

History of Extracorporeal Circulation: The Invention and Modification of Blood Pumps

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Abstract: The first roller pump was patented in 1855 by Porter and Bradley and was hand operated. A modification first named “surgical pump”, designed and manufactured by E. E. Allen in 1887, was intended for direct blood transfusion. Truax, who also distributed and promoted the Allen pump with one roller, developed the first double roller pump in 1899. In the following decades, several researchers, including Beck, Van Allen, Bayliss and Müller as well as Henry and Jouvelet, refined the apparatus and recommended the use of roller pumps for blood transfusion and other applications. After further modifications made by DeBakey in 1934, and application of this pump in one of the first heart–lung machines constructed by Gibbon, DeBakey’s name became inseparably attached to this type of pump. For perfusion experiments, an electrically powered roller pump was first used

by Fleisch in 1935. Today, the roller pump is the most frequently used blood pump for cardiopulmonary bypass worldwide, having prevailed against the early pulsatile tube compression pumps and ventricular pumps. In recent years, centrifugal pumps have increasingly competed with roller pumps as systemic blood pumps for cardiopulmonary bypass and have become the preferred arterial pump in a variety of centers. Application of mechanical cardiac assistance has evolved from nonpulsatile roller pump support, followed by an era of pulsatile ventricular pumps to the rediscovery of the nonpulsatile flow mode with modern axial flow pumps. **Keywords:** history, roller pump, centrifugal pump, extracorporeal circulation, blood transfusion. *JECT* 2003;35: 184–191

EARLY PUMPING DEVICES FOR BLOOD

Early experimental organ perfusion by physiologists and pharmacologists from the middle of the 19th century was accomplished using gravity as the driving force for perfusion by hanging the reservoir containing the perfusate under the ceiling of the room. During the period following, these reservoirs were pressurized by use of a column of mercury or hydraulic pressure generated by a water pipe (1,2). With the invention of the closed perfusion circuit by Max von Frey and Max Gruber in 1885, however, active pumping devices became necessary to propel the blood through the oxygenator to the target organ (3). The first such pumping devices were engine-powered syringe pumps (4). In 1889, the electrical pendular cock, a pulsatile pumping device, was introduced by Gustav Hamel (5). It was associated with a reduced manifestation of tissue edema because of the pulsatile flow character. Subsequently, other researchers tried to construct pulsatile pumping devices (6–8). In the year 1890, Jacoby used a rhythmically compressed rubber balloon for this purpose, and the same technique was subsequently used by other

researchers (9–11). The pulsatile membrane pump, introduced by Dale and Schuster in 1928, gained the greatest popularity in the following decades (12). During the 1950s, this pump was used, after several modifications, in conjunction with cardiopulmonary bypass. These pulsatile blood pumps, however, needed additional valves for directing perfusion blood flow. The first pumping device without valves was the roller pump, probably first patented by Porter and Bradley on 17 April, 1855 (13,14). It worked, like the subsequently modified versions by other researchers, with only one roller.

ROLLER PUMP FOR BLOOD TRANSFUSION

The manually operated roller pump developed and manufactured by Allen was patented on 21 June, 1887 and described in the *Journal of the American Medical Association* on 9 July, 1887: “*Seldom has the ingenuity of the inventor brought to the aid of the physician and surgeon a more useful instrument than that designed and manufactured by Mr. E. E. Allen, of Grand Rapids, Mich., and named by him the ‘Surgeon’s Pump’.*” . . . “*As a transfusion apparatus the instrument was first brought to my attention by Mr. Allen some months ago, and it was for this purpose it was originally designed; and in meeting the conditions necessary for the ready transmission of blood from the*

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veins of one body to another it is, as far as I am aware, far superior to any other instrument ever used for this purpose" (15) (see Figures 1 and 2).

Therefore, in its earliest developmental phase, the roller pump was also intended for blood transfusions, although the blood groups were to be discovered as late as 1900/1901 by Karl Landsteiner and 1902 by von Decastello and Sturli (16–18). Identification of the rhesus factor was not accomplished until 1940 (19).

Charles Truax, a manufacturer of surgical instruments from Chicago, constructed his own version of the Allen pump, which was able to function by means of such suitable attachments as an aspirator, injector, stomach pump, bladder syringe, cupping pump, dilator, universal syringe, breast pump, and force and vacuum pump, all combined into one. The pump was introduced on 3 September, 1887 at the 9th International Medical Congress in Washington, DC: "A handle with a crank movement brings a roller in contact with the interior coil of indiarubber tubing enclosed in the metal case. In revolving, the roller subjects the tubing to pressure, so as to close the calibre of the tube, and in that way a powerful aspirating effect is exerted. By a simple mechanism the roller can be brought into different degrees of contact with the tubing, or, when not in use, altogether set free from it" (20). In the 1889 prospectus of Truax and Co., the pump was described as follows: "As a blood transfuser it possesses important advantages not found in any other instrument, and is practically the only perfect one in use. For this purpose we manufacture a special instrument having a small tube of pure rubber. If the operator desires to maintain the blood, while in transit, at or near its normal temperature, he may place the pump, while in use, in a basin or vessel of water having a temperature of about 105°F. As there are no valves or stop cocks, and as the blood while being transfused may kept moving at the same rate of speed as when in the veins, there is but little liability of any change taking place, and consequently no necessity for defibrination. It is not brought into contact with the air, and there is but little if any danger of coagulation" (21) (see Figures 3 and 4).

Truax's *The Mechanics of Surgery* catalog of 1899 introduces the "Author's Surgical Pump," a newly developed pump patented on 8 September, 1891: "It consists of a horse-shoe shaped frame, on the inner surface of which is clamped a piece of rubber hose so adjusted as to describe the form of the letter 'U'. Passing through the case is a shaft moved by a suitable crank, to which is attached a rotating arbor carrying two rollers. These rollers are connected through the center of the arbor by a double-threaded rod, moved by a milled-edged wheel. By turning this small wheel any degree of pressure desired can be produced upon the rubber hose.... As the rollers in passing around the circle rest continuously on the tubing completely closing it at some point, there is no necessity for valves" (22) (see Fig-

ure 5). This seems to be the first description of a double roller pump, already with fine adjustment for occlusion, as it is used today in modern heart-lung machines, with the exception of the way the pump is powered.

Alfred Beck from Kiel, Germany described his blood pump for transfusion in 1924 with a modification in 1925. This apparatus initially had only one roller and was able to produce a continuous blood flow in one direction while allowing exact measurement of the transfused blood volume. The preparation of his pump for use was described by Beck: "The apparatus is placed, readily assembled with cannulas, into a pot with boiling water, in such a way that the actual drum and crank are still overflown with water. . . Of course, the agglutination test has to be performed before" (23). One year later, Beck introduced an improved apparatus with three rollers, in which two short tubes could be inserted and the blood flushed with saline by means of a four-way stopcock (24). In Germany, this pump became known as "Satrans III" or "Beck'sche Mühle" (Beck's mill). This type of pump was also recommended by Brukhonenko in 1927 in a publication on anticoagulation. In this text, artificial circulation of the isolated head and the whole body of animals with temporarily excluded heart and lungs was mentioned (25). Michael E. DeBakey modified the roller pump in 1934 by integrating a flange on the rubber tube that was securely attached to the pump housing, "thus stabilizing the rubber tubing and preventing any 'creeping', which has been an objectionable feature in those previously described instruments utilizing this principle" (26). In the same year, Henry and Jouvelet in France presented a small roller pump for blood transfusion (27).

ROLLER PUMPS IN EXPERIMENTAL PERFUSION APPARATUSES

A rotation pump for experimental long-term perfusion of isolated organs was constructed by Fröhlich in 1913. This pump can be seen as a precursor of the roller pump in perfusion apparatuses (28). Instead of the already invented rollers, Fröhlich used four free-moving metal septa in the axis of an eccentric disc, so that in each position of the eccentric disc, the septa came into close contact with the pumping chamber. This form of rotation pump, however, did not stand the test.

The perfusion apparatus constructed in 1927 by von Issekutz of the Royal Hungarian University's Pharmacological Institute in Szeged included a primitive roller pump. However, this pump was not used for the transportation of blood, but for the transportation of oxygen, which was subsequently mixed with blood: "The pumping device consists of a rubber tube, that lies in a steel shuttle of adjustable bend. On this rubber tube four ebonit drums move along that are located on a wheel driven by a motor,

and thereby blowing the air in the direction of the rotation. The amount of the transported air can be changed by adjustment of the rubber tube diameter, by the rotational speed of the wheel. . .in a wide range" (29). For the transportation of blood von Issekutz used a pumping device which moved the blood rhythmically with a motor-driven syringe.

In 1928, Bayliss and Müller developed a modification of the roller pump in which 11 rollers were used for the transportation of liquids or gas with only two rollers compressing a tube at the same time. The correlation between the revolutions and the pump flow rate was graphically charted in their manuscript (30).

Van Allen's roller pump had six rollers. He reported from China in 1931 that his pump had been used for several years for the transportation of gas and liquids for various applications. In addition to blood transfusions, he described aspiration of liquids from body cavities and the pump's use in conjunction with pneumothorax and for the purpose of circulation (31).

In 1935, for the first time, a double-roller pump was used by Fleisch in a perfusion apparatus for the transportation of blood (32). A second innovation was the use of an electrical motor for activation of this device. According to Fleisch, the advantages of his pump were that no valves were needed, and the priming volume was very small, so that perfusion experiments were possible with undiluted blood of the laboratory animal. Above all Fleisch felt that, in the previous experiments of other researchers, registration of the perfusion blood flow velocity was missing. He now had a pump at his disposal that was able to produce a constant blood flow. In the same year, a belt-driven electrical "Beck'sche Mühle" was used for dialysis by Georg Haas in Giessen, Germany (33).

In 1937, John Heysham Gibbon, Jr., the pioneer of cardiopulmonary bypass, initially used a modification made by deBurgh Daly of the pulsatile Dale and Schuster pump (34). However, by 1939, Gibbon was working with roller pumps for his perfusion apparatus for the systemic perfusion of cats during his experiments with temporary occlusion of the pulmonary arteries (35). He mentioned the modification of the roller pump by DeBakey, and this eventually led to an inseparable connection of the name of this great surgeon with the roller pump.

BLOOD PUMPS FOR CLINICAL CARDIOPULMONARY BYPASS

The first open-heart operation was attempted on 5 April, 1951 by Clarence Dennis in conjunction with a modified Dale-Schuster membrane pump.

"The pump consists of a methacrylate dome over a rubber diaphragm. The rubber diaphragm is made to oscillate

by water pressure from a rubber bellows and motor-driven camshaft arrangement below. Valves in the dome give directional flow."... "This apparatus has behaved admirably in one human trial, although extraneous factors led to the loss of the patient" (36).

The first successful intracardiac operation was performed by Gibbon in 1953 with the aid of total cardiopulmonary bypass. His oxygenator and the entire extracorporeal circuit apparatus were designed and constructed by engineers from International Business Machines (IBM) (37). Blood transport was accomplished with an "artery pump," a "recirculation pump" as well as with two "venous pumps" by "DeBakey roller pumps" (37,38). This pumping principle was also to be used in subsequent modified versions, such as in Kirklin's Mayo-Gibbon machine (39) or the "Mark-DeBakey Pump Units" in the commercially distributed devices built by the Mark Company (Randolph, MA).

Several other pioneers of extracorporeal circulation used pulsatile pumps for their first clinical cases. The widest known type was the Dale-Schuster pump, but pneumatically compressed ventricles were also part of Woodward's Army pump (Harry Diamond Laboratories, Washington, DC) and the Brunswick pump (Brunswick Manufacturing Company, MA). Harken worked with Birtwell's ventricle pump, the Davol Heart pump (Davol Rubber Co., Providence, RI), a pneumatically operated, hydraulically actuated ventricle pump with passive valves.

Tube compression pumps, such as the Medical Monitor pump, consisted of flexible chambers with inlet and outlet control valves that were compressed mechanically. The same principle was used in the pump designed by Björk and Crafoord in Stockholm. They showed their development of a heart-lung machine as early as 1948: *"The pump consists of a metal cylinder with a rubber cuff on the inside. The rubber tube for the blood passes through the center of this cuff between the two valves, made of a thin rubber band on a metal frame. The pumping action is attained by rhythmically inflating the cuff with compressed air, so squeezing the rubber tube" (40).* With the help of the Crafoord-Senning-AGA pump, the second successful heart operation worldwide and the first such European operation with total cardiopulmonary bypass was performed on 16 July, 1954 (41).

In Clarence Walton Lillehei's first successful series of intracardiac corrections, he used cross circulation with a finger pump called the Sigmamotor pump, made by Sigmamotor, Inc. (Middleport, NY) (42). This type of pump was described earlier by Salisbury (43). With this pump (Models T-6S and TM1), the tubing segment was inserted in a straight track and alternately compressed by multiple fingers in a sinus curve mode following the longitudinal axis of the tubing segment, propelling the blood in

the tubing segment in a nonpulsatile flow mode. Later, this pump was also used in conjunction with the Lillehei-DeWall oxygenator (44).

ROLLER PUMPS

With industrial production of heart-lung machines, the nonpulsatile roller pump became the standard for cardiopulmonary bypass, not only as an arterial pump but also for cardiotomy suction and other special applications; for example, infusion of cardioplegic solution, ultrafiltration and selective cerebral perfusion.

The roller pump is an instrument that, when adjusted to be fully occlusive, makes additional valves and a flow meter obsolete. It is also a system that reduces the contact with blood to the inner surface of a sterile tube, which can be effortlessly exchanged and, therefore, is quite inexpensive to operate. In contrast to other devices, roller pumps may also be manually operated with hand cranks in the case of power failure.

Roller pumps can be controlled externally and their pump minute volume regulated using impulses from pressure, air bubble, and low level sensors. In conjunction with a special controlling unit, it became possible to generate a pulsatile flow. With the advent of this pulsatile controlling unit, the interest in pulsatile flow during extracorporeal circulation grew again in the 1970s, and several studies were able to demonstrate better organ function preservation in comparison with continuous flow (45-47). Nevertheless, pulseless circulation was believed to be tolerated by the human organism, at least temporarily.

Another type of roller pump, the nonocclusive peristaltic M-Pump (Avecor Cardiovascular, Plymouth, MN), was brought into clinical practice in the 1990s (48,49). This pump produces a lower level of hemolysis than conventional roller and centrifugal pumps (50,51). The pumping principle is based on an invention made in the 1970s that became known as the Rhône-Poulenc pump (52). A special collapsible pump boot is suspended on a rotor, the pump segment is passively filled by the venous reservoir, and it produces a very low negative pressure as opposed to conventional roller and centrifugal pumps. Rupture of the tubing system in the case of an outflow obstruction is impossible because the pump does not generate such a high positive pressure. These features made the nonocclusive roller pump the preferred pump for long-term extracorporeal membrane oxygenation (52,53).

CENTRIFUGAL PUMPS

The centrifugal pump became the first serious competitor to the roller pump. For the first time, Saxton and Andrews presented this pump type in 1960 for possible application in an artificial heart (54). However, this early

pump caused marked destruction of the formed elements of the blood. In 1964, the University of Minnesota began the development of an implantable centrifugal pump. The ensuing collaboration with the University of California at San Diego and Medtronic Inc. (Minneapolis, MN) led to the development of a magnetically coupled centrifugal pump. The initially high hemolysis rate could be reduced with the model 1861 (55), which was manufactured by the Hemadyne division of Medtronic. Development and further improvement of this pumping principle by Rafferty in 1968 showed that the centrifugal pump had the ability to handle blood atraumatically, proposed for use in situations when gentle handling of a liquid medium is desired. Although the pump was presented as an artificial heart, Rafferty added that "*It should also find application as an atraumatic, efficient heart-lung machine pump*" (56). As a result of extensive research conducted jointly with the United States National Institutes of Health on an artificial heart development program, in 1973 Bio-Medicus, Inc. (Eden Prairie, MN) presented the Model 600 centrifugal pump. In 1975, Bernstein reported animal experiments for long-term left ventricular support with the centrifugal pump in calves (57). On 21 August, 1978, Golding reported the clinical use of Medtronic Model 1861 for ventricular support of patients with low cardiac output following corrective cardiac surgery (58). Pennington shortly afterwards also described centrifugal pump cardiac assistance (59). In July, 1980, the first heparin-coated Bio-Medicus centrifugal pump was used without systemic heparinization by Magovern (60). Subsequently, several more manufacturers developed centrifugal blood pumps of various designs.

The centrifugal pump eliminates pump boot tubing spallation as one of the most prominent disadvantages of the roller pump with the associated danger of embolization of particulate matter. The danger of air embolism is reduced in centrifugal pumps compared with roller pumps because of the pumping principle but not, as often thought, completely eliminated. Centrifugal pumps need an additional flow probe because pump minute volume at a given pump revolution speed changes with varying pump preload and afterload.

Initially designed for the purpose of mechanical cardiac support, the centrifugal pump became the most frequently used system for uni- and biventricular assistance (61-64). Soon, centrifugal pumps were also used during operations for the replacement or repair of the thoracoabdominal aorta (65-67).

The centrifugal pump may, under certain conditions, cause less hemolysis than the conventional roller pump, although investigations have shown mixed, conflicting results (68-70). The advantages of this type of pump made the centrifugal pump the preferred arterial pump for rou-

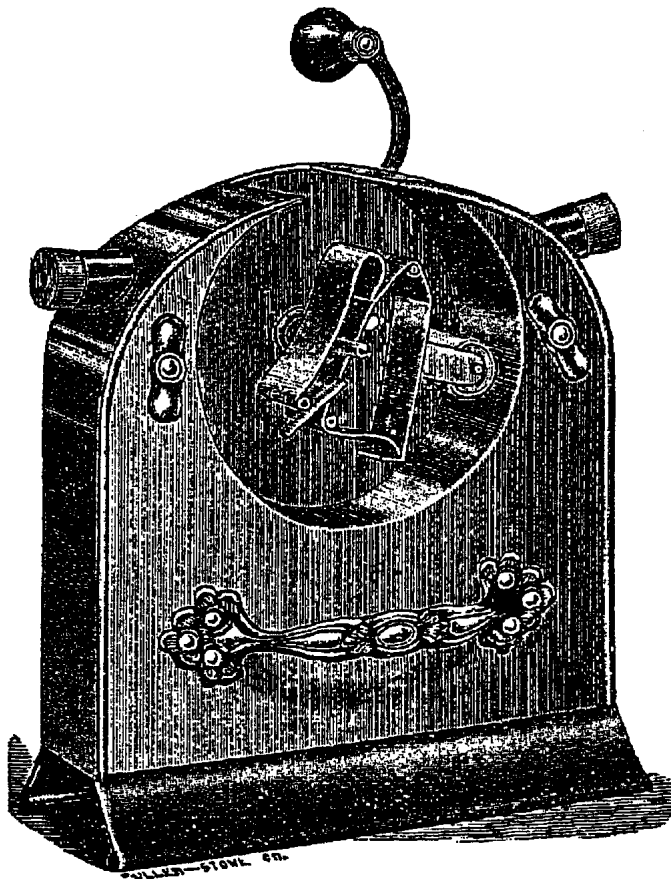


Figure 1. "Surgical Pump" (1887), designed and manufactured by E. E. Allen. Probably the first published illustration of a roller pump for the transportation of blood (15).

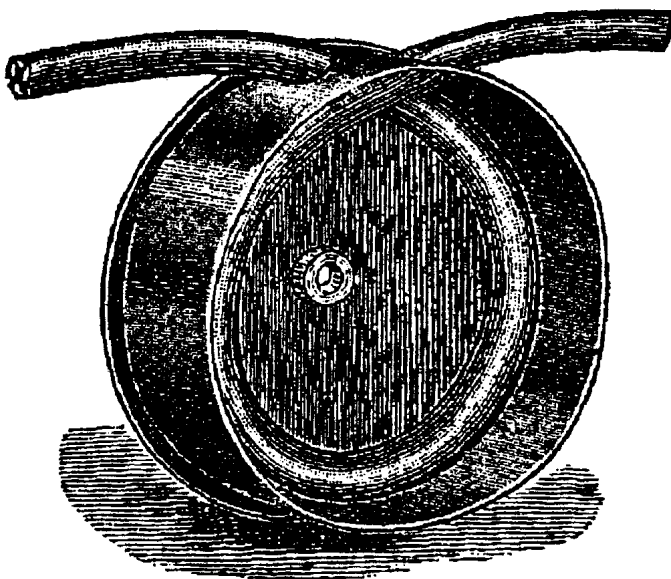


Figure 2. The same pump as in Figure 1: "The invention consists of a rubber tube a yard or more in length, upon which a single loop is formed near the middle, and this loop enclosed in a circular wooden or metal box" (1887) (15).

THE ALLEN SURGICAL PUMP.

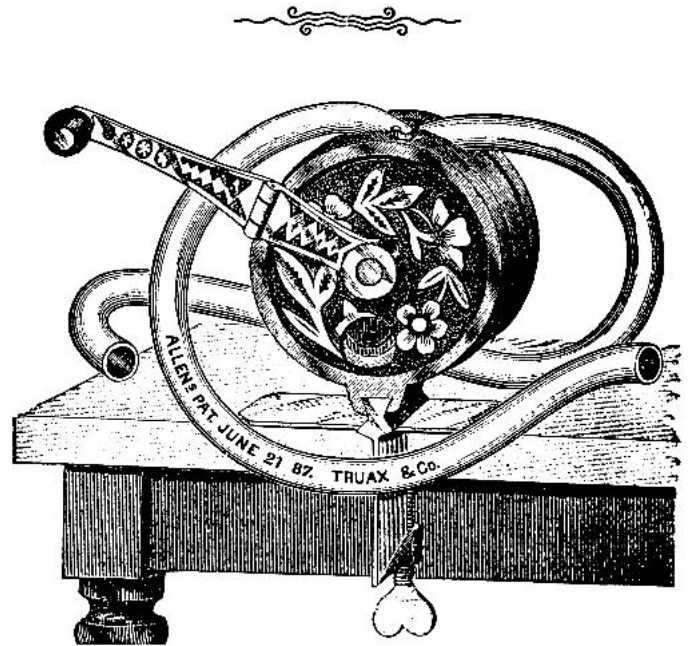


Figure 3. The Allen Surgical Pump (1889), as manufactured and distributed by Charles Truax. From the title page of his prospectus. Note the rich ornamentation on the pump, common at this time (21).

tine cardiopulmonary bypass in some centers, regardless of the higher price as compared to conventional roller pumps (71).

MECHANICAL CIRCULATORY SUPPORT

The first attempts at clinical temporary extracorporeal mechanical circulatory support were mostly undertaken by using nonpulsatile roller pumps in the 1950s and 1960s (72–74). Decades later, nonpulsatile centrifugal pumps

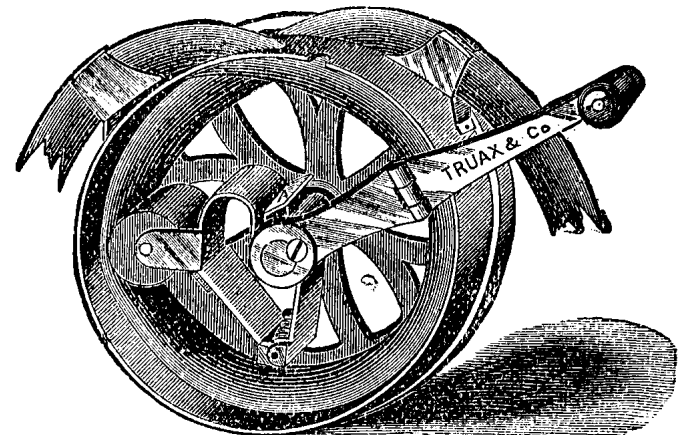


Figure 4. The same pump as in Figure 3, but without cover: "One side of the metal box can be easily removed, so that the intestinal mediastinum can be at once got at, and the tubing removed and replaced by a fresh piece as often as necessary" (20).

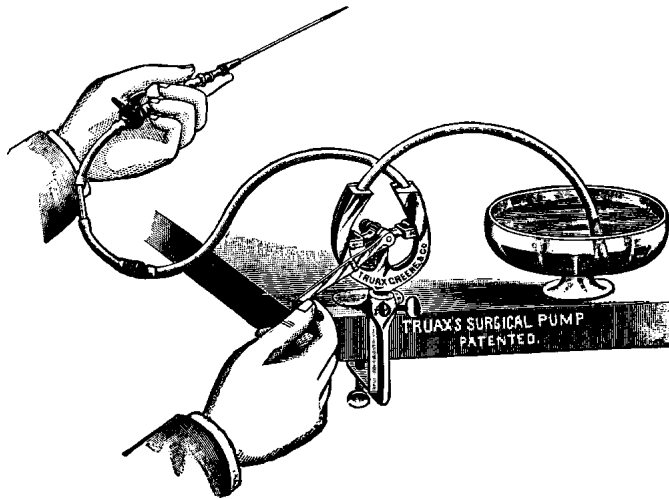


Figure 5. "Author's Surgical Pump (The improved Allen)" (22). The first double roller pump for transportation of blood, improved by Truax (1899): "As the rollers in passing around the circle rest continuously on the tubing completely closing it at some point, there is no necessity for valves."

were used for this purpose (58). Long-term or permanent mechanical circulatory support, however, was first attempted with pulsatile membrane pumps by DeBakey in 1966 and Cooley in 1969 (75,76). Contemporary pneumatic paracorporeal assist devices such as the Thoratec (Thoratec Laboratories Corp., Berkeley, CA), the Berlin Heart (Berlin Heart, Berlin, Germany), the Medos (Medos, Stolberg, Germany), or the extracorporeal Abiomed BVS 5000 (Abiomed, Danvers, MA) are among the most commonly used artificial ventricles. Implantable pulsatile left ventricular assist devices, such as the Novacor LVAS (World Heart, Oakland, CA) or the Heart Mate VE (Thermo Cardiosystems Inc., Woburn, MA) consist of electromechanically powered artificial ventricles with biological valves. Other designs, such as the LionHeart (Arrow, Reading, PA) are fully implantable without transcatheter leads and use mechanical valves. Implantable non pulsatile axial flow pumps, such as the DeBakey MicroMed (MicroMed, Houston, TX), the Jarvik 2000 (Jarvik Heart Inc., NY), Heart Mate II, or Berlin Heart Incor I, are currently being evaluated. Total artificial hearts, such as the CardioWest (CardioWest Inc.) or Abiocor (Abiomed), use the ventricle pump technology with mechanical valves, powered either pneumatically as in the CardioWest or electromechanically as in the Abiocor. Finally, biomechanical devices, such as pumps powered by the patient's own skeletal muscles (*M. latissimus dorsi*), activated by electrical stimulation, have been tested for support of the failing ventricle.

SUMMARY

Both flow modes, pulsatile and nonpulsatile, have been

used for cardiopulmonary bypass and mechanical circulatory support. The history of perfusion starts with continuous flow in experimental organ perfusions, followed by pulsatile blood pumping. In early clinical cardiopulmonary bypass, both pulsatile and nonpulsatile pumps were used. Following the widespread application of heart-lung machines, nonpulsatile roller pumps and later the centrifugal pumps became predominant. Long-term mechanical circulatory support successfully uses both pumping principles.

The principle of pumping blood with a roller pump is more than 100 years old. Only minor modifications took place during this period. This type of blood pump, successfully used by Gibbon in 1953, today—50 years later—is still the pump most often used for extracorporeal circulation procedures, including cardiopulmonary bypass.

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