Cardiopulmonary Resuscitation
History, Current Practice, and Future Direction

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At least 350 000 people will suffer cardiac arrest each year in the United States, 1 every 90 seconds.[1] Many will then undergo cardiopulmonary resuscitation (CPR) by bystanders and emergency medical services in a desperate attempt to restore life. Numerous studies report that the majority of these efforts will not succeed. Prolonged anoxia, the inability to restore spontaneous circulation, neurological devastation, and other complications combine to limit survival. Nonetheless, thousands will surmount these obstacles and resume normal lives. CPR is a triumph of medicine but also is frequently performed in vain. It is a young science; the term "CPR" was first publicized less than 50 years ago. The roots of resuscitation, however, extend back centuries, with a gradual course of evolution that has been periodically impeded by rejection of inadequate techniques, curiously slow adoption of proven interventions, and even a cyclic process of abandonment and subsequent rediscovery. Examining the history of resuscitation is an essential first step to understanding and following the evolution to modern practices. A detailed review of more current observations, inventions, and clinical trials, in the context of the disappointing statistics of conventional CPR, will elucidate the rationale behind the most recently published resuscitation guidelines, as well as provide fuel for future research. Although components of life support apply to the predominantly asphyxia-related arrests seen in pediatrics, the focus of this review is on resuscitation after cardiopulmonary arrest in the adult.

The History of Resuscitation

Airway

"But that life may . . . be restored to the animal, an opening must be attempted in the trunk of the trachea, into which a tube of reed or cane should be put."

Andreas Vesalius, 1540[2]

The Babylonian Talmud, a sixth century collection of Jewish oral tradition, records that a lamb with a neck injury was saved by a hole into the trachea, supported by a hollow reed.[3] Andreas Vesalius, the Belgian anatomist quoted above, conducted experiments with similar design a millennium later.[2] This knowledge lay dormant until the 18th century, however, because of a lack of appreciation for its applicability to humans. In 1768, the Dutch Humane Society was founded, in which physicians and laypersons collaborated to aid victims of drowning in the waterways. Rules for resuscitation were created and disseminated, and monetary rewards were distributed for success.[4]

On the basis of the prevailing impression that death from drowning resulted from inhaled water obstructing the airway, early revival efforts centered on clearing the trachea by suspending the injured upside down or rolling them inverted on a barrel.[5] Early endotracheal cannulae were also used to secure access to the airway, and in 1895 Alfred Kirstein invented the laryngoscope to aid visualization of the trachea.[6] In the mid-20th century, Peter Safar methodically investigated techniques for airway management. In a series of daring experiments, he paralyzed volunteers with curare or succinylcholine to demonstrate that optimal patency was achieved when the neck was extended, the mandible was supported (today known as the jaw thrust), and an oropharyngeal tube was employed to deliver oxygen.[7] The development of the cuffed endotracheal tube by Sir Henry Head[8] in 1889 and invention of the low-pressure cuff by Cooper to reduce airway injury[9] together resulted in the modern method for securing the airway.

Breathing

"I applied my mouth close to his, and blowed my breath as strong as I could."

William Tossach, 1744[10]

The earliest recorded reference to artificial breathing is in the Old Testament, in the book of Kings, where the prophet Elisha restored the life of a boy through a technique that included placing his mouth on the mouth of the child,[11] although there is little mention of this method for another 2000 years. The early efforts to clear the trachea of water were accompanied by a complementary interest in artificial breathing. Fireside bellows-to-nostril resuscitation in humans is first mentioned by Paracelsus in the 1500s, and early mouth-to-mouth techniques are described in several 18th century sources, including one by D.J. Larrey, Napoleon's chiefbattlefield surgeon.[4] William

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The online-only Data Supplement is available with this article at http://circ.ahajournals.org/cgi/content/full/114/25/2839/DC1.

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(*Circulation.* 2006;114:2839-2849.)

***Circulation* is available at http://www.circulationaha.org** **DOI: 10.1161/CIRCULATIONAHA.106.610907**

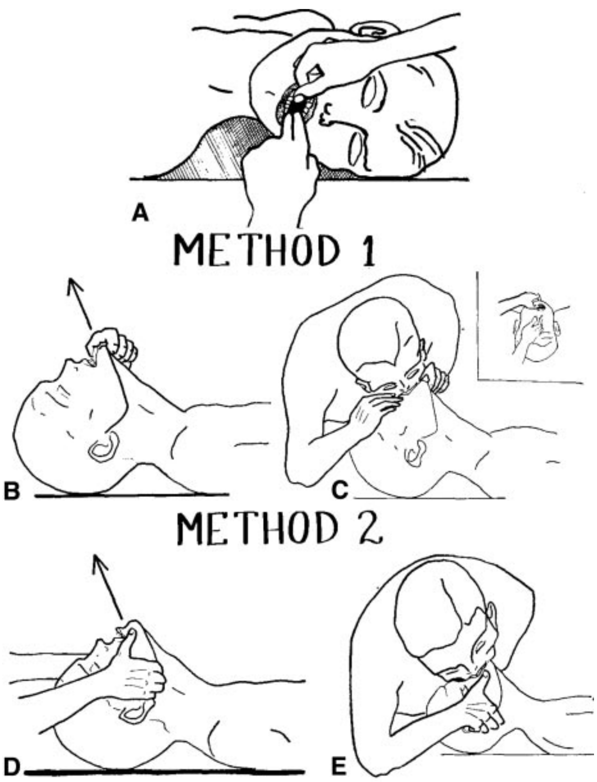

Figure 1. Figure from publication by Safar and McMahon[16] illustrating the need for neck extension and jaw thrust to maintain a patent airway during mouth-to-mouth artificial ventilation. Reproduced from Safar and McMahon[16] with permission. Copyright © 1958, American Medical Association. All rights reserved.

Tossach, a British surgeon, used mouth-to-mouth resuscitation of a coal miner in 1732, as reported in the quotation above.[10] In the 1770s, however, use of exhaled air for resuscitation was discredited when Scheele discovered oxygen[12] and Lavoisier studied its relevance in respiration.[13] Expired air was then perceived to be devitalized by already passing through another's lungs. Because of this concern, as well as reports of lung barotrauma from bellows, alternative methods for reproducing breathing were explored and favored. In 1857, Marshall Hall advanced the chest-pressure method, which was modified in 1861 by Silvester to become the chest-pressure arm-lift method in supine patients.[14] Variants of this technique continued to be practiced with fervor until the 1960s.[15] A series of elegant experiments directed by Archer Gordon, James Elam, and Peter Safar demonstrated that the prone position, which was advocated by some, did not allow a consistently patent airway for air exchange and that expired air did indeed provide sufficient oxygen for effective artificial ventilation (Figure 1).[16–20]

Initially, tools for respiratory resuscitation were exclusively in the domain of emergency medical services and were not available in hospitals. Claude Beck, a surgeon at Western Reserve University, recounts having to call the fire department in 1921 for a "pulmotor," an artificial breathing apparatus, to attempt resuscitation in a patient who unexpectedly expired during surgery.[21] Thereafter, innovations like the Drinker respirator ("iron lung") paved the way for the advent of modern intensive care units in hospitals (Figure 2). In 1952, an epidemic of poliomyelitis struck Copenhagen, overwhelming the supply of negative pressure ventilators. Dr Bjørn Ibsen proposed positive pressure ventilation as a substitute, and hundreds of medical students provided the manpower for manual ventilation via a tracheostomy tube and a rubber bag (Figure 3). Necessity overturned conventional practice, and endotracheal positive pressure ventilation became the standard of care and was routinely implemented in intensive care units, which were first formed in the 1960s.[22]

Circulation

> *"I now had to regard the patient as dead. In spite of this, I returned immediately to the direct compression of the region of the heart."*
>
> Friedrich Maass, 1892[23,24]

Palpation of pulses and heartbeat has been described for over 3000 years.[25,26] Cardiac action was felt to be dependent on ventilation, however, because starting and stopping breathing were known to secondarily start and stop the action of the heart.[2,27] The first cardiac compressions were performed in the open thorax. Moritz Schiff, in 1874, noted carotid pulsation after manually squeezing a canine heart, giving rise to the term "cardiac massage."[28,29] Soon thereafter, Rudolph Boehm and Louis Mickwitz demonstrated cardiac compression in cats by pressing on the sternum and on the ribs.[30] Until that time, external pressure applied to the thorax in humans had intended to assist breathing, as reported by Balassa in 1858.[31,32] Friedrich Maass, quoted above, is credited with the first successful closed-chest cardiac massage in a person, reported in 1892. His contribution nevertheless would be forgotten for nearly 70 years.[24]

In 1849, John Snow, the father of modern epidemiology, reported cases of chloroform-induced cardiac arrest.[33] There was no remedy for these deaths until the first successful open-chest cardiac massage in 1901, performed by Kristian Igelsrud after anesthesia-induced arrest.[34] Thereafter, in the first half of the 20th century, sudden cardiac death was only survivable in an operating room or urgent hospital setting, where direct cardiac massage was possible. Almost 60 years later, Guy Knickerbocker was researching defibrillation in dogs and noticed by chance that when he pressed the electrode paddles firmly on the thorax, a simultaneous rise in arterial pressure resulted. This led to the rediscovery of external cardiac massage, today known as chest compression, which was reintroduced to patient care in 1958 by William Kouwenhoven (Figure 4).[35] Because this method did not require scalpels or significant technical expertise, it became widely taught and quickly eclipsed the open-thorax approach.

Defibrillation

> *"Abildgard . . . in 1775 relates to having shocked a single chicken into lifelessness and on repeating the shock, the bird took off and eluded further experimentation."*
>
> Bernard Lown, 2002[36,37]

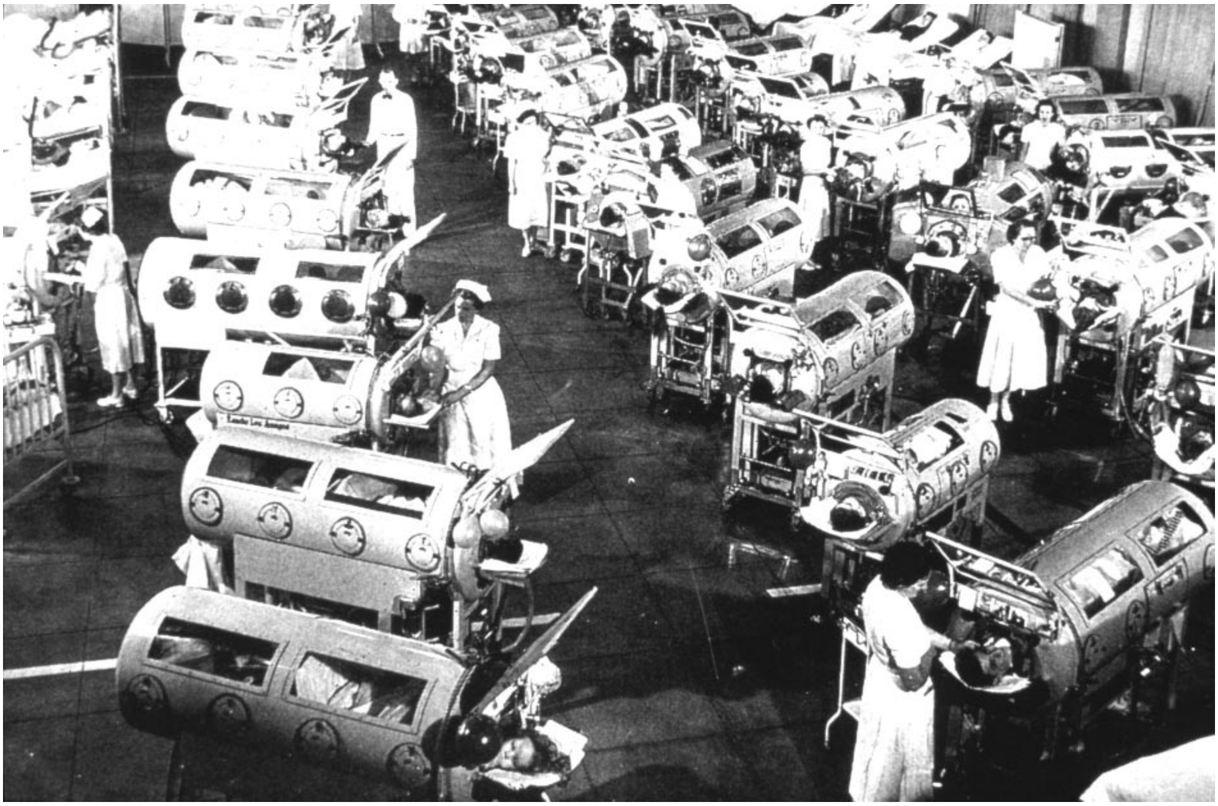

Figure 2. The polio ward at Rancho Los Amigos Rehabilitation Center, in 1952, was filled with rows of Drinker respirators, or "iron lungs." They assisted respiratory paralysis by cyclic negative pressure generated inside the cylinder surrounding the patients' bodies. Only their heads were not enclosed in the chamber. Photograph courtesy of the March of Dimes.

Electricity was discovered in the mid-1700s, and its ability to cause muscle tissue to contract was appreciated by Galvani in 1791.[38] The experiment of Abildgard cited above was not appreciated to have affected the heart, and therefore early application of electricity was designed to nonspecifically stimulate unconscious victims or verify their unconscious state. That electric current could cause irregular quivering of the ventricles was appreciated in 1850 but was considered only a curiosity (Figure 5).[39,40] Dr John McWilliam systematically studied the effects of electricity on mammalian hearts and described that death was not associated with immediate cardiac standstill, but instead "fibrillar" motions took place. In 1889, he published his view that this fibrillation of ventricles probably took place in humans, with fatal results.[41] Prevost and Battelli applied alternating and direct current shocks to fibrillate dog ventricles and discovered that a repeat shock or "countershock" could reverse or "defibrillate" the ventricles.[42] Gurvich and Yuniev, working under Negovsky in the Soviet Union, discovered that direct current shocks stored in capacitors could successfully defibrillate dogs,[43] while in America, Wiggers's experiments prompted human studies of defibrillation.[4] Hooker and Kouwenhoven, funded by the Edison Electric Institute to study accidental electrocution, showed that defibrillation could take place in an intact thorax, without applying current directly to the heart muscle.[44] Combining the observations of closed-chest current application with Willem Einthoven's invention of the string galvanometer in 1901 allowed quality noninvasive recording, diagnosis, and treatment of abnormal electric cardiac activity.[45]

Figure 3. Positive pressure ventilation of an awake polio victim via a tracheostomy and manual compression of a rubber bag. With permission from Elsevier, reprinted from Management of Life Threatening Poliomyelitis, Lassen, © 1956 Livingstone.

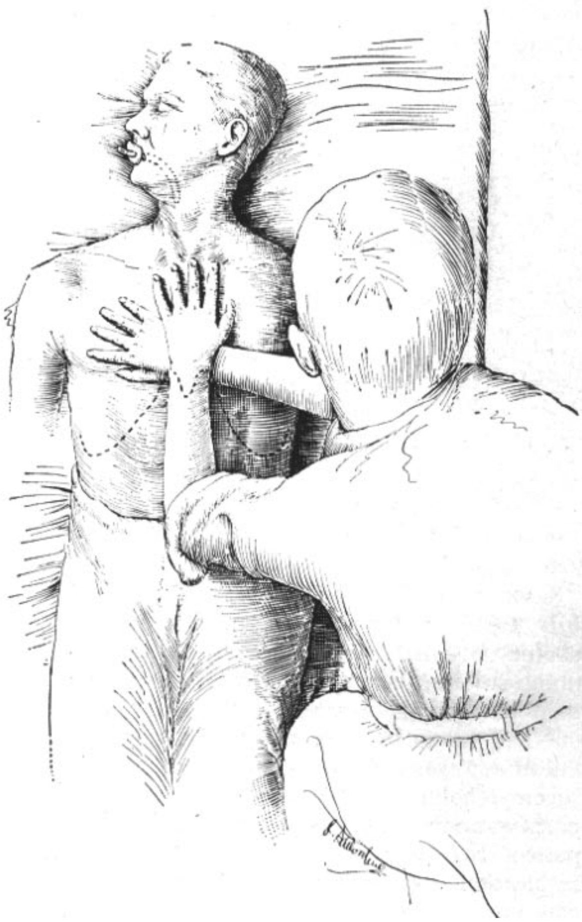

Figure 4. Demonstration of the technique of closed-chest cardiac massage. Reproduced from Kouwenhoven et al[35] with permission.

The first successful (open) human defibrillation with recovery of the patient was performed by Claude Beck in 1947 (Figure 6).[46] A 14-year-old boy underwent surgery to repair a sternal deformity and, during wound closure, his pulse stopped, the chest was reopened, and he was found to be in ventricular fibrillation. Open cardiac massage was performed for 70 minutes, and, after 2 series of electric shocks were delivered to the heart, a regular pulse was restored, and no adverse neurological sequelae resulted. Paul Zoll recorded the first successful closed-chest human defibrillation in 1955 on a man with recurrent syncope and ventricular fibrillation,[47] and Bernard Lown showed that direct current was superior to alternating current defibrillation in 1962.[48] In 1979, the first portable automatic external defibrillator was developed, with a pharyngeal electrode for sensing, shocking electrodes on the abdomen and tongue, and a simple algorithm to detect abnormal rhythms and automatically deliver rescue pacing or a defibrillation shock, as appropriate. It is remarkable that the automatic external defibrillator, which has recently revolutionized resuscitation via mass deployment,[49] was first shown to be effective more than 25 years ago. Michel Mirowski's landmark 1981 article that described the use of an implantable automatic defibrillator in humans, along with prospective studies that have demonstrated mortality benefit of implantable defibrillators in patients at risk for ventricular arrhythmias, has transformed the field by preventing sudden death.[50–52]

Education and Dissemination

The tools of resuscitation are useless in the absence of people who are trained to apply them. In the 1930s, Drs Beck and Leighninger formed and trained one of the first in-hospital resuscitation teams to administer emergency life-saving care to inpatients with sudden death.[4] Because most cardiac arrests do not occur in the hospital, however, mobile intensive care unit ambulances, staffed by physicians, were created in the 1960s. Dr Pantridge demonstrated that these mobile intensive care units could be used successfully by medical personnel to resuscitate outpatients with sudden cardiac death after acute myocardial infarction.[4,53] To provide the means by which resuscitation techniques could be demonstrated and taught, Åsmund Laerdal, whose plastic-toy company manufactured a popular doll named Anne, created a mannequin to facilitate CPR education, calling it "Resusci Anne." He modeled the mannequin's face after the famous visage of an unnamed girl who drowned in the Seine river (the story that his daughter drowned and served as the inspiration for Anne is apocryphal).[54] After Kouwenhoven's publication of the technique for external cardiac massage in 1960, the paradigm of integrating modern airway, breathing, and closed-chest circulation methods was published and advocated by Safar et al in 1961.[55] In 1966, the first CPR guidelines were published, encouraging practice with mannequins but disapproving of teaching resuscitation to laypersons out of concern for iatrogenic complications.[4,56]

The concept of educating the lay public in the techniques of resuscitation was advocated by Dr Beck in the late 1950s,

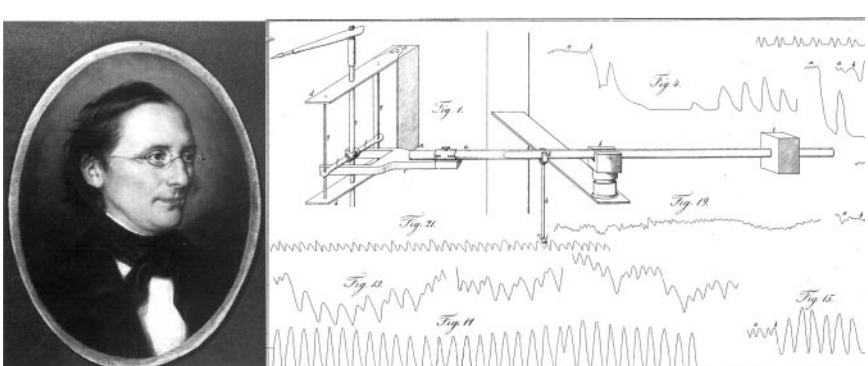

Figure 5. Dr Carl Ludwig and his discovery of electrically induced quivering of the ventricles. The clinical significance of this finding was not yet appreciated.

Figure 6. Dr Claude Beck and his first cardiac defibrillator. Images courtesy of Dr Igor Efimov (left) and the Dittrick Medical History Center, Case Western Reserve University (right).

when he created a short teaching film in which he introduced a group of 11 patients who were successfully resuscitated and in which he stated that "a massive teaching program is needed" (see movie in the online-only Data Supplement). Dr Beck and Lois Horwitz, a motivated layperson, first educated a group of lay rescuers in 1961 in Cleveland. Large-scale promulgation of community resuscitation, however, was championed by Drs Cobb, Kopass, Eisenberg, and colleagues in Seattle. Beginning in 1970, they developed and implemented an ambitious project that instructed 100 000 citizens to perform CPR, taught 911 dispatchers to coach bystander basic life support over the telephone, intensively trained paramedics in a tiered emergency response system with the fire department, delivered a rapid response to fallen victims, and efficiently transported them to hospitals.[57] Their early access to patients, early CPR delivery by bystanders and paramedics, and rapid transportation for definitive care all increased the likelihood of survival to hospital discharge.[58] Training of laypersons was formally sanctioned in 1974.[59]

Advanced Life Support and the Chain of Survival

The final step for out-of-hospital resuscitation was the instruction of paramedics in advanced cardiac life support (ACLS), which allowed medications to be administered in the field. These included epinephrine, discovered in 1894[60] and used in human resuscitation since 1922,[61] and atropine, whose properties were recognized by Linnaeus in the 18th century (the genus of its source, the deadly nightshade plant, he named *Atropa*, after the oldest of the 3 Fates that determined the life and mortality of humans in Greek mythology).[62] Endotracheal intubation was also to be performed by trained paramedics for definitive airway management before arrival in the emergency department. The American Heart Association highlights the stepwise nature of successful out-of-hospital resuscitation, framing it as a "chain of survival" with 4 links: early access (alerting emergency medical services), early CPR, early defibrillation, and early ACLS (Figure 7).[63] A study from the Ontario Prehospital Advanced Life Support (OPALS) Study Group determined that the odds ratios for increased survival attributable to the presence of the first 3 links were 4.4, 3.7, and 3.4, respectively.[64] Data supporting the fourth link, early ACLS, has been less definitive. Although a meta-analysis suggested that the odds ratio of survival from outpatient arrest by resuscitation with ACLS versus without ACLS was 2.3,[65] the OPALS study found no improvement in outpatient survival with the addition of ACLS.[64]

The Modern Era of Resuscitation

Statistics of Survival

Modern published studies of resuscitation for cardiac arrest (all cardiac rhythms) show rates of survival to hospital discharge that range from 1% to 25% for outpatients[64,66–69] and 0% to 29% for inpatients.[70,71] A compilation of the mortality statistics from the largest of these recent studies is reported in the Table, revealing overall survival rates of 6.4% after out-of-hospital arrest and 17.6% after in-hospital arrest. Survival varied greatly by initial cardiac rhythm, with higher success rates for resuscitation from ventricular arrhythmias and markedly worse outcomes if asystole or pulseless electric activity was initially noted. These statistics are somewhat sobering, especially when the rates of survival that were achieved when resuscitative techniques were first being developed and reported are considered. Of the first 20 patients who underwent closed-chest cardiac massage, only 3 had ventricular fibrillation, and yet 14 survived the arrest (70% survival).[35] In 1953, a review of 1200 in-hospital cardiac arrests reported that, despite only 11% having ven-

Figure 7. The chain of survival was first introduced in 1991 as a model of efficiency and synergy in resuscitation efforts. Reproduced with permission from American Heart Association, 1991.

Adult Survival Rates to Hospital Discharge After Inpatient and Outpatient Arrest

	Inpatient[71]	Outpatient* [64,72,73]
Location	United States, Canada	United States, Canada, England, Norway, Sweden
Dates included	1/00–3/04	2/98–6/02 3/02–10/03 1/99–12/00
Total No. (% survival)	36 902 (17.6)	5234 (6.4)
% VF or VT (% survival)	22.7 (36.0)	33.2 (16.1)
% Pulseless electric activity (% survival)	32.4 (11.2)	24.7 (2.7)
% Asystole (% survival)	35.3 (10.6)	39.0 (0.9)
% Unknown rhythm	9.6	3.0

Summary of results from 4 large studies of arrest survival,[64,71-73] showing proportions of presenting cardiac rhythm and percentage survival to hospital discharge, divided by location of arrest. Ventricular fibrillation (VF) and ventricular tachycardia (VT) are proportionally more common in the outpatient than the inpatient setting, as is asystole, whereas the reverse is true for pulseless electric activity. Survival rates to hospital discharge show an increased likelihood of survival for all rhythms when the arrest occurred in hospital setting.

*Outpatient data are pooled from the 3 studies cited.

tricular fibrillation, 28% were resuscitated to "permanent survival."[74] The disparity between these historical reports and modern data might be explained by a higher level of acuity in present-day hospitals or different causes of the arrests. In the cardiac arrest cohort from over 50 years ago, the majority of patients were undergoing surgery, and they were therefore healthy enough to attempt an operation. These patients also benefited from intensive perioperative monitoring.

In addition to overall survival rates, recent statistics on neurological recovery after resuscitation are also disappointing when put into historical perspective. Dr Stephenson's 1953 article reported that 56% of the 1200 resuscitations were successful in restarting the heart, and only 8 of these patients were rendered decerebrate.[74] The first successful human defibrillation, in 1947, involved cardiac massage for over an hour, and yet the patient had no long-term neurological deficits.[46] These data contrast with the current experience, in which brain damage is a frequent cause of death after cardiac arrest.[75] The impact of cerebral anoxic damage today may even be underreported because resuscitation efforts may be terminated solely because of elapsed time before return of spontaneous circulation is achieved, amid concern for neurological sequelae if the heart is eventually restarted. Because intracranial catastrophes are rarely the cause of cardiac arrest, neurological injury after resuscitation from a witnessed arrest almost universally signifies a failure to provide sufficient cerebral oxygen flow during CPR efforts. It is therefore with the dual goal of achieving cardiopulmonary and neurological recovery that novel CPR techniques are being investigated and resuscitation guidelines are being revised to optimize the basic steps of life support: airway, breathing, circulation, and defibrillation. The American Heart Association guidelines were most recently revised in 2005, with recommendations being strongly driven by evidence-based medicine.[76] The following sections summarize the study data that have resulted in changes to the guidelines and report the most recent developments that will likely shape the future of resuscitative practices.

Improving Airway and Breathing

Bag-mask airway management has traditionally been viewed as inferior to endotracheal intubation; no prospective randomized trial has adequately addressed this question, however. The OPALS study did not demonstrate mortality benefit from the addition of ACLS, including endotracheal intubation, to survival after out-of-hospital resuscitation.[64] Insertion of an endotracheal tube can be time consuming, interrupting chest compressions and thereby halting cerebral blood flow at times for >60 seconds. Unrecognized misplacement into the esophagus can also occur. Therefore, the benefits of an endotracheal tube in protecting the airway from aspiration and ensuring air delivery to the lungs must be weighed against these potential detriments. If undertaken, an advanced airway should be placed rapidly by experienced rescuers, with minimal interruption of chest compressions.[76] Consideration should also be given to laryngeal mask airways because of the ease and rapidity of their insertion.

Extensive recent human data have indicated that ventilation during CPR is usually overzealous. Both emergency medical personnel and in-hospital resuscitation teams have been shown to deliver artificial breaths at rates far exceeding the published recommendations of the time (12 to 15 breaths per minute), averaging 20 to 30 breaths per minute.[77,78] Despite retraining efforts, ventilation remained excessive with rates that, although slower, still exceeded guidelines, with an observed increase in breath duration as well.[77] Positive pressure in the thoracic cavity hinders circulation by decreasing venous return, increasing intracranial pressure, and decreasing coronary perfusion pressure, a critical predictor of return of spontaneous circulation.[79,80] In animals, hyperventilation during 4 minutes of resuscitation reduced absolute survival by 70%.[77] Furthermore, before a secure airway is obtained, breathing efforts interrupt chest compression, and 2 breaths take the average lay rescuer >15 seconds (stopping circulation for at least 25% of each minute).[79] In an intriguing randomized trial of CPR technique, Seattle's 911 telephone staff randomly instructed bystanders to perform both ventilation and chest compressions versus performing chest compressions alone. Both groups had similar outcomes, with a trend toward higher survival to hospital discharge in patients assigned to the latter.[81] The apparent benefit of withholding artificial respiration in this trial was likely the exclusive consequence of maintaining uninterrupted circulation because the human unconscious airway is often obstructed, and chest compressions do not provide any meaningful airflow.[70]

Animal models show that arterial blood is completely desaturated in <2 minutes of chest compression without ventilation, and therefore at least some air exchange is necessary to oxygenate blood.[82] Recently published guidelines advocate delivering a slower ventilatory rate of 8 to 10 breaths per minute.[76] Even slower rates may be optimal, and ongoing experiments will clarify the necessary ventilation rate in states of low blood flow. Furthermore, breaths should be delivered quickly, over approximately 1 second, because prolonged breaths increase the duration of positive intrathoracic pressure. Keeping artificial ventilation rates low is difficult because the high-adrenaline state of the rescuer alters time perception, and the rapidly refilling bag-ventilation systems set up a reflex in which rescuers are inclined to deliver breaths as soon as the bag inflates. Because even focused reeducation did not ensure compliance with the guidelines, the use of adjunct devices that indicate when 6 to 7.5 seconds have elapsed (for delivery of 8 to 10 breaths per minute) should be encouraged.

Optimizing Circulation

Friedrich Maass, who resuscitated a teenager for 60 minutes with closed-chest cardiac massage in 1891 (with return of mental function), described that the optimal technique was to apply forceful pressure and to do so at a rapid rate.[24] The quality of modern chest compression efforts in and out of hospitals has been quantified through use of an accelerometer placed on the sternum. Results demonstrated that chest compressions were frequently interrupted, and cardiac massage was withheld for an astonishing 48% of pulseless resuscitation time. Furthermore, compression depth was frequently too shallow.[72,78] The observation that modern chest compressions are not performed adequately is disconcerting in the context of the current statistics of survival and neurological recovery after cardiac arrest, with the healthy appreciation that cerebral perfusion is zero in the absence of both native and artificial circulation. The 2005 American Heart Association resuscitation guidelines therefore advocate that chest compressions be performed at 100 per minute ("push hard and fast") with few and very brief interruptions for ventilation and pulse checks. There is also a new recommended ratio of compressions to breathing of 30:2, and compressions should be immediately reinitiated after shock delivery instead of reassessing the rhythm or pulse.[76] These interventions increase the number of chest compressions delivered each minute. If retraining life support personnel does not improve performance of external cardiac massage, feedback devices that evaluate the quality of each compression should be employed to promote proper technique.

Data on arterial blood pressure achieved during CPR in humans have been disappointing, with systolic and diastolic pressures rarely exceeding 60 and 23, respectively.[83] The original proposed mechanism for external chest compressions resulting in forward flow, known as the "heart pump model," involved the ventricles being squeezed between the sternum and the vertebral column (Figure 8A).[35] Echocardiography, however, revealed that left ventricular size does not always change with compressions and that the mitral valve may be open during compression.[84] An alternate mechanism, known as the "chest pump model," suggested that cyclical pressure applied to the chest, along with the differential compressibility of arteries and veins, caused forward blood flow, while the heart behaved as a passive conduit (Figure 8B).[85] Currently, both ideas are believed to be relevant.[80,86] These insights, combined with the data on poor arterial blood pressure during standard chest compressions, have prompted interest in alternative compression techniques. One method involves placing a strap around the chest, called a load-distributing band, connected to a device that briskly tightens and loosens the band at fixed intervals. This device was developed with the chest pump model in mind, in which circumferential pressure can be delivered around the thorax, and not just to the sternum, for forward flow to occur (Figure 8C). Animal and human studies suggested that this type of device improved myocardial perfusion pressure.[87,88] Two recent human trials were published in 2006, one showing a trend toward decreased survival and the other showing improved survival with load-distributing band CPR.[89,90] Several methodological differences may explain the discrepant results and also highlight the challenges of conducting and comparing human studies of resuscitation. In the conventional CPR arm of these 2 trials, for example, survival to hospital discharge after outpatient ventricular tachycardia/ventricular fibrillation arrest was 22.7% in one and 5.2% in the other, despite the latter having shorter response times, with a similar mean age and occurrence of bystander CPR in the 2 cohorts.

Active compression-decompression CPR was investigated after a published anecdote of successful resuscitation in which a toilet plunger was used.[91] This method mechanically lifts the sternum between depressions, thereby actively decreasing intrathoracic pressure during diastole and promoting venous return to the heart rather than relying on passive recoil of the thorax (Figure 8D). Although initial animal studies suggested improved flow parameters with active compression-decompression CPR,[92] a meta-analysis of human trials did not show clear improvement in survival.[93] An impedance threshold device attached to an endotracheal tube can augment venous return into the thorax during diastole by preventing air suction into the chest when there is negative intrathoracic pressure. This device improves hemodynamics during chest compression in an animal model,[94,95] and combining an impedance threshold device with active compression-decompression CPR has improved short-term survival in humans.[96] The interposed abdominal compression CPR method requires 2 rescuers, who alternately compress the chest and the abdomen in a seesaw motion (Figure 8E), with the possible mechanisms of augmenting diastolic aortic pressure as well as forcing visceral venous blood into the chest between thoracic compressions. Clinical trials have demonstrated improved survival with interposed abdominal compression CPR over conventional CPR after inpatient[97] but not outpatient cardiac arrest.[98] A mechanical piston device can replicate manual chest compressions, shows improvements in some physiological parameters, and can be used as an approximately equivalent alternative to traditional CPR.[99]

In summary, many different techniques and devices for chest compression exist, but direct comparison between them is not possible, and no single method has been definitively shown to produce the best outcomes. The most significant confounder of these trials is the highly variable quality of conventional CPR technique, which is difficult to quantify, especially in out-of-hospital resuscitation. Future trials should strive to better characterize the quality of chest compression delivery in the context of current CPR guidelines to permit more valid comparison between studies, as well as to discover the best outcomes that can realistically be achieved with closed-chest CPR.

If, despite optimizing external chest compression, hemodynamics, neurological recovery, and overall survival do not improve, consideration should be given to revisiting open-chest cardiac massage whenever prolonged resuscitation is expected.

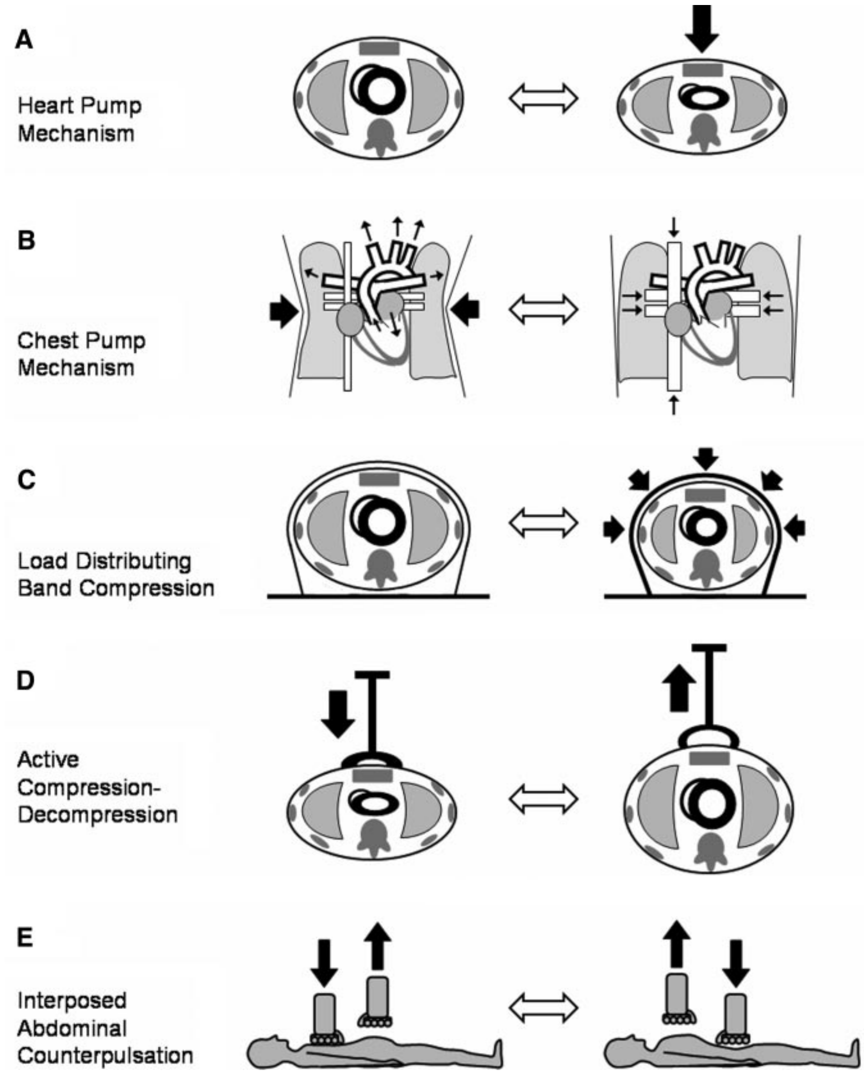

Figure 8. Techniques and mechanisms of cardiac massage. Conventional closed-chest compressions generate forward blood flow via 1 or both of the mechanisms depicted in the top 2 panels, known as the heart pump and the chest pump models, respectively (A and B). Several alternative methods of cardiac massage have been studied. Load-distributing band CPR (C) raises intrathoracic pressure and, with it, systolic pressure via the chest pump model. Active compression decompression (D) was designed to augment venous blood return via increased negative intrathoracic pressure, which may be improved with an impedance threshold device. Interposed abdominal counterpulsation (E) may augment perfusion by increasing diastolic aortic pressure or by several other proposed mechanisms.

Resuscitation of all cardiac arrests from 1901 to 1960 exclusively used direct compression of the heart and produced considerable success (28% survival).[74] In the modern era, however, open cardiac massage is rarely taught or applied even though it has been shown to provide superior cardiac output in animals[100] and humans,[101] better perfusion pressure,[102] improved neurological outcome,[103] and an increased likelihood of successful resuscitation when instituted in a timely fashion (after 15 minutes of conventional CPR).[102] This last point is critical because human trial data suggest that converting to open cardiac massage after 20 minutes of closed CPR does not improve survival.[104] As we strive to realize the goal of full neurological recovery after cardiac arrest, future investigations should examine the strategy of initiating open cardiac massage by trained individuals if closed-chest CPR for ≈15 minutes (or less) fails to resuscitate victims.

Expediting Defibrillation

Historically, ventricular fibrillation and ventricular tachycardia together represented the initial rhythm in half of all outpatient cardiac arrests,[63,69] although recent trends show a decline in their relative frequency.[73] Data suggest that with each passing minute of untreated ventricular fibrillation, the likelihood of survival is reduced by 7% to 10%.[63] There has therefore been rapid expansion of defibrillation services by emergency medical services and public access to automatic external defibrillators, including high-traffic areas such as airports, shopping centers, and office buildings.[105–107] The improvement in survival has been dramatic (Figure 9).[108,109] Among the most rapid response times anywhere has been that

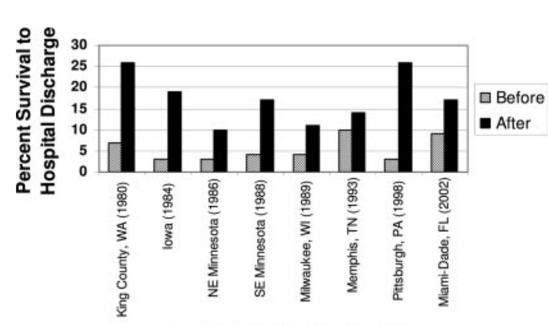

Figure 9. Survival from ventricular fibrillation before and after implementation of rapid defibrillation programs. Most sites more than doubled the likelihood of patients being discharged alive after suffering from a ventricular fibrillation arrest by focusing on immediate delivery of electric therapy at the time of arrest.

achieved in casinos, where dedicated training of responders, a confined environment, and numerous security cameras have effected a mean time from collapse to delivery of shock of 4.4 minutes. A study of resuscitation in casinos reported survival to hospital discharge rates of 74% if a shock was delivered within 3 minutes of arrest.[110] Survivors of an early defibrillation program (applying an automatic external defibrillator immediately on arrival of emergency medical services) were reported to have good quality of life and neurological outcome.[111] The 2005 American Heart Association guidelines endorse rapid defibrillation, especially for inpatients, in which the goal is delivery of a shock within 3 minutes of victim collapse.[76] It is important to remember, however, that performing chest compressions for 1.5 to 3 minutes before defibrillation in ventricular fibrillation arrests actually shows a trend toward improved survival.[112,113] CPR should therefore be initiated during automatic external defibrillator retrieval and setup if more than 1 rescuer is present, but defibrillation should be delivered immediately when the equipment is ready.[76]

Therapeutic Hypothermia

References to using hypothermia to preserve living tissue date back to Hippocrates, who advocated packing bleeding patients in snow.[114] Wilfred Bigelow first showed that blood flow could be entirely arrested in cooled animals without deleterious effects.[115] This discovery allowed procedures to be performed on a stopped heart in a blood-free environment, which made modern cardiac surgery possible. In fact, using a technique devised by Charles Drew in which patients were cooled to 15°C, Ronald Belsey performed human cardiac surgery without any circulation for >60 minutes (the perfusionist would step out of the operating room) without deleterious cerebral consequences.[116,117] The utility of hypothermia in resuscitation was initially appreciated but fell out of favor because of increased predisposition to infection and inconsistent research. Ann Radovsky and Peter Safar noticed that recovery from induced ventricular fibrillation in dogs was better tolerated if the animals incidentally had lower body temperatures.[118] Impressive initial results have been achieved in humans with the use of mild hypothermia (32°C to 34°C) when ventricular fibrillation was the presenting arrest rhythm.[119,120] One study even showed significantly reduced mortality and improved neurological outcome 6 months after treatment, with a number needed to treat to save 1 life (at 6 months) of only 7 patients.[119] The 2005 American Heart Association guidelines recommend postresuscitation cooling in certain circumstances.[76] Although hypothermia research in cardiac arrest has focused on ventricular arrhythmias, this treatment is intended to mitigate the effect of hypoperfusion on the brain, which is present in any pulseless cardiac arrest, regardless of initial rhythm. The animal research by Drs Safar, Radovsky, and colleagues[121] demonstrated that initiating hypothermia with a 15-minute delay after successful resuscitation negates the functional and histological benefit seen when dogs were cooled immediately on return of circulation. The same group recently published that initiating hypothermia 10 minutes into resuscitation in a dog model of ventricular fibrillation resulted in improved survival compared with starting after 20 minutes of resuscitation efforts.[122] Hypothermia should be viewed as a lifesaving component of postresuscitation care, and immediate administration of cooled intravenous saline will likely play an increasing role in future resuscitation practice. Further research should endeavor to clarify which patients benefit from therapeutic cooling and how to best deliver hypothermia therapy.

Conclusion

Resuscitation has developed over thousands of years, following a circuitous course of brilliant experimentation, serendipitous observation, slow adoption, and forgotten-then-rediscovered wisdom, which converged in the 1950s to bring about the era of modern CPR. The frontiers continue to be advanced in the quest to revive "hearts too good to die."[123] Our rate of successful resuscitation remains disappointing, and aggressive dissemination of the current CPR guidelines should be encouraged because these evidence-based recommendations have been shaped by numerous observations and studies that share the common goal of improving resuscitation outcomes. Continued investigation is needed to assess the quality of standard CPR and to ensure adherence to performance guidelines as well as to explore ways to improve cardiac massage and preserve neurological function. A combination of novel techniques and broad implementation strategies will almost certainly yield further improvement in our efforts to resuscitate men and women who suffer cardiopulmonary arrest.

Disclosures

None.

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KEY WORDS: arrhythmia ■ cardiopulmonary resuscitation ■ death, sudden ■ defibrillation ■ heart arrest ■ respiration ■ tachyarrhythmias