In the United States, more than 6.5 million people live with varying stages of heart failure. About 4,000 of those suffer with hearts so compromised that a transplant is the only treatment current medicine can offer. Yet only about half that many transplant-suitable hearts become available each year.

Fortunate patients who do get a match still face heavy challenges. Having already suffered rigors of very advanced heart failure, they then face the trauma of lengthy transplant surgery, with its risks and prolonged deep anesthesia, followed by the side effects of lifelong anti-rejection drugs.

That is the outlook now, but change is coming.

Ralph Metcalfe, professor of mechanical and biomedical engineering, oversees a revolutionary research project with William Cohn, director of the Center for Technology and Innovation at the Texas Heart Institute. Results are so promising that Metcalfe predicts radical improvement in treatment of failing hearts will happen within a decade.

“This device, once perfected, can have as much impact on society as the polio vaccine had in the 1950s,” he says. “Breakthroughs are coming very fast.”
Working under the guidance of Metcalfe and Cohn, mechanical engineering Ph.D. candidate Alex Smith studies how blood flows through a next-generation mechanical blood-pumping device. This will not be like the larger and more cumbersome pumps of past decades, but a small device that can be implanted without major surgery, even removed later if appropriate.

In Texas Heart Institute laboratories in the basement of St. Luke’s Hospital in the Texas Medical Center, Smith focuses on refining the size, shape and angle of a pair of tiny spinning impellers that propel blood through the pump. He also monitors individual blood cells to spot any damage they may incur on their trip through the device.

The goal is to develop better, less invasive treatments that can happen early in the course of cardiovascular problems, long before critical stages of heart failure manifest. Potential benefits are enormous.

“If you look at the causes of death in 2015, the most recently reported year, about 23 percent were related to heart disease. Heart failure is a major part of that,” Metcalfe says.

About two decades ago, Metcalfe witnessed the journey of a colleague whose damaged heart eventually limited his blood flow to only 10 to 15 percent capacity. With such poor blood circulation, cells throughout the body suffer a lack of oxygen, which damages the liver, kidneys, lungs and other organs. “The quality of life goes down very significantly,” he says.

For Metcalfe’s colleague, the call came on Christmas Eve in 1996 that a donor heart was being readied for him. “Usually things go fairly well from there, but not in this case,” Metcalfe said. Despite all efforts, the body rejected the organ and the patient died three days after surgery.

Inspired by what he had witnessed, Metcalfe began to consider the human cardiovascular system. His expertise in fluid mechanics from his original specialty of computational fluid dynamics provided an ideal link with medical innovators’ skills when it came to the challenge of developing much-improved cardiovascular devices.

The device that the team now works to refine offers the potential of saving millions of heart patients, plus improving quality of lives, while it sidesteps the most difficult parts of current protocols. For some patients early intervention might even provide enough rest for the heart to actually heal, something infrequently heard of in today’s state-of-the-art practices.

Back in the lab, performance of the particular heart pumps under study — called LVADs, or left ventricular-assist devices — depends in great measure on the small impellers Smith works hard to perfect. To maintain ideal speed and pressure, the impellers must maintain a flow that is neither so mild the pump is inefficient nor so forceful that cells become misshapen or otherwise damaged by shear in the blood flow. 3D printers replicate Smith’s designs in about eight hours, a process that used to take a machinist months to craft by hand. “This is a huge advance, hard to overemphasize,” says Metcalfe.

Looking back

But we’re getting ahead of the story. The background actually begins in the 1960s when the first artificial hearts were implanted. It was a decade rich with its own scientific breakthroughs. The race to the moon was on. Silicon chips and integrated computer circuits had kicked off an electronics revolution. A vaccine at last foretold victory over polio. And so much more was unfolding.

In medicine, the biggest news was made by human-organ transplants. First a liver was transplanted in Colorado, then hearts in South Africa and later in Houston.

At the Texas Medical Center and its newly chartered Texas Heart Institute, heart-pump research pioneers like Drs. Denton Cooley and Bud Frazier as well as Dr. Michael DeBakey at nearby Baylor College of Medicine
pondered whether an artificial device might become a safe stopgap for patients awaiting transplants of human hearts, or perhaps even become a lasting alternative. Research intensified, and the first implantations of mechanical heart pumps soon followed.

?DeBakey wanted it to happen before a man got to the moon,? Smith says. The first successful total artificial heart was implanted in April 1969, beating the moon landing by only a few months.

Those early artificial hearts were huge and heavy, but only a small part of the mechanism is implanted into a patient?s chest. The rest of the (often noisy) equipment was left outside of the body, either bedside or on a cart that trailed the patient. Survival was measured in weeks at first, then in months. Today, patients often live a decade with their circulatory system at least partially dependent on an implanted mechanical pump with a wearable external battery.

Current artificial heart pumps are not replacements for a biologic heart. Instead, they are assistants that function alongside a weakened heart, helping do the job of pumping blood. These left ventricular-assist devices (LVADs) are implanted close to the patient?s own heart, in the subclavian artery and vein, located in the upper right chest. They most often are considered a ?bridge-to-transplant? treatment, a way to carry a very sick patient until a suitable donor heart is found.

The heavy, bulky equipment that functioned outside a patient?s body may be long gone, but the heart pumps now being implanted are still ungainly enough to cause discomfort.

Tiny miracles

The small device the team is developing fits easily in the palm of a hand. It will be implanted percutaneously, meaning it will be passed through an incision in the skin, most likely into the subclavian vein just beneath the collar bone then carried to the heart?s atrial septum (the wall separating the left and right atria). By contrast, implanting a current heart pump requires a surgeon to make a large chest incision and open the patient?s chest.

These new devices in some cases ? perhaps most ? will be lifelong helpers for the heart. But for some, the device is expected to give the heart enough of a rest that the heart can actually heal. (In the future, stem cells may facilitate the healing.) Intervening early in the disease process, before the heart is too seriously damaged, allows the best chance for such healing to happen.

?It?s like an athlete whose injury is immediately immobilized on the playing field,? Metcalfe explains. ?By being immobilized, the injured area heals quicker. We haven?t been able to immobilize a living heart, of course. But with this device, many unhealthy hearts may get the rest they need and be able to recover.?

If complete healing is accomplished, the LVAD will be removed and the heart left to function on its own, healthy and strong. Those patients could expect full lifespans and enjoy normal lifestyles.

Looking even further into the future, Metcalfe foresees TAHs, total artificial hearts, to be designed along the same concepts as these next-generation LVADs, just more complex.

As the technology races ahead, some basic challenges remain. For example, left-right blood flow must be balanced, Smith points out. In ideal function, a heart?s left side must dependably propel oxygen-rich blood as far down as a body?s toes and, defying gravity, up to the brain. At the same time, its right side must pulse more gently to move oxygen-hungry blood for a refueling through the lungs, located just inches away. A healthy biologic heart instinctively adjusts. A mechanical pump must be designed to respond to differing needs.
Blood-cell shear produces a different challenge. Just as wind shear affects aircrafts? flight patterns, too much speed or pressure can affect blood flow by deforming cells. Excessive deformation under high shear can cause cells to break, burdening the kidneys with the task of cleaning up the pieces of broken cells. On the other hand, a flow that is too slow or under low shear stress can lead to coagulation or clotting.

Blood flow conditions change continuously. Make just one simple cough, Smith explains, and pressure in your lungs and heart spikes sharply then quickly settles again. A well-functioning heart adjusts just fine. A more serious coughing spell does the same but more intensely and for longer ? still not a big deal for a healthy heart. But how do you design a mechanical pump to cope when changes in the environment can be extreme and frequent, and can happen without warning?

?A lot of my work started with managing pressure and flow. Now it?s shifted to the process of energy transfer,? Smith says.

Far reaching studies

Metcalfe, Cohn and Smith are joined by investigators as far as China and as close as the lab next door. The project links UH with the Texas Heart Institute, St. Luke?s Hospital and Rice University in Houston, as well as Soochow University in China, Griffith University and ICETLAB at Prince Charles Hospital in Australia, Gunma University in Japan, and University of Cambridge and University of Bath in the United Kingdom.

In October, Smith presented a paper at the International Society for Mechanical Circulatory Support that will become one chapter in his soon-to-be-completed dissertation. In addition, a paper based on his thesis work has now been accepted for publication in the International Journal of Artificial Organs. Smith came to UH with biomedical engineering bachelor?s and master?s degrees from Texas A&M. His advisor there prompted him to change his career path a bit.

?Not only did he recommend a potential mentor, but also that mentor had a project,? Smith says. Ralph Metcalfe welcomed Smith to the LVAD project and became his advisor for doctoral studies at UH. In addition, Smith joined the Texas Heart Institute in January 2014, gaining Cohn as a second mentor and advisor.

But you could say Smith?s first mentor appeared much earlier and lots closer at hand, with his chemical engineer father joining him in tinkering around the family home in Kingwood, just northeast of Houston.

?My first car had been my mother?s car when she was pregnant with me,? Smith recalls. Over the years, father and son kept the 1983 Volvo running so well that it was recently passed to its next driver. (In case you?re wondering: 500,000 miles and ?green, on what little paint was left.?) Across the hall, just steps from his own Texas Heart Institute lab, Smith?s sister, Stephanie, who followed her big brother into bio-medical engineering studies, works on a different cardiovascular project for the Texas Heart Institute in collaboration with an industrial partner.

Although Smith?s doctoral degree may be in hand soon, he expects his professional involvement in this LVAD project to continue for at least a decade and perhaps far beyond as future developments take him deeper into this revolution in cardiovascular treatments.

© University of Houston Cullen College of Engineering