United States to surgically remove a clot from the artery. In the European medical literature, reports indicated that only nine patients out of 140 surgical attempts had survived. As JHG's monitoring proceeded, there was an indescribable tension, an atmosphere of anxious anticipation, while everyone waited. His own thoughts ran along one path: If only we could remove the blood from her body by bypassing her lungs, and oxygenate it, then return it to her heart, we could almost certainly save her life. The wish was only that—no one had devised a way to perform the functions of the heart and lungs outside the body, that is, extracorporeal circulation (ECC).

Finally, at 8 o'clock the next morning, the patient's condition notice-

ably worsened; Dr. Churchill immediately opened her chest. Within less than 7 minutes, he had removed several large clots from the pulmonary artery. Despite efforts to revive the patient following the surgery, she never regained consciousness.[24]

Beginnings

This "critical event" had a profound effect on JHG and determined his course for the next 23 years. During the weeks following the death of the woman, JHG thought about nothing other than the possibility of developing a machine that could take over the functions of the heart and lungs during short critical periods, just long enough for emergency surgery to correct a life-threatening problem or a cardiac defect. With characteristic determination, JHG made up his mind to try to develop such an apparatus—a heart-lung machine.

The fellowship year came to an end between the time JHG and Maly became engaged in January 1931 and were married on March 14. When they returned from their honeymoon, they lived in the family home on Spruce Street until 1940, except for the two fellowship years—1934–35 and 1938—at Harvard and Massachusetts General. In 1931, JHG was offered, and accepted, a position as Fellow in Medicine at the University of Pennsylvania School of Medicine. At the same time, he was named Assistant Surgeon at the Pennsylvania Hospital. Although his father very much wanted JHG to confine his work to clinical practice there, where he himself had spent so much of his professional life, JHG was determined to continue on his dual path of surgical research and clinical practice.

JHG practiced surgery in the mornings and did research in the afternoons under Dr. Eugene H. Landis, recently returned from Europe where he had worked with Sir Thomas Lewis in London and Dr. Augustus Krogh in Copenhagen. Landis later became Professor of Physiology at Harvard Medical School. JHG and Landis began studying the effect of temperature and tissue pressure on the movement of fluid through the human capillary wall. JHG later said that he learned a great deal about research methodology from Landis, particularly the painstaking replication of carefully planned experiments in an attempt to obtain the same results time after time, thus establishing validity and reliability.

In these experiments, they used hot water in a pressure plethysmograph around their forearms. JHG noted that during the experiments he became uncomfortably warm all over. Curious, he built a homemade thermocouple apparatus to measure the skin temperature of fingers and toes. He and Maly experimented at home by filling a hand basin with hot water

and immersing their hands and forearms after attaching thermocouples to their toes. They observed the sharp rise in skin temperature of the toes, which rose to a maximum level after 30 minutes of immersion. Then, immersing their feet and lower legs in hot water, they noticed a similar rise in skin temperature in their fingertips. Results of this study were published in 1932.[23] He and Maly performed other experiments at home involving effects of cold on temperature, with cold applied both internally and externally.

During those three years—1931–34—JHG frequently talked to physician colleagues and others about his idea of oxygenating blood outside the body, but no one seemed interested. Despite the lack of encouragement, JHG persisted. He soon realized, however, that such an undertaking would require full-time work, which was not possible in his current position. He therefore wrote to Dr. Churchill to request another year's fellowship. While not enthusiastic about the prospects for developing a workable heart-lung machine, and seriously doubting that it would ever be done, Dr. Churchill nevertheless offered JHG the research fellowship and, in addition, offered Maly a position as JHG's laboratory assistant to enable them to work together on the project.

A friend of JHG, Walter Bauer, who was then in the Department of Medicine at Massachusetts General, was even less enthusiastic than Churchill about the proposed heart-lung machine and in fact tried to talk JHG out of proceeding in that direction. Bauer suggested that if JHG wanted to pursue an academic career in surgical research he should undertake a number of smaller and less ambitious projects that could be reported in the medical literature regardless of results. The problem, he said, with doing research on a pump oxygenator was that if the project failed, the results would not be worth reporting. The only colleague who actually encouraged him, said JHG later,[21] was Dr. Landis at Penn. His advice was that, if JHG thought it had a chance of being a success, he should give it a try. That was all the encouragement JHG needed. He and Maly packed themselves and their two children—Mary, born February 28, 1932, and John, born February 12, 1934—and headed once more for Boston.

JHG's Exploration of the Literature

History of Artificial Circulation

The idea of extracorporeal circulation was born when physicians and anatomists learned the relationship of the heart to oxygenation. The concept was

first recorded in 1812 by LeGallois,[34] who said, "If one could substitute for the heart a kind of injection of arterial blood, either natural or artificially made, one would succeed in maintaining alive indefinitely any part of the body whatsoever."

The idea seemed, initially, simple enough: All that was needed was a pump, a system for oxygenating the blood, and a blood supply sufficient to maintain blood flow at the necessary rate. During the ensuing decades, many scientists experimented with perfusion of individual animal and human cadaver organs, during which adequate oxygenation was maintained for short periods of time using the concept of flow of oxygenated blood through the organ by means of a small pump. The literature indicates, however, that at the beginning no one ever envisioned the possibility that a person's entire circulation could be maintained by an oxygenator for *any* length of time. Dr. Churchill's spoken doubts typified the prevailing opinion.

Sixteenth to Nineteenth Centuries

Initially, work focused on techniques for making blood transfusions possible. Lower is credited with performing the first direct blood transfusion in 1665. Results of this early work were published in *Philosophical Transactions* in 1666. Problems with clotting in succeeding attempts throughout the following decades diminished incentives for continuing the work.

Lavoisier's work with "vital air" late in the eighteenth century revitalized interest in extracorporeal circulation and perfusion experiments, based on new knowledge about oxygen ("vital air") as being essential for the maintenance of life, and the relationship of blood and oxygen in terms of gas exchange in the lungs.[2]

Early in the nineteenth century, Prevost and Dumas,[41] French physiologists, placed blood into a rotating cylinder that caused fibrin from the blood to collect on the walls of the cylinder. The result was their discovery that this process produced defibrinated blood, which did not clot as readily as blood with the normal amount of fibrin.

Throughout the seventeenth and eighteenth centuries, scientists had tried using various substances to control clotting, but none was found to be sufficiently effective for transfusing blood except in small amounts. The widespread use of leeches during this time, however, resulted in the discovery in 1855 that a substance in the saliva of leeches was effective as an anticoagulant. This substance was used in transfusing blood until World War I.[38]

During the nineteenth century, many experimenters developed equipment to perfuse body organs, demonstrating that perfusion could maintain

an organ outside the body for relatively long periods of time. Trendelenburg's work in the area of pulmonary artery embolism was another factor in the emerging hope for the development of an oxygenator. Mortality rates relating to surgical removal of blood clots from the pulmonary artery were so high that most surgeons would not attempt the procedure.

As Churchill stated, quoting another surgeon, "Nystrom[40] advised postponing surgery to remove a pulmonary embolism until the patient is practically moribund, because of the difficulty in making the diagnosis and the uncertain prognosis. When one waits that long, the procedure can perhaps be more properly termed an immediate postmortem examination rather than a surgical procedure." The cause of death in massive pulmonary embolism is a greatly decreased cardiac output. The blockage in the pulmonary artery prevents the heart from continuing to transfer blood from the venous to the arterial side of the circulatory system.[7]

In this and similar circumstances, the only possible method of securing and maintaining an acceptable level of oxygen in a patient's circulation is by means of an oxygenator. Using a pump oxygenator, oxygenation of the blood can be carried on outside the body. The venous blood is gradually removed from the patient using one or two of the larger veins such as the internal jugular vein or the venae cavae. The superior and inferior venae cavae are the largest veins and empty all venous blood returning from the general circulation directly into the right atrium.

By bypassing the heart and lungs, the pump oxygenator removes the deoxygenated venous blood and circulates it through the oxygenator where it is exposed to an atmosphere of a high concentration of oxygen. In the process of gas exchange, oxygen replaces carbon dioxide, which is dispersed. From the oxygenator's "lung," the oxygenated blood is returned to the arterial system, usually through the femoral artery, through the arteries, arterioles, and capillaries, and thus to every cell in the body.

Two objectives which provided motivation for attempting to develop this technical capability were: 1) to make physiological observations not readily obtained by other means, and 2) to perform intracardiac operations under direct vision while the circulation of blood through the heart and lungs is temporarily bypassed.[8]

External perfusion of kidneys was first tried in 1849 by Loebell,[36] using Carl Ludwig's laboratory. Between 1848 and 1858 Brown-Séquard,[4] showed the need to oxygenate blood used as a perfusate. In experiments on the limbs of guillotined criminals, he used his own blood to demonstrate that muscles at the stage of rigor mortis, while not responsive to galvanic stimulation, could be reactivated by perfusion with oxygenated blood and

kept responsive at the same time that the unperfused part of the body degenerated. In 1868 Ludwig and Schmidt[37] described an apparatus which enabled artificial blood to be infused under constant pressure from a reservoir into an isolated mammalian organ.

In 1881 Von Schröder[42] developed the method of bubbling air through venous blood from the bottom of a bottle, producing foam and thereby aerating blood. This method, used by von Frey and Gruber[16] in 1885 in their oxygenator, had to be abandoned because it was later discovered that excessive air in the circulation produces air emboli that cause death when they reach the heart or lungs.

Twentieth Century

The discovery of heparin by McLean in 1916[39] became the critical event in treating blood to prevent clotting and thus keeping it in a fluid condition for as long as was necessary in order to carry out artificial circulation (AC). According to Edwards,[15] the first oxygenation of perfusion fluid is credited to scientist/aviator Charles A. Lindbergh.[35] Working with Alexis Carrel in 1920,[6] the young Lindbergh developed a system whereby perfusion fluid was oxygenated and driven by compressed oxygen gas. Belt, Smith and Whipple,[1] writing in 1920, discussed factors relevant to perfusing living organs and tissues.

Early in the twentieth century, remarkable advances in thoracic and cardiac surgery were made. JHG, Sr. had written an article about repair of traumatic wounds to the heart. As JHG, Jr.[19] pointed out: "The experimental demonstration of the nature of Pick's disease and its operative cure constitute a past chapter in the history of cardiac surgery. The repair of wounds of the heart is being accomplished with an increasingly lowered mortality rate. Recently a method of establishing a collateral blood supply for the myocardium when the coronary vessels become occluded has been demonstrated on animals and applied successfully to patients." However, attempts to carry out surgical procedures within the cardiac chambers or great vessels at the base of the heart were essentially unsuccessful. The Trendelenburg operation for pulmonary embolectomy was associated with a discouraging mortality in European countries, and was not carried out successfully in the United States until many years later. Surgical procedures designed to relieve stenosis of the mitral valve were even less successful.

It was obvious to JHG and other surgeons that procedures on the heart could be performed effectively only if the heart could be temporarily relieved of its function of pumping blood. "If the flow of blood through the heart and lungs could be safely stopped for 30 minutes," said JHG, "it is

conceivable that *a new field of cardiac surgery might be developed*" [italics added].[20]

Researchers persisted, despite continuing problems and failed animal experiments. The mechanization of the pumping part of the circuit (of artificial circulation), although seemingly simpler to devise than that of the exchange of gases, proved to be quite difficult. Experimenters tried intermittent and constant pressures, and various levels of pressures, none of which was successful. The idea that pulse pressure was a necessary factor in perfusion was emphasized as early as 1910 by Hooker.[29] In 1928 Dale and Schuster,[10] working at the National Institute for Medical Research in Hempstead, England, developed a double perfusion pump intended to carry out whole-body perfusion for both the arterial and venous circulation. Although the pump was used in perfusion experiments, it was not sufficiently developed to support whole-body perfusion.

In 1929 Gibbs[25] developed an artificial heart while working at Dalhousie University in Nova Scotia. It consisted of two bellows within a round brass container. Using this equipment he carried out total bypass of the heart and lungs in cats, but none of the animals survived. He did further work with dogs using artificial heart equipment at McGill University and at the Pharmakologisches Institute in Vienna. DeBakey's[12] work with a simple roller pump device that he perfected during the 1930s contributed to the efficiency of blood flow during extracorporeal circulation experiments by decreasing the degree of damage to blood cells.

Animal experiments in which the pulmonary artery was occluded by means of a compression clamp (Figure 1) were carried out by Cohnheim[9] and by Haggart and Walker.[27] These early experiments resulted in the same conclusions that Churchill and JHG obtained in their 1930–31 experiments: compression of the pulmonary artery by small increments caused little change in the blood pressure until the artery was 81% to 96% occluded, at which time the animal died unless the artery was released quickly.

Early Anesthesia

With respect to anesthesia, the first use of pentobarbitone occurred in 1931. JHG's and Churchill's experiments at this same time can be considered pioneering work since the anesthetic's effects on animals during surgery were still not fully known. The dosage by intraperitoneal injection did not give consistent results in that there were cases in which only narcosis was obtained, frequently accompanied by excitation. In other cases, anesthesia became alarmingly deep and in a few rare cases resulted in death.

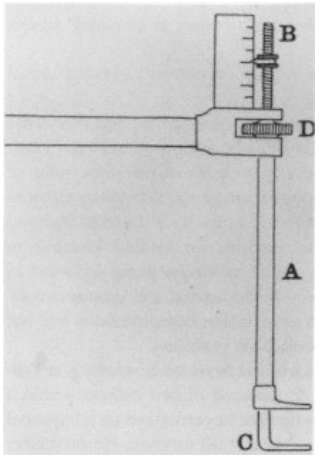


Figure 1:
Compression Clamp. The compression clamp was used in all early animal experiments to gradually compress (close off) the pulmonary artery, which normally carries deoxygenated blood from the venous system to the lungs for oxygenation—the point at which the oxygenator takes over the functions of the heart and lungs. As the pulmonary artery was clamped, the oxygenator was activated.
Source: Gibbon JH, Jr (1937). Artificial maintenance of circulation during experimental occlusion of pulmonary artery. Arch Surg, 34:1105–1131, p. 1120.

Wright and his colleagues[28] decided to use only the intravenous method for injecting the anesthetic, stopping when the required depth of anesthesia was obtained. By 1938, they had used this method in over 2000 surgical cases with cats and dogs in the Beaumont Hospital of the Royal Veterinary College of London. In 800 consecutive cases, there was not a single death attributable to the anesthetic.

JHG's reading during the beginning of his fellowship year strengthened and reinforced his idea of developing a pump oxygenator that could be used on humans. His goal was to develop an oxygenator that would take over the functions of both the heart and the lungs for a period of time long enough to permit corrective procedures while the heart was at rest and in a bloodless operative field. He felt that nothing less would suffice. The accumulated knowledge derived from his reading emphasized the difficulties that lay ahead, but JHG was undeterred.

Components of an Extracorporeal Apparatus

From past experience and from his reading, JHG was familiar with the components of any heart-lung machine that he would build.

1. A venous reservoir.

This reservoir is placed so that venous blood can be siphoned off by gravity. Gravity is used to collect excess blood (cup at bottom of oxygenator) and for escape of any air bubbles that might combine with the blood during the perfusion process.

2. The oxygenator.

Before developing this part, JHG talked with a faculty engineer at Harvard about the design that would most effectively carry out the process of oxygenation of the blood. Together, they decided that a revolving, slightly cone-shaped cylinder would be best. The venous blood would be continuously added at the top of the cylinder and, as it flowed downward, the centrifugal force of the revolutions would cause it to film out thinly along the sides of the cylinder. This thin film of moving blood could then easily pick up oxygen that would be flowing into the cylinder, and give off carbon dioxide during the oxygenation process. JHG's goal was 95% oxygenation of the blood. The filmed blood descended on the inner surface of the cylinder and flowed out the bottom—narrowed almost to a knifelike edge—where it then passed into a stationary cup that closely surrounded the bottom of the cylinder. The knifelike edge and the proximity of the stationary cup were so designed to eliminate, as far as possible, trauma to the cellular elements of the blood that occurs from abrupt changes in flow rate or direction of flow. With a wider gap between the cylinder and the bottom cup, greater damage would occur. The bottom of the collecting cup was made of glass and had a glass jacket around it through which warm water was continuously circulated to maintain a constant temperature. A second warm water jacket was applied to another portion of the circuit for the same purpose.

Dr. Clarence Dennis[13] remarked that the revolving cylinder method for filming blood for oxygenation was probably the best method ever devised. The only problem—and it was the same problem that caused JHG to look to IBM in the 1940s for assistance—was that to develop the oxygenating capacity required for an adult the cylinder would have to be exceptionally tall. JHG estimated that it would have to be two stories high to achieve the necessary oxygenating capacity.

3. Heating of the blood or perfusate.

Heating is necessary for controlling the temperature of the blood to result in both systemic cooling and

rewarming. JHG accomplished this by placing the cylinder into an outer sleeve to which water was added. The water could be heated or cooled as necessary to maintain appropriate temperatures of the blood.

4. An arterial pump.

This pump is needed to deliver the oxygenated blood back into the body through the femoral artery. JHG decided to use the Dale-Schuster pump, which seemed to meet his needs because it provided sufficient but not excessive pressure that would cause hemolysis (breaking up) of the blood cells. Any pump would have to be calibrated frequently in order to regulate precisely the flow rates deemed appropriate for the situation.

To ensure that all of these components would work efficiently and flawlessly under changing conditions, and to carry out surgical procedures on the heart, each component had to be developed and thoroughly tested. The testing procedures had to assess the component's capability not only under laboratory conditions, but also under clinical conditions during actual surgery. It was also necessary to determine the effect(s) of each component on the animal's body and physiological processes.

Design and testing of the combined components involved research in many areas. JHG therefore had to:

• determine the amount of blood necessary to provide sufficient oxygen to all cells and tissues in the body for relatively prolonged periods of time.

• determine what materials would be best suited to each of the components to prevent damage to blood cells and allergic reactions in body tissues, and would allow for appropriate designs of cannulas, tubing, reservoirs, and other parts of the apparatus. JHG had limited materials from which to choose: gum rubber for tubing, glass or metal for cannulas and connections.

• design part, including cannulas and connections, that would in all cases cause the least damage to blood cells, prevent clotting, and provide for most effective and efficient blood flows, rates of flow, etc.

• design parts to allow for efficient cleaning.

• design parts that would allow for adequate maintenance of blood volume at all times during the oxygenation circuit.

• design or use pumps that would provide for both pulsatile and laminar (smooth) flows so that testing could be done on each, and determine the effects of each.

• design and select materials for inflow and outflow valves.

• design and select materials and surface area where gas exchange would occur.

• provide for continuous recording of temperatures of both patient and perfusate.

• provide for continuous recording of oxygen and carbon dioxide levels in both venous and arterial blood.

• provide for continuous recording of pump pressures.

JHG designed, built or arranged to have built, and tested all the parts needed for the apparatus. Knowledge about biochemical components and their relationships and about the patient's physical and physiological responses to extracorporeal circulation was almost totally lacking at that time. However, as JHG said later,[21] he had either solved, or become aware of, all of the major problems associated with ECC during the animal experiments of the 1930s. His habit of performing laboratory experiments with meticulous care and making adequate laboratory notes during each procedure accounted for his later success based on the enormous amount of experience and information gained from these early experiments, often accumulated through trial and error. He used his innate intellectual abilities and extensive knowledge of physiology to recognize relationships and to deduce outcomes based on his precise observations. His experiences at Lynfield Farm while he was growing up were also helpful to his experiments; he was accustomed to handling tools and knowing how equipment and parts such as motors and pumps worked.

Appendix Table 14 summarizes the tests (Experiments #1-P to #22-P) that were carried out in the period 1934–35 in conjunction with the animal experiments done during the same period (Observations #1-A to #14-A, Appendix Table 15).

From the beginning, neither the actual process of ECC nor the operative procedure changed significantly over time. JHG's apparatus was well designed and continued to work well, with periodic improvements aimed at increasing efficiency and oxygenating capacity, throughout the 1930s. Both the apparatus and the operative procedure are described below.

The Extracorporeal Circulation Process

The first apparatus developed at this time can be seen in the schematic drawing in Figure 2. The revolving cylinder marks the start of the process,

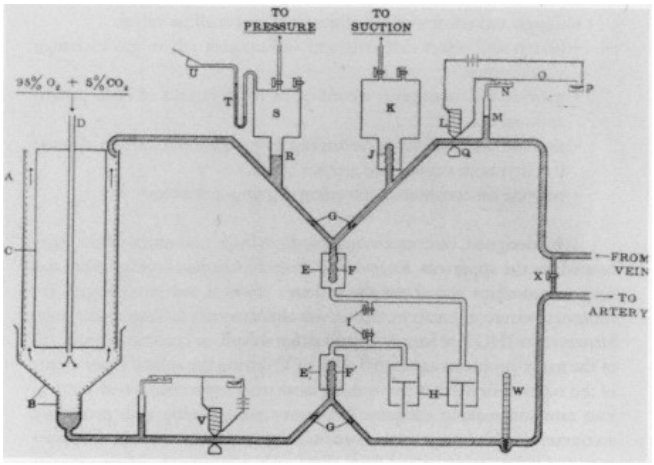


Figure 2:
Diagram of the First Apparatus. The drawing shows the path of blood from the venae cavae or jugular vein through the extracorporeal circuit, with oxygenation occurring within the large rotating cylinder, from which the blood was withdrawn and pumped back into the arterial system.
Source: Gibbon JH, Jr (1937). Artificial maintenance of circulation during experimental occlusion of pulmonary artery. Arch Surg, 34:1105–1131, p. 1108.

when blood is added at the top (A) in the direction of revolutions. The film of blood moved downward by gravity, and the blood was collected in a stationary cup (B) at the bottom. The greater part of the space within the revolving cylinder was occupied by a hollow, closed, stationary cylinder (C) through the center of which passed a metal tube (D). A mixture of 95% oxygen and 5% carbon dioxide was conveyed through this tube to the bottom of the oxygenator. From there the gas passed up between the stationary cup and the revolving cylinder over the film of blood and escaped at the top. The apparatus was designed to meet the requirements of this particular problem. The ratio between the amount of oxygen introduced per minute into the blood and the volume of blood contained in the oxygenator was higher than in other oxygenators that had been described up until that time. JHG's oxygenator provided a flow of blood

of 500 cc or more per minute. Variations in the rate of flow did not produce foaming.

Blood was moved through the artificial circuit by two pumps. One (E) transferred the blood from the venous cannula to the oxygenator, while the other (E') returned the blood from the oxygenator to the arterial cannula. The pumps were based on de Burgh Daly's[11] modification of the perfusion pump of Dale and Schuster.[10]

The principal feature of each pump was a rubber finger-cot (F, F') which was alternately compressed and expanded by air. The finger-cot was placed in the blood circuit between two valves (G) that directed the flow of blood. Expansion and compression of the air in the finger-cot chamber were accomplished by an air piston pump (H). A small air compressor pump was converted to this purpose by removing the valve in the cylinder head and sealing the valve in the piston head. The outlet at the top of the cylinder was connected by rubber pressure tubing with a small air chamber surrounding the finger-cot. The downstroke of the piston decreased the air pressure in the closed system and the finger-cot (F) expanded, drawing blood into it through the inlet valve and closing the outlet valve. The upstroke of the piston compressed the air in the closed system and collapsed the finger-cot, which expelled its contained blood, closed the inlet valve and forced blood through the outlet valve.

A side arm closed by a needle valve (I) projected from the tubing between the air pump (H) and the blood pump (E). By adjusting this needle valve (I), varying degrees of leakage to and from the closed system could be produced. The amount of air leakage controlled the degree of compression and expansion of the finger-cot and therefore governed the amount of flow of blood through the pump. The venous blood pump (E) and the arterial blood pump (E') were similar in all respects. The air piston pumps were driven by a 1/4-horsepower electric motor. The motor was geared by means of pulleys to the piston pumps; the latter made 150 complete up and down strokes per minute. This approximates the rate of a cat's heart under barbital anesthesia.[18]

The Early Oxygenator Experiments—1934–1935

Heparin, first extracted for human use by McLean in 1916, had recently become available in Canada in a form sufficiently purified for use in humans. Although no drug antagonistic to heparin was then available, such a

drug was not really necessary, as the effects of heparin wore off in the body after several hours, a period that could be as long as 24 hours. Still to be investigated was whether researchers could operate on animals without a resulting fatal hemorrhage because heparinized blood will not clot readily.

JHG and Maly chose cats as the experimental animals, primarily because JHG knew that any apparatus he built would not have a capacity to sustain the heart and lung functions of larger animals. Also, cats were readily obtainable, were less expensive than dogs, and were of a size in which manipulation of vessels and organs would be relatively easy, and in which cannulation could be carried out without too much difficulty. For anesthesia, JHG elected to continue using sodium barbiturate intraperitoneally or intravenously as indicated. Later, ether was used for supplemental anesthesia as needed.

To simulate a massive pulmonary embolism, JHG planned to compress the pulmonary artery gradually until the systemic arterial pressure fell and the systemic venous pressure rose. At that time, he and Maly would continuously withdraw venous blood from the cat by means of gravity, pass it through the apparatus where the blood could pick up oxygen and give off carbon dioxide, and then return this arterialized blood to the systemic arterial circulation by means of inflow, using a pump, into a peripheral artery.

Because they wanted to observe the effect of these procedures on respiration, the pulmonary artery had to be exposed for clamping in a naturally breathing animal. This was accomplished in the early experiments by using the Drinker preparation (Figure 20).[14]

They removed a portion of the cat's sternum, opened both pleural cavities, incised the pericardium longitudinally, and sutured the cut edges of the pericardium to the tissues of the chest wall. This made an airtight closure which, at the same time, presented the open heart for further surgery during the second stage of the procedure involving the use of artificial circulation. This procedure required artificial respiration but at its conclusion, after aspiration of all residual air from both pleurae, the pulmonary artery was exposed for compression by the clamp in a cat that was breathing naturally.

JHG then had to decide upon the appropriate method of withdrawing blood from the cat and subsequently reinjecting it. He selected a single vein (the external jugular) from which to withdraw blood, and a single artery (femoral) into which to inject the arterialized blood. Venous blood was withdrawn through a thin-walled metal cannula inserted through the jugu-

lar vein into the superior vena cava so that the tip of the cannula lay just above the right atrium (directed toward the head of the cat). Following cannulation and perfusion, simple ligation of the femoral artery did not cause any impairment of the circulation to the hind leg; therefore, no repair of the artery was done. Similarly, ligation in lieu of repair of the jugular vein in the neck produced no ill effects.

Pumping Blood Through the System

Pumping blood through the extracorporeal circuit was not a great problem. Many types of pumps had been developed in the past for such a purpose. During the 1934–35 experiments, JHG used a pump that required internal valves, although in subsequent animal experiments (1938), he used a valveless roller-type pump developed by DeBakey (Figure 3).

The valves in the pump, as well as parts of much of the other areas of the apparatus JHG developed, were handmade from various substances tried out in order to find the best material to use for a particular part or purpose. The diagrams in Figures 2 and 3 illustrate points in this description of valves and pumps. The valves in the pump, for example, were constructed by cutting four-fifths of the way through the small end of a rubber cork with a razor blade, thus constructing a flap of 1 or 2 mm in width. Elevating this rubber flap, he then bored a channel through the center of the cork. With a glass tube in this channel and with the cork inserted into a larger glass tube, he had a valve that permitted adequate flow through the circuit in only one direction. One of these valves was then attached to each of two arms of a Y-tube. The third arm was attached to a rubber finger-cot, which was subjected first to suction and then to pressure. This caused blood alternately to be sucked through one of these valves into the finger-cot and then to be ejected from the finger-cot through the other valve.

The blood pumps were activated by a piston-type air pump. One of these pumps pushed the blood into the artificial lung, while the other pump pushed the blood that had passed through the lung into the animal's femoral artery. These pumps were rather crude, but proved adequate for JHG's purposes.

With this contrived apparatus, JHG was able to achieve his initial objective. That objective was to show that the use of an extracorporeal circulation device embodying a mechanical heart and lung made it possible to temporarily maintain a part of the cardiorespiratory functions in the face of an obstruction to the pulmonary artery, which, in the absence of any extracorporeal circulation, would have caused death.

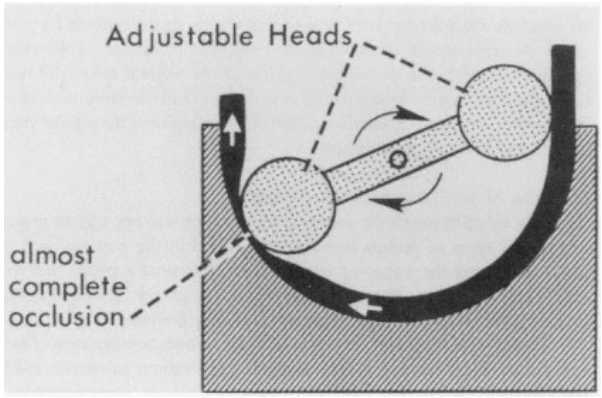


Figure 3:
DeBakey Pump. This pump is a constant injection roller type used first in blood transfusions. This design eliminated the need for valves and caused minimal damage to blood cells. A modification of the original pump, driven by an electric motor, was adopted by JHG in his second pump-oxygenator. Versions of this pump are still used in modern heart-lung machines.
Source: DeBakey ME (1934). Simple continuous flow blood transfusion instrument. New Orleans Med Surg J, 87:386.

A little later that year—1935—JHG was able to maintain the entire cardiorespiratory functions of cats when the pulmonary artery was completely occluded for as long as 2 hours and 51 minutes. Finally, he was able to show that, after he and Maly relieved the obstruction to the pulmonary artery and disconnected the animal from the extracorporeal blood circuit, the cat was able to spontaneously resume and maintain its own cardiorespiratory functions for a period of several hours.

Problems

One of the early difficulties encountered was to obtain a rapid, free flow of venous blood through the *cannula in the jugular vein* without sucking the thin wall of the vena cava into the tip of the cannula and occluding it. When this occurred it produced an immediate cessation of flow and often resulted in the death of the animal. The difficulty was overcome by two means.

The first of these consisted of converting the intermittent flow pro-

duced by the pump into a continuous one. By so doing, almost double the flow of blood could be obtained without increasing the suction developed by the piston pump; conversely, the same volume output of the venous blood pump could be obtained with approximately one-half the velocity of the blood flow at the tip of the venous cannula. This decrease in the velocity of the blood flow through the venous cannula diminished the tendency of the wall of the vein to be sucked into the tip of the cannula. The conversion to a smooth flow was accomplished by connecting a rubber finger-cot (Figure 2, J) to the side arm of a Y-tube inserted in the blood circuit between the inlet blood valve and the venous cannula. The finger-cot projected into a closed air chamber (K) with a capacity of 1000 cc in which the air was maintained by a vacuum (slight suction) just sufficient to expand the finger-cot (J) at the end of the expulsion period of the venous blood pump (E). With the intake phase of the venous blood pump (E), the finger-cot (J) partially collapsed, while with the output phase it reexpanded. There was thus maintained a continuous suction of blood through the venous cannula. The rubber finger-cot was used to separate the blood from the air in the chamber (K), because direct exposure of the blood to the low partial pressure of oxygen in the air chamber would have resulted in further removal of oxygen from the already deoxygenated venous blood.

The second method of dealing with occlusion of the tip of the cannula by the wall of the vena cava consisted of using an automatic magnetic clamp (LQ). The action of the clamp was controlled by the following device. A T-tube with a vertical side arm (M) was placed in the blood circuit, between the magnetic clamp and the venous cannula. The top of the side arm was connected by narrow tubing with a small membrane manometer (N). The lever (O) of the manometer carried a wire that was bent at its end just above an insulated cup containing mercury (P). Contact of the tip of the manometer lever (O) with the mercury (P) completed a circuit through an electromagnet (L). This drew up the bar (Q), which compressed the tubing and thus prevented further suction by the venous blood pump. If the tubing between the vertical T-tube (M) and the venous cannula was occluded by pressure with the fingers while the pump (E) was operating, or if the wall of the vein were drawn into the opening of the venous cannula, there occurred a sharp lowering of the meniscus in the vertical T-tube and an increase in the vacuum of the closed air system leading to the membrane manometer (N). The manometer lever was in consequence drawn down, closing the electrical circuit to the magnetic clamp and shutting off the suction of the blood pump from the venous cannula. With the suction cut

off, the wall of the vein fell away from the tip of the cannula. Blood would again flow into the cannula and raise the meniscus in the T-tube, thus raising the lever (O), breaking the electric circuit, and allowing suction to begin again.

When the magnetic clamp began to act, it was an indication that blood was being withdrawn too rapidly from the superior vena cava. At that time, the air needle valve (I) controlling the flow of blood through the venous blood pump (E) was opened slightly to reduce the flow of blood. The magnetic clamp therefore served two purposes. It prevented sudden, complete, and relatively permanent occlusion of the cannula by the wall of the vein, and it indicated how rapidly blood could be withdrawn from the superior vena cava.

Difficulty was encountered at first in constructing satisfactory *valves* (G) for the blood pumps. The flap valves described by Dale and Schuster could not be adapted to the small lumen of the tubing used. The valves which JHG and Maly made by hand from rubber corks could be used for months without deterioration or leakage.

A pulsatile flow of blood into the oxygenator produced foaming and splattering. To correct this, a second air chamber was introduced to convert the *pulsatile flow into a smooth one*. A Y-tube with one branch (R) in a vertical position was placed in the blood circuit between the pump (E) and the oxygenator. The vertical branch communicated with an air chamber (S) with a capacity of 500 cc in which the air was maintained at a positive pressure. Blood was forced up into the vertical branch of this Y-tube with every stroke of the pump. When the stroke was completed, the blood was forced down again by the pressure of the air in the chamber. This produced a relatively smooth flow of blood into the oxygenator.

The pressure in the air chamber (S) was recorded by a water manometer (T). The pressure readings gave some indication of the *volume of blood flowing* through the venous blood pump because the resistance offered by the tubing between the tube (R) and the oxygenator was a constant factor. This was true only if the viscosity of the blood was constant and if the blood level in the tube (R) was maintained at a constant level with varying rates of flow produced by adjusting the pressure in the air chamber (S). In several experiments the movements of water in the manometer were recorded on the kymograph record by a small brodie[3] bellows (U) connected to the manometer. The tracing was used merely as an indication of whether the flow through the artificial circuit was increasing or decreasing at any particular moment.

After the blood was exposed to oxygen on the inner surface of the revolving cylinder (A), it collected in the cup (B). From here it was withdrawn by the arterial blood pump (E'). Unless constant attention was paid to the output of the arterial blood pump, the *blood level* would either rise or fall in the cup (B) because of slight differences in the output of the two pumps (E and E'). Both occurrences were undesirable. If the blood rose in the cup, the volume of blood in the animal's own vessels was reduced. On the other hand, if the level fell to the bottom of the cup, bubbles of oxygen were drawn into the rubber tubing and pumped into the animal's arterial circulation with resultant gas embolism. Both these undesirable consequences were obviated by the use of a second automatic magnetic clamp (V), which operated on the same principle as the one previously described. A T-tube was inserted between the cup (B) and the magnetic clamp (V). The top of the T-tube was connected to the air chamber of a membrane manometer, the lever of which could make and break the electrical circuit that operated the magnetic clamp. When the blood rose in the vertical side arm of the T-tube, the circuit was activated and the magnetic clamp opened. When the blood level fell, the arm of the manometer was depressed, the electrical circuit was broken, and the magnetic clamp closed. By this method the blood in the cup was prevented from falling below the desired level. The arterial blood pump (E') was always operated at a larger volume amount of flow than the venous blood pump (E). This tended to make the level of blood in the cup fall. The fall was continuously checked by the magnetic clamp (V). The combination of driving the arterial blood pump at a larger amount of flow than that of the venous pump, plus the constant checking of the magnetic clamp, maintained the level of the blood in the cup within a range of 1 cm.

The importance of maintaining the *pulse pressure* in the perfusion of organs had been pointed out by numerous investigators. Hence, a pulsatile flow through the arterial cannula was thought to be desirable. However, it was found that the pulse pressure produced by the pump was too large and also that the required amount of blood could not be forced through the arterial cannula with a completely intermittent flow. Consequently, a short section of wider, more elastic, rubber tubing was placed in the blood circuit between the outlet valve of the arterial blood pump and the arterial cannula. This resulted in a continuous flow with pulsatile increments, and the required amount of blood was easily injected through the arterial cannula.

Rough estimates of the *flow of blood through the artificial circuit* were made by timing the collection of 10 cc of blood in the cup at the bottom of

the oxygenator. Two horizontal marks were scratched on the lower glass portion of the cup (B), so that the volume contained between these marks was 10 cc. During the course of an experiment the level of blood was brought to the lower mark by cutting out the lower magnetic clamp and partially compressing the tubing with the fingers. The tubing was then completely occluded with the fingers until the level reached the upper mark, when the tubing was released and the automatic clamp started again. The time required for the level of blood to rise from the lower to the upper mark was measured with a stopwatch. Even when the lowest value obtained on three or four trials was used, the estimated flow was approximately 10% under the actual flow (measured by collecting the fluid output of the arterial pump). Consequently, the estimates for the flow of blood made during the experiments were probably all slightly low.

The original pumps and tubing held 65 cc each, and their output was only 300 cc of water per minute. The output of blood, because of its higher viscosity and greater frictional resistance, was always less than the output of water. As the *total blood volume* of the cats on which the experiments were performed was usually between 150 and 300 cc (if the volume were computed as 70 cc per kg of body weight), it was desirable to reduce the amount of fluid contained in the pumps and tubing. As finally perfected, the venous blood pump with all its tubing and connections, including the venous cannula, held only 21 cc of fluid at any moment and was able to deliver 653 cc of water per minute. The arterial blood pump with all its tubing and connections, including the arterial cannula, held only 20 cc of fluid and was able to deliver 741 cc per minute. At the higher rates of blood flow, the oxygenator held 35 cc of blood on the sides of the revolving cylinder and flat surfaces of the cup. In addition, it was necessary to maintain a small reservoir of 15 cc in the glass cup at the bottom of the oxygenator. Thus the pumps, tubing, and oxygenator contained a total volume of about 90 cc of fluid while operating at a flow rate of from 300 to 500 cc of blood per minute.

As the average cat weighing 3 kg has a *volume of blood* of only 210 cc, it was obviously impossible to withdraw enough blood (90 cc) from the experimental animal to fill the pumps and oxygenator without producing a fatal depletion of blood in the animal's own vessels. Nor was it desirable to fill the pumps and oxygenator with salt solution, as this would rapidly leave the animal's blood vessels (by osmosis) when injected into the femoral artery, the fluid moving into the animal's tissues. Therefore, the apparatus was filled with 6% solution of acacia (a blood substitute) in physiologic

solution of sodium chloride. Then when blood was withdrawn from the superior vena cava the solution of acacia was simultaneously injected into the femoral artery, so that the volume of fluid in the animal's own vessels remained constant. Theoretically, by this procedure, the red cells in the average cat would be reduced to roughly two-thirds of their previous concentration, producing anemia. (Actual degree of anemia would be measured in later experiments.) Anemia was avoided in some experiments by using heparinized blood from another cat instead of the solution of acacia.

To maintain a *constant temperature* of circulating blood or fluid, as much of the apparatus as possible was surrounded by a water bath through which water was constantly circulated at a rate of 1300 cc per minute by a small rotary water pump. The water bath circulation has been omitted from Figure 4 for the sake of simplicity. The venous blood pump and adjacent portions of the blood circuit were surrounded by water in an inverted bell jar (Figure 4).

It was not possible to surround the moving parts of the oxygenator with water. The lower portion of the stationary cup at the bottom of the oxygenator was made of glass and sealed to the upper metal portion. The glass portion had a double wall. Water was circulated through the jacket between the inner and the outer wall. The arterial pump was also surrounded by water. In addition, a 40-cm condenser jacket enveloped the tubing leading from the outlet valve of the arterial blood pump to the arterial cannula. The temperature of the water was controlled by two electric heating units placed in a water reservoir with a capacity of 10 liters. The water in this reservoir was constantly circulated through the baths by the water pump. The temperature of the blood entering the femoral artery was recorded by a thermometer inserted in the tubing between the end of the condenser jacket and the arterial cannula.

With the water bath maintained at about 42° C, the temperature of the blood as it entered the arterial cannula could be maintained constantly between 37 and 38° C. The rectal temperature of the animal was usually between 0.2 and 0.3° C below the temperature of the blood entering the arterial cannula. The temperature of the water bath had to be maintained about 4° C above the temperature of the blood because of the short exposure of the blood to the heating surfaces after it left the oxygenator, in which most of the cooling occurred.

To maintain the acacia solution in the pumps and tubing at an even temperature, it was kept in circulation by the pumps during the operative

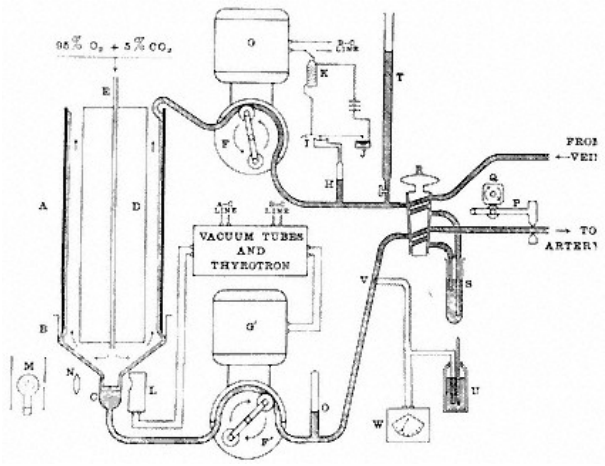


Figure 4:
Diagram of Second Apparatus. The second apparatus had the same basic design as the first pump-oxygenator, using the rotating cyclinder as the "lung." The venous blood was injected from the top, and it then spread by means of centrifugal pressure in a thin film along the walls of the cylinder in an atmosphere of 95% oxygen and 5% carbon dioxide. Dale-Schuster pumps were used in earlier oxygenator, while DeBakey pumps were used in the second machine which had a larger capacity for oxygenating an increased volume of blood in a given time.
Source: Gibbon JH Jr (1939). The maintenance of life during experimental occulsion of the pulmonary artery followed by survival. Surg Gynec Obsstet, 69:602–614, p. 604.

preparation of the animal. This continuous circulation through the oxygenator and pumps was accomplished by opening the short circuit and closing the tubing leading to the arterial and venous cannulae.

The oxygenator was warmed by the circulating acacia solution to a temperature above that of the room. Thus the cooling and heating factors were stabilized before blood entered the artificial circuit. To start the artificial circulation of the animal it was necessary only to open the tubing leading to each cannula and to close the short circuit.

Observations

Partial Occlusion of the Pulmonary Artery

The preliminary animal experiments (Appendix Table 15) involved occluding the pulmonary artery to simulate a pulmonary embolus. This was done to establish that they could maintain the cat's heart and lung functions by means of the apparatus. JHG was testing to determine the capacity of both the apparatus and the cat. By proceeding in a step by step fashion, he could observe the effects of the gradual occlusion of the pulmonary artery and the effects of the use of extracorporeal circulation on the animal's individual organs and total body systems.

The animal's vital signs—blood pressure, pulse, and respirations—were recorded by means of the kymograph tracings (Figure 5).

In the early experiments, many problems were encountered both in the apparatus itself and in carrying out the procedure. While JHG had been able to foresee many problems, others arose during the actual process. The experiments became a matter of continual problem solving. As each problem arose, it was analyzed and solved as far as possible on the spot, then further analyzed following the procedure in order to decide what long-term actions should be taken to deal with the problem if it recurred.

Complete Occlusion of the Pulmonary Artery

In twenty-one experiments the blood pressure was maintained at an adequate level, and the animal continued to breathe and the heart to beat while the pulmonary artery was completely closed for periods varying from 15 minutes to 2 hours and 51 minutes.

Recovery After Complete Occlusion of the Pulmonary Artery

In a few experiments an attempt was made to study the capacity of the animal to recover spontaneously after a period of complete occlusion of the pulmonary artery. In three experiments with complete occlusion of the pulmonary artery for 30, 33, and 39 minutes, respectively, the animals were observed for more than 2 hours after the release of the pulmonary artery and cessation of the artificial circulation. The blood pressure was maintained at an adequate level by the animal's own heart, and the respiratory movements, although deep and rapid, were quite regular. After the artificial circulation was stopped, the mixture of blood and acacia solution remaining in the pumps and oxygenator was removed, and some of it was cen-

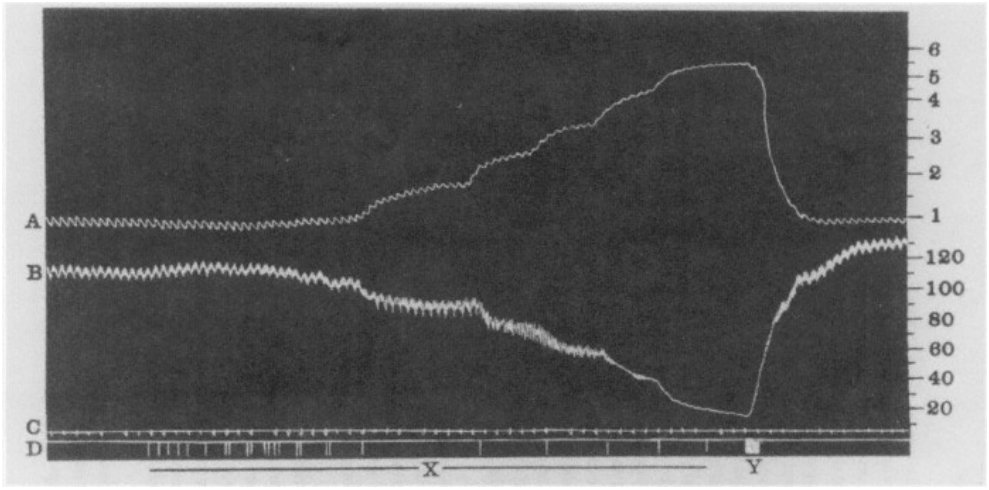


Figure 5:
Kymograph Tracing. Kymograph tracings, in which ink-fed movable pens traced variations in temperature and blood pressure readings on graph paper attached to a slowly rotating drum, were done in all early animal experiments to measure effects of extracorporeal circulation on these physiological parameters. Laboratory measurements were still relatively primitive at this period.
Source: Gibbon JH, Jr (1937). Artificial maintenance of circulation during experimental occlusion of pulmonary artery. Arch Surg, 34:1105–1131, p. 1116.

trifuged to concentrate the red cells. To counteract the anemia that invariably occurred during perfusion, 18 cc of the mixture of blood and the acacia solution and 18 cc of the concentrated suspension of red cells were returned to the animal's circulation. Even so, the hematocrit reading, taken immediately after the experiment was terminated, showed only 27% cells (normal = 24–45% for a cat weighing 3–5 lb or 6–10 kg).

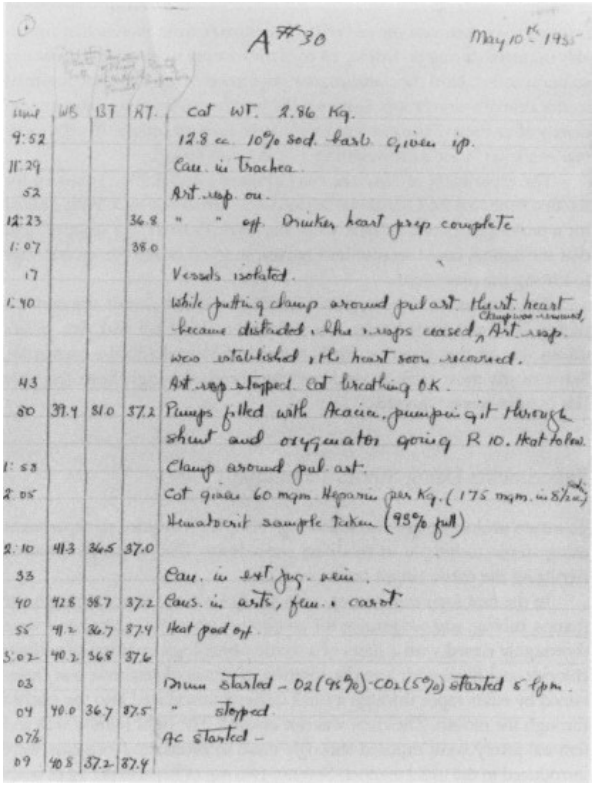
The experiment of May 10, 1935 (Figure 6 and Table 1) showed for the first time that ECC could be successfully carried out on a living animal for a prolonged period of time while the animal's heart was stopped, and that the animal could recover and remain in good health for several days following the procedure.

The success of this experiment, which seemed almost miraculous, caused JHG and Maly to dance joyfully around the lab that day. JHG's dream was, at that point, virtually assured of being fulfilled—eventually. Some of the most difficult work still lay ahead, although from this date JHG's hope never wavered.

Experiments Using Sterile Technique

To assure prolonged survival following ECC, JHG decided to experiment using sterile technique in modified procedures. This objective involved sterilizing the entire circuit before each use.

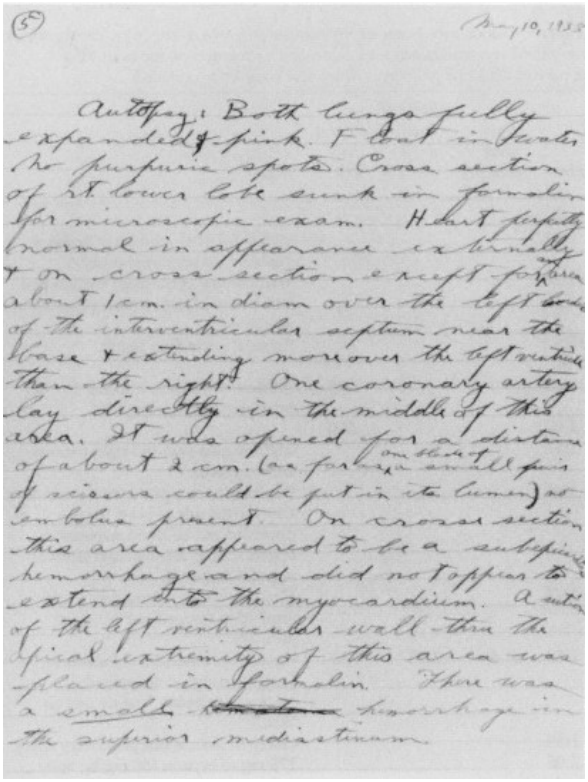
In the first such experiment, 70% alcohol was circulated through the pumps, tubing, and oxygenator for 30 minutes, then the components were thoroughly rinsed with 4 liters of a sterile physiologic solution of sodium chloride and filled with a sterile solution of acacia. Anesthesia was maintained by ether vapor through a small catheter introduced into the trachea through the mouth. The chest was not opened. The right jugular vein and femoral artery were exposed through small incisions, and cannulas were introduced in the usual manner. Seventy-two mg of heparin per kg of body weight was given intravenously. The cannulas were then connected with the artificial circuit, and blood was withdrawn from the jugular vein and reinjected into the femoral artery at a rate varying from 150 to 200 cc per minute. Passage of blood through the artificial circuit at this rate was continued for 1 hour, after which the cannulas were removed and the vessels ligated. The wounds were then sutured. A sample of blood withdrawn at the end of the experiment contained 28% cells and showed slight hemolysis. Recovery was uneventful except for the development of hema-



A 30 May 10th 1935

time	WB	BT	RT	
				Cat WT. 2.86 Kg.
9:52				12.8 cc. 10% sod. barb. given ip.
11:29				Canc. in Trachea.
52				Art. resp. on.
12:23			36.8	" " off. Drinker heart prep complete.
1:07			38.0	
17				Vessels isolated.
1.40				While putting clamp around pul art. thyr. heart became distracted, like resps ceased, Art. resp. Clamp was removed, was established, the heart soon recovered.
43				Art. resp stopped. Cat breathing OK.
80	37.4	81.0	37.2	Pumps filled with Acacia, pumping it through shunt and oxygenator going R 10. Heat holes.
1:53				Clamp around pul. art.
2:05				Cat given 60 mgm. Heparin per Kg. (175 mgm. in 8½ cc)
				Hematocrit sample taken (95% full)
2:10	41.3	36.5	37.0	
33				Canc. in ext. jug. vein.
40	42.8	38.7	37.2	Canc. in artr, few c carot.
55	41.2	36.7	37.4	Heat pad off.
3:02	40.2	36.8	37.6	
03				Drum started – O2 (95%) CO2 (5%) started 5 fpm.
04	40.0	36.7	37.5	" stopped.
07½				Ac started –
09	40.8	37.2	37.4	

Figure 6:
Replica of Pages from Laboratory Notes—May 10, 1935. This shows the format used in the original laboratory notes during the 1930s. Experiment #30-A on May 10, 1935, conclusively demonstrated that the pump-oxygenator could sustain the animal's heart and respiratory functions for at least 39 minutes. JHG's distinctive handwriting is easily distinguishable from Maly Gibbon's, which was smaller and more vertical.



(5)

May 10, 1933

Autopsy: Both lungs fully expanded & pink. Pleura smooth. No purpuric spots. Cross section of rt. lower lobe sunk in formalin for microscopic exam. Heart perfectly normal in appearance externally & on cross section except for area about 1 cm. in diam over the left side of the interventricular septum near the base & extending more over the left ventricle than the right. One coronary artery lay directly in the middle of this area. It was opened for a distance of about 2 cm. (as far as a small pair of scissors could be put in its lumen) no embolus present. On cross section this area appeared to be a subpleural hemorrhage and did not appear to extend into the myocardium. A section of the left ventricular wall thru the apical extremity of this area was placed in formalin. There was a small ~~hemorrhage~~ hemorrhage in the superior mediastinum.

Source: Mary Gibbon Clarke: personal papers of her mother, Mary Hopkinson Gibbon (Maly), ,Martha's Vineyard, October 1988. The original laboratory notes will be placed in the Gibbon Collection, MS C 313, National Library of Medicine, Bethesda, Maryland.

Table 1 Laboratory Notes of Experiment 30A—May 10, 1935, during which the animal was maintained for 2 hours and 51 minutes on the heart-lung apparatus while the pulmonary artery was completely occluded.

Time	*Temp of water bath (C)*	*Temp of fluid in artific circ (C)*	*Rectal temp (C)*	*Notes*
A.M.				
9:52				12.8 cc. of 10% solution of barbitol injected into peritoneal cavity.
11:29				Tracheotomy performed; cannula tied into trachea. Drinker heart preparation completed.
11:52				Artificial respiration begun.
P.M.				
12:23			36.8	Artificial respiration stopped. Drinker heart preparation completed.
1:07			38.0	
1:17				Right jugular vein and right femoral artery exposed.
1:40				While clamp was put around pulmonary artery, right side of heart became distended and blue and respirations ceased. Clamp removed and artificial respiration started.
1:43				Heart recovered normal tone; artificial respiration stopped; cat breathing normally.
1:50	41.3	36.5	37.2	Circulation of solution of acacia by pumps through shunt started; oxygenator started; heating pad on "low."
1:58				Clamp in place about pulmonary artery.
2:05				175 mg of heparin (60 mg/kg body weight) in 8.5 cc of saline solution injected intravenously; hematocrit sample #1 taken.
2:10	41.3	36.5	37.0	
2:33				Cannula in jugular vein.
2:40	42.8	36.7	37.2	Cannulas in femoral and carotid arteries.
2:55	41.2	36.7	37.4	Heating pad turned off.
3:02	40.2	36.8	37.6	

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Table 1 Laboratory Notes of Experiment 30A—May 10, 1935, during which the animal was maintained for 2 hours and 51 minutes on the heart-lung apparatus while the pulmonary artery was completely occluded.

Time	*Temp of water bath (C)*	*Temp of fluid in artific circ (C)*	*Rectal temp (C)*	*Notes*
3:03				Flow of 95% oxygen, 5% carbon dioxide started into oxygenator at rate of 5 l/minute.
3:04	40.0	36.7	37.5	
3:07				Shunt closed and tubing to arterial and venous cannulas opened; starting artificial circulation.
3:09	40.8	37.2	37.4	
3:12				Compression of pulmonary artery begun; five turns of knurled nut on clamp (17% occlusion).
3:13				Three full turns and three half turns of nut (66% occlusion).
3:15	40.7	36.3	37.1	
3:16				Four quarter turns of nut (83% occlusion).
3:18				Rate of revolution of oxygenator increased.
3:20	41.0	36.6	36.8	One quarter turn of nut (87% occlusion); color of arterial blood bright red now.
3:22				Rate of revolution of oxygenator reduced because of tendency of blood to foam at faster rate.
3:24	41.3	36.8	36.8	
3:28				160 mg of heparin given intravenously.
3:30	42.0	36.8	36.8	Right ventricle moderately distended; heart rate is synchronous with blood pump.
3:32				Oxygenator rate, 467 revolutions/minute; moderately deep respirations.
3:34				Blood flow through artificial circuit timed: 10 cc in 2.3, 2.9, 2.2, and 2.0 seconds; blood flow about 300 cc/minute.
3:37	42.4	37.1	36.8	
3:41	42.6	37.3	36.8	
3:45	42.2	37.1	36.8	

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Table 1 Laboratory Notes of Experiment 30A—May 10, 1935, during which the animal was maintained for 2 hours and 51 minutes on the heart-lung apparatus while the pulmonary artery was completely occluded.

Time	*Temp of water bath (C)*	*Temp of fluid in artific circ (C)*	*Rectal temp (C)*	*Notes*
3:49	42.2	37.2	36.8	
3:52	42.3	37.3	36.8	
3:55				5 cc of acacia solution added to blood in artificial circuit.
3:56	42.7	37.3	36.8	
4:00				Oxygenator rate increased to 519 revolutions/minute; no frothing; arterial blood a good red.
4:01				Venous cannula broken; clamp compressing pulmonary artery widely opened; artificial circulation stopped.
4:05				Broken cannula removed and jugular vein ligated.
4:09			36.4	Heating pad turned to "high."
4:15			36.5	
4:21			37.2	A little bloody fluid from artificial circuit injected into femoral artery; heating pad turned to "low."
4:31			37.8	Heating pad turned off.
4:43			37.8	
4:48			37.7	
4:59			37.2	9 cc of bloody fluid from artificial circuit injected into femoral vein. Heating pad turned to "medium."
5:01			37.2	Heating pad turned to "low."
5:28				9 cc of same fluid injected into the right femoral vein.
5:29			37.3	
5:40			37.4	Heating pad turned off.
5:45			37.4	Slight Traube-Hering waves in blood pressure tracing; heating pad turned to "low."
5:50				8 cc of sedimented red blood cells injected into femoral vein.
6:00			37.3	Traube-Hering waves almost imperceptible.
6:14				5 cc of sedimented red blood cells injected into femoral vein.
6:15			37.4	

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(table continued from previous page)

Table 1 Laboratory Notes of Experiment 30A—May 10, 1935, during which the animal was maintained for 2 hours and 51 minutes on the heart-lung apparatus while the pulmonary artery was completely occluded.

Time	*Temp of water bath (C)*	*Temp of fluid in artific circ (C)*	*Rectal temp (C)*	*Notes*
6:25			37.3	
6:27				5 cc of sedimented red blood cells injected into femoral vein.
6:30			37.3	Traube-Hering waves present.
6:33				Traube-Hering waves gone.
6:36				Hematocrit sample #2 taken from femoral artery.
6:43				Animal killed.

NB: Hematocrit sample #1 (before artificial circulation) - 50% cells.
Hematocrit sample #2, no hemolysis of plasma; 27% cells.
Autopsy: There was a small hematoma in the superior mediastinum. Both lungs were expanded and pink and floated in water. There were no purpuric spots on the surface of the lungs or on cross-section. Microscopic examination of a section of the lower lobe of the right lung showed a few minute areas of atelectasis.
Source: Gibbon JH, Jr. (1937). Artificial maintenance of circulation during experimental occlusion of the pulmonary artery. *Arch Surg, 34*:1105–1131, pp. 1122–24.

toma in both wounds. Five days later there was evidence of infection in the wounds, and the animal was killed. Blood obtained at autopsy was not hemolyzed, and no organisms were grown on culture of the blood.

JHG showed in these experiments that 1) it is possible to operate on an animal and render the blood incoagulable by the administration of heparin without causing a fatal hemorrhage from the operative wounds, and 2) an animal can live for 5 days after its blood has been passed through the artificial circuit for a period of 1 hour.

Several attempts were made to perform the entire experimental procedure under sterile conditions: occluding the pulmonary artery, maintaining life by artificial circulation, and then releasing the pulmonary artery and allowing the animal to recover. Fifteen such attempts were made unsuccessfully. In addition to the difficulties encountered in performing the experiments under aseptic conditions, two other major complicating factors were present—the first was the length and complexity of the procedure, the second was anesthesia. With respect to the first problem, the procedure was too long and too shocking to be completed entirely in one stage, so that in the majority of these fifteen experiments a preliminary

operation was performed that exposed the pulmonary artery just beneath the skin and muscle layers of the chest (modified Drinker preparation). Two weeks later the major part of the experiment was performed. The old incision was reopened, and the pulmonary artery was immediately exposed beneath the pectoralis major muscle.

Occasionally infection prevented the performance of the second stage and the animal was sacrificed. At other times a dense plaque of scar tissue was found overlying the pulmonary artery, adherent to it and to the opening in the wall of the chest. In these instances an adequate exposure of the pulmonary artery could be obtained only by a tedious, time-consuming, and hazardous dissection. In this situation, following a few unsuccessful attempts to carry out the dissection, JHG decided to sacrifice the animal.

The second major difficulty encountered was that of anesthesia. Sodium barbital (0.45 gm per kg of body weight) injected intraperitoneally in the nonsterile experiments always produced prolonged narcosis and a lowering of the blood pressure. Both these effects were undesirable in the sterile survival experiments. Reduction of the amount of barbital resulted in inadequate surgical anesthesia. For these reasons ether was used in the sterile experiments, as it did not lower the blood pressure and the cats recovered consciousness a short time after the inhalation of ether vapor was stopped. The use of an inhalation anesthetic increased the difficulties of the experimental procedure because anesthesia could not be maintained in the ordinary manner when the pulmonary artery was completely occluded. While the pulmonary artery was occluded, ether vapor was circulated through the oxygenator in order to maintain anesthesia. The following technique was used during the operative procedures when anesthesia was maintained by ether entering the lungs through an intratracheal catheter. As the pulmonary artery was gradually occluded by the clamp, the amount of ether vapor entering the tracheal catheter was reduced and ether vapor was added in increasing amounts to the oxygen and carbon dioxide mixture entering the oxygenator. Finally, the administration of ether by the intratracheal catheter was discontinued entirely, and anesthesia was maintained by ether vapor in the oxygenator. When the pulmonary artery was released, the reverse procedure was carried out. This double administration of ether required the undivided attention of one person throughout the experiment.

That the entire procedure could be successfully carried out with the animal under ether anesthesia was shown by experiment 24 (Appendix Table 15). This experiment was not sterile, but the technique was otherwise similar to that used in the sterile experiments and ether anesthesia was

employed throughout. The pulmonary artery was completely occluded for 30 minutes, during which time life was maintained by the artificial circulation. The artificial circulation was continued at a reduced volume for 53 minutes after the pulmonary artery was released. It was then stopped. The cannulas were removed from the femoral artery and the jugular vein. These vessels were ligated, and the wounds were closed. The wound in the chest was also closed after the clamp was removed from the pulmonary artery. However, the animal died 2 hours after the artificial circulation was stopped. Autopsy findings showed bilateral pneumothorax and practically complete collapse of both lungs.

Summary of the 1934–35 Animal Experiments

The object of these experiments was to determine whether the circulation could be aided by artificial means in the presence of partial or complete occlusion of the pulmonary artery (Appendix Table 15). This was done by withdrawing blood from a peripheral vein, introducing oxygen into that blood, and then reinjecting the blood into a peripheral artery in a central direction. The blood was thus short-circuited around the obstruction in the pulmonary artery, and part or all of the work of the heart and lungs was temporarily taken over by the artificial means. This mechanical method to maintain circulation in the presence of partial or complete occlusion of the pulmonary artery was satisfactorily demonstrated.

Conclusions derived from these experiments were as follows:

1. Short-circuiting blood around a partial obstruction in the pulmonary artery by means of a perfusion apparatus aids in maintaining the blood pressure and respiration.

2. Life can be maintained for short periods in the presence of complete obstruction of the pulmonary artery by a perfusion method that does not involve damage to the great vessels of the body.

3. The normal circulation and respiration can be spontaneously reestablished and maintained for several hours after a 30-minute period of complete occlusion of the pulmonary artery.

The experiments also showed that several features of the apparatus and method could be improved. For example, all the experiments were performed in the presence of marked acute anemia. Hematocrit readings were

made at the conclusion of 27 experiments. The percentage of cells varied between 4 and 29, the median value being 13.5%. This anemia resulted from dilution of the animal's blood with the acacia solution in the artificial circuit. The dilution was avoided in a few experiments by filling the pumps and tubing with blood from one or more cats other than those used in the experiments. The dilution could be diminished further by reducing the fluid capacity of the pumps, tubing, and oxygenator. During these experiments the volume of the pumps and tubing was reduced from an initial 130 cc to a final 41 cc. Any further reduction in volume would entail a relatively large increase in the velocity of the blood, causing additional trauma and hemolysis. However, modifications in the design of the components of the apparatus would reduce the volume of fluid required in the pump and tubing. It was not possible to significantly reduce the volume of blood required in the oxygenator, although here too a different design might have resulted in some decrease. The success obtained despite the severe anemia indicated that the circulation could easily be maintained if the anemia were avoided, provided the blood was still adequately oxygenated.

Preventing hemolysis was difficult. At times hemolysis was due to inadequate rinsing of the pumps and oxygenator with a physiologic solution of sodium chloride. In 26 experiments the degree of hemolysis was noted. It varied from none to 40%. The latter figure refers to the color on a Tallqvist hemoglobin scale which the color of the plasma most nearly matched. The hemolysis of 40% occurred immediately after a marked reduction in size of the glass and rubber tubing used in the artificial circuit. It was reduced to less than 10% by the use of larger tubing where the flow of blood was most rapid—that is, between the blood valves of each pump where the flow was completely intermittent. Avoiding sharp changes in direction of blood flow also tended to decrease trauma and hemolysis.

Heparin was used as an anticoagulant. The amount given was sufficient to render all the blood incoagulable. In one experiment in which the animal survived for 5 days, a single dose of 350 mg of heparin was given to a cat weighing 4.9 kg. Gross[26] showed that heparin given intravenously produces an immediate increase in clotting time. The rate of return to normal is rapid at first and then slower. He noted that the effect of heparin in rabbits tended to vary directly with the dose. In one experiment 10 mg of heparin was injected in a rabbit weighing 1.7 kg. A return to the normal clotting time began in 20 minutes and was complete in 1-1/2 hours. Howell[30] reported that when enough heparin was used to make all of an animal's blood incoagulable, the coagulation time returns to normal in 3

hours. In a dog weighing 13 1/2 pounds (6 kg), enough heparin to render the blood incoagulable was injected daily for 6 days without noticeable effect on the red or white cells, platelet count, or clotting time 24 hours after each injection.[32] Using a purified preparation of heparin, Howell and his team gave 10 transfusions of blood to humans with slight reactions in only two instances.[32]

In 21 of JHG's experiments the pulmonary artery was completely occluded for 15 minutes or more. In only one of these experiments was the occlusion maintained for more than 1 hour. In this instance (May 10, 1935) respirations continued for 2 hours and 51 minutes with the pulmonary artery completely occluded. In all the other experiments it was possible to maintain the occlusion of the pulmonary artery for only one hour or less.

A frequent cause of failure to maintain the occlusion for longer periods was some defect in the apparatus. In other cases, however, a gradual decrease occurred in the amount of venous blood that could be withdrawn without sucking the venous wall into the tip of the cannula. This probably indicated a decreased venous return to the heart that was not due to a failure of respiration; in fact, the respiratory movements were almost invariably deeper than normal. The decrease may have been due to the gradual loss of fluid from the blood into the tissues. This seems likely, although the blood pressure was generally maintained above the level associated with the development of shock. However, the increased depth of the respiratory movements indicated an insufficient supply of oxygen to both the capillaries and the tissues. Lack of oxygen increases permeability of the capillaries,[33] and this in turn might account for loss of fluid from the blood. Many physiological responses are interdependent, resulting in a "Catch 22" situation.

In most of JHG's experiments there was probably an adequate saturation of the arterial blood with oxygen, but there was always a severe acute anemia, and the amount of blood flow may not have been adequate to compensate for this. Reversal of the blood flow in the abdominal and the thoracic aorta may have been a contributing factor, because the branches during surgery formed acute angles with the direction of the flow of blood instead of forming angles between 90 and 180 degrees; this would likely cause a diminished flow of blood through these branches. This situation applied to the abdominal viscera but not to the branches of the aorta supplying the head and upper extremities. However, on gross examination at autopsy, no hemorrhages or edema were seen in the abdominal viscera.

There was another possible cause of the gradually diminishing venous

return: minute bubbles of oxygen might have been drawn into the lower arterial blood pump and then physically dissolved in the plasma by the high pressure developed in the tubing leading to the arterial cannula. With a return to the lower pressure in the animal's vessels, the bubbles of oxygen might re-form and thus block the systemic capillaries.

There was undoubtedly an excessive loss of water vapor from the blood as it passed through the oxygenator. In the experiment in which the occlusion was maintained for 2 hours and 51 minutes, the mixture of oxygen and carbon dioxide was warmed to 30° C and saturated with water vapor before being passed through the oxygenator. The water vapor, however, condensed on the cool copper tube leading through the stationary cylinder of the oxygenator and dripped into the blood, possibly causing the excessive hemolysis.

The rate of condensation under similar conditions was determined the following day. Water was found to drip from the copper tube at the rate of 23 cc per hour. As blood passed through the artificial circuit for over 3 hours, probably more than 70 cc of water was introduced into the circulation by this means. No further attempts were made to saturate the gas entering the oxygenator with water vapor, although this probably should have been done and the condensation avoided by warming the metal tube.

The Laboratory Work Day

Maly[24] in later years described a typical work day in JHG's animal laboratory in the 1930s. Her description illustrates the time and effort required, and the seemingly endless difficulties that occurred almost as a matter of routine.

> To do these experiments we had to be at the laboratory bright and early, as they often continued all that day and sometimes well into the evening. We could manage only about three such experiments a week. First we had to bring the cat down to the lab from its upstairs quarters and anesthetize it, perform a tracheotomy and connect the animal to artificial respiration while the Drinker heart preparation was done to expose the pulmonary artery in a (later) naturally breathing animal. . . . Next, the vessels to be used for the perfusion were exposed, and a 5% solution of gum acacia was circulated slowly round the heart-lung apparatus. The clamp was placed around the pulmonary artery, ready for gradual compression of the artery. A cannula for recording blood pressure and a device for recording respiration on the kymograph record was arranged, the vessels for perfusion were cannulated and, last, heparin was

injected into the animal's vein and a blood sample taken to determine the hematocrit. These preparations usually took four to five hours and it was midafternoon before we were ready to start the actual procedure. Any one of a number of complications could occur during the procedure which would further lengthen the time: the thin wall of the vein frequently got sucked into the opening of the cannula, and it was essential to immediately stop the pumping action of the venous blood pump. Sometimes we had to release the clamp around the pulmonary artery, readjust the cannula in the vein, and wait for things to get more or less stabilized. Then we would begin again, more gingerly. We judged the performance of the oxygenator by the color of the blood returning from it to the cat's artery—in those years, we had neither the skill nor the time to do oxygen determinations. Other possible complications that could occur included: foaming of the blood in the cup at the bottom of the oxygenator, movements of the cat because of too-light anesthesia, and these movements could sometimes cause breakage or loosening of tubes or cannulas. In the midst of this, the animal's blood pressure would suddenly drop because the wall of the vein was being sucked into the cannula, the arterial blood would begin to look like venous blood because of poor filming on the cylinder. Either the experiment would have to be terminated at that point, or it would be continued, depending on the ability of the animal to recover. At the end of the experiment—whenever that occurred—the watchful nursing of the animal would take precedence over the other tasks, which came later. When the cat's condition appeared to be satisfactory for an hour or so during recovery from anesthesia, we would then sacrifice the animal in order to do the autopsy to discover effects of the heparin, anesthesia, procedure, or other aspects of the experiment. Following that, the kymograph record had to be shellacked to preserve it from smudging, the equipment and instruments had to be washed and sterilized, and the room thoroughly cleaned, ready for the next try. Altogether, long, often difficult, and frustrating days.

End of the Fellowship Year

When JHG and his family returned to Philadelphia in 1935 he was offered a position of Surgical Research Fellow in the Harrison Research Laboratory at the University of Pennsylvania. This offer was based on recognition of the 1934–35 experiments which unequivocally showed that artificial circulation in cats could be maintained for periods up to 2 hours and 51 minutes. This position provided the opportunity he so much desired—to continue work on the pump oxygenator using sterile technique, for his next goals were to ensure survival of the animals following ECC, and to solve the major problems of anemia and hemolysis that occurred during the 1934–35 experiments.

Settled once again in the Spruce Street house with his parents, JHG and Maly learned that their family would expand again. Shortly after the New Year's Day in 1936, their third child, Alice, was born on January 9. As before, however, Maly continued her work alongside JHG in the laboratory, knowing that the children were well cared for under the watchful eyes of her mother-in-law and full-time household help, which was still relatively inexpensive during these waning years of the Depression.

Franklin Delano Roosevelt's New Deal held great promise for a brighter future for all. And, although JHG and Maly remarked, along with others, on the sudden rise to power of Adolf Hitler in Germany, neither had much time to consider what the consequences might be for the rest of Europe. Life went on at its previous hectic pace for the Gibbon family. JHG was becoming assimilated into the Harrison Laboratory and organizing his own part of it. When his equipment arrived from Boston, he and Maly set it up, testing each part as it was unpacked to check for breakage. Experiments began again in the late spring of 1936.

While JHG's research efforts were becoming known, and he was seeing some success for the first time, the majority of his colleagues continued to consider his efforts fruitless and bordering on the ridiculous.[5] JHG continued as though unaware of these opinions. As one physician recently wrote: "Few people have the integrity, capacity for hard work, or persistence of a John H. Gibbon."[5]

The subsequent experiments, conducted from January 26 to July 28, 1938, resulted in survival of a significant number of experimental animals.

The 1938 Laboratory Experiments

In 1939 JHG[19] reported the results of animal experiments done during the previous years in the Harrison Laboratory with partial financial support provided by grants from the Josiah Macy, Jr. Foundation of New York and from the National Institutes of Health (Appendix Table 16).

In these experiments one of the objectives was to prevent the severe anemia that had occurred in the 1934–35 experiments caused by the hemodilution that resulted from the use of acacia or saline to replace blood that was drawn off and circulated through the system. In the 1938 experiments, JHG consistently used blood from cats other than those used in experiments; the blood was obtained under sterile conditions the day prior to surgery. An equal amount of saline was given to the donor cat to replace

the blood. Before blood was taken, the cat was given heparin (10 mg per kg of body weight). The heparin was obtained from the University of Toronto and contained 15 units of heparin per mg.

The cats used in these experiments were anesthetized with ether by introducing through the mouth an intratracheal catheter that was connected to a closed circuit containing two Krogh respiratory valves, a sodalime chamber, a distensible rubber bag, a spirometer containing oxygen, and an ether vapor bottle. This setup was similar to an anesthesia machine used in surgery on humans. Using this carbon dioxide absorption method permitted a more easily controlled anesthesia than did the simpler opendrop ether technique, and avoided the possibility of anoxemia throughout the procedure.

The venous cannulas used were made of stainless steel tubing with a very thin wall and an internal diameter of about 1.5 mm. Each cannula was 7 cm long and had two slight curves corresponding to the shape of the external jugular and the innominate veins. After the extracorporeal circuit was connected with the animal and the donor blood mixed with that of the experimental cat, the pulmonary artery was gradually occluded by the clamp. The rate of blood flow was simultaneously gradually increased to a maximum of about 100 cc per minute per kg of body weight, to provide sufficient oxygen by means of the oxygenator and to maintain adequate blood pressure levels.

Complete occlusion of the pulmonary artery was maintained for periods of 10 to 25 minutes, after which the clamp was removed gradually from the pulmonary artery and the animal's heart and lungs took over their normal functions.

The average rate of blood flow through the circuit during these experiments was 242 cc per minute, with an average rate per kg of body weight of 99 cc per minute. This rate of flow was necessary in order to maintain an adequate blood pressure.

The postoperative convalescence of these animals was not remarkable. In a few cases, about 100 cc of 5% glucose in saline was given intraperitoneally for a day or two after surgery to provide sufficient fluid and caloric intake.

In this series of 39 experiments done under sterile conditions, thirteen animals survived 24 hours or more. However, because a sufficient supply of oxygen could not be maintained by the circuit in use, JHG saw that an oxygenator with a 75% increase in (blood) filming surface was needed to correct this deficiency.

Table 2 Summary of Thirteen Experiments

		Time of occlusion of pulmonary artery (min)				*Blood flow through circuit (cc/min)*			
Experiment no.	*Wt of cat (kg)*	*Partial*	*Complete*	*Time artificial circulation continued after release (min)*	*Time required for exp. (min)*	*Rate*	*Rate/kg body wt*	*Hematocrit at end (%)*	*Survival (days)*
9	2.25	22	15	16	108	225	100	28	1
13	2.2	22	10	11	143	240	109	30	23
15	1.9	15	10	13	132	190	100	32	8
16	2.85	10	12	5	114	250	88	33	370+
20	3.2	11	20	18	117	270	84	32	34
27	2.6	12	10	9	92	198	76	40	22
28	3.3	6	12	14	107	280	85	34	15
30	2.3	7	15	14	98	235	102	36	2
31	2.2	6	15	12	96	280	127		1
34	2.55	8	13	11	89	255	100	34	293+
37	2.8	8	25	8	93	260	96	34	11/2
38	2.1	5	18	7	97	234	111	25	279+
39	2.1	4	15	9	98	230	109	27	2
Average	2.5	10.4		11.3	106	242	99	32	

Source: Gibbon JH, Jr. (1939). The maintenance of life using experimental occlusion of the pulmonary artery followed by survival. *Sury Gynecol Obstet, 69*:p. 613.

With regard to survival time (Table 2), the animals were considered in terms of length of survival time following perfusion. Five cats survived from 24 to 48 hours, in experiments 9, 30, 31, 37, and 39. The major factor in the cause of death of these animals was believed to be anoxemia due to inadequate oxygenation while the pulmonary artery was occluded. Contributory factors were lowered blood pressure, shock, and body temperatures that were too low. A second group of four cats lived 1 week or more (experiments 13, 15, 27, and 28). Pericarditis was the cause of death in two of the animals, and another one died from distemper. The fourth died on the 23rd day after developing severe jaundice; autopsy revealed extensive hepatic necrosis in this animal. The last group of four cats survived for 1 month or longer, all in healthy condition (experiments 16, 20, 34, and 38). Three of these cats survived for over 9 months, one of them producing a litter of healthy kittens.

Successes of the 1930s

As JHG pointed out following this series of experiments, it was the first report of successful temporary substitution of an entirely mechanical apparatus for the functions of the heart and lungs in animals, followed by prolonged survival of some of the animals. He speculated about the possibility of developing an oxygenator with a greatly increased oxygenating capacity in order to maintain a human for at least short intervals, long enough to perform corrective intracardiac procedures.

During the decade of the 1930s, JHG was able to show that whole body perfusion was possible for up to 25 minutes in animals the size of cats with subsequent survival in which 30% of cats in one series of thirteen lived for 6 months or longer. This had never before been demonstrated. He had confronted and solved most of the major problems associated with extracorporeal circulation. It is exciting today to understand that, at this period, JHG was the only one in this country with this level of knowledge and experience in performing ECC on animals. Galletti and Brecher[17] state: "The concept of extracorporeal circulation as an aid to cardiac surgery originated in 1937 with the now classic publication of Gibbon on artificial maintenance of the circulation during temporary occlusion of the pulmonary artery." In the decade following many researchers—physicians and physiologists—joined the growing group who believed in a future for the heart-lung machine. But in the 1930s, JHG stood alone.

JHG the Inventor

As an inventor, JHG can be compared most closely to Thomas Alva Edison. Both can be considered "practical" inventors in that they were not seeking to solve great universal theoretical questions, or even to base their inventions on theoretical foundations. Both can be classified as inventors of technologies.

Edison was considered the first of the "independent" inventors of the nineteenth-century school.[20] Some thought of him as a transitional figure who pointed the way toward the systematic research of the technological age. The team of experts working together at Menlo Park, New Jersey was in itself a totally new concept in that the laboratory served as a model for the huge industrial research laboratories organized later, such as those of the Bell Laboratory System and General Electric. Edison's decisions not to undertake inventions unless there was a definite market demand for them was of great historical importance, as observed by Crowther,[12] in that Edison "was the first great scientific inventor who clearly conceived of invention as subordinate to commerce."

Edison also clearly delineated discovery from invention: "Discovery is not invention, and I dislike to see the two words confounded. A discovery is more or less in the nature of an accident. A man walks along the road intending to catch the train. On the way his foot kicks against something and . . . he sees a gold bracelet imbedded in the dust. He has discovered that—certainly not invented it. He did not set out to find a bracelet, yet the value is just as great."[22]

Edison and JHG were similar in other ways as well. Although they were different in terms of educational, social, and environmental development during their formative years, both had exceptional intelligence, analytical minds, the capability for hard, repetitive work, the power of acute observation, unusual persistence, and tremendous competitiveness. Edison's youngest son, Theodore, described him in regard to the last characteristic: "Father was intensely competitive. As soon as another firm turned out an improved phonograph and record, he must surpass them at all

costs."[26] Edison himself said in an interview with a newspaper reporter, "I don't care so much about making my fortune, as I do for getting ahead of the other fellows."[25] To have money meant little to him; he had enough for his needs. But to stand as leader among the world's foremost inventors, to make . . . a great impact on society and industry—even to "change the world," if possible—meant everything.[25] It is possible that JHG shared these attitudes, as can be seen in his first meeting with IBM's Thomas J. Watson, during which JHG indicated that he was not interested in personal gain from his invention, and in his belief that professionals—particularly physicians—should contribute toward improving the world.[2]

The great difference between Edison and JHG, of course, is that JHG invented only one thing. However, the type of technology that the heart-lung machine represented, and its purpose—to make possible life-saving surgery—made it much more complex, and the imperative to have it work perfectly every time was intensely pressing. However, the methodology that each used—Edison with his many inventions and JHG with his one—followed the same pattern, as described by Edison:

> It has been just so in all my inventions. The first step is an intuition—and comes with a burst, *then* difficulties arise. This thing gives out, and then that—bugs, as such little faults and difficulties are called—show themselves, and months of anxious watching, study, and labor are required before commercial success—or failure—is certainly reached. I have the right principle, and am on the right track, but time, hard work, and some good luck are necessary, too.[23]

Like Edison, JHG seemed to sense clearly the dependence of invention and discovery on the total accumulation of knowledge, including that which seems to be forgotten.[22] Edison's approach to all his inventions showed how little he depended on Providence or luck, and how much on systematic search. Nevertheless, Edison acknowledged the role of "accident" or "chance" that occurs frequently in the process of invention or discovery, and tried to differentiate the results of his work as to whether they came from his own effort alone, in the form of systematic experimentation, or whether there was also an element of "chance" involved. He found, however, that such differentiation is often difficult, if not impossible. Both men recognized, along with Pasteur, that "chance favors the mind that is prepared."[16]

Both men also recognized Weber's premise—that the essence of all great scientific work is that it is transitory, because, particularly with respect to technological inventions, it is linked to the course of progress.[31] What-

ever great invention appears today will, in ten, twenty, fifty years, be antiquated. Obsolescence, said Weber, is the very meaning of *scientific* work.[31]

With regard to family life, the demands of their work created tensions and difficulties in their relationships. Edison's second wife said that "he had few friends and lived a great deal by himself and in himself, shut out from the contacts open to most men."[25] Edison's son Theodore recalled, "Sometimes, it was as if he never saw us."[25] This kind of "inwardness" was perhaps less true of JHG than of Edison, who devoted so much of his time to thinking about his inventions in their various stages of development or difficulty. JHG was clearly a more social being, or had more opportunities for meetings with his colleagues than did Edison. During the years following the successful surgery in 1953, JHG was away from Jefferson Medical College a great deal, attending meetings of professional organizations, pursuing the duties of elected office in them, and giving papers about the heart-lung machine. He also made tennis and chess part of his activities, outside the realm of work. Nevertheless, one can see that the intensive work demanded of an inventor affects his life in many ways, not the least of which is his relationships with his wife and children. Edison could be considered fortunate in that both his wives made his work the center of their lives; everything in the household revolved around him and his work.[10]

Edison believed that inventions develop from or arise out of man's developing culture, his environment, his social and industrial relations. These factors certainly played a role in the case of the heart-lung machine. JHG was among the first to see the need for such an apparatus and devoted his inventive talents toward its development. By the 1940s, however, others in the field of thoracic surgery, both in the United States and in many other countries, were beginning to see the importance of the heart-lung machine and to apply pressure on JHG and others to complete the work and do the first surgery on humans.

Among these were American surgeons such as Alfred Blalock[5, 6] and Helen Taussig,[6] both at Johns Hopkins; Clarence Dennis at the University of Minnesota and, later, Kings County Hospital/Downstate, who had begun developing his own heart-lung machine while at Minnesota and subsequently performed the second successful bypass surgery in 1955;[14] Robert E. Gross, a renowned pediatric surgeon at Boston Children's Hospital, where he was also the William E. Ladd Professor of Children's Surgery and Professor of Surgery at Harvard University Medical School;[19] Kirklin and his colleagues at the Mayo Clinic;[15] DeBakey at Baylor University; Bjørk in Denmark;[4] Clarence Crafoord in Sweden;[11] Andreasen and

Watson in Britain;[1] and Brukhonenko and his colleagues in Russia.[7] All of these surgeons were in touch with one another. Many (Dennis, Crafoord, Gross, Blalock) visited JHG at Jefferson to observe how far his machine had developed. JHG visited Dennis, Bjørk, and Crafoord to see their methods and progress.

Surgical techniques for correcting defects in the heart were becoming more sophisticated and therefore more successful, even in light of their limitations regarding operative time and the condition of the operative field, which the heart-lung machine would solve.[3, 5, 6, 8, 11, 14, 19, 27, 28, 29, 30] New instruments and related technologies were being developed during the 1940s and early 1950s, further driving the impetus for a workable heart-lung machine.

One final comparison between Edison's and JHG's work can be noted: in each case, it was only after many months—and, in some cases, years—had passed before others came to realize the significance of their inventions. Nor did either inventor, at the time his invention was completed, fully comprehend and evaluate the scope of the work or its historical importance.[24] Evidently, time must pass in order for the inventor and others to realize the true worth of any discovery or invention.

Invention is the result of problem solving. As an inventor, JHG faced and solved a multitude of problems with respect to the heart-lung machine, both in its development and in the animal experiments to test its practicality and effectiveness. He used both creative and research processes to carry out his work.

The 1940s—Model I

In 1940 JHG and his growing family moved from their apartment at 1608 Spruce Street to a large house in West Philadelphia at 4035 Pine Street. JHG continued to do clinical operative work in the mornings and investigative work in the afternoons. Maly continued as his part-time assistant in the laboratory, working about 30 hours a week.

With Europe's involvement in World War II, JHG and Maly began to take a more active part in local and national political organizations. School for the children became important. These activities enlarged JHG's and Maly's circle of friends, although work on the heart-lung machine was still paramount.

JHG, a reserve officer in the Medical Corps, was among the first to enter active service in January 1942, soon after the Pearl Harbor attack by the Japanese on December 7, 1941. His assignment was the South Pacific—New Caledonia, specifically. At that time, the four Gibbon children ranged in age from 1 1/2 to 10.

New Caledonia was a major medical station for the injured who had received initial treatment at the portable hospital units closer to the battle areas. Located in the Coral Sea, due east of Australia and south of the Solomon Islands (Guadalcanal), New Caledonia was large enough to accommodate air-lifted wounded, to perform more definitive surgery than was possible at the field hospital units, and to provide short-term rehabilitative care with return to active duty, or return to the United States for further treatment and recovery. JHG had been Chief of Surgical Services at the 364th Station Hospital for 32 months when, because of a back injury, he returned to the States and was assigned to the Galesburg, Illinois military hospital. He was separated from the Medical Corps in 1946.

JHG's four years away from his family was quite likely the cause of an estrangement—especially from his children—that would last throughout his life. His son,[6] in particular, said that he and his sisters felt abandoned by their father. During the years that JHG was away, Maly had to cope with several major crises at home. John fell from a tree and sustained multiple

fractures; recovery took several months. Mary had to have back surgery that required a spinal fusion. The best orthopedic surgeon was at a Manhattan hospital. Mary had to be transported by stretcher on the train before and following surgery. Maly felt compelled to be with Mary as much as possible during her hospitalization, and thus she felt torn between being with Mary and being with the younger children at home. Recovery for Mary, too, was lengthy and required physical therapy for some months.

In addition to her responsibilities at home during the war years, Maly continued to work at the University of Pennsylvania Medical School on a project that was sponsored by the Office of Scientific and Research Development. She worked with a group of scientists attempting to find a cure for phosgene poisoning. At this period, it was considered a grave possibility that chemical warfare might eventually be used. However, neither the work done by this group, nor studies by several similar groups working in different parts of the country, resulted in a cure for the damage that phosgene does to the lungs. In this work, dogs were used as the experimental animal.

When JHG returned, the children were ages 5 to 13 years. JHG's long absence resulted in his missing many of their important developmental stages. JHG's experiences in the Medical Corps were totally different from theirs at home—experiences that they could not even imagine and certainly could not appreciate. Similarly, Maly and the children had shared events in which JHG had no part. The years and differing experiences resulted in some degree of alienation which, JHG and Maly hoped, would disappear over time. However, the children's feeling of abandonment by JHG persisted.

The study of psychology and psychiatry had not been part of JHG's education. These disciplines were relatively new and regarded with some skepticism by many physicians who were not in those fields. One can reasonably assume that JHG did not examine nor seek information regarding his family relationships from a psychological perspective.[6]

They all looked forward to the reunion in Galesburg, when the family was able to join JHG for the remaining year of his active military service. Mary[3] recalls a great many social events and entertaining of the surgical residents and their wives during this time. She remembers this period as happy in many ways, but it required adjustments for everyone. A major, albeit subtle, change had occurred within the family that persisted.

However, the move back to "home" in Philadelphia in 1946, when JHG was separated from the Medical Corps, helped to get the family on a more even keel.

Post-World War II

Toward the end of his years in the Army Medical Corps, JHG wrote an interesting, almost prophetic, piece in which he described medicine as it was practiced in the Army, and suggested that this model could well be used in civilian life. The article was "The Army Doctor Comes Home and Looks at Civilian Practice," and appeared in *Harper's* in February 1946.[8] Reading the article forty years after its publication, Dr. Frank Allbritten observed that, had the country's policies and the medical profession allowed us to go in the direction recommended by JHG, both the country—with respect to health care—and the medical profession would no doubt have been better served.[1] In the article, JHG recommended changes both in standards of practice and in methods for delivery and payment of care. These recommendations covered better monitoring of physicians with respect to competence, so that unqualified and incompetent physicians would not be allowed to practice. Only in 1990 did the National Practitioner Data Bank[15] come into existence under the Department of Health and Human Services. The Data Bank provides records of payments to physicians by insurance companies resulting from written claim, suit, or judgment on the part of medical malpractice insurers. This identification will prevent incompetent physicians from practicing in other states. JHG also addressed the importance of professional organizations in maintaining and improving professional practice standards, the necessity for a system of critical review of all papers submitted for publication to ensure the quality and integrity of scientific writing, and the need to provide basic health care to all citizens through a system of group practice and prepaid and regular health insurance programs—a description of what was considered "socialized medicine," which was anathema to many physicians who believed strongly in the fee-for-service system of payment. He advocated the group practice system developed at the Mayo Clinic, a system also used in other medical centers. In these precepts and recommendations, JHG was also thirty years ahead of his time, as he was in his conception of extracorporeal circulation.

When JHG returned to Philadelphia, he resumed his position as assistant professor of surgery at the University of Pennsylvania from December 1945, until January 1946, when he was offered the position of Professor of Surgery and Director of Surgical Research at Jefferson Medical College. This offer was made by Dr. Thomas Shallow, who was the Samuel D. Gross Professor of Surgery at that time. Dr. Shallow thought that more research should be taking place at Jefferson and knew of JHG's experience and interest in doing experimental work to further develop a

temporary heart and lung substitute. At Jefferson, JHG immediately returned to his work on the apparatus, using the slightly larger model that he had built just before he went into the Army in 1942. JHG felt that it was time to test the new model regarding its oxygenating capacity. He and his surgical residents began a series of experiments using dogs. This experimental animal research was, in part, funded by a grant from the National Institutes of Health.

Enter IBM

In the group of surgical residents working with JHG during the late 1940s was John Y. Templeton III who had recently returned from service with the Army Medical Corps. He was offered a surgical residency by Dr. Shallow, Dr. John DeTeurk was the other resident at that time; it was he, in fact, who was JHG's first resident. Dr. Frank F. Allbritten had not yet returned to Philadelphia from the Army Medical Corps, although he did join JHG later in 1946. E. J. Clark, a medical student, was shortly to play a significant role in JHG's life.

Clark was, at that time, engaged to the daughter of the president of Lafayette College, a good friend of Thomas J. Watson, Chairman of the Board at IBM. Clark had spent the war years flying Air Force transport planes and was better acquainted with the world of business than the younger residents. Knowing of the friendship between his future father-in-law and IBM's Thomas J. Watson, and knowing JHG's need to develop a heart-lung machine with a greater oxygenating capacity for larger animals, Clark thought that it would be worthwhile for JHG to talk with Mr. Watson to find out whether IBM could help in some way. IBM was still working on keypunch machines and other office machinery, not yet having gotten into the development and manufacture of computers. Clark knew, however, that many excellent engineers and machinery experts were employed by IBM, and could be of assistance in the design and fabrication of an oxygenator. The meeting between JHG and Mr. Watson took place as arranged. Watson did not hesitate to offer assistance. JHG himself and his idea immediately intrigued Watson, an intuitive gentleman who was able to "size up" men and situations rapidly and accurately. He placed one of his best engineers, Gustav V. A. Malmros, in charge of the group assigned to work on the project. Using the oxygenator that JHG had designed and built, Malmros, along with John R. Engstrom, an electrical engineer, and Edmund A. Barber, Jr., began by incorporating this design into a larger model of the machine that JHG was then using. The IBM model became Model I.

Donald K. Rex, the IBM engineer who later did a great deal of the work on Models II and III, recalled the period just after World War II.[16] Rex had been discharged from the Navy in the summer of 1946 and joined IBM that fall. When he arrived in Endicott, New York, IBM headquarters, he learned that Alf Malmros and his group of engineers were working on the first heart-lung machine, Model I. Rex did not join that group until the following year. Work on the Model I was well under way by the end of 1946. At that time, IBM was quite small with about twelve in the group of engineers. None of the engineers really wanted the assignment. None had previously worked with physicians, and the problems posed by JHG were not like those they usually dealt with. The responsibility for mobilizing the group fell on Alf Malmros, whom Rex describes as a true genius, extremely inventive and creative.

JHG and Templeton made a number of trips to IBM headquarters in Endicott during 1947 and 1948, and worked closely with the engineers as they developed, built, and tested each part of the apparatus.

Templeton[18] remembers his own perception as they stepped into this "other world" of IBM—that other world seemed to be one of unlimited resources. JHG, said Templeton, had done most of his pre-war work on a shoestring—making many of the components of his early oxygenator with "off the shelf" laboratory supplies modified with his own hands, such as the valves, and doing all the testing and readjustments himself, with Maly's help. IBM, on the other hand, used only the finest materials: stainless steel, for example, which although highly durable, was difficult and expensive to machine.

Another aspect of the business world that was different for the doctors was that, at five o'clock, the IBM people left their desks, offices, and laboratories, and went home. The physicians would have been eager and quite happy to work with the new oxygenator parts, or to sit and talk about it, until the wee hours of the morning. The IBM folks, recalls JYT, were smarter than we were. IBM maintained a large residence hall that included a fine library where the doctors were sometimes lodged overnight. Watson, a teetotaler, had a strict rule that no alcohol was permitted on the premises. This restriction, observed Templeton,[18] "tended to limit the length and scope of the philosophical discussions that JHG and I might otherwise have had."

A Trip Abroad

In the fall of 1947, JHG was able to attend the first meeting of the International Society of Surgery to be held in seven years, because of the

war. The meeting was to take place in London, but he arranged to travel also to Stockholm in order to visit Dr. Clarence Crafoord. Both Dr. Crafoord and Dr. Clarence Dennis from the University of Minnesota had visited JHG in the spring of 1946 to discuss problems associated with extracorporeal circulation. JHG's oldest daughter accompanied him on this trip, which he reported in an article for the Jefferson Medical College publication *Clinic* in 1948.[9] This visit helped to cement a strong lifelong friendship between JHG and Crafoord.

Model I

In 1949 the apparatus was completed by IBM and delivered by truck to Jefferson Medical College. Templeton was given the responsibility of receiving it and seeing that it was brought up to the appropriate floor by freight elevator. As soon as it arrived, however, he saw that it was far too heavy for the available elevator. He immediately called the IBM office in Philadelphia and explained that the problem was, emphasizing that this project was near and dear to President Watson's heart. IBM promptly arranged for riggers to hoist the oxygenator by crane to the designated floor, where it was taken into the building through a large window.

The Model I oxygenator was built using JHG's basic design and incorporating the modified and larger revolving cylinder as the chamber in which oxygenation took place. JHG was perhaps excessively careful about testing equipment with animals, which he considered an essential part of clinical research with any machine or apparatus that would be used on humans. While he wanted testing to be successful with animals, he knew that during the perfecting stages some animals would inevitably die as a result of experimentation. He took every precaution to assure that the equipment would work well in these experiments, and required the surgical residents working with him in the laboratory to do everything they could to make the animal's recovery a goal of each experiment. During testing of the Model I, dogs were used to see whether the new apparatus would successfully perfuse an animal of that size and whether blood flows, temperatures, and oxygenation of the blood would be adequate to ensure survival of the animal. Sterile surgical techniques were used. Hopes were high as the Model I was put into use. The apparatus (shown in Plate 6) and its operation were described by Stokes and Gibbon:[17]

> The unit consists of two metal cabinets mounted on wheels and connected by a cable for electrical transmissions between the two. The cabinets are small enough to pass through the average sized doorway.

The basic parts of the extracorporeal circuit are indicated diagrammatically in Figure 4 in the previous chapter.

Blood is withdrawn from the animal through cannulas in the venae cavae by a roller type pump (A), the venous pump. If this pump operates too rapidly, the walls of the venae cavae will be drawn into the open ends of the venous cannulae, occluding them. When this occurs the blood level in the vertical tube (B) falls, permitting light (C) to reach the photoelectric cell (D), thus setting into operation an electric circuit that stops the venous pump. The continued intermittent interruption of the venous pump is an indication that its pumping rate should be reduced. The blood from the venous pump flows in a thin film down the inner surface of the vertical revolving cylinder (E). During the passage of this film down the inner surface of the cylinder, oxygen enters the blood and carbon dioxide is extracted. The blood is collected in a stationary bowl (F) and cup (G), from which it is pumped by the arterial pump (H) through the monel metal filter (I) to a cannula directed cephalad in the femoral artery. A constant flow of blood is maintained in the extracorporeal circuit by means of a photoelectric unit consisting of cell (J) and light source (K). The unit varies the pumping rate of the arterial pump to hold constant a level of blood in the collecting cup, G. The closed vertical tube (L) eliminates the slight pulsations of the pump (H) resulting in a smooth nonpulsatile flow into the femoral artery. Oxygen is humidified (M) and blown over the blood film in the cylinder (E). A quarter turn of the stopcock (N) permits a change from recirculation of blood in the apparatus to the perfusion of the animal. The circuit is filled with blood through the burette (O).

Preparation of the Apparatus

The apparatus was carefully cleaned prior to each perfusion experiment. Since fibrin tended to collect at glass-rubber junctions, these parts were removed and scrubbed separately with an alkaline detergent and rinsed with a large volume of water. All rubber and glass parts were coated internally with silicone in order to decrease the amount of fibrin deposited in the apparatus during circulation of blood. For 1 hour prior to perfusion, sterile water and then sterile saline were recirculated through the apparatus. No antiseptic solutions were used.

About 550 ml of blood was required to fill the tubing, collecting cup, and filter, and to lay a film on the inner surface of the cylinder. To avoid depletion of blood volume in the experimental animal, the apparatus was filled with donor blood before each perfusion.

Dog blood is far more delicate than human blood because its cells are more fragile and it clots more readily. Canine blood which has circulated in

a heart-lung machine causes apnea and circulatory collapse when transfused into healthy dogs. Transfusion reactions characterized by hypotension, bradycardia, and respiratory depression are also frequent in dogs although they are often obscured by hemodynamic changes brought about by the perfusion itself. Use of autogenous blood for priming extracorporeal circuits minimizes these difficulties.[5]

Donor dogs were anesthetized with sodium pentothal (25 mg per kg of body weight) and given heparin (5 mg per kg of body weight). Then, under sterile precautions, about 700 ml of blood was withdrawn by femoral artery puncture 1 hour before the perfusion experiments. The temperature in the air-conditioned cabinet was raised to 37° C. The extracorporeal circuit was then filled with the donor blood, which was recirculated slowly through the apparatus at 200 ml per minute. The cylinder was rotated at 50 revolutions per minute (rpm) and a film of blood established on its inner surface. A mixture of 96% oxygen and 4% carbon dioxide was blown over the blood film at 5 liters per minute. When the circuit was connected to the animal, the gas mixture was changed to 100% oxygen. The tubing by which the extracorporeal circuit was to be connected with the animal was filled with blood, and care was taken to eliminate air bubbles.

Partial Circulation Experiments Without Occlusion of the Venae Cavae

A series of experiments was performed to observe the effect upon animals of continuous passage of a part of their circulating blood volume through the apparatus. The apparatus was prepared as described. Dogs of 10 to 25 kg body weight were anesthetized with sodium pentothal intravenously, 25 mg per kg of body weight. Under sterile conditions, a cannula was inserted cephalad in the right femoral artery and the right atrium was cannulated through the right external jugular vein with a glass cannula 12 cm long and having an internal diameter of 3.5 mm. Venous blood was continuously withdrawn from the dog's right atrium, exposed to 100% oxygen in the revolving cylinder, and returned to the animal at the same rate through the femoral artery. The venae cavae were not clamped.

Eleven of these experiments were performed. From 5 to 43 ml of blood per kg of body weight per minute was withdrawn from the right atrium, passed through the apparatus and continuously injected into the femoral artery for periods varying from 81 to 188 minutes. These animals

lived less than 12 hours, exhibited no reflexes and died in coma. At post-mortem examination, multiple small emboli were found throughout the viscera. No other cause for the deaths of these dogs could be found.

Three pairs of experiments were performed to determine whether the lungs might be used to filter these small emboli from the blood. Seven hundred ml of blood was drawn from a donor dog and recirculated for 1/2 hour through the apparatus at a moderate flow rate, 225 ml per minute. Half of this blood was injected intravenously at a rate of 20 ml per minute into a dog anesthetized with sodium pentothal, without ill effects. The other 350 ml of blood, injected at the same rate intra-arterially into a similarly anesthetized dog, resulted in the death of the animal. The same results were obtained in the other two paired experiments. It appeared, therefore, that the lungs act as an efficient filter for small embolic particles in the blood.

It was thought that arterial embolic phenomena might be avoided if the donor animal's blood, which had been recirculating in the apparatus, was filtered through the lungs of the animal to be perfused before injection into an artery. This hypothesis was tested in seven experiments by passing the donor blood through the perfused animal's lungs in the initial part of each experiment. An additional four-way stopcock was placed in the circuit, and this enabled the flow of blood from the venae cavae and to the femoral artery to be reversed. Thus, the venous pump continually withdrew blood from the femoral artery and the arterial pump simultaneously reinjected it at an equal rate into the venae cavae during the first 5 minutes of a 30- to 40-minute perfusion. The stopcock was then turned so as to restore the customary direction of blood flow through the circuit. In this way the donor blood was filtered through the animal's lungs before the arterial perfusion was begun. However, there was no further filtration of the blood which passed into the animal's arterial system during the rest of the perfusion. All seven of the dogs used in these experiments died during or following perfusion. The autopsy findings were similar to those in animals that received unfiltered blood from the apparatus. Thus, it appeared that preliminary filtering of the donor blood through the lungs was not sufficient to prevent death from multiple small emboli.

It appeared necessary, therefore, to pass the blood through some mechanical filter before injecting it into an artery. A monel metal filter, similar to that described by Bjørk,[2] with a 300 by 300 micron mesh and thread thickness of 140 microns, was put in the circuit (Figure 7).

The donor blood used to fill the extracorporeal circuit was recirculated

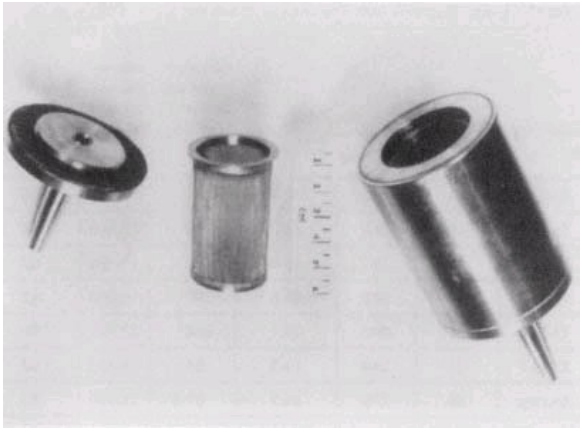


Figure 7:
Filter Used in Perfusion Experiments to Decrease Clotting. Small arterial emboli caused by some degree of damage to blood cells as blood passed through the extracorporeal circuit resulted in many deaths. JHG thought that the donor blood could be adequately filtered through the animal's lungs prior to surgery to remove these microscopic fragments. However, this filtering method provided unsuccessful. Therefore, a mechanical filter was designed, similar to one used by Bjork, with a 300 by 300 micron mesh and thread thickness of 140 microns, and placed in the circuit. This filter consistently prevented further deaths from emboli.
Source: Stokes TL, Gibbon JH, Jr (1950). Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. Surg Gynec Obstet, 91:138–154, p. 143.

through the apparatus for about 15 minutes prior to perfusion, so that all of it passed through the filter several times. During the perfusion, this filter provided continuous filtration. In long experiments the filter became coated on both inner and outer surfaces with a gray gelatinous layer, which appeared microscopically to consist of fibrin and disintegrated cells. The filter did not appreciably increase hemolysis.

With the filter in the circuit, six consecutive partial circulation experiments were performed and all the animals survived in these experiments (Table 3).

Table 3 Partial Perfusion with Filtration of Blood and Survival of Dogs

		Blood flow				
Experiment no.	*Wt of dog (kg)*	*(ml/min)*	*(ml/kg/min)*	*Duration continuous partial perfusion (min)*	*Total volume passed through machine (ml)*	*Survival time before sacrifice (days)*
O-135	24	225	9.4	40	9,000	106
O-138	18	264	14.7	60	15,840	53
O-139	16	166	10.4	91	15,106	43
O-140	15	401	26.8	60	24,060	42
O-141	11	266	24.1	120	31,920	50
O-142	24	348	14.5	154	53,592	46
Average	18	278	16.7	87.5	24,920	57

Source: Stokes TL and Gibbon JH, Jr. (1950). Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. *Surg Gynecol Obstet, 91,* p. 7.

The largest blood flow (experiment 0–140) through the apparatus was 401 ml per minute (26.8 ml per kg per minute). In another experiment (0–142) about 350 ml of blood per minute (14.5 ml per kg per minute) was pumped through the extracorporeal circuit for 2 1/2 hours. The volume of blood passed through the apparatus in this experiment was 53,592 ml. Recovery of all six animals was rapid and uncomplicated. The six dogs then were sacrificed from 42 to 106 days after perfusion. At autopsy there was no evidence of infarction or other organic damage in any of the 6 dogs. One of the dogs, which was sacrificed because of the presence of severe mange on the 53d day following perfusion, was found to have only one kidney. Its recovery had been without renal complications.

These experiments demonstrated that, with continuous filtration, a part of the circulating blood volume of dogs could be continuously passed through the apparatus for a period of as long as 2 1/2 hours and that this procedure was followed by prolonged survival of the dogs in healthy condition.

Total Circulation Experiments with Occlusion of the Venae Cavae

To demonstrate that an apparatus could supplant, temporarily but completely, the functions of a dog's heart and lungs, the blood flow through these organs had to be interrupted. In the experiments described in this section, JHG and his team accomplished this by occluding the superior and inferior venae cavae at their junctions with the right atrium. Under these circumstances the only blood entering the right side of the heart was that from the coronary veins.

Because a thoracotomy was necessary to occlude the venae cavae, it seemed expedient to insert large cannulas directly into the cavae to obtain a maximum flow of venous blood. In four experiments small incisions were made in the superior and inferior venae cavae and wide bore glass T-tubes were introduced into these vessels. Once tied into place in the cavae, blood could flow through the horizontal limb of the T-tubes to the heart and lungs until the cavae were occluded by bulldog clamps between the tubes and the heart. When the cavae were occluded, blood was withdrawn by the venous pump through the vertical limbs of the T-tubes and the cardiorespiratory functions were entirely maintained by the extracorporeal circuit. Adequate flow rates were obtained, but the method was discarded for three reasons. First, at the end of the period of perfusion, in order to remove the cannulas, it was necessary to clamp the venae cavae until Pott's clamps could be applied to repair the vessels. The animals withstood poorly this brief interim of total occlusion without an artificial circulation. Second, the wounds in the venae cavae continued to ooze in the heparinized animal. And third, the procedure was time consuming.

The following technique was found to be practical and satisfactory. Through a right thoracotomy, the venae cavae were isolated close to the pericardium and braided silk ligatures were passed loosely about them. The superior vena cava was cannulated by way of the azygos vein. The azygos vein was ligated at its junction with the superior intercostal vein and a curved metal cannula introduced proximal to the ligature. The cannula was inserted medially through the azygos vein into the superior vena cava where its orifice was directed cephalad. It was then tied in place in the azygos vein (Figure 8).

The inferior vena cava was cannulated by way of the right auricular appendage. The pericardium was opened, the right auricular appendage

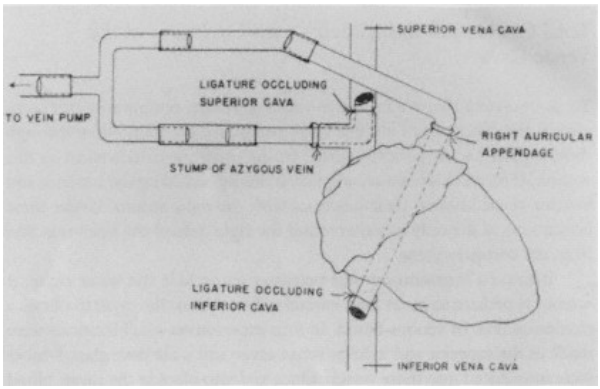


Figure 8:
Diagram Showing Method of Cannulating Venae Cavae. Cannulae (small hollow tubes) made from various materials (limited to either glass, metal or rubber in the 1930s until plastic materials came into wide use following World War II) are inserted into the large veins, and then attached to the venous pump to withdraw deoxygenated blood from the venae cavae, send it through the oxygenator for exchange of blood gases—oxygen and carbon dioxide. The oxygenated blood is then pumped from the oxygenator through a cannula inserted in the femoral artery.
Source: Stokes TL, Gibbon JH, Jr (1950). Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. Surg Gynec Obstet, 91:138–154, p. 145.

grasped, and a curved cannula was inserted via a small incision in the appendage through the right artium into the inferior vena cava where its orifice was directed caudad. The curved cannula was then tied in place in the auricle.

These thin-walled, stainless steel cannulas were filled with sterile physiological saline prior to insertion. The external diameters of the cannulas in the superior and inferior venae cavae were 5 and 6 mm respectively. In dogs of 6 to 11 kg, cannulas of this size did not obstruct the return of venous blood to the heart until the ligatures around the venae cavae were tied over the cannulas. When it was desired to stop the flow of blood to the right side of the heart, the braided silk ligatures previously placed around the cavae were tied tightly over the cannulas. In this way the entire flow of venous blood could be diverted from the dog's heart and lungs to the extracor-

poreal circuit, which then assumed the functions of the cardiorespiratory system.

The operations were performed under sterile conditions. Adult mongrel dogs weighing 6 to 11 kg were anesthetized intravenously with sodium pentothal (25 mg per kg of body weight), and a flexible tube with an inflatable rubber cuff was inserted into the trachea (Figure 9).

Oxygen was introduced through a rubber catheter into the tracheal tube at a rate of 2 liters per minute. Because of the light general anesthesia, local anesthesia—1% procaine—was used for both the thoracic and femoral incisions. Before the perfusion of the dog was begun, the depth of anesthesia was increased by an additional dose of 10 mg of sodium pentothal per kg of body weight. Usually no additional sodium pentothal was required during a 30- to 45-minute perfusion period.

The right femoral artery was cannulated for return of oxygenated blood from the apparatus. The left femoral artery was cannulated for direct blood pressure measurements with a mercury manometer. The stainless steel cannulas were thin-walled and of as large a bore (2.5 to 4.0 mm) as the lumen of the arteries would admit. Each was connected to a short piece of rubber tubing filled with physiological saline solution containing a small amount of heparin. The endotracheal tube was connected to a positive pressure respirator and the lungs were intermittently insufflated 8 to 12 times a minute with air at a pressure of 15 centimeters of water. The right pleural cavity was then opened either through an incision in the fourth interspace or through the bed of the fourth rib, and the venae cavae were cannulated as described. Heparin was given intravenously, 5 mg per kg of body weight, after the operative procedures had been completed and immediately before the perfusion was begun.

To connect the extracorporeal circuit with the dog's own vascular system, the stopcock, N, (Figure 4) was turned one quarter of a circle. At the same time the gas flowing into the oxygenator cylinder was changed from 96% oxygen and 4% carbon dioxide to 100% oxygen. The output of the venous pump, A, was slowly increased until the venae cavae were almost collapsed. The braided silk ligatures about the venae cavae were then tied tightly over the venous cannulas, diverting all the blood returning to the heart through these vessels to the extracorporeal circuit. After the cavae were occluded it was usually possible to increase the venous pumping rate as the cannulas were carefully aligned in the center of the cavae.

During the period of occlusion of the venae cavae the heart appeared smaller. The rhythm was regular and the rate usually varied between 100

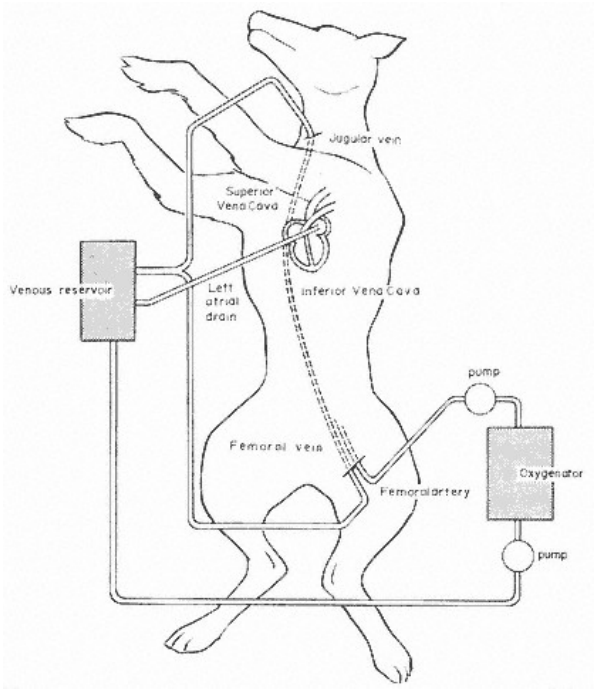


Figure 9:
Drawing of a Cannulated Dog. Dogs were used in the laboratory experiments of the 1950s and 1960s because of their variable sizes for testing equipment and establishing that animals of this size could be maintained on the heart-lung machine for relatively long periods, and that survival following surgery was possible for indefinite lengths of time. The animals were treated the same way that human patients would be treated later, with respect to care and treatment. For surgery, the dogs were anesthetized, then cannulated as seen in the drawing for the attachment of the connections with the heart-lung machine.
Source: Lower RR, Stofer RC, Shumway NE (1961).
Cannulation technique for cardiopulmonary bypass.
J Thorac Cardiov Surg, 41:196.

and 115 beats per minute. The myocardium, which was receiving oxygenated blood through the coronary arteries, did not change in color during the perfusion, but the lungs blanched noticeably after the venae cavae were occluded. The corneal reflex was often lost during perfusion but the lid reflex usually remained intact and occasionally the animals moved their heads. The color of the buccal mucosa was pink. Several dogs voided clear colorless urine during or shortly after the period of perfusion. Rectal temperature was maintained at about 36° C.

Upon termination of the perfusion it was possible to restore the cardiorespiratory functions to the animal's own heart and lungs abruptly. The ligatures about the cavae were cut and removed and partial circulation was maintained for 3 or 4 minutes, until the cannulas could be removed from the cavae and the auricular appendage and azygos vein ligated. A search for small bleeding vessels was made and the chest closed in layers. Positive pressure breathing was then discontinued. A small soft rubber catheter was usually left in the right costophrenic angle. Blood that was removed through this catheter was transfused intra-arterially. After the arterial cannulas were removed, the femoral arteries were ligated and the wounds were closed. At the conclusion of the period of perfusion, protamine (protamine sulfate 5 ml ampule, 0.1% strength diluted to 0.025%, with 5 mg per kg of body weight given over a 10-minute period) was given to the animal to decrease the coagulation time. One mg of protamine was given for each mg of heparin the animal had received.

The dogs usually recovered from anesthesia within 3 to 4 hours and were able to drink water and stand shakily within 6 to 8 hours. The hind legs were cooler than the forelegs for the first 2 days after operation, but no difficulties were encountered from the bilateral ligation of the femoral arteries. Rectal temperature for the first 48 hours after perfusion varied between 38° C and 40° C. Penicillin, 100 000 units, was given intra-arterially at the end of the perfusion, and then intramuscularly each day for the first week.

Results

The venae cavae of 39 dogs were clamped for periods of up to 1 hour and 53 minutes, while the extracorporeal circuit maintained life in the animals' tissues. These 39 experiments fall into three groups. In the first group of 30 animals, the venae cavae were occluded for periods up to 35 minutes. In the

second group, the venae cavae in six dogs were clamped from 33 to 47 minutes. One of these animals survived a period of caval occlusion of 46 minutes. In three experiments, the venae cavae were clamped for 60 to 113 minutes. All three of the dogs in these experiments died.

A large proportion of the deaths occurred in the early phase of the investigations. Several of the animals whose blood had been heparinized died of hemorrhage. Experience with the use of protamine and meticulous hemostasis largely decreased this danger. Maintenance of a physiologic acid-base balance became possible only after the proper use of carbon dioxide in the aerating mixture was learned. Some deaths were due to mechanical difficulties with the apparatus. The most frequent cause of death, however, was anoxia due, first, to the inability to withdraw a volume of blood from the cavae equivalent to the animal's cardiac output and, second, to failure of the oxygenator to saturate this blood with oxygen.

The longest period during which the venae cavae were completely occluded and life was maintained by the extracorporeal circuit was 113 minutes. During the 113 minutes of perfusion the animal's heart rate remained regular and the blood was adequately oxygenated. Corneal reflexes were depressed but lid reflexes were active throughout. Function was restored to the animal's heart without arrhythmia at the end of the perfusion period. Respirations began immediately upon disconnecting the positive pressure apparatus. The animal in this experiment died 2 hours after perfusion was stopped. Death was believed to have been caused by a period of hypoxia and hypotension immediately before perfusion.

The data on animals surviving complete occlusion of the venae cavae for 30 to 46 minutes are summarized in Table 4.

Four of the eight surviving animals died between 5 and 25 days following perfusion, and four remained normal and healthy for 6 months or longer. Dog 0-178 made a normal recovery following a period of caval occlusion of 33 minutes. The animal ate well, played with the other dogs and appeared to have no organic damage; however, on the evening of the fourth day he developed nystagmus, unsteadiness of gait, and hyperpyrexia, and was sacrificed the next day. At autopsy a right cerebellar hemorrhage was found. None of the visceral organs showed signs of emboli. Dog 0-167, which had survived a 30-minute period of caval occlusion, died 22 days later from severe injuries to the right chest and right hind leg sustained on the preceding day in an accidental fall from a tall laboratory table. It had shown no signs of organic damage following the perfusion and autopsy failed to reveal any evidence of embolic phenomena in any of the organs

Table 4 Animals Surviving Complete Occlusion of the Venae Cavae

						Blood flow			
Experiment no.	*Date 1949*	*Wt of dog (kg)*	*Time total occlusion venae cavae (min)*	*Time artificial circulation continued after release (min)*	*Total duration artificial circulation (min)*	*(ml/min)*	*(ml/kg/min)*	*Survival (days)*	*Cause of death*
O-159	Mar 24	9.0	30	3	36	756	84	306+	
O-167	Apr 7	9.3	30	2	35	812	87	22	Accidental
O-177	May 2	9.8	32	10	47	890	91	25	Pericardial effusion
O-178	May 4	7.8	33	2	38	792	102	5	Cerebellar hemorrhage (sacrificed)
O-182	May 13	6.4	33	2	40	747	117	257+	
O-184	May 18	6.1	32	2	39	774	127	252+	
O-186	May 23	9.0	46	5	56	854	95	23	Pericardial effusion
O-187	May 25	10.0	35	9	67	854	85	245+	
Averages		8.4	34	4.4	45	810	99		

Source: Stokes TL and Gibbon JH, Jr. (1950). Experimental maintenance of life by a mechanical heart and lung apparatus during occlusion of the venae cavae followed by survival. *Surg Gynecol Obstet,* 91:148.

including the brain. Two dogs (0-177 and 0-186) died on the 25th and 23rd days following clamping of the venae cavae for 32 and 46 minutes, respectively. Both these deaths were a result of pericardial effusion. The pericardial opening had been loosely approximated with one suture. The pericardial effusion in the animal that survived 46 minutes of caval occlusion (0-186) was diagnosed by fluoroscopy on the 15th day following perfusion, and was treated unsuccessfully by pericardiocentesis. Four days later, therefore, a right thoracotomy was done, the pericardial sac widely opened, and about 185 ml of serosanguineous fluid removed. The animal recovered from this second operation but the pericardium became densely adherent to the heart; an effusion reaccumulated, resulting in the death of the animal on the 23rd day following perfusion. This 46-minute period of occlusion of both venae cavae was, it was believed, the longest period ever reported during which cardiorespiratory functions were completely maintained by an extracorporeal circuit, followed by survival of the animal. The four remaining surviving animals were alive and well between 8 and 10 months after the experiments.

Summary

For a mechanical heart and lung to take over temporarily a *part* of the cardiorespiratory functions, the following requirements had to be met.

1. The blood returning to the subject from the apparatus must be saturated with oxygen.

2. The carbon dioxide tension, and thus the pH, of the blood returning to the subject must lie within the normal range.

3. Destruction of the cellular elements of the blood during its passage through the mechanical heart and lungs must be minimal.

4. The blood must be rendered incoagulable during its passage through the extracorporeal circuit and at the conclusion of the procedure blood coagulability must be restored.

5. The blood must be filtered before returning it to the subject if it is passed through an extracorporeal circuit.

For a mechanical heart and lung to take over temporarily *all* of the cardiorespiratory functions so as to permit operations to be performed within any of the cardiac chambers, the conditions above plus two others should be met.

1. The flow of blood through the extracorporeal circuit must approximate the normal cardiac output of the subject. A pulsatile blood flow in the subject's arteries is apparently not necessary for the normal function of vital organs, at least for periods as long as 46 minutes.

2. *All* the blood returning to the heart through the venae cavae must be diverted to the mechanical heart and lung.

Oxygenation

Levy and Blalock[13] found the oxygen consumption as measured by a Benedict spirometer in 13 unanesthetized dogs to be approximately 6 cc per kg per minute. With the apparatus used in these experiments the maximum amount of oxygen that could be introduced into the blood was 70 cc per minute. Consequently small dogs, 6 to 11 kg in weight, were used in all experiments with occlusion of the venae cavae, in order not to exceed the capacity of the apparatus to introduce a sufficient amount of oxygen. The possible role of anoxia as a cause of death in these experiments can be seen by referring to Table 5. In the three surviving animals, 7.4, 7.1, and 5.0 cc of oxygen were introduced per kg per minute. Three animals failed to survive when oxygen was introduced at 6.0, 5.1, and 3.6 cc per kg per minute. A more efficient method of oxygenating blood had been devised—screens—and would be used in the future.

Kabat[12] found that the respiratory center of newborn dogs continued to function seventeen times as long as the center of the adult animal during complete arrest of the cerebral blood flow. He and his co-workers[11] also reported that very young animals would tolerate arrest of the cerebral circulation for a period four times as long as that tolerated by an adult, followed by complete functional recovery. All the animals used in these experiments were older than 4 months, the age at which Kabat noted a decrease to the adult level in resistance to anoxia.

Acid-Base Balance

During recirculation of donor blood in the apparatus prior to perfusion, a mixture of 4% carbon dioxide and 96% oxygen was blown over the blood film in order to keep the pH of the blood constant. When oxygen alone was used the pH rose in one experiment to 8.5 because of the washing out of carbon dioxide (Figure 10).

On the other hand, during perfusion, when the animal's metabolic

Table 5 Blood Gas and pH Determinations with Complete Occlusion of the Venae Cavae

			Oxygen saturation							
Experiment no.	*Wt. of dog (kg)*	*When blood sample was taken*	*Venous (%)*	*Arterial (%)*	*Oxygen added to blood (cc/min)*	*CO_2 removed from blood (cc/min)*	*pH of arterial blood (mm Hg)*	*CO_2 tension of arterial blood (mm Hg)*	*Blood flow (ml/kg/min)*	*Result*
O-178	7.8	Before perfusion	43	96	57.5	39.8	7.41	28	102	Survived
		After 25 mins' P					7.74	9		
O-179	7.9	Before perfusion		94			7.30	41		
		After 28 mins' P	41	87	40.5	39.9	7.39	19	64	Died
O-184	6.1	Before perfusion		96			7.61	15		
		After 26 mins' P	63	100	43.0	37.7	7.44	16	127	Survived
O-187	10.0	Before perfusion		92			7.54			
		After 12 mins' P	57	94	48.2	57.2	7.57	17		
		After 32 mins'P	50	87	50.1	43.4	7.50	19	85	Survived
O-188	7.3	Before perfusion		94			7.54	23		
		After 60 mins' P	53	92	43.7	50.3	7.49	18	95	Died
O-194	11.0	Before perfusion		87			7.50	31		
		After 24 mins' P	42	66	39.8	50.9	7.54	21	78	Died
O-196	9.0	Before perfusion		92			7.56	17		
		After 18 mins' P		81			7.50	17	60	Died
Average		Before perfusion		93			7.49			
		After perfusion	50	88	46.1	45.6	7.52		87	

Source: Stokes TL and Gibbon JH, Jr. (1950). Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. *Surg Gynecol Obstet, 91:* 147.

carbon dioxide had to be removed, the use of 100% oxygen proved necessary to wash out this carbon dioxide and keep the pH within a physiologic range (Figure 11).

In three experiments in which 4% carbon dioxide was used in the gas mixture during perfusion of the animal, the carbon dioxide rose and resulted in severe uncompensated acidosis. In one such experiment the pH fell to 6.54 (Figure 11), and the carbon dioxide tension of the blood rose to 284.5 mm of mercury. This animal died 5 hours later.

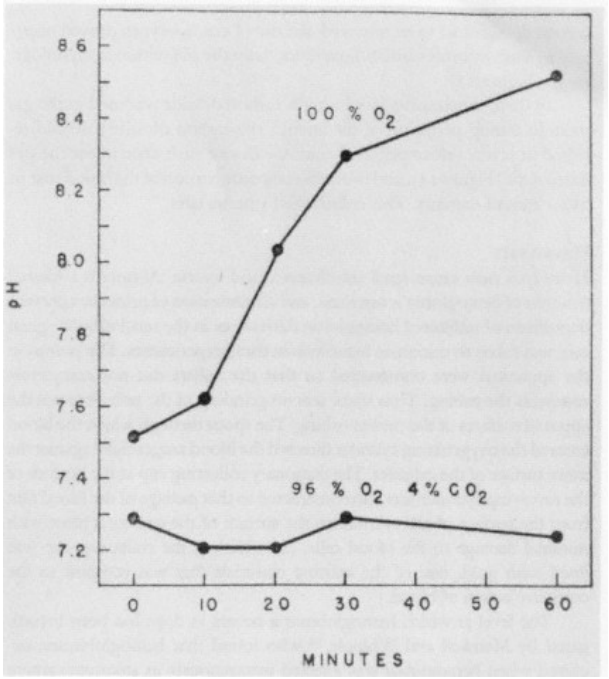
Hemolysis

Hemolysis may cause renal insufficiency and anuria. Although a filtered solution of hemoglobin is not toxic, and alkalinization of urine may prevent deposition of unfiltered hemoglobin derivatives in the renal tubules, great care was taken to minimize hemolysis in these experiments. The pumps in the apparatus were constructed so that the rollers did not completely compress the tubing. Thus there was no grinding of the cells between the apposed surfaces of the rubber tubing. The spout through which the blood entered the oxygenating cylinder directed the blood tangentially against the inner surface of the cylinder. The stationary collecting cup at the bottom of the revolving cylinder was also constructed so that passage of the blood film from the surface of the cylinder to the surface of the cup took place with minimal damage to the blood cells. (In addition, the collecting cup was lined with gold, one of the existing materials that was resistant to the corrosive action of blood.)

The level at which hemoglobinuria occurs in dogs has been investigated by Manwell and Whipple,[14] who found that hemoglobinuria occurred when hemoglobin was injected intravenously in amounts varying between 190 and 250 mg per kg of body weight. The hemolysis observed in these experiments with surviving animals did not exceed 200 mg of hemoglobin per 100 ml of plasma, and none had hemoglobinuria during or after perfusion. From these experiments it seemed that hemolysis was not likely to be a major impediment to the successful perfusion of humans.

Blood Clotting

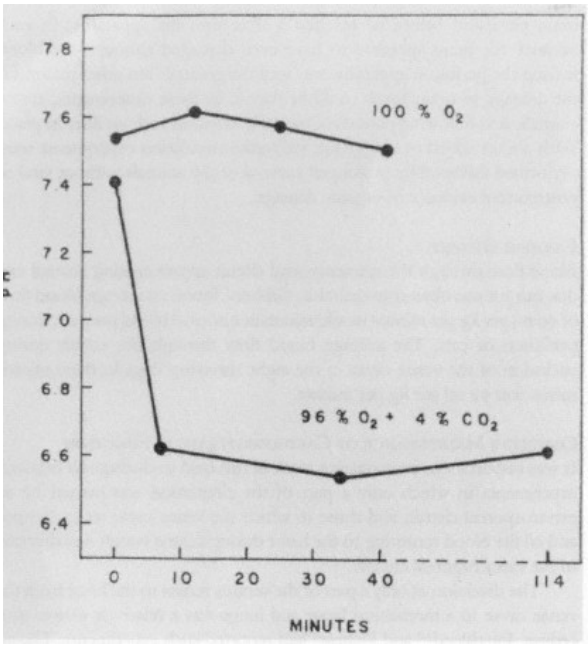
A single large initial dose of heparin prior to perfusion renders the blood incoagulable for the duration of an experiment. Postoperative intrathoracic bleeding was a contributory cause of death in several of the early experiments. Very careful hemostasis was used, and protamine at the appropriate dosage, given at the conclusion of perfusion, restored normal blood coag-



Figures 10, 11

Effect of CO_2. These graphs show the effects of carbon dioxide on the pH of the blood during circulation of blood through the heart-lung machine (Figure 10) and during actual perfusion experiments with dogs (Figure 11). The pH of the blood must be maintained to assure survival. Through trial and error, JHG learned that a mixture of 4% carbon dioxide and 96% oxygen was best prior to perfusion, while 100% oxygen was necessary during perfusion to adequately remove metabolic carbon dioxide.

Source: Stokes TL, Gibbon JH, Jr (1950). Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. Surg Gynec Obstet, 91:138–155, pp. 150, 151.



ulability. None of the surviving animals developed hematoma, although there was always some collection of serosanguineous fluid in the right pleural cavity. In these experiments, 1 mg of protamine per mg of heparin was used, and it was noted that if the protamine was given rapidly or in concentrations greater than 0.025%, a fall in blood pressure of 40 to 80 mm of mercury consistently occurred. When the same amount of protamine in dilute solution was administered over a 10-minute period, no drop in blood pressure or other undesirable effects were noted.

Filtration of Perfused Blood

Most investigators found it necessary to filter blood used for perfusion. Bjørk,[2] for example, reported the death of eleven animals during or after

brain perfusion before he inserted a filter into his apparatus. In each instance the brain appeared to have been damaged although the blood leaving the perfusion apparatus was well oxygenated. No other reason for the damage to brain tissue could be found. In these experiments, eleven animals died following periods of partial circulation with no filter in place. With a filter added to the circuit, six partial circulation experiments were performed followed by prolonged survival of the animals without vital or postmortem evidence of organic damage.

Cardiac Output

Blood flow through the extracorporeal circuit approximating normal cardiac output was obviously desirable. Gibbon[7] found an average blood flow of 99 ml per kg per minute would maintain a normal blood pressure during perfusion of cats. The average blood flow through the circuit during occlusion of the venae cavae in the eight surviving dogs in these experiments was 99 ml per kg per minute.

Complete Maintenance of Cardiorespiratory Function

It was important in investigative work in this field to distinguish between experiments in which only a part of the circulation was carried by an extracorporeal circuit, and those in which the venae cavae were clamped and *all* the blood returning to the heart through these vessels was diverted to the extracorporeal circuit.

The diversion of only a part of the venous return to the heart from the venae cavae to a mechanical heart and lungs was a relatively simple procedure. Jongbloed[10] and Dennis[4] had reported such experiments. The six consecutive experiments seen in Table 3 showed that it was quite possible to take over a part of the cardiorespiratory functions by means of a mechanical heart and lungs without detriment to the animal. Clinical application to human patients was to be initiated soon.

To open the chambers of the heart for operative procedures, the venous return to the heart by way of the venae cavae had to be *completely* diverted. With both venae cavae clamped at their junction with the right atrium, the only impediment to a bloodless operative field within the cardiac chambers was the blood entering the right side of the heart through the coronary sinus and the coronary veins. This blood had to be aspirated during the operative procedure and returned to the extracorporeal circuit. It appeared to be just as important to supply the myocardium with oxygenated blood as to supply other organs such as the liver and kidneys. Indeed,

in cases in which the heart is already handicapped by a congenital malformation, or by diseased valves, the maintenance of the coronary circulation is of particular importance.

In these experiments, the myocardium continuously received oxygenated blood from the aorta by way of the coronary arteries. Even when the extracorporeal circulation was suddenly stopped and the burden of the entire circulation was abruptly restored to the animal's heart, there was no drop in blood pressure or disturbance of cardiac rhythm.

The first clinical application of extracorporeal circuits was to take over a part of the burden of circulation in patients with acute failure of the cardiac or respiratory functions. In conditions such as pulmonary edema or coronary thrombosis, the blood could be withdrawn from a peripheral vein and returned to the body through a peripheral artery. The value of relieving the heart and lungs of part of their burden by such a procedure is greatly diminished unless a mechanical lung is in the extracorporeal circuit. In fact, the injection of venous blood into the systemic arteries could even be detrimental to the patient. Thus an extracorporeal circuit had to include a mechanical lung to be of value in these conditions.

With respect to intracardiac operations, it seemed that where septal defects were present, the use of a mechanical lung would greatly simplify the operative procedure. In the absence of septal defects, it was possible that the elimination of a mechanical lung from the extracorporeal circuit could, at that stage of development, simplify an operative procedure within the chambers of the right heart. The approach to the left side of the heart, without using a mechanical lung, appeared to present technical difficulties which, while not insurmountable, were easily as great as those entailed in the use of a mechanical lung. The importance, therefore, of developing and perfecting an extracorporeal circuit that could take over the function of not only the heart but also the lungs seemed unquestionable.

Templeton,[18] in recalling the work done in the laboratory in the late 1940s, said that his time in the laboratory ended at about the time that that of Dr. T. Lane Stokes was beginning, but he knew that Stokes worked prodigiously and was able, by enormous effort and attention to every detail, to have dogs survive the procedures. Even up to this time, however, JHG and his assistants were working at marginal levels in terms of blood flow, level of oxygenation of the blood, and other parameters. The long and varied circuit of blood through the apparatus, for example, resulted in a higher level of hemolysis than was desirable. The circulating blood had to undergo several changes of speed and direction of flow; these changes

caused damage to the cellular elements of the blood. After the blood was filmed through the revolving cylinder, it was collected in the stationary cup at the bottom of the cylinder, a change from downward flow to almost a complete stop in flow. This collecting cup was intricately designed with many compound curves, aimed at keeping hemolysis at a minimum. However, stainless steel could not be machined to conform to the design. Blood is extremely corrosive; stainless steel and gold were the only two metals at that time that were relatively impervious to its effects. Therefore, the collecting cup was plated with gold. From the cup, blood was then propelled into a linear flow into the rest of the circuit.

Introduction of Screens in the Artificial Lung

Some time during the late 1940s, Dr. Stokes and Dr. John Flick, Jr., who were working in the lab together, discovered that oxygenation was greatly improved when there was turbulence in the blood. They developed the concept of using screens to take the place of the revolving cylinder, because screens provided a much larger surface area for oxygenation of the blood, in addition to providing a certain level of turbulence which increased oxygen uptake by the blood.

It is interesting to note that JHG and Maly cited a stable flow of bright red blood during the experiment on May 10, 1935, when the speed of the revolving cylinder was increased. However, they did not attribute the bright red color to turbulence in the flow, but to increased surface area due to bubbles. In addition, the increased speed of the cylinder caused an increase in hemolysis and foaming, factors that they considered more undesirable than having blood oxygenated at a lower rate of revolutions.

The promise of increased oxygenating capacity, introduced by the use of multiple parallel screens to act as the lung, was a powerful incentive to JHG, the residents, and the IBM engineers to develop the Model II oxygenator.

The 1950s—Model II

Toward the end of 1949, JHG informed Malmros at IBM that the Model I was not capable of performing at the level required for extracorporeal circulation in humans. Larger tubing size was needed to increase blood flow, and greater oxygenating capacity was required to ensure oxygenation of 90% to 95%. The latter problem might be solved using a screen that would provide more surface area and would produce slight turbulence to improve oxygenation.

Miller and Gibbon[5] expressed the problem succinctly. The problem consisted of converting a stream of blood into a thin film exposed to an atmosphere of oxygen, and then reconverting the film flow into a stream flow without producing foam and with minimal damage to the cellular elements of the blood. Stokes and Flick[8] had shown that introducing some turbulence in the blood increased the efficiency of the exchange of gases between the blood and the atmosphere by about eight times. They built a small apparatus that used a 2-inch strip of screen enclosed in a plastic cylinder that acted as the atmosphere of oxygen (Figure 12).

The oxygen was saturated with water vapor at body temperature. Various rates of blood flow were tested, computing the oxygen uptake, volume of blood in the film, pH, and carbon dioxide content. Several types of materials were tested for use in the screen—stainless steel screens of different wire sizes, meshes, and configurations, and plastic and smooth metal perforated surfaces. The wire screen that proved to be the most efficient for oxygen transfer was Type #538, manufactured by Tyler Wire Company in Cleveland. Made of stainless steel with a diameter of 0.029 inches, and with rectangular meshes, it provided the appropriate amount of turbulence and produced the least amount of damage to the filmed blood.

The first screen oxygenator was built in the form of a vertical cylinder, capped by a bullet-shaped head of smooth stainless steel. Blood was distributed on the bullet-shaped top by a rotating jet that produced a film on the bullet nose. The blood then descended by gravity over the screen and collected in the cup at the bottom of the cylinder. The wetting process was a

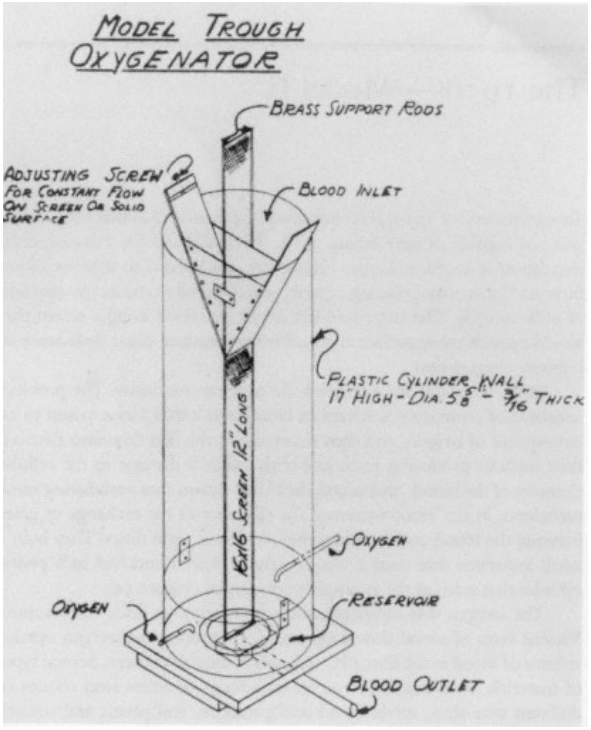


Figure 12:
Sketch of the apparatus used in testing the oxygen uptake of blood filmed on 2-inch strip of screen. This miniature device was used during the testing phase when the concept of having blood flow across screens, which enhanced oxygenation as a result of turbulence in the blood flow caused by the uneven surface, in contrast to the smooth surface of the rotating cylinder. This design greatly increased the capacity of the heart-lung machine, and made it possible to maintain the heart and respiratory functions of adult human patients, a true breakthrough.
Source: Miller BJ, Gibbon JH, Jr, Gibbon MH (1951). Recent advances in the development of a mechanical heart and lung apparatus.
Ann Surg, 134(4):694–708, p. 696.

problem in that the blood did not film evenly prior to introducing the blood by jet. Designed to increase the oxygen saturation of blood from 65% to 95% at a flow rate of 1000 ml per minute, the oxygenator worked perfectly during laboratory experiments using beef blood. Subsequently, eight animal experiments were performed using the new lung. The longest of these partial perfusions was 4 hours; all eight dogs survived for long periods of time in healthy condition.

JHG and his residents determined that for whole-body perfusion in average-sized dogs, it was necessary to have an oxygenator that provided 95% oxygen saturation of the blood, but with a flow rate of 2000 ml per minute. If one screen were to be used, its area would need to be about 8000 square centimeters. The problem of design was turned over to the IBM engineers, Malmros and Rex, on December 28, 1949.[7] To accommodate the screen oxygenator and the required increased blood flow rate, all the components of the Model I had to be reworked to provide for larger tubing, increased pumping action in all pumps, and an increased electrical capacity. New gauges and methods for recording data were also needed.

The final design of the oxygenator consisted of six rectangular flat stainless steel screens suspended parallel to one another from a blood distributing chamber, and enclosed entirely in a clear plastic case (Figure 13). The resulting capacity was a screen area of 8235 cm, with each screen 45 cm high and 30.5 cm wide. Blood could be filmed on both sides of each screen for a total of 1.6 square meters of filming surface.

This battery-type screen oxygenator operated with three pumps in the circuit. These pumps were of the roller type without internal valves, modified from the DeBakey pump. A diagram of the entire circuit is shown in Figure 14. Nichrome wires embedded in the wall of the case were heated by an electric current to maintain the temperature of the case at slightly above body temperature. This arrangement prevented condensation from water vapor on the inside of the case and helped maintain the temperature of the circulating blood at the appropriate level.

The oxygenator was built so that it could be easily disassembled and cleaned between perfusions.

The filming procedure involved thoroughly wetting the screens with physiologic saline. Simply circulating saline through the circuit was not sufficient to provide complete filming; it was necessary to flood the oxygenator chamber with saline, and then drain it immediately before introducing blood into the system. Blood in the reservoir at the bottom of the oxygenator had to be maintained at a minimal level to prevent air from

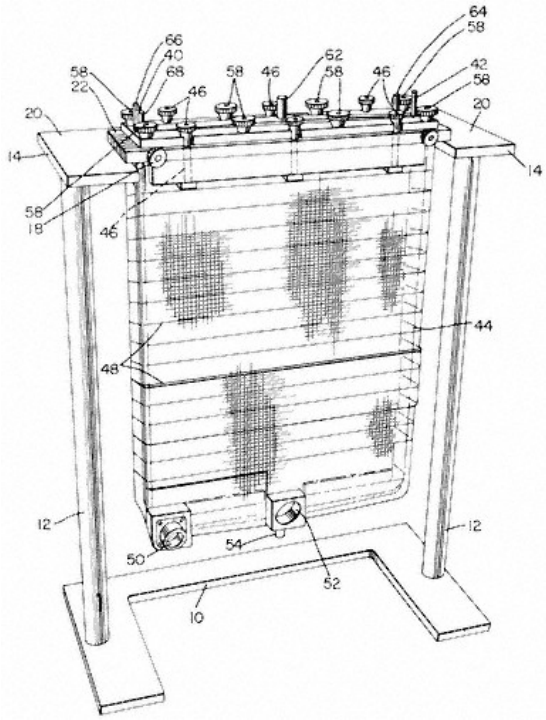


Figure 13:
First Page of the Patent on the Screen Oxygenator. The capacity (blood flow) could be changed by varying the number of vertical parallel screens. The capacity needed for an infant or child is less than that required for an adult. Dr. Thomas L. Stokes, one of JHG's surgical residents, conceived the idea of introducing turbulence in the blood flow to enhance oxygen uptake by the red blood cells, and the IBM engineers developed the "lung" and patented the design.
Source: U.S. Patent Collection (microfilm), Engineering Library, University of Maryland, College Park.

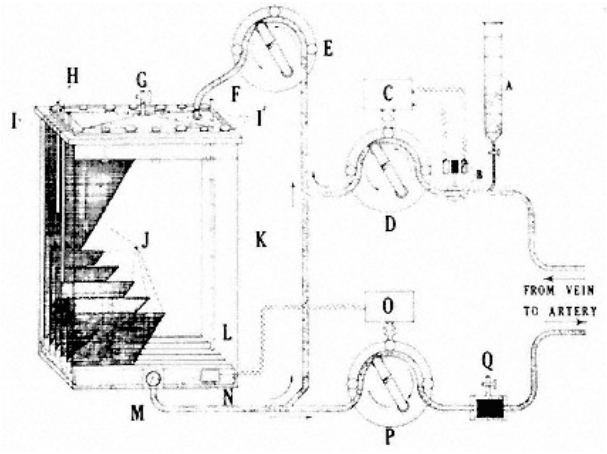


Figure 14:
Diagram of the First Screen Oxygenator. This schematic of the modified Model II oxygenator in 1951 shows the following parts: A) blood reservoir, B) venous pressure transducer, C) automatic venous pump shutdown control, D) venous pump, E) recirculating pump, F) oxygen input, G) reservoir pressure relief valve, H) oxygen exhaust, I and I') weir assembly, J) stainless steel screens, K) oxygenator plate, O) automatic electronic artery pump motor control, P) artery pump, and Q) reverse flow filter. The vertical screens vastly improved the oxygenation capacity/efficiency by introducing turbulence, achieved by the screens, at the point of gas exchange.
Source: Miller BJ (1982). The development of heart-lung machines.
Surg Gynec Obstet, 154:403–414, p. 406.

entering the system. Air in the system could possibly result in a fatal embolism in the body.

The Model II oxygenator was crated for shipment by truck to Jefferson Medical College Hospital on June 19, 1951.[7]

Model II: Description

The apparatus was designed for the purpose of maintaining either a part of or all of the cardiorespiratory functions *in human patients*. With the excep-

tion of the battery-type screen oxygenator, the apparatus was a new one and differed in many respects from the machine previously used. The electrical components were contained in a closed cabinet, 66 inches long, 32 inches wide, and 48 inches high.

The blood circuit was on top of the cabinet. The oxygenator was suspended in a vertical position at one end of the cabinet. The four pumps, blood filter, thermocouples, glass electrode assembly, and pressure transducers that indicated excessively low or high pressures in different parts of the system, were placed on top of the cabinet.

The switches that placed the pumps and control circuit in operation were mounted on the front of the cabinet panel. The electrical meters in the upper portion of the control panel indicated the degree of vacuum in the tubes drawing blood from the venae cavae, the speed of each pump, and the position of the blood level at the bottom of the oxygenator case. Four self-balancing and recording potentiometers occupied most of the lower and right sides of the panel. One of these periodically indicated and recorded the temperatures of the venous and arterial blood and the rectal temperature of the patient. Another continuously indicated the pH of the blood that passed through the oxygenator. This system also controlled the valve that allowed carbon dioxide to mix with the oxygen flowing through the oxygenator whenever the pH of the blood rose above the desired level. The remaining two recorders marked the saturation of the blood with oxygen before and after leaving the oxygenator, and the blood flow rate by means of an electromagnetic flow meter.

To minimize the explosion hazard when the apparatus was used in the presence of anesthesia gases, the cabinet was filled with nitrogen at a pressure slightly above that of the atmosphere. The only electrical component in the cabinet in which high-intensity sparks occurred was the DC motor of the arterial pump. Since the pressure within the cabinet was always greater than atmospheric pressure, explosive anesthetic gas mixtures could not enter. Audible and visual signals operated if the nitrogen pressure within the cabinet was not maintained. Mercury-type manually operated switches were used in high-current circuits. Conventional switches were used in low-current circuits only. All relays were hermetically sealed. Those relays carrying large currents, such as those in the breaking circuits of the motors driving the venous pumps, were the mercury plunger type.

Gas tanks containing oxygen, nitrogen, and carbon dioxide were in a separate unit and connected to the main apparatus through long flexible metal tubes. This unit also contained a water bath that could warm the

heparinized blood used to fill the machine. An additional unit held an electric motor generator operated from self-contained storage batteries. This unit became automatically operative in the event of line voltage failure and supplied current to the critical components—the motor and level control circuits—for 2 hours. Recording circuits were not operative during such an emergency.

The four pumps in the ECC blood circuit were the same roller types as were used in Model I. These pumps consistently performed well, with negligible hemolysis. The flow of venous blood from the superior and inferior venae cavae was conducted through the individual pumps (D and E, Figure 14). With this arrangement, occlusion of one venous cannula did not affect the flow rate through the remaining cannula, and did not completely interrupt blood flow.

When there was either a diminished blood volume in the patient or excessive flow rate through the venous pumps, there was intermittent and momentary collapse of the vein from which blood was being drawn before complete collapse of the vein occurred. This intermittent collapse or "fluttering" could be stopped either by adding blood to the circuit from the burette (A) or by decreasing the flow rate through the appropriate pump.

The degree of suction produced by the venous pumps was qualitatively measured by sensing the change in diameter of a small segment of rubber tubing interposed in the Tygon tubes connecting the venae cavae with the venous pumps (D and E). Small displacements in the core of a transformer during fluttering produced sufficient signal voltage to operate a warning buzzer, a signal light, and an indicating meter on the front panel of the cabinet. If complete occlusion of a vein occurred because of collapse of the vein wall, the electrical current produced a warning light and buzzer noise, full deflection of the indicating meter, and stopped the motor of the respective venous pump. Although the ideal was for the motor to be stopped immediately when occlusion occurred, this instantaneous response was not possible because of the AC capacitor type of motor used. However, by applying a DC voltage to the motor at the moment of occlusion, braking could be accomplished within one-third of a revolution of the pump arm. The motor was reactivated only after the occlusion was cleared.

Blood leaving the venous pumps passed through the oxygenator pump (P). This pump drew blood from the bottom of the oxygenator through the bypass as well as from the venous pumps (D and E). The flow rate through pump P was fixed at a rate that was greater than the sum of the maximum flow rates through pumps D and E. By maintaining a constant flow rate over

the screens of the oxygenator (J), the volume of blood held on the screens was kept constant. This avoided changes in the patient's blood volume.

The oxygenator consisted of eight parallel vertical stainless steel screens, enclosed in a plastic case. Each screen was 30 cm wide and 60 cm high. This oxygenator permitted venous blood that was 45% oxygenated to be 95% saturated with a flow rate of 2500 ml per minute. At a blood flow rate of 4500 ml per minute, 250 ml of oxygen could be added to venous blood per minute.

The pH of the blood leaving the oxygenator (M) was continuously monitored by the electrodes (H). The carbon dioxide tension of the gas passing over the screens in the oxygenator was automatically adjusted to maintain the pH in a normal range.

The arterial pump (P) returned the oxygenated blood from the circuit to the patient's aorta. The output of pump P was automatically controlled to maintain a constant level of blood in the bottom of the oxygenator.

The temperature of the venous and arterial blood was measured by copper Constantan thermocouples placed within stainless steel hypodermic needles. These needles were supported in the blood stream by a Teflon block. A cycling type Brown Instrument Company recording potentiometer located on the front panel periodically recorded these temperatures and also the rectal temperatures by means of an additional thermocouple.

Devices were incorporated in the apparatus to safeguard against abnormally high pressure developing within the system that could result in the separation of connections. An anvil and a spring-held plunger were placed around the Tygon tube leading to the distributor chamber of the oxygenator (K). Pressure greater than 300 mm of mercury developing at this point as a result of occlusion of the distributing slits at the top of the oxygenator due to a clot or a foreign body activated this system, causing all pumps to stop.

Visible and audible signals indicated a problem. Similarly, a device located at point O sensed high pressure developing as a result of accidental occlusion of the tube returning blood to the patient or clotting in the filter. In this case, the blood pumps stopped automatically, but recirculation through the oxygenator was maintained.

The best and most rapid method of altering body temperature was to vary the temperature of the blood passing through the ECC circuit during the period of total perfusion. All the tissues of the body tend to quickly assume the temperature of the perfusing blood. Body temperatures of dogs

during animal experiments were allowed to fall 3 or 4°C during the course of perfusions, but controlled hypothermia was not used.

All the blood entering the patient from the apparatus passed through the Monel metal filter (Q). Although successful animal experiments had been conducted without the filter, for human application the air trap and the insurance against emboli provided by the filter were additional safeguards.

Animal Experiments Using the Model II

As soon as the Model II arrived at Jefferson, work began in the laboratory, to determine the full parameters of the machine and to acquaint the lab personnel with its operation and maintenance. A large number of tests were run using beef blood to assess the filming process within the oxygenator, the degree of oxygen saturation, and the clearance of carbon dioxide. A few minor defects were discovered and corrected. JHG and his laboratory assistants initiated a whole new series of animal experiments.

Prior to each experiment, the machine was prepared by disassembling all parts of the blood circuit and mechanically cleaning all tubes and connections with detergent solution. The machine was then reassembled and filled with 1:1000 aqueous Zephiran solution for about 1 hour. The Zephiran was then removed and the machine filled with 9000 ml of saline solution. The saline was removed and the entire circuit was washed with individual 15-minute rinses of 1500 ml of sterile 0.85% sodium chloride solution. The pH apparatus was standardized by placing the electrodes in a special holder containing buffer solution.

About 1400 ml of heparinized blood was needed to fill the machine. An additional 300 ml of heparinized blood was available to replace blood lost from the operative field during perfusion and to compensate for blood taken for analysis during the perfusion. Citrated donor blood was also on hand to replace blood lost in the postoperative serosanguineous pleural effusion that generally occurred.

The dogs received an intramuscular injection of morphine (3 mg per kg of body weight) 45 minutes before surgery. Anesthesia was induced and maintained by an intravenous injection of 2.5% sodium pentothal solution. An endotracheal tube with an inflatable cuff was placed in the trachea and the balloon inflated. During thoracotomy, ventilation was maintained with a laboratory-type positive and negative pressure respirator.

The operative procedure was the same as that done in all previous cases using the oxygenator. The following variations were performed in order to analyze the outcomes of each: 1) complete occlusion of the venae cavae without opening the cardiac chambers, 2) complete occlusion of the venae cavae with the right atrium widely opened, and 3) complete occlusion of the venae cavae with the right ventricle widely opened.

Complete occlusion of the venae cavae without opening the cardiac chambers was performed on nineteen dogs in the first set of experiments. The cardiorespiratory functions were maintained for periods varying between 26 and 100 minutes during complete occlusion of the venae cavae. Six of the nineteen dogs survived the perfusion but died within 48 hours (Table 6).[4]

Dog #454 suffered a 14-minute period of anoxia that occurred a few minutes after the ECC circuit was disconnected from the animal and while the chest wound was being sutured. The inflatable cuff around the endotracheal tube ruptured and the lungs collapsed. Despite immediate tracheotomy and re-expansion of the lungs, the animal died 10 hours after perfusion, with evidence of damage to the central nervous system. Thirteen of the dogs (Table 5) survived in a healthy condition for two to 20 months following perfusion.

Dog #459 was in excellent condition at the conclusion of the total perfusion which lasted 61 minutes. The dog recovered from anesthesia and was walking around the laboratory within 5 hours after surgery. During the night, the ligature on the femoral artery slipped off and the animal bled to death.

Severe blood loss occurred during experiment #462 when the arterial tube of the ECC circuit suddenly separated because of a faulty joint. Another problem during this procedure was that the saturation of arterial blood with oxygen was abnormally low because of imperfect filming of the oxygenator screens. At autopsy, marked pulmonary edema was found.

Cause of death in dogs #463 and #467 appeared to be persistent bleeding within the pleural cavity during the postoperative period. About 500 ml of blood was found in the pleural cavity of each dog at autopsy.

Dog #465 died 48 hours following perfusion with symptoms of pulmonary edema. At autopsy, both gastrointestinal hemorrhage and pulmonary edema were seen.

In the thirteen dogs that survived perfusion, blood flow rates in the ECC circuit varied between 52 and 130 ml per kg per minute (Table 7). The average flow rate was 89 ml per kg per minute. The oxygen saturation

Table 6 Dogs Failing to Survive Occlusion of the Venae Cavae Without Opening the Cardiac Chambers

				Rate of blood flow from venae cavae		*Oxygen saturation (%)*		*Blood determinations during latter part of caval occlusion*					
Experiment no.	*Date (1951)*	*Wt of dog (kg)*	*Time venae cavae occluded (min)*	*ml/min*	*ml/kg/min*	*Venous blood*	*Arterial blood*	*Oxygen added to blood (cc/min)*	*Arterial blood pH*	*Hematocrit (%)*	*Hemolysis in plasma (mg/Hgb/100 ml)*	*Survival time after perfusion (hrs)*	*Cause of death*
454	Aug 28	11	26	712	65	60	108	47.2	7.50	32	102	10	Postperfusion anoxia
459	Oct 12	12	61	1280	107	50	89	80.3	7.45	40	96	8	Postoperative hemorrhage
462	Oct 31	13	30	1236	95	34	60	58.9	7.38	37	63	8	Hemorrhage and anoxia
463	Nov 2	16	76	1000	63	47	84	77.5	7.40	45	207	8	Postoperative hemorrhage
465	Nov 29	12	101	990	83	63	99	67.8	7.47	38	82	48	Pulmonary edema
467	Dec 10	14	44	890	64	61	104	67.9	7.45	40	87	12	Postoperative hemorrhage
Average		13	56	1018	80	53	91	66.6	7.44	39	101	15	

Source: Miller BJ, Gibbon JH, Jr., and Fineberg C (1953). An improved mechanical heart and lung apparatus. *Med Clin North Am, 37*(6):1603–1624, p. 1613.

Table 7 Dogs Surviving Occlusion of the Venae Cavae Without Opening the Cardiac Chambers

				Blood determinations during latter part of caval occlusion							
				Rate of blood flow from venae cavae		*Oxygen saturation (%)*					
Experiment no.	*Date (1951–1952)*	*Wt of dog (kg)*	*Time venae cavae occluded (min)*	*(ml/min)*	*ml/kg/min)*	*Venous blood*	*Arterial blood*	*Oxygen added to blood (cc/min)*	*Arterial blood pH*	*Hematocrit (%)*	*Hemolysis in plasma (mg Hgb/100 ml)*
451	Aug 15	11	32	1075	98	71	99	49.5	7.49	43	54
455	Aug 30	9.5	67	1020	102	47	101	72.5	7.58	—	—
456	Sept 5	13	73	740	57	68	96	43.7	7.48	45	101
457	Sept 12	9.5	100	1300	130	65	98	70.9	7.40	36	81
458	Oct 8	12	60	625	52	50	97	48.9	7.51	38	285
461	Oct 19	13	62	920	70	57	100	67.8	7.52	39	79
464	Nov 6	10	60	680	68	52	96	55.6	7.49	40	80
466	Dec 5	12	60	1080	90	68	98	58.3	7.29	43	71
468	Dec 14	9	60	980	108	68	100	44.6	7.37	32	63
470	Jan 2	11	60	910	83	68	101	55.5	7.20	39	35
472	Jan 16	10.5	71	1070	102	71	99	54.8	7.52	40	60
473	Jan 18	10.5	60	1080	105	71	102	56.1	7.40	42	158
475	Jan 26	13	64	1170	88	67	95	69.1	7.43	41	57
Average		12	64	973	89	63	99	57.5	7.44	40	94

Source: Miller BJ, Gibbon JH, Jr., and Fineberg C (1953). An improved mechanical heart and lung apparatus. *Med Clin North Am*, 37(6):1603–1624, p. 1612.

of arterial blood was maintained at 95% or above in surviving dogs. In the six dogs that did not survive, the blood flow rate varied between 63 and 107 ml per kg per minute, with an average flow rate of 80 ml per kg per minute. Hemolysis of blood was lower in this series of experiments than in previous animal experiments. Two possible reasons offered to explain this decrease were more thorough humidification of gas passing to the oxygenator and more careful cleaning of the machine.

During total body perfusion with an ECC pump-oxygenator circuit and caval occlusion, the heart muscle is continuously supplied with oxygenated blood returned from the circuit to the aorta; therefore, venous blood continues to enter the heart chambers. In order to control the amount of venous blood return so as not to overwhelm the heart, a venous blood-collecting apparatus was constructed and used successfully in the animal experiments of the early 1950s (Figure 15).

In the second set of experiments, the right atrium was widely opened through an incision extending from the tip of the auricular appendage to the inferior vena cava. The incisions were held widely open for periods varying between 21 and 35 minutes. The surgeons considered this amount of time to be adequate for repairing most cardiac defects. At the end of the perfusion, the atrial wound was closed with a continuous suture of 5-0 Deknatel silk, and aspiration of the cardiac venous blood was discontinued before final closure to allow the right atrium to fill with blood. The ECC circuit was then disconnected.

Nine of the ten dogs in this series of experiments survived the procedure for prolonged periods in healthy condition. Information about these experiments is seen in Table 8.

Experiment #484 was omitted because of difficulties with oxygenation before the procedure could be fully carried out; the animal died from hemorrhage 8 hours after surgery.

The only death in the ten experiments was #485. The right atrium was widely open for 30 minutes; death occurred 12 hours following perfusion. At autopsy, a 2.5-cm tear in the posterior wall of the stomach with gastric contents in the peritoneal cavity was found. Surgeons surmised that the artificial respirator had forced air into the animal's stomach, causing the rupture.

The other nine dogs survived in healthy condition for long periods with no evidence of damage to any organ system. The survivors were sacrificed at intervals of 2 months to 1 year to analyze body tissues. At autopsy, the venae cavae and cardiac chambers were free of emboli and there was no evidence of damage to the inner tissues. Cardiac wounds were well healed.

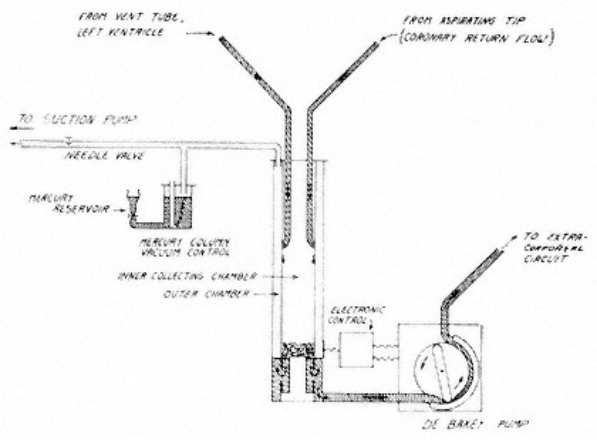


Figure 15:
Diagram of the Venous Blood Collecting Device. This addition was created to manage the venous blood flow from the right atrium and the blood diverted from the left ventricle by means of a vent of a vent (Figure 16). This circuit activated an additional pump, which returned both the cardiac venous blood and the left ventricular blood and air, to the extracorporeal circuit.
Source: Miller BJ, Gibbon JH, Jr, Fineberg C (1953). An improved mechanical heart and lung apparatus and its use during open cariotomy in experimental animals. Med Clin N Amer, 37:1603-1624, p. 1615.

In the third set of experiments, the interior of the right ventricle was exposed by an incision extending from the pulmonary conus to the apex and parallel to the interventricular septum (Table 9).

The wound was held widely open for periods of 11 to 40 minutes. The entire cavity of the right ventricle could therefore be seen and explored, with the operative field bloodless. The pulmonary valve cusps and the first portion of the pulmonary artery could also be easily seen and explored. All five animals were alive 1 month following perfusion. Dog #492 was sacrificed 32 days after surgery because of progressive gangrene of the left hind leg. This was the only instance in which collateral circulation was inadequate after ligation of the femoral artery. Dog #493 died 35 days after perfusion because of bilateral empyema; this was the only case of infection

Table 8 Dogs Surviving Occlusion of the Venae Cavae with Opening of the Right Atrium

					Blood determinations during latter part of caval occlusion								
					Rate of blood flow from venae cavae		*Oxygen saturation (%)*					*Hemolysis in plasma (mg Hgb/100 ml)*	
Experiment no.	*Date (1952)*	*Wt of dog (kg)*	*Time venae cavae occluded*	*Time atrium open (min)*	*(ml/min)*	*(ml/kg/min)*	*Venous blood*	*Arterial blood*	*Oxygen added to blood (cc/min)*	*Arterial blood pH*	*Hematocrit (%)*	*Extracorporeal circuit*	*Coronary circuit*
480	Apr 16	12	43	32	500	42	57	101	—	7.32	34	79	—
481	Apr 23	12	50	31	836	67	44	99	—	7.29	34	51	69
482	Apr 28	10	36	25	900	90	73	101	—	7.46	44	102	85
483	May 1	12.5	47	35	932	75	43	91	—	7.39	32	54	57
486	May 19	10	44	35	837	84	25	62	—	7.45	41	119	—
487	May 26	14	34	31	1170	84	71	99	—	7.44	41	49	49
488	Jun 4	13	40	32	740	57	81	96	—	7.32	45	92	103
489	Jun 11	12	25	21	1021	85	40	73	—	7.41	38	71	72
490	Jun 23	12	36	33	925	77	41	79	—	7.45	33	255	271
Average		11.9	39	31	873	73	53	89	—	7.39	38	97	101

Source: Miller BJ, Gibbon JH, Jr., and Fineberg C (1953). An improved mechanical heart and lung apparatus. *Med Clin North Am,* 37(6): 1603-1624, p. 1617.

Table 9 Dogs Surviving Occlusion of the Venae Cavae with Opening of the Right Ventricle

					Blood determinations during latter part of caval occlusion								
					Rate of blood flow from venae cavae		*Oxygen saturation (%)*					*Hemolysis in plasma (my Hgb/100 ml)*	
Experiment no.	*Date (1952)*	*Wt of dog (kg)*	*Time venae cavae occluded*	*Time ventricle open (min)*	*(ml/min)*	*(ml/kg/min)*	*Venous blood*	*Arterial blood*	*Oxygen added to blood (cc/min)*	*Arterial blood pH*	*Hematocrit (%)*	*Extra-corporeal circuit*	*Coronary circuit*
491	Jul 2	10	19	11	650	65	75	104	—	7.59	28	29	43
492	Jul 7	11	41	38	925	84	57	89	—	7.71	35	90	85
493	Jul 16	9.5	50	34	500	52	56	101	—	—	32	154	158
494	Jul 20	10	38	32	991	99	65	103	—	7.41	32	—	—
495	Sept 15	12.4	48	40	800	66	64	97	—	7.34	38	89	92
Average		10.6	39	31	773	73	63	101	—	7.51	33	91	94

Source: Miller BJ, Gibbon JH, Jr., and Fineberg C (1953). An improved mechanical heart and lung apparatus. *Med Clin North Am, 37*(6):1603–1624, p. 1618.

Table 10 Improvement in Survival Rate of Animals with Complete Occlusion of the Venae Cavae

				Average period of perfusion	
Date	*Number of experiments*	*Number of deaths*	*Mortality rate (%)*	*Dogs surviving time (min)*	*Dogs failing to survive (min)*
Feb–Jun 1949	39	31	79	34	35
Jan–Apr 1951	21	14	66	52	44
Aug 1951–Jan 1952	19	6	31	64	56
Mar–Sep 1952	16	2	12	40	28

Source: Miller BJ, Gibbon JH, Jr., and Fineberg C (1953). An improved mechanical heart and lung apparatus. *Med Clin North Am, 37*(6):1603–1624, p. 1621.

among the dogs in this series. The remaining survivors were sacrificed at 8, 10, and 11 months, respectively, following surgery. In each case, the ventricular wounds were well healed, and the endocardia of the cardiac chambers and venae cavae were smooth and glistening.

Data in Table 10 show the improvement in survival rates over 3 1/2 years.

Mortality rates during this period dropped from about 80% to about 10%, a decrease that was particularly significant in that the length of perfusion time steadily increased over the same period. The improved mortality rate occurred because several major problems were solved during this period, including venting of the left ventricle to prevent air embolism in the cardiac and general circulation. Other factors which contributed to this success were the ongoing cooperation between the Jefferson team of surgeons and the IBM engineers, and the combined knowledge and expertise of the surgeons involved under the leadership of JHG.

A note included in the report of these animal experiments acknowledged the support of the National Institutes of Health, and of IBM and IBM engineers who computed the degree of turbulence needed to increase oxygenation maximally without significantly increasing damage to blood elements:

> The oxygenator and the entire extracorporeal circuit apparatus was designed and constructed for us by International Business Machines Corporation, through the generosity of Thomas J. Watson, Chairman of the Board. We are

especially indebted to Alf Malmros, John Engstrom, Leo Farr, and Don Rex for their design and engineering work on the project. Jack R. Caddell, Charles M. Cooper and David M. Hurt suggested the introduction of turbulence and made the mathematical analysis of the experimental results in order to define the geometric configuration and area of the turbulent film necessary to saturate blood with oxygen at any degree of unsaturation and at any flow rate.[5]

Contributions Made by Surgical Residents to the Development of the Heart-Lung Machine

Many surgical residents, from 1946 through 1953 and beyond, each of whom spent about one year working in the laboratory along with JHG, contributed significantly to the development of the heart-lung machine. Maly Gibbon, who had been a long-standing member of the team, continued to assist in all aspects of the laboratory work; JHG always included her in acknowledging those who contributed substantially to the development of the heart-lung machine.

JHG delegated a large part of the responsibility for overseeing the day-to-day work on the surgical units to Frank F. Allbritten, Jr., so that JHG could spend as much time as possible supervising the work in the laboratory and administering the Department of Surgery. However, JHG's schedule also included time for patients in his regular practice which he considered absolutely essential in order to maintain knowledge and skills regarding current practice, teaching, consultation, and administrative duties. His ideal was to engage in clinical research as well as practice because he believed strongly that the two were complementary and essential for the physician/researcher.

The residents brought their own particular expertise, commitment, and experience to the laboratory; each contributed maximally to the work.

John Y. Templeton III completed his residency at Jefferson under JHG at about the same time as did Bernard J. Miller, who was appointed research assistant to JHG in January 1950. JHG designated Templeton to be the expert in fluids and electrolytes, and requested that he visit a number of medical centers in a given time in order to learn as much as possible about current research in this area and its application to the work on the heart-lung machine.

Miller[3] recalls that the first IBM oxygenator had been used in animal experiments for some time, and that Stokes and Flick had done consider-

able work with the Model I. Among the problems identified with the Model I were oxygenation limitations, carrying out perfusion smoothly, and aspects of adequate blood flow and pump action.

Miller was involved in the laboratory during the time that the Model II was being designed and built. Templeton remembers Miller as being "superbly qualified to do this kind of work because he understood electricity, both theoretically and practically, and he was a fine machinist. He had done some previous research. He had the unique capability of envisioning something and then being able to transform it into reality."[9] Miller contributed much time, effort, and creativity to the final product. In a paper presented by IBM engineer Engstrom entitled "Electronic control circuits in the mechanical heart and lungs," sponsored by the Professional Group on Industrial Electronics of the Institute of Radio Engineers, May 22, 1952, he credited Miller with conceiving and testing the blood level control mechanism on the cup at the bottom of the lung—the oxygenator, where gas exchange takes place.

During the time that Miller was in the laboratory, Miller met regularly—about twice a month—with Engstrom who was in charge of the electrical design, and with Farr, who was in charge of electronic design and who handled problems involving mechanical and fluid engineering. At these meetings, problems involving extracorporeal circulation and the use of a mechanical heart and lung were discussed at length. Decisions about the number and size of screens for Model II, materials to be used, and design of related parts were considered. Final decisions, however, were made by JHG and Malmros, head of the IBM engineers group.

Other people in the laboratory at that time were Dr. Charles Fineberg, then a resident in the Department of Surgery assigned to the lab for a year as part of his residency training. Miller describes Fineberg as "an indefatigable worker, completely and utterly enthusiastic and completely faithful to the project. No chore was too small or too large for him to do. His constant humor and jokes bolstered all when these were most needed."[3]

Jo Ann Cruthers, R.N., was the chief technical assistant in the laboratory, having been with the project for about three years by the time Miller arrived. Her major responsibilities were preparation of the dogs, typing and cross-matching of blood, and a multitude of other similar kinds of duties. Miller describes her as "one of the most faithful workers and a delight to work with."[3]

Other visitors came to work in the lab for several months during the summer, including JHG's son John and his daughter Alice. Many foreign

surgeons came for various periods of time, simply for the experience of working in the lab with JHG and his team members. George Haupt[2] said that JHG's residents and others—staff and visitors—felt that his lab at Jefferson was the most exciting place in the medical world during this period.

Summing Up: The Early 1950s

The early 1950s and the experiments using the Model II, in retrospect, can be considered the most vital and important phase of the development of the heart-lung machine. JHG and his colleagues overcame major problems of blood flow through the unit, blood clotting, and low oxygenation levels, as seen in the increasingly successful experiments in larger dogs.

The early phases of animal experiments with Model II were only moderately successful. The mortality rate of animals was unduly high, despite the fact that their condition during perfusion appeared satisfactory. After examining possible factors, the team concluded that one problem was that the method of anesthesia neither provided sufficient oxygenation nor prevented acidosis. This was further substantiated by the determination of blood gases within the subjects during their period of anesthesia prior to perfusion, and following perfusion. The problem was inadequate washing out of carbon dioxide and inadequate saturation of blood with oxygen. The concept of assisting expiration by introducing a negative phase was considered a possible solution. Therefore, a laboratory model of a ventilator device containing a timing circuit which alternately operated solenoids both on the inspiratory and expiratory lines of the device was conceived by Haupt, then a resident. Aspiration was also assisted by using the Venturi jet to provide vacuum. Tests using this device showed that oxygenation was complete. It was possible to supersaturate blood with oxygen using room air; a large amount of carbon dioxide could thus be removed from the circulating blood to the point where the animal would remain apneic for a number of minutes. The ventilator was incorporated into the procedure and used in all subsequent animal experiments.

Another problem that began to recur was that air was being trapped beneath the leaflets of the mitral valve when the left atrium was open, as a result of the creation of an interatrial septal defect. These bubbles passed into the coronary arteries as air emboli, causing sudden death in the dogs. Miller and the residents considered various approaches to solve the problem, but nothing seemed to work. Finally, JHG asked Allbritten to join

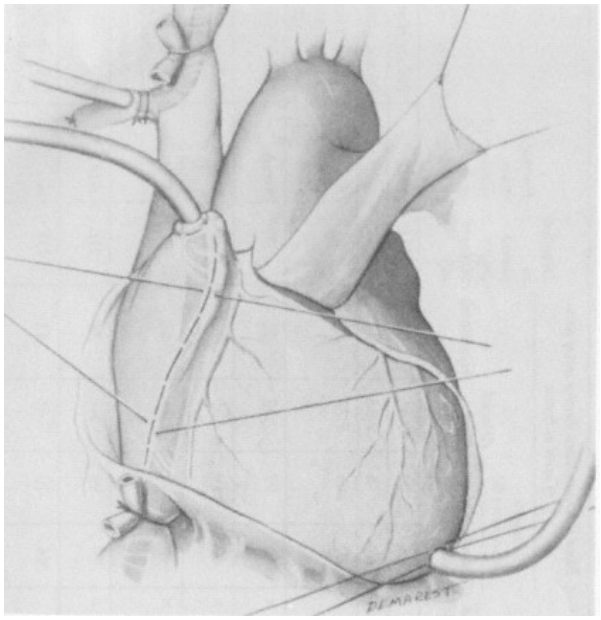


Figure 16:
Drawing of the Heart Showing Cannulation and Ventricular Vent. In early animal experiments, JHG and his colleagues observed that air trapped in the mitral leaflets leaked into the coronary arteries and the aorta, and then into the general circulation as emboli, causing death. The remedy, as conceived by Dr. Frank F. Allbritten, was to create a vent by means of a stab wound in the ventricle with insertion of a small-bore tube to allow for escape of air prior to surgical correction of the defect. At the end of the repair, the tubing is removed and the vent closed. Use of the ventricular vent is now a standard procedure in all open-heart operations.
Source: Miller BJ, Gibbon JH, Jr, Greco VF, Allbritten FF, Jr (1953). The use of a vent for the left ventricle as a means of avoiding air embolism to the systemic circulation during open cardiotomy with the maintenance of the cardiorespiratory function of animals by a pump oxygenator. Surg Forum: 29–33.

Table 11 Production and Repair of Interatrial Septal Defects Without a Vent in the Left Ventricle

						Blood determinations during latter part of caval occlusion						
						Oxygen saturation (%)						
Exp. no.	*Date (1952–1953)*	*Wt of dog (kg)*	*Time venae cavae occluded (min)*	*Time heart open (min)*	*Size of defect (cm)*	*Venous blood*	*Arterial blood*	*Arterial blood pH*	*Hematocrit (%)*	*Hemolysis in plasma (mg Hgb/100 ml)*	*Interval before sacrificed (s) or death (d) (days)*	*Remarks*
497	Oct 1	10	55	44		64	104	7.43	32	194	s-92	Pedicle graft
498	Oct 3	11	60	42	1.5	42	75	7.33	30	174	s-90	Pedicle graft
499	Oct 6	10	32	27	1.2 × 0.9	70	105	7.37	33	51	d	Died 4 1/2 hrs from post-operative hemorrhage
501	Oct 10	11	41	36	1.6 × 1.0	62	97	7.38	38	74	s-116	Pedicle graft
502	Oct 14	11	57	50	1.5 × 1.2	60	99	7.30	43	49	s-157	Pedicle graft
503	Oct 16	11	43	32	1.5 × 1.4	46	93	7.35	40	95	d	Died during procedure from air embolism
505	Oct 24	12	37	33	1.9 × 1.5	59	98	—	38	216	s-147	
506	Oct 28	13	70	22	—	44	72	7.38	43	118	d	Died during procedure from air embolism

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Table 11 Production and Repair of Interatrial Septal Defects Without a Vent in the Left Ventricle

						Blood determinations during latter part of caval occlusion						
						Oxygen saturation (%)						
Exp. no.	*Date (1952–1953)*	*Wt of dog (kg)*	*Time venae cavae occluded (min)*	*Time heart open (min)*	*Size of defect (cm)*	*Venous blood*	*Arterial blood*	*Arterial blood pH*	*Hematocrit (%)*	*Hemolysis in plasma (mg Hgb/100 ml)*	*Interval before sacrificed (s) or death (d) (days)*	*Remarks*
507	Oct 30	11	36	29	1.5 × 1.2	53	81	—	37	81	s-141	
508	Nov 3	10	37	34	—	63	95	7.52	28	60	s-63	
520	Dec 17	11	33	30	2 × 2	47	100	7.42	34	40	s-14	
521	Dec 19	10	44	41	—	41	95	7.37	—	89	d	Died 24 hrs. from overdose morphine SO-4
522	Dec 22	11	43	41	—	62	104	7.35	32	54	s-22	
523	Dec 29	13	31	35	2 × 2	62	102	7.42	38	96	d	Died during procedure from air embolism
524	1953 Jan 6	12	39	35	2	61	103	7.47	34	87	s-7	Air in coronary circuit
524	Jan 16	13	47	43	—	70	103	7.30	43	65	d	Died in 10 hrs. from postoperative hemorrhage
527	Jan 16	12	40	41	1.5 × 2	64	103	7.35	38	65	s-17	Air in coronary circulation
Average		11	44	36		57	96	7.38	36	93		

Source: Miller BJ, Gibbon JH, Jr., Greco VF, Smith BA, Cohn CH, and Allbritten FF, Jr (1953). The production and repair of interatrial septal defects under direct vision with the assistance of an extracorporeal pump oxygenator circuit. *J Thorac Surg, 27:598*—, p. 606.

Table 12 Production and Repair of Interatrial Septal Defects with a Vent in the Left Ventricle

						Blood determinations during latter part of caval occlusion						
						Oxygen saturation (%)						
Exp. no.	*Date (1953)*	*Wt of dog (kg)*	*Time venae cavae occluded (min)*	*Time heart open (min)*	*Size of defect (cm)*	*Venous blood*	*Arterial blood*	*Arterial blood pH*	*Hematocrit (%)*	*Hemolysis in plasma (mg Hgb/100 ml)*	*Interval before sacrificed (s) or death (d) (days)*	*Remarks*
529	Jan 21	13	44	31	1.7 × 1.7	46	101	7.36	39	85	s-22	
530	Jan 23	12	36	42	1.8 × 1.8	60	100	7.35	39	63	d	Died 10 hrs from post-operative hemorrhage
537	Feb 12	23	40	54	2 × 2	56	103	7.09	40	63	d	Died 9 hrs from post-operative hemorrhage
538	Feb 16	33	45	40	1.9 × 1.9	—	—	—	47	44	s-8	
539	Feb 18	16	40	48	2 × 2	40	102	7.38	39	66	d	Died 16 hrs from post-operative hemorrhage
540	Feb 20	14	30	32	1.5 × 1.5	53	95	7.36	32	51	s-8	
543	Mar 2	30	50	54	1.8 × 2	70	103	7.36	39	80	d	Died 20 hrs from post-operative hemorrhage
Average		20	42	43		56	101	7.32	39	65		

Source: Miller BJ, Gibbon JH, Jr., Greco VF, Smith BA, Cohn CH, and Allbritten FF, Jr (1953). The production and repair of interatrial septal defects under direct vision with the assistance of an extracorporeal pump oxygenator circuit. *J Thorac Surg*, 27:598– ,p. 608.

Table 13 Value of Ventricular Vent in Open Cardiotomy with a Septal Defect

	Without vent		*With vent*	
Operations involving	*No. of dogs*	*Instances of air embolism*	*No. of dogs*	*Instances of air embolism*
Interatrial septal defects	17	5	12	0
Interventricular septal defects			15	0
Totals	17	5	27	0

Source: Miller BJ, Gibbon JH, Jr., Greco VF, and Cohn CH (1953). The use of a vent for the left ventricle as a means of avoiding air embolism to the systemic circulation during open cardiotomy with the maintenance of the cardiorespiratory functions of animals by a pump oxygenator. *Surg Forum*, p. 32.

them in the surgical experiments to see what he thought could be done to prevent air bubbles in the cardiac circulation. Allbritten immediately perceived the cause of the problem and suggested creating a vent—introducing a small tube through a stab wound in the apex of the left ventricle through which the trapped air could escape into the atmosphere.[6] This solution was entirely successful and is now used as part of the technique in all open-heart procedures (Figure 16).

By the end of the first year of animal experiments, the success rate with the oxygenator using medium-sized dogs had risen markedly, and the perfusion time had increased concomitantly to about 100 minutes. New residents joined the team as the older ones left: Drs. Anthony Dobell, Victor Greco, and Hal Cohn. Dr. Hans Engell from Denmark spent a year in the lab. Animal experimentation continued, using total bypass and opening of the right atrium to determine the amount of return of venous blood from the system. Various types of cardiac defects were created in the dogs then repaired, including interventricular septal defects.[1] The difference in survival of animals with use of the left ventricular vent is shown in Tables 11 and 12, respectively.

Table 13 shows a comparison of the frequency of occurrence of air embolism in operations without and with a left ventricular vent.

The continued successes in these later animal experiments using the Model II provided JHG and his associates with the confidence needed to attempt ECC circulation in humans. They all felt that the time for the final bold move had arrived.

Bypass Surgery in Humans

JHG, on the basis of the series of successful experiments with dogs, decided that the heart-lung machine was safe to use with humans.

The first patient, operated on in February, 1952, was a 15-month old female weighing 11 pounds. The cardiologists all agreed that the infant had a large atrial septal defect which caused her heart to remain in failure. Because of the baby's small size and edematous limbs, it was not possible to perform a cardiac catheterization prior to surgery. With the diagnosis apparently established, JHG went ahead with the surgery, using an approach through the right chest. After the heart-lung apparatus was connected, the right atrium was explored but no defect was found. The baby's condition was precarious from the time she was born; she died on the operating table. At autopsy, she was found to have a huge patent ductus arteriosus, which a more thorough exploration of the area could have uncovered had there been enough time. This experience underscored the absolute necessity for preoperative cardiac catheterization. JHG therefore sent one of his residents, Robert G. Johnson, to learn the technique under Dr. Richard Bing at the University of Alabama.[6]

The second operation, entirely successful, was done on an 18-year-old woman. About 6 months before the surgery, she began to develop symptoms of right-sided heart failure, as diagnosed by the family physician who sent her to JHG. Cardiac catheterization revealed that she had a large interatrial septal defect with a left-to-right shunt of 9 liters per minute. Her increasingly severe symptoms resulted in three hospitalizations in the six months prior to surgery. Even with quite restricted activity, her symptoms persisted.

The surgery was scheduled for May 6, 1953. JHG was the surgeon; Dr. Allbritten was his first assistant; Dr. Thomas Nealon and Dr. Bernard J. Miller also scrubbed and assisted.

The Operative Note

[Name and Address] Age: 18 Jefferson Hospital JHG 1779 W
May 6, 1953

Referring Physician: [Name and Address]
Preoperative Diagnosis: (1) Interventricular septal defect?
(2) Interatrial septal defect?
(3) Mitral stenosis??

Operation: Closure of interatrial septal defect under direct vision with complete maintenance of cardio-respiratory function with heart-lung machine for 26 minutes.
Postoperative Diagnosis: Large interatrial septal defect.
Surgeon: John H. Gibbon, Jr., M.D.
Assistants: Frank F. Allbritten, Jr., M.D.
Bernard J. Miller, M.D.
Thomas F. Nealon, Jr., M.D.
Anesthesia: Intravenous sodium pentothal with intra-tracheal tube and manual assistance to ventilation.
Suture Material: Cotton and catgut
Operative Time: Approximately 5 hours.

Preoperative Note:

We felt rather definitely on the basis of the cardiac catheterization findings that we were dealing with a septal defect. On the surface it would appear that this was an interventricular septal defect. However, the low right ventricular and pulmonary artery pressures would be against this finding and in favor of an interatrial septal defect with streaming of the blood and hence the finding of high oxygen content only in the mixed blood of the right ventricle.

Procedure:

The patient was anesthetized with intravenous sodium pentothal solution. Direct arterial blood pressure readings were made by Dr. Robert Finley through a needle inserted in the right brachial artery and connected to a mercury manometer. Veins in both ankles were cannulated for the administration of intravenous fluids. The heart-lung machine had been completely prepared the day before, and the large lung with eight screens, twenty-three inches in length, was used instead of the smallest lung with six screens of seventeen inches in length. The apparatus was filled with heparinized blood obtained from donors of the same blood grouping and type as the patient. One difficulty which developed later on was due to the fact that only 10 mg of heparin was placed in each pint of blood whereas 25 mg of heparin should have been placed in each of these pints.

The chest was opened by a transverse incision from one mid-axilla to the other. This incision curved beneath each breast and crossed the sternum at a somewhat higher level. The breasts were elevated and

both pleural cavities were widely opened through the 4th interspace. Both internal mammary vessels were ligated and divided and the sternum transected at a somewhat oblique angle. With the rib spreader in place, this gave a beautiful exposure of the entire heart. It was immediately apparent that there was an enormous right ventricular hypertrophy and a huge pulmonary artery with a very palpable thrill over it. It seemed apparent that we were dealing with an interatrial or interventricular septal defect. A large flap of the anterior pericardium was then cut, leaving the base attached to the base of the heart. Two traction sutures were placed on the lower corners for handling of this pedicled graft which was drawn up and out of the operative field.

In addition to finding a huge pulmonary artery and an enormous right ventricular hypertrophy, it was apparent on opening the pericardium that the right atrium was also greatly dilated. A purse-string suture was placed around the base of the right auricular appendage, and the atrial chamber explored. A large defect could be easily palpated between the two atria. It was roughly the size of a silver dollar. It was easy to insert the finger through the tricuspid valve and up into the pulmonary artery. There was no apparent interventricular defect and there was certainly no obstruction of the outflow of blood through the pulmonary artery. It was apparent, therefore, that we were dealing with a large interatrial septal defect, and we planned to completely divert systemic blood flow through the apparatus in order to close the interatrial septal defect under direct vision.

The left subclavian artery was dissected free, and a ligature placed around it but not tied. The azygos vein was obviously too small to be used for cannulation; therefore, a heavy silk ligature was placed around the superior vena cava between the right atrium and the azygos vein. A similar ligature was placed around the inferior vena cava but not tied. At this junction, the patient was heparinized. Following this, we had considerable difficulty in inserting the arterial cannula from the machine which was of plastic material into the left subclavian artery. This was finally accomplished but not until after the artery had been divided in order to obtain a proper angle to cannulate it. It was very securely fixed in position. The inferior vena cava was then cannulated with a large plastic tube inserted through the base of the cut auricular appendage. The superior vena cava was then cannulated with a similar plastic tube inserted through the auricular wall.

After partial circulation had been started, some difficulty was encountered in leakage of blood from the large lung. It appeared that there had been some deposition of fibrin in the upper part of the lung with a partial loss of film on some of the screens, due to the inadequate heparinization of donor blood. It was a rather crucial point but Dr. Allbritten and I decided to go ahead with the insertion of the plastic vent in the left ventricle and to proceed rapidly with the closure of the interatrial defect. The heart was then elevated and a small stab wound made in the apex of the left ventricle, through which a small plastic tube was inserted which was attached to suction. It was not necessary to tie the purse-string suture as the plastic catheter fit quite snugly. The heart was then returned to its normal position. The ligatures around the superior and inferior venae cavae were tied over the indwelling cannula, thus completely diverting the systemic blood flow through the apparatus. The right auricle was then widely opened, exposing the large interatrial septal defect. The field could be adequately visualized by sucking the cardiac venous return away through the suction cannula. I started to close the defect by a pericardial graft and placed one suture approximating the pericardium to the edge of the opening. Dr. Allbritten then suggested that it might be quicker and easier to close the opening with a running suture. This I did and it went very quickly and easily, giving a secure closure. It was reinforced with an interrupted stitch at one place where there still seemed to be a slight opening. The wound in the atrium was then closed and the ligatures around the superior and inferior venae cavae removed, returning them to partial circulation. Following this, the catheter in the left ventricle was removed and the purse-string suture tied. The cannulas in the superior and inferior venae cavae were removed, and the wounds in the atrium closed with sutures. The cannula in the left subclavian artery was also removed and the vessel ligated. No extra precautions were taken to prevent leaking from the cardiac wounds as they appeared to be quite securely sutured. The chest was then closed in the usual fashion with pericostal sutures of catgut and interrupted cotton stitches in layers.

The patient was quite light at the conclusion of the operation and struggled slightly during the placing of the skin sutures. An hour later when returned to her bed in the hospital ward, she was awake and could recognize people and talk.

Postoperative Note:

At no time during her convalescence from her

operation did she show any signs of cerebral anoxia or central nervous system injury, or any evidence of intravascular clotting or embolism. Her urinary output was quite satisfactory from the beginning and throughout her postoperative convalescence. She had no albumin, casts, or blood in the urine. There was a very slight elevation of the serum bilirubin on the first postoperative day to somewhat above 1 mg percent. She never showed any signs of clinical jaundice. Her wound healed per primam without difficulty, and she left the hospital in about the usual time following her operation. After her interatrial septal defect had been closed, no thrill could be palpated over the pulmonary artery. When she left the hospital, her murmur had disappeared and she felt quite well.

Note:

Concerning the performance of the heart-lung machine.

The heart-lung machine worked quite adequately. However, because of the inadequate heparinization of the donor blood, there was some clotting in the upper part of the lung with a loss of filming on several screens.

Thus, during the 26-minute period when the machine was carrying the entire circulation, there occurred a progressive decline in the oxygen saturation of the arterial blood being returned to the patient. However, this was for a limited period of time, and produced no untoward difficulties. In the future, 25 mg of heparin will be placed in each 500 cc of donor blood used.

The patient was connected to the apparatus for a total of forty-five minutes and for twenty-six minutes all cardiorespiratory functions were maintained by the apparatus.

John H. Gibbon, Jr., M.D.

JHGjr/nm

The handwritten operative note was done by Dr. Robert Finley for JHG immediately after the surgery. JHG later said that this was the first and only time that he did not write his own operative note immediately following surgery.[3] The mixture of feelings that occurred at that time and which persisted for some time after, included extreme exhilaration, relief, and joy that the patient had done well. Later that evening, he personally telephoned two people: Dr. Alfred Blalock at Johns Hopkins, and Dr. Clarence Crafoord in Stockholm, to let them hear the good news.

5/6/53 - Op Note:[1]

With patient under pentothal and oxygen endo anesthesia, Dr. Gibbon opened the chest through the 4th interspaces bilaterally. The right atrium was large and by invaginating the appendage, a large interauricular defect could be felt. The patient was then placed on the oxygenating apparatus (26 minutes on total substitution of heart and lungs), the right auricle opened and the defect sutured closed with 50 silk (dekenate). The defect was high, oval, and measured about 1 1/4" by 3/4" at its widest diameter. The auricular wall was closed, then cannulae removed (the ventricular catheter was also removed), and the chest closed in layers with interrupted cotton sutures. Two drainage tubes were placed in the chest.

The patient tolerated the procedure well. While on the artificial heart and lung machine her mean pressure was 60. After she came off the machine, her pressure was 100 to 110.

At the termination of the procedure, her blood did not clot. By 5:00 pm, she had a clotting time of 4 minutes.

See typed op note for details.

Robert K. Finley, Jr.

Progress Notes[2]

May 6, 1953 - 9:00 pm: Condition satisfactory. BP 110/60, P 82. Chest clear to A & P anteriorly and posteriorly. Patient completely lucid. Has taken 500 cc orally at own request. Very little urinary output yet.

T. F. Nealon, M.D.

5/6/53, 11:30 pm:

1) BP 110/75, P 84, R 12, T 100.

2) Patient warm, dry, well oriented, and alert.

3) Breath sounds clear ant & post.

4) 150 cc clear urine output so far since insertion of catheter.

5) a. 1000 cc fluids orally post-op

b. 1400 cc blood post-op

c. 600 cc 5% glucose in water

d. 250 cc PSS (w/ 50 mg protamine)

6) Coagulation time post-op—4 minutes.

7. Hematocrit and hemoglobin determination to be done in A.M. by Dr. Gibbon's lab. Serum bilirubin and portable chest film ordered.

8) Color good. Receiving nasal oxygen. Both chest catheters—100 cc. Drainage bloody.

9) Condition at this time—highly satisfactory.

10) Pulse absent left hand. Right slightly warmer.

T. L. Stokes

5/7/53, 2:00 am:

1) BP 120/70. P 88.

2) Breath sounds clear bilat. Tubes open.

3) 450 cc clear urine now

4) Left hand still cooler than right.

5) Cough satisfactory.

T. L. Stokes

5/7/53, 4:00 am:

BP 118/64, P 84, R 22, T 99.6

Recap of Intake & Output:

Intake: 1500 cc orally

1000 cc IV (750 cc 5% GW; 250 cc PSS w/ 50 mg Protamine).

1400 cc blood post-op

Output: Chest drainage: left—1100 cc; right—500 cc Urine: 700 cc

Chest clear bilaterally with breath sounds audible both bases, louder on left.

Left hand warmer than at 2:00 am with *definite* radial pulse palpable and good capillary filling in nail beds.

Post-op condition—excellent.

J. McKeown

Summary of Record on — —[2]

[Name, address, telephone number, DOB, sex, age, marital status, race.]

[Referring physician.] Jefferson History No.: PH 14200 Previous Jefferson History No.: PH 11377.

There has been one previous hospital admission for this patient.

Summary of previous admission: Date of Admission: 1/28/53. Date of discharge: 2/20/53. Provisional diagnosis: Rheumatic heart disease. The patient had no complaint on admission to the hospital, but she had been referred to Jefferson Hospital from [X] Hospital by her family physician for diagnosis and treatment of a congenital heart lesion. Her family had been told shortly after her birth that she had congenital heart disease. This diagnosis was maintained throughout her childhood but her activity was not limited in any way, and at no time had she had symptoms attributable to her heart. The patient feels that she was a very healthy youngster and at no time did she have any symptoms suggestive of rheumatic fever. She had not experienced exertional dyspnea, palpitation or fainting spells at any time through her childhood. On November 15, 1952, while engaged in strenuous activity, she experienced an episode of extreme weakness and faintness, and her surroundings seemed to become black. It was necessary for her to lie down on the couch at this time, and shortly after this the weakness passed away spontaneously. Following this episode she experienced pain in her left arm. She was seen by her family physician, Dr. [X] who had her admitted to the hospital for observation. She was admitted November 15, 1952, and remained in the hospital for seven days. She was told that her heart was enlarged, and was not functioning properly. She was treated only symptomatically, and was discharged. She remained asymptomatic until about the 30th of November when she developed fever, chills, and perspiration, and sharp pains confined to the left side of the thorax. Her family physician made a diagnosis of pleurisy or pneumonia and she was treated symptomatically. Following this, she developed a gastrointestinal upset, which lasted for about two weeks. From about December 15, 1952, until January 19, 1953, she again was asymptomatic, but on January 19, she noticed that she had an irregular heartbeat, which was also noted for the first time by her physician. She also experienced palpitation. About five days prior to this, her family physician had placed her on one tablet of digitalis daily. Following the development of these symptoms on January 19, she was again admitted to the [X] Hospital with a diagnosis of pneumonia. From there she was discharged and referred to Jefferson for further care and treatment as indicated. Past medical history was not significant. There is definitely no history of rheumatic

fever or scarlet fever at any time during her childhood. There have been no serious injuries, no allergic diseases. The systemic review was essentially negative. The social history discloses no unusual findings. She had been normally active throughout her childhood. She is a freshman in college and had planned on becoming a teacher. She has enjoyed sports and has not had her activity limited in any way. She is the youngest of seven children; her mother is 63. Her father died at the age of 83 from cancer.

Physical examination showed a well-nourished, well-developed, eighteen-year-old white female who did not appear to be ill. The positive physical findings were limited to the cardio-vascular system. The blood pressure was 110/80, pulse 92, respirations 20. There was no cyanosis, dyspnea, or orthopnea. There was no venous distention. The lungs were clear to percussion and auscultation. There was no precordial bulge or precordial heave. The heart was enlarged to the left. The point of maximum impulse was approximately 1 cm medial to the left anterior axillary line in the fifth interspace. There was no precordial thrill. There was a loud snapping mitral first sound with a Grade III apical systolic murmur. There was a soft apical diastolic murmur. The systolic murmur at the base was transmitted to the neck; the pulmonary second sound was accentuated and reduplicated. There was normal sinus rhythm; rate 92 per minute. The fluoroscopy of the chest showed a prominent pulmonary conus with some cardiac enlargement. The hilar markings appeared to be increased. There were no other significant findings on the initial examination. The working diagnosis was rheumatic heart disease with mitral insufficiency and mitral stenosis and possibly early aortic stenosis, left ventricular enlargement, normal sinus rhythm, grade two. The second working diagnosis was Lutembacher's syndrome.

The laboratory studies showed hemoglobin 85% with a 13.3 gm, 4.7 million red blood cells, 7.9 thousand white blood cells with a normal differential. The urine showed no abnormality. The blood serology was negative. The blood urea nitrogen was 9.2 mg %; plasma proteins were 7.7 gm % with 5.7 gm of albumin and 2.0 gm of globulin. The plasma chloride was 102.6 milliequivalents per liter, the CO_2 capacity was 20.6 milliequivalents. Sodium was 126 milliequivalents per liter, potassium 4.0 milliequivalents per liter. X-ray of the chest was done on January 29, 1953, and was reported as follows: Fluoroscopy and films of the chest show no evidence of recent infiltra-

tion or consolidation. There is evidence of pulmonary congestion of both hili. The transverse cardiac diameter measures 12.7 cm which is approximately 15% enlargement for a patient of this height and weight. The heart is of the mitral configuration with prominence of the pulmonary artery segment and enlargement predominantly to the left. The aortic arch does not appear prominent. There is no displacement of the barium-filled esophagus to suggest definite left atrial enlargement. The hilar pulsations are somewhat prominent. Impression: findings are suggestive of rheumatic heart disease without left atrial enlargement. A patent ductus arteriosus cannot be ruled out from this study. (Signed: Dr. Nasis).

An EKG of January 29, 1953, was reported as showing the findings of an enlarged right auricle and right ventricle. The ST segment changes indicated digitalis effect and right bundle branch block. A phonocardiogram was made on February 12, 1953. The phonocardiogram recorded over the aortic area showed a long low-pitched systolic murmur with no diastolic component. The phonocardiogram at the apex showed a loud first sound followed by a systolic murmur; soft, low-pitched diastolic murmur. When these studies were completed, no definitive diagnosis had been reached, but she was discharged from the hospital with a diagnosis of rheumatic heart disease, possible active carditis with mitral and aortic valvulitis. The possibility of an interatrial septal defect is likely and should be investigated at a later date.

The second hospital admission was on March 29, 1953. During the interval of time she was out of the hospital, she had continued to note slightly exertional dyspnea on climbing one flight of stairs or running, and palpitation with intermittent precordial pain. In the record of her history on this admission there are some findings that had not been present on the previous admission. It is stated that she had one bout of hemoptysis (about one teaspoon of dark blood) in November, 1952, while hospitalized, and that for the past five or six months preceding admission she had noticed slight exertional dyspnea on walking four or five blocks or up one flight of stairs. She has had frequent upper respiratory infections since 1951. There has been no orthopnea, paroxysmal nocturnal dyspnea, ankle edema, or cough. There has never been a history of cyanosis. It is also noted in the other portions of this recorded history that she had had a bout of hemoptysis in November, 1952, and had had another bout of hemoptysis (blood-streaked phlegm from a cold with cough) in January, 1953, preceding her first

admission to the hospital. This was not recorded on her previous admission to the hospital. The examination on this admission did not show any additional findings that had not been previously noted. The recorded examination of the cardiovascular system is as follows: the blood pressure in the right arm was 134/84, the left leg was 160/110. There was no dyspnea or orthopnea, no cyanosis, no clubbing of fingers or toes. There is no venous distention. There is a forceful apical impulse; no definite thrill at rest. The murmurs were as previously described. It was the impression of the cardiac consultant on his initial examination that a cardiac catheterization was indicated. A cardiac catheterization was done April 6, 1953, and the note is recorded as follows: With the patient in the supine position the left arm was prepared surgically and draped with sterile linens. The left basilic vein was isolated with some difficulty and a #7 French cardiac catheter was inserted into the right atrium, under fluoroscopic control. A blood specimen was taken at this point and a stylet withdrawn. The catheter was inserted into the right pulmonary artery with ease and wedged into a pulmonary capillary. Pressures were recorded continuously with the catheter in the pulmonary capillary, and as the catheter was withdrawn successively into the right pulmonary artery, the main pulmonary artery and the right ventricle. The tracings were free of artefact and were undamped. The catheter was then reinserted into the right pulmonary artery and blood samples were obtained for gas content analysis from the right pulmonary artery, the main pulmonary artery and the right ventricle inflow and outflow tracts. A blood sample was then taken in the inferior and superior venae cavae. The catheter was reinserted into the right ventricle in an effort to find a septal defect. Ventricular extra-systoles occurred in rapid succession and the catheter was rapidly withdrawn. The basilic vein was ligated with #80 cotton. The patient was returned to the ward in good condition. The findings of the blood specimen are recorded in the cardiac catheterization data. On April 13, 1953, an angiocardiogram was done which was recorded as follows: On the initial film there is good filling of the superior vena cava and the right atrium. There is beginning filling of the right ventricle. On subsequent films, there seemed to be less filling of the right ventricle, and there is never satisfactory opacification of the left side of the heart in this series of films. The heart has the appearance of having a large, high, interventricular septum defect with a left to right shunt diluting the opaque material in the right ventricle. No other lesions are

demonstrated. Incidentally, all films were taken in an oblique position in order to better demonstrate the interventricular septum defect. Opinion: interventricular septal defect; no other lesions demonstrated. An EKG of March 31, 1953, interpreted as showing findings indicative of right bundle branch block and probably right ventricular hypertrophy. The patient was seen by Dr. Louis LaPlace in consultation on April 25, 1953, and it was his clinical impression that the patient had mitral stenosis. Because of the uncertainty of the diagnosis it was recommended that she have an exploratory cardiotomy with the extracorporeal circulation apparatus available. This was done on May 6, 1953. Additional note to be typed at the end of this summary: A letter from Dr. William D. Allison dated April 22, 1953, reads as follows: "The vector cardiogram performed on April 21, 1953, shows evidence of right ventricular hypertrophy. The depolarization of the atria was irregular. The mean vector directed inferiorly. The depolarization of the ventricles was regular. The initial vectors were directed superiorly and slightly to the left suggesting clock-wise rotation of the heart. The vector loop then progressed to the left and inferiorly before the major portion which was directed anteriorly and to the right. There was no sudden change of direction, delay, or irregularity in the terminal portion, ruling out any right bundle branch block. From the studies performed up to this date, I don't think that an interauricular septal defect has been excluded, i.e., if the pressure of 42/o in the right ventricle is correct." (Signed: William D. Allison).

Following the recovery from the surgery on May 6, 1953, the patient returned for one day in July, 1953, when Dr. Robert G. Johnson performed a cardiac catheterization. His note at that time read: "Since her discharge on May 19, 1953, the patient has shown progressive subjective improvement. She is now able to walk an unlimited amount without tiring. She can climb two or three flights of stairs without shortness of breath or undue fatigue. . . . At the present time she is taking 1/10 mg of digitoxin daily. (Discontinued at this time). Cardiac catheterization reveals there is no longer an intracardiac shunt."[2]

On her last admission during this period, she was hospitalized in November, 1953, for eleven days because of a respiratory infection that required intensive treatment. The amount of mail, telephone calls, requests for photographs and public appearances, and other kinds of communica-

tions from people all over the country who had read of the historic surgery, she found overwhelming by this time, too. During this admission, however, she was relieved to know that physically she was able to do anything that she wished; activity was unrestricted. She regained her confidence in herself and in her abilities.

Other Surgery Using the Model II

JHG operated on two additional patients in July 1953.[3] They were both underdeveloped girls, both 5 1/2 years old. The first child had a large interatrial septal defect proved by catheterization. Cardiac arrest occurred after opening the chest and before any vessels were cannulated. The team tried to restore normal cardiac contraction but was unable to do so. JHG elected then to cannulate the vessels and as soon as the patient was connected to the heart-lung apparatus, the heart action became strong and the color of the heart became pink. Each time that the heart was allowed to take over some circulation, the heart dilated and it was necessary to return her to the heart-lung machine. The patient died. JHG speculated on the cause of death: "Death, of course, in the patient cannot be attributed in any way to the use of the heart-lung apparatus, as cardiac failure occurred prior to the use of the apparatus. Perhaps, the dilatation of the heart and cardiac arrest were the result of reversal of the shunt through the interatrial defect because of the blood transfusion given during the early part of the operation."[4]

The second child had a proven interatrial septal defect, but the catheter could not be passed to prove an interventricular defect. At operation, she was found to have not only an interatrial defect but also an interventricular defect and a small patent ductus arteriosus. JHG noted: "As we could not get a clear field to work in, and the flow of bright red blood was so excessive, we closed the atrium and removed the cannulae. The child died after the operation, which was to be expected because of failure to correct any of the cardiac defects."[4]

JHG was extremely distressed at these failures, and declared a year's moratorium on any more cardiac surgery using the heart-lung machine until more work could be done to solve the problem of blood clotting and other studies done on coagulation defects. He assigned Dr. Anthony R. C. Dobell to do a long-term study on these coagulation problems in conjunction with the Cardeza Foundation for Hemotological Research at Thomas Jefferson University. Dr. Dobell later became Chief of Cardiac Surgery at the Royal Victoria Hospital in Montreal.

Don Rex,[5] in recalling this period, said that JHG had postponed doing any more cardiac surgery because of problems with, in particular, one patient who developed bleeding problems following surgery. The man simply oozed continuously for several days and finally died. Soon after JHG assigned Dr. Dobell to do the additional studies, JHG placed JYT in charge of all cardiac surgery.

Model III

Even before the first successful bypass surgery had been achieved, Rex recalls receiving orders on September 23, 1952 that he was to meet with Dr. Gibbon to redesign Model II. "Mr. McElwain, Mr. McPherson, and I met with Dr. Gibbon in Philadelphia. Together, we developed a list of the areas in the machine that were continuing to have problems or in which improvements could likely be made." The initial plan was to "fix up" the Model II. But after some weeks of trying to redesign particular parts—do "patch-up work," as Rex put it—he decided that an entirely new model needed to be done, using parts from the Model II. His immediate supervisor was not enthusiastic about the idea of beginning again from scratch, but Rex went to the next higher administrative level. The decision was that IBM wanted the next model to be the best that they could build.

Rex's detailed plan was outlined in a memo to his superior:[3]

Plan for Revision of Model II

October 23, 1953

Memorandum to: Mr. J. A. Haddad

Subject: Oxygenator Revisions Proposal

The attached Oxygenator Revisions Proposal explains in some detail what revisions are to be made on the IBM Model II Oxygenator to meet the requirements of Dr. Gibbon and his staff. it is felt that at this time it is not necessary to build a special laboratory machine in addition to rebuilding the present machine.

It is quite likely that there will be but one staff of surgeons and technicians capable of utilizing the device. Because the machine is mobile, it will be possible to duplicate those units through which the blood flows, quickly replace unsterile units with the standby ones and

transport the machine from the laboratory to the operating room for use on a human patient. It would seem that such an undertaking should require no more than two hours. The reassembly and transportation should not seriously impede its utilization because the contemplated use of this device is not of an emergency nature. One lung capable of oxygenating 2500 cc per minute and a second lung capable of oxygenating 5000 or 6000 cc per minute will be constructed.

If Dr. Gibbon and his staff should decide that a blood cooling system is required in the oxygenator, it will be possible to provide him with this apparatus. The device can be controlled to gradually reduce the temperature of the blood returned to the patient and then maintain this low temperature for the remainder of the operation.

D. K. Rex

Attachment

CC: Mr. E. A. Barber Mr. C. F. McElwain Mr. J. C. McPherson

Oxygenator Revisions Proposal

1. The revised venous blood withdrawal system will require the design and construction of a blood reservoir with a source of variable negative pressure. The AC motor and Graham Transmission will be replaced by a DC motor with an electronic motor control chassis to maintain the proper blood level in the reservoir.

The blood withdrawal system must be modified to permit a more uniform flow of blood from the patient's veins. The present pumping system causes momentary periods of high flow with the result that the frictional losses causes a pressure decrease high enough to result in vein collapse. Dr. Miller has removed the pumping pulsations by drawing blood from the veins into a reservoir from which the air is exhausted. The liquid level in the reservoir is maintained by controlling the speed of the vein pump in the same manner that the artery pump maintains the level at the bottom of the lung.

To incorporate this withdrawal system in the present machine will

mean the construction of a withdrawal chamber with a variable source of negative pressure. The vein motor drive will have to be changed from an AV motor and Graham Transmission to a DC motor with a standard worm reduction. A control chassis will have to be constructed to govern the speed of this DC motor.

It may be possible to discover a method whereby the pulsating flow from the patient can be eliminated in a more simple fashion. The least complex system which will fulfill the requirement of regular flow rates will be built into the machine.

2. A cardiac blood withdrawal system will mean the design and construction of a blood reservoir and air trap. The AC motor and Graham Transmission will be replaced by a DC motor with an electronic motor control chassis to maintain the proper blood level in the reservoir.

In addition to withdrawing blood from the veins, a pump must be provided to remove blood from the heart proper during an operation. Dr. Miller has accomplished this in a manner which is similar to the non-pulsating venous withdrawal system. A reservoir is partially evacuated by a variable source of negative pressure which causes blood to be drawn from the patient's heart. Because air is inadvertently drawn from the heart into the reservoir, a foam trap is provided to keep the air from being sent to the lung.

To build Dr. Miller's system into the machine will mean the addition of a combination reservoir and foam trap with a variable source of negative pressure. The AC motor and Graham Drive will be replaced with a DC motor and worm reduction. Another control chassis will have to be constructed to govern the speed of the DC motor and thus control the level of blood in the reservoir.

As in the case of the venous withdrawal system, the problem of removing blood from the heart will be given careful consideration and the most simple adequate solution will be adopted.

3. The pumps will be rebuilt to increase their pumping capacity.

In addition to the possible changes in the pump drive system outlined above, the pumps whose flow is to be increased will be modified by the addition of a third tube.

4. The 2500 cc per minute lung will be brought up to date and a 5000 cc per minute lung built.

One lung will be provided to oxygenate 2500 cc per minute and another to oxygenate 5000 cc per minute. The 2500 cc per minute

lung will be built by reworking the lung now used in the Model II Oxygenator. Both of these lungs will be designed with the objective of being able to autoclave the screen assembly immediately prior to encasing it with the lucite jacket. Several small changes will be made to the lung design to bring it up to date.

5. Blood handling units will be duplicated for standby purposes. Units which transport the blood through the system will be duplicated so that a sterile set of standby units can be kept on hand to be in readiness should the machine be used in the hospital. These standby units include:

A. pH electrode holder

B. Thermocouple holder

C. Venous and cardiac withdrawal reservoirs

D. Filter

E. Tube connectors

F. Burette

6. pH instrumentation will be brought up to date.

The instrumentation allied with the measurement of pH will be studied and the improvements resulting from this study will be incorporated.

7. The top cover will be replaced.

The extent of the revisions listed above may make it necessary to replace the top cover of the machine.

8. The machine will be rewired.

The machine will be rewired to include the new electric and electronic devices. The original wiring will be removed and replaced with new wiring.

The program outlined above will require a period of nine months from the starting date to complete. The Model II Oxygenator should be returned to IBM at the end of the sixth month and remain until the end of the ninth at which time it will be returned to the Jefferson Medical College.

DKR: GB

10-23-53

The work plan as described by Rex to his superiors was put into action at IBM as soon as it was approved at all administrative levels in the corporation.

In a memo to his supervisor on May 13, 1954, Don Rex wrote:[3]

MEMORANDUM: Richard Taylor

SUBJECT: Status of Oxygenator Program

Because the decision has been made to abandon the present pH measuring system and replace it with a Leeds and Northrup device, two possible approaches to the Oxygenator design program should be considered. The work necessary to adapt the L & N system to the Model II machine is extensive enough so that it now becomes reasonable to consider rebuilding the entire machine utilizing as much of the present equipment as is practical.

To aid in the process of making this decision I have prepared the following estimates of the time and money that will have to be expended to accomplish each of the possible programs.

A. If the Model II Oxygenator is returned to Endicott June 1, 1954 and it is rebuilt as outlined in my plan of May 11, 1953, the following schedule is my estimate of the situation.

TIME FOR COMPLETION—14 weeks

COMPLETION DATE—Sept. 20, 1954

TOTAL EXPENDITURES—$71,750.00

B. If the Model II Oxygenator is returned to Endicott June 1, 1954, and this machine is stripped of its useful parts to build the Model III Oxygenator, which will adhere to the specifications as set forth in my plan of May 11, 1953, but built into a new frame, in my estimation the work will require the following:

TIME FOR COMPLETION—16 weeks

COMPLETION DATE—Oct. 4, 1954

TOTAL EXPENDITURES—$79,650.00

The final decision, made at a higher administrative level using Rex's data, was that the Model II machine would be stripped, with usable parts placed in the Model III, resulting in an almost entirely new machine. The Model II, therefore, ceased to be a working machine; it was cannibalized for parts and the rest used for scrap metal.

Model III was delivered to Jefferson Medical College in July 1954, well ahead of schedule.

Later, in 1960, JHG was approached to exhibit the Model II for the thirtieth anniversary of the first bypass surgery. Not only was the Model II not in existence, but the blueprints were missing. JHG had sent them to Dr. Hans Engell. Because of the short time frame in which to prepare the exhibit, Rex had to redraw the plans from written descriptions and mem-

ory, rather than from the more precise blueprints, which he received much later.

Other Surgical Teams Using Oxygenators

The second successful bypass surgery did not occur until 1955, when Dennis and his team at Kings County Hospital, Brooklyn used his own disk oxygenator. At almost the same time, the Mayo Clinic team reported its first successful bypass procedure, using Gibbon's Model II oxygenator, which they had modified and renamed the "Gibbon-type oxygenator." DeBakey's team at Baylor College of Medicine in Houston was also well into treating cardiac defects by means of intracardiac techniques. The Stanford University group under Richard Lower, which included Norman Shumway, began later to concentrate their efforts on heart transplantation.

JHG's oxygenator was a breakthrough in the area of cardiac and thoracic surgery, and its successful use marked the beginning of this "new field of cardiac surgery" that he had predicted.

The Mayo Clinic

During this same period a parallel story developed involving JHG and the team at the Mayo Clinic. The Mayo group comprised probably the greatest combination of people related to cardiac surgery that ever existed.[3] Howard Burchell returned to the clinic following his army experience as a flight surgeon and subsequently invited Jesse Edwards, a cardiac pathologist, and Earl Wood, a cardiac physiologist, to join.[3] James DuShane, a pediatric cardiologist, joined the group in the late 1940s. When John Kirklin became a member of the team in 1950, the group was complete. Kirklin was already keenly interested in cardiac surgery because of his association with Robert Gross, first as a medical student at Harvard before going into the Army, and then as a resident for two years following his army service.[3]

Here, as at Jefferson, the Karolinska Institut in Stockholm, and elsewhere, cardiac surgery per se did not exist. Immediately after World War II, however, much pent-up energy was creating an atmosphere of excitement and movement. The need for knowledge during the war had greatly advanced the basic sciences and surgery. At the Mayo Clinic, as at Jefferson and several other centers, there developed a "hotbed of intellectual ferment."[3] Blalock and Taussig at Johns Hopkins, and Robert Gross in Boston, were performing extracardiac procedures. In 1948 the first surgery for commissurotomy for mitral stenosis was performed by Harken in Boston and by Bailey in Philadelphia. In 1949–50 Gross devised the atrial well, a procedure that surgeons could use to close atrial septal defects without a pump oxygenator. The Mayo Clinic team adopted this technique and performed several hundred such procedures in the early 1950s. Intracardiac surgery was pioneered in the late 1940s by F. John Lewis at the University of Minnesota and by Henry Swan at the University of Colorado, who used surface cooling and circulatory arrest (not cardiac arrest) to perform selected procedures. For intracardiac surgery to advance, however, it was recognized that a workable heart-lung machine was absolutely essential.

In 1948 JHG presented a paper on the development of his heart-lung apparatus at the Fundamental Forum of the American College of Surgeons.

His report was both encouraging and discouraging, according to Kirklin. His machine, built by IBM, looked very complex. While he said that he believed that "we are getting there," the tone of his paper did not support that belief.[3] He talked about the problems stemming from insufficient oxygenation, bleeding, and the relatively high mortality rate in the animal experiments.

By 1952 the Mayo Clinic group decided that it would concentrate its efforts on developing intracardiac procedures by using a pump oxygenator. Three people went on a scouting expedition to see what was available in pump oxygenators. The group included Kirklin, Wood, and David Donald, a veterinarian who had been working with them in the animal laboratory. They visited Toronto, where W. T. Mustard was doing experiments using monkey lungs as the oxygenator; Gibbon's lab at Jefferson; and Detroit, where F. D. Dodrill was using a heart-lung machine built for him by General Motors. Wood observed that "the machine in Philadelphia looked a little like a computer, and the machine in Detroit like a car motor."[3]

The group returned to the clinic, resumed their animal experiments using a bubble oxygenator, and thought about what they would do. They decided that Gibbon's machine looked the best, particularly with the innovative addition of the parallel screens as the lung, which greatly increased the machine's oxygenating capacity. Dr. Priestly, a senior surgeon at the clinic and a long-time friend of Gibbon's, approached JHG to ask for the blueprints since the group had decided to build a duplicate of the IBM machine and then make changes as the group deemed necessary, based on their experiences using it in animal experiments. The group was aware that C. W. Lillehei, at the University of Minnesota, was considering using cross circulation, a technique the Mayo group rejected, believing that it had limitations which would eventually impede progress in cardiac surgery.

Dr. Priestly reported that when he asked JHG whether they could acquire the plans for the Model II, JHG was delighted.[3] However, Rex[5] said that Gibbon was somewhat reluctant because, knowing the resources available at the Mayo Clinic and the capability of the group, he feared that they would move ahead quickly and be the first to perform bypass surgery in humans. This fear was certainly a natural reaction, and to some extent, justified. Having worked so long to develop the machine, and being so close to performing a first successful heart-lung procedure, JHG did not wish to be second in this achievement. Further, JHG had not envisioned that the apparatus be used indiscriminately or as the center of a "factory." He was still seeing it as a method to be used in quite specific and circum-

scribed cases where cardiac surgery was needed to correct congenital defects or in particular kinds of pulmonary problems where only bypass surgery could cure life-threatening conditions. His vision was that the machine would have limited application.

Nevertheless, despite his brief hesitation, JHG indicated to Malmros at IBM that the blueprints be given to the Mayo Clinic engineer, Richard Jones. A two-day meeting was arranged between IBM and Mayo representatives at Endicott, at which Garvey and Rex fully explained and demonstrated the Model II. By the end of the two days, Jones and the other Mayo group members were fired up and eager to obtain the plans and drawings of the Model II. In a letter dated November 17, 1952, Jones wrote to Garvey at Endicott to thank him for "the most enjoyable and informative visit" on November 11.[5] Jones's assessment of the Model II was quite positive: "I believe I can say that without question the oxygenator and associated equipment which was designed and built in your laboratories was the best designed and most conveniently operated equipment that I saw at the various laboratories I visited."[5]

The IBM engineer, Garvey, called JHG to inform him that the meeting had taken place and that IBM was agreeable to giving Mayo the blueprints, operating instructions manual, and technical assistance to construct a machine in Minnesota. JHG concurred.

Rex was selected by IBM to provide technical assistance at the Mayo Clinic. He called JHG and asked him if he would like to send a representative from the Jefferson Medical Center group to the Mayo Clinic when they delivered the Model II materials. JHG selected Miller as the Jefferson expert.

In February 1953 Garvey sent the blueprints and an instruction manual to Jones. The list of materials sent included plans for 164 different machine parts; the manual described 105 parts of the machine. Therefore, according to the records, Mayo received all the information needed to construct a machine similar to the Gibbon oxygenator. Rex[5] stated that from observations he made during visits to Rochester to provide technical assistance at the time their machine was being built, very few changes were made from the original plans. In March 1953, when Jones visited IBM again, he was given information about sixteen additional parts to the machine that were part of the redesign of the Model II in preparation for building Model III. Therefore, the Mayo group was kept apprised of all developments as Model III was planned and constructed. Duplicate blue-

prints for 104 parts were requested by Mayo in July 1953 to send to contractors and subcontractors who were building various parts for their machine.[5]

In a letter from the Mayo engineer, Jones, to IBM in May 1953, he indicated that the group was making such excellent progress in building its machine that the time schedule for performing laboratory experiments and, subsequently, bypass surgery on patients, would be moved ahead "nearly a year." In this same letter, the Mayo staff supplied IBM with information involving the blood level control maintenance system and the flow measuring apparatus built into their machine, both of which were different from those parts that were in the Jefferson Model II. Miller had designed the blood level control apparatus for the Model II, but the Mayo staff considered it unreliable.

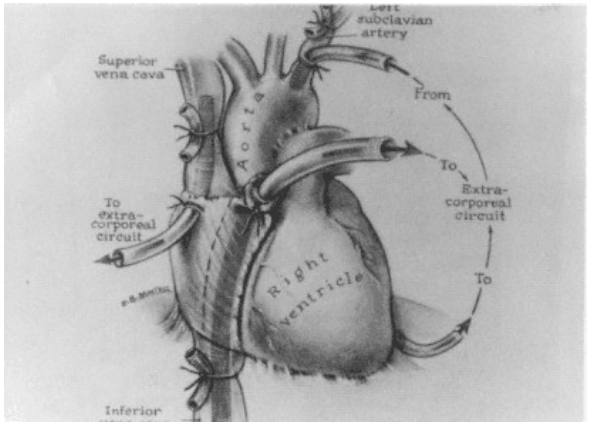
In a report from Rex and Leo Farr to their administrative superior at IBM about a visit they made to the Mayo Clinic on October 7 and 8, 1953, they describe a guided tour they had of the new Medical Science Building that had just been completed at a cost of four million dollars: "This building houses all of the Mayo Clinic's experimental laboratories and includes their 25-man Development Engineering Department. Elaborate facilities are provided for experimentation in nearly all branches of medical science." These facilities were far superior to those available at Jefferson.[5]

A preliminary report of the use of the Mayo Gibbon-type oxygenator in animal experiments was published in the medical literature in 1955,[2] in which it was concluded that "the ability of this apparatus to reproducibly maintain adequate extracorporeal circulation and oxygenation of the blood has been tested in 10 animals in which the heart and lungs were functionally excluded from the circulation of the animal for a period of 30 minutes. Nine of these animals made an uncomplicated recovery from the procedure, followed by indefinite survival."

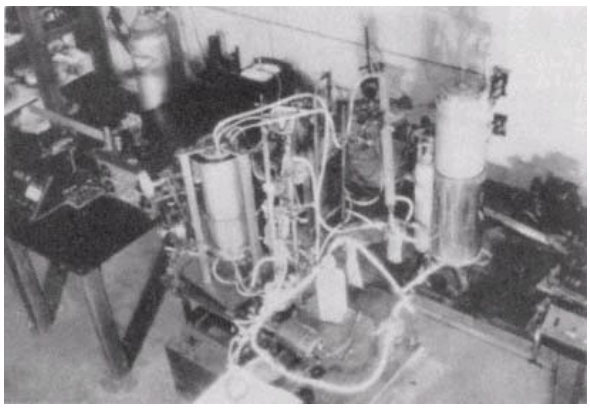
Progress in the use of the Gibbon-type oxygenator was reported in two 1955 articles.[14] The later article reported on bypass operations on eight patients, in which four (50%) of the patients did well following surgery. In the other four cases, one died in the operating room due to blood loss, the three others died at 2 and 48 hours postoperatively, and the last patient died 6 days postoperatively. Death in these three was not related to the perfusion itself but to underlying cardiac problems associated with the defect.[4]

JHG's heart-lung apparatus, therefore, was used in a slightly modified

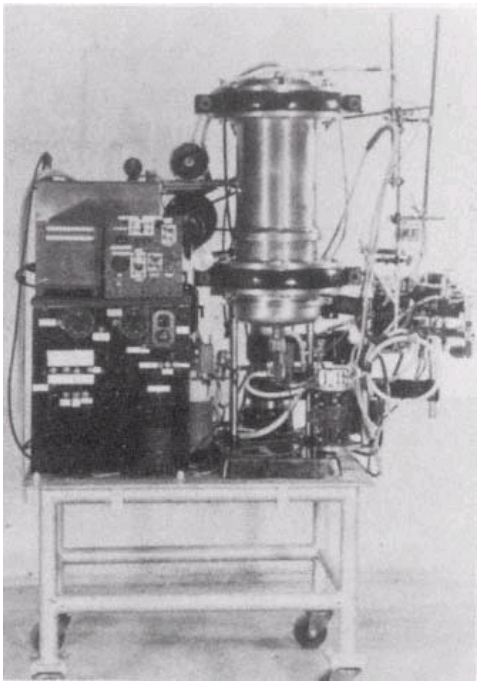
form by the surgeons at the Mayo Clinic for several years. During that time they operated on hundreds of patients of all ages. As a result of their knowledge and expertise, the mortality rate for open-heart surgery fell from 50% at first, to 20% the following year, and to 10% the next year. Thus, the Mayo Clinic team helped to make intracardiac surgery—a new field of surgery—accepted and relatively safe.



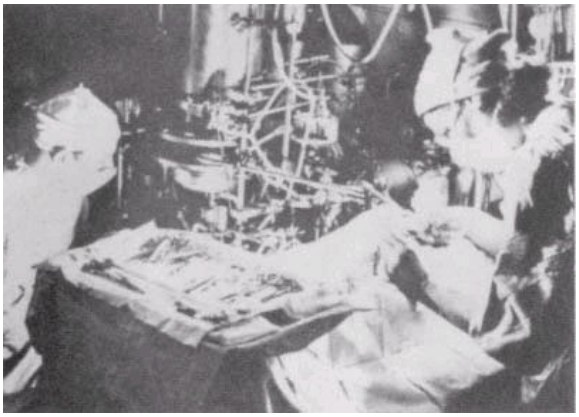
1.
Circulation via ECC in the heart.



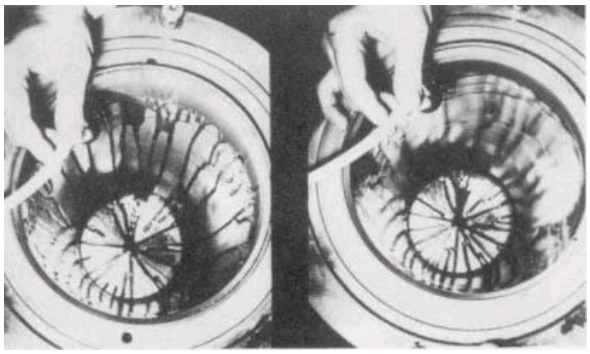
2.
First mechanical heart apparatus built by JHG, Boston, 1934–35.



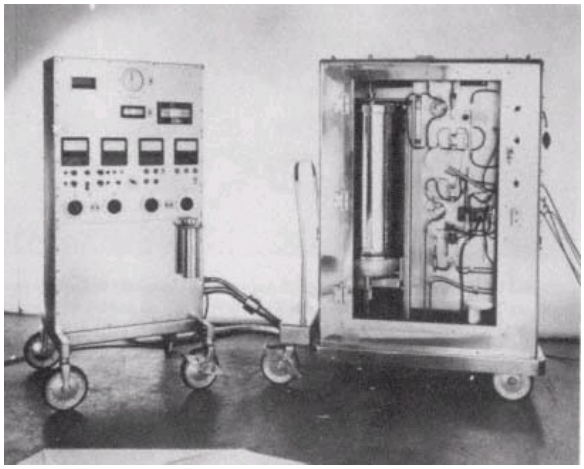
3.
Second oxygenator with larger capacity, 1938.



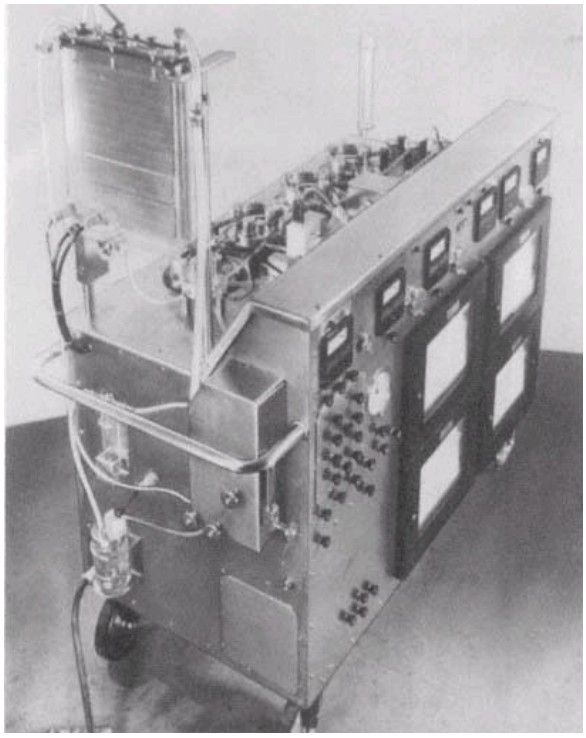
4.
Animal laboratory at Harrison Research Laboratory, University of Pennsylvania, 1938–40. Maly Gibbon (right), Charles Kraul (left).



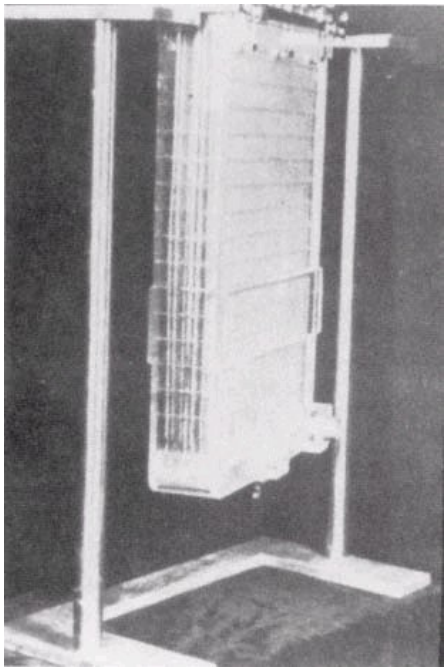
5.
Comparing blood flow in stationary (left) and rotating (right) cylinder, showing filming of blood.



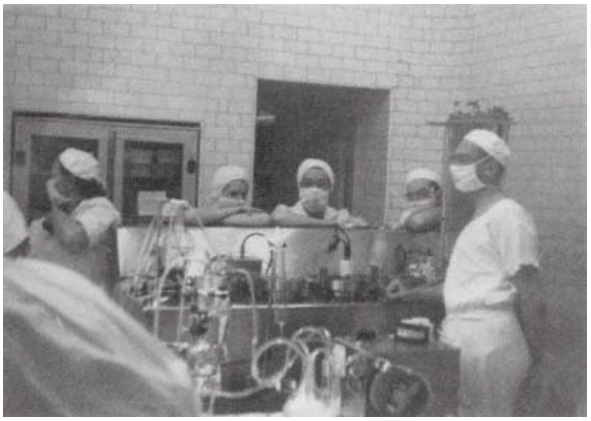
6.
Model I, first oxygenator built by IBM, 1949.



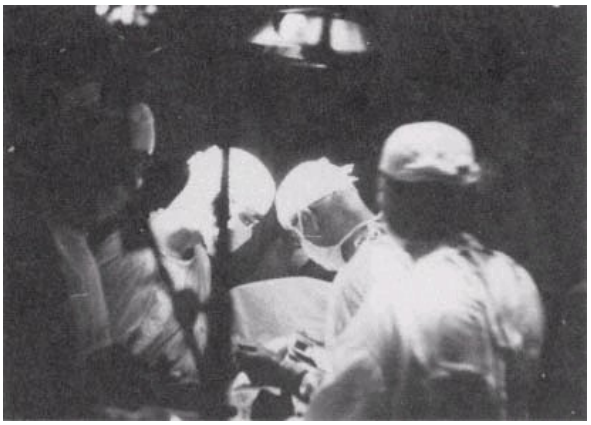
7.
Model II, just before shipment to JHG, 1951.



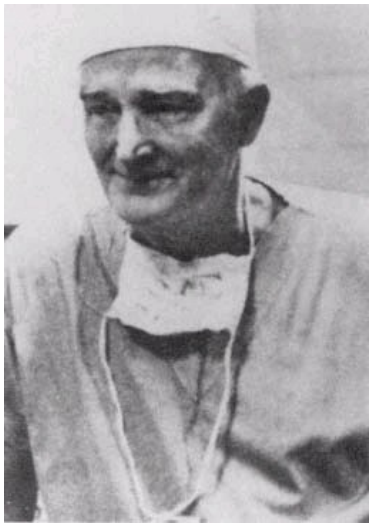
8.
Parallel screens encased in Plexiglas—the "lung" for model II.



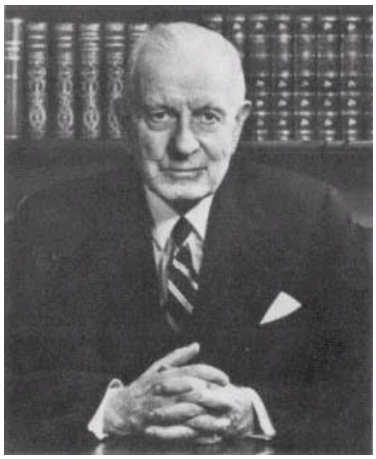
9.
Operating room team during the historic first successful heart bypass surgery using a pump oxygenator, May 6, 1953. Model II performed flawlessly.



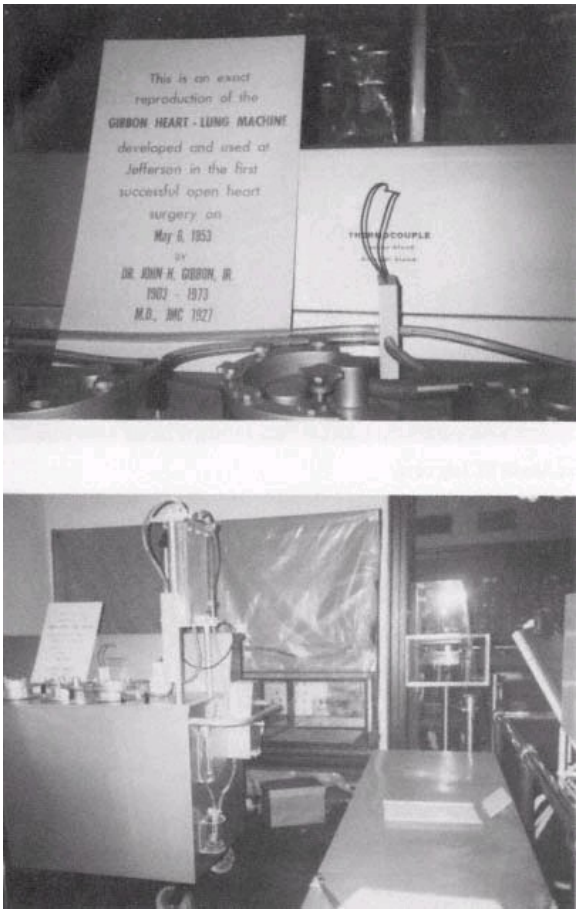
10.
May 6, 1953. Gibbon (right center), Allbritten, first assistant (left center).
Photo by G. J. Haupt.



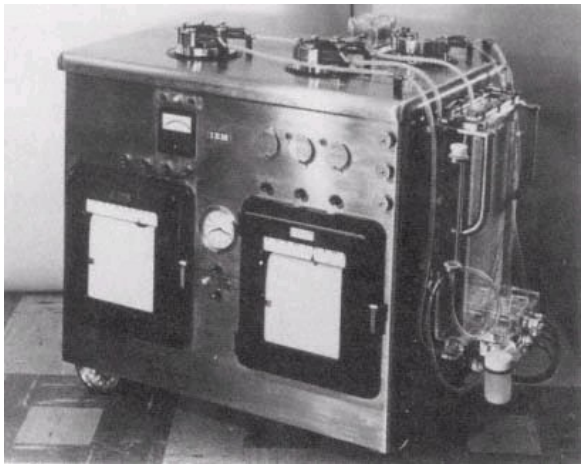
11.
Gibbon following surgery on May 6, 1963.



12.
Thomas J. Watson, Chairman of the Board at IBM, 1914–1956.

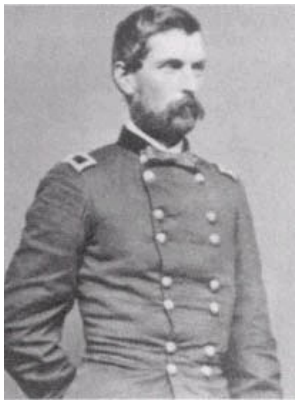


13–14.
Replica of Model II on permanent display at the Mutter Museum, College of Physicians of Philadelphia. The replica was built to celebrate the thirtieth anniversary of the May 6, 1953 surgery.



15.
Model III, July 1954.

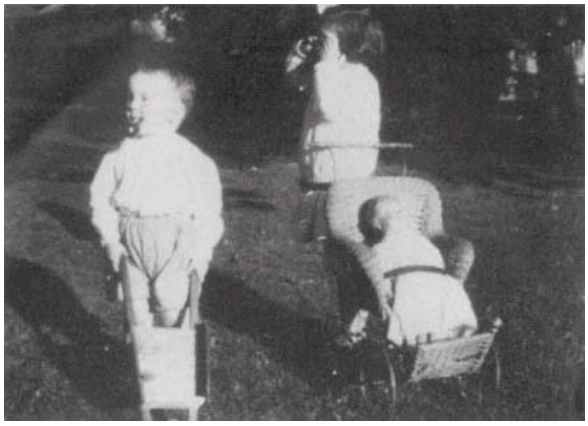
16.
IBM team with Gibbon and Stokes from Jefferson. Left to right: Ron Avery, Don Rex, Bill Wright, Cy McElwain, Harry Kuntzelman, Stan Abramson, John Pisarcheck, JHG, T. Lane Stokes, Richard Taylor, Alf Malmros.



17.
Great-Uncle General John Gibbon.
National Archives.

18.
1608 Spruce Street, Philadelphia, Gibbon family home for 50 years.

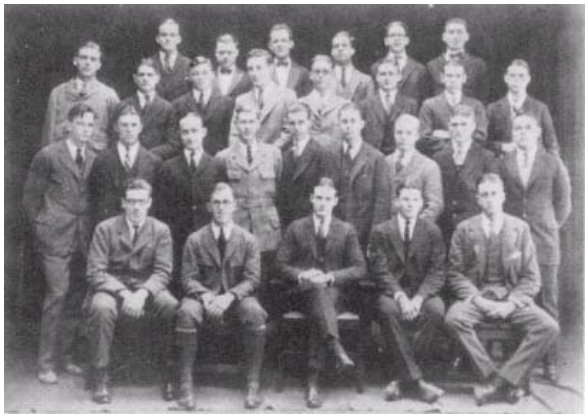
19.
Marjorie Young Gibbon, daughter Marjorie (right), and JHG, c. 1904.



20.
Marjorie and Jack playing "mother and father," c. 1906.

21.
Lynfield Farm, Media, Pennsylvania, the family home from 1912 to 1980.

22.
JHG's graduation photograph,
Princeton University, June 1923.



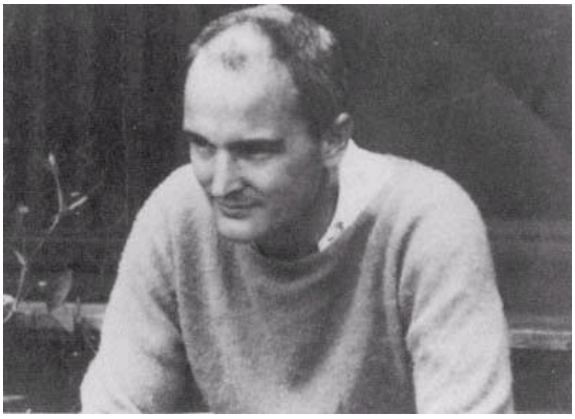
23.
JHG, member of Princeton's Medical Club, 1922–23 (first on left, second row).

24.
Father and son clearing land at Mount Desert Island camp.

25.
JHG, medical student at Jefferson Medical College, 1924–27.

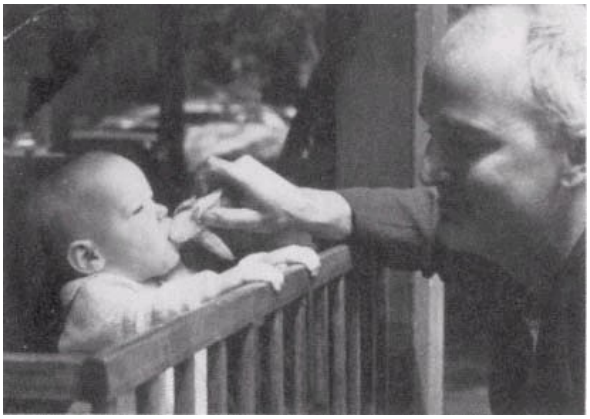
26.
Marriage, March 14, 1931, Manchester, Massachusetts.

27.
JHG and daughter Mary, c. 1935.



28.
JHG, c. 1939–40.

29.
1940: move to 4035 Pine Street as family expands.



30.
Last child, Marjorie, 1940.
On vacation at Maly's home, Manchester, Massachusetts.

31.
Lieutenant Colonel JHG, 1945.

32.
A trip to Europe, JHG and daughter Mary, fall 1947.

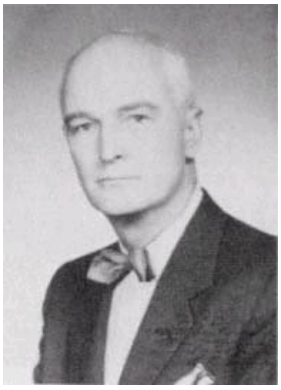
33.
Frank Allbritten, Jr. (left), Bernard J. Miller, and John Y. Templeton III at a surgical conference in Quebec, 1952.

34.
JHG's "Rib-crackers," then current and former residents, 1957.

35.
Maly and JHG at daughter Mary's wedding,
Lynfield Farm, June 1955.

36.
JHG's parents, 1955.

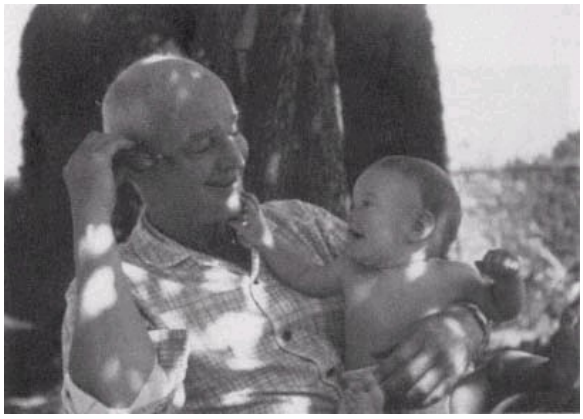
37.
JHG lecturing in "The Pit," amphitheater at
Jefferson Medical College, c. 1964.



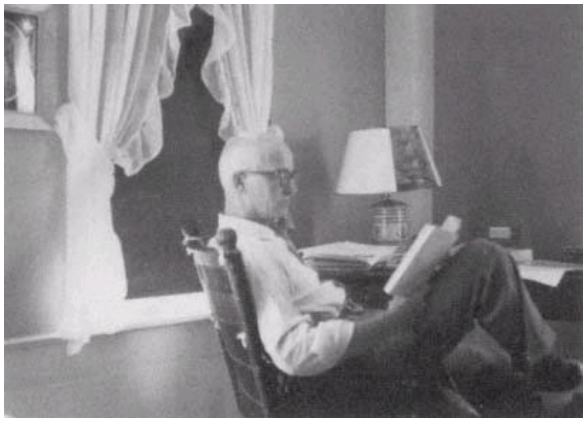
38.
JHG portrait, c. 1958.

39.
JHG receiving the Philadelphia Award, 1964.

40.
Trip to Russia. Maly in checked jacket, JHG center, August 1971.



41.
JHG at the Farm enjoying one of his grandchildren, 1971.



42.
Favorite indoor sport, reading.

43.
Favorite outdoor sport, tennis.

44.
JHG and Maly at the Farm, 1972.

The Mid-1950s to the 1970s

In several of the talks regarding the development of the oxygenator that he gave during the 1960s and early 1970s, JHG alluded to the profound psychological effect that performing the first bypass surgery had on him and on the patient.[13] So many years had been devoted to its development, and so many animal experiments had been done, that when the eighteen-year-old girl with the atrial-septal defect was referred to him for treatment, and the operation done with the oxygenator performing almost flawlessly, there was an overwhelming feeling of unreality, coupled with relief. The exuberance that JHG and Maly had felt after the first success with cats, when they knew that the apparatus would work, was repeated. JHG likely realized for the first time that, more than at any other time in his professional life, he literally had held a life in his hands.

In any case, after the first unquestionably successful surgery, the two subsequent failures with the small girls were terribly disappointing, and led him to declare a moratorium on bypass surgery on humans for a year. Many of his colleagues at Jefferson and in other parts of the country questioned this drastic decision. JHG had never been one to place humans at risk. This conviction was the basis for his rejection of the use of Lillehei's[20] crosscirculation technique to achieve bypass surgery. Haupt[15] later remarked that this was the only known procedure associated with a possible mortality risk of 200%.

During the time immediately following the May 6 surgery, JHG was still busy doing thoracic surgery which was then, and remained, his major métier. His responsibilities for managing the surgical services on both the A Service and the B Service at Jefferson Hospital weighed heavily. Frank Allbritten, who had so capably assisted JHG in carrying out these responsibilities, left in 1954 to assume the chairmanship of the department of surgery at the University of Kansas. Other circumstances were a cause for concern to JHG. Allbritten[2] alluded to some possible internal frictions occurring at Jefferson Medical College in which JHG likely had to be involved. JHG's children were at that time in the turbulent adolescent and

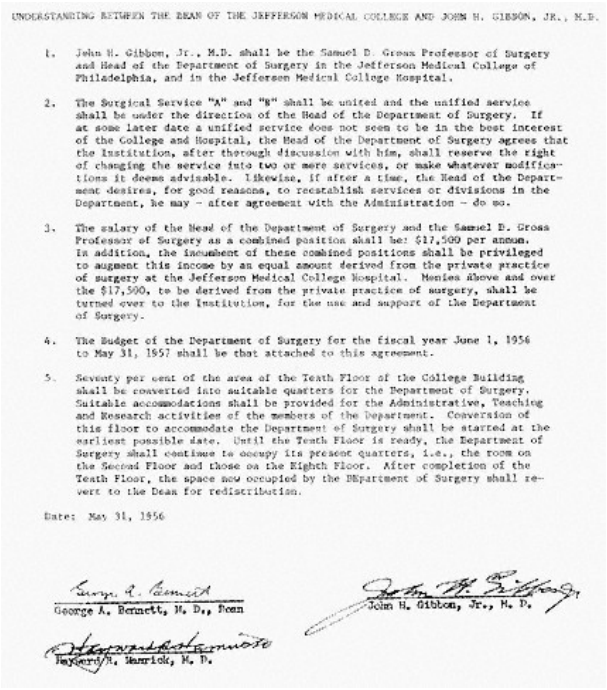
young adult years, which may have created some family tensions, resulting in additional distractions and worries. Many factors could have played a part in JHG's decision to turn over to Templeton full responsibility for all cardiac surgery, not the least of which was his conviction that surgeons should not confine themselves to one specialty. Dr. Rudolph C. Camishion[4] states that JHG had achieved his goal of developing a practical and workable heart-lung machine. JHG had never envisioned continuing to do cardiac surgery exclusively, or even to any great extent. At the time of the May 6 surgery, he was almost 50 years old. Much of his professional life had been devoted to the apparatus. He had reached the stage where he wanted to move on to other things in surgery, teaching, and administrative work. Camishion, who completed his surgical residency under JHG from 1955 to 1959, and then was JHG's partner in practice until 1967 when JHG retired, says that this decision was entirely in character for JHG. In the twelve years of working closely with JHG, Camishion came to know him probably better than anyone else. Often, at the end of a long, difficult day, JHG would suggest that they go to a nearby pub for a drink. They frequently talked on a more intimate level, discussing ideas, personal and professional problems, ethical issues, and philosophical matters. He was content to leave the development of the new field of cardiac surgery in younger hands.

In 1955 JHG's oldest child Mary was married at Lynfield Farm. This was the last time that family members on both sides were all together. In March 1956 JHG's parents died within a week of one another, marking the first great loss of his life. He particularly felt the loss of his mother, who had been his strongest support throughout his life, offering that solid, unstinting devotion that only mothers seem to provide.

Two months later, on May 31, 1956, JHG was named the Samuel D. Gross Professor of Surgery at Jefferson Medical College, and Head of the Department of Surgery at Jefferson Medical College Hospital (Figure 17).

These mid-life years were, then, laden with change, heavy responsibilities, and professional and personal concerns.

Recognition for JHG's accomplishment came slowly. In the fall of 1953, Dr. Clarence Dennis[7] asked JHG to present a paper about the heartlung machine at the Symposium on Recent Advances in Cardiovascular Physiology and Surgery, at the University of Minnesota in Minneapolis on September 16, 1953. Dennis asked JHG why no report of the successful surgery had yet been published in the medical literature. He suggested that if JHG would submit the paper that he would be presenting, it would be



UNDERSTANDING BETWEEN THE DEAN OF THE JEFFERSON MEDICAL COLLEGE AND JOHN H. GIBBON, JR., M.D.

1. John H. Gibbon, Jr., M.D. shall be the Samuel D. Gross Professor of Surgery and Head of the Department of Surgery in the Jefferson Medical College of Philadelphia, and in the Jefferson Medical College Hospital.

2. The Surgical Service "A" and "B" shall be united and the unified service shall be under the direction of the Head of the Department of Surgery. If at some later date a unified service does not seem to be in the best interest of the College and Hospital, the Head of the Department of Surgery agrees that the Institution, after thorough discussion with him, shall reserve the right of changing the service into two or more services, or make whatever modifications it deems advisable. Likewise, if after a time, the Head of the Department desires, for good reasons, to reestablish services or divisions in the Department, he may - after agreement with the Administration - do so.

3. The salary of the Head of the Department of Surgery and the Samuel D. Gross Professor of Surgery as a combined position shall be: $17,500 per annum. In addition, the incumbent of these combined positions shall be privileged to augment this income by an equal amount derived from the private practice of surgery at the Jefferson Medical College Hospital. Monies above and over the $17,500, to be derived from the private practice of surgery, shall be turned over to the Institution, for the use and support of the Department of Surgery.

4. The Budget of the Department of Surgery for the fiscal year June 1, 1956 to May 31, 1957 shall be that attached to this agreement.

5. Seventy per cent of the area of the Tenth Floor of the College Building shall be converted into suitable quarters for the Department of Surgery. Suitable accommodations shall be provided for the Administrative, Teaching and Research activities of the members of the Department. Conversion of this floor to accommodate the Department of Surgery shall be started at the earliest possible date. Until the Tenth Floor is ready, the Department of Surgery shall continue to occupy its present quarters, i.e., the room on the Second Floor and those on the Eighth Floor. After completion of the Tenth Floor, the space now occupied by the Department of Surgery shall revert to the Dean for redistribution.

Date: May 31, 1956

George A. Bennett, M. D., Dean

John H. Gibbon, Jr., M. D.

Thackery H. Harrick, M. D.

Figure 17.
Agreement between JHG and Jefferson University Hospital.
For some years, JHG had been trying to combine the two sections of the surgical department into one. When he became chairman of the Department of Surgery, he presented his ideas for change in a formal statement.
Source: Thomas Jefferson University and Jefferson Medical College archives, courtesy of Dr. Frederick B. Wagner.

published quickly in *Minnesota Medicine*. Dennis was Chief of Surgery at Kings County Hospital, Brooklyn, but had spent many years at the University of Minnesota and still retained strong ties there. It was in this publication that the account of the historic surgery appeared.[12]

After JHG was named Samuel D. Gross Professor of Surgery at Jefferson Medical College in 1956, his practice grew quickly. Having placed Templeton in charge of cardiac surgery, JHG became more involved in cancer of the lung and esophagus. Thoracic surgery was his forte, and he devoted most of his remaining years of professional practice to that field. He became, in fact, a well-known authority regarding diseases of the lung; he was frequently consulted as a diagnostician as well as a surgeon.

Maly had earned a master's degree in social work in 1954, and had opened her own practice as a marriage counselor. The older children had left home and were either in college or settled in their own professional spheres. Within a few years after 1953, JHG became a celebrity. He received hundreds of requests to present papers at professional meetings or to give talks to professional or civic groups about the development of the heart-lung machine. School children besieged him with requests for information. Old Princeton University or medical school classmates wrote to congratulate him. After so many years of being labeled "crazy," JHG reveled in the acknowledgment of his accomplishment. These were probably his happiest and most satisfying years as a surgeon. His partnership with Camishion, whom he considered to be absolutely trustworthy—"solid as a rock"—also brought stability, knowing that he could entrust his patients to Camishion when he had to be away.

And he was away frequently, attending professional meetings and serving as officer in several prestigious organizations. This was the period when, at Jefferson, he became known as "the visiting professor," because he was away from campus so much.

Maly accompanied him most of the time; they were considered a team even outside the laboratory. Indeed, Maly had given up her lab work at about the time of the May 6, 1953 surgery, primarily because JHG was not as directly involved in the lab. Of the two, Maly was probably more at ease in groups and in repartee than JHG. Her skill as a pianist was also an asset, particularly at holidays when singing Christmas carols required piano accompaniment. While no longer an active participant in JHG's laboratory, Maly found her own niche as a counselor, from which she gained deep satisfaction. For both JHG and Maly, the late 1950s was a period of enjoyment in their professional accomplishments.

Further Development of the Heart-Lung Machine

Camishion, when asked why the heart-lung machine did not receive greater notice, and why surgeons did not immediately begin using it, said that the early machine was still far from perfect. Mortality rates were 50% or greater for open-heart surgery in the early years. Methods for establishing precise preoperative diagnoses had yet to be developed. Surgeons would begin an operation expecting to see one type of cardiac anomaly, but find one that was unknown and had never been described in the literature. Within a few seconds, the surgeon had to decide how best to deal with this defect. However, Camishion continued, the evolution of the oxygenator was entirely predictable even at that time. Every knowledgeable surgeon was aware of the significance of JHG's achievement. Only as the oxygenator was refined, and as surgeons became more skilled in doing cardiac procedures, did it come into wider acceptance and use.[4] By 1961, advertisements for oxygenators were appearing in medical journals (Figure 18).

The oxygenator that the Mayo Clinic group developed and began using, which they called the Gibbon-Mayo Pump Oxygenator, seemed to be the best machine at that time. The Mayo surgeons had immediately gone ahead with their initial plans to use it on humans, scheduling three or four cases every week and thus quickly accumulating experience, which resulted in improved outcomes and a much lower mortality rate. Patients with cardiac problems, and parents whose children had congenital cardiac anomalies, besieged the Mayo Clinic with requests for surgery. There was no lack of prospective surgical patients who were willing to undergo surgery even if the chances of complete recovery were small.

The Model I had been patented under JHG's name, with three of the IBM engineers: Malmros, Engstrom, and Barber. The Model II and several related additions to the Model II were patented separately. The engineers at the Mayo Clinic wished to patent the revised oxygenator under the names of JHG and members of the Mayo group: Dr. Wood and Mr. Jones. JHG had made it clear from the outset, when he had first approached IBM, that he had no wish to make money on the machine, nor did he want others to realize unwarranted profits from it. He felt his apparatus was the result of his effort to improve the care and treatment of patients. He considered that this kind of contribution was part of the responsibilities of being a surgeon and a researcher; to receive monetary rewards for such work was a breach of professional ethics.

The patents for the Model I and Model II had by that time been turned

Figure 18:
Advertisement for Heart-Lung Machine in a Surgical Journal, July 1961. Within only a few years of JHG's first successful open-heart surgery using the heart-lung machine, manufacturers began producing similar machines and advertising them in many professional journals. JHG's machine opened up an entirely new field—cardiac surgery.
Source: International Medical Instrument Company (1961). J Thorac Cardiov Surg, 42(1):4.

over to the trustees of Jefferson Medical College. Teaching institutions were requesting blueprints of the Model II from JHG. In a letter dated August 14, 1956 JHG informed such a requestor: "To date, no company has been licensed to manufacture this apparatus and the IBM Corporation is not at present contemplating manufacturing other models. We have been turning over blueprints to reputable physicians in teaching institutions in order to permit them to construct such an apparatus for their own use."[21] Templeton indicated in a letter dated August 24, 1956 that the heart-lung machine was "presently in use in the OR [at Jefferson] with a full schedule all during September."[21]

JHG did not want to be involved in the manufacture or sale of the equipment. Therefore, the combined Mayo-Jefferson group sought an intermediary company that would handle the legal details and become the licensee for the Gibbon-Mayo patents. JHG contacted the Research Corporation in New York City in 1957 to investigate their capability and willingness to take on the responsibility for these details. This corporation agreed to be the licensee, and they entered into an agreement with the Custom Engineering and Development Company in St. Louis,[14] which would manufacture and sell the oxygenator to only those professional groups that would use it for its intended purpose. JHG rejected offers from intermediaries who wished to market it at a handsome profit for themselves. The manufacturing company that was selected to produce the machine would do so at a cost that was reasonable and ensured that those who did the actual work would be fairly and equitably remunerated.

Even at this point, JHG himself did not envision the oxygenator's being used as extensively as it is today. In a letter to the Research Corporation dated July 16, 1957, in response to a question about what he considered an appropriate name for the oxygenator—the name that would go on the patent and on the machine—JHG said, "It seems to me that the necessity for a short name does not exist in view of the fact that the market for these machines will be a limited one and not a mass market." His choice was "Gibbon-Mayo Extracorporeal Cardiopulmonary Blood Circuit," as the best descriptor of the machine. However, he was agreeable to having the name be the "Gibbon-Mayo Pump-Oxygenator," which he considered less accurate.[14]

In an August 1, 1957 letter, the Research Corporation told JHG that another company had contacted them, wanting to manufacture the machine. Here, too, the Research Corporation representative wrote: "We have written this firm . . . expressing the fact that we have licensed Custom

Engineering and Development Company under your and the Mayo patents to manufacture the pump-oxygenator and that in view of the limited market for this machine we did not contemplate issuing any further licenses in the foreseeable future." In the same letter he stated: "our license to CE&D requires that they meet any standard that we may prescribe for the machine and refrain from making claims in advertisements and promotional materials that would be objectionable to us. We feel that this provision will fully protect the good names of Jefferson and Mayo and the people associated with these institutions."[14]

In a note dated February 5, 1958, JHG wrote to Dr. John J. McKeown, then a member of the Department of Surgery at Jefferson, asking him to do a "thorough search of the college [Jefferson] storeroom to see whether any of the cylinder-type oxygenators are still available."[14] The Smithsonian Institution had requested this piece of equipment to be placed on display during an exhibit illustrating the development of modern surgery. Likely, none of the older apparatuses was found. Dr. Ray Kondratas,[19] Chief of the Medical Sciences Division of the Museum of American History, Smithsonian Institution, in a telephone conversation with this author, indicated that such was the case. However, the Smithsonian has pictures, trade catalogs, and literature regarding currently manufactured heart-lung machines.

Less than five years after the first surgery, surgeons all over the world were already using the heart-lung machine, having obtained the blueprints from Jefferson.

In February 1958, JHG received a letter from a company in France which was manufacturing the oxygenator, the Instrumentation Médico-Chirurgicale Société à responsibilité limitée au capital de 6,000,000 francs, 107 Boulevard Richard-Lenoir, Paris XIe, Roquette 58-70 + ch. Post. Paris 15710-17:

> as you know, we are now manufacturing in France your heart-lung machine for Professor Bénichoux of the Faculté de Médicine de Nancy according to the drawings communicated to us by IBM. We experience some difficulty to get the special gum tubing utilized with the pumps. Could you be so kind as to tell us what is the name of the Firm which manufactures this tubing for you, so that we can write them immediately?[14] [The company was Davol Rubber Company in Providence, Rhode Island.]

Later, correspondence (September 20, 1968) containing an annual report to Jefferson from Research Corporation regarding the pump-oxygenator, states:

> This letter is our Annual Report for 1967 in accordance with the patent assistance agreement dated May 15, 1962. We are currently handling for Jefferson only the Gibbon pump-oxygenator. Last year we reported a change of management at Med-Science Electronics, our only licensee for this device. The new management has reported sales during only one quarter of 1967 and has paid royalties for that quarter amounting to $2,023.00. This is somewhat less than in previous years, but demonstrates that the present management is endeavoring to supply the demand for these units. Since the license is non-exclusive, we have the right to seek other licensees if we deem it desirable. We will keep a close watch on the Med-Science marketing activities during 1968, and if sales as reflected by royalty payments appear to decline too severely, we will review the situation with Med-Science. If they are not able to explain the decline satisfactorily, we will try to develop licensing interest from other firms. Of the total royalties paid on the Gibbon invention, 75% or $1,517.25 is subject to division between Jefferson and Research Corporation. Jefferson's share (57.5%) of this amount is $872.42. Our check for Jefferson's share is enclosed herewith. No new inventions were submitted for evaluation during 1967.[14]

In 1971, a copy of a similar report was sent to Jefferson for 1970 describing the status of

> your invention, the "Pump Oxygenator." Attached is Professional Status Report, 1970:
>
> Project No. 41-402, JMC. Inventors: JHG et al. Patents Issued:
>
> U.S. Patent # 2,659,368—11/17/53
>
> U.S. Patent # 2,700,320—1/25/55
>
> U.S. Patent # 2,702,035—2/15/55
>
> U.S. Patent # 2,705,493—4/05/55
>
> U.S. Patent # 2,792,002—5/14/57
>
> U.S. Patent # 2,847,008—8/12/58[24]
>
> Licensing: Med-Science Electronics, Inc., continues as the sole licensee under a license covering the six patents listed above plus two

others which cover closely related pump-oxygenator inventions and were assigned to Research Corporation by the Mayo Clinic. The oldest patent of the Jefferson group expired 11/17/70. Med-Science reported no sales of units during 1970.[14]

This last report marked the end of the first phase of the heart-lung machine. By 1971, newer, smaller, and more efficient oxygenators, including the bubble and the membrane types, were being manufactured by a number of companies.

In an interview, Templeton[22] stated that the bubble oxygenator is intended for short procedures. However, he said, no surgeon, beginning an operation, ever really knows whether the procedure will be short or may need to be continued over an extended period. For this reason surgeons usually elect to use membrane oxygenators as a safeguard for the patient if the procedure has to be lengthened.

By the time of the report in 1970, JHG had been retired for three years. He had been true to his word that he wanted no monetary reward for the oxygenator. All royalties, from the first, went to Jefferson. While the figures regarding the total amount of royalties derived from the oxygenator during this time are not known, one might roughly estimate an average of $1,500 a year for 12 years, for an estimated total of $18,000. Had JHG or Jefferson deliberately set out to make a profit, they likely would have realized a figure at least ten times this amount. Dennis estimates current profits from heart-lung equipment and treatment are in the millions of dollars.[7]

Types of Oxygenators

The Model II and its counterpart, the Mayo-Gibbon pump oxygenator, are classified as "film oxygenators." They were used extensively throughout the 1950s, even while other types of oxygenators were being developed and manufactured. Of the Model II, Gerbode[11] states: "It had excellent characteristics for blood oxygenation and was a very atraumatic instrument." However, its major drawback was the fact that it was not disposable, and had to be meticulously cleaned and sterilized between each use. It "required one or two technicians for maintenance at all times." Its performance, however, was always reliable. Using the Mayo-Gibbon oxygenator, John W. Kirklin successfully repaired a ventricular septal defect on March 23, 1955;

this was the first in a series of relatively successful applications of the technology at the Mayo Clinic.[17]

Other types are the bubble and the membrane oxygenators.

Bubble Oxygenators

Scientists for some time realized that a large gas-liquid interface can be created in a relatively small volume by bubbling gas through a liquid. In the case of oxygenation of blood, the gas (oxygen) is bubbled through the liquid (blood). The amount of oxygen that can be transferred into the blood depends largely on the total surface of exchange that can be developed by the bubbling process.[10] The one major difficulty, until the early 1950s, with "bubblers" was the great risk of introducing air (gas) embolism into the patient's body; air embolism can cause instant death. However, this problem was solved when Clark, Gollan, and Gupta[5] first introduced silicone antifoaming compounds. Following oxygenation, the blood is then exposed to surfaces coated with silicone. These silicone products cause the gas bubbles to burst; the air escapes through exhaust portals. The oxygenated blood is then collected in a settling chamber to be filtered and reinfused into the patient's arterial system. Bubble oxygenators are considered useful because they are compact, economical, disposable, easy to use, and safe for relatively short procedures.

Film Oxygenators

Stationary screen, stationary sponge, rotating spiral, rotating disc, and rotating screen oxygenators are grouped as film oxygenators, in that the blood is filmed over surfaces during the oxygenation process. JHG's heartlung machine was the first stationary screen oxygenator. The Model II was well designed and functioned efficiently. The first artificial lung in which rotating disks provided the support for the blood film was built by Bjørk[3] in Crafoord's laboratory. This oxygenator was modified and improved by Aird and Melrose.[1] The result was a combination of features of the rotating disc and rotating cylinder oxygenators. Kay and Cross[16] developed a rotating disc oxygenator which initially contained 59 stainless steel discs 0.4 mm thick and 12.2 cm in diameter, mounted 0.5 mm apart on a horizontal shaft, and enclosed in a Pyrex cylinder. Disc oxygenators have a large surface of gas exchange per unit of time in a relatively small machine. They have been widely used in clinical heart-lung bypass surgery. Dennis[7] and his colleagues at the University of Minnesota, and then at Kings County Hospital/Downstate, developed a rotating screen oxygenator—a design

that combined centrifugal distribution of blood with the advantages of a wire mesh screen support. This machine proved its efficiency in heart-lung bypass procedures.

Membrane Oxygenators

In normal respiration in mammals, there is no direct contact between the blood and gas; oxygenation occurs by molecular diffusion through a membrane. Kolff,[18] Clowes,[6] and Thomas[23] were leaders of surgical teams who developed similar membrane oxygenators during the 1950s. Major features of stationary membrane oxygenators include low hemolysis, disposable parts in contact with the blood, no risk of air embolism, and simplicity of volume control. Although initially expensive, membrane oxygenators are now disposable, relatively low-cost, and considered safer than other oxygenators and therefore preferred by many cardiac and thoracic surgeons.

The 1960s and 1970s

JHG's active professional life continued throughout the 1960s until he retired July 1, 1967. From 1953 until he died 20 years later, he authored or co-authored 69 articles and wrote and edited his book on chest surgery, which he also updated periodically. He received 22 awards, including honorary doctorates from five universities, was involved in 37 professional activities such as being a member of the board for reviewing and accepting candidates as fellows in the American College of Surgeons, and was president of several professional organizations. Maly had been a staff member of the Marriage Council of Philadelphia from 1955 to 1960; at that time, she resigned in order to accompany JHG on his trips to professional meetings, at which he was often the guest lecturer or keynote speaker. She later resumed her membership in the Marriage Council and was chairman of that organization for a time. They spent two weeks or so every winter in the Caribbean. After he retired, JHG continued to attend professional meetings when he could, was editor of *Annals of Surgery* until his death, and gave lectures occasionally. He even maintained a small practice, but no longer performed surgery.

Support for Medical Research—1930 to 1955

JHG had little in the way of funds to support his research, at least in the beginning. As JHG describes his experiences:[1]

> Imagine for a moment the way research was carried on in a research laboratory in the 1930s. The Federal Government was not then pouring out hundreds of millions of dollars to doctors to perform research. Harvard provided my fellowship and the Massachusetts General Hospital provided the laboratory. I bought an air pump in a second-hand shop down in East Boston for a few dollars, and used it to activate finger cot blood pumps.

JHG did obtain grant funds from the Josiah Macy, Jr. Foundation to support animal experiments in 1938. In the late 1940s and 1950s, research support from the National Heart Institute at NIH provided funds for the animal experiments. While Watson of IBM was willing to build the three successive oxygenator models, he himself was not an advocate of research using animals.

The United States Constitution provided no specific mechanism for the support of either science or medicine beyond patent protection and the regulation of interstate commerce. Throughout most of the nineteenth century, medical research was conducted by a few interested practicing physicians in their spare time.[2]

Between 1900 and 1940 there was a gradual increase in appreciation of the relationship between basic and applied research, with a consequent growth of government aid for both areas.[2] The rather sudden emergence of basic science in the United States was due primarily to the support that business leaders were willing to provide, although this support did not occur until science had reached a point where its implications for the development of technology became apparent. Businessmen saw the advantages of increased technology for the growth of their companies. Following the First World War, for example, there was a rapid increase in demand for manufactured products. Owners of these companies began to appreciate

that scientific research was able to develop new methods and materials to increase productivity. However, as Shryock[4] points out: "It seems clear . . . that economic interests and technology will not of themselves lead automatically into basic investigations. *Other variables influence the outcome*" [italics added]. Individual interest, motivation, perseverance, and capabilities play major roles.

The amount of funds available for medical research through the federal government increased remarkably between 1947 and 1974. In 1947 the amount appropriated for medical research was $27 million or 3.9% of the amount ($691 million) that the U.S. government spent on research and development, including defense and space exploration.[3] By 1975 medical research was provided with $951 million, or 14.1% of the total research and development (R&D) budget ($6,730 million).

Since 1975, the amount of funding available for medical research has increased every year. In 1988, the amount had risen to $2,592 million. This figure, however, represents about the same proportion—14.3%—of the total R&D budget. These sums were unthinkable in JHG's time—the Depression years. People counted themselves well off if they had ten or fifteen extra dollars a month.

The difference between JHG and others in relation to their productivity with respect to research probably was his bulldog determination, his keen intelligence, and Maly's support. Each played an important role in JHG's work. Gibbon, in effect, created his own "era."

In Support of Animal Experimentation

JHG's work on the heart-lung machine demonstrates the need for animal experimentation for the advancement of knowledge, research, and practice in medicine and surgery. White[9] stated that "there is virtually no major treatment or surgical procedure in modern medicine that could have been developed without animal research. Among the treatments and pharmacological substances that were first tested and developed using animals, are *open-heart surgery*, cardiac pacemaker, organ transplantation, insulin, and vaccines for polio, smallpox, diphtheria, and other diseases (including, now, AIDS).

Westacott[8] wrote that the antivivisectionist movement began with Frances Power Cobbe, a reform-minded Irish zealot from Bristol, England, who stumbled upon physiological experiments in progress during a trip to Florence, Italy in 1863. Then, as now, one finds experimental animals being treated well in some situations and badly in others. Most people decry treatment of animals that is cruel and sadistic, where laboratory and housing environments are crowded and dirty, and where experiments place animals at needless risk of disability and even death.

In England, the first law to protect animals was passed in 1822, aimed primarily at protecting horses and cattle. Two years later, the Royal Society for the Prevention of Cruelty to Animals was founded and, in 1835, the Animal Protection Act was expanded to include dogs and other domestic animals.[3]

In this country, Henry Bergh initiated the development of the American Society for the Prevention of Cruelty to Animals (ASPCA), founded April 10, 1866. Nine days later, the New York legislature passed the first anticruelty law, giving the ASPCA power to enforce the prohibition against cruelty. Early in the twentieth century, this legislation enabled the ASPCA to be responsible for the care of stray animals.[2] This mandate is still in place. The New York Metcalf-Hatch Act provides for a supply of pound animals to the experimental laboratories in and near New York City. The research laboratories are open for inspection by state and ASPCA representatives.[3]

In 1947 Shryock[7] related the antivivisectionist movement to the general moral attitudes prevalent during the Victorian age. He contended that the antivivisectionist movement was an Anglo-Saxon phenomenon that had handicapped the biological sciences, and that "this dangerous type of sentimentality is still much alive in the United States today."

More recently, the Animal Care Bill was introduced in 1964, which outlined the responsibilities of federal agencies and departments relative to animal research and training, and to the dissemination of information on laboratory animal health, care, and use. In 1965 a group antagonistic to animal research developed a bill aimed at blocking the acquisition of laboratory animals.

During the mid-1960s, when legislative activity was at a critical level, Dr. Maurice B. Visscher was elected president of the National Society for Medical Research (NSMR), a group that actively promoted the use of animals in research with appropriate legal sanctions and standards of care. The NSMR merged with the National Association for Biomedical Research in 1984 to combine their efforts to affect and effect animal research policy at the federal level. With the support of member institutions and companies, and the cooperation of many academic, industrial, professional, and voluntary health groups, NABR has established an effective presence in Washington, D.C. and has become the acknowledged voice of the research community on the laboratory animal issue. Because of its broad-based constituency and proven track record, the association has earned the respect of members of Congress and their staff associates as well as that of the executive branch and federal agency officials.[1]

In the 1970s and 1980s, animal rights activists have defended the notion that *all* animal research should cease. However, as the facts show, over 90 percent of the more than 20 million animals used annually in medical research are mice, rats, and other rodents. Farm animals, monkeys, dogs and cats comprise only a small percentage of animals used in medical research each year. This number is small when one considers that about two hundred thousand dogs and cats are abandoned every week in the United States, to fend for themselves.[9] In some cases, these dogs and cats are picked up by public-operated pounds where they are kept for a limited time to see whether the owner will claim the animal. If the animal has not been claimed within the designated time period, it is destroyed. In 1986 about 10 million dogs and cats were destroyed because they had been abandoned or were simply "strays." The only way that most medical research laboratories can afford animals is by buying these strays from city pounds at a cost of fifteen to

twenty dollars per animal. Animals obtained through private breeders, such as "puppy farms," often cost many times that amount.

Legislation is in place to protect animals used in federally operated medical research laboratories. In these facilities, their care overseen by an institutional Animal Care and Use Committee. No reputable animal researcher objects to activities and legislation aimed at instituting standards of care for animals. These safeguards are reasonable. However, when the research activities themselves are infringed upon or restricted by overzealous animal rights activists, researchers then feel that the rules and regulations are too burdensome. Creditable researchers performing experiments to test procedures or equipment *want* the animals to be in the best possible physical condition before, during, and after the experiment.

Animal research is of great importance today because of the scientific and biochemical knowledge that has accumulated over the last forty years. This knowledge, much of which resulted from animal research, forms the basis for technological advances which produce more accurate diagnostic and treatment procedures. Recently, Karpati[5] stated the case for animal research and the imperative for scientists and medical researchers themselves to counteract the protests of the extremists among the animal rights activists.

One of the questions posed to each surgeon interviewed for this book was whether the development of the heart-lung machine would have come about without animal research. *No* was the emphatic response from each.

Gibbon spoke briefly about his animal research in the 1930s:[4] "The animals used were cats and when our supply ran short, I can recall prowling around Beacon Hill at night with some tuna fish as bait and a gunnysack to catch any of the numerous stray alley cats which swarmed over Boston in those days. To indicate their number, the SPCA was killing 30,000 a year."

In mid-1990, the Agriculture Department issued a new proposal intended to carry out the most controversial part of Congress's 1985 amendments to the Animal Welfare Act.[6] This new proposal does not include specific requirements, such as amount of exercise that laboratory animals are to receive every day, but requires each facility to determine its own requirements regarding improved treatment of laboratory animals. The National Association for Biomedical Research indicated that the new proposal is "a vast improvement" over the previous proposal, which was considered to be financially burdensome to most facilities. However, the new proposal would likely require laboratories to spend as much as half a billion dollars to meet the altered levels of expectations.

The director of laboratory animals for the Humane Society of the

United States indicated that the Agriculture Department's new proposal represents elimination of some standards and weakening of others, to the extent that, he says, the Department has "abdicated its responsibility" with respect to the 1985 amendments. Animal rights advocates do not consider the new proposal to be sufficiently rigorous to ensure standardized improvement in laboratory conditions for some time.[6]

One needs to consider the benefits derived over the years from animal research. As with all benefits, there are costs. The decision stems from the question of whether the benefits outweigh the costs. From those people—parents, children—who have experienced the benefits, the answer is unequivocally yes.

Impact of the Heart-Lung Machine

Galletti[67] described the evolution of the heart-lung machine and its attendant terminology over the first thirty years. He cited Dennis,[4] Dogliotti and Constantini,[5] and Gibbon[8] among the pioneers who first used the artificial lung in clinical practice. Gibbon was the first to successfully perform open heart surgery in a human patient using a heart-lung machine. The heart-lung machine was next used by Kirklin,[9] Melrose,[11] Clowes,[3] Bucherl,[2] and Lillehei.[10]

Regarding terminology, from Gibbon's "mechanical heart and lung apparatus" or "pump-oxygenator," and Constantini's, Melrose's and Bucherl's "heart-lung machine," has emerged a commonly accepted generic label, "artificial lung," used widely both in the U.S. and in other countries.

The impact of the artificial lung on cardiac surgery grew slowly but steadily from 1955 to 1965, when it was used most commonly to correct congenital heart defects. About twenty-five thousand babies are born each year with cardiac defects, not all of which are reparable. From about 1965 to 1973, its application was broadened to include correction of valvular defects. Since then, the artificial lung has been used extensively to perform aorta-coronary bypass surgery for correction of obstructed arteries within the heart itself, and this accounts for the majority of open-heart surgery procedures.

In the three decades following the first successful bypass surgery, improvements have occurred in all aspects of open-heart surgery. In addition to improvements in equipment, diagnosis of cardiac defects became much more definitive because of more sophisticated cardiac catheterization and radiologic methods. Cardiac surgeons became more skillful in performing complex procedures. Interactions among the surgeon, the perfusionist, and the anesthesiologist resulted in greater efficiency of the surgical team.

Taken together, these advances have made cardiac surgery as safe and as acceptable as other surgical procedures.

The number of cardiac and thoracic procedures involving the need for an artificial lung has increased dramatically since 1953, and include heart transplantation, and aortic arch and cardiac valve replacement. Cardiac sur-

Figure 19.
Cardiac Surgeons in Cape Town, South Africa, 1968. Dr. Christiaan Barnard's announcement of his first successful heart transplant surgery in Cape Town, South Africa, in December, 1967, exploded onto the surgical scene with dramatic force. Soon after, most of the world's distinguished cardiac surgeons met in Cape Town to discuss surgical, technical, and ethical problems surrounding this new area. The group included (left to right seated): Euriclides Zerbini (Brazil), C. Walton Lillchei (New York), Denton A. Cooley (Houston), P.K. Sen (India), Adrian Kantrowitz (Brooklyn), Edward B. Stinson (Stanford); standing: James Mowbray and Donald Ross (England), Pierre Grondin (Canada), Michael Bellizzi (Argentina), Christiaan Barnard (South Africa), James Pierce (Richmond).
Source: Time:49–50, July 26, 1968. Courtesy of Time Inc. Magazines, Time Picture Syndication Department. Photographer: Cloete Breytenbach.

geons, spurred by the heart transplant achieved by Dr. Christiaan Barnard on December 3, 1967, met as a group the following July (Figure 19).

More recently, combined lung-and-heart transplant procedures are being done with increasingly encouraging outcomes. The most current data available from the American College of Cardiology are for the year 1987, when 332,000 bypass operations were performed in the United States.[1] Estimates of the number of procedures being done worldwide on a daily or weekly basis are difficult. The number done annually ranges between 750,000 and 1,000,000. Disposable oxygenator units now cost about $150 to $200; this amounts to $150 million per year in sales. However, as Galletti pointed out, the cost of equipment is only a small part of the total

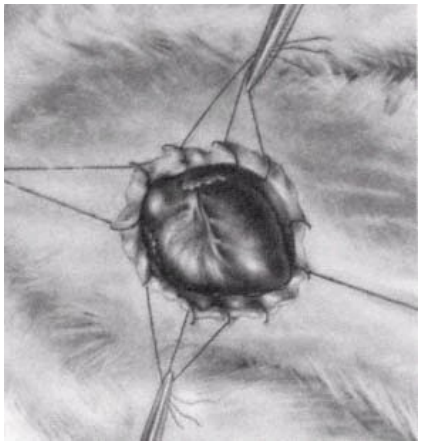


Figure 20:
Drinker Preparation. In the early 1920s, Dr. Cecil Drinker published a short article about the procedure he developed to perform open-heart surgery on laboratory animals. His procedure allowed full exposure of the heart, while closing the thorax to enable the animal to breathe naturally. Only a pump-oxygenator can support a nonbeating heart and provide a bloodless operative field, however, for extensive surgical procedures.
Source: Drinker CE (1921).
A useful heart method. J Exper Med, 33:675 .

cost of an open-heart operation; he estimated the average cost at $10,000 in 1979.

Today, surgery using the artificial lung to correct thoracic and cardiac problems is done as routinely as other types of major surgery. The mortality rate, which in the beginning was about 50%, has dropped to less than 5%, with the risks considered no higher than for other complex procedures. While many surgeons, scientists, and engineers contributed enormously to the development of the artificial lung, JHG was the first to use it successfully with a human patient. His twenty-two years of work to develop the apparatus also made it possible for him to be first among his peers. JHG's first successful case proved to others that such a procedure was possible, and stimulated the rapid development of associated equipment and procedures needed for repair of more complex cardiac problems and for greater safety in their accomplishment.

Summing Up: JHG the Man

Although all his life JHG tried to be absolutely independent, to develop his own reputation as a surgeon, to gain recognition for achievements in his own right and through his own efforts, others never let him forget that he was the son of a famous surgeon, that he came from a well-to-do family, and that he had every advantage as he grew up. Nevertheless, JHG fought fiercely to remain separate from the shadow of his father in his professional life.

In 1954 JHG was elected president of the American Surgical Association, considered the most prestigious of the professional organizations related to surgery. A colleague shook his hand in congratulations and said, "How nice that you now occupy the same position once held by your famous father"—to which remark JHG took umbrage, but without letting his true feelings show on the outside. He merely thanked the man at the time, but later remarked to a colleague who had heard the exchange, "I hope that Dr. [Y] doesn't think that my being elected was only because my father was once president of the ASA!"[9]

This characteristic—reliance on one's self—portrays the type of person known as an "internal" as described by Rotter, a psychologist who developed a personality analysis questionnaire that identifies an individual as either "internal" or "external."[5] For example, an internal person's reaction to failing an examination is likely to be, "I didn't study hard enough"; that of the "external" person may be "The instructor didn't fully explain the test," or, "The alarm didn't go off this morning." The internal person believes that he or she controls what happens, while the external person believes that outside events are the major controlling factors.

Personality traits such as these may be innate, part of a person's genetic makeup, rather than learned behavior or attitudes. JHG believed that each individual should work toward making his own way and reputation in the world, rather than relying on the "pull" of influential relatives or friends. He did not, for example, use every avenue open to him as a renowned surgeon and researcher to promote the careers of his residents when they

had completed their residencies and were beginning to seek positions in particular institutions or with particular surgeons. He always willingly wrote references for them, and contacted individuals, but he never considered using his influence to seek favors from members of the many professional organizations in which he held high-level elected positions. In his own mind, that simply was not the way an honorable person conducted himself (refer again to Aristotle's Ideal Man). JHG held this attitude, even with regard to his own family members. He would do everything he could, as an individual, but he would not go to others to ask for their help in securing a place for one of his children in a particular institution. Many of his residents later criticized his "lack of support" in this area, knowing that many other well-known and highly respected heads of surgical departments *did* ask others in higher positions for favors with regard to their residents.[1]

Regardless of JHG's strict standards of conduct for himself, which even then were sometimes viewed as old-fashioned, he did not demonstrate in any way that he was a prig, or that he judged the behavior of anyone else; he did not. His only concern was his own behavior; what others did was of no interest to him.

JHG the Intellectual

Every one of JHG's colleagues who was interviewed remarked on JHG's exceptional intellectual abilities. Even among highly intelligent and capable peers, he was regarded as outstanding. One of his early mentors, Dr. Eugene Landis, recognized immediately JHG's characteristics as a potential scientist and researcher: to conceptualize and synthesize complex ideas, to think logically and analytically, to communicate clearly in writing and in speaking, to concentrate fully, to pay attention to the smallest details, and to persevere even in the face of repeated failure.

JHG the Teacher

JHG, in his role as teacher and mentor to medical students, usually taught in the traditional way. On Monday mornings he took the residents with him as he made rounds on the men's surgical units, going over in detail the diagnosis, treatment, and probable outcome for each patient. He asked questions of the residents, testing their knowledge of pathophysiology, pharmacology, and laboratory procedures and results. He repeated the process on Wednesday mornings, when he made rounds on the women's surgical units. Once a week, he lectured to medical students in "the pit," the amphitheater, using the case study method. This was where his knowledge,

clinical analysis skills, and teaching ability shone the brightest; he loved lecturing in the pit. He rarely prepared lectures in advance, but preferred that the presentation, questions, and discussions stem from the case (patient) itself. Symptoms and signs were presented, analyzed, and discussed. The differential diagnoses were listed and each dealt with in detail. Treatment modalities were presented and critiqued. Other faculty members frequently attended JHG's lectures to refine their own knowledge and teaching techniques.

He was not the type of teacher to be a chum to his students, nor did he sit around and chat with them casually. Many of the residents, over the years, considered him aloof and reserved. One of his closest friends later said that in all likelihood this attitude also characterized the way his children regarded him and that this probably accounted for the lack of warmth between him and them. With his children, he was the parent, not a pal.

JHG as Colleague

One or two former residents who worked in the animal laboratory considered JHG arrogant and narcissistic. An excellent explanation of the characteristics associated with narcissism can be found in a biography of Karen Horney:[6]

> Narcissism is the psychic state of loving the attributes of one's idealized image. The narcissist believes in his greatness, uniqueness, omnipotence, infallibility and freedom from limitations. He must impress others and needs their admiration. He overlooks [his own] flaws or transforms them into virtues. But his relations with others are poor; he imagines criticism and becomes easily enraged by it. He disregards the needs and feelings of others. His work suffers from being too grandiose in its aims. So he often incurs further failure through real limitations. He may seem optimistic and happy, but just underneath the surface are pessimism and despondency.

However, those who knew him well said the characteristics associated with narcissism were simply not part of JHG's personality. However, the former colleague based his opinion of JHG on the following situation.

The colleague ("Dr. X") had been working for several years in the animal laboratory at Jefferson Medical College under the direction of JHG. Dr. X, indeed, had made many improvements on the apparatus, and his work came to the attention of an organization that wanted to present him with an award as one of the ten outstanding young men of the year. Dr. X was delighted; so was JHG, when told about the honor. However, in the citation that was to accompany the award, Dr. X described himself as *co-*

inventor of the heart-lung machine. This information did not reach JHG until a day or so before the presentation was to be made. JHG on this occasion—the only occasion so far as is known—was furious, and spoke to Dr. X in private, advising him to withdraw his name from the list of honorees in view of the fact that the award was apparently being given on the basis of the claim as co-inventor. As a result, Dr. X resigned from the laboratory a few months later.

After that one confrontation, however, JHG never referred to it again, either to Dr. X or to anyone else. Before this incident, through all the years that JHG was head of the surgical department at Jefferson, it was well known that he disliked confrontations of any kind with anyone, for any reason. His closest colleagues and residents said that, whenever discipline of any sort had to be meted out, JHG would ask his second-in-charge to do the necessary dressing down.[1] True to his innate nature, JHG was not comfortable with disharmony or discord around him. His usual stance was to make everyone feel as comfortable as possible, and to smooth things out in order to avoid unpleasant situations.

Those who knew him best described him as a true gentleman. He did not present himself as infallible, omnipotent, grandiose. When he was approached by the Smithsonian Institution in the 1960s to have the Model II as one of its permanent exhibits, his response was, "What on earth for?"[4] His extreme caution in consenting to the use of the machine with human patients indicates his uncertainty, his need to test and retest to make sure that the machine worked perfectly.

Even after the first successful bypass, it was Clarence Dennis who, some months later, asked JHG to present that case at the Downstate Medical Center. When they met, Dennis asked JHG why nothing had yet appeared in the medical literature about such a great accomplishment. JHG's response was that the apparatus could not be accepted on the basis of one positive outcome. Dennis, however, said that success in even one case certainly warranted publication. The result of this conversation was JHG's article in *Minnesota Medicine*. JHG did not actively seek the limelight. That is not to say that JHG did not enjoy the praise, awards, and admiration that came to him later as a result of his work. In this regard, JHG was as human as any of us. The praise, awards, and admiration were honestly and rightly earned. He had spent almost 20 years developing the machine when no one else would even touch it. He had solved most of the major problems associated with ECC during those 20 years; and for those problems that he did not solve, he at least identified and pointed the way to their solution.

Another colleague[9] stated that JHG "did not suffer fools gladly." Rather, JHG preferred to spend his time with people who were positive, creative, energetic, and productive.

Further indicators that JHG was both highly respected and well liked by his colleagues are that he was elected to high offices in all the national surgical organizations and was president of several of these. He was sought out by and became friends with many famous surgeons of the time: Alfred Blalock, Helen Taussig, Michael DeBakey, Clarence Dennis, Clarence Crafoord, Robert Gross, and many others. He was a guest in the homes of many of these renowned surgeons, and many were frequent guests at Lynfield Farm.

Those with whom he worked at Jefferson were devoted to him, including his secretary for over 10 years, Marguerite Stadvic. Every year, he and Maly hosted the two annual Jefferson social events at the Farm: the Christmas party and the Spring picnic. His professional correspondence was voluminous; he received inquiries about the heart-lung machine and requests for reprints of his articles from around the world.

Relationships with Family and Friends

After JHG had become well established as a thoracic surgeon to whom many prominent people of Philadelphia came for treatment of chest problems (particularly after he was named the Samuel D. Gross Professor of Surgery) he sought his father's advice about what fee to charge a well-known, wealthy banker whose lung disease required a pneumonectomy. JHG, Sr. had been surgeon to many of Philadelphia's prominent citizens during his own career, and was well aware of appropriate levels of fees. JHG followed his father's advice and charged his client $3,000 to perform the removal of the lung—more than he had ever charged any patient in his life. The banker paid the fee without blinking an eye.

JHG grew closer to his father as they both got older. In later years, JHG had succeeded in establishing his own reputation, in gaining the esteem and recognition of his fellow surgeons on the basis of his own accomplishments rather than as the son of "that distinguished surgeon, John Heysham Gibbon," and their relationship became collegial rather than father-and-son. After JHG, Sr. retired, he no longer tried to persuade JHG to go in one direction or another. The two had long been chess opponents; this activity continued with a lessening of the competitive spirit in them both, and with an increased pleasure in the sheer intellectual capacities that each brought to the game. They often spent hours together,

discussing new developments in surgery and medicine, in theorizing about possible new technological discoveries and their application to this or that diagnostic situation. They respected one another and came to be almost on an equal footing.

While JHG and his father shared professional and scientific interests, it was his mother who provided him with nourishment for his deeper, more philosophic side. Instead of topics related to medicine and technology, JHG and his mother shared aspects of their interest in religion, literature, and philosophy. JHG preferred the philosophy of William James, whose major theme was pragmatism. Outwardly neither JHG nor his mother was particularly religious; JHG rarely attended church, but approached religion from the perspective of the scholar. Yet both were religious in that they believed in a Power or Force greater than themselves, often discussing the eternal philosophic questions that people have posed for millennia: Who am I? What am I doing here? Where am I going?

They shared knowledge of new authors and their works, examined poetry to extract its more subtle shades of meaning, and exchanged some of their dreams and hopes for the future.

The blending of the two parents provided, for JHG and his siblings, an ideal background in which to flower fully into adulthood. The environment was at once loving, understanding, demanding, and stimulating.

JHG's close relationship with his brother Sam developed when they were boys and continued into their adult lives. Both were handsome, outgoing, fun-loving, so that others were delighted to be drawn into their plans and activities. Sam eventually was almost an inch taller than JHG, who was six feet. Sam later became a widely known and respected businessman, particularly as head of the Air-Shields Company. JHG admired Sam's success in the business world, although he himself had little interest in financial matters on a large scale. However, he often sought Sam's advice about particular aspects of business as they related to the oxygenator and other kinds of surgical equipment and technologies at Jefferson, as these were developing rapidly. As an administrator, JHG had to be involved in financial and purchasing decisions.

Although the brothers' disparate lives following graduation from Princeton University caused them to move further and further apart, Sam's company later was the sole manufacturer of the Haupt/Jefferson ventilator developed during the 1950s, and they had many interests in common. They shared a love of tennis and played together as often as possible. However, while JHG's favorite sport continued to be tennis, Sam's became sailing.

Over the years Sam owned several boats and sailed frequently, particularly after retiring to Florida.

JHG, in the role of husband, was extremely supportive of Maly, both in her position as laboratory assistant to him and later when she wished to pursue a master's degree in social work and counseling in the early 1950s. At this time his own professional activities—teaching and clinical practice—frequently drew him away from the lab. They were always a team, and JHG would rarely consider attending conferences or professional meetings without Maly. One major exception was when he was invited to become a member of and to attend the annual meeting of the Association of Internal Organs in London. He also wanted to spend some time in Sweden visiting his friend Clarence Crafoord, who had come to Jefferson the year before to see the development of JHG's heart-lung machine. This meeting took place soon after the end of World War II, at a time when Maly felt that she could not leave the younger children. JHG took Mary, their oldest daughter, with him to Europe in the fall of 1947.[3]

Often, at a party or conference, JHG would see Maly across the room chatting with members of the group, and remark to whomever he was talking with at the moment, "Isn't she lovely?"[8] In every talk he gave about the oxygenator, following the first successful bypass surgery in 1953, he never failed to give Maly full credit for her contribution to its development. In the official press photograph of him and the Model III machine in 1954, he insisted that she be in the picture with him.

The many snapshots of JHG taken with children—his own and others' and his grandchildren—clearly show that he loved children. However, as each of his adult children indicates, his work came first, to the extent that they felt abandoned by their father because he was so frequently away from home. His four years of army service during World War II, when he was totally absent, was probably the critical factor that crystallized the children's perception of his having abandoned them. Although Maly was away a good deal of time, they never felt that her work came first, nor did they feel abandoned by her. Even after he returned from the Army, his professional responsibilities claimed most of his time. In addition, JHG had an unusual devotion to his patients, as noted after JHG's death by Maly, who herself sometimes felt that she and the children took second place in JHG's list of priorities. If a patient called, or if a patient's condition demanded his presence, JHG never hesitated—he was there. This aspect of his professional life gradually exacted a toll on his family life, and resulted in resentment by family members, so that his home life was, as one of his closest

colleagues recently indicated,[2] perhaps not as warm and satisfying as it might have been. This same colleague, himself a well-known cardiac and thoracic surgeon, said that most fathers in that era, professional or not, were obliged to be away from home much of the time, to earn a living. Physicians in general, and surgeons in particular, had to be on call twenty-four hours a day for emergencies that were often a matter of life or death. Therefore, JHG was by no means the only father who did not spend much time with his family.

He was nevertheless absolutely devoted to Maly and the children. He wanted nothing more than to have each of their children well educated and to have them take their place in the world as solid citizens. And that is what happened. Mary, the oldest, earned her undergraduate degree at Oberlin College where she majored in sociology, and later earned a master's degree in social work at Boston University. John, their only son, holds a doctoral degree in psychology and is well known in his field of animal behavior. Alice earned a doctorate in anthropology. Marjorie is a wife and devoted mother. JHG was content to have the children select their own careers and, of course, to establish their own reputations.

One of JHG's major personality traits was his innate ability to draw others to him by means of the force of his personality—his charisma. He loved being with groups of people. He and Maly frequently invited friends and colleagues to their home, wherever that happened to be at the time. They entertained his residents and their wives, foreign visitors, and distinguished surgeons from all over the world. Their style of entertaining was, although extremely warm, highly casual. Visitors might see that the grass had not been cut for several weeks, or that the ceiling plaster in the dining room was loose in one spot and might come falling down onto someone's head if laughter was too loud. None of these domestic details were even alluded to in the form of apology or excuse; they simply didn't exist as deterrents to an active social life for the Gibbons.

Colleagues indicated that JHG frequently stated that he intended to cut down or stop smoking, and to eliminate drinking alcohol. Over the years, his tolerance for hard liquor had become almost legendary, perhaps beginning in his Princeton years with the bootleg whiskey. At the same time, no one recalls ever seeing him intoxicated. Smoking and drinking were quite acceptable behaviors in the period of the 1920s to the 1960s. Early on, he was aware that smoking was a likely cause of lung cancer; this knowledge, however, was not a sufficient impetus for him to stop smoking.

Only two persons of those contacted by this author refused to partici-

pate in this project: one was a person who had been out of touch with JHG for many years; the second was a physician and former resident under JHG who has negative feelings about Gibbon. Evidence of contradictory attitudes toward JHG occurred occasionally, although the majority of his long-time colleagues and friends indicated that he was a real human being, having both lovable and very few not-so-lovable traits. The characteristics that tend to be most obvious are his active intellect and his deep and abiding study of philosophical issues. Although he left very little written information about himself as a person or about his concerns, his few poems tend to illuminate his deeper thoughts. His poem about boxes is revealing:

> The boxes line up row on row
> In and out of boxes all our lives
> The womb's a box
> The coffin, too
> Big concrete slabs pushing to the skies
> Filled with boxes
> Inside the box, softness lies here and there
> To cushion our bodies in chairs and lounges
> To hold our bodies in gentle sleep
> As we coast down hill from cradle to the grave.
> 'Tis not the compass that we box
> In looking for direction
> Enough! we cry. A pox
> On all your correction.[7]

His attempts to find ways of expressing himself—his inner self, which he had begun cultivating in his late teens and early twenties—such as portrait painting and poetry, met with failure and frustration because he had little time to develop these modes of self-expression while pursuing his busy and demanding professional career. By the time he came to them, following retirement, he was not prepared to paint or to write poetry very well. In a sense, he died within the cage that surrounded him, never having been able to break out and mingle with others on a level that would have ensured total human contact and sharing. Because of his stature, people hesitated to approach him; because of his inability to reach out, he did not draw others close to him.

His intellectual life sustained him enormously, for instance, the capabilities he brought to his position as editor of the *Annals of Surgery* and his lifelong love of reading, particularly material of a philosophical nature

that allowed him to think about universal questions. These questions still prodded his mind up to his death, as indicated in what probably was the last poem he wrote:

> Having lived 68 years
> I don't know what I am, why
> I am, or where I am.
> I only know that here I am,
> Now, this instant of time,
> This no-dimensional dot
> In the geometry of the universe.[7]

He lived at a time when psychiatry, psychoanalysis, and psychotherapy were suspect—not yet quite accepted by other professional disciplines. Whatever benefit he might have derived from these sources was closed to him, largely by his own choice. He considered it a sign of weakness to admit to needing help; he needed to be totally self-sustaining and internally invincible. However, this attitude was prominent among most people at that time, particularly men in positions equal to his. It is interesting to note that Maly and two of his four children selected psychology and counseling as careers.

As with many people, regardless of their degree of productivity during life, JHG was not satisfied with his accomplishments and felt that he could have or should have done more.[7] By the time he retired, however, he accepted what he had done as being the most that he could do, given the environment and circumstances within which he lived and worked. Several years after he retired, in fact, his daughter Alice asked him whether he missed the old life—the involvement in professional organizations, the perpetual meetings, the presentation of papers, his surgical practice. His answer was no, that he had reached the phase of his life where it seemed right to retire. His long-time colleague, Camishion, said that when JHG retired, he "made a clean break." His vast amount of energy was probably beginning to wane as he reached 65. As a prominent surgeon, he was perpetually "on stage," which consumes a great deal of energy. His constant search for perfection took added energy. Since his youth, he had run on "full charge" in everything he did—walking the forty miles from Princeton to Spruce Street, pursuing his educational goals, performing intricate surgery, overseeing the care of countless patients, doing and then supervising the animal experiments, working with colleagues, serving as president or in other high offices in many professional organizations, traveling in connec-

tion with his work, and playing chess and tennis. Even a battery as highly charged as his had to begin running down at some point.

Was he a happy person? Probably not entirely, in light of the few rare glimpses he allowed of himself. While his work and interactions with colleagues certainly brought him a measure of satisfaction and pleasure, his innate aloofness from people, his inability to "connect" with others, and his inability to express his deepest thoughts and feelings were a source of frustration and discontent, the greatest pathos being the fact that he did not recognize the cause of his dissatisfaction with himself and with his life. He so readily assumed his "social face" when in groups, which led him to think that he was interacting fully with others. He did not recognize his social face as a mask, or the fact that most of his interactions were not at a deeply satisfying level. He was popular and well liked, sought after and highly respected by his colleagues; it is not surprising that he was unable to fathom the real source of his dissatisfaction, or to take steps that might have been helpful toward bridging the gap between himself and others.[7]

Despite his judgment about himself regarding his accomplishments, which he felt could have been more, perhaps the judgment of others is more valid and, very likely, more accurate, both during his lifetime and since his death. It is natural for us to want those having great gifts to also be happy and satisfied with their accomplishments. The fact that JHG was not completely happy and not fully satisfied with his life's work does not, nor should not, detract from it. He contributed more to his profession than most of us are able to do. Throughout his life, he maintained his intellectual honesty and high ethical integrity. He gave of himself as much as he could—to his family, his patients, his professional obligations, his volunteer work, his fellow man. He was open and unbiased regarding ideas and people from other cultures, races, and ethnic backgrounds. He did not harbor grudges, and was not mean-spirited. Few of us can contribute as much as JHG did, and accept as little in return.

In July 1972 JHG suffered his first heart attack, from which he recovered rapidly. In November, he gave what was probably his last presentation, about the development of the pump oxygenator at Baylor College of Medicine in Houston, Texas. Determined not to be a cardiac invalid or to play the "sick role," JHG resumed his usual activities, including tennis. It was on the tennis court that his second heart attack occurred, causing him to die almost instantly on February 5, 1973 at age sixty-nine. His family and friends agreed that he died exactly as he would have wished, still active physically and mentally.

Afterword

After JHG's death, Maly continued to live at Lynfield Farm. She welcomed family, guests, and visitors for a meal, a day, or weeks. She continued in her work as marriage and family counselor, and vacationed in the Caribbean as before. She contemplated writing a book about the heart-lung machine and their work on it. In this regard, she contacted several friends who were publishers, and friends who she thought would be helpful in structuring the book. But although she developed an outline and wrote some introductory pages, she did not continue her efforts. Her personal papers did contain these early writings with, in particular, a detailed account of the day JHG remained with the patient who developed the pulmonary embolism which, in turn, stimulated his idea for a heart-lung machine. A detailed description of a typical day in the animal laboratory in the 1930s was also among her personal papers.

One of the friends Maly contacted in reference to the possibility of her writing a book was publisher Lovell Thompson from Massachusetts; they had been friends from before her marriage to JHG. They renewed their friendship, found that they had many interests in common, and were married September 16th, 1978 in Manchester, Massachusetts. They lived in nearby Ipswich until her death from cancer of the esophagus in 1987.

Lynfield Farm was sold in 1980. The house is still there, but the surrounding property was subdivided and houses were built on these parcels of land.

The children remain close, are frequently in touch with one another, and try to spend every August together on Martha's Vineyard.

As he had hoped, JHG left a legacy that is a product of his own creative genius.

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Summing Up: JHG the Man

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Glossary

A

A, AB, A pump—arterial pump.

ABI—arterial blood inlet.

ABO—arterial blood outlet.

AC—artificial circulation.

acacia—gum arabic. A dried, gummy exudation from the tree *Acacia senegal,* used as a suspending agent or vehicle in pharmaceutical or industrial products.

acid-base balance—the mechanisms by which acids and alkalis are kept in a state of equilibrium so that the hydrogen ion concentration of the arterial blood is maintained in the pH range 7.35 to 7.45. This is accomplished by action of buffer systems of the blood and the regulatory (homeostatic) functions of the respiratory and urinary systems. Disturbances in acid-base balance result in acidosis or alkalosis.

air cushion—a volume of air that acts to prevent undue pressure of substance (fluid, air) upon the vein or artery.

anoxia—absence or lack of oxygen; level of oxygen in body below physiologic parameters.

apnea—cessation of breathing.

art. can.—arterial cannula.

art. resp.—artificial respiration.

AT—arterial blood temperature.

atrium (plural, atria)—the upper chamber of each half of the heart.

auricle—term, now obsolete, previously used for "atrium" of the heart.

autogenous—originating within the body.

B

beaker—glass vessel with wide mouth for mixing or holding liquids.

BJM—Bernard J. Miller, M.D.

BP (B.P., bp)—blood pressure.

bradycardia—slowness of the heart rate to less than 60 beats/min.

BT—blood temperature.

C

C—Celsius, or centigrade, temperature scale.

cannula, can. (Latin, a small reed)—A tube or sheath enclosing a trocar, the

tube allowing the escape of fluid after withdrawal of the trocar from the body.

caudad—toward the tail; in a posterior or downward direction.

cc—cubic centimeter(s).

CD—Clarence Dennis, M.D.

cephalad—toward the head.

cm—centimeter(s).

CO_2—carbon dioxide.

comp. (comp), C—compression (of the clamp on the pulmonary artery).

CR, comp release—complete release of the pressure of the clamp on the pulmonary artery.

cot, finger—similar to a rubber condom, of a size small enough to fit snugly on an adult's finger.

D

d, diam, dm—diameter.

DKR—Donald K. Rex, IBM engineer who worked on Model II and Model III.

drum—kymograph drum (see kymograph).

dyspnea—difficult or labored breathing.

E

ECC—extracorporeal circulation; artificial circulation; circulation carried on outside the body.

empyema—accumulation of pus in the thoracic (unless designated elsewhere, e.g., abdominal) cavity of the body.

exertional dyspnea—dyspnea provoked by physical effort or exertion.

ext. d, dm, diam—external diameter.

F

FFA—Frank F. Allbritten, Jr., M.D.

flask—small bottle with a narrow neck.

G

GJH—George J. Haupt, M.D.

H

hematocrit—volume of erythrocytes (red blood cells) packed by centrifugation in a given volume of blood. The hematocrit is expressed as the percentage of total blood volume which consists of erythrocytes or as the volume in cubic centimeters of erythrocytes packed by centrifugation of blood. Normal values at sea level: Men—average, 47%, range 40–54%; women—average, 42%, range 37–47%; children—range 35–49%.

hematoma—a swelling or mass of blood (usually clotted) confined to an organ, tissue, or space and caused by a break in a blood vessel.

hemoglobin—the iron-containing pigment of the red blood cells. Its function is to carry oxygen from the lungs to the tissues. Amount of

hemoglobin in the blood averages 12–16 gm/100 ml of blood in adult females; 14–18 gm in males. One gm of hemoglobin can combine with 1.36 cc of oxygen, the resulting compound being oxyhemoglobin.

hemolysis—destruction of red blood cells with the liberation of hemoglobin which diffuses into the fluid surrounding them.

H_2O—water.

Hg—mercury.

Ht, hrt—heart.

I

in—inch.

int, d, diam, dm—internal/interior diameter.

intraperitoneal, i.p.—within the peritoneal (abdominal) cavity.

J

Jefferson—Jefferson Medical College.

JHG, Jr., JHG—John Heysham Gibbon, Jr., M.D.

JHG, Sr.—John Heysham Gibbon, M.D.—JHG's father.

JMC—Jefferson Medical College; JMCH—Jefferson Medical College Hospital.

jug.—jugular vein.

JYT—John Y. Templeton III, M.D.

K

kymograph—an apparatus for recording movements of a writing pen. The apparatus is designed so that the pen moves in response to force applied to it. Widely used in physiology to record activities such as blood pressure changes, muscle contractions, respiratory movements, etc. Consists of a drum rotated by a spring or electric motor. Drum is covered by a paper upon which the record is made.

L

L, lt—left.

Lutembacher's syndrome—a congenital cardiac abnormality consisting of a defect of the interatrial septum, mitral stenosis, and enlarged right atrium.

M

m, mk—mark (on the kymograph record).

manometer—device for determining liquid or gaseous pressure.

mg—milligram. One-thousandth of a gram.

ml, (mL)—milliliter. One-thousandth of a liter, or 1 cc.

mm—millimeter(s).

N

nystagmus—rhythmical oscillation of the eyeballs, either horizontal, rotary, or vertical.

O

O, O_2, o-gen—oxygen.

ophthalmoscope—instrument for examining interior of the eye, especially the retina.

orthopnea—inability to breathe except in an upright position.

P

PA (p.a.)—pulmonary artery.

perfusion—supplying an organ or tissue with nutrients and oxygen by injecting blood or a suitable fluid into an artery.

pp (p.p.)—perfusion pump.

R

R—revolution(s).

RCC—Rudolph C. Camishion, M.D.

rpm—revolution(s) per minute.

Rt (rt), R (r)—right.

RT—rectal temperature.

S

saline (solution, physiologic)—a solution of sodium chloride and distilled water. A 0.9% solution of sodium chloride is an isotonic solution. A normal saline solution consists of 0.85% salt solution, which is necessary to maintain osmotic pressure and the stimulation and regulation of muscular activity.

SR (S.R.)—saline reservoir.

stromuhr—device for measuring velocity of blood flow.

T

TLS—T. Lane Stokes, M.D.

Traube-Hering waves (or curves)—slow oscillations in blood pressure usually extending over several respiratory cycles; related to variations in vasomotor tone; rhythmical variations in blood pressure.

V

VB—venous blood, or venous blood pump.

VBI—venous blood inlet.

VBO—venous blood outlet.

VBT—venous blood temperature.

v.c.—vena cava.

vena cava (plural, venae cavae)—the principal veins (superior, inferior) draining venous blood from the upper and the lower parts of the body; empty directly into the right atrium of the heart.

ven. can.—venous cannula.

W

WB—water bath.

WT—water temperature.

Z

zephiran—brand name for refined benzylkonium chloride, an antiseptic solution widely used in the 1940s to 1960s but largely replaced now with newer compounds.

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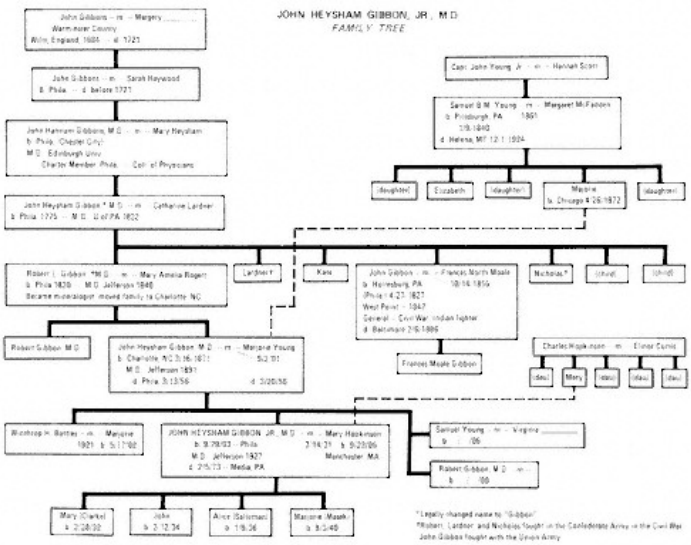
Appendix



Genealogy of the Gibbon Family

Chronology of the Life of John Heysham Gibbon, Jr.

1903	born September 29, Philadelphia.
1919	graduated from Penn Charter School, Philadelphia.
1923	A.B., Princeton University, Princeton, New Jersey.
1927	M.D., Jefferson Medical College, Philadelphia.
1927–1929	Internship, Pennsylvania Hospital (11/27–11/29).

The 1930s

1930–1931	Research Fellow in Surgery, Harvard Medical School.
1930	Middleton R and Gibbon JH, Jr. The prognostic value of the initial leukocyte and differential count in lobar pneumonia. *American Journal of Medical Science*, No. 1, clxxx: 31, July.
	Gibbon JH, Jr. and Churchill ED. Changes in the pulmonary circulation induced by experimentally produced arteriovenous fistula. *Arch Surg, 21:*1188.
1931	March 14. Married Mary Hopkinson.
1931	Gibbon JH, Jr. and Churchill ED. Mechanical influence of the pericardium on cardiac function. *J Clin Invest, 10:*405.
1931–1932	Fellow in Medicine, School of Medicine, University of Pennsylvania.
1931–1937	Assistant Surgeon, Pennsylvania Hospital.
1932	February 28. Birth of first child, Mary.
1932	Gibbon JH, Jr., Hopkinson M, and Churchill ED. Changes in the circulation produced by gradual occlusion of the pulmonary artery. *J Clin Invest, 11:*543.
1932	Gibbon JH, Jr. and Landis EM. Vasodilatation in the lower extremities in response to immersing the forearms in warm water. *J Clin Invest, 11:*10019.
1933	Landis EM and Gibbon JH, Jr. The effects of temperature and tissue pressure on the movement of fluid through the human capillary wall. *J Clin Invest, 12:*105.
1933	Landis EM and Gibbon, JH, Jr. Effects of alternate suction and pressure on circulation in the lower extremities. *J Clin Invest, 12:*593.
1933	Landis EM and Gibbon JH, Jr. A simple method of producing vasodilatation in the lower extremities. *J Clin Invest, 12:*785.

1933 Landis EM and Gibbon JH, Jr. The effects of alternate suction and pressure on blood flow to the lower extremities. *J Clin Invest, 12:*925.

1934 February 12. Birth of son John.

1934 Gibbon JH, Jr. Actinomyocosis of abdominal wall. *Ann Surg, 99:*861.

1934 Flick JB and Gibbon JH, Jr. Pericardectomy for advanced Pick's disease. *Arch Surg, 20:*126.

1934–1935 Research Fellow in Surgery, Harvard Medical School.

1935 May 10. First successful attempt to use the heart-lung machine as substitute for cardiac and respiratory functions in animal (cat).

1936 January 9. Birth of second daughter, Alice.

1936 Flick JB and Gibbon JH, Jr. Total removal of the left lung for carcinoma. *Ann Surg, 103:*130.

1936–1942 Harrison Fellow of Surgical Research, School of Medicine, University of Pennsylvania.

1936–1942 Assistant Surgeon, Bryn Mawr Hospital.

1936 Flick JB and Gibbon JH, Jr. The application of thoracoplasty to the treatment of pulmonary tuberculosis. *Penna Med J, 39:*768.

1936 Gibbon JH, Jr. and Churchill ED. The physiology of massive pulmonary embolism—An experimental study of the changes produced by obstruction in the flow of blood through the pulmonary artery and its lobar branches. *Ann Surg, 104:*811.

1937 Gibbon JH, Jr. Artificial maintenance of the circulation during experimental occlusion of the pulmonary artery. *Arch Surg, 34:*1105.

1937 Flick JB and Gibbon JH, Jr. Hyperparathyroidism relieved by removal of a parathyroid tumor. *Bull Ayer Clin Lab of U of Pa Hosp, 3:*73.

1937–1950 Surgeon, Pennsylvania Hospital.

1938 Certified, American Board of Surgery.

1939 Gibbon JH, Jr. Pulmonary embolism: A review of recent contributions. *Penn Med J, 42:*77.

1939 Gibbon JH, Jr. The immediate effect of scalenectomy upon the size of apical tuberculosis cavities. *J Thorac Surg, 9:*633.

1939 Gibbon JH, Jr. An oxygenator with a large surface volume ratio. *J Lab Clin Med, 24:*1192.

1932 Gibbon JH, Jr. The maintenance of life during experimental occlusion of the pulmonary artery followed by survival. *Surg Gynecol Obstet, 69:*602.

1939 Gibbon JH, Jr. and Smith H. Blood chemical aids to surgical therapy. *Surg Clin NA,* December.

The 1940s

1940 Weinberger LM, Gibbon MH, and Gibbon JH, Jr. Temporary arrest of the circulation to the central nervous system. I. Physiologic effects. *Arch Neurol & Psychiat, 43:*615.

1940 Weinberger LM, Gibbon MH, and Gibbon JH, Jr. Temporary arrest of the circulation to the central nervous system. II. Pathologic effects. *Arch Neurol & Psychiat, 43:*961.

1940 September 3. Marjorie born.

1940–1942 Major, Medical Corps (MC), Army of the United States (AUS) (Reserves).

1941 Gibbon JH, Jr. and Kraul CW. An efficient oxygenator for blood. *J Lab Clin Med, 26:*1803.

1941 Gibbon JH, Jr. and Hodge CC. Aseptic immediate anastomosis following resection of the colon for carcinoma. *Ann Surg, 114:*635.

1941 Gibbon JH, Jr. and Hodge CC. The treatment of minor war injuries. The Military Surgeon. *Med Clin of NA,* November.

1941 Allbritten FF, Jr., Flick JB, and Gibbon JH, Jr. The use of sulfanilamide in resection of the lung. *J. Thorac Surg, 11:*107.

1942 Gibbon JH, Jr., Gibbon MH, and Kraul CW. Experimental pulmonary edema following lobectomy and blood transfusion. *J Thorac Surg, 12:*60.

1942 Gibbon JH, Jr. and Gibbon MH. Experimental pulmonary edema following lobectomy and plasma infusion. *Surgery, 12:* 694.

1942–1944 Major, Medical Corps, AUS. Stationed in New Caledonia, South Pacific.

1944 Promoted to Lieutenant Colonel, April.

1945 Chief of Surgical Service, Mayo General Hospital, Galesburg, Illinois, January–October.

1946 Expiration of terminal leave from Medical Corps, 2 February.

1945–1946 Assistant Professor of Surgery, School of Medicine, University of Pennsylvania, December 1945–January 1946.

1946 Gibbon JH, Jr. and Freeman L (Capt., MC, AUS). The primary closure of decubitus ulcers. *Ann Surg, 124:*1148.

1945–1954 Member of Council, American Association for Thoracic Surgery.

1946 Gibbon JH, Jr. The Army doctor comes home and looks at civilian practice. *Harper's:*175–180, February.

1946–1956 Professor of Surgery and Director of Surgical Research, Jefferson Medical College, January 1946–May 1956.

1946–1956 Attending Surgeon, Jefferson Medical College Hospital, January 1946–May 1956.

1947–1957 Chairman, Editorial Board, *Annals of Surgery*.

1948 Gibbon JH, Jr., Clerf LH, Herbut PA, and DeTuerk JJ. The diagnosis and operability of bronchiogenic carcinoma. *J Thorac Surg, 17:*419.

1948 Gibbon JH, Jr. A trip to Europe. *Clinic.* Philadelphia: Jefferson Medical College.

1949 Templeton JY, III and Gibbon JH, Jr. Experimental reconstruction of cardiac valves by venous and pericardial grafts. *Ann Surg, 129:*161.

1949 Gibbon JH, Jr. Cancer of the lung. *Trans & Studies Coll of Phys of Phila, 17*(2).

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1949 Gibbon JH, Jr. and Stayman JW, Jr. The physiology of cardiac surgery. *Surg Clin of NA,* December.

The 1950s

1950 Certified, Board of Thoracic Surgery.

1950–1964 Fellow and Member of Board of Governors, American College of Surgeons.

1950 Allbritten FF, Jr., Lipshutz H, Miller BJ, and Gibbon JH. Blood volume changes in tuberculous patients treated by thoracoplasty. *J Thorac Surg, 19:*71.

1950 Goldstein F, Gibbon JH, Jr., Allbritten FF, Jr., and Stayman JW, Jr. The combined manometric determination of oxygen and carbon dioxide in blood in the presence of low concentrations of ethyl ether. *J Biol Chem, 182*(1):815.

1950 Gibbon JH, Jr., Stayman JW, Jr., and Allbritten FF, Jr. Controlled respiration in thoracic surgery. *Internat J Surg,* April.

1950 Healey JE, Jr. and Gibbon JH, Jr. Recent advances in the surgical treatment of carcinoma of the esophagus. *Penna Med J, 53:*811.

1950 Stokes TL and Gibbon JH, Jr. Experimental maintenance of life by a mechanical heart and lung during occlusion of the venae cavae followed by survival. *Surg Gynecol Obstet, 91:*138.

1950 Gibbon JH, Jr. Carcinoma of the lung with an analysis of symptoms and end results in 243 cases. *Bull Chic Med Soc.*

1950 Gibbon JH, Jr., Allbritten FF, Jr., Stayman JW, Jr., and Judd JM. A clinical study of respiratory exchange during prolonged operations with an open thorax. *Ann Surg, 132:*611.

1950 Gibbon JH, Jr. Machines that work like men. Frontiers in Medicine. *The March of Medicine.* New York: Columbia University Press.

1950–1967 Consulting Surgeon, Pennsylvania Hospital.

1950 Gibbon JH, Jr. Controlled respiration in thoracic and upper abdominal operations. *Minn Med, 33:*1031.

1950–1967 Consultant in General Surgery, Veterans Administration Hospital, Philadelphia.

1950 Allbritten FF, Jr. and Gibbon JH, Jr. Bronchiectasis. *Cyclopedia of Med, Surg Specialites, 2:*751.

1951 Gibbon JH, Jr, Allbritten FF, Jr., and Templeton JY, III. Carcinoma of the esophagus and gastric cardia. *JAMA, 145:*1035.

1951 Gibbon JH, Jr. An extracorporeal circulation for the temporary maintenance of the cardiorespiratory functions. *Congres de la Societe Internationale de Chirurgie.*

1951 Finley RK, Jr., Templeton JY, III, Holland RH, and Gibbon JH, Jr. Changes in urine and serum electrolytes and plasma volumes after major intrathoracic operations. *J Thorac Surg, 22:*219.

1951 Miller BJ, Gibbon JH, Jr., and Gibbon MH. Recent advances in the development of a mechanical heart and lung apparatus. *Ann Surg, 134:*694.

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1953 Gibbon JH, Jr. and Nealon TF, Jr. *Cancer of the lung.* Sharp & Dohme Seminar, Philadelphia.

1953–1956 Member, Examination Committee for Surgery. National Board of Medical Examiners.

1953–1956 Member, Subcommittee on Cardiovascular System, National Research Council.

1953–1956 Member, Advisory Committee on Research on the Therapy of Cancer, American Cancer Society.

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septal defects under direct vision with the assistance of an extracorporeal pump oxygenator circuit. *J Thorac Surg, 26:*598.

1953 John Scott Award, Board of Directors of City Trusts of Philadelphia.

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1955–1956 Vice Chairman, American Board of Surgery.

1955 Nealon TF, Jr., Haupt GJ, Price JE, and Gibbon JH, Jr. Pulmonary ventilation during open thoracotomy: Inflation and deflation time ratios and pressures. *J Thorac Surg, 30:*665.

1955 Gibbon JH, Jr., Stokes TL, and McKeown JJ, Jr. Surgical treatment of carcinoma of the lung. *Am J Surg, 89:*484.

1955 Gibbon JH, Jr. The education of a surgeon. Presidential Address, The American Surgical Association. *Ann Surg, 142:*321.

1956 George A. Ball Visiting Professor of Surgery, Indiana University.

1956 Churchill Lecture, Excelsior Surgical Society.

1956 March 13, 20. Deaths of father, mother.

1956 Gibbon JH, Jr. and Engell HC. Congenital malformations of the heart and great vessels. Chapter in Cole's *Operative Technic*, New York: Appleton-Century-Crofts.

1956 Gibbon JH, Jr., Nealon TF, Jr., and Greco VF. A modification of Glassman's gastrostomy with results in 18 patients. *Ann Surg, 143:*838.

1956 Nealon TF, Jr., Haupt GJ, Chase H, Price JE, and Gibbon JH, Jr. Inefficient carbon dioxide absorption requiring increased pulmonary ventilation during operation with an open thoracotomy. *J Thorac Surg, 32:*464.

1956–1967 Samuel D. Gross Professor of Surgery and Head of the Department of Surgery, Jefferson Medical College and Hospital.

1956–1967 Attending Surgeon-in-Chief, Jefferson Medical College and Hospital.

1956–1958 President, Philadelphia Academy of Surgery.

1957 Charles Mickle Fellowship, University of Toronto.

1957 Clarence E. Shaffrey, S. J. Medal, St. Joseph's College Medical Alumni.

1957 Gibbon JH, Jr. and Nealon TF, Jr. Carcinoma of the lung and tumors of the thorax. Chapter 4d, *Surgery, Principles and Practice*. Eds. Allen, Harkins, Moyer and Rhoads. Philadelphia: Lippincott.

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1958 Connor Memorial Lecture, American Heart Association.

1958 Harvey Lecture, New York Academy of Medicine.

1958 Rudolph Matas Award in Vascular Surgery, Tulane University.

1958–1960 Member of Council, Philadelphia Academy of Surgery.

1958 Gibbon JH, Jr. and Templeton JY, III. Current status of pump oxygenator in cardiac surgery and persistent problems in their use. *Progress in Cardiovasc Dis, 1:*56.

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1958 Nealon TF, Jr., Chase HF, and Gibbon JH, Jr. Factors influencing carbon dioxide absorption during anesthesia. *Anesthesiology, 19:*75.

1958–1959 President, Heart Association of Southeastern Pennsylvania.

1958–1961 Member, Committee on International Exchange of Persons.

1959–1960 Vice-President, American Association of Thoracic Surgeons.

1959 Distinguished Service Award, International Society of Surgery.

1959 Honorary Fellow, Royal College of Surgeons of England.

1959–1963 Member, Editorial Board, *Circulation Research*.

1959–1965 Member, Conference Committee on Graduate Training in Surgery.

1959 Schecter DC, Nealon TF, Jr., and Gibbon JH, Jr. The removal of excessive potassium and ammonium from bank blood prior to transfusion. *Surg Gynecol Obstet, 108:*1.

1959 Schecter DC, Nealon TF, Jr., and Gibbon JH, Jr. An ion exchange resin artificial kidney. *Surg Forum, IX:*110.

1959 Gibbon JH, Jr. Extracorporeal maintenance of cardiorespiratory functions. Harvey Lecture No. 53, May 15, 1958. Chapter 9: *The Harvey Lecture Series*.

1959 Gibbon JH, Jr. Maintenance of cardiorespiratory functions by extracorporeal circulation. Lewis A. Connor Memorial Lecture, American Heart Association. *Circulation, 19:*646.

1959 Ballinger WF, II, Haupt GJ, Hering N, and Gibbon JH, Jr. Technique for sampling mixed hepatic venous blood in dogs. *Surgery, 46:*806.

1959 Nealon TF, Jr., Cathcart RT, Fraimow W, McLaughlin ED, and Gibbon JH, Jr. The effect of mean endotracheal pressure on the cardiac output of patients undergoing intrathoracic operations. *J Thorac Surg, 38:*449.

1959 McLaughlin ED, Nealon TF, Jr., and Gibbon JH, Jr. A cation exchange artificial kidney. *Trans Amer Soc Artif Intern Org, 5:*8.

1959 ScD (Hon.) University of Buffalo.

1959 Taub Visiting Professor of Surgery, Baylor Medical College.

The 1960s

1960 Visiting Professor of Surgery, Harvard Medical School.

1960 Gairdner Foundation International Award, University of Toronto.

1960 Ballinger WF, II, Gibbon JH, Jr., Templeton JY, III, and Nealon TF, Jr. The complications of esophageal hiatal hernia. *Penna Med J, 63:*51.

1960 Haupt GJ, Camishion RC, Templeton JY, III, and Gibbon JH, Jr. Treatment of malignant pleural effusions by talc poudrage. *JAMA, 172:*918.

1960 Fineberg C, Foris NP, and Gibbon JH, Jr. Experimental sham coronary endarterectomy with and without coronary artery perfusion. *Surgery, 47:*160.

1960 Gibbon JH, Jr. and Nealon TF, Jr. Principles of pre- and postoperative management in the treatment of neoplasms of the chest. Chapter: *Treatment of Cancer and Allied Diseases, 2nd Edition*. Eds. Pack and Ariel. New York: Paul B. Hoeber, Inc.

1960 Fineberg C, Cohn HE, and Gibbon JH, Jr. Cardiac arrest during nasotracheal aspiration. *JAMA, 174:*410.

1960 Gibbon JH, Jr. and Nealon TF, Jr. Complications of pulmonary resection. Chapter: *Complications in Surgery and Their Management*, Eds Artz and Hardy. Philadelphia: Saunders.

1960 Gibbon JH, Jr. and Nealon TF, Jr. Physiological effects of pulmonary ventilation during operations under general anesthesia. *Surg Clin NA, 40:*1491.

1960 McLaughlin ED, Nealon TF, Jr., and Gibbon JH, Jr. Treatment of bank blood by resins. *J Thorac Cardiovasc Surg, 40:*602.

1960–1964 Member, Board of Scientific Counselors, National Heart Institute.

1960–1973 Member, Awards Committee, The Gairdner Foundation.

1961 Nealon TF, Jr., Templeton JY, III, Cuddy VD, and Gibbon JH, Jr. Instrumental perforation of the esophagus. *J Thorac Cardiovasc Surg, 41:*75.

1961 Gibbon JH, Jr. Two views of the specialty boards: A) A surgeon's view. Chapter 7: Report of the Second Institute on Clinical Teaching, Association of American Medical Colleges, Chicago, October 27–31, 1959, Part 2. *J Med Ed,* April.

1961 Gibbon JH, Jr. The road ahead for thoracic surgery. Presidential Address, American Association of Thoracic Surgery. *J Thorac Surg, 42:*141.

1961 Camishion RC, Templeton JY, III, and Gibbon JH, Jr. Leiomyosarcoma of the esophagus: Report of two cases and a review of the literature. *Ann Surg, 153:*951.

1961 Camishion RC, Ota Y, and Gibbon JH, Jr. Blood flow through the superior mesenteric artery with antegrade and retrograde refusion of the aorta. *Circ, 24:*900.

1961 Gibbon JH, Jr. What's new in anesthesia and pulmonary problems. *Surg Gynecol Obstet, 112:*223.

1961 Ota Y, Camishion RC, and Gibbon JH, Jr. Pulmonary arterial blood flow through an acutely atelectatic lung. *J Thorac Cardiovasc Surg, 42:*599.

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1961 Gibbon JH, Jr. Bronchoesophagology and thoracic surgery: The team effort. *Trans Amer Broncoesoph Assoc:*19.

1961 ScD(Hon.) Princeton University.

1961–1963 Chairman, Conference Committee on Graduate Training in Surgery.

1961–1963 Philadelphia County Medical Society: Alternate Delegateat-Large, Pennsylvania Medical Society.

1961 Honorary Member, Society of Thoracic Surgeons of Great Britain and Ireland.

1962 Distinguished Service Award, Pennsylvania Medical Society.

1962 Alvarengo Prize and Lectureship, College of Physicians of Philadelphia.

1962 Arthur Dean Bevan Lecture, Chicago Surgical Society.

1962 Gibbon JH, Jr. Cardiorespiratory dynamics with an intact thorax. Chapter: *Surgery of the Chest.* Ed. JH Gibbon, Jr. Philadelphia: Saunders.

1962 Gibbon JH, Jr. Postoperative management. Chapter: *Surgery of the Chest.* Ed. JH Gibbon, Jr. Philadelphia: Saunders.

1962 Gibbon JH, Jr. and Camishion RC. The esophagus. Chapter: *Surgery of the Chest.* Ed. JH Gibbon, Jr. Philadelphia: Saunders.

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1962 Camishion RC, Gibbon JH, Jr., and Nealon TF, Jr. Talc poudrage in the treatment of pleural effusion due to cancer. *Surg Clin NA, 42:*1521.

1962 Gibbon JH, Jr. The future of cardiac surgery. *Conference on Cardiac and Vascular Surgery,* New York Heart Association: 34, January.

1962 Honorary member, Chicago Surgical Society.

1963 Strittmatter Award, Philadelphia County Medical Society.

1963–1964 President, Pennsylvania Association for Thoracic Surgery.

1963 Gibbon JH, Jr. Remarks made on receipt of the Strittmatter Award of the Philadelphia County Medical Society, May 15, 1963. *Phila Med, 59:*913.

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1963 Camishion RC, Scicchitano LP, Trotta R and Gibbon JH, Jr. Blood flow through the superior mesenteric artery during retrograde perfusion. *Surgery, 54:*651.

1964 The Philadelphia Award.

1964–1973 Member, Board of Trustees, The Philadelphia Award.

1964–1967 President, College of Physicians of Philadelphia.

1964 Gibbon JH, Jr. and Camishion RC. Problems in hemostasis with extracorporeal apparatus. *Ann NY Acad Sci, 115:*195.

1965 Gibbon JH, Jr. Presidential Address. *Trans & Studies Coll of Phys of Phila, 32:*149.

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1965 Member, International Cardiovascular Society.

1965 ScD(Hon.) University of Pennsylvania.

1965 Research Achievement Award, American Heart Association.

1966 Chairman, Research Committee, Heart Association of Southeastern Pennsylvania.

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1966 Gibbon JH, Jr. Clinical diagnosis of lung cancer including bronchoscopy. Special Graduate Course on Cancer for Latin American Physicians. American Cancer Society, New York.

1966 Roswell Park Medal.

1967 Gibbon JH, Jr. and Nealon TF, Jr. Complications of pulmonary resection and thoracoplasty. Chapter, Hardy & Artz: *Complications in Surgery, 2nd ed.* Philadelphia: Saunders.

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1967 Member, American Academy of Arts and Sciences.

1967 ScD(Hon.) Dickinson College.

1967 Barney Brooks Visiting Professor of Surgery, Vanderbilt University.

1967 Gibbon JH, Jr. The early development of an extracorporeal circulation with an artificial heart and lung. Guest Lecture, Chicago: Sixth Annual Meeting, American Society for Artificial Internal Organs. *Trans, ASAIO, VIII:*77.

1968 Gibbon JH, Jr. Human heart transplantation. *Bull Jeff Alumni Assn,* Summer.

1968 Albert Lasker Clinical Research Award.

1969 Gibbon JH, Jr. Building a heart-lung machine. *RN:*34a–e, July.

1969 LL.D(Hon.) Jefferson Medical College.

The 1970s

1970 Gibbon JH, Jr. Foreword, Kennedy: *support of the Failing Circulation: The Use of a Heart-Lung Machine in Clinical Cardiac Failure.* New York: Charles C. Thomas Company.

1970 Gibbon JH, Jr. The development of the heart-lung apparatus. *Review of Surgery.*

1970 ScD(Hon.) Duke University.

1971 Trip to Russia, August.

1972 Dixon Prize in Medicine, University of Pennsylvania.

1972 First myocardial infarction, July.

1972 Lecture at Baylor University Medical College, Houston, November 17.

1973 Died of massive myocardial infarction while playing tennis, Lynfield Farm, February 5.

Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
10/10/34		Testing perfusion apparatus	3.95								
10/12/34		Testing equipment, fluid volumes, rates of flow, etc.									
10/13/34		Same, with animal	3.85	Sod. barb. i.p. (0.4 gm/kg)							
12/17/34	Obs. #1-P	Tested air pumps, blood pumps, flows, water baths for heating blood									
12/18/34	Obs. #2-P	Tested equipment as it will be used in actual animal experiments.									
12/19/34		Added new pumps, replaced parts									
12/20/34		Tested new air pump									
12/21/34		Tested volumes, pressures created by pumps									

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
12/22/34	Obs. #3-P	Tested parts, redesigned some									
12/27/34	Obs. #4-P	All equipment set up as for actual animal experiment.									
1/16/35	Obs. #5-p	Tested equipment, manometers									
1/20/35		Built control board for suction, pressure, controlling levels in cushions of blood pumps									
1/21/35	Obs. #6-P	Tested equipment									
1/22/35	Obs. #7-P	Tested equipment set up as for animal experiment. Two cats bled; tested blood compatibility between the two.									Blood of Cat #B caused agglutination when added to blood of Cat #A. No; agglutination when blood of Cat #A added to that of Cat #B
1/23/35	Obs. (no #)	Tested complete set-up. Cats anesthetized. Tested heparin in blood to determine amount needed to prevent clotting. Cats bled.	#A: 3.0; #B: 2.65	Sod. barb. (0.4 gm/kg) i.p.							

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
1/24/35		Blood collected 1/23 filtered.									Fine clots found in mixture of B cells in A blood.
2/08/35	Obs. #8-P	Tested equipment, air pressures, blood flow.									Table indicating air cushion, VBO pressure, flow rate.
2/09/35	Obs. #9-P	Tested equipment, connections, kymograph, amount of flow per second. [at end, list of things to check.]									
2/11- 12/35	#10-P	Calibration of flow of saline using various pressures in VBO.									

VA pump	Press. (VBO) cm H_2O	Flow (cc/min)
80	12	407
60	14	440
40	15	490
30	15.7	511
20	16	518 (exception!)
10	16.5	547
0	17.7	576

cm H_2O	mm
10	18.5
12	22.5
14	26.5
16	31.0
18	35.0
20	39.0

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
2/12/35	#10-P	Flow of saline timed (kept having trouble with valves, pump).									400 cc in 44.0 sec (546 cc/min); 200 cc 22.0 (545 cc/min); 350 cc 38.2 (550 cc/min)
3/12/35	#11-P	Attempt made to estimate blood flow through the artificial circ by a kymograph tracing on a fast drum of the rate of filling of the glass cup at bottom of oxygenator.									Calibration of results gave estimates of the flow 25% under actual flow. Method discarded.
3/13/35	#12-P	Maximum output of saline from AB through two #18 gauge needles was 522 cc/min. With saline flows of 380 to 390 cc/min, collection of 10 cc in glass cup at bottom of oxygenator was timed with stop-watch.									Estimated flows with stop-watch were 10%–15% under actual rate of flow. This method was thought to be sufficiently accurate for use.
3/13/35	#13-P	It was thought that one of difficulties in the animal experiments was due to the marked dilution of the blood with Acacia. The old pump system and tubing held about 200 cc of fluid.				255					New pumps and tubing were made today, containing total volume of 125 cc.

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/25/35	# 14-P	Volume of fluid in pumps reduced again. Air cushions in ABI, ABO, & VBI dispensed with. Air cushion VBO made much smaller. Animal board moved nearer pumps. AB pump & tubing now holds only 30 cc fluid & delivers 515 cc of H_2O/min. VB pump & tubing now holds 45 cc fluid & delivers 465 cc/min.									Total fluid volume in pumps & tubing = 75 cc.
		Mercury manometer in control of magnetic clamp discarded, replaced w/wire on Brodie bellows dipping into mercury cup.									New set-up controls level in glass cup at bottom of O-genator to within 5 mm.

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
4/10/35	#15-P	Both pumps revamped in order to cut down volume.									VB w/ all tubing & connections as in animal exp. hold 31 cc w/fluid near top of VBO air cushion, & 21 cc w/fluid near bottom of air cushion. AB w/ all tubing & connections as in animal exp. holds 31 cc. Total volume in pumps & tubing = 52 cc + 50 cc in oxygenator = 102 cc. ABO & VBI connected by shunt of pressure rubber tubing. Continuous circ. of fluid thru both pumps & o-genator (R = 12) maintains very even temps: WB 40–41 deg. C, fluid 37 deg. C.
5/6/35	#16-P	Flow controller of Soresi blood transfusion pump received today; its water output tested w/ maximum capacity of AA pump.									With tubing & all connections as in animal exp., maximum output only 280 cc, as compared with about 500 cc in old pump w/ rubber valves. Attempt will be made to use old rubber valves pinned in place w/ small staples.
5/7/35	#17-P	Attempt made to hold the cemented rubber flap valves in place w/ fine wires.									The wire interfered with the action of the valves and reduced output.
5/8/35	#18-P	Flap valves made by cutting thru 3/4s of the end of a rubber cork w/ a razor, making a flap about 1-1 1/2 mm thick.									This was found to be efficient & to permit large outputs thru both pumps.

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
5/13/35	#19-P	Metal cannula between 2 & 2 1/2 mm in external diameter was curved in the same manner as the glass cannulas that we have used recently.									VB was able to deliver 540 cc H_2O/min thru it. It will be used hereafter instead of glass cannulas.
6/11- 12-21/35	#20-P	In #38-A (6/10) hematocrit reading after 19 minutes of AC in a 2.6 K cat was 9% cells. Blood dilution w/ Acacia too great. Pumps (4/10) held 31 cc apiece = 62 cc in all. New pumps built using rubber tubing of 3 mm internal diameter & glass tubing of 3 mm int. diam. throughout.									VB nows hold 16 cc and delivers 600—800 cc H_2O/min. AB holds 21 cc & delivers 540 cc H_2O/min. Total volume = 37 cc—a reduction of about 1/2 their previous volume, with no reduction in output.

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Table 14 Laboratory Experiments 1934–35 (testing equipment)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
7/10, 15/35	#21-P	New VA pump received yesterday & mounted today. Same size exactly as AA. O-genator cylinder cleaned & polished (as possible cause of hemolysis).									Both pumps made slightly more compact, saving possibly 3–4 cc altogether. AB at capacity delivers 200 cc in 22.4 sec (535 cc/min).
7/19/35	#22-P	Because of persistent hemolysis since reducing size of pumps on 7/10, it was decided to enlarge glass & rubber tubing *between the valves* of both AB & VB from 3 mm to 4 mm bore.									VB w/ all connections now holds 21 cc, & through medium silver cannula delivers 350 cc in 32.2 sec (653 cc/min). AB w/ all connections now holds 20 cc & delivers 100 cc in 8.1 sec (741 cc/min). Lower magnetic clamp works to perfection. AB = arterial pump; VB = venous pump (blood from animal).

Source: JHG's laboratory notes.

Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
12/04/34	Obs. #1-A	Four cats bled. Anti-coagulant used: dry powdered sodium oxalate (0.15 gm per flask).									Clotting was quite troublesome.
12/04/34		Blood drawn on 12/4 combined in one flask, placed in ice box.									
12/08/34	Obs. #2-A	Animal experiment in which attempt was made to maintain arterial pressure while pulmonary artery clamped. Blood collected 12/4 used. Assistants: Barber and Bruno.									Failure to obtain venous blood from jugular vein fast enough by gravity alone showed that two blood pumps are needed, one to pump blood from the animal to oxygenator, and another to pump blood from oxygenator to animal.
1/24/35	Obs. #3-A	Preparation time: 3 1/2 hrs (equipment & operative work). Heparin 20 cc of 1% heparin in saline injected into cat. Clean-up time: 1 1/2 hrs.	4.2	Sod. barb. i.p.	67					From time of anesth. to R/HS: 6 hrs, 40 min.	Autopsy: Tip of cannula in superior vena cava (correct). Next: Will try introducing cannula into inferior v.c. during Drinker prep.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
1/26/35	Obs. #4-A	Second attempt to pump blood out of ext. jug. vein, oxygenate it, and reinject it into femoral artery with pulmonary artery clamped. Start: 9:45 am. End: 5:25 pm—cat died. Clean-up: 6:33 pm, except blood pumps.	3.22	Sod. barb. i.p., suppl. ether	46						Changes: 1) Heparin 2% solution in saline. 2) 1.6% solu. of sod. oxalate (2 cc instead) of 10 cc of blood.
1/28/35		Cats bled.									Heparin added, placed in flasks (labeled) in ice box.
1/29/35	Obs. #5-A	Third attempt to withdraw venous blood, oxygenate it, & return it to arterial system. AC carried out for some minutes. Time between Drinker prep & start: 4 1/2 hrs. AC time: 27 min.	3.86	Sod. barb. i.p.	42						
2/14/35 2/15/35	Obs. #6-A	2/14: Bleeding 2/15: Surgery. Start: 10:35 am End: 4:45 pm—cat died.	3.49	Sod. barb. i.p.	49						Conclusion: 1) 60 cc 1.6% sol. sod. oxalate is adequate anti-coagulant for any size cat. 2) Amount of blood in cat's circulation: 200–300 cc sufficient for average-size cat. Cat died—heart stopped.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
2/20/35	Obs. #7-A		3.63	Sod. barb	50	12	406				Cat died 1 1/2 min. after AC started. AC continued for 20 min. on dead cat with BP maintained at 60 mm Hg. Cause of death: Possible blood incompatibility
2/15/35	Obs. #8-A	5% acacia used instead of blood to avert incompatibility problem. Start: 11:00 am End: 4:34 pm—cat died in OR.	4.6		60		350 for 5 min				BP maintained at 83 mm Hg. Cause of death: insufficient venous flow.
2/27/35	Obs. #9-A	Acacia used. Start: 10:00 am End: 3:59 pm—cat died.	3.9	Sod. barb. i.p.	55						Foaming. Cat died—heart stopped. Autopsy: Tracheal cannula full of mucous. No pneumothorax. Tip of cannula in sup. vena cava about 2 cm above Rt. auricle. Lungs bright pink & fully inflated.
2/28/35	Obs. #10-A	150 mg Heparin used. Start: 8:45 am End: 1:42 pm—cat died.	3.5	Sod. barb. i.p.	58	260					1) Hereafter take a sample of blood at end of observation for hematocrit (Hct). Autopsy: No pneumothorax. Lungs pink & expanded. Tip of glass cannula in sup. v.c. about 2 cm above Rt auricle. No sizeable clots seen. Cause of death: unable to maintain adequate BP by AC.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/02/35	Obs. #11-A	Acacia solu. used, mixed with cat's own blood. Pulmonary artery partly occluded till BP falls to 20 mm Hg. Resp. stopped for 90 sec. AC on for 24 min; increased BP to 68 mm Hg; resp. resumed.	5.2		67			71%			AC stopped, started. When stopped, BP fell & respiration ceased. When started, BP rose & respiration resumed. Venous cannula became blocked after 24 min. of AC. Cat died 10 min later. Things to do: 1) Make a great many venous cannulas for differ-sized cats; put in right-angle bend. 2) Repeat Heparin every hr. (15 mg/kg).
3/15/35	Obs. #12-A	Blood withdrawn from ext. jug. vein via glass cannula & reinjected into anterior tibial arteries via large needles. Start: 10:38 am End: 4:30 pm	3.9	Sod. barb. i.p.	40						Unsuccessful. Blood leaked into water bath from rubber tubing on AB. Cat died. To do: Add suction to tracheal catheter.
3/18/35	Obs. #13-A	Mixture of blood & acacia from ext. jug. vein to anterior tibial arteries as before. Start: 10:55 am. End: 4:15 pm—cat died. Total 300 mg Heparin used.	3.95	Sod. barb. i.p.	50						Problem: withdrawing sufficient blood from venous system.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/19/35	Obs. #14-A	Procedure carried out as before but after complete occlusion of pulmonary artery, BP did not rise sufficiently when PA released. Acacia used. Start: 10:37 am End: 4:15 pm—cat died.	4.4	Sod. barb. i.p.	45						Problem: Obtaining sufficient flow from sup. v.c. Rt ventricle because distended (3:59); ventricular fibrillations occurred just before death.
3/21/35	Obs. #15-A	PA compressed for 5 1/2 min, BP gradually fell to 36 mm Hg (from 108) Start: 8:20 am End: 12:19 pm—cat died.	3.6	Sod. barb. i.p.	45						Heart was distended. Autopsy: 2 small perforations on anterior wall of v.c. & a large amount of blood in anterior mediastinum which contributed to death. Left lung: slight atelectasis. Tip of glass venous cannula in sup. v.c. just about Rt auricle.
3/26/35	Obs. #16-A	Blood withdrawn from sup. v.c. & reinjected into femoral art. (no open chest). Resp stopped 1 hr 5 min after starting AC. Acacia used & added fairly constantly. Start: 11:50 am End: 4:32—cat died.	1.9	Sod. barb. i.p.							Autopsy: Marked hemorrhagic edema of sup. mediastinum. Cause of death: 1) Too much blood loss, 2) too much acacia, 3) multiple small emboli. 4) poisoning from the copper cup in the O-genator.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/29/35	Obs. #17-A	AC without open chest. Start: 11:07 am End: 4:09 pm—cat died.	2.3	Sod. barb. i.p.							Cause of death: Loss of blood into AB pump system because of clot in the femoral artery or cannula; or: 1) IV clotting, 2) bleeding because of clot in femoral artery or cannula, 3) cat may have become acapnic because of insufficient washing through o-genator with 25% oxygen & 5% CO_2; 4) prolonged low BP; 5) blood clots in system.
4/03/35	Obs. #18-A	Purpose was to determine whether blood which had passed thru O-ator system was injurious to animal. Chest not opened. Copper cup at bottom of O-ator had been chrome-plated. Heparin 50 mg/kg. Start: 1:20 pm. End: 6:26 pm—cat died	3.5	Sod. barb. i.p.					9% cells		BP at start—132 mm Hg, resp. 30/min. AC started but obstructed by clot in filter. BP after 74 min. of AC—90 mm Hg, resps 23/min. Blood loss (undetected) into saline reservoir—cause of anemia, low BP, & subsequent death. *Presence of a filter does not appear to be necessary. No real deleterious effects from AC. Autopsy: Not remarkable. Death caused by too much blood loss.
4/06/35	Obs. #19-A	Aborted surgery. Cat ceased to breathe shortly after complete occlusion of PA. Start: 12:10 pm End: 4:22 pm—cat died.	3.2	Sod. barb. i.p.	40						Problem: Unable to obtain sufficient flow from superior vena cava.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
4/08/35	Obs. #20-A.	AC carried out for 16 min. with PA clamped. Cannulas in Rt & Lt carotid arteries & Rt jugular vein. Acacia used.	3.2	Sod. barb. i.p.	34		286	16m.	13% cells	1 hr	BP & resp. very stable during procedure. Some distention of Rt heart. AC (min) BP Resps 15 69 mm Hg 26/min Min after AC stopped: 17 112 mm Hg 47 84–118 mm Hg (Traube-Hering waves began) 65 77–112 mm Hg (Traube-Hering waves marked.) Cat killed by bleeding. Conclusion: Still too much anemia at end of Obs. because pumps require too much fluid.
4/11/35	Obs. #21-A	Unsuccessful attempt to maintain AC with PA compressed. Acacia used. Start: 9:48 am End: 3:02 pm—cat died.	4.82	Sod. barb. i.p.	36						Problem: Obtaining sufficient blood from superior v.c. No autopsy.
4/12/35	Obs. #22-A	Successful AC carried out for 2 hrs, 51 min. Acacia used. Start: 12:55 pm End: 8:14 pm—heart & resps. stopped	3.55	Sod. barb. i.p.	32			2 hr, 51 min	6% cells; marked hemolysis		BP & resps. stable during procedure. Record of these taken at 15 min intervals. 7:22 pm—Traube-Hering waves beginning.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
4/22/35	Obs. #23-A	AC carried out for short time. Found impossible to introduce the clamp usually used on PA through small incision. Heavy silk thread substituted.	3.10	Ether by intermit- tent insuf.		12					Problem: Inadequate supply of venous blood. Hct at start: 47% cells.
4/23/35	Obs. #24-A	Same attempt as in #23-A. Acacia used. Heparin (60 mg/kg)—260 mg. given by vein. Start: 10:30 am End: 12:10 pm. Cat died.	4.3	Ether	25	12					Failure this time because rubber valve in ABO came off. Output from venous supply should be at 400 cc.
4/24/35	Obs. #25-A	Same attempt as in #24-A. Two cats used.; 1) Start: 9:45 am End: 10:42 am; 2) Start: 1:20 pm End: 4:15pm	1 = 3.4; 2 = 2.63	Ether 9:45; Ether 1:20	50						Both failures: 1) Death from hemorrhage in PA due to inadequate exposure. 2) Unable to obtain adequate blood flow. JHG: Cat too small, blood dilution too great. Animal killed with ether. Autopsy: Lungs in both fully expanded.
4/29/35	Obs. #26-A	Purpose, procedure: same as in #s 23, 24, 25-A. Acacia used.	3.5	Ether							Failure due to inadequate exposure. JHG: Sterile procedure would be greatly improved by not using Heparin & using rolling wheel on rubber tubing instead of pumps. *O-ator does not introduce enough oxygen.
4/30/35	Obs. #27-A	Unsterile procedure.; Acacia used.; Start: 12:37 pm; End: 3:55 pm—cat died.	3.72	Sod. barb. i.p. Suppl. ether.	77						Problem: Venous cannula broke.

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Table 15 Laboratory Experiments 1934–35 (animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
5/01/35	Obs. #28-A	AC carried out for 37 min with partial occlusion of PA. Oxygen given at 6 1/min. Heparin: 250 mg IV. Acacia used.	4.0	Sod. barb. i.p.	53	321		37 min	16% cells with hemolysis.		Trouble: Insufficient flow through venous cannula. Hct at start: 43% cells.; 5:40 pm—Rt heart distended.; 6:10 pm—Traube-Hering waves.; 6:23 pm—Resp stopped. AC continued on dead cat.; 7:45 pm—Hct #2 taken.; JHG: PA completely occluded.
5/04/35	Obs. #29-A	AC attempted. Large hole in pericardium. Leak fixed. Acacia used. Heparin—200 mg given IV. Start: 10:28 am End: 5:05pm. Cat died.	2.95	Sod. barb. i.p.	80 (leak)	14					Good venous flow, but value in ABO became loose & exp. was terminated. AB could not handle output of VB. Autopsy: Lungs fully expanded.
5/10/35	Obs. #30-A	AC carried out for 39 min with PA completely occluded. AC stopped because glass venous cannula broken during adjustment.			31		300	39 min	27% cells, no hemolysis		Adequate BP for 2 1/2 hrs post-op. Hct at start—5% cells.; *Metal cannula will be used hereafter. *Found that blood from O-ator could be maintained at a bright red color by merely revolving the O-ator fast enough to produce very fine, light foaming. Microscopic: Lungs—no edema. Few areas of atelectasis. Bronchi OK. Heart—no fragmentation of muscle fibers. Slight sub-epicardial hemorrhages in area about coronary artery & its accompanying veins. No thrombi in either organ.; 5:47 pm—slight Traube-Hering waves. 6:43 pm—Animal bled to death.

Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
1/28/38	Exp. #S-1	Sterile surgical procedure to withdraw blood from ext. jug. vein, oxygenate it, and return it to arterial system while PA compressed. Start: 11:22 am End: 2:30 pm—cat died.	3.1	Sod. Nemb. 4% 2.8 cc i.p.	31	300		18 m.			Death 18 min after starting AC, probably due to cold blood in AC—4 degrees C below rectal temp. Specific cause (?): 1) alcohol in circuit (used for washing), 2) air embolism, 3) cold blood.
3/08/38	Exp. #S-2	Complete occlusion of PA for 10 min.	2.7	Sod. Nemb. 4% i.p. 2.8 cc	100	150–280			38% cells;	3 hrs	Cat died at 5:07 pm. Cause: shock? Autopsy: completely negative. No emboli in any organs. Clear urine in bladder. Heart OK.
3/10/38	Exp. #S-3	AC for one hour without clamping PA.	3.8	Sod. Nemb. i.p.	63	100–330 (foam)	90		19% cells, slight hemolys.	?	Still under anesthesia 2 1/2 hrs. after procedure. Died during night. Found stiff & blown-up. No autopsy.
3/15/38	Exp. #S-4	AC with PA completely occluded.	3.1	Sod. Nemb. i.p.	42	100–200					Died soon after AC started because of accidental hemorrhage from femoral artery when cannula pulled out.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/16/38	Exp. #S-5	AC for 30 minutes without clamping PA. Start: 10:09 am End: 5:08 pm	2.9	Sod. Nemb. 4% i.p.	20	180–250				5 hrs, 20 min	Death 5 hrs & 20 min after AC stopped. Post-op retching & vomiting. Cause of death: Chemical peritonitis from i.p. Nembutal. *Will use 1/2 dose of Nembutal & supplementary ether hereafter.
3/17/38	Exp. #S-6	AC for 20 minutes without clamping PA.	4.9	Sod. Nemb. 4% (1.8 cc) i.p. & either	30	220			35% cells, slight hemolys.	6 days+	
3/22/38	Exp. #S-7	AC for 25 minutes without clamping PA.	4.0			200			37% cells, 10% hem	2 days+ 1 mon seq.	Alive & well 2 days plus. 4/22/38: Cat sacrificed. Purulent discharge & nasal discharge.; Autopsy: negative. *Two other cats had same symptoms—purulent eye discharge & nasal drainage.
3/23/38	Exp. #S-8	AC for 50 minutes with partial occlusion of PA.	3.3		25	170–280		50 m	42% cells, 20% hem	4 1/2 mon	Cat in good shape 1 day+ except for inflammation left eye. Sacrificed 8/12/38 to obtain specimen of organs.
3/24/38	Exp. #S-9	AC for 15 minutes with PA completely occluded. Total time: 1 hr 43 m.	2.25		25	160–360		15 m.	28% cells, 20% hem	26 hrs	Heart and resps stopped 26 hrs. after AC discontinued. *Normal coagulation 26 hrs after heparin given.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./ compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
3/29/38	Exp. #S-10	AC for 15 min with complete occlusion of PA. Total time: 1 hr, 52 m	2.85		41	180–350		15m	41% cells, 30%	53 min	Problem: Inadequate oxygenation. Much foaming with oxygenator at 350 rpm. Autopsy: Marked congestion of lungs, no bloody urine in bladder, no emboli.
3/31/38	Exp. #S-11	AC for 15 min with complete occlusion of PA. Start: End: 1:25 pm—cat died	3.2	Ether	28	120–400		15 m	48% cells, 15% hem		Autopsy: Right ventricle distended, lungs congested. Some bloody fluid in abdomen. Large neoplasm in liver 3 inches in diameter.
4/14/38	Exp. #S-12	AC for 9 minutes with complete occlusion of PA.	3.0	Ether	38	200–400		9 m			Cat died 14 min after complete release of clamp. Autopsy: air in left heart. Death caused by air embolism.
4/19/38	Exp. #S-13	AC for 10 minutes with complete occlusion of	2.2	Ether	38	370–420		10 m		1 mon	Cat given too much ether at one point in procedure; revived. Died 5/12/38 from jaundice & pneumonia. Autopsy: All fat very yellow. Superficial skin infection Rt side of chest. No connection with surgical wound. Skin yellow. Neck wound infected. Markedly jaundiced. Spleen greatly enlarged. Liver very pale & enlarged; edges rounded. Kidneys larger than normal & pale yellow. Gall bladder full of thick bile. Heart: no pericarditis, adhesions or thickening of pericardium. Pulm. artery: no evidence of any injury. Lungs: marked congestion throughout, especially both lower lobes where they appear almost solidified. Microscopic: Liver-marked cirrhosis & fatty degeneration. Kidney: tubular nephritis. Spleen: marked congestion & hemorrhage. Heart & pulm. artery: not remarkable. Brain: not remarkable.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
4/21/38	Exp. #S-14	AC for 15 minutes with complete occlusion of PA.	2.45		25			15m	35% cells, 15% hem.	51 min	Oxygenation good except at high rates of 330–370 which produced foam. Cat died 51 min after complete release of clamp. Autopsy: essentially negative. Death: inadequate oxygenation, low BP.
4/26/38	Exp. #S-15	AC for 10 minutes with complete occlusion of PA.	1.9	Ether	32	190–280		10 m	32% cells, 20% hem	9 days	At start: both eyes watery & discharging. Clamp released because cat struggled (light anesthesia). 5/4/38: Cat sacrificed. Clot in jug. vein & sup. V.C. Purulent pericarditis, otherwise negative.
4/27/38	Exp. #S-16	AC for 12 minutes with complete occlusion of PA.	2.85	Ether	25			12 m	33% cells	3 mon	Clamp released because cat struggling—light anesthesia. 4/29/38: Aborted kittens. 7/26/38: Healthy litter of kittens. Movies taken 7/29/38.
4/28/38	Exp. #S-17	AC for 7 minutes with complete occlusion of Total anesthesia time: 2 hrs, 17 min Total operative time: 1 hr, 34 min	2.7	Ether	30			7 m + 34 m	27% cells, 10% hem		Clamp released because respirations had stopped. Artificial resp. begun. Respirations resumed & AC continued for 34 minutes. Problem: too deep anesthesia, too low BP.
5/3/38	Exp. #S-18	AC for 25 minutes with complete occlusion of PA. Total time: 1 hr, 52 min	2.3	Ether	38	150		25 m	30% cells, 15% hem	3 hrs	Cat died 3 hrs after stopping AC. Autopsy: Negative except for stomach—greatly distended with hair & paper.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
5/24/38	Exp #S-19	AC for 15 minutes with complete occlusion of PA. Anesthesia time: 1 hr, 59 min Operative time: 1 hr, 34 min			32	180–270		15m	35% cells, 20% hem	1 hr, 23 min	Cat died 1 hr & 23 min after stopping AC. Autopsy: Large spleen. One lobe of liver adherent to peritoneum. Bladder full of bloody urine. Thorax: few hemorrhagic spots in lungs which are markedly congested. No pneumothorax, no injury to sup. V.C. Liver markedly congested. Heart: Rt ventricle distended. Microscopic: Liver—necrosis of hepatic tissue. Lungs: congestion.
5/25/38	Exp #S-20	AC for 20 minutes with complete occlusion of PA. Anesthesia time: 1 hr, 57 min Operative time: 1 hr, 37 min	3.2	Ether	37	180–300		20m	32% cells, 20% hem	2 wks+	Cat alive & well 6/7/38.
5/26/38	Exp. #S-21	AC for 16 minutes with complete occlusion of PA. Anesthesia time: 1 hr, 48 min. Operative time: 1 hr, 30 min	3.6	Ether	34	170–400	260	16 min	36% cells, 30% hem	5 hrs +	Blood very blue throughout. Cat found dead next morning with arched back, head thrown back, puffed up, stiff, foul smelling. Conclusion: cat too big for size of oxygenator.
5/31/38	Exp. #S-22	AC for 15 minutes with complete occlusion of PA. Anesth: 1 hr, 46 m Oper. time: 1 hr, 22 m	2.45	Ether	29	160–310	190	15 min		2 hrs	Blood moderately red throughout. Cat died 2 hrs, 36 min after AC stopped. Cause of death: air embolism.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
6/01/38	Exp. #S-23	AC for 10 minutes with complete occlusion of PA.	2.9	Ether	40	170		10 m			Problem: Large hemorrhage from pulmonary artery before clamp placed. *Pulm art. opened & attempt made to close it.
6/02/38	Exp. #S-24		2.5	Ether							Cat died an anesthesia death due to failure of closed anesthesia circuit. Cause: too much ether or insufficient oxygen.
6/08/38	Exp. #S-25	AC for 10 minutes with complete occlusion of PA. Anesth time: 1 hr, 50 min Oper time: 1 hr, 30 min	3.3		39	180–280		10 min	29% cells, 10% hem	5 hrs	Blood not red—poor circulation. Cat lived 5 hrs+— died during night. No autopsy.
6/09/38	Exp. #S-26	AC for 30 minutes with complete occlusion of PA. Anes time: 1 h, 50 min; Oper time: 1 hr, 49 min.	1.8		44	150–200	166	30 m	26% cells	5 hrs+	Cat found dead in morning. Blood good red during procedure. Autopsy: unremarkable. Bladder empty. No embolism. Lungs expanded. No hematoma. 1–2 cc bloody fluid in pericardium. Heart OK except for Rt ventricle: place on wall, 1 cm in diameter. Cause of death: inadequate blood supply.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
6/14/38	Exp. #S-27	AC for 10 minutes with complete occlusion of PA.; Anesth time: 1 hr, 32 min; Oper time: 1 hr, 13 min	2.6	Ether	25	250–310	200	10 m	40% cells, 10% hem	10 days+	Ist 5 days: glucose i.p. twice a day. Bad case of snuffles Lt eye—blind. Oxygen given at usual rate. Cat died 7/7/38. Autopsy: no ascites. Small bluish discoloration beneath capsules of both kidneys. Other viscera: normal. Lungs fully expanded. Numerous small white spots over ext. surfaces of both lungs—tubercles? Firm white thrombus in both sup. & inf. v.c. & into Rt auricle, pulm. art. & both branches. Possibly slight jaundice.
6/17/38	Exp. #S-28	AC for 12 minutes with complete occlusion of PA.; Anesth time: 1 h, 47 min; Oper time: 1 hr, 27 min	3.3	Ether	40	220–280	280	12 m	34% cells, 10% hem	2 wks	Blood fairly good red. Found dead 7/2. No autopsy. While alive: purulent pericarditis.
6/24/38	Exp. #S-29	AC for 15 minutes with complete occlusion of PA.; Anes. time: 1 hr, 55 min. Oper. time: 1 hr, 36 min.	3.2	Ether	30	180–345	255	15 m	35% cells, 10% hem		Blood fairly good red. Cat died during night. Found stiff in morning. No autopsy.
6/28/38	Exp. #S-30	AC for 15 minutes with complete occlusion of PA. Anes time: 1 hr, 58 min.; Oper time: 1 hr, 38 min.	2.3	Ether	24	170–330	235	15 m	36% cells, 10% hem		Died 6/30. No autopsy. Before death: clawed around in cage with head thrown back. Cat stiff & bloated, bloody froth from nose.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	*Exper. no.*	*Work done*	*Cat wt (kg)*	*Type of anesthesia*	*Operat. prep. (min)*	*Oxygenator rate (rpm)*	*Flow rate (cc/min)*	*Occlus. time part./compl.*	*Hct at end (%)*	*Surviv time*	*Findings*
6/29/38	Exp. #S-31	AC for 15 minutes with complete occlusion of PA. Anes: 1 hr, 36 min Oper: 1 hr, 13 min	2.2	Ether	20	160–370	280	15 m			Blood good red. Died next day. Autopsy: pale abdominal viscera. No emboli. Marked congestion Lt lung. Cause of death: anemia, shock, fatal lowering of body temp
7/01/38	Exp. #S-32	AC for 10 minutes with complete occlusion of PA. Anes: 1 hr, 31 min Oper: 1 hr, 20 min	3.5	Ether	40		300	10 m	23% 0 hem		7/2: Found dead in morning. No autopsy.
7/06/38	Exp. #S-33	AC for 11 minutes with complete occlusion of PA.	2.0	Ether	30			11 m	27% cells, 25% hem	30 min	Cat died 30 min after surgery. Both eyes: marked protuberance. Autopsy: generally negative.
	Exp. #S-34?										
7/14/38	Exp. #S-35	AC for 17 minutes with complete occlusion of PA. Anes: 1 hr, 31 min.	2.6	Ether	20	150—330	240	25 m	35% cells, 15% hem		Blood fair red during procedure. Cat died during night—bloated. No autopsy.

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Table 16 Laboratory Experiments 1938 (sterile animal experiments)

Date	Exper. no.	Work done	Cat wt (kg)	Type of anesthesia	Operat. prep. (min)	Oxygenator rate (rpm)	Flow rate (cc/min)	Occlus. time part./compl.	Hct at end (%)	Surviv time	Findings
7/22/38	Exp. #S-37	AC for 25 minutes with complete occlusion of PA.	2.8	Ether	20	150–320	260	25 m	34% cells	24–36 h	Blood fair red during procedure. 7/23: Small hard lump under neck wound, but looks OK. Rt pupil larger than Lt. 7/24: Cat found dead. Stiff. No autopsy. Cause: Possible injury with large needle during glucose injection (?)
7/26/38	Exp #S-38	AC for 18 minutes with complete occlusion of PA. Anes: 97 min. Oper: 74 min.	2.1	Ether	28		234	18 m	25% cells, 5% hem.	2 mon+	Blood good red. 7/29: Movies taken. Post-op: snuffles. 8/9: Snuffles & discharge from eyes entirely cleared up. (Tx: Argyrol 10%). 9/13: Sneezing & coughing in last week or so. Allowed to run about most of day.
7/28/38	Exp. #S-39	AC for 15 minutes with complete occlusion of PA. Anes: 1 h, 38 m. Oper: 1 hr, 17 m.			27	270	230	15 m	27% cells, 10% hem.		Blood poor red. 7/29: Alive & well 1 day post-op. 7/31: Found dead. No autopsy. Cause: purulent pericarditis.

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