Originally published in June 1998

Defibrillation: The Spark of Life

In the 50 years since doctors first used electricity to restart the human heart, we have learned much about defibrillators and little about fibrillation

by Mickey S. Eisenberg

The operation had gone well. There was a brief period of fast heart rate, when the ether was given, but that was easily controlled with digitalis. The two-hour surgery had been technically demanding. The 14-year-old boy's congenitally deformed chest allowed respiration only 30 percent of normal. The task of the attending surgeon, Claude S. Beck, was to separate the ribs along the breastbone and repair nature's botched work. Beck relaxed as the easy part began. But as the 15-inch wound was being closed, triumph abruptly turned to crisis: the boy's heart stopped. Beck grabbed a scalpel, sliced through his sutures, enveloped the heart in his hand and rhythmically squeezed. He could feel the heart's ineffective quivering and knew at once that it had gone into the fatal rhythm called ventricular fibrillation. In 1947 no one survived this rhythm disturbance, but that did not deter Beck.

He called for epinephrine and digitalis to be administered and calmly asked for an electrocardiograph and a defibrillator, all the while continuing to massage the boy's heart. It took 35 minutes to obtain an electrocardiogram, which—wavering and totally disorganized—confirmed the distinctive appearance of ventricular fibrillation. Ten minutes later assistants wheeled in an experimental defibrillator from Beck's research lab adjoining the University Hospitals of Cleveland. Beck positioned the machine and placed its two metal paddles directly on the boy's heart. The surgical team watched the heart spasm as 1,500 volts of electricity crossed its muscle fibers. Beck held his breath and hoped.

The goal of a defibrillatory shock is to jolt the heart into a momentary standstill. With the chaotic pattern of contractions interrupted, the cardiac muscle cells have the chance to resume work in an orderly sequence again. The first shock did not work, and Beck began open-heart massage again while calling for additional medications. Twenty-five minutes passed, and Beck ordered a second shock. This time the shock blasted away the fibrillatory waves, and a normal

rhythm ensued. Three hours later the boy responded appropriately to questions and went on to make a full recovery.

Beck realized the significance of this first successful human defibrillation. In the 1940s the nation was in the midst of an epidemic of coronary artery disease—an epidemic that continues today and one that remains the leading cause of death in adults. Beck knew most coronary deaths, especially from sudden cardiac arrest, were triggered by ventricular fibrillation. Ventricular fibrillation is the fatal rhythm in some 65 percent of cardiac arrests. About 3 percent of arrests are caused by ventricular tachycardia (a very fast heart rate), which usually deteriorates into fibrillation, and the remainder is the consequence of an asystolic (flat line) rhythm or a rhythm called pulseless activity (a flaccid heart unable to contract).

The exact cause of ventricular fibrillation is poorly understood. In many instances, it is triggered by a partially or completely occluded coronary artery causing an ischemic—and irritable—area of muscle in the heart. But sometimes the heart goes directly into ventricular fibrillation without an obvious cause. At the instant of fibrillation, the heart pumps no blood, so the pulse ceases and the blood pressure falls to zero. This is called clinical death, and it will turn into irreversible biological death if circulation is not restored within minutes.

Ventricular fibrillation, though it occasionally happens during surgery, most often occurs outside a hospital setting, during routine activities. Of the 350,000 sudden cardiac deaths a year in the U.S., 75 percent happen at home, striking people who are in the prime of their lives.

In 1947 Beck's only option was to reopen the chest and manually compress the heart. Cardiopulmonary resuscitation (CPR), as we know it today, would not be invented until 1960. Beck knew that manually compressing the heart only bought time—electricity was (and remains) the only means for treating ventricular fibrillation. For a decade, Beck had developed and perfected his machine, defibrillating hundreds of dogs, but he needed to demonstrate its lifesaving potential on a human. One case was all he needed. He published a report in the *Journal of the American Medical Association* and immediately proselytized physicians to recognize fibrillation and learn how to use defibrillators.

Beck envisioned being "at the threshold of an enormous potential to save life." He saw the defibrillator as the tool for dealing with, to use his expression, "hearts too good to die"—hearts that would remain undamaged if the defibrillation could occur quickly enough. His expression is apt because a heart that is successfully defibrillated usually has many years of mileage left; a heart that fibrillates is like a million-dollar piece of equipment failing because of a 20-cent fuse.

Fifty years later is a good time to ask whether Beck's vision has been achieved. Did the world embrace his invention? Has its huge potential been realized? What does the future hold?

Beck's defibrillator was a large, ponderous machine. It used alternating current directly from a wall socket and required a bulky and heavy step-up transformer. The voltage, usually 1,000 volts, was applied for a quarter or half of a second. The machine was barely portable, although wheels gave it some mobility. Its biggest drawback was the supposed need to place its metal paddles directly on the ventricles, because not enough was known about how much electricity to use to shock through the chest. But it was a start. From such humble beginnings, defibrillators have grown smaller, smarter and far more sophisticated. As the technology developed, so did the clinical applications.

Shortly after Beck's 1947 report, defibrillators were placed in operating rooms throughout the Western world. But they would remain in operating rooms and have very limited use so long as the chest had to be opened and the paddles placed directly on the heart. This problem was solved in 1956 by Paul M. Zoll of Harvard Medical School, who demonstrated that defibrillation could successfully occur across an intact chest. Now the device could move to the rest of the hospital. Defibrillators began appearing in emergency departments as well as coronary care units.

Because defibrillators were large and inherently stationary and required alternating current to operate, they were confined to hospitals. To leave the hospital, defibrillators had to become portable, and there had to be a way of bringing them to patients where they lived. The obstacles were overcome in 1960 by Bernard Lown of the Harvard School of Public Health and K. William Edmark of the University of Washington. They demonstrated not only that defibrillators could be powered by direct current but also that these DC machines were, in fact, safer because there were fewer postshock complications such as heart blocks or other difficult-to-treat rhythm disturbances. Also, direct current allowed relatively portable batteries to power the device and used capacitors for collecting and concentrating the charge. Although these first-generation battery-powered devices weighed 35 pounds, portable defibrillators could at last enter the community. Now all that was needed was a means to transport them to the patient.

At Royal Victoria Hospital in Belfast, Northern Ireland, two cardiologists saw the mounting toll from coronary artery disease—an almost invisible carnage because it was occurring before their patients were admitted, usually within an hour of symptoms. J. Frank Pantridge and his colleague John S. Geddes reasoned that the only way to reach patients dying from ventricular fibrillation was to go after them directly in their homes. Resurrecting an old ambulance, they established the world's first mobile intensive care unit in 1966. The unit was staffed with a doctor and nurse and equipped with a jerry-rigged defibrillator powered by two 12-volt car batteries.

Success came slowly, but within 18 months they had accumulated enough experience to publish their findings in the international medical journal *Lancet*. Of groundbreaking importance: information on 10 patients with cardiac arrest. All had ventricular fibrillation, and all were resuscitated and admitted to the hospital. Five were subsequently discharged alive.

An Evolving Technology

The concept spread rapidly. By the late 1960s programs to implement mobile intensive care units were established in several cities. The U.S. version replaced the doctor and nurse with specially trained individuals called paramedics. For the first time in history, people dying suddenly in the community were being brought back to life. Paramedic programs delivering advanced emergency care are now found in virtually every urban and suburban area of the U.S. and in many Western countries.

But paramedics and ambulances are not enough. When a person goes into defibrillation, every minute counts, and waiting for an ambulance to arrive eats away at precious time. Clearly, it would be beneficial to have defibrillators in the hands of a still wider group of laypeo-

ple or emergency service personnel.

Up into the 1970s defibrillators were manually operated. The operator—doctor, nurse or paramedic—had to interpret the cardiac rhythm on a small oscilloscope and then, if ventricular fibrillation was present, apply the paddles and shock the patient. To bring defibrillators to a larger audience, the device would have to become easier to use. The next technological evolution provided just that. In the 1980s the defibrillator grew "brains." Computer algorithms, able to detect ventricular fibrillation, were incorporated into standard defibrillators. Such "smart" defibrillators, known as automatic external defibrillators, interpret the patient's rhythm and will deliver a shock only if ventricular fibrillation is present. Using voice-chip technology, automatic external defibrillators, some weighing as little as four pounds, "talk" to the operator and coach him or her through the procedure. Smart defibrillators spread the technology to another level of emergency care, namely, the hundreds of thousands of medical technicians who staff basic ambulance services.

Each new technological breakthrough has seen a corresponding increase in the number of defibrillators and the situations in which they are used. Today there are more than 250,000 defibrillators in the U.S. Some 110,000 are deployed outside hospitals, and perhaps half of those are automatic external defibrillators.

The American Heart Association launched a public-access defibrillation effort in 1994, advocating automatic external defibrillators in the hands of first responders and other public personnel (such as police and security guards). Clearly, we are on the cusp of another surge in defibrillator availability. There is no question that efforts to place more defibrillators in the community and into the hands of public personnel will be useful. But the payoff will be small because most cardiac arrests do not happen in stadiums or shopping malls; they happen in bedrooms and living rooms. In Seattle and King County, Washington, for instance, only 15 percent of cardiac arrests occur in public locations.

The promise for defibrillators will most probably be realized only when they become consumer products and can be purchased at the neighborhood pharmacy. For this to happen, the price must be made affordable, and the Food and Drug Administration would have to allow companies to market defibrillators to consumers. Currently automatic external defibrillators are prescription devices that cost $3,000, although it is likely that mass production (on the scale of one million units a year) could lower the selling price to $350. There is nothing inherently dangerous about an automatic home defibrillator, because the device shocks only for ventricular fibrillation and will not allow a shock to be delivered if the condition is not present. One day consumer automatic external defibrillators may be as common as fire extinguishers in the home.

Small Enough to Implant

The concept of building smaller, more intelligent defibrillators and moving them from the operating room to people's living rooms can be logically carried even further. Why not place the defibrillator in the person's chest? This is exactly what Michel Mirowski of Sinai Hospital of Baltimore did after a tragic personal experience in 1966. His mentor and friend was hospitalized for recurrent heart arrhythmias unresponsive to medications and required constant monitoring and repeated defibrillatory shocks in the coronary care unit. The friend chose not to live his life in the hospital and, against advice, checked himself out. He died days later. Although there was nothing anyone could do then, Mirowski vowed to solve the problem.

Working in a basement laboratory at Sinai and without research funding, Mirowski and his colleague Morton M. Mower set out to miniaturize defibrillators and implant them in the chests of high-risk patients. After prototypes were tested on dogs, the first human implantation occurred in 1980 at Johns Hopkins Hospital. It was a success. Another five years of clinical testing passed before the device received FDA approval.

The first marketable implantable defibrillators were the size of a Walkman and weighed 12 ounces. Because of their size and weight, they had to be placed in a skin pocket in the abdomen with wires and electrodes running to the heart. Open-heart surgery was required because the electrodes had to be sewn directly onto the heart's ventricle. The device constantly monitored the heart's rhythm, and if it detected fibrillation, it charged its capacitors and its battery delivered a shock of 34 joules. The lower energy, compared with 200 or 300 joules for standard external defibrillation, was sufficient because it was applied directly to the heart and did not have to travel through the chest.

Implanting a defibrillator was major surgery, to be undertaken only in the most dire circumstances. But it was a start, and it demonstrated that lives could be saved. From 1985 until today, several generations of implantable cardioverter defibrillators have been developed. Each generation has resulted in a smaller and more sophisticated device. The latest version weighs only three ounces, small enough to be placed under the skin in the upper chest, similar to a pacemaker. The titanium can housing the device serves as one of the electrodes, and a single wire, threaded through a large vein directly into the heart, acts as the other. Thus, open-heart surgery is not needed, and placement is a simple, one-hour outpatient procedure. The most recent designs have a battery life of eight years. They can also store hours of sensing and electrocardiographic information that can then be downloaded through the skin, enabling the cardiologist to diagnose and troubleshoot ongoing problems. Such technology does not come cheap: these defibrillators cost $30,000, plus another $15,000 to $20,000 for implantation. In the U.S., more that 100,000 such devices have been implanted to date. At a projected rate of 30,000 a year, it is a $1-billion-a-year industry.

The Definitive Solution

Claude Beck would be amazed if he could see today's defibrillators. Smart defibrillators and three-ounce devices implanted in patients are advances inconceivable in 1947. But have these 50 years of development achieved defibrillation's promise for saving lives? The answer is a resounding no. Despite hundreds of emergency medical service programs and thousands of paramedics trained in defibrillation, only a tiny proportion of cardiac arrest victims are saved every year in the U.S. The small number (at best a few thousand) is not higher because defibrillation occurs too late. A strategy based on rushing defibrillators to collapsed individuals is destined to achieve minimal success.

The sad reality is that we do not understand the cause of fibrillation and cannot predict it, and therefore we cannot put defibrillators in the hands, and chests, of everyone who might benefit

from them. (Twenty percent of ventricular fibrillation cases occur in people who have not been diagnosed with heart disease.) We can only speculate that its triggers include ischemia (insufficient blood to part of the heart muscle, making it irritable); electrolyte abnormalities; autonomic imbalances, caused by abnormal surges in hormones such as adrenaline; drugs; and inherited disorders.

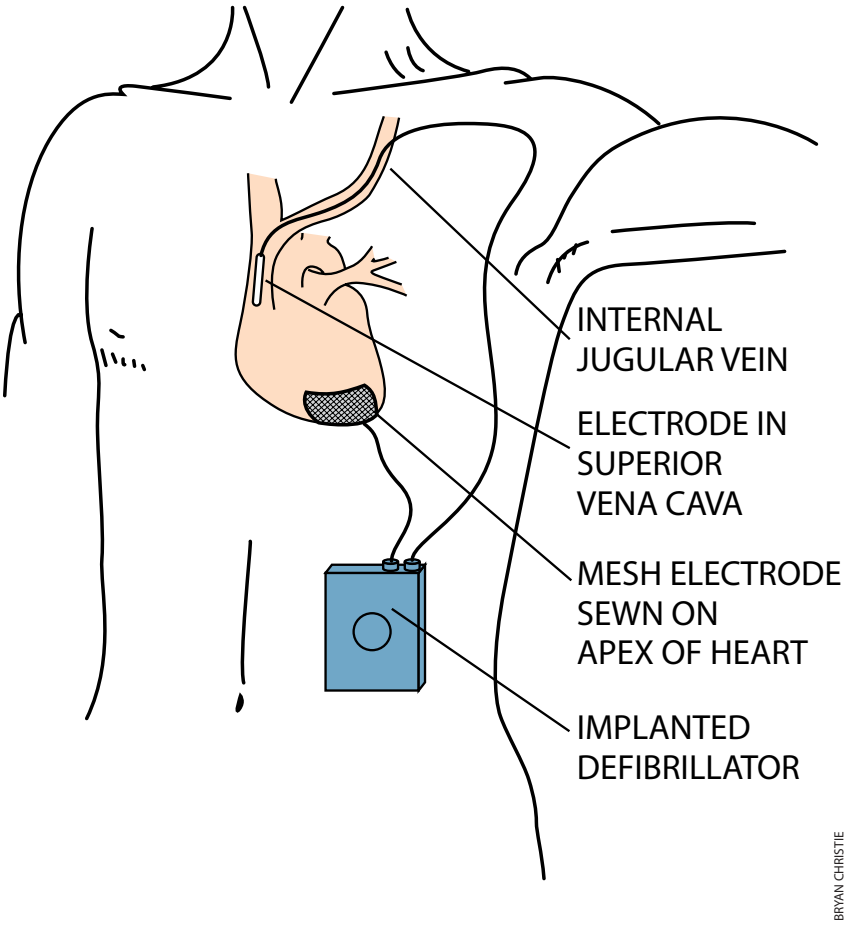
In fact, we know very little about why defibrillation works in the first place. It is believed that the electrical shock simultaneously depolarizes every muscle fiber in the heart, allowing its internal timing mechanism to reset and return to normal. In a way, it is like rebooting a computer that has suddenly and mysteriously seized. Not only can we not predict it, but we also cannot prevent it. Whether the future brings widespread availability of consumer automatic external defibrillators or liberalized indications for implantable devices, it is important to realize that the only definitive solution to the problem of ventricular fibrillation lies in prevention.

For now, rapid defibrillation offers the only hope for victims of sudden cardiac death. Defibrillators seem to epitomize medical high technology and offer thousands of patients the promise of extended life. Yet within that promise lies a paradox first described by essayist and physician Lewis Thomas. What we think of as high technology—in this case, defibrillation—is really low technology, because we have only a rudimentary understanding of the disease.

The highest level of medical technology is the least expensive and comes about only with a good understanding of the disease—vaccination, for example. The lowest level is very expensive and results from treatment of the ravages of the disease rather than its prevention. We can miniaturize defibrillators and place them in people's chests. But we do not yet know what causes the heart suddenly to fibrillate. And we cannot yet define the harbingers of ventricular fibrillation.

Fifty years have witnessed astounding technological and clinical progress in defibrillation. Yet the problem of ventricular fibrillation still looms as the leading cause of death in adults. I would have to say Beck's vision is only 50 percent achieved. When home defibrillators are approved, perhaps the enormous potential of defibrillation will finally be attained.

But this will be a false victory. The true victory will occur when we understand ventricular fibrillation and can prevent its occurrence. Wouldn't it be nice one day to view a defibrillator as an outdated piece of low technology? SA



THE EARLIEST IMPLANTABLE defibrillators (*above*) were relatively bulky affairs of 12 ounces implanted in the abdomen, with electrodes running directly to the apex of the heart and the superior vena cava.

The Author

MICKEY S. EISENBERG is professor of medicine and adjunct professor of epidemiology at the University of Washington and director of the emergency medicine service at the University of Washington Medical Center. He received a B.A. from the University of Michigan, an M.D. from Case Western Reserve University and an M.P.H. and Ph.D. from the University of Washington. Eisenberg has been investigating sudden death for the past two decades. He is the author of 20 books and 80 scientific articles dealing with emergency medicine and sudden cardiac death, including a history of cardiac resuscitation entitled *Life in the Balance: Emergency Medicine and the Quest to Reverse Sudden Death* (Oxford University Press, 1997).

Further Reading

VENTRICULAR FIBRILLATION OF LONG DURATION ABOLISHED BY ELECTRIC SHOCK. C. S. Beck, W. H. Pritchard and H. S. Feil in *Journal of the American Medical Association,* Vol. 135, pages 985–986; 1947.

A MOBILE INTENSIVE-CARE UNIT IN THE MANAGEMENT OF MYOCARDIAL INFARCTION. J. F. Pantridge and J. S. Geddes in *Lancet,* No. 7510, pages 271–273; August 5, 1967.

SUDDEN CARDIAC DEATH. M. S. Eisenberg, L. Bergner, A. P. Hallstrom and R. O. Cummins in *Scientific American,* Vol. 254, No. 5, pages 37–43; May 1986.

DEFIBRILLATION OF THE HEART. W. A. Tacker et al. Mosby, 1994.

If You Don't Have a Defibrillator

by Carl E. Bartecchi

Cardiopulmonary resuscitation, commonly known as CPR, can save the lives of victims of ventricular fibrillation and its common predecessor, ventricular tachycardia. Nationwide, however, the technique successfully salvages fewer than 5 percent of out-of-hospital cardiac arrests. The reasons are sobering. The elderly, who need it most often, are least likely to have CPR training. Bystanders are unlikely to respond because of concern for their own health in this era of AIDS, hepatitis and drug-resistant tuberculosis. Also, although cardiac arrest tends to occur in the home, most family members of cardiac patients remain unfamiliar with CPR techniques. And the hyperacute atmosphere surrounding cardiac arrest does not lend itself to the clear, methodical process taught in CPR courses.

There is an alternative to CPR that is simple and easily learned, especially by the elderly. It features maneuvers that can be performed quickly—during the four- to six-minute window of opportunity for restoring circulation and oxygenation. As with basic CPR, one should not expect these steps to be successful in a high percentage of cases. The nature of cardiac arrest itself, together with age and underlying problems, may make saving the victim impossible. Yet simply doing *something* can sometimes save a life. Chest compressions alone, for example, can keep a person alive for a few minutes until trained medical help arrives. The important lesson to remember is to do something and to do it fast.

What to Do

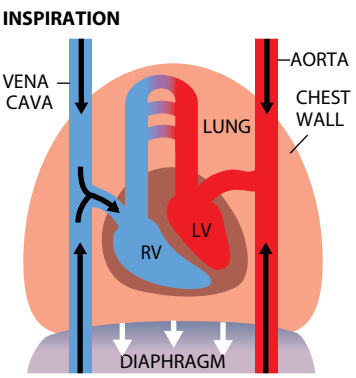
When an individual suddenly collapses, first quickly check for pulse or heartbeat. If one is present, raise the victim's legs two feet above the plane of the reclining body (to augment fluid return to the central circulation); then, call for medical assistance.

If there is no pulse, immediately suspect cardiac arrest. Check the airway for obstruction and clear it. Because most victims resuscitated from cardiac arrest have ventricular tachycardia or ventricular fibrillation, assume that is the problem and follow one of these two procedures:

Cough

If the victim is conscious and capable, he or she should be encouraged to cough vigorously once or twice. Forceful coughs have been shown to transmit a small amount of current to the heart capable of terminating these catastrophic dysrhythmias and allowing for an effective cardiac rhythm to be reestablished. This maneuver is especially suited for self-administration; a patient with known cardiac disease who suddenly feels palpitations in the chest followed by lightheadedness and the feeling of impending loss of consciousness could do little harm by bringing forth one or two vigorous coughs.

ILLUSTRATIONS BY DANA BURNS-PIZER



During the cough's inspiratory phase, the downward movement of the diaphragm facilitates the return of blood from the body to the heart's right ventricle and even oxygenates the blood flowing through the lungs at that time. During the expiratory phase, contraction of the abdominal muscles forces the diaphragm into the chest cavity, generating high pressures that are applied to the heart and its associated large blood vessels, which in turn propels blood through the open heart valves to the brain and other organs.

Regular, repeated, forceful coughs—at a rate of up to 60 per minute—can be as effective as classical CPR in providing blood flow to critical organs, thus supplementing the stricken heart. Cough CPR has proved effective for approximately 90 seconds, although isolated cases for up to five minutes have been reported. The only problem is that the patient is certain to develop fatigue. But cough CPR can buy time.

Thump

If the patient is not capable of coughing, one or two thumps to the midchest can be given with a clenched fist within no more than one minute of collapse. The thump should be applied from six to eight inches above the chest and directed at an area about two thirds of the distance down the breastbone. Should the first blow not result in a pulse, a second, stronger blow should be given immediately. The thump can also be self-administered.

It is not known how the thump procedure works, although it is suspected that the thump causes a mechanoelectrical stimulus that terminates the undesirable rhythm disturbance.

CARL E. BARTECCHI is clinical professor in the department of medicine at the University of Colorado Health Sciences Center.