

The Hemopump, The First Intravascular Ventricular Assist Device

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AQ3 Development of durable left ventricular assist devices (LVADs), based on rotary flow blood pumps, began in earnest after the successful implantation of a catheter-mounted axial flow blood pump *via* intravascular access in 1988. This device, the Hemopump, successfully supported the circulation of a patient in cardiogenic shock secondary to acute rejection of a transplanted heart. Duration of support was 46 hours, resulting in complete recovery of cardiac function and hospital discharge. In effect, this sentinel event demonstrated that continuous-flow blood pumps could be used to support patients in cardiogenic shock. This held true in spite of many widely held paradigms against rotary blood pumps regarding blood damage, diminished pulsatility, and thrombosis. At this writing, 50,000 patients have been implanted with durable LVADs based on rotary blood pumps as a bridge to cardiac transplantation or destination support as long as 10 years. *ASAIO Journal* XXX; XX:00–00.

Key Words: catheter pump, intravascular pump, continuous flow, Hemopump

Background

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On April 24, 1988, I flew to the Texas Heart Institute in Houston, Texas, to perform the first human implantation of a Hemopump with our principle investigator, O. Howard (Bud) Frazier. Two Hemopumps were in my carry-on luggage—still crackling with the smell of ozone fresh from the radiation sterilizer. My mood ranged from great excitement and anticipation to stark terror, tormented by a nagging sense that I did not really know what I was doing. Nimbus, Inc. had embarked on a bold, many said fool hardy, journey to develop a technology that challenged many of the paradigms of the day. Our ignorance was our only defense. The Hemopump was the first catheter-mounted axial flow pump that could be introduced *via* the femoral artery across the aortic valve such that it could assist the left ventricle by pumping blood from the ventricle into the systemic circulation. Most notable was that this was possible while avoiding the risk of major surgery and cardiopulmonary bypass.

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Device Description

The Hemopump system comprised a disposable catheter-mounted pump assembly (**Figure 1**) which included a 7 inch flexible inflow cannula connected to the inlet of a miniature (7 mm diameter) axial flow blood pump with a maximum rotational speed of 27,000 rpm. The flexible inflow cannula was placed retrograde across the aortic valve such that blood could be removed from the left ventricle and pumped into the descending aorta (**Figure 2**). Torque was supplied to the pump rotor by a flexible drive cable within a drive shaft sheath. The flexible drive cable was connected, proximally, to a permanent magnet within the housing. The pump housing was inserted into an external motor which electromagnetically applied torque to the permanent magnet. Sensorless commutation was achieved by back electromotive force (EMF) sensing. Blood was excluded from the pump bearings by means of a continuous flush of 100 cc/d of 40% dextrose infused at the pump console. The Hemopump was capable of producing a nominal flow of 3.5 lpm at a mean aortic pressure of 70 mm Hg.

Although the use of high-speed rotary pumps is commonplace today, in 1982, the proposal to use an axial flow blood pump with an operating speed of 27,000 rpm was heretical, if not delusional. It was widely believed that such a device would be a “waring blender” for blood and that if hemolysis did not kill the patient, nonpulsatile blood flow surely would.

We were doing something radical and unproven, and in spite of the fact that we had completed over 100 *in vivo* studies¹ and *in vitro* durability validation, we still did not know how a patient in cardiogenic shock would respond to an intravascular continuous-flow pump.

We were constantly reminded of the nonphysiologic nature of nonpulsatility, such as the loss of baroreceptor response and the juxtaglomerular response of the kidney. These facts, as Bud reminded me and as Don Quixote had observed, could be the “enemy of truth.”

Would hemolysis be comparable to what we had seen in the animals?

How would circulatory physiology react to diminished pulsatility?

Would something catastrophic happen in humans that we did not see in the animals?

I spent a very restless night.

Patient Selection

I met with Bud early in the morning and we visited two potential candidates. We selected our first candidate, Mr. Herbert Kranich, a recent heart transplant recipient who was in the midst of a profound acute episode of rejection and cardiogenic shock with a cardiac index of 1.8 L/m² and a pulmonary wedge pressure (PWP) of approximately 20 mm Hg and impaired renal function. He was on respiratory support,

Pump Assembly

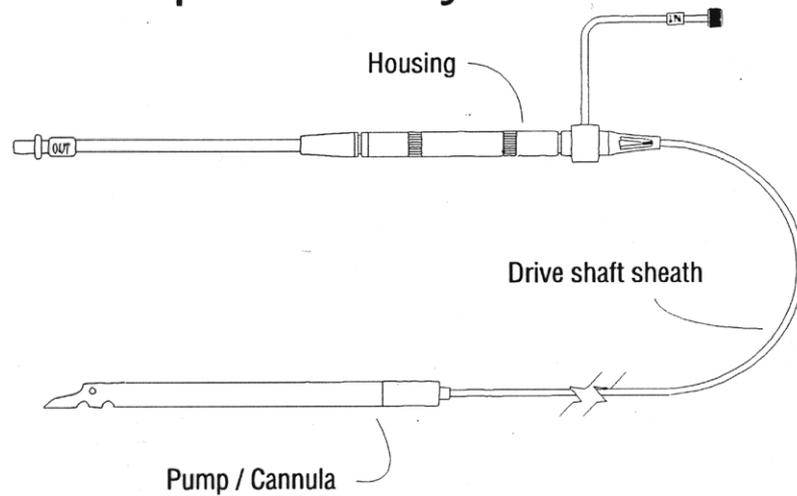


Figure 1. Pump assembly.

intra-aortic balloon pump counter pulsation, and an array of pharmacologic agents. A cardiac biopsy was performed which the cardiologist described as “mushy” and later was read as acute severe rejection, probably not reversible. Prospects for cardiac recovery were grim with an ejection fraction of 27% on maximum therapy. We had no doubt that Mr. Kranich was

at the end of the therapeutic road and that he easily met the criteria for inclusion in the clinical trial. Bud confessed to me years later that he, in part, selected Herb because he was so sure he was going to die that his guilt would be eased if something catastrophic happened with the Hemopump that we had not seen in animals.

Bud introduced me to Herb’s wife Leslie and daughter Adelle. Our summary of the situation felt brutal at the time. We said that people in Herb’s condition had little, if any, hope for survival and that existing therapy was failing. We offered the possibility of enrolling him in a clinical trial with a new technology invented by myself and developed by a team of aerospace engineers at a small engineering company in California (Nimbus Medical, Inc.). Indeed, we previously completed a lot of testing and were quite confident to move to clinical trials. The device seemed to work pretty well in the animals and we had run durability tests in the laboratory. The Food and Drug Administration and The Institutional Review Board of St. Luke’s Hospital had approved the trial. Herb would be the very first patient. We then went over a long list of potential catastrophic adverse events and admitted there was, probably, another list we had not yet imagined. As I listened to our conversation, I was somewhat surprised Leslie and Adelle stayed to the end. I was even more surprised, after all we said about risk, that Leslie gave us permission. Later when I complimented her bravery in signing, she told me that it was, rather, a desperate act of hope.

Case Report

We rushed to the operating room, and under general anesthesia, Bud anastomosed an end to side 10mm woven Dacron graft to the femoral artery. A heparinization dose of 2 mg/kg was given and the activated clotting time maintained at 2.0–2.5 times control with continuous heparin infusion. The Hemopump was introduced into the abdominal aorta, and a silicone rubber plug with a center hole for the flexible drive cable sheath and a 9mm outer diameter was secured to the proximal end of the graft with a ligature to prevent egress of blood. As soon as the pump was in the abdominal aorta, pumping was

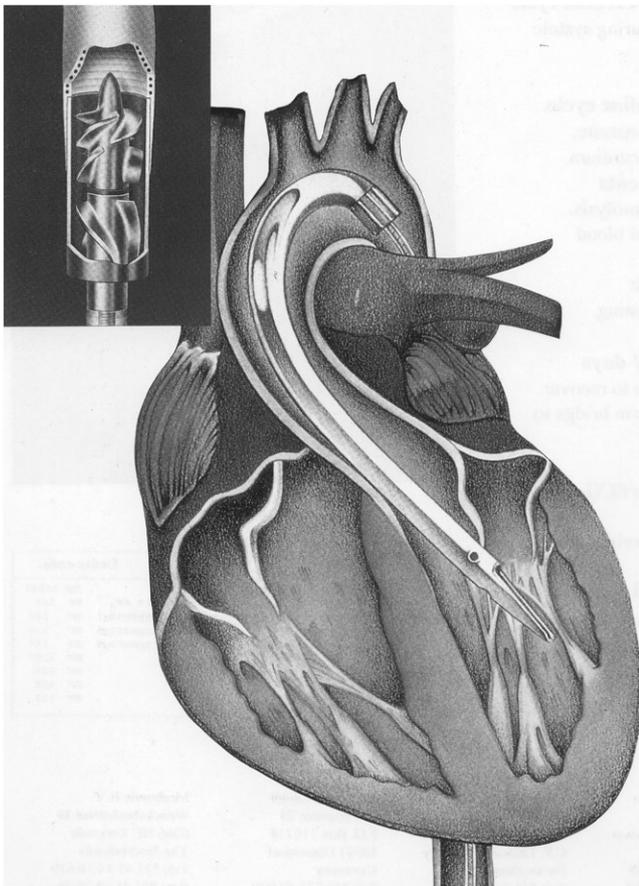


Figure 2. Pump position.

initiated to keep blood moving to prevent thrombus formation. Dr. Wayne Deer, a cardiologist, then advanced the pump up the aorta and readily introduced it retrograde across the aortic valve and into the left ventricle. The insertion into the heart took less than a minute. Acutely, the cardiac output rose from about 3 to 5.5 lpm, but by the time we left the operating room, the flow was back down to the low 3 lpm range. I was initially discouraged with this development since my simplistic surgical reasoning expected the flow of the Hemopump to arithmetically increase the cardiac output. This was the first of many lessons in the “new” physiology and clinical management of continuous-flow pumps. Although Mr. Kranich’s cardiac output was not significantly increased from preinsertion levels of 3 lpm, his PWP fell from the mid 20s to 10mm Hg and some remarkable, unexpected, events unfolded. Vasopressor infusions were reduced to maximize pump flows by decreasing the hydrostatic load on the pump to a mean aortic pressure of 55 mm Hg. This maneuver resulted in peripheral warming, onset of urine production, and normal mentation despite a mean pressure of 55 mm Hg. I began to speculate that the perfusion requirements of a working heart drive the pressure in the aorta and that brain and kidney can function well at these nonphysiologic pressures and with extremely diminished pulsatility. A number of deeply entrenched paradigms would fall in the years to come.

Over the next 46 hours, Mr. Kranich was treated with OKT3 (generic name muromonab-CD3), a new antirejection drug at the time, and he continued to improve with an increase in cardiac output and pulsatility of the arterial pressure. Lightning struck at 46 hours when the flexible drive cable broke with complete loss of support and the onset of some aortic insufficiency through the pump. Ironically, we had not seen drive cable fractures in the animals or the endurance tests. Urgent

removal of the Hemopump was performed at the bedside without anesthesia. The insertion graft was ligated close to the anastomosis and the excess graft excised. The patient tolerated the short period of aortic insufficiency well. It was necessary to reinstitute pharmacologic support but, fortunately, there had been sufficient recovery of myocardial contractility that this setback was overcome.

In spite of all dark prognostications, Mr. Kranich did return home to Colorado with a normal ejection fraction and lived for another two and a half years (Figure 3).^{2,3}

Reflections

After all these years, I can still go back to that moment in Houston, standing by Herb’s bed as he was supported by my invention, in a state of wonder and astonishment as I watched this modern miracle take place—it just does not get any better than that.

After a press conference at Texas Heart Institute, I got my Andy Warhol moment of fame as articles appeared in the New York Times, the Wall Street Journal, Sacramento Bee, and the National Enquirer, to name the most notable. During the press conference, Bud extolled on how amazing it was that this pump, spinning at 2,700rpm, did not damage the blood. As he sat down, I whispered in his ear, “Bud, actually it was 27,000rpm.” Afterward he confided in me that he might not have tried if he had realized it was 27,000 rpm—sometimes ignorance can be a good thing.

I immediately headed to Reno for the annual meeting of ASAIO where we presented a poster. Amidst the media attention, we made quite a splash. I was honored to receive personal congratulations from Dr. Willem Kolff. In this moment of triumph, I did not foresee the disappointments and difficult



Figure 3. Dr. Richard Wampler (left), Mr. Herb Kranich (middle), and Dr. O. H. “Bud” Frazier (right).

struggles to come. Nor did we realize that this “Kitty Hawk” moment in the field of rotary blood pumps would have such a dramatic impact on the field of mechanical circulatory assistance (MCA) and would spawn the development of numerous new rotary blood pumps of all types and description.

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In many ways, as the inventor, the Hemopump was like a child to me, so the failure to make the technology available for clinical use was a bitter disappointment. Even so, I find satisfaction and peace that descendants of the Hemopump such as the HeartMate II and my invention the HeartWare HVAD play a prominent role in the treatment of heart failure. In many ways, the Hemopump may have been ahead of its time, but years after disappearing from the scene, the Abiomed Impella has claimed the mantle of the Hemopump and has taken a prominent position in the treatment of patients.

This accomplishment owes a special debt of gratitude to the village of El Bayad, Egypt, which was the site of my inspiration for the invention of the Hemopump; the story of which follows.

During my surgical residency at the University of Oregon in 1976, I volunteered for a medical missionary trip to a tiny Egyptian village, El Bayad, on the Nile River. I knew that life and health issues in this primitive Bedouin society had changed little since the time of Christ. There was little need for my knowledge in surgery or modern medicine or exotic drugs. Significant impact on the health of the people in El Bayad would best be achieved by addressing sanitation and clean water. It was clear to me that I should become an “expert” on water supplies. And so I read on well design from engineering texts as I flew. And, particularly, I read on deep wells and submersible pumps. Walking along a dusty road next to the Nile River, I observed pumps, based on the ancient principle of the Archimedes screw, drawing water from the Nile River into irrigations canals. In my inventive journey, I have found that it sometimes takes a while to connect the dots. I am sure that I did not once, in the midst of that hot, desolate, primitive, wonderful place, ever think of pumping blood with an Archimedes screw. Nor did I ever consider that the principle of a submersible pump could just as well be a Hemopump sustaining the flow of lifeblood to an injured heart. It was not until 1982, as I began thinking of alternate ways of implementing vascular access for (MCA), that I suddenly found myself in a plane, a book in my hand opened to a diagram of a submersible pump. It was then that serendipity and inspiration helped me connect the dots and the invention of an intravascular blood pump was born. Sometimes the problem has to be reframed and, in a metaphorical sense, rather than taking Mohammad to the mountain, the mountain should be taken to Mohammad. My “eureka” moment imagined a miniature intravascular pump placed inside, not outside the body or heart. Whether or not such an imagined device was technically feasible would take several years.

Herb Kranich and his family, in the midst of a time of great suffering and uncertainty, made a critical contribution to the

field of MCA and I will forever be in their debt. In addition, I am forever grateful to Nimbus Medical, Inc, particularly Ken Butler and John Moise who believed in me when no one else did. We walked a long road together and, although things turned out very differently than we imagined, our contributions came to something. Although the Hemopump failed to achieve business success, it gave birth to the HeartMate II and, ultimately another invention, the HeartWare HVAD, which have changed the left ventricular assist device (LVAD) paradigm from pulsatile to continuous-flow durable technologies and have evolved to a standard of care in the treatment of heart failure.

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This incredible journey of my life has been humbling with a good mix of both joyous successes and soul crushing defeats. Even so, this work has made a difference in ways I never imagined, and on the horizon, I can see the ripples as they spread into uncharted waters and are picked up by others. I am grateful to have shared in the adventure. As of this writing, there have been over 50,000 of rotary ventricular assist devices implanted in patients with severe heart failure. It has been my privilege to meet some of them outside the hospital. On one occasion, I discovered that the bass player at a church picnic was a HeartMate II recipient. His only complaint was that the motor controller produced some noise in his speaker. Last year, I met three HeartMate II ambassadors at the meeting of the International Society of Heart Lung Transplantation in San Diego. There is no way to describe the deep sense of satisfaction and peace that these chance encounters have given me.

Fairy tales end “Happily ever after” in a way that lets you close the cover and feel good. Dickens closed “A Tale of Two Cities” with the sublime ending;

“It is a far, far better thing that I do, than I have ever done; it is a far, far better rest I go to, than I have ever known.”

But the best stories never really end at all. And it is so with the Hemopump, the ending is still unwritten. There are more improvements to be made, battles to fight, and a few more modern day dragons to slay if it is to be finished.

It has been my honor and privilege to have been a part of this journey. I have great hopes for the future; I wait to see what will happen next.

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