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Recent advances in mechanical cardiopulmonary resuscitation devices
[Cardiopulmonary resuscitation]

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Abstract

Over the past 40 years since standard closed-chest cardiopulmonary resuscitation was first described, several mechanical devices have been developed to increase vital organ perfusion in patients in cardiac arrest. The newer approaches aim to increase forward blood flow by increasing intrathoracic pressures and by direct cardiac compression during the “compression phase.” Equally important is the enhancement of venous return during the decompression phase of cardiopulmonary resuscitation. New approaches designed to increase venous return to the thorax during cardiopulmonary resuscitation include innovations that decrease “decompression phase” intrathoracic pressure and those that alternate abdominal compression with chest wall compression. The potential clinical value of these newer mechanical approaches is reviewed. In addition, some devices in the development stage are described.

Abbreviations:ACD active compression-decompression, CO_2 carbon dioxide, CPR cardiopulmonary resuscitation, IAC interposed abdominal counterpulsation, PCACD phased chest abdominal compression-decompression,

Performance of standard closed-chest manual cardiopulmonary resuscitation (CPR) provides only approximately 20% of normal left ventricular blood flow to patients in cardiac arrest [1,2]. Although widely practiced, survival rates with standard CPR remain dismal for patients suffering from cardiac arrest, particularly in the out-of-hospital setting [3–5]. Over the past 40 years, several new CPR devices have been developed in an effort to enhance vital organ perfusion and, ultimately, resuscitation rates for patients suffering from cardiac arrest. Building on mechanistic studies that have demonstrated the importance of both increasing intrathoracic pressure during the compression phase of CPR and decreasing the intrathoracic pressure during the decompression phase of CPR, many of these new devices are undergoing clinical evaluation. Although none of these newer approaches are currently recommended by the American Heart Association or the European Resuscitation Council, several have significant potential to improve resuscitation rates and some have been shown to be of only marginal or no benefit at all. This article includes those devices that increase intrathoracic pressure (eg, the circumferential vest [6–16] and the mechanical resuscitators [15,17–24]), devices that enhance negative intrathoracic pressures during the decompression phase (eg, active compression-decompression [ACD] CPR [19,23,25,26•–46] and phased chest abdominal compression-decompression [PCACD] CPR [Lifestick][47–49] and adjunctive devices that enhance negative intrathoracic pressure during the decompression phase of CPR (eg, an inspiratory impedance threshold valve [50–55•], the Hayek Oscillator [81–83], and a transcutaneous electric muscle stimulator for CPR [56]. Interposed abdominal counterpulsation (IAC) CPR [57–75] is also discussed because it provides an alternative manual means to standard CPR.

Mechanisms of action

Two major mechanisms are thought to be responsible for blood flow to the vital organs during CPR [2,76,77]. The first, an increase in intrathoracic pressure during chest compression, must be sufficient to propel blood from the thoracic cavity to the vital organs, in particular the brain and coronary arteries. Intrathoracic pressure must be increased repetitively at a sufficiently high frequency to maintain adequate perfusion. In addition, the increase in intrathoracic pressure must be of a sufficiently long duration to maintain a pressure to adequately perfuse the brain and other vital organs. Typical compression rates range from 60 to more than 100 compressions per minute, and the duration of compression is thought to be optimal at approximately a 50% duty cycle. By compressing the chest, the ribs and sternum act as a bellows. Increases in intrathoracic pressure and collapse of venous vessels at the thoracic inlet contribute to forward blood flow during chest compression. Although respiratory gas exchange is affected to some degree, the most important effect of chest compression during CPR is forward blood flow.

The second mechanism that promotes vital organ blood flow during CPR is indirect cardiac compression. During the compression phase of CPR, in addition to increasing intrathoracic pressure, some degree of cardiac compression occurs [2,77]. During cardiac arrest, the heart functions in a passive manner. Although the valves may lose their competence after prolonged CPR, they provide an important physiologic role in directing blood out of the left ventricle and into the aorta in the early phases of CPR. Direct cardiac compression has been observed by echocardiography and is thought to play a particularly important mechanistic role in the early phases of CPR.

Promotion of venous blood return to the chest is another fundamental aspect of CPR. During the period of time that the chest is not actively compressed, intrathoracic pressures decrease. With standard manual closed-chest CPR, the recoil of the lungs and chest wall musculature lead to a small but important decrease in intrathoracic pressure. When intrathoracic pressure decreases to less than atmospheric pressure, venous blood and respiratory gases are drawn into the thorax. When the chest wall is actively decompressed, eg, with ACD CPR, then negative intrathoracic pressures during the decompression phase of CPR are actively increased, and, consequently, both venous blood return and inspiration are enhanced. Further increases in intrathoracic pressure during the decompression phase of CPR have been achieved using an inspiratory impedance threshold valve that prevents inflow of respiratory gases during the decompression phase of CPR, thereby decreasing intrathoracic pressures further and promoting greater venous return to the thorax during chest wall decompression [51,54]. Several approaches have been used to try to increase negative intrathoracic pressure during CPR. These include ACD CPR, phased thoracic abdominal compression-decompression CPR, and transcutaneous diaphragmatic or intercostal muscle electric stimulation. Each of these is discussed later.

An alternate way to promote venous return to the chest during CPR is by active compression of the abdomen during the relaxation phase of CPR. IAC CPR is performed in a rhythmic manner in which venous return to the thorax is enhanced by repetitive compressions of the abdomen. Other methods that have been tried in the past include the use of abdominal binders and lower extremity compression devices designed to promote venous return in a pulsatile manner.

Ultimately, each of these mechanisms should be maximized to optimize mechanical CPR efforts. Although this is theoretically possible, current devices are often too heavy, cumbersome, physically exhausting to use, or too difficult to teach. Consequently, further research is in progress to try to develop devices that optimize the multiple mechanisms underlying the most efficient means to promote vital organ perfusion and ventilation during resuscitation efforts.

Specific devices

Circumferential vest

Building on the work of Kouwenhoven et al.[76] describing standard closed-chest manual resuscitation, researchers from Johns Hopkins University introduced the idea of a circumferential chest wall cuff to provide pulsatile increases in intrathoracic pressure during cardiac arrest [6]. The technique, which has been termed vest CPR, is performed by the rapid application of a pneumatically powered vest to patients in cardiac arrest [6]. Rapid inflation and deflation of the vest by a pneumatic compression system results in a marked increase in systolic arterial pressures in animal models [6] and patients in cardiac arrest [7]. Although issues related to size, expense, and ease of application of the device must be resolved, the use of vest CPR results in a consistent increase in hemodynamic parameters in humans compared with standard CPR [6,7]. Limited clinical data comparing vest CPR to standard CPR in humans have been published [7]. To date, no large-scale clinical trials have been performed, in large part because of regulatory issues related to CPR trials in general. Vest CPR may result in an increase in complication rates, eg, rib fracture, liver laceration, and pneumothorax; however, few data suggest any harm from this device. The use of vest CPR seems reasonable in patients in cardiac arrest when the device is available and can be used safely and correctly, particularly during the early resuscitation phase and when patients are in or near rescue vehicles. Issues related to device weight and energy requirements, ability to train personnel in application and use, and expenses associated with its use will ultimately determine whether vest CPR will have a significant role as an adjunctive CPR device.

Active compression-decompression cardiopulmonary resuscitation

Active compression-decompression CPR is performed with a small hand-held suction device called the CardioPump™ (Ambo International, Glostrup, Denmark) that is used both to compress and actively decompress the midsternum and chest wall. Inspired by the use of a household plunger to resuscitate a patient in cardiac arrest [78], research and clinical application of this new approach has led to a greater understanding of the basic principles underlying vital organ blood flow during CPR. Performance of ACD CPR increases intrathoracic pressures during compression, forcing blood out of the chest region, and decreases intrathoracic pressure during the decompression phase of CPR. By actively decompressing the chest, venous blood flow into the thorax is enhanced. Compression of the chest following the decompression phase results in an enhanced cardiac output. In animals and patients in cardiac arrest, performance of ACD CPR has been shown to increase systolic and diastolic blood pressures and enhance coronary perfusion and cerebral perfusion, and in some large clinical trials this hemodynamic benefit has translated to a significant increase in short and long-term resuscitation rates [25,26•,27,31,35,42]. ACD CPR requires more energy to perform than does standard CPR [79]. Nonetheless, proper application of this technique in some communities has led to a sharp increase in resuscitation rates. Despite these results, ACD CPR is not widely used, in part because of results from other clinical trials in which little or no benefit was observed [27–30].

The success of ACD CPR depends upon several critical factors, including 1) availability of sufficient personnel to rotate performance of ACD CPR on a 3-minute to 5-minute basis to avoid rescuer fatigue; 2) willingness to perform ACD CPR for at least one half-hour to optimize the potential value of “priming the pump,” which occurs during the course of the resuscitation effort; 3) use of low-dose rather than high-dose epinephrine during resuscitation efforts [42]; and 4) proper use of the force gauge that is designed to assist the rescuer in applying the proper amount of compression and decompression force during the performance of CPR. Figure 1 shows a significant increase in survival rates when ACD CPR is compared with standard CPR when ACD CPR is performed by well-trained rescuers in an efficient emergency medical service system [26•]. Despite the successful application of ACD CPR in some clinical settings, this device, like the others described in this review, serves at best as a means to provide enhanced blood flow to the ventricle; however, ACD CPR is not a panacea, and time to initiation of CPR remains the most important prognostic indicator of success; however, the use of ACD CPR may extend the period in which patients can successfully be resuscitated.

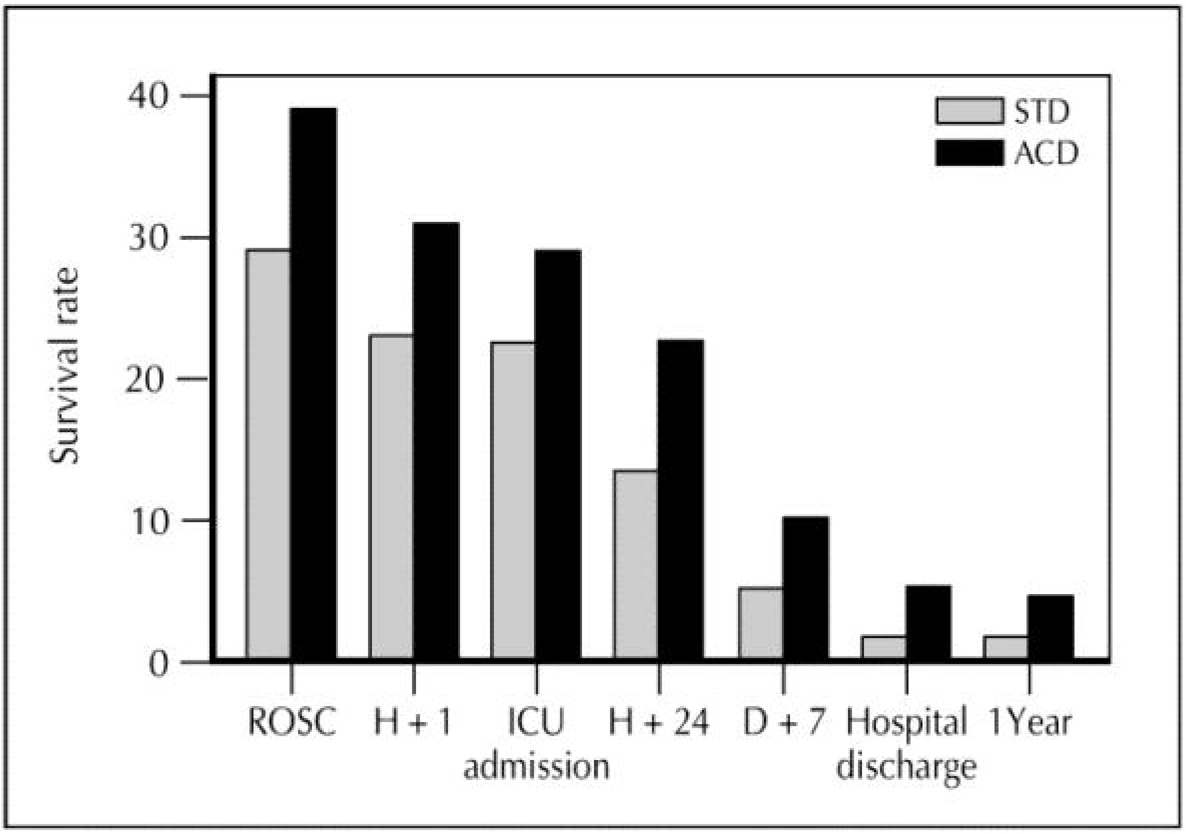

Figure 1.Survival outcome for patients receiving standard vs. active compression-decompression CPR Survival outcome for patients in cardiac arrest receiving standard CPR upon the arrival of an advanced life support team (STD-ACLS) versus those receiving active compression-decompression CPR (ACD-ACLS) are compared. Return of spontaneous circulation (ROSC), survival at 1 hour (H + 1), intensive care unit admission (ICU), survival at 24 hours (H + 24), survival at 30 days (D + 30), hospital discharge and survival at 1 year were significantly higher in the ACD-ACLS group compared with the STD-ACLS group. (From Plaisance et al.[26•]; with permission.)

Inspiratory impedance threshold valve

Research on ACD CPR has led to the development of an inspiratory impedance threshold valve (Resusci-Valve-ITV™, CPR × LLC, Minneapolis, Minnesota) [50,51,53–55•]. This small, one-way valve is placed between the endotracheal tube or face mask and the ventilation bag, thus becoming part of the respiratory circuit. While providing no resistance to active ventilation or expiration, the impedance valve functions to occlude inspiratory gas exchange during, and only during, the decompression phase of CPR. This results in a decrease in intrathoracic pressure, thereby promoting venous return to the thorax during decompression. The inspiratory impedance threshold valve does not interfere with the performance of CPR and may be used with several methods of CPR (eg, standard, ACD, vest, IAC, PCACD, mechanical CPR, and the transcutaneous electric inspiratory muscle stimulator). Animal studies have shown that hemodynamic variables were significantly improved when the impedance valve was used with both standard and ACD CPR [50–54]. In addition, results from a clinical study in Paris demonstrated that coronary perfusion pressure (Fig. 2A), diastolic arterial pressure, and end-tidal carbon dioxide (CO_2) (Fig. 2B) were significantly higher when ACD was performed with the valve compared with ACD CPR alone [55•]. Additional clinical studies are underway to evaluate the inspiratory impedance threshold valve with standard CPR in humans. Positive results from studies evaluating the valve and practical issues, eg, its small size, low cost, and easy use for rescuers, indicates that the inspiratory impedance threshold valve provides promise as a new adjunctive device to CPR.

Comparison of hemodynamic variables from a study of patients who received active compression-decompression (ACD) CPR with the impedance threshold valve (ACD + valve) and without a valve (ACD). Coronary perfusion pressure (CPP; *panel A*) and end-tidal CO_2 ($ETCO_2$; *panel B*) were significantly greater when ACD CPR was performed with the valve than with ACD CPR alone. Inserts show data from individual patients who survived. (From Plaisance *et al.* [55•]; with permission.)

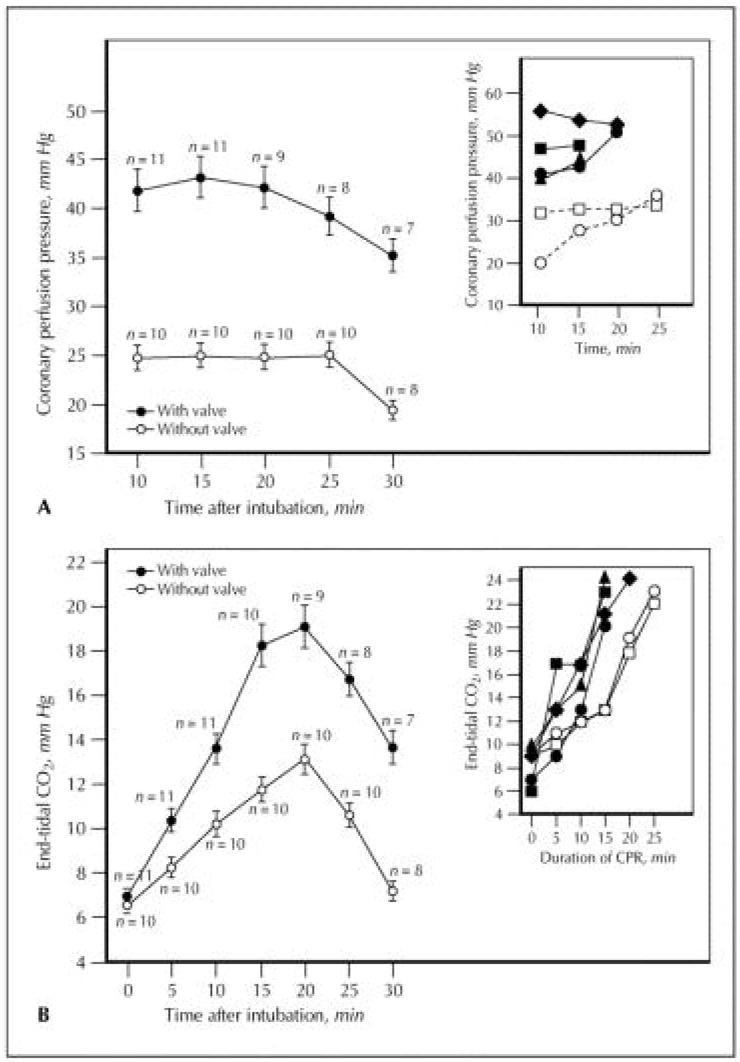

Figure 2.Hemodynamic results from patients receiving standard vs. active compression-decompression CPR Comparison of hemodynamic variables from a study of patients who received active compression-decompression (ACD) CPR with the impedance threshold valve (ACD + valve) and without a valve (ACD). Coronary perfusion pressure

(CPP;panel A) and end-tidal CO_2 ($ETCO_2$;panel B) were significantly greater when ACD CPR was performed with the valve than with ACD CPR alone. Inserts show data from individual patients who survived. (From Plaisance et al.[55•]; with permission.)

Phased chest abdominal compressiondecompression cardiopulmonary resuscitation

Building on the hemodynamic benefit observed with ACD CPR, the use of PCACD CPR has also been shown to be an effective means to enhance vital organ perfusion during CPR [47–49,80]. Although no large clinical trials have yet been performed, PCACD CPR in animal models and in acute hemodynamic studies of patients in prolonged cardiac arrest has been shown to significantly improve systolic and diastolic arterial pressures and coronary perfusion pressures and to increase end-tidal CO_2, a surrogate for cardiac output and successful resuscitation [47–49]. Performed with a hand-held device that includes an adhesive surface attached at one point to the chest and another to the abdomen, PCACD CPR enhances venous return during the decompression phase of CPR. Despite its potential for benefit, one theoretic concern with this approach is that active enhancement of venous return by compression on the abdomen results in an increase in central venous pressures and right atrial pressures during the decompression phase of CPR. Because the coronary perfusion gradient is generally determined by the difference between diastolic aortic and right atrial pressures, the enhanced venous return and an increase in central venous pressures that result from abdominal counterpulsation may decrease coronary perfusion pressure with this approach. Performance of PCACD CPR in patients in prolonged cardiac arrest has resulted in a significant increase in systolic pressures [49]. Larger clinical trials are anticipated in an effort to demonstrate the potential value of PCACD CPR in enhancing resuscitation rates during cardiac arrest.

Hayek Oscillator

One of the principles of the iron lung is to transform the rib cage and chest into a bellows to actively move respiratory gases into and out of the chest. The Hayek Oscillator built upon this idea. This boxlike device is designed to act as a thoracic cuirass to actively compress and then decompress the thorax. Although based on sound physiologic principles, application of this device has been limited because of its size and weight. It has been tested clinically and found to be effective as a ventilator in normal, conscious patients [81] and in patients undergoing microlaryngeal surgery [82]. When used with mechanical CPR, the Hayek Oscillator increases coronary perfusion pressure in humans in cardiac arrest, compared with mechanical CPR alone [83]. Investigators have little experience with this device in patients in cardiac arrest, and no studies have been performed assessing the Hayek Oscillator with standard CPR. Currently its potential role in the prehospital or in-hospital setting for patients in cardiac arrest remains undetermined.

Mechanical resuscitator

Efforts to increase intrathoracic pressure with an automated device during the decompression phase of CPR date back to the early 1960s. Since that time, several mechanical resuscitators have been developed that function primarily to compress the chest in a controlled and rhythmic fashion [84,85]. Attached to a piston and a motor, application of the resuscitator-compression pad on a patient's chest results in a rapid increase in intrathoracic pressure and arterial blood pressure. Although human studies comparing standard CPR with a mechanical resuscitator have shown that both approaches result in similar aortic pressures to coronary perfusion pressures [20], some studies have demonstrated that standard CPR provides more effective and higher systolic-aortic and diastolic-aortic pressures than those obtained with a mechanical resuscitator [17,19]. Nonetheless, in clinical settings where the mechanical resuscitator is available and adequate personnel are not available to perform CPR, the mechanical resuscitator can be helpful.

Metronomes and pressure gauges

Several simple devices have been developed to try to improve the delivery of standard manual CPR. These include a simple metronome device that can be used by the operator to more accurately compress the chest at 80 to 100 bpm. Studies with this approach have suggested that CPR can be more efficiently delivered, but none has demonstrated any change in any clinical outcome, including resuscitation rates, hospital admission, and hospital discharge. Similarly, a small pressure gauge called the CPR-Plus (Kelly Medical Products, Princeton, New Jersey) has been developed to also assist in the delivery of standard CPR. This pressure gauge is positioned in the midsternal region between the rescuer's hands and the patient. The CPR-Plus helps the rescuer deliver compressions with a uniform pressure or force. Although studies on mannequins have demonstrated that use of a simple force gauge can result in the more uniform delivery of chest compressions [86,87], its potential clinical value has not been tested and remains undetermined.

Interposed abdominal counterpulsation cardiopulmonary resuscitation

Although IAC CPR does not require a mechanical device, it represents a potential advance in the performance of CPR. IAC CPR is performed by compression of the chest without abdominal compression, followed by chest wall relaxation with abdominal compression [88,89]. This results in an increase in venous return to the thorax. In animal models, IAC CPR increases cardiac output and myocardial perfusion [62,67,68, 71,72,74], and in humans, IAC CPR increases systolic arterial pressures [90]. Clinical testing with this device has yielded conflicting results: in-hospital trials have generally been positive [57,58] whereas prehospital studies have been neutral [60]. One theoretic disadvantage of IAC CPR is that the right atrial pressure is increased just at the time that maximal coronary perfusion occurs. When IAC CPR is performed using a mechanical resuscitator, eg, the Thumper (Michigan Instruments Inc., Grand Rapids, Michigan), it is not as effective as standard CPR because chest decompression is impeded by the weight of the compression piston. IAC CPR seems to be a safe and efficacious alternative to standard CPR in the hospital setting as long as adequate personnel are available and well trained. Given the lack of support for this technique from out-of-hospital cardiac arrest patients, IAC CPR is not recommended for use in the prehospital arena. Future studies are needed to determine whether IAC CPR will eventually play a role in patients with out-of-hospital cardiac arrest.

New directions

Development of an electric stimulator to enhance decompression phase negative intrathoracic pressures

Although the use of diaphragmatic stimulation to induce inspiration dates back more than 100 years, only recently have efforts focused on developing an electric “gasping” device for CPR [56]. Building on the concept of ACD CPR performed with a hand-held suction cup device, the authors have more recently evaluated the potential for using an electric device to stimulate inspiratory effort during the performance of CPR. The authors have found that it is feasible to electrically stimulate diaphragmatic or intercostal muscles to markedly reduce intrathoracic pressure and, in effect, to stimulate gasping. Simultaneous with the inspiratory effort, use of an impedance threshold valve to prevent inspiration results in a further decrease in intrathoracic pressure during the decompression phase of CPR and prevents the problems of hyperventilation. In this case, the impedance threshold valve, described earlier, is incorporated in the ventilatory circuit. Studies are ongoing to optimize the method of electric stimulation and the sites of electric stimulation to optimize electrically induced gasping during CPR with simultaneous use of the impedance threshold valve. Physicians may ultimately be able to stimulate the abdominal, chest wall, and diaphragmatic musculature in an alternating fashion to perform “electric” CPR in the absence of any chest wall compressions.

Minimally invasive direct cardiac massager

Another potential future device for performing CPR is the Minimally Invasive Direct Cardiac Massager [101]. Based on open-chest direct cardiac massage, used commonly in the operating room, this new device is inserted via a parasternal intercostal incision. A plungerlike apparatus is placed on the pericardium and can be hand-powered to directly compress the heart without the challenges associated with open chest cardiac massage in the field. Evaluation of this minimally invasive approach is under way.

Conclusions

Over the past 40 years, since the first description of standard closed-chest CPR by Kouwenhoven et al.[76], several new mechanical devices have been developed to improve the efficiency of CPR. ACD CPR has been the most widely studied and is the only new type of CPR that is in active clinical practice. This new approach, although more labor intensive, has resulted in a more than 100% increase in 1-year survival in some clinical trials, most notably in Paris. Although ACD CPR has not been shown to be effective in other clinical test sites, physicians generally agree that the use of this approach leads to higher systolic and diastolic blood pressures and greater coronary perfusion. Other techniques that continue to show promise include vest CPR and phased chest abdominal counterpulsation CPR (Lifestick). These approaches have also been demonstrated to improve coronary perfusion pressures and vital organ perfusion in animal models and show significant promise as alternatives to standard CPR.

One of the important observations emerging from the research on ACD CPR was the discovery of the importance of inspiratory impedance during the performance of CPR. Enhancement of negative intrathoracic pressure during the decompression phase of CPR is associated with a marked improvement in vital organ perfusion. When coupled ACD CPR, the use of the impedance threshold valve in patients in cardiac arrest has resulted in diastolic blood pressures of more than 50 mm Hg. These kinds of pressures have not been previously observed in patients in cardiac arrest.

Perhaps one of the biggest challenges in performing CPR, after a rescuer has arrived at the scene, is the work itself. The performance of standard CPR is tiring, and actively decompressing the chest during ACD CPR can be exhausting. Although some emergency medical systems have developed a means to use more personnel to perform ACD CPR, other promising devices on the horizon include an electric stimulator to induce gasping, a mechanical resuscitator with an attached suction cup to perform automated ACD CPR, a minimally invasive direct cardiac massager, and more simplified versions of the initial vest CPR device that are easier to apply and lighter in weight. With the increased emphasis in the cardiovascular research community worldwide on improving the currently poor resuscitation rates after cardiac arrest, investigators anticipate that one or more of these devices will be available within the next decade.

Despite the recent excitement surrounding the increased availability of automatic external defibrillators for patients in cardiac arrest, a fundamental aspect of all resuscitation efforts will always involve the use of some mechanical means to propel blood from the thorax to the vital organs. When these new mechanical means are used in conjunction with newer pharmacologic agents, eg, vasopressin-based drug therapy [91–100], investigators anticipate a significant increase in resuscitation rates worldwide.

Acknowledgments

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•• Of outstanding interest

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