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Surgical Treatment of Cardiac Arrhythmias

To save the life of a doomed patient, the author and his colleagues developed a now standard surgical procedure for correcting lethally fast heartbeats in many people susceptible to them

by Alden H. Harken

In 1978 a vice president of a bank in Philadelphia collapsed at work when his heart began to beat dangerously fast. Fortunately, his co-workers were able to administer cardiopulmonary resuscitation immediately, keeping him alive until emergency medical workers arrived. He was soon brought to the Hospital of the University of Pennsylvania, where I was a junior member of the surgical faculty.

Little did either of us know that within weeks of this episode we would participate together in making a small piece of surgical history. Desperate to prevent the banker's imminent death, my colleagues and I devised a new surgical treatment to correct the underlying disturbance that caused his heart to malfunction. Since then, hundreds of other patients have been aided by this therapy. At the same time, further research has expanded insight into why our treatment strategy, born of necessity, proved so useful.

I well remember our initial evaluation of the banker's medical condition because we were in for a surprise. When he first appeared at the hospital, we suspected he had suffered a heart attack (myocardial infarction): the death of cardiac muscle after blockage of an artery feeding that tissue. But tests told a different story. Indeed, the muscle was in good shape, except for a small area that had been damaged during a heart attack several years before.

His heart had malfunctioned now because it became suddenly and lethally unstable electrically. The electrical wiring system that regulates the heartbeat induces the cardiac muscle to contract and thus push blood into the arterial circulation some 72 times a minute. The man's muscle had begun to receive much more frequent signals, leading to abnormally fast pumping. If the heart beats too rapidly, its interior chambers do not have time to fill with blood. Be-

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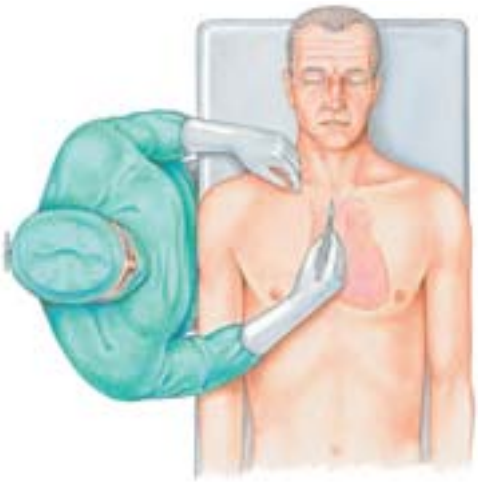

LIFESAVING OPERATION involves excising flap of diseased muscle (lined area in image at right), about three square centimeters in area and several millimeters thick, from the inner surface of a patient's heart. When successful, the surgery halts propagation of impulses through a pathway known as a reentrant circuit, which may arise months or years after a heart attack and can fatally disturb normal cardiac rhythms. The surgeon has entered the left ventricle through an incision (broken line in inset) in dead scar tissue (shaded area in inset) left by the heart attack. Clamps hold back the edges of the incision.

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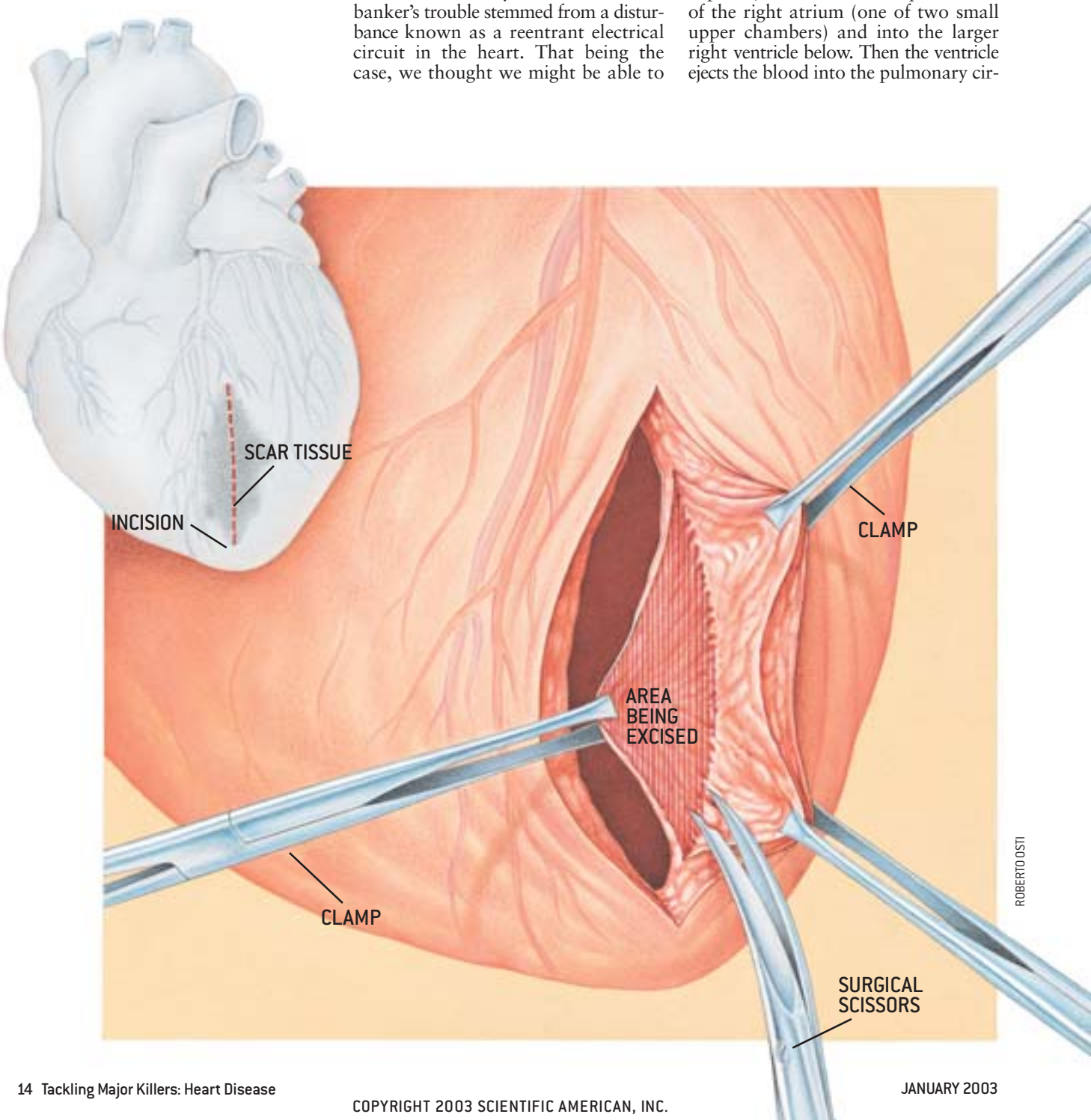
cause the organ cannot eject something it does not receive, delivery of blood to the body's tissues, including to the cardiac muscle itself, can drop precipitously, causing the heart to stop. Although we had originally expected to find evidence of a new heart attack, we were also aware that the banker's electrical derangement was not unique. Six years earlier Hein J. J. Wellens, then at the University of Limburg in the Netherlands, observed that excessively fast pumping occurred in certain patients months or years after a heart attack.

We understood as well that medications designed to prevent arrhythmias, or abnormal heartbeats, could restore proper functioning in some people, and so we tried every type available. Each failed. In a span of three weeks at the hospital, the banker seriously extended his metaphysical line of credit, suffering three additional cardiac arrests. To let him leave under those conditions would most assuredly have been fatal—and he knew it.

At the time, I was privileged to be working with Mark E. Josephson and Leonard N. Horowitz, who specialized in diagnosing cardiac electrical abnormalities. They concluded that the banker's trouble stemmed from a disturbance known as a reentrant electrical circuit in the heart. That being the case, we thought we might be able to interrupt the circuit surgically.

To follow our logic, it helps to know a bit about how the heart's electrical system controls cardiac activity. The heart, which is divided into four chambers, is essentially a ball of muscle (myocardium) lined by conduction tissue: unique fibers that form a kind of internal nervous system. These special fibers convey electrical impulses swiftly to the entire cardiac muscle.

In response to the impulses, the muscle contracts—first at the top of the heart and slightly thereafter at the bottom. As contraction begins, oxygen-depleted, venous blood is squeezed out of the right atrium (one of two small upper chambers) and into the larger right ventricle below. Then the ventricle ejects the blood into the pulmonary cir-



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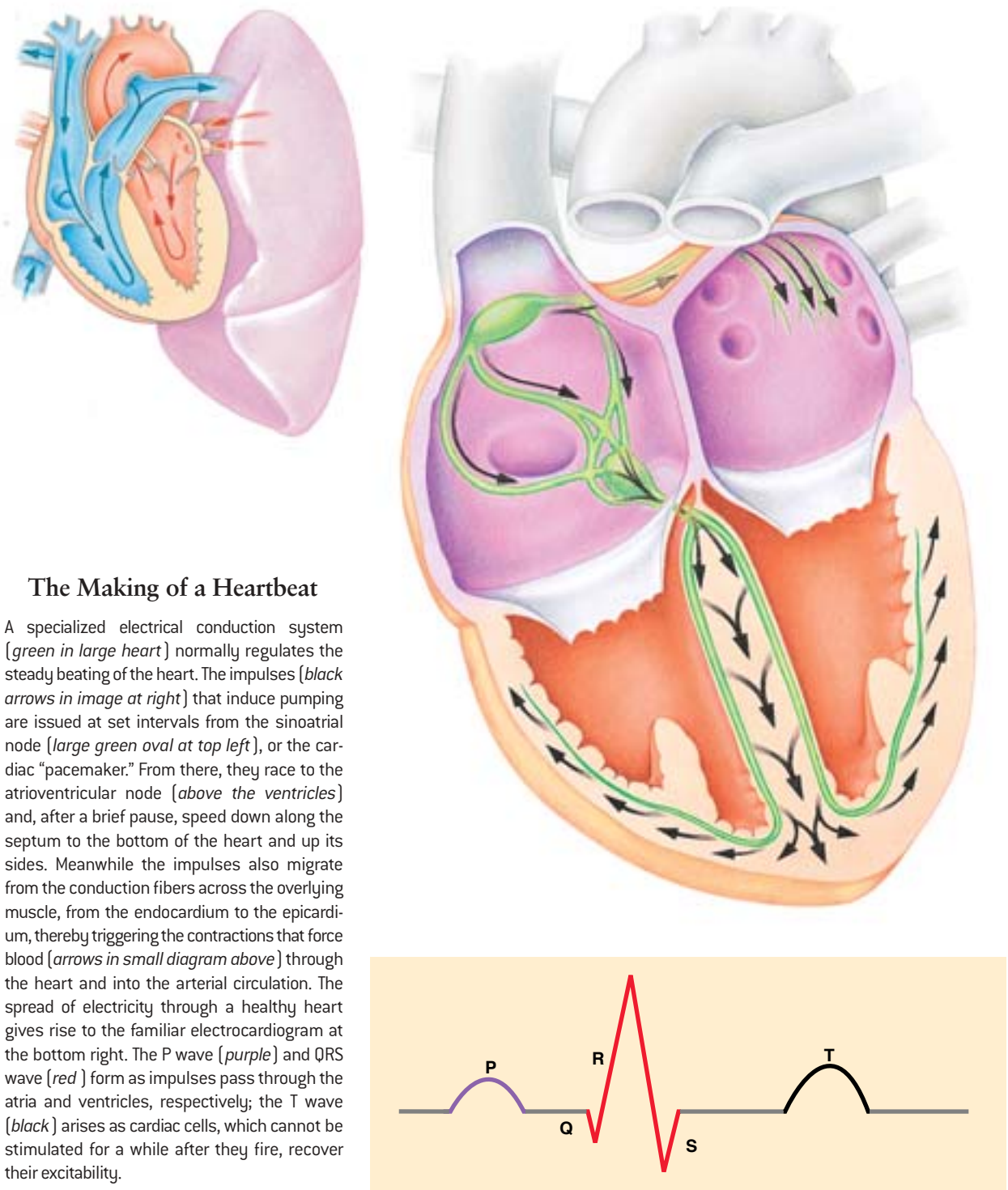
culation, which resupplies oxygen and delivers the blood to the left side of the heart. In parallel with the events on the right, the muscle pumps newly oxygenated blood from the left atrium into the left ventricle and, from there, out to the aorta, which distributes it to every part of the body.

The signal giving rise to these machinations emanates from a cluster of conduction tissue cells collectively known as the sinoatrial node. This node, located at the top of the right atrium, establishes the tempo of the heartbeat; hence, it is often referred to as the cardiac pace-maker. It sets the tempo simply because it issues impulses more frequently than do other cardiac regions, once about every 830 milliseconds. If something provoked another part of the heart to fire at a faster rate, as occurred in the banker, it would become the new pacemaker. Although the sinoatrial node can respond to signals from outside the heart, it usually becomes active spontaneously. In other words, it is on "automatic pilot," a capability known as automaticity.

Such automaticity stems from the unique leakiness of the membrane encasing nodal cells. As is true of the mem-



The Making of a Heartbeat

A specialized electrical conduction system (*green in large heart*) normally regulates the steady beating of the heart. The impulses (*black arrows in image at right*) that induce pumping are issued at set intervals from the sinoatrial node (*large green oval at top left*), or the cardiac "pacemaker." From there, they race to the atrioventricular node (*above the ventricles*) and, after a brief pause, speed down along the septum to the bottom of the heart and up its sides. Meanwhile the impulses also migrate from the conduction fibers across the overlying muscle, from the endocardium to the epicardium, thereby triggering the contractions that force blood (*arrows in small diagram above*) through the heart and into the arterial circulation. The spread of electricity through a healthy heart gives rise to the familiar electrocardiogram at the bottom right. The P wave (*purple*) and QRS wave (*red*) form as impulses pass through the atria and ventricles, respectively; the T wave (*black*) arises as cardiac cells, which cannot be stimulated for a while after they fire, recover their excitability.

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brane surrounding muscle cells and neurons, the nodal cell membrane is studded with pumps that transport ions into and out of the cell. The net result of this exchange is the creation of an electrical potential, or unequal charge distribution, across the membrane. Yet unlike muscle and nerve cells, which maintain their resting potential until they are jogged by an outside stimulus, nodal cells allow certain ions to leak back out of the cells. This outflow reduces the membrane potential to a critical value.

At that point, the membrane permits a flood of other ions to rush back into the cells. This onslaught momentarily depolarizes the cells (eliminates the membrane potential) and actually reverses the membrane polarity. Such depolarization constitutes an impulse. After the impulse is generated, cells repolarize and prepare for firing anew.

Impulses born at a cell in the sinoatrial node typically speed instantly through the rest of the node; from there, they course through the entire heart in the span of 160 to 200 milliseconds. Traveling along conduction fibers, they first race across both atria and then regroup at the atrioventricular node, a cellular cluster centrally located atop the ventricles. After a pause, they course down the ventricles along a conduction cable that divides into two branches known as conduction bundles; these further ramify to form arbors of thinner projections called Purkinje fibers. One arborized bundle serves each ventricle, sending signals first along the surface of the septum (a wall dividing the two ventricles) to the tip of the heart (the apex) and, from there, up along the inner surface of the external (lateral) walls to the top of the ventricle.

As impulses from the conduction fibers reach muscle, they activate the overlying cells. Muscle cells, too, are capable of relaying impulses, albeit more slowly than do conduction fibers. The cells of the endocardium (the inner surface of the wall) depolarize first and relay the impulses through the thickness of the muscle to the outer surface (the epicardium). Depolarization, in turn, triggers contraction.

Josephson and Horowitz suggested that diseased cells had distorted this normal flow of electricity in the banker's heart. After a heart attack, many cells surrounding the resulting scar (the group of cells killed by lack of blood delivery) continue to live but are abnormal electrically; they may conduct impulses unusually slowly or fire when they would typically be silent.

These diseased areas, my co-workers indicated, might perturb smooth signaling by forming a reentrant circuit in the muscle: a pathway of electrical conduction through which impulses can cycle repeatedly without dying out. In our patient's case, the circuit was thought to be in the left ventricle, where his heart attack, in common with most others, occurred. (Activation of reentrant circuits some time after a heart attack is now believed to take place in a sizable number, perhaps 10 percent, of the roughly 1.2 million Americans who suffer heart attacks every year.)

Passage of impulses through a reentrant circuit can be envisioned by imagining a wave of impulses encountering, say, the bottom of an oval scar in the left ventricle. On reaching the scar, the wave would split in two, to detour around both sides of the dead area. If diseased cells somehow interrupted impulses propagating along one of those branches, impulses might still flow up along the opposite branch and over the top of the oval. Then they might traverse the previously blocked path and return to the beginning of the circuit—a region we call the origin.

If this circuit were negotiated slowly enough, the origin would have repolarized and become responsive once again to stimulation. (Between the time cells depolarize and repolarize, they are generally refractory, or incapable of responding to new impulses.) In that case, the impulses could reexcite the origin, sending impulses back into the diseased circuit and also out to the rest of the ventricular muscle.

Despite the slow conduction, the impulses could complete the circuit in a shorter time than the interval between normal heartbeats. Hence, persistent cycling could enable the origin of the circuit to become the new pacemaker and to provoke sustained ventricular tachycardia: excessively rapid pumping by the ventricles.

We knew that continuous passage through reentrant circuits could occur in humans because Wellens had established that fact in the 1970s. Fortunately for us, he also introduced a procedure for determining whether a quiescent circuit lurks in a patient who survives a life-threatening episode of tachycardia and whether any existing drugs can prevent renewed activation of the pathway. A physician threads an electrode known as a pacing catheter into the heart and issues a series of specifically timed impulses. Initiation of sustained premature heartbeats confirms that a patient harbors a reentrant pathway. (In contrast, impulses delivered to a healthy heart would yield only single contractions that would not be repeated.) Next, the individual is given an antiarrhythmic drug. If paced stimuli now fail to trigger sustained tachycardia, the finding implies the drug should be helpful.

When Josephson and Horowitz performed the procedure on the banker, they found they could indeed induce persistent tachycardia and that, sadly, no antiarrhythmic medications could aid him. I met with the two of them soon afterward in their tiny, windowless catheterization laboratory. Knowing our patient carried a life-threatening electrical pathway inside his heart, we began wondering if we might prevent its activation by surgically removing all or part of the culprit circuit, especially the origin. We realized the plan could fail, or that by removing the tissue, we might actually create other problems. But we were out of options.

Before proceeding, we had to develop a way to locate the renegade pacemaker. We hoped we might find it by analyzing signals reaching an electrode placed directly on the inner or outer surface of the heart. More specifically, we planned to induce sustained tachycardia with a pacing electrode. During each heartbeat, we would measure electric currents produced at a single site (consisting of a small cluster of cells) along the diseased border of the heart attack scar. We would start at a position arbitrarily designated as 12 o'clock and proceed around the "clock face" back to the beginning.

We would delineate the circuit by comparing the time of electrical activation in each region against that seen in healthy tissue. Regions that generated currents before the healthy tissue did would be revealed as belonging to the circuit; the area that became excited earliest would be the pacemaker. We could not rely on standard electrocardiography for this purpose because it lacked the specificity we needed. Familiar electrocardiogram tracings, made by attaching electrodes to the skin, reflect the summed activity of many thousands of cells in the heart; they cannot identify the precise swatch of muscle that is depolarized at any given moment.

Our general approach made sense, but no one had ever attempted to "map" the flow of signals in the living, pumping chambers of the human heart by recording directly from the organ's surface. We had no idea whether we could obtain decipherable results. The next day

I was scheduled to remove a cancerous lung from a different patient. He kindly agreed to let us try to detect signals directly from the outside of his heart. To our delight, we could clearly discern when a wave of impulses crossed any point on the muscle.

I was now ready to discuss our proposed strategy with the banker. Not knowing whether the origin of the circuit—the zone of earliest activation—was closer to the inside or outside of the cardiac muscle, we intended to map both the inner and outer surfaces. We planned to reach the interior by opening the heart through the existing scar. (Cutting into healthy tissue would, after all, destroy new tissue unnecessarily.) If we found the troublesome region, we proposed to remove it surgically. To keep blood moving through the patient's body during the operation, we should have to attach him to a heart-lung machine. This device diverts unoxygenated blood into an artificial lung. Blood containing oxygen is then pumped back into the arterial circulation via the aorta.

People often call physicians "courageous," but it was our patient who was brave. After I described our therapeutic strategy in great detail, he posed the dreaded question: "How many times have you done this before?" I told him, "Never." Then he asked how many times anyone had performed the operation previously. I informed him it was untried. Despite these unsettling answers, he gave me a confident smile and said, "Go ahead."

The next morning we were able to pinpoint and excise the region of earliest activity, which turned out to reside on the inside surface. (Today we know that virtually all reentrant pathways weave through cells in or close to the endocardium.) Our patient not only resumed banking but also went on to become the county tax assessor. I lost track of him a few years ago, but as of a decade after our treatment, he had suffered no further arrhythmias.

Not everyone who has the surgery is as lucky as the banker was, however. Of all the patients who undergo the procedure after surviving an episode of persistent tachycardia, approximately 9 percent succumb either during the operation or within a month after it. On the other hand, 80 percent of surgically treated patients live for at least a year without recurrence of tachycardia, and 60 percent survive for five years or more. The candidates most likely to do well are those whose heart muscle is damaged least.

In addition to assembling survival statistics, we have discovered since 1978 that reentrant pathways need not be as large as we originally thought. Those occurring at a microscopic level can be equally pernicious. In fact, microanatomic reentrant circuits seem to be the most common form of all.

The notion that microcircuits could exist was first suggested in the early 1970s by another surgeon: James L. Cox, then at Duke University. He argued that a small bit of mottled tissue, consisting of diseased cells interspersed with islands of dead cells, could set up the conditions needed to establish reentrant tachycardia. In such a microscopic circuit, impulses that encounter a divided pathway at an entryway to a mottled patch would split and travel along both routes.

As is true of larger, "macro" reentrant circuits, impulses propagating along one branch would encounter a one-way blockade. At the same time, impulses flowing along the other branch would meander through a maze of diseased cells and return along the previously blocked lane.

If conduction through the diseased tissue were su ciently slow, the impulses would come back to the entryway, or origin of the circuit, after that site was no longer refractory. Excitation of the site would then stimulate the ventricular muscle to contract and, at the same time, would send the impulses back into the microcircuit again and again. Instead of traveling along the circumference of a scar, then, a reentrant circuit could trace a recursive path through a more localized maze of cells in the diseased boundary between a heart attack scar and fully healthy tissue.

Two of my colleagues, Glenn J. R. Whitman and Michael A. Grosso, decided to test this idea in the early 1980s. They were able to create small heterogeneous zones consisting of mixed dead and living but diseased cells in the ventricles of test animals. These animals, not previously susceptible to the electrical induction of self-sustaining tachycardia, became highly prone to it.

Whitman and Grosso assumed that if the mottled tissue were at fault, killing all the cells in the patch should restore appropriate electrical activity in the heart. Instead of wandering through a dangerous maze, impulses encountering the homogeneous patch of killed tissue would either be extinguished or zoom around it through adjacent healthy cells. Sure enough, when the mottled patches were destroyed, the predisposition to arrhythmia vanished.

These findings revealed that mottling could set the stage for reentrant tachycardia. They also provided the hindsight needed to explain why a different surgical treatment tested by us and others in various patients had not worked well. Believing that the scar itself was somehow responsible for the electrical disturbances, we had previously removed only the dead tissue. Whitman and Grosso's work indicated that this approach was doomed to failure because it left the true culprit—the zone of mixed living and dead cells—in place.

Yet we still faced two significant puzzles, one scientific and one clinical. Why is it that reentrant circuits do not become active every time the heart beats in susceptible patients? In other words, why can people often survive for months or years before deadly disturbances of rhythm arise? We also wondered how we might noninvasively identify patients at risk for reentrant tachycardia before they experienced a potentially life-threatening episode.

The simplistic explanation for why a reentrant circuit does not jump into action with each heartbeat seemed to be that impulses fired by the sinoatrial node cannot cycle repeatedly through the troublesome pathway. At the end of the first cycle, they return to a still refractory starting site. Blocked from reentering the circuit, they go no further. Unfortunately, this explanation did not clarify how persistent cycling does arise. We now think it is triggered when, in a case of exquisite bad luck, an electrically irritable cell lying adjacent to a reentrant pathway fires spontaneously in a narrow window of time between one activation of the sinoatrial and atrioventricular nodes and the next.

We came to this conclusion after reviewing research reported in the late 1970s by our colleagues E. Neil Moore and Joseph F. Spear of the Hospital of the University of Pennsylvania. By impaling cells on tiny, needlelike electrodes, Moore and Spear were able to track changes in the membrane potentials of single, diseased cardiac cells taken from the area surrounding heart attack scars. After healthy cells depolarize, they repolarize smoothly. In the diseased cells, by contrast, the membrane potential fluctuated markedly during the repolarization period.

We presumed that these fluctuations would sometimes progress to premature depolarization, or firing of an impulse. If an irritable cell happened to lie next to a reentrant pathway, it might well insert an impulse into the worrisome channel during the interval between normal heartbeats.

This insertion might activate a reen-

trant circuit, whereas an impulse originating at the sinoatrial node would not, because recent passage of an impulse through a pathway can alter the electrochemical characteristics of that pathway and slow conduction of a subsequent signal. Thus, the impulse delivered by the irritable cell could pass through the circuit more slowly than would a prior signal originating at the sinoatrial node. If delivery of the wayward impulse were timed properly, the impulse propagating through the circuit would return to the entryway at a most devastating moment: after the site regained excitability (and so could relay the impulse onward) but before the sinoatrial node fired for a second time (thereby gaining control of the heartbeat). Hitting a receptive target, the impulse might proceed to run many unimpeded laps around the lethal circuit.

Our second problem—readily identifying patients at risk for reentrant tachycardia—was resolved masterfully by our co-worker Michael B. Simson, a person of many talents. Aside from being a superb cardiologist, he is, as I sometimes say, an enthusiastic sports-car hack and computer driver. Steering his beat-up sports car home one night after sitting in on one of our surgical research meetings, he began to ponder the electrical noise, or seemingly random signals, emanating from the hood of his car. If he simply monitored the currents reaching the hood, he reasoned, the resulting data would be indecipherably chaotic. But if he wanted to track the electrical impulses coming specifically from his distributor, he might well discern them by signal averaging.

In this procedure, he would record the voltage and direction (the electrical vector) of currents flowing toward and away from the hood during particular phases of rotation by his distributor rotor. If he summed the signals obtained by repeated measurements in a given phase, random currents would tend to cancel one another out, leaving a record of only those produced by the rotor. Dividing the result by the number of readings made in a selected phase would give him a measure of the current generated by the distributor in that phase.

It then occurred to Simson that he might apply much the same approach to screen heart attack victims for susceptibility to reentrant tachycardia. Perhaps signal averaging would enable him to detect very slow electrical activity persisting after the normal flow of signals passed through the ventricles. Most of the extra activity he found would reflect impulses propagating belatedly through a potentially dangerous reentrant channel. Put another way, Simson thought he could place electrodes on the skin, as for a standard electrocardiogram, but then record only those currents produced in the 40 milliseconds immediately after formation of the familiar QRS wave seen on electrocardiograms. (The QRS wave reflects the spread of impulses through the ventricles.) Heart cells are generally quiet at that point, giving rise to a flat line on the electrocardiogram tracing. Signal-averaged deviations from this normal pattern would signify slow conduction in a reentrant pathway.

Simson spent that night in his basement building a signal-averaging device. The next day Josephson, Horowitz and I were scheduled to remove tissue that had earlier caused reentrant arrhythmia in one of our patients. Before surgery, Simson attached his new recorder to the patient and noted, as expected, that there was a flurry of electrical activity in the usually quiescent span following ventricular excitation. But was the signal, in fact, an indication of late impulse conduction in a reentrant circuit? The answer would be yes if the fluctuations disappeared after the operation. The surgical procedure went well. Josephson and Horowitz identified the circuit, and I excised the entryway. After surgery, Simson reattached his device to the patient. The post-QRS fluctuations were gone.

We had come a long way since 1978. We had learned why our surgical approach, initially designed by guesswork, is useful. It interrupts the diseased anatomic pathway that, in response to aberrant firing by a nearby cell, gives rise to the repeated flow of impulses through a recursive circuit. Moreover, we had gained the ability to identify noninvasively patients at risk.

At the University of Colorado, where I moved in 1984, we use Simson's screening test routinely. We usually wait two or three months after a heart attack to be sure we are not detecting a predisposition to "automatic" tachycardias. For a week or so after a person has a heart attack, dying cells often fire when they should be silent. This behavior can cause the heart to beat prematurely. If the cell depolarizes repeatedly, the activity could lead to fast beating, and sometimes failure, of the heart. A tendency to automatic tachycardia generally resolves within a few weeks, as the sputtering cells expire.

If a propensity for reentrant tachycardia is discovered after a suitable waiting period, and if medications do not suffice, patients can consider other treatment options. I speak of more than one choice because surgery is no longer the only therapeutic alternative to drugs. A device known as an implantable defibrillator has been available since 1980.

When the heart begins to beat quickly, the machine issues a shock that depolarizes the entire heart instantly, giving the sinoatrial node a chance to resume its pacemaker function.

About half as many patients die from complications of the implantation procedure for the device as from consequences of undergoing our surgery. But, in contrast to the surgery, the device offers only palliation, not a cure. Recipients continue to face episodes of tachycardia and may lose consciousness each time they are shocked back into normal rhythm. Consequently, they cannot drive or engage in other activities where sudden blackouts could be dangerous. If surgery to eliminate a reentrant circuit is deemed the better therapy for a given patient, it can now be obtained at many medical centers.

Overall, it is fair to say that the majority of patients who survive a heart attack are not vulnerable to reentrant arrhythmias. Perhaps half of the small group who are susceptible can be treated with medication. Of those who do not respond to drugs, however, as many as 80 percent are likely to die from their electrical abnormality within a year after their first bout of reentrant tachycardia unless they receive some other therapy. It is reassuring to know that for many of those individuals the courage of a Philadelphia banker has permitted a cure. SA

FURTHER READING

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