# Fifty Years of Open Heart Surgery at the Mayo Clinic

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Fifty years ago, a young surgeon, supported by a multidisciplinary team of physicians and technicians at the Mayo Clinic in Rochester, Minn, embarked on a planned series of clinical cases using a heart-lung machine to allow direct visualization of the inside of the opened human heart to repair otherwise fatal intracardiac defects. Of the initial 8 patients, 4 survived.[1] This achievement was a breakthrough and showed the clinical feasibility of using a mechanical pump-oxygenator to support the circulation while working inside the heart. John W. Kirklin (Figure 1) and his team had effectively made open heart surgery a therapy that could become widely available.

A surgical risk of 50% sounds prohibitive today, but before the advent of the heart-lung machine, most patients with congenital, valvular, or ischemic heart disease had a poorer prognosis than we appreciate today, often leading to early fatality. Even ventricular septal defects (VSDs) were fatal in most children before they reached the first grade.

Extracardiac procedures such as closure of a patent ductus arteriosus (PDA) (first done in 1939) and repair of coarctation of the aorta (first done in 1945) were becoming common by the 1950s. One of the pioneers in this work was O. T. Clagett at the Mayo Clinic. Confidence for performing surgery within the heart evolved from the military experiences during World War II. Dwight E. Harken, a US Army surgeon, reported the removal of 100 intracardiac foreign bodies during the war.[2] These experiences led to closed mitral commissurotomy and closure of some atrial septal defects (ASDs) using the "atrial well" technique.[3] However, it was apparent that complex cardiac repairs would require some means of pumping oxygenated blood for the patient while the surgeon worked inside the heart. Noting his interest in open heart surgery during his residency training period, Kirklin recalled, "My fellow residents and I filled pages of notebooks with drawings and plans of how we would close ventricular septal defects and repair the Tetralogy of Fallot once science gave us a method to get inside the heart.'"[4]

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In the early 1950s, surgical confidence, medical and anesthetic advances, and technological improvements culminated in surgical efforts to "get inside the heart." At the University of Minnesota, F. John Lewis used deep hypothermic circulatory arrest to visualize and directly close an ASD.[5] Clarence Dennis, also at the University of Minnesota, attempted to close an ASD in 2 patients (2- and 6-year-old girls) using cardiopulmonary bypass with a mechanical pump and a screen-disk oxygenator in 1951; both patients died. While efforts to develop a suitable mechanical pump-oxygenator continued at the university, C. Walton Lillehei worked on controlled cross circulation. In this procedure, the cardiopulmonary bypass "machine" was another human, generally the patient's parent. The parent's femoral vessels were cannulated, and his or her oxygenated blood was pumped into the patient undergoing cardiac repair. After establishing the technique in the laboratory, Lillehei proceeded with clinical cases beginning in March 1954. A total of 45 such operations were done in subsequent months with 18 deaths.[6] The technique was controversial, with a mortality of 40% and potential risk to the donor. However, cross circulation clearly allowed support of the patient's systemic physiology during exposure of the inside of the heart, and many argued that further pursuit of machines for cardiopulmonary bypass should be abandoned.

At the time, a number of teams worldwide were working to develop a machine for cardiopulmonary bypass. John H. Gibbon, Jr, at Jefferson Medical College in Philadelphia, Pa, had been working on such a device since 1937.[7] His work was supported partially by Thomas J. Watson, chairman of IBM. In 1952, Gibbon attempted to close a presumed ASD in a 1-year-old child using a mechanical pump with a screen oxygenator. Unfortunately, the diagnosis was incorrect—an indication of the challenges of making accurate diagnoses in that era; the patient died and was found to have a PDA at autopsy. Even today, an unrecognized PDA can result in catastrophic consequences during cardiopulmonary bypass surgery. Gibbon successfully closed an ASD in an 18-year-old woman on May 6, 1953, with use of his machine, the only successful procedure before Kirklin's work. However, 2 subsequent patients died (both 5-year-old girls with ASD who underwent surgery in July 1953), and Gibbon made no further attempts.[4,8] In 1980, Kirklin, in a personal communication with Gibbon, alluded to 2 further unsuccessful procedures.[9]

John W. Kirklin anticipated the dawning era of open heart surgery. In 1952, he assembled a team of experts at the Mayo Clinic to develop a cardiac surgical program for the clinical application of a mechanical pump-oxygenator. The team included Jesse E. Edwards in pathology, Earl H. Wood and H. Jeremy Swan in physiology, Howard B. Burchell in cardiology, James W. DuShane in pediatric cardiology, Robert T. Patrick in anesthesiology, David E. Donald in research, and Richard E. Jones in mechanical engineering. After evaluating a number of potential devices, Kirklin obtained the blueprints of the Gibbon-IBM pump-oxygenator. On the basis of this design and additional refinements and modifications, a pump-oxygenator (screen type) was developed in the engineering shops at the Mayo Clinic.[10]

Many of the initial failures in open heart surgery resulted from incorrect preoperative diagnoses or incomplete understanding of the anatomy and pathophysiology of the congenital heart defects that the surgeons were attempting to correct. Denis G. Melrose from London later noted, "Consider a group of people practicing in animals the management of an open heart operation. Remember the clumsy perfusion equipment, primitive anesthesia, little or no measuring equipment, a host of mysteries gradually overcome, and then the first attempt at clinical application. Suddenly, the rules established are completely without validity, drowned in a torrent of blood streaming into the heart from an [unexpected] patent ductus, a large bronchial [collateral] or an incompetent aortic valve above the septal defect."[4]

During the research and development phase, Kirklin worked with Edwards, the pathologist, to develop a detailed understanding of congenital heart disease to plan surgical repairs. Edwards became a leader in the description and categorization of the anatomy and pathology of congenital heart defects.[11] In addition, great strides were made in establishing correct preoperative diagnoses. Cardiac catheterization was developed at a few academic centers such as The Johns Hopkins Hospital and Peter Bent Brigham Hospital, but many major contributions came from the Mayo Clinic. While developing suits to combat G forces encountered by military flight pilots, Wood noted strain gauge pressure transducers used by aircraft manufacturers to test aircraft wings. Wood adapted this technology to allow continuous monitoring of arterial pressures.[12] Other innovations from the Mayo Clinic included cuvette oximetry, tricarbocyanine (Fox green) dye measurement of shunts and cardiac output,[13,14] and other pioneering work in cardiac catheterization.[15]

The mechanical pump-oxygenator built at the Mayo Clinic was a relatively complex and sophisticated machine (Figures 2 and 3).[10] Safety features included devices to sense the level of blood in the venous and lower arterial reservoirs, an automatically activated occluder mechanism to maintain blood flow to the oxygenator, high-pressure safety stops, automatic control of arterial pH, and an arterial filter. Initiation and maintenance of bypass depended on vacuum-assisted drainage of the superior and inferior

FIGURE 1. Mayo Clinic surgeon John W. Kirklin led a team that showed the clinical feasibility of the mechanical pump-oxygenator for supporting circulation.

FIGURE 2. The heart-lung machine first used at the Mayo Clinic in March 1955. The screen oxygenator is the rectangular box on the top of the machine.

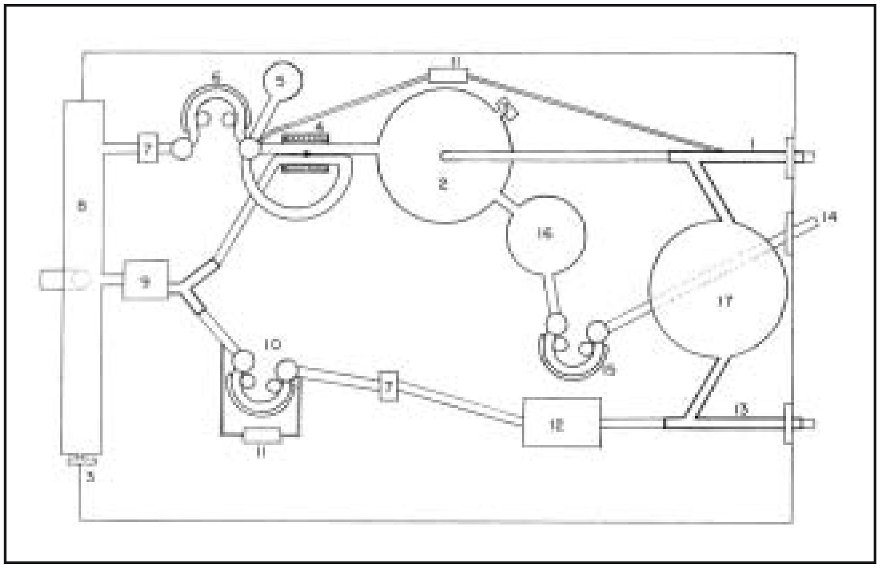

FIGURE 3. Schematic of heart-lung apparatus from the *Proceedings of the Staff Meetings of the Mayo Clinic,* May 1955.[10] 1 = the venous inflow line; 2 = the venous reservoir; 3 = level-sensing devices; 4 = occluder; 5 = input for the administration of blood and fluids; 6 = recirculation pump; 7 = high-pressure stops; 8 = oxygenator; 9 = location of pH electrodes; 10 = arterial pump; 11 = arterial and venous cuvette oximeter; 12 = arterial filter; 13 = arterial output to animal; 14 = coronary sinus inflow; 15 = coronary sinus pump; 16 = coronary sinus reservoir; 17 = priming reservoir.

vena cavae (at pressures of about –5 mm Hg). The patient's venous blood was not entirely exsanguinated into the venous reservoir; rather, the machine was designed to maintain the venous reservoir at a constant level. Blood flow to the oxygenator was maintained at a constant rate by an occluder mechanism that controlled the source of the blood flow to the oxygenator (with use of either venous reservoir or recirculated blood). When the venous reservoir level moved above or below a set point, the level-sensing device in the reservoir caused the occluder arms to open automatically, partly occluding or fully occluding flow from either the venous reservoir or the recirculation line. A second level sensor automatically maintained a constant level of blood in the lower oxygenator reservoir by controlling the arterial blood pump rate.

The oxygenator consisted of up to 14 wire-mesh screens, each 12 × 18 in, enclosed in a lucite case. Carbon dioxide flow to the oxygenator was controlled automatically by a pH meter to maintain a pH of 7.43 to 7.45; oxygen flow into the chamber was constant at 10 L/min. The pump-oxygenator required 6 U of blood to prime, a separate operating room in which to prepare, and about 6 hours to clean after each operation. There was no heat exchanger except for the lucite oxygenator casing, which was heated to prevent condensation and maintain predictable gas exchange.

In a series of experiments with the pump-oxygenator, 9 of 10 dogs survived 40 to 60 minutes of bypass with no discernable ill effects. Death in the nonsurvivor was related to a faultily ligated femoral artery. In subsequent experiments, ASDs and VSDs were repaired.[16]

Meanwhile, Lillehei used the cross circulation technique for open heart surgery in humans.[6] Lillehei's outcomes with cross circulation, despite controversy reflected in comments made at surgical meetings where he presented his results, led some individuals at the Mayo Clinic and elsewhere to urge Kirklin to abandon the notion of a mechanical pump-oxygenator and to adopt the cross circulation technique. However, Kirklin recognized the limitations of the broad applicability of cross circulation (the need for a donor and the risk to the donor, among others) and pressed on with the mechanical pump.[9]

After 2½ years of research and development, the team planned to proceed with a series of 5 (later expanded to 8) patients, recognizing that a high percentage might not survive the operation (Figure 4). No cardiac surgical procedures had been performed with use of a mechanical pump-oxygenator since Gibbon's experience. Families were told about the risks, imponderable factors, and possible benefits of this new and unproven surgical treatment.[9] The first procedure was performed on March 22, 1955 (Figure 5). A 5½-year-old child underwent repair of a large VSD. The arterial cannula became dislodged shortly after bypass was initiated, requiring rapid correction and deairing of the circuit. Fortunately, the well-prepared team was up to the task, and the operation was successful. The VSD was repaired with 5 silk sutures. The patient's postoperative course was uneventful, and she was dismissed from the hospital after 10 days. The first publication of this experience was published in May 1955 in the *Proceedings of the Staff Meetings of the Mayo Clinic*[10] (subsequently renamed *Mayo Clinic Proceedings*). The report described the 8 patients, 4 of whom died postoperatively, and represented the first clinical series of open heart surgeries performed with a mechanical pump-oxygenator (Table 1).[1] Cardiopulmonary bypass was maintained for 20 to 73 minutes, and flows were 100 mL/kg per minute. Kirklin concluded, "Use of this system established excellent conditions for precise, unhurried intra-cardiac surgery." This series pioneered the new era of open heart surgery. Cardiac surgery had become a reality, and surgical treatment of heart disease could become widely available by dissemination of the heart-lung machine.

Four months after the publication of the first Mayo Clinic series of open heart surgeries using cardiopulmonary bypass, Lillehei at the University of Minnesota abandoned the cross circulation technique and started using the DeWall pump, a bubble oxygenator–based device developed at the university. Reflecting on this era, Norman Shumway of Stanford later remarked, "There for a shining moment the only institutions in the world where one could go for open heart surgery were 90 miles apart, at the Mayo Clinic and the University of Minnesota."[4]

The success of this initial series of open heart operations at the Mayo Clinic depended on the multidisciplinary effort

FIGURE 4. The heart-lung machine (foreground) in the operating room at the Colonial Hospital.

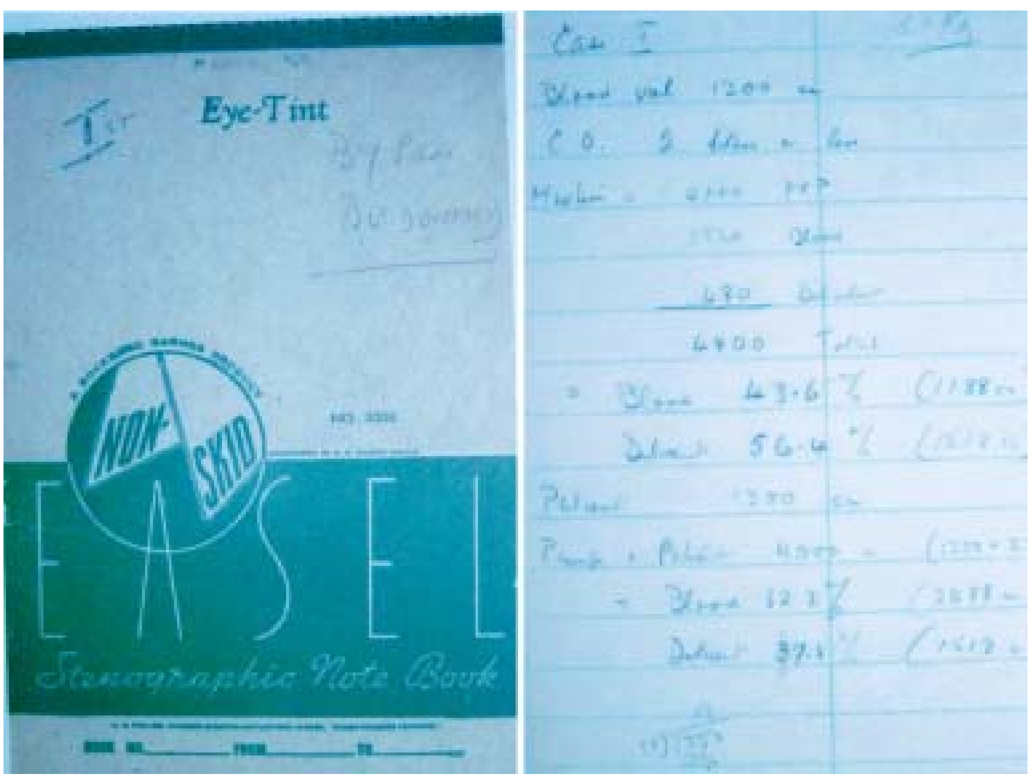


FIGURE 5. Notebook containing calculations for setting up the heart-lung machine for the first patient to undergo a cardiac surgical procedure with use of a mechanical pump-oxygenator. The name on the front of the notebook is D. E. Donald, research assistant and perfusionist for the first patients.[16]

TABLE 1. **First 8 Patients Who Underwent Open Heart Repair of Intracardiac Defects With Use of a Heart-Lung Machine at the Mayo Clinic[1]**

| Diagnosis | No. of patients | Age | No. of deaths |
|---|---|---|---|
| Ventricular septal defect | 4 | 4 mo to 11 y | 2* |
| Atrioventricular canal | 2 | 1 y, 5 y | 1† |
| Tetralogy of Fallot | 1 | 5 y | 1‡ |
| Atrial septal defect | 1 | 2 y | 0 |

*Due to repair dehiscence, respiratory failure at day 6 related to scoliosis.
†Due to hypovolemia.
‡Due to left ventricular failure.

of a group of talented and dedicated individuals. The team had expertise in anatomy, pathology, physiology, biomedical engineering, cardiology, and anesthesiology. This expertise led to the building and refinement of the pump-oxygenator machine, the capability to make the proper preoperative diagnosis, the development of precise surgical techniques based on a detailed understanding of the defect to be repaired, and careful intraoperative monitoring and care.

In 1957, cardiac surgery at the Mayo Clinic was moved from the Colonial Hospital to Saint Marys Hospital to provide facilities for the expanding practice, Dwight C. McGoon joined the surgical staff, and one of the first intensive care units in the world was established.[9]

As more centers sought the means to perform open heart surgery, a medical-industrial complex emerged that resulted in rapid technological advancements and expanded the applicability and reliability of open heart surgery. Today, oxygenators are disposable membranes purchased for less than $300 and are primed with blood-free crystalloid solution. The technology continues to be refined and to evolve. Surgical risk has become minimal and now primarily depends on patients' noncardiac conditions and on the condition of the heart muscle itself. The operative mortality for surgical repair of tetralogy of Fallot in 1955 was 50% but was reduced to 15% by 1960; by 1980, the risk approached zero.[4]

Kirklin became Chairman of the Department of Surgery at the Mayo Clinic in 1960 and became Chairman of Surgery at the University of Alabama Birmingham in 1966. He served as Editor for *The Journal of Thoracic and Cardiovascular Surgery*, authored more than 500 scientific articles, and coauthored (with Sir Brian Barrett-Boyes) the definitive text *Cardiac Surgery*. He died on April 21, 2004. McGoon was similarly prolific. McGoon described the surgical repair of many congenital heart defects and served as Editor for *The Journal of Thoracic and Cardiovascular Surgery*. McGoon died on January 27, 1999.

Cardiopulmonary bypass has been used to perform more than 63,000 cardiac operations at the Mayo Clinic, and currently, more than 2300 such procedures are performed annually. In the United States, more than 400,000 open heart operations are performed each year. All categories of heart disease are potentially treatable.

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