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Operating on a Beating Heart

Coronary bypass surgery can be a lifesaving operation. Two new surgical techniques should make the procedure safer and less expensive

by Cornelius Borst

After climbing just one flight of stairs, Mr. Patnaki must rest before he ascends to the next story. He feels as though an elephant has stepped on his chest. Such pain results from blockages in Mr. Patnaki's coronary arteries, the vessels that supply oxygen-rich blood to the muscles of the heart. He needs coronary artery bypass surgery but cannot afford the operation and the lengthy hospital stay required. (In the U.S., for example, the surgery and hospitalization cost around $45,000; in Europe, about half this amount.)

Mrs. Wales is an elderly lady crippled by attacks of chest pain after just the slightest movement. Getting up and putting on her clothes takes at least an hour. She badly needs a coronary bypass. Fortunately, she lives near a cardiac care facility, and her medical insurance will pay for the procedure. Yet Mrs. Wales has lung problems and kidney disease, and she recently suffered a stroke. The cardiac surgeon considers it too dangerous to perform a bypass operation on her.

Mr. Brennick runs his own software business from an office at home. He needs triple bypass surgery but fears that the operation will put him out of business by diminishing his programming skills. Heart operations can sometimes impair a patient's brain function, and Mr. Brennick is not willing to take this chance. (Mr. Patnaki, Mrs. Wales and Mr. Brennick represent composite portraits based on numerous patients.)

Coronary bypass surgery is common—about 800,000 people undergo the procedure every year worldwide. But the operation is expensive and risky. To reroute the flow of blood around blockages in coronary arteries, surgeons must graft other vessels (taken from the patient's chest and leg) onto the diseased vessel, past the obstructions. Before doing so, however, they must open the chest (called "cracking" the chest, because the sternum must be split with a saw and the chest cavity spread open). They must then stop the heart, typically for around an hour. A surgeon simply cannot suture a vessel onto the heart accurately while it is still beating.

During the time the heart is stopped, the patient must be put on a heart-lung machine, which artificially circulates blood and supplies the body's tissues with oxygen until doctors restart the heart. This sophisticated machine ushered in the era of modern cardiac surgery some 40 years ago. Yet to this day, the artificial circulation provided by the heart-lung machine remains associated with serious complications, particularly in elderly or debilitated patients. It is the major cause of the long postoperative hospital stay (typically between six and eight days) and often results in a two- or three-month convalescence period at home. Furthermore, people may recover slowly from having had their chest cracked, and they are susceptible to certain infections, including pneumonia, as they recuperate.

In the mid-1990s two surgical techniques emerged that could signal a revolution in coronary bypass surgery. Researchers, including myself, began examining whether the heart-lung machine could be discarded by having doctors actually operate on a beating heart. Other teams have been investigating methods for performing endoscopic surgery on the heart—an operation that requires little more than a few keyhole-size incisions in the chest. I expect that over the next decade, coronary bypass surgery will become dramatically safer and less expensive thanks to these new technologies.

The chest pain experienced by Mr. Patnaki, Mrs. Wales and Mr. Brennick results from atherosclerosis—commonly known as hardening of the arteries—inside the major coronary arteries. Over time, substances such as cholesterol can build up in arterial walls, eventually narrowing these passageways. The disease progresses gradually, but in 19 percent of U.S. men between the ages of 30 and 35, the most important coronary artery has already closed by at least 40 percent. By around middle age, people might notice a bit of chest pain when they exert themselves because the coronary blood flow can no longer keep up with the extra amount required during vigorous activity. A clogged vessel may be likened to a garden hose that won't spray after someone has stepped on it.

People are often crippled by the chest pain of atherosclerosis, and millions around the world have been stricken with this devastating disease. Genetic factors play a role in its development, but diet and lifestyle are also important. Although my emphasis—both in this article and in my research—is on improving therapeutic procedures to treat coronary heart disease, I want to stress that its prevention, through encouraging proper diet, exercise and not smoking, must be the medical community's primary focus.

Once a patient's chest pain has been diagnosed as a symptom of atherosclerosis, drugs may be recommended. Other patients opt for angioplasty, a procedure in which a cardiologist inserts a small, sausage-shaped balloon into the obstructed artery; inflating the balloon reopens the vessel by stretching the diseased wall. In addition, the cardiologist might position a tiny metal structure, or stent, inside the vessel to keep it open. But in some cases, when the cardiologist foresees that the artery will renarrow soon after angioplasty, a bypass is the best option for restoring adequate blood flow to the heart. Coronary bypass surgery usually involves grafting between three and five vessels onto the arteries of the heart. For each bypass graft, surgeons must spend up to 20 minutes carefully placing more than a dozen tiny stitches through both the graft vessel and the coronary artery.

The need to use a heart-lung machine is one of the greatest sources of complications during cardiac surgery. To connect a patient to the device, the doctor must insert tubes in the inflow and outflow vessels of the heart, close off the aorta with a clamp and introduce a cardioplegic solution into the coronary arteries, which stops the heart from beating. This complex procedure can dislodge particles of atherosclerotic plaque from the wall of the aorta. Such debris, if it reaches the brain, can cause a stroke. In addition, the heart-lung machine upsets the body's natural defense system, frequently resulting in fever, organ damage and blood loss; after the operation, it can also leave a patient temporarily unable to breathe without the aid of a ventilator. Finally, when the heart does resume beating, it often shows signs of impaired function: a patient may suffer low blood pressure, reduced blood flow through the body and reduced urine production. In rare cases, the patient cannot be weaned from the heart-lung machine without a mechanical pump to maintain acceptable blood pressure.

Several studies have quantified these hazards. In particular, the likelihood of death soon after coronary bypass surgery increases with age. In the U.S., for example, it rises from a 1.1 percent chance between the ages of 20 and 50 to 7.2 percent between ages 81 and 90. One out of three patients suffers at least one operative complication. A 1997 report on more than 100,000 U.S. health insurance records revealed the dangers posed to bypass patients 65 and older: 4 percent died in the hospital; 4 percent were discharged to a nursing home; and 10 percent were discharged after at least two weeks in the hospital. Memory and attention loss as well as physical weakness and emotional depression often prevent patients from returning to normal activities for at least two or three months.

The practical implications of these potential risks vary. The possibility that a patient will require an extended stay in the hospital, perhaps in the intensive care unit on a ventilator, raises the odds that the final bill will be too high for someone like Mr. Patnaki. People who have a history of stroke, for instance, are more likely to have another one during the operation—which is why Mrs. Wales's physician recommended that she avoid bypass surgery. And the specter of possible memory loss scares away candidates like Mr. Brennick.

For the past 15 years, my research has centered on devising better ways to treat coronary artery disease. By using a mechanical device to stabilize only the clogged vessel, not the entire heart, I believe my colleagues and I may have developed an improved and less expensive surgical therapy for this common disease.

In March 1993 in Palm Coast, Fla., at a workshop for physicians and researchers interested in the use of lasers in medicine and biology, I listened intently to Richard Satava, then a U.S. Army physician. He described a military initiative to design robots that would be remotely controlled by doctors to perform emergency surgery in the battlefield. Satava's photograph showing a prototype robot prompted me to think of using robots to operate on a beating heart inside a closed chest.

While exploring a robotic approach to the surgery, I began to consider the feasibility of operating on a beating heart without such complex and expensive equipment.

The "Octopus"

In the spring of 1994 my colleague at the Heart Lung Institute in Utrecht, cardiac surgeon Erik W. L. Jansen, and I attempted to reproduce an approach to beating-heart surgery developed independently in the 1980s by Federico J. Benetti of the Cardiovascular Surgical Center of Buenos Aires and Enio Buffolo of the Paulista School of Medicine of the Federal University of São Paulo. Benetti and Buffolo had each reported their experiences with human patients; Jansen and I operated first on pigs.

In their work, the two South American doctors immobilized a small region of the heart's surface, which then allowed them to suture the coronary artery bypass successfully. They secured the region of interest with the help of a number of stabilizing sutures placed in tissue adjacent to the bypass site and through the use of pressure, applied by an assistant with a stable hand, who held a large surgical clamp. By restraining only part of the beating heart—just a few square centimeters—they hardly impeded its overall pumping action. Other surgeons, however, found it difficult to master this elegant, simple and cheap approach, and Benetti and Buffolo initially had few followers.

One day in May 1994 in Utrecht, during an experimental operation on a pig, I served as the assistant to the surgeon, charged with holding the clamp steady. Unfortunately, we failed to fully arrest the region of the heart where we wanted to place a bypass graft. But the failure inspired me. Unsteady tissue sutures and the human hand could be replaced by one rigid mechanical gadget to stabilize the heart. Exhilarating weeks followed, in which Jansen was able to construct with ease perfect bypasses on a pig's beating heart with the aid of prototype cardiac stabilizers crafted by technician Rik Mansvelt Beck.

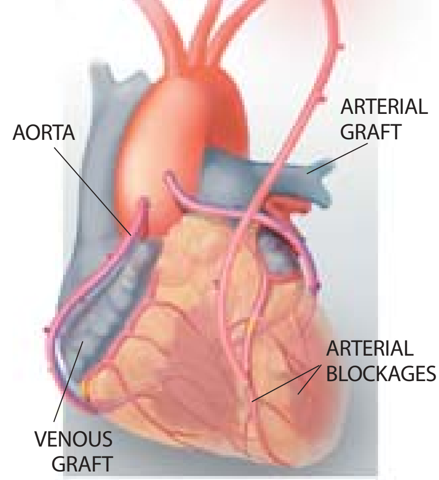
Shortly thereafter my Utrecht colleague Paul Gründeman joined our team, and we invented the Octopus cardiac stabilizer—an instrument that can immobilize any small area on the surface of a beating heart. The name originated from the fact that we use suction cups to attach the instrument to the heart and from "Octopussy," one of the laboratory pigs (all our animals were named after characters in James Bond movies). We first used the Octopus during bypass surgery on a human patient in September 1995. By mid-2000, more than 50,000 people had been treated with the Octopus worldwide (more than 400 of them here in Utrecht; in this select group of patients, the mortality rate, both during the operation and for 30 days afterward, is zero).

As is often the case in medical research, other investigators independently began developing mechanical stabilization devices around this time. In contrast to the Octopus, which holds onto the heart by suction, most of the other devices rely on pressure and friction—they resemble a large surgical clamp pressing on the heart. Currently there are some 13 different types of mechanical stabilizers available to cardiac surgeons. In 1994 fewer than 0.1 percent of coronary operations worldwide were performed without the aid of a heart-lung machine. In 1999 this number was about 10 percent. This year we expect it to rise to around 15 percent and by 2005 to more than 50 percent. At hospitals that lack sophisticated facilities with heart-lung machines—especially those in the developing world—the ability to perform beating-heart surgery will make coronary procedures available to patients for the first time.

Around this same time, Benetti, the surgeon from Argentina, gave the beating-heart approach another boost. He pioneered an operation involving a limited eight-centimeter incision be- tween the ribs on the left side of the chest, which could be used in patients who needed only one bypass graft to the most important coronary artery on the front of the heart. Although this procedure still requires surgeons to separate adjacent ribs, it is significantly less damaging than cracking open the entire chest.

A number of other surgeons quickly recognized the potential advantages of this technique for beating-heart surgery, notably Valavanur Subramanian at Lenox Hill Hospital in New York City and Michael Mack at Columbia Hospital in Dallas. In November 1994 Subramanian showed a video presentation of his technique at a workshop in Rome; as a result, the limited-incision, beating-heart surgery spread quickly through Europe. In addition, Antonio M. Calafiore at the San Camillo de Lellis Hospital in Chieti, Italy, subsequently reported such good results in a large number of patients that beating-heart surgery began to attract worldwide attention. By the start of the first international workshop on minimally invasive coronary surgery, held in September 1995 in Utrecht, several thousand patients had undergone beating-heart surgery.

For the time being, beating-heart surgery will not fully replace traditional bypass surgery. For many candidates, the conventional operation will remain the better choice. But we continue to refine our method, expanding the types of cases for which it can be used. For example, when someone needs a bypass performed on the back of the heart (a common scenario), beating-heart surgery is often difficult. To reach the back of the heart, the surgeon must lift it partly out of the chest. This maneuver, when performed on an active heart, significantly deforms the organ, reduces the amount of blood it can pump and typically leads to a dangerous drop in blood pressure.



GRAFTING BYPASSES onto the heart typically involves attaching between three and five vessels to existing arteries so that blood flow through the bypasses will circumvent blockages. Surgeons can use either arterial grafts (arteries redirected from the vicinity of the heart) or venous grafts (vein segments taken from the leg).

CAROL DONNER (*illustration*)

In the past few years, however, researchers have discovered a number of simple measures that can be taken to avoid this hazard. In my laboratory, Gründeman has shown that tilting the operating table 15 to 20 degrees down, so that the head is lower than the chest, helps to prevent a serious drop in blood pressure. At the Real Hospital Português in Recife, Brazil, Ricardo Lima found another elegant way to expose the back of the heart without compromising blood pressure too much. Most surgeons have now adopted his technique of using the pericardial sac surrounding the heart to lift the organ partly out of the chest.

By mid-2000, close to 200,000 patients had undergone beating-heart bypass surgery with the aid of a mechanical stabilizer. The first round of follow-up studies that we and many other centers conducted indicated that these people experienced fewer complications during surgery, required fewer blood transfusions, remained on an artificial respirator or in intensive care for less time, and left the hospital and returned to normal activities sooner than patients who had undergone traditional cardiac surgery. In addition, preliminary reports for single bypass procedures show that the overall cost was lower by about one third. Virtually all these studies, however, involved carefully selected patients. Thus, the results may not represent the general coronary surgery population. My colleagues and I await definitive results on the risks and benefits of beating-heart surgery that will be available once randomized clinical trials end. The Octopus trial in the Netherlands should conclude in late 2001.

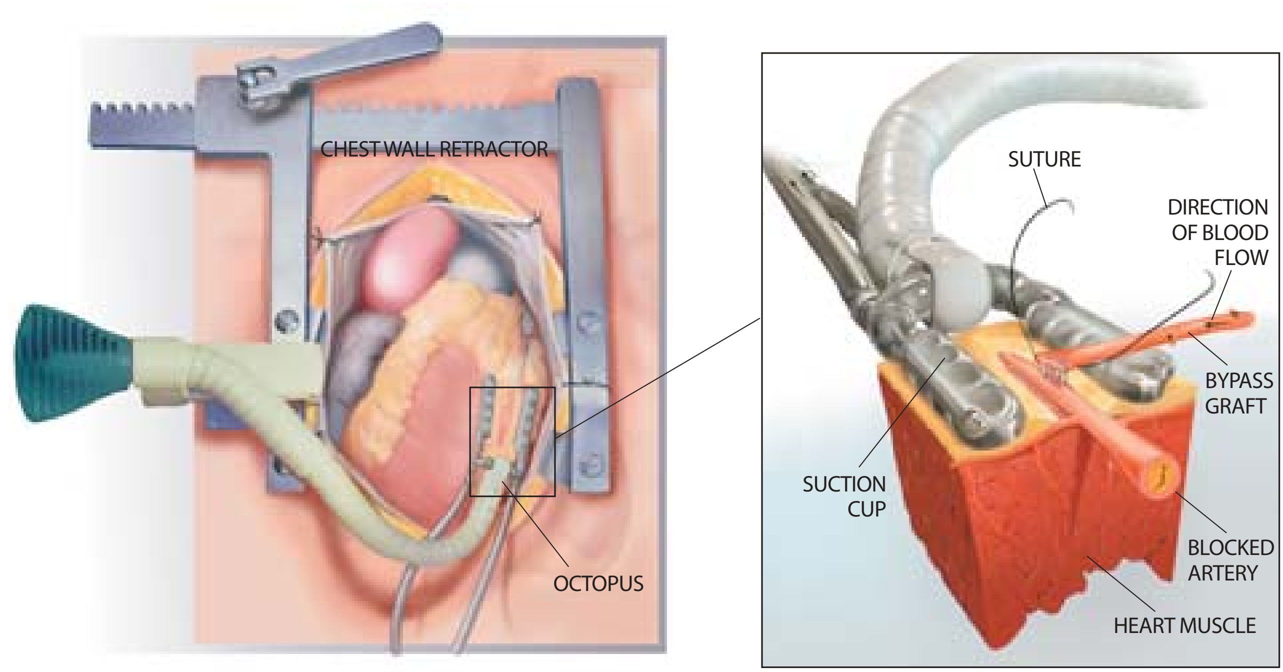
Keyhole Surgery

The crucial advantage of beating-heart surgery is that the heart-lung machine can be turned off. Unfortunately, though, the other major drawback to conventional bypass surgery—the need to open the chest widely—remains. But this should not always be the case. In abdominal surgery, for example, physicians can perform entire operations, such as removing the gallbladder, through small, keyhole-size incisions, thanks to endoscopic surgery. In this technique, doctors insert a rigid tube connected to a miniature video camera (the endoscope) through one incision and the required surgical instruments through two other incisions; a video feed from the endoscope guides the surgeons' movements. So why not operate on the heart in a minimally invasive way, through one-centimeter openings between the ribs?

Researchers at Stanford University took just such a leap in 1991. The Stanford initiative led to the founding of the company Heartport, now in Redwood City, Calif., dedicated to performing closed-chest endoscopic cardiac surgery on a stopped heart with the patient hooked up to a heart-lung machine.

To connect a Heartport patient to the heart-lung machine and to stop the heart without opening the chest, various tubes and catheters required for the task had to be manipulated from the groin area. This procedure did not go smoothly in all patients. Furthermore, the actual bypass suturing proved even more demanding. Because of the limitations of conventional endoscopic surgical instruments and the tight maneuvering space in the closed chest, these initial attempts to operate on the heart endoscopically had to be abandoned after just three patients. Only by making larger incisions (between six and nine centimeters) could surgeons reliably suture grafts to the coronary arteries. By mid-2000, more than 6,000 coronary patients had been treated in this manner.

Ideally, cardiac surgeons would like to perform a truly minimally invasive bypass operation: closed-chest, beating-



OCTOPUS HEART STABILIZER immobilizes an area on the surface of the beating heart so that surgeons can accurately suture a bypass graft. The Octopus, invented by the author and his colleagues, uses suction to take hold of a small region of the heart; tightening the blue knob anchors the Octopus to the metal device used to retract the chest wall (*left*). Although the heart continues to beat almost normally, the graft site (*right*) remains virtually still, allowing the surgeon to suture a bypass to the blocked artery.

heart coronary surgery. To avoid the restrictions of conventional endoscopic instruments, researchers—proceeding with great caution—have begun to use robotic endoscopic surgery systems for such operations. In these systems, the surgical instruments are not controlled directly by a surgeon's hands but instead by a remotely operated robot. Doctors can see inside the chest cavity in three dimensions, and their hand motions at the computer console are accurately translated to the surgical instruments inside the chest. Indeed, the computer automatically filters these motions to remove natural tremor and thus actually augments precision.

The first surgeons to take advantage of robotic equipment for closed-chest coronary surgery (but with a heart-lung machine) were Friedrich Mohr, Volkmar Falk and Anno Diegeler of the Heart Center of Leipzig University, and Alain Carpentier and Didier Loulmet of the Broussais Hospital in Paris. Working in 1998, in a renewed attempt to apply the original Heartport arrested-heart approach, these doctors combined Heartport with the so-called da Vinci robotic endoscopic surgery system, which was developed by Intuitive Surgical in Mountain View, Calif.

In September 1999, at the University of Western Ontario Health Center in London, Ontario, Douglas Boyd utilized the Zeus robotic surgical system, which was developed by Computer Motion in Goleta, Calif., to perform the first computer-assisted, closed-chest, beating-heart surgery. But in contrast to the two hours that a single bypass, limited-incision operation on a beating heart usually requires, this first procedure lasted most of the day. By mid-2000, however, surgeons at five centers—in Munich, Leipzig, Dresden, London, Ontario, and London, England—had reduced operating-room time to between three and five hours for some 25 successful closed-chest, beating-heart, single-bypass operations.

Robotic techniques such as those required for a closed-chest operation are likely to become an integral part of the operating room. As the technology advances, surgical residents might one day be able to practice endoscopic coronary surgery just as pilots practice flying aircraft, and physicians might be able to rehearse upcoming operations. Other innovations may further facilitate the surgical treatment of coronary heart disease. For example, a "snap" connector in development may allow surgeons to attach a bypass rapidly without sutures.

Ultimately, the coronary bypass operation may very well become extinct. In the meantime, however, improving coronary surgery while keeping the cost reasonable remains an important goal—particularly because such advancements could make surgical interventions against coronary heart disease available worldwide to every patient who needs them. But regardless of new developments in surgical techniques, prevention of coronary heart disease must remain at the top of the medical agenda. SA

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Further Information

Minimally Invasive Coronary Artery Bypass Grafting: An Experimental Perspective. Cornelius Borst and Paul F. Gründeman in *Circulation,* Vol. 99, No. 11, pages 1400–1403; March 23, 1999.
Minimally Invasive Cardiac Surgery. Edited by Robbin G. Cohen et al. Quality Medical Publishing, 1999.
Minimal Access Cardiothoracic Surgery. Edited by Anthony P. C. Yim et al. W. B. Saunders Company, 2000.

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