Crafting The Perfect Shock

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the recipients of a shock. In Portland, Ore., meanwhile, police found that 25 to 30 percent of the situations in which a Taser was employed met the criteria for the use of deadly force. Other police departments have released statistics showing a decline in the number of deaths of suspects and officers in the months following the introduction of Tasers. But research by the Police Executive Research Forum has raised the concern that multiple activations of Tasers may increase the risk of death.

Even if Tasers are proven to be entirely safe, there's the bigger question of whether the stun guns encourage police brutality. A Taser shock leaves almost no visible scarring or bruising, as a clubbing or a beating typically would. Could the absence of physical scars lift a psychological restraint on officer behavior? Should every Taser gun have a built-in video camera?

Equipping law-enforcement services with Tasers is likely to reduce the number of bullets officers fire from their handguns and therefore the number of serious injuries and deaths. At the same time, it may lead police to inflict an unwarranted amount of pain on individuals who commit only minor crimes.

The broader questions regarding the social effects of stun guns are, however, beyond the scope of this discussion. The two articles that follow investigate the physiological effects of electric shock. The first is by Mark W. Kroll, an electrical engineer who has helped invent numerous electrical medical devices and who sits on the board of Taser International. The second is by Patrick Tchou, a cardiac electrophysiologist at the Cleveland Clinic, who has tested Tasers experimentally on pigs.

—***Sandra Upson***

CRAFTING THE PERFECT SHOCK

BY MARK W. KROLL

YOU KNOW AN ENGINEERING problem is difficult when the prevailing technology dates back to the Stone Age. Let's face it, the police officer's baton is barely more sophisticated than a cave dweller's club, and with it comes all the same crudeness.

One reason that finding a good replacement has been such a confounding problem is the nature of the task. Police officers often need to take into custody a violent criminal who has overdosed on a stimulant. Most people probably would be surprised to learn that, at present, the main methods police use in such situations all rely on inflicting pain. The old standbys are wrist twists and other forms of joint distortion, pepper spray, and clubbing.

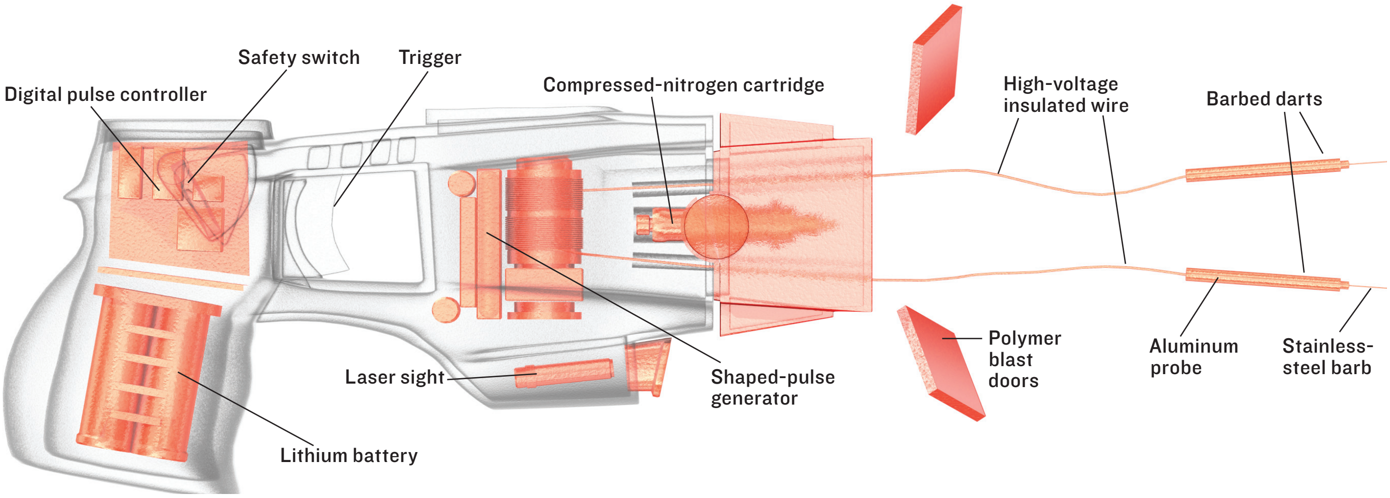
The problem is complicated by the fact that many illegal drugs are painkillers, and as a result standard subduing techniques are frequently ineffective at bringing troublemaking drug users to heel. Even worse, many of the dangerously drug-addled perpetrators exhibit superhuman stamina and strength. There are numerous accounts of a person on a drug overdose manhandling half a dozen law-enforcement officers at once. Many officers are injured along with those they are trying to take into custody.

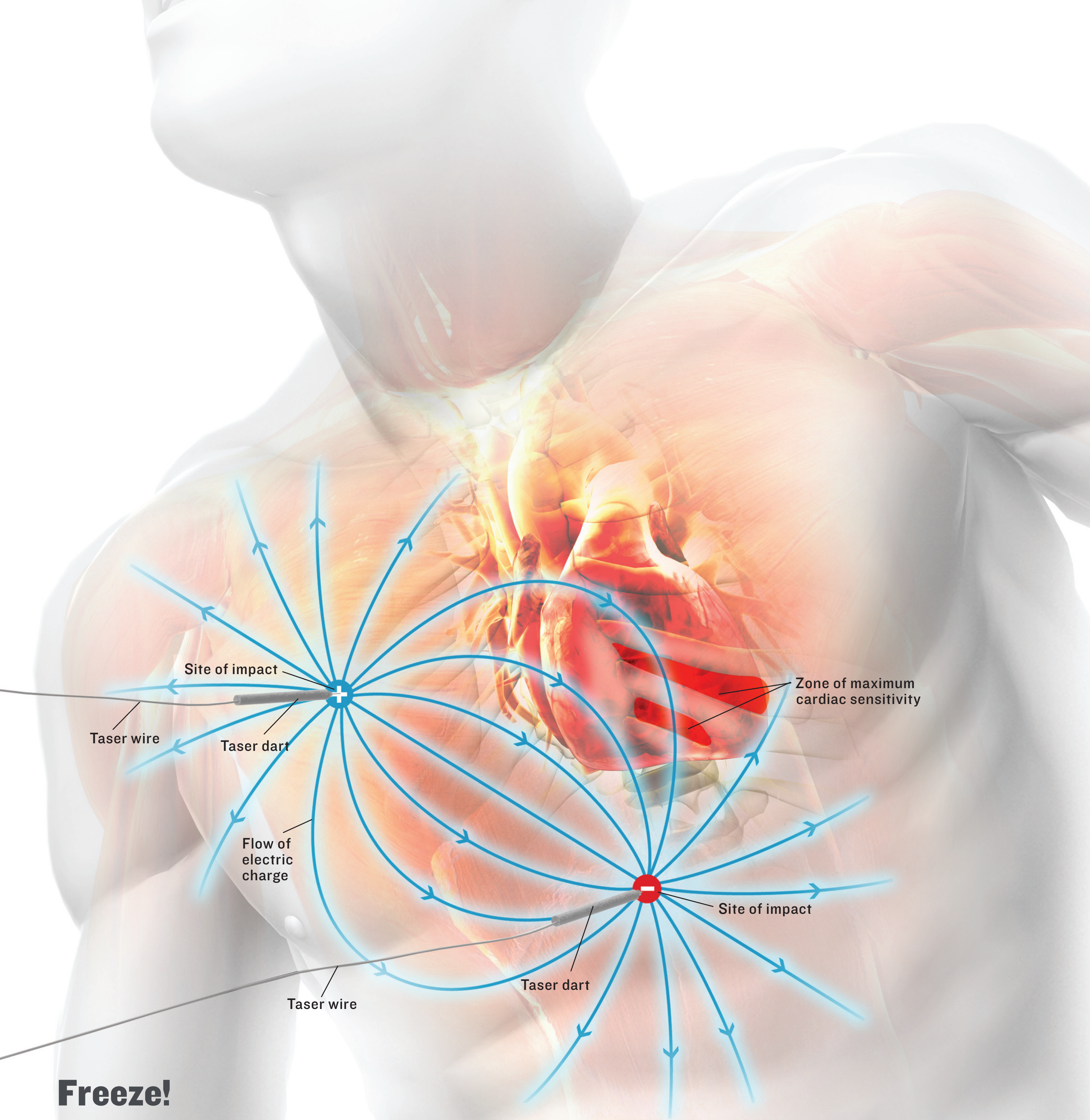
The ideal arrest tool, then, must meet a number of requirements. First, it must be able to temporarily disable even the largest, most determined drug-anesthetized individual. Second, it must do so without causing serious injury to anyone involved. Third, its effectiveness cannot be dependent on causing pain. Fourth, it must work reliably. And finally, it must be able to be used from a safe distance—let's say 5 meters—so that an arresting officer need not come within range of a suspect's blows.

Some approaches to meeting those criteria have come close, but not close enough. These include powerfully launched nets, which still require an officer to come into contact with a thrashing suspect, and body-immobilizing glues, which don't perform well in cold weather.

A solution that satisfies all the requirements is a device that was once playfully dubbed the "Thomas A. Swift electric rifle" (after the exploits of the fictional Tom Swift, a teenage inventor made famous in a series of juvenile adventure novels published from 1910 to 1941) and is now known as the Taser Electronic Control Device. Under microprocessor control, the device temporarily, and relatively harmlessly, immobilizes a suspect with a carefully engineered electric signal that is specifically designed with human physiology in mind.

WHEN YOU PULL THE TRIGGER of a Taser gun, a blast of compressed nitrogen launches its two barbed darts at 55 meters per





Freeze!

When the trigger on a Taser gun is pulled, the compressed-nitrogen cartridge breaks open. Enough pressure builds up inside the device to launch the two darts. The darts are tipped with barbs that grab hold of a target's clothing, and current travels down the wires to the person. The gun generates a brief arcing pulse to close the circuit, at which point the voltage drops. Shots from a Taser gun land, on average, about 15 centimeters apart on the torso.

The differences between the cells that make up heart muscle and skeletal muscle are key components of the Taser's safety. For example, the cells in the heart generate a longer electric impulse than those in skeletal muscle do, and it takes much more current to trigger cardiac muscle cells.

second, less than a fifth the speed of a bullet from a typical pistol. Each projectile, which weighs 1.6 grams, has a 9-millimeter-long tip to penetrate clothing and the insulating outer layer of skin. Two whisper-thin wires trail behind for up to 9 meters, forming an electrical connection to the gun.

Because the barbs get stuck in clothing and fail to reach the skin about 30 percent of the time, the gun is designed to generate a brief arcing pulse, which ionizes the intervening air to establish a conductive path for the electricity. The arcing phase has an open-circuit peak voltage of 50 000 volts; that is, the voltage is 50 kilovolts only until the arc appears or until the barbs make contact with conductive flesh, which in the worst conditions offers around 400 ohms of resistance [see illustration, "Freeze!"].

The target's body is never exposed to the 50 kV. The X26—the model commonly used by police departments—delivers a peak voltage of 1200 V to the body. Once the barbs establish a circuit, the gun generates a series of 100-microsecond pulses at a rate of 19 per second. Each pulse carries 100 microcoulombs of charge, so the average current is 1.9 milliamperes. To force the muscles to contract without risking electrocution, the signal was designed to exploit the difference between heart muscle and skeletal muscle.

Skeletal muscle constitutes 40 percent of a typical person's mass and is responsible for making your biceps flex, your fingers type, and your eyelids wink. It's organized into bundles of single-cell fibers that stretch from tendons attached to your skeleton. When your brain orders a muscle to flex, an electrical impulse shoots down a motor nerve to its termination at the midpoint of a muscle fiber. There the electrical signal changes into a chemical one, and the nerve ending sprays a molecular transmitter, acetylcholine, onto the muscle. In the milliseconds before enzymes have a chance to chew it up, some of the acetylcholine binds with receptors, called gated-ion channels, on the surface of the muscle cell. When acetylcholine sticks to them, they open, allowing the sodium ions in the surrounding salty fluid to rush in.

The movement of those ions raises the cell's internal voltage, opening nearby ion channels that are triggered by voltage instead of by acetylcholine. As a result, a wave of voltage rolls outward along the fiber toward both ends of the muscle, moving as fast as 5 meters per second. As the voltage pulse spreads, it kick-starts the molecular machinery that contracts the muscle fiber.

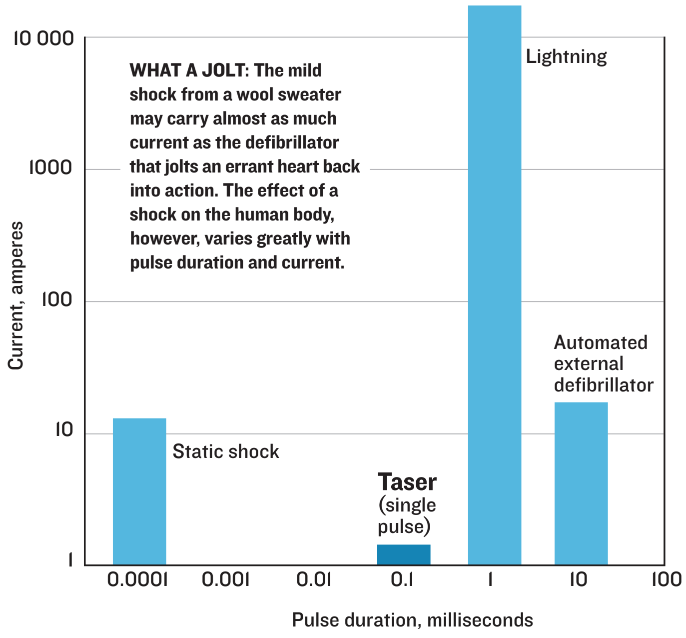
By directly jolting the motor nerves with electricity, a Taser can stimulate the muscle and get the same effect.

The force with which a skeletal muscle contracts depends on the frequency at which its nerve fires. The amount of contraction elicited is proportional to the stimulation rate, up to about 70 pulses per second. At that point, called tetanus, contractions can be dangerously strong. (The same thing happens in the disease tetanus, whose primary symptom, caused by the presence of a neurotoxin, is prolonged contraction of skeletal fibers.) The Taser, with its 19 pulses per second, operates far enough from the tetanus region so that the muscles contract continuously but without causing any major damage.

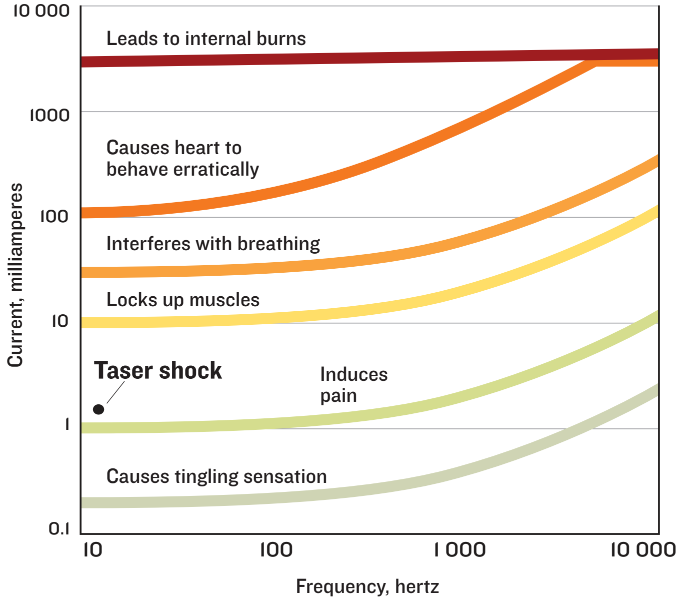
Heart muscle has a somewhat different physical and electrical structure. Instead of one long cell forming a fiber that stretches from tendon to tendon, heart muscle is composed of interconnected fibers made up of many cells. The cell-to-cell connections have a low resistance, so if an electrical impulse causes one heart cell to contract, its neighbors will quickly follow suit. With the help of some specialized conduction tissue, this arrangement makes the four chambers of the heart beat in harmony and pump blood efficiently. A big jolt of current at the right frequency can turn the coordinated pump into a quivering mass of muscle. That's just what electrocution does: the burst of electricity causes the heart's electrical activity to become chaotic, and it stops pumping adequately—a situation known as ventricular fibrillation.

The Taser takes advantage of two natural protections against electrocution that arise from the difference between skeletal and cardiac muscle. The first—anatomy—is so obvious that it is typically overlooked. The skeletal muscles are on the outer shell of the body; the heart is nestled farther inside. In your upper body, the skeletal muscles are arranged in bands surrounding your rib cage. Because of skeletal muscle fibers' natural inclination to conduct low-frequency electricity along their length, a larger current injected into such a muscle tends to follow the grain around the chest rather than the smaller current that penetrates toward the heart.

The second protection results from the different timing requirements of the nerves that trigger muscle contractions and the heart's intrinsic electronics. To lock up skeletal muscle with-



WHAT A JOLT: The mild shock from a wool sweater may carry almost as much current as the defibrillator that jolts an errant heart back into action. The effect of a shock on the human body, however, varies greatly with pulse duration and current.



LEVELS OF SHOCK: The Taser X26 puts out 2 milliamperes at 19 hertz. The gun packs its current into 100-microsecond pulses, so it can capture muscle with lower current than if it had been delivered as a sine wave, as the rest of the chart shows.

out causing ventricular fibrillation, an electronic waveform has to have a specific configuration of pulse length and current.

The key metric that electrophysiologists use to describe the relationship between the effect of pulse length and current is chronaxie, a concept similar to what we engineers call the system time constant. Electrophysiologists figure out a nerve's chronaxie by first finding the minimal amount of current that triggers a nerve cell using a long pulse. In successive tests, the pulse is shortened. A briefer pulse of the same current is less likely to trigger the nerve, so to get the attached muscle to contract, you have to up the amperage. The chronaxie is defined as the minimum stimulus length to trigger a cell at twice the current determined from that first very long pulse. Shorten the pulse below the chronaxie and it will take more current to have any effect. So the Taser should be designed to deliver pulses of a length just short of the chronaxie of skeletal muscle nerves but far shorter than the chronaxie of heart muscle nerves.

And that's the case. To see just how different skeletal and heart muscles are, let's look at what it takes to seriously upset a heart's rhythm. Basically, there are two ways: by using a relatively high average current, or by zapping it with a small number of extremely high-current pulses.

In terms of average current, the 1.9 mA mentioned earlier is about 1 percent of what's needed to cause the heart of the typical male to fibrillate. So the Taser's average current is far from the danger zone for healthy human hearts.

As far as single-pulse current goes, the Taser is again in the clear. The heart's chronaxie is about 3 milliseconds—that's 30 times as long as the chronaxie of skeletal muscle nerves and the pulse lengths of a Taser. The single-pulse current required to electrocute someone by directly pulsing the most sensitive part of the heartbeat using 3-ms pulses is about 3 A. Because a Taser's 100-µs pulses are such a small fraction of the heart's chronaxie, it would take significantly higher current—on the order of 90 A—to electrocute someone using a Taser.

When you factor in that the Taser barbs are likely to land in current-shunting skeletal muscle not near the heart, you wind up with a pretty large margin of safety. For barbs deeply inserted directly over the heart, the margin is slimmer, though, and the key question is whether that margin is adequate. To answer that definitively, one needs to consider what has been learned from the devices' use in everyday life.

In the United States, about 670 people die each year under police restraint, according to the U.S. Department of Justice's Bureau of Justice Statistics. These incidents include arrests and attempts to control an uncooperative person who needs medical assistance, as well as suicides after arrest. Studies have shown that stun guns were used during about 30 percent of in-custody deaths in the United States. Although Tasers were involved in a sizable fraction of these deaths, one should not leap to the conclusion that Tasers caused them. One study found that 100 percent of in-custody deaths involved the use of handcuffs, and one might apply the same faulty logic to argue against "killer cuffs," but that would, of course, be absurd. Medical examiners have cited Tasers as the primary cause of death in only four cases to date, and three of those were later thrown out of court.

There will always be some degree of violence in many police arrests, and a reliance on handguns and hand-to-hand combat can lead to terrible use-of-force dilemmas for police officers. For example, when a suspect brandishing a knife is within striking distance, law-enforcement officers in the United States are trained to shoot that person. Having a Taser gun in their holsters allows those officers an opportunity to disarm suspects in a manner that's likely to be safer for all involved. It's the prevalence of such scenarios that has persuaded so many police departments to pay twice as much for a Taser—on the order of US $1000 per device—as they do for a traditional handgun. Tasers are expensive and controversial, but in the end it's safety that's on everyone's mind. ■

FINDING THE EDGE OF HEART SAFETY

BY PATRICK TCHOU

WITH THE USE OF TASER Electronic Control Devices by law-enforcement officers on the rise, it's no wonder that questions about the guns' safety come up again and again. As Mark Kroll describes [see "Crafting the Perfect Shock"], Tasers produce uncontrollable muscular contractions, which temporarily immobilize a subject. Those questions of safety can be answered in two ways: from a medical standpoint—that is, in terms of the bodily harm that can result from a Taser shock—and from the point of view of someone working in law enforcement.

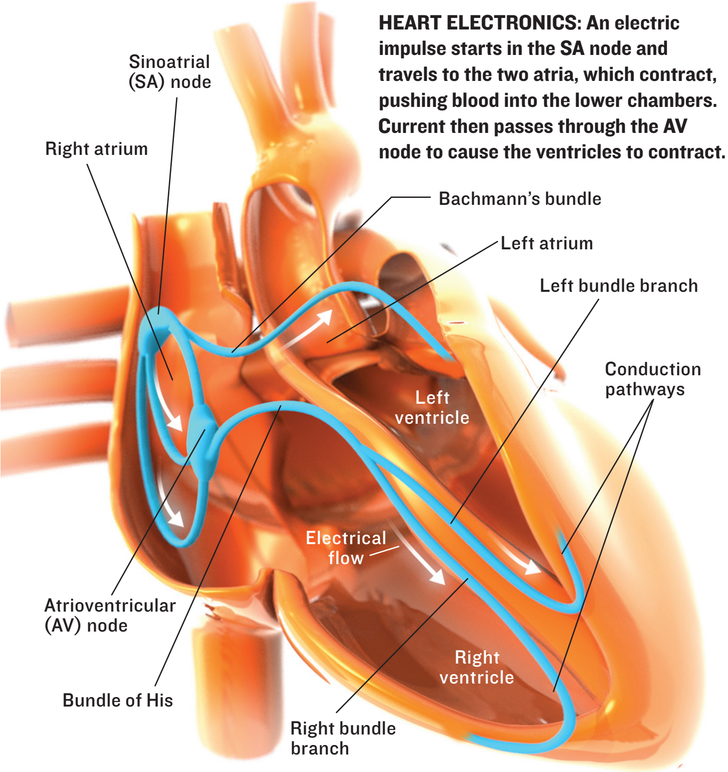
The second perspective is much broader. How would one minimize injury to both the police officer and the person being taken into custody, not to mention bystanders, while restraining a violent and uncooperative subject? To probe further, one must ask how alternative means of restraint compare with the use of a Taser.

As a physician, I contribute to the former perspective by investigating whether Taser shocks can cause serious damage to a heart's normal function.

Let's begin with some basics about how the heart works. Each heartbeat is activated by an electrical impulse that propagates through the four chambers of the heart [see illustration, "Heart Electronics"]. A number of troubles can throw off the internal rhythm of the impulse as it travels along, and the most dangerous kind of these arrhythmias is ventricular fibrillation, which is typically the cause of death in someone who is electrocuted. What brings on death is the uncoordinated electrical activation of the heart's main pumping chambers. The heart tissue still carries electrical impulses, but they propagate at chaotic and rapid rates, and the heart ceases to function as a pump, so blood pressure quickly plummets. It takes 10 to 20 seconds for a person to lose consciousness, less if he or she is standing.

So the most important question regarding the safety of Tasers is how likely it is that the use of one will induce ventricular fibrillation. Statistics alone suggest that, so far, the incidence of Taser-induced ventricular fibrillation is low. To investigate this question further in a more rigorous experimental setting, my Cleveland Clinic colleagues and I designed experiments to assess the threshold for bringing about ventricular fibrillation using pigs, taking into account the distance between the heart and the Taser darts at the body surface. Taser International covered the costs of the testing equipment and the costs of laboratory use, but none of Taser's funding covered my time or that of any other physicians involved in the studies.

The pigs were under general anesthesia when we performed the experiments. We selected five points on each animal's torso



HEART ELECTRONICS: An electric impulse starts in the SA node and travels to the two atria, which contract, pushing blood into the lower chambers. Current then passes through the AV node to cause the ventricles to contract.

corresponding to sites where Taser darts commonly make contact with human subjects. We used a custom-built circuit that matched the waveform and typical 5-second shock duration of an X26 Taser gun, but our device could deliver a much larger shock. To boost the output current, we increased the capacitor sizes in the device. After inducing ventricular fibrillation, we immediately rescued the animal using an ordinary defibrillator. We then stepped down the current to determine the highest amount that could be delivered without inducing ventricular fibrillation.

We calculated that quantity, cast in terms of multiples of the capacitances, for each of the body sites we'd chosen to test. Of the various positions we examined, some were a mere centimeter or two away from the heart, which sits just under the chest wall, touching it on the inside. Not surprisingly, we found that darts near the heart had the lowest thresholds for inducing ventricular fibrillation. At the closest spots—with one dart hitting at the lower end of the chest wall, and the other at the top of the breastbone—such a cardiac crisis would ensue with about four times the standard Taser capacitance.

Our experiments were the first to document that Taser-like impulses, albeit more energetic ones, applied close to the heart on the chest wall in pigs could have serious cardiac consequences. Even at the standard output of a Taser, we found that current applied to the most vulnerable part of the chest was able to drive the heart to beat up to 250 beats per minute, which is about twice the normal rate for pigs. These experiments also showed us that the onset of ventricular fibrillation is related to how fast the heart is driven by the impulses—which scales with the amount of current used.

Because the standard Taser output proved on average to be one-fourth what was needed to cause fibrillation, one is tempted to conclude that the device is fundamentally safe. But there's another factor to keep in mind: a large portion of the violent individuals with whom the police have to deal are under the influence of cocaine, methamphetamine, or other stimulants. So the Taser has to be safe even for those whose physiology is distorted by the presence of such powerful drugs. Cocaine in particular is a concern with respect to cardiac complications because it raises heart rate and blood pressure and significantly increases the risk of a heart attack even without any kind of shock.

My colleagues and I supposed that the presence of such drugs would increase the potential for cardiac arrhythmias, and we later tested this hypothesis in a separate study, published in the *Journal of the American College of Cardiology*. To our surprise, the amount of current needed to bring on ventricular fibrillation didn't go down; indeed, it *increased* significantly when the pigs were administered cocaine. After some thought, we realized that our initially puzzling findings were not entirely out of line, because cocaine has certain anesthetic properties that can affect the electrical behavior of the heart in ways that protect it against shocks and decrease its vulnerability to fibrillation. Applying enough voltage to a heart cell will open its sodium-ion channels and start the contraction machinery, but cocaine stops up the voltage-activated sodium channels, making it more difficult for electricity to trigger a muscle contraction.

Another study carried out at our clinic more recently showed that implantable defibrillators and pacemakers function normally after a typical 5-second electric shock from a Taser. It remains to be seen, however, how well such medical devices stand up to repeated or longer shocks.

It is a challenge to relate experiments conducted under controlled laboratory conditions to the vagaries of real life. For one thing, we obtained our results from anaesthetized pigs with ostensibly normal hearts. It's possible that an abnormal or diseased heart—or even a heart under stress or one affected by amphetamines—might be more vulnerable. No one has yet studied the effects of Taser shocks on such hearts, information that is sorely needed to understand what might prove to be the greatest danger from Tasers.

Even so, we were comforted to learn that stun guns do not normally pose any cardiac risk. The full length of the Taser dart tip would have to embed itself into the skin and chest-wall muscle of a relatively small, thin person to get within the range of distances where we found the heart to be most vulnerable. Furthermore, the most sensitive region for the induction of fibrillation covers just a small area. And it is unlikely that two darts would land there.

Much remains unknown about the physiological effects of a Taser shot, but the absence of conclusive medical knowledge doesn't necessarily mean that the devices shouldn't be used—as long as evidence continues to support their safety. Rarely is any biological phenomenon or medical device fully understood and tested, and the Taser is no exception. As more information becomes available, law-enforcement agencies and their officers will better understand the consequences of each pull of the trigger. ■

ABOUT THE AUTHORS

MARK W. KROLL is an IEEE senior member who holds more than 250 U.S. patents as an inventor of electrical medical devices. He sits on the board of Taser International. **PATRICK TCHOU** is a cardiologist who specializes in treating cardiac rhythm disturbances at the Cleveland Clinic, a leading research hospital in Ohio.

TO PROBE FURTHER

The Police Executive Research Forum's report on standards for "conducted energy devices" is on its Web site at http://www.policeforum.org/library.asp?MENU=356.

Recent U.S. Department of Justice findings on arrest-related deaths can be found at http://www.ojp.usdoj.gov/bjs/abstract/ardus05.htm.

The Institute for the Prevention of In-Custody Deaths has related research available at http://www.incustodydeath.com.