Mechanical advances in cardiopulmonary resuscitation

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Challenged by the continued high mortality rates for patients in cardiac arrest, the American Heart Association and the European Resuscitation Council developed a new set of guidelines in 2000 to help advance several new and promising cardiopulmonary resuscitation (CPR) techniques and devices. This is the first time these organizations have taken such a bold move, in part because of the poor results with standard closed-chest cardiac massage. The new techniques, interposed abdominal counterpulsation and active compression decompression CPR, each provide greater blood flow to the vital organs in animal models of CPR and lead to higher blood pressures in patients in cardiac arrest. In some clinical studies, both techniques have resulted in a significant increase in survival after cardiac arrest in comparison with standard CPR. Three of the four new CPR devices that were recommended in the new guidelines also provide superior vital organ blood flow and increased blood pressures in comparison with standard CPR. The three devices that improve the efficiency of CPR are the circumferential vest, an active compression decompression CPR device, and an inspiratory impedance valve used in combination with the active compression decompression CPR device. The fourth device type, one that compresses the thorax using an automated mechanical piston compression mechanism, was recommended to reduce the number of personnel required to perform CPR. However, no studies on the automated mechanical compression devices have showed an improvement in hemodynamic variables or survival in comparison with standard CPR. Taken together, these new technologies represent an important step forward in the evolution of CPR from a pair of hands to devices designed to enhance CPR efficiency. Each of these advances is described, and the recent literature about each of them is reviewed. Curr Opin Crit Care 2001, 7:170–175 © 2001 Lippincott Williams & Wilkins, Inc.

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Dr. Lurie is a coinventor of the ACD CPR device and the impedance valve. As such, he receives royalties from the sale of these devices.

Current Opinion in Critical Care 2001, 7:170–175

Abbreviations

ACD	active compression decompression
CPR	cardiopulmonary resuscitation
IAC	interposed abdominal counterpulsation
ITV	impedance threshold valve

ISSN 1070–5295

Recognizing the consistently poor outcomes associated with the performance of standard manual cardiopulmonary resuscitation (CPR), the American Heart Association and the European Resuscitation Council have recently, for the first time, recommended new approaches and technologies for the performance of CPR [1••]. There have been many efforts over the past 50 years to develop new mechanical therapies to increase the overall efficiency of CPR. Many of these innovative concepts have been tested and evaluated in patients in cardiac arrest. The new American Heart Association and European Resuscitation Council CPR guidelines were based on an evidence-based approach to the assessment of these new technologies. Experts from around the world evaluated the published literature on new devices and techniques related to CPR. After discussion and debate, any new CPR technique or device that was found to be of at least hemodynamic benefit in patients, without any deleterious effects, was recommended in the new guidelines. As a result, two alternative techniques and four alternative devices were recommended. The first technique, interposed abdominal counterpulsation, relies on active depression of the abdomen by either a person or a device to propel venous blood back into the chest after each chest compression. The second method, active compression decompression (ACD) CPR, uses a hand-held suction device to compress and then actively decompress the chest during CPR. This causes the chest to function like a bellows, first pushing blood out of the heart and then sucking both respiratory gases and blood back into the chest during the active decompression phase. CPR has been further enhanced by the use of a small one-way valve to transiently block the inflow of respiratory gases into the chest during the passive (during standard CPR) or active (during ACD CPR) decompression phase. This results in a marked augmentation of blood into the heart and causes a significant increase in the efficiency of CPR. Taken together, these newer methods each offer a new opportunity to enhance the effectiveness of CPR.

The devices recommended by the new guidelines include the circumferential vest for CPR (vest CPR), a device for ACD CPR, an inspiratory impedance threshold valve (ITV) used in combination with ACD CPR, and automated mechanical piston compression devices. In this report, the theory and practice of each of the advances will be reviewed. In addition, there are several promising newer approaches that remain in the development stages. Some of these approaches will also be discussed.

Mechanisms of blood flow during cardiopulmonary resuscitation

Although many factors contribute to the currently poor survival statistics for patients with cardiac arrest, the inherent inefficiency of standard closed-chest CPR technique remains a fundamental factor. Though much better than no CPR at all, the manual closed-chest technique introduced by Kouwenhoven *et al.* [2] more than 40 years ago has fallen far short of expectations. Indeed, standard CPR provides only 10 to 20% of normal myocardial perfusion and only 20 to 30% of physiologically normal cerebral perfusion [3,4]. Consequently, survival rates worldwide from out-of-hospital cardiac arrest remain at less than 10%.

For a better understanding of the function of the new CPR advances, it is important to review what is known about the mechanisms of blood flow during CPR. During cardiac arrest, the heart no longer serves as the driving force to propel blood to the vital organs. Moreover, the heart does not actively function to help facilitate the return of blood into the heart. While this "blood return" function is less clearly understood and is frequently neglected during discussions related to the mechanisms of blood flow during CPR, the return of blood to the heart after each compression is essential for optimizing vital organ perfusion during cardiac arrest. A vacuum created after each systolic contraction contributes to the refilling of the normally contracting heart. This mechanism is diminished, if not absent, when the heart is flaccid during ventricular fibrillation, pulseless electrical activity, and asystole. As a result, blood return to the heart during CPR depends on the elastic recoil of the chest wall itself after each chest compression, as well as the integrity of the cardiac valvular structures and valves in the great veins.

Chest compression and decompression

During the compression phase of CPR, the increase in intrathoracic pressure promotes blood flow out of the chest to the brain and other extrathoracic organs. In some patients, the chest compression phase causes a significant degree of myocardial compression that further promotes blood flow out of the chest cavity. In this respect, the circumferential vest technology was developed to optimize the compression phase physiology of CPR.

It is during the decompression phase (or passive relaxation phase) of CPR that blood flows back to the thorax. Myocardial perfusion occurs predominantly during the decompression phase. The difference between the diastolic aortic and the right atrial pressures (coronary perfusion pressure) is thought to be the critical determinant of CPR. With low right atrial pressures and high diastolic aortic root pressures, there is a high coronary perfusion gradient, and blood flows through the myocardium.

During the decompression phase, blood flow to the chest can be enhanced when the intrathoracic pressure within the chest is lowered by mechanical measures. These measures include the natural recoil of the chest wall after standard closed-chest CPR; active decompression of the chest wall by use of a suction cup or other adhesive device on the chest to actively lift the chest upward, as in ACD CPR; and enhancement of venous return to the chest by active compression of the abdomen during the decompression phase. By preventing respiratory gases from entering the lungs during the decompression of all methods of CPR, the impedance threshold valve (ITV) lowers intrathoracic pressure and creates a vacuum to draw more blood back into the heart [3]. By contrast, active compression of the abdomen during the chest decompression phase of interposed abdominal counterpulsation forcibly pushes more blood back to the right side of the heart [5–10]. With this approach, the essential new element is abdominal counterpulsation. This counterpulsation must be performed in the latter half of the decompression phase, or the venous return will occur at the expense of an increase in right atrial pressure and may result in a decrease in the coronary perfusion pressure [10].

Babbs [11•] has reviewed these mechanisms and has created a mathematical model to begin to optimize CPR, based on some of these mechanisms. Like many models, however, the variables associated with each of the parameters modeled may strongly influence the conclusions from the calculations. The variables evaluated included compression and decompression phase pressures, intrathoracic pressures, intravascular volumes, effects of varying venous return, and cardiac preload and afterload. Although this approach provides an important theoretical template, it remains unknown whether the predictions of the model will result in an accurate measurement of the true benefit derived from optimizing the multiple parameters evaluated.

The new technologies

Interposed abdominal counterpulsation cardiopulmonary resuscitation

Interposed abdominal counterpulsation CPR increases arterial blood pressure in animal models and patients in cardiac arrest [5–10]. By compressing the chest and then the abdomen in an alternating fashion, this approach increases venous blood flow back into the heart during the chest decompression phase. It has been difficult, however, to demonstrate that interposed abdominal counterpulsation will consistently and significantly improve outcomes after cardiac arrest. While two in-hospital studies at the same institution showed a significant improvement in outcome, an out-of-hospital study showed that the use of interposed abdominal counterpulsation CPR may actually decrease survival rates [8–10]. Problems associated with training have been considered a likely cause of the negative results of the prehospital studies. However, another potential reason for the results observed with interposed abdominal counterpulsation relates to the effect of abdominal counterpulsation on the coronary perfusion pressure. Coronary perfusion pressure is generally calculated as the diastolic difference between aortic pressure and right atrial pressure. Thus, the higher the aortic pressure and the lower the right atrial pressure, the greater the coronary perfusion pressure. Although interposed abdominal counterpulsation does force venous blood back into the thorax, and consequently the right side of the heart, it also causes an increase in right atrial pressure and left ventricular pressure during diastole. This can result in a net decrease in the coronary perfusion pressure at the very time when the arrested heart is starved for blood.

This problem was previously evaluated by Christenson *et al.* [10], who pointed out, correctly, that in order for interposed abdominal counterpulsation to be effective, the abdominal counterpulsation phase should occur during the latter half of the diastolic period, well after the chest wall has recoiled. A pause between the initial chest relaxation phase and the initiation of abdominal counterpulsation results in a brief but essential period of time wherein the coronary perfusion gradient is increased by the chest recoil. Once the elastic recoil of the chest is complete, then abdominal counterpulsation does indeed enhance overall cardiovascular circulation. From a practical standpoint, therefore, if one is to teach or perform interposed abdominal counterpulsation CPR, it is important to delay the abdominal counterpulsation for a long enough time to allow the chest to recoil. This approach requires that the rescuers understand the importance of the counterpulsation timing issues, and it requires rigorous practice, training, and coordination between rescuers.

Active compression decompression cardiopulmonary resuscitation

Active compression decompression CPR is performed by use of a hand-held suction cup device attached to the sternum [12–15]. When the chest is compressed and then actively decompressed, this creates a transient vacuum within the chest. The lower intrathoracic pressure during the chest decompression phase draws more blood and respiratory gases into the chest. This improves hemodynamics, ventilation, and vital organ perfusion. In animal models, blood flow to the heart and brain and minute ventilation are increased by approximately 50% with ACD CPR in comparison with standard CPR [3,14]. In some trials, ACD CPR has improved both short-term clinical endpoints and neurologic function [15–20]. In other trials, wherein training and implementation of that technique has been subsequently questioned, the results with standard and ACD CPR were equivalent [21–23]. The most rigorous study evaluating the long-term endpoints of ACD CPR was performed in France [15,16]. One-year survival doubled with the use of ACD CPR in that trial. This has led to widespread use of this technique in some European countries and the new recommendation for use by the American Heart Association and European Resuscitation Council [1].

Active compression decompression CPR requires rigorous training and regular retraining [16,24–26]. A pressure gauge and a metronome incorporated in the handle guide the operator in determining the proper degree and rate of downward and upward force to apply during compression and decompression. The device is placed in the midsternal position, and compressions and decompressions are performed at a rate of 90 times per minute with a compression depth of 1.5 to 2 inches for an adult of average size. Decompression is performed by actively pulling up on the ACD device. The decompression gauge is used to make sure sufficient upward force is consistently applied. Suction should be applied to –20 pounds, the decompression gauge on the ACD device being used as a guide. A newer handle, which includes a metronome, has recently been developed and makes it easier to use the device effectively.

When performing ACD CPR, the rescuer should kneel on the right side of the patient and should be positioned directly over the patient. By rocking back and forth while kneeling, the rescuer uses his or her weight to compress and decompress the chest. Some find it easier to kneel on a blanket or pad so that they are positioned above the patient. ACD CPR requires more energy than standard CPR. Rescuers should rotate frequently, preferably every 3 to 5 minutes, to avoid fatigue [16].

Active compression decompression CPR must be rigorously taught, and compression and decompression depth should be monitored, using the gauge continuously. Like standard CPR, retention of the ACD technique requires continuous practice. Skogvolle and Wik [27] have shown that when training and retraining was not rigorous, correct compression frequency was applied by only 20% of rescuers in their system. Moreover, in that study, only 20% of rescuers applied sufficient decompression force, as specified in the manufacturer's instructions for use. This again points out the importance of adequate training. Monthly retraining was initially required for the fire department personnel in Paris, France, where ACD CPR is now the standard of care [16]. Proper performance of this technique results in a similar complication rate to standard CPR [16], although studies on cadavers, which are stiffer and less compliant than the chest of a living person, suggest that sternal fracture rates may be higher with ACD CPR [28].

Two other important variables must be recognized if ACD CPR is going to be effective. The first is the duration of CPR. It takes time to prime the pump, as shown in hemodynamic studies of patients with ACD CPR with and without the inspiratory impedance valve [29•]. In France, where the results with ACD CPR have been most impressive, rescuers performed ACD CPR for at least 30 minutes after intubation before terminating their efforts. This has been shown to led to a steady increase in coronary perfusion pressure and diastolic blood pressures. The second key variable relates to the dose of epinephrine used during advanced life support. A large multicenter trial in France and Belgium compared the efficacy of high versus low doses of epinephrine during CPR [30]. Nearly 1000 patients in a patient subgroup received ACD CPR. When ACD CPR was used with low-dose epinephrine, the hospital discharge rate was 50% higher than in patients who received standard CPR and low-dose epinephrine. However, when high-dose epinephrine was used, there was no improvement with ACD CPR in comparison with standard CPR; high-dose epinephrine with both techniques resulted in the poorest hospital discharge rates [30].

Impedance threshold valve

One device recommended in the new American Heart Association and European Resuscitation Council Guidelines was the ResQ-Valve (CPRxLLC, Minneapolis, MN) [1••]. It is an inspiratory impedance valve that occludes the airway during the decompression phase when rescuer ventilation is not being performed [31•]. When rescuer ventilation is performed, air flows freely to the patient with positive pressure ventilation, and out of the patient during the exhalation phase. The ResQ-Valve selectively prevents respiratory gases from entering the lungs during the decompression phase of CPR, thereby achieving a greater vacuum with active decompression of the chest, and thus greater venous blood return and overall blood flow on subsequent compression. The ResQ-Valve attaches to existing manual ventilation equipment (between the ventilation bag and the endotracheal tube or mask). Inserting and connecting the ResQ-Valve to the ventilator bag and endotracheal tube or mask is simple. However, as soon as the patient has been resuscitated, it must be removed from the patient's airway because it is hard for a spontaneously breathing patient to breathe through the ResQ-Valve. It should be used only during CPR and removed as soon as the patient has a return of spontaneous circulation.

Use of the ResQ-Valve results in a significant increase in blood flow to the vital organs [3,4,31•]. When it is used with ACD CPR, blood flow to the heart and brain is more than threefold higher than in standard CPR [3,4,31•]. The new valve enhances both standard and ACD CPR efficacy, providing nearly normal blood pressures to patients in cardiac arrest [29,31•]. In patients in prolonged cardiac arrest, the combination of the valve and ACD CPR resulted in a mean systolic pressure of 108 mm Hg and a mean diastolic pressure of 57 mm Hg [29••]. Ongoing outcome studies suggest that this approach may have a major impact on survival for patients in cardiac arrest.

Circumferential vest

Vest CPR is performed with a bladderlike circumferential vest that is rapidly applied around the thorax of a patient in cardiac arrest [32–34•]. The use of a circumferential vest has been shown to increase intrathoracic pressures more uniformly during CPR. This results in a higher pressure within the chest during the compression phase, resulting in greater blood flow to the brain. Hemodynamic studies have shown that coronary perfusion pressures are significantly and consistently higher with this approach than in standard CPR [32]. The initial devices, developed more than 20 years ago, were heavy and expensive, and their use was limited. Newer, lighter, and less expensive models, which will include means to both ventilate and defibrillate patients, are being developed. This will make it easier and more practical to use this important new technology.

Mechanical compression devices

The earliest mechanical devices used for CPR were automatic chest compressors. Wik comprehensively reviewed this technology, which was also recently formally recommended in the new CPR guidelines [34•]. While this technology has been used for many years, only a few clinical studies support the use of this approach. Clearly, the devices can compress the chest in a regular fashion, and in some cases they also provide synchronous chest compressions with ventilation. As such, they provide support when adequate numbers of rescue personnel are not available. However, there are conflicting data related to the efficacy of these mechanical compressor devices. In most cases, key hemodynamic variables are similar to, or actually worse than, those measured during the performance of standard CPR. No short- or long-term survival studies have shown any benefit of this approach in comparison with standard manual CPR. This group of devices was recommended in the new guidelines to be used when adequate numbers of rescue personnel are not available to help perform standard CPR, because of the fatigue associated with the performance of adequate standard CPR for a long time [1••]. One of the fundamental theoretical problems with the early mechanical compressor devices was that they did not lift upward after each compression phase. As a result, the chest wall recoil was impeded, resulting in a decrease in venous return to the chest after each compression phase. An additional note of caution relates to the use of automated compression devices during the performance of interposed abdominal counterpulsation. Caution is advised when using an automated compression device instead of a pair of hands to perform chest compression. This is probably the worst possible way to perform interposed abdominal counterpulsation, because most of the currently available chest compression devices do not recoil on their own but instead rely on the chest recoil to propel the compression pad or piston upward. Consequently, chest wall decompression is inhibited at the same time right atrial pressure is increased by the abdominal counterpulsation.

Future developments

At least three new approaches have been evaluated that may lead to further improvements in the delivery of CPR in the near future. These most recent advances have been evaluated in animal models of CPR. The first is a device termed the Lifestick, which is used to perform ACD CPR and interposed abdominal counterpulsation simultaneously [35,36]. An adhesive is used to secure the leverlike device to the chest and the abdomen. The chest and then the abdomen are compressed and decompressed in an alternating fashion. This approach has resulted in high vital organ perfusion pressures and an increase in cerebral perfusion. The second device is a minimally invasive apparatus that is inserted through the intercostal space and makes direct contact with the heart to provide direct cardiac massage during CPR [37]. It is also being developed with a defibrillator and, to date, has resulted in an increase in end-tidal CO_2 in patients in cardiac arrest. The third device is a phrenic nerve stimulator, which, when coupled with the impedance valve, results in a significant increase in venous blood return to the chest during hypovolemic shock and short-term survival in an animal model of hemorrhagic shock [38,39]. The approach is conceptually similar to multiple repetitive Mueller maneuvers. In an animal model of hemorrhagic shock, the stimulator/valve combination increased systemic pressures and survival times. The potential application of these approaches to patients in cardiac arrest remains under study.

Conclusions

There are been a renaissance in the world of CPR technology over the past decade. The recent wave of success with automatic external defibrillators has refueled an intense interest in the field and helped to refocus attention on the plight of patients in cardiac arrest. The two new CPR techniques and four new devices recently recommended in the new CPR guidelines by the American Heart Association and European Resuscitation Council will serve to further promote the chances for survival after cardiac arrest. These new CPR device recommendations provide further momentum to investigators and device developers, who strive to optimize the efficiency of CPR by the American Heart Association and European Resuscitation Council for the hundreds of thousands of patients with sudden cardiac death each year.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:
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- •• Of outstanding interest

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The 2000 Guidelines have, for the first time, recommended newer CPR techniques and devices to improve the efficiency of CPR. This was a large step forward in the field, breaking with a long tradition of advocating only standard CPR. Recognizing the deficiencies of standard CPR, each of the new technologies has been shown to improve hemodynamic parameters and other key predictors of improved outcome after cardiac arrest in patients.

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