1 History of the Science of Cardiopulmonary Resuscitation

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THE WILL OF RESUSCITATION

Through much of recorded history, resuscitation was forbidden. Although written accounts of resuscitation can be found, it is clear that successful reversal of death was thought to have been performed directly by God or through appointed agents. For example, stories of resuscitation in the Bible involve prophets acting clearly as vessels through which God's power restores life *(1,2)*. In these and other resuscitation accounts, reversal of death was considered the province of God and not something mere mortals should undertake. This "prohibition" against resuscitation was challenged during the Enlightenment, an amazing period of scientific discovery. Starting around 1750, scientists and philosophers questioned the dogma of the past and came to believe that humans could understand and control their own destinies. They wished to discover the workings of the universe as well as the ticking of life itself. To speak of the science of resuscitation one must begin where science begins. And there is no more crucial ingredient to science than the scientific method—a key achievement of the Enlightenment. The intellectual giants of the Enlightenment claimed that the world could best be understood through scientific discovery, and the means to achieve this was the scientific method.

From the experiments and swirling discoveries of the Enlightenment came the belief that if life could be understood, then death itself could be reversed. The will to resuscitate manifested itself in the first organized effort to deal with the problem of sudden death.

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In the 1700s, drowning, particularly in the large European port cities, was the leading cause of sudden death. In response, Amsterdam founded the first organized resuscitation effort—there were as many as 400 deaths per year in that city *(3)*. The establishment of the Amsterdam Rescue Society in 1767 represents humanity's collective desire to attempt resuscitation of the suddenly dead. No longer was religion invoked as the sole life-saving force, instead humankind empowered itself to deal with matters of life and death. Within 4 years of its founding, the Amsterdam Rescue claimed to have saved 150 persons from watery deaths. The Royal Humane Society in London began a few years later in 1774 *(4)*. The Society's emblem shows an angel blowing on an ember with a Latin inscription that translates "A little spark may yet lie hid." This emblem is a wonderful metaphor of the prevailing belief that as long as there was warmth in the body, life could be reignited. The will to resuscitate began with the Enlightenment. It would take approx 200 years for the way to be found *(5)*.

THE SEARCH FOR THE WAY OF RESUSCITATION

Rescue societies were formed in many European and American cities after the Enlightenment, and all of these societies recommended techniques to deal with drowning victims *(6)*. For example, one technique advocated placing the victim over a barrel and rolling him or her back and forth while holding the legs. This technique allowed the abdomen to be alternatively squeezed and to perhaps allow a small amount of air to reach the lungs. Another recommended procedure was to use bellows to directly blow air into the victim's mouth. Clearly, most of the air would go into the stomach or out the nose. There were even recommendations to use tobacco smoke inserted rectally in the drowning victim *(7,8)*. Tobacco was a stimulant, and there were animal experiments suggesting that smoke in the rectum could revive unconscious individuals. These techniques relied on common sense. It seemed logical to stimulate the body to restart breathing. With these and many other fanciful methods it is tempting to ridicule the science of the 18th century. What is important, however, is not the success of these early methods, but rather their very existence as emblematic of the quest to reverse sudden death.

From 1767 to 1949, there were literally hundreds of techniques and procedures recommended for artificial ventilation *(9)*. Most relied on direct pressure to the abdomen, chest, or back. The inventors of these techniques thought, wrongly, that passive entrainment of air into the lungs was sufficient to maintain adequate oxygenation. Hundreds of thousands of individuals in Europe and the United States learned these techniques, although none of the methods were very effective *(10)*. Perhaps it is surprising that no scientist recommended direct mouth-to-mouth respiration, but it must be remembered that for many years it was considered loathsome for a rescuer to place his or her lips on another person's mouth. And then there was the belief, strongly held for many decades, that expired air did not contain enough oxygen to sustain life.

THE WAY IS FOUND

It wasn't until James Elam, an anesthesiologist, entered the scene that mouth-to-mouth resuscitation was rediscovered. I say "rediscovered" because it had been known for many centuries that it could be useful in newborn resuscitation. Elam's discovery occurred in the middle of a polio outbreak in 1949 in Minneapolis. Here is how Elam describes the event.

I was browsing around to get acquainted with the ward when along the corridor came a gurney racing—a nurse pulling it and two orderlies pushing it, and the kid on it was blue. I went into total reflex behavior. I stepped out in the middle of the corridor, stopped the gurney, grabbed the sheet, wiped the copious mucous off his mouth and face, . . . sealed my lips around his nose and inflated his lungs. In four breaths he was pink (5).

The evening before this rediscovery, Elam read a chapter on the history of resuscitation in which mouth-to-mouth ventilation for newborns was described. He credits this chapter for his "reflex behavior." It is comforting to think that historians played a crucial role in scientific discoveries. Elam's passion led to his proselytizing about the merits of mouth-to-nose ventilation. He set out to prove that exhaled air was adequate to oxygenate non-breathing persons. To accomplish this he obtained permission from his chief of surgery to do studies on postoperative patients before the ether anesthesia wore off. He demonstrated that expired air blown into the endotracheal tube maintained normal oxygen saturation *(11)*.

Several years later, Elam met Peter Safar, and Safar joined the effort to convince the world that mouth-to-mouth ventilation was effective. Safar set out on a series of experiments using paralyzed individuals to show that the technique could maintain adequate oxygenation *(12)*. Safar describes the experiments.

Thirty-one physicians and medical students, and one nurse volunteered. . . . Consent was very informed. All volunteers had to observe me ventilate anesthetized and curarized patients without a tracheal tube. I sedated the volunteers and paralyzed them for several hours each. Blood O_2 and CO_2 were analyzed. I demonstrated the method to over 100 lay persons who were then asked to perform the method on the curarized volunteers (5).

Within a year of these experiments, Safar and Elam convinced the world to switch from manual to mouth-to-mouth ventilation. The US military accepted and endorsed the method in 1957 and the American Medical Association (AMA) followed suit in 1958. *The Journal of the American Medical Association* (*JAMA*) stated the following endorsement, "Information about expired air breathing should be disseminated as widely as possible" *(13)*.

Unlike cessation of respiration, an obvious sign of sudden death, the cessation of circulation, and particularly the rhythm of the heart, was invisible to an observer. Perhaps as a result, the appreciation of artificial circulation lagged considerably behind the obvious need for artificial respirations. Plus, even if scientists in the post-Enlightenment period appreciated the need to circulate blood there was simply no effective means to do so. Even though closed chest massage was described in 1904 *(14)*, its benefit was not appreciated and anecdotal case reports did little to promote the benefit of closed chest massage. The prevailing belief was described in a physician's quote from 1890, "We are powerless against paralysis of the circulation."

Here's where serendipity plays a role. It would be nice to believe that all scientific discoveries are the result of the painstaking accumulation of small facts leading to a grand synthesis, yet, the role of accident cannot be discounted. Chest compression was really an accidental discovery made by William Kouwenhoven, Guy Knickerbocker, and James Jude. They were studying defibrillation in dogs and they noticed that by forcefully applying the paddles to the chest of the dog with a fair amount of force, they could achieve a pulse in the femoral artery. This was the key observation that led them eventually to try it on humans. The first person saved with this technique was recalled by Jude as ". . . rather an obese female who . . . went into cardiac arrest as a result of flurothane anesthetic. . . . This woman had no blood pressure, no pulse, and ordinarily we would have opened up her chest. . . . Instead, since we weren't in the operating room, we applied external cardiac massage. . . . Her blood pressure and pulse came back at once. We didn't have to open her chest. They went ahead and did the operation on her, and she recovered completely" *(5)*. They published their findings on 20 cases on in-hospital cardiac arrest (CA) in a 1960 *JAMA* article *(15)*. Of the 20 patients, 14 (70%) were discharged from the hospital. Chest compression ranged from 1 to 65 minutes in the patients. The authors write in their landmark article, "Now anyone, anytime, can institute life saving measures." Later that year, mouth-to-mouth ventilation was combined with chest compression and cardiopulmonary resuscitation (CPR), as we practice it today, was developed. The American Heart Association (AHA) formally endorsed CPR in 1963 *(5)*.

THE SEARCH FOR DEFIBRILLATION

The discovery of electricity was another product of the Enlightenment. In the late 1700s, many scientists began experimenting with this "newly discovered" force called electricity. There were early descriptions of possible defibrillation *(16)*. For example, in this account from 1780 there is a report of "Sophia Greenhill who fell from a window and was taken up, by all appearances, dead." The report goes on to say that "Mr. Squires tried the effects of electricity, and upon transmitting a few shocks to the thorax, perceived a small pulsation" *(17)*. Protodefibrillators had two electrodes and glass rods to protect the operator. They even had a capacitor and a means to dial in a variable amount of current.

Ventricular fibrillation (VF) was first appreciated in animals 150 years ago when two German scientists noticed that strong electric currents applied directly to the ventricles of a dog's heart caused VF. It was considered a medical curiosity with no relevance for humans. John McWilliam made the first detailed descriptions of VF in animals and he was the first to postulate an importance for humans in a series of articles from 1887 to 1889 published in the *British Medical Journal* (*BMJ*) *(18,19)*. In McWilliam's day it was assumed that sudden cardiac collapse took the form of a sudden standstill—in other words, no electrical activity. Experiments performed by McWilliam on dogs disproved this idea. McWilliam's descriptions of VF, written more than 100 years ago, are classic:

> *The normal beat is at once abolished, and the ventricles are thrown into a tumultuous state of quick, irregular, twitching action. . . . The cardiac pump is thrown out of gear, and the last of its vital energy is dissipated in a violent and prolonged turmoil of fruitless activity in the ventricular walls. . . . It seems to me in the highest degree probable that a similar phenomenon occurs in the human heart, and is the direct and immediate cause of death in many cases of sudden dissolution (18).*

In addition to studying dogs, McWilliam performed experiments on both young and adult cats, rabbits, rats, mice, hedgehogs, eels, and chickens. He noted that the lower and smaller mammals, and the fetal hearts of larger animals, could not sustain VF. The hearts were simply too small to sustain the rhythm. His delineation of heart size and its ability to maintain VF were major factors in his speculation that fibrillation is an important cause of sudden death in humans. At the time McWilliam was writing, VF had never been observed directly in humans, as the electrocardiogram (ECG) wasn't invented until 1930.

Although McWilliam used an electric current to induce the fibrillation, he never tried electricity to stop the fibrillations of a heart muscle. One would not intuitively assume that the electrical stimulation that caused the fibrillation could not also defibrillate the heart. Nevertheless, McWilliam deserves recognition for his landmark studies in fibrillation and for being the first scientist to defibrillate animals.

MODERN CURRENTS

The connection between electricity and defibrillation was picked up again in the 1920s. The Edison Electric Institute, concerned about fatal electrical shocks suffered by its utility workers, funded research to prevent fatalities. The researchers were Hooker, Langworthy, and Kouwenhoven *(20)*. This is the same Kouwenhoven who later was one of the codiscoverers of CPR—he was working on defibrillation involving dogs and noticed how the pressure of the paddles on the dogs' chest led to a pulse. This accidental observation led to modern CPR. Throughout the early 1930s, Hooker et al. showed that even small electric shocks could induce VF in the heart and that more powerful shocks could erase the fibrillation. These investigators induced VF in dogs and then were able to defibrillate the heart without opening the chest. But their closed-chest defibrillation was successful only if the fibrillatory contractions were vigorous and the period of no circulation or breathing did not exceed several minutes. If the period was longer than several minutes, open-heart massage was necessary before the electric shock could defibrillate the heart. The term "countershock" was derived from their research. Because an initial shock was required to place the heart in VF, it was only logical to call the subsequent shock, which defibrillated the heart, the countershock. The term countershock for many years was used synonymously to mean defibrillation.

Hooker et al.'s research was well on its way toward developing effective defibrillation in humans; unfortunately, however, their work had to be halted because of World War II.

Claude Beck, professor of surgery at Western Reserve University (later to become Case Western Reserve) in Cleveland, worked for years on a technique for defibrillation of the human heart. Beck probably witnessed his first CA during his internship in 1922, while on the surgery service at the Johns Hopkins Hospital. During a urological operation, the anesthetist announced that the patient's heart had stopped. To Beck's amazement, the surgical resident removed his gloves and went to a telephone in a corner of the room and called the fire department. Beck remained in total bewilderment as the fire department rescue squad rushed into the operating room 15 minutes later and applied oxygen-powered resuscitators to the patient's face. The patient died, but the episode left an indelible impression on Beck. Twenty years later, Beck wrote, "surgeons should not turn these emergencies over to the care of the fire department." Recalling the same event, he remarked to medical students in typically understated fashion, "The experience left me with a conviction that we were not doing our best for the patient" *(21)*. Beck ultimately developed techniques to take back the management of CA from the fire department and place it in the hands of surgeons. Ironically, 20 years after his accomplishment, CA management was utilized by emergency medical technicians (EMTs), thus returned to the fire department.

Beck realized that VF often occurred in hearts that were basically sound and he coined the phrase "Hearts Too Good to Die." In 1947, Beck accomplished his first successful resuscitation of a 14-year-old boy using open-chest massage and internal defibrillation with alternating current. The boy was being operated on for a severe congenital funnel chest. In all other respects, the boy was normal. During the closure of the large incision in the boy's chest, his pulse suddenly stopped and his blood pressure (BP) fell to zero.

Seeing the boy was in CA, Beck immediately reopened his chest and began manual heart massage. As Beck looked at and felt the heart, he realized that VF was present. Massage continued for 35 minutes, then an ECG was taken that confirmed the presence of VF. Another 10 minutes passed before the defibrillator was brought to the operating room. The first shock, using electrode paddles placed directly on the sides of the heart, was unsuccessful. Beck administered procainamide and then gave a second shock that wiped out the fibrillation. Within a very few seconds a feeble, regular, and fast contraction of the heart occurred. The boy's BP rose from 0 to 50 mmHg. Beck noted that the heartbeat remained regular and that the pressure slowly began to rise. Twenty minutes after the successful defibrillation, the chest wound was closed. Three hours later, the BP rose to a normal level, and the child awoke and was able to answer questions. The boy made a full recovery, with no neurological damage *(22)*.

The defibrillators used by Beck were individually made. Ever the scientist, Beck kept experimenting with different models in order to improve the efficiency of the machine. Because these models were intended for open-heart defibrillation, Beck designed a model that would both shock and perform heart massage. Suction cups were attached to the walls of the heart and alternating suction would expand and allow the heart to relax. According to Beck, the machine could massage at the rate of 120 beats per minute, and relieved the surgeon of performing cardiac massage. The suction cups doubled as defibrillator electrodes. It was an ingenious device, but closed-chest compression and closed-chest defibrillation ultimately turned Beck's defibrillator machine into an historical curiosity.

For Paul Zoll, the development of an external defibrillator was a natural extension of his earlier work with an external cardiac pacemaker. Zoll was also quite aware of open-heart defibrillation. He worked in a hospital where that procedure was used to resuscitate people whose hearts went into fibrillation during operations. The standard procedure would then be to crack open the patient's chest and massage the heart by hand to restore blood circulation. Then, the doctors would apply an electrical alternating current (AC) countershock directly to the heart.

The decision to develop an external defibrillator using AC rather than direct current (DC) was a practical one. DC batteries and capacitor technology that were both powerful and portable for practical use simply did not exist in the early 1950s. In 1955, a 67-year-old man survived several episodes of VF, thanks to Zoll's external defibrillator, and went home from the hospital after 1 month. Over a period of 4 months, Zoll had successfully stopped VF 11 times in four different patients. The energy required for defibrillation ranged from 240 to 720 volts (V). Zoll's findings were published in the *New England Journal of Medicine* (*NEJM*) in 1956 *(23)*.

The defibrillator designed by Zoll, as well as earlier versions invented by Kouwen-hoven and Beck, utilized AC and were run off the electricity from any wall socket, or line current. These AC defibrillators were very large and heavy, primarily because they contained a transformer to step up the line current from 110 V to 500 or 1000 V. Not many lives would be saved unless the inherent nonportability of AC defibrillators could be solved.

The portability problem was finally solved by Bernard Lown. Lown devised a defibrillator that utilized DC instead of AC. With DC it was possible to use power, supplied by a battery, to charge a capacitor over a few seconds. The capacitor stored the energy until it was released in one massive jolt to the chest wall. The availability of new, small capacitors considerably reduced the size and weight of the device. No longer would defibrillators require bulky transformers and no longer would they be tied to line current. The cord was cut—the defibrillator could travel to the patient.

In 1960, little was known about the effect of DC current on the heart. Lown divided the problem into two parts: What is safe? What is effective? A series of animal experiments on dogs in 1960 and 1961 established that DC shocks were extremely effective in shocking the heart. What's more, it was clear that DC would be many times safer than AC when applied through the chest wall.

In a 1962 article in the *American Journal of Cardiology (24)*, Lown noted that the incidence of VF was 10 times more frequent after AC than DC cardioversion. Lown did discover one short period of time during the procedure when a DC shock could induce VF. Thus, the trick was simply to build a device that would shock the heart while avoiding this so called "vulnerable period" of a few milliseconds. It was his breakthrough to DC that eventually made the portable defibrillator practical.

The development of small but powerful DC batteries and small capacitors would be the next technological link. At that point, the need to carry a 50-pound step-up transformer to the patient and the need to find an electrical outlet in which to plug an AC-based defibrillator vanished.

PRESENT CURRENTS

With DC defibrillation proved, all the elements were in place for widespread dissemination of the procedure. Defibrillation spread quickly into hospital coronary care units, emergency departments, and, then, in the late 1960s and early 1970s the first paramedic programs began. Now the defibrillator traveled directly to a patient in VF. The first programs began almost simultaneously in Seattle, Portland, Columbus, Ohio, Miami, and Los Angeles *(5)*. By the 1980s, studies to demonstrate successful defibrillation by EMTs were conducted in King County, Washington. The first study demonstrated an improvement in VF survival from 7 to 26%. Slowly, other communities began EMT defibrillation programs *(25)*.

The idea for an automatic defibrillator was first conceived by Dr. Arch Diack, a surgeon in Portland *(26)*. Diack's prototype, literally assembled in a basement, utilized a unique defibrillation pathway—tongue to chest. There was a breath detector that was a safeguard to prevent shocking breathing persons. The electrode was essentially a rate counter, far more crude than today's sophisticated VF detectors. The production model weighed 35 pounds and gave verbal instructions. It was an idea ahead of its time. Most people viewed it as a curiosity. By the late 1980s, however, other manufacturers entered the field leading to the crop of automated external defibrillators (AEDs) we have today. AEDs, with ease of training and use, allowed EMT defibrillation programs to expand rapidly. The first program to demonstrate the safety and effectiveness of EMT defibrillation with AEDs was also conducted in King County (by Richard Cummins) *(27)*. From EMT defibrillation with AEDs, there was a natural and logical progression to the early First Responder defibrillation and finally the current situation of widespread public access defibrillation. Perhaps the future will witness AEDs in homes, and they will be thought of as personal safety devices.

FUTURE CURRENTS

Future AEDs will likely interact more with the victim of CA and provide feedback to the rescuer. For example, a device may obtain information from the heart's ECG, or wall motion or internal sound that could be fed back to tell the rescuer to perform CPR prior to defibrillation. In other words, the ECG signal may be a surrogate for downtime that in turn can better advise how to proceed with the resuscitation. Back in the early 1970s, it was dogma that CPR should precede defibrillation to "prime the pump" and rid the heart of lactic acid. By the 1980s, there was a growing body of information to suggest that time to shock was the best predictor of outcome. Thus, defibrillation became the priority and defibrillatory shocks were to be given as rapidly as possible. The mantra became, "CPR until the defibrillator arrives." Now with recent studies from Seattle and Oslo, some are once again questioning whether CPR should be given prior to defibrillation. It may well turn out that both are correct, namely immediate shock for witnessed VF or VF of short duration and CPR prior to shock for VF of longer duration.

We now appreciate that there is an interaction between CPR and defibrillation. Each procedure is not independent of the other. It is possible to learn much from the VF signal that can be used to provide feedback regarding whether CPR or immediate defibrillation is the procedure of choice. Recent studies coming from the world of engineering demonstrate that the probability of return of spontaneous circulation (P_{ROSC}) based on the VF signal can be calculated. This probability is determined from calculations of spectral densities, frequency, amplitude, and other electrical terms. This information is translated into a probability. And because it can be calculated every second, it will be possible to determine if the P_{ROSC} is rising or falling. This in turn can guide the resuscitation. For example, if the P_{ROSC} is 20% after attaching the pads, then CPR is indicated and perhaps medication. Once the P_{ROSC} reaches 60% then, a shock is indicated. Shocking for low P_{ROSC} are not indicated because they are likely to damage the heart with low likelihood of success and deprive the heart of CPR during the pause for defibrillatory shock. It is possible to gain the information from the VF signal even in the presence of chest compressions and ventilation.

THE SCIENCE OF RESUSCITATION CONTINUES

The will to resuscitate, as exemplified by rescue societies, emerged during the Enlightenment. It took approx 200 years for the way of resuscitation to be found. The elements of mouth-to-mouth ventilation, chest compression, and defibrillation each had to be discovered separately and integrated for reversal of sudden death to become a reality. The science of resuscitation is founded on the scientific method of experimentation. Many false starts, particularly in ventilation and defibrillation, happened before new understandings led to effective techniques. We now can reverse sudden death reliably and numerous scientists and investigators can take pride in this accomplishment. But the real challenge remains for the future. The real challenge is to fully understand the causes and triggers of VF and to develop preventive measures. Whether this will require 20 or 200 years, one thing is certain—future chapters in the science of resuscitation are still to be told.

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