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Mechanical devices for cardiopulmonary resuscitation: an update

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This article focuses on the new noninvasive devices and methods for cardiopulmonary resuscitation. These new techniques and devices include the circumferential vest, interposed abdominal counterpulsation, an active compression-decompression device, an impedance threshold valve, phased thoracoabdominal active compression-decompression counterpulsation, and a mechanical piston device. Challenges to implementing these new techniques also are discussed.

The most fundamental element in the treatment of cardiac arrest is the rapid restoration of blood flow to the heart and brain. Without adequate vital organ perfusion, there is no chance for survival. The first recorded efforts to "bring back the dead" can be found in historical texts dating back thousands of years; however, the modern history of cardiopulmonary resuscitation (CPR) began with the description of closed chest manual chest massage by Kouwenhoven et al [1] in 1960. This manual technique was initially thought to be simple to teach, easy to perform, and promised a 70% survival rate for patients in need of resuscitation. Although it remains the only CPR technique to achieve widespread and universal acceptance, the dismal results often observed after a person has received the Kouwenhoven method has led to the following realizations: the technique is difficult to teach and remember effectively, it is challenging to perform correctly for any prolonged period of time, and the 70% survival rates can never be achieved with this approach alone. In retrospect, most of the patients described by Kouwenhoven et al were apneic secondary to halothane overdose, which was rapidly reversed with ventilation.

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Disclosure: Dr. Lurie is a founder of CPRx, a medical device company that develops new cardiopulmonary resuscitation (CPR) devices, including the impedance threshold valve and active compression-decompression CPR device.

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Despite the shortcomings of standard closed chest cardiac massage, it has remained the gold standard of CPR nearly 50 years after it was first described. The marginal success of closed chest cardiac massage has fueled an explosion of research into the mechanisms underlying vital organ blood flow during CPR. The result has been the discovery of many techniques, methods, and devices developed to provide more blood to the heart and brain in patients experiencing cardiac arrest. From this research, the American Heart Association (AHA) has recommended, for the first time, new ways to perform CPR [2]. To date, none of these recent advances has been widely accepted as an alternative to the Kouwenhoven approach; however, each advance has been shown to increase blood flow to the heart and brain when compared with the Kouwenhoven technique.

This article focuses on the new noninvasive devices and methods for CPR. These new techniques and devices include the circumferential vest, interposed abdominal counterpulsation, an active compression-decompression device, an impedance threshold valve, phased thoracoabdominal active compression-decompression counterpulsation, and a mechanical piston device. Most devices remain under investigation and lack sufficient clinical experience to warrant recommendation by the panel of experts convened by the AHA to evaluate and recommend these devices.

Mechanisms of blood flow during cardiopulmonary resuscitation

The challenge for any CPR technique is to optimize the mechanisms underlying blood flow to the heart and brain during cardiac arrest. There are at least three fundamental mechanisms that promote forward blood flow during CPR. The first is an increase in intrathoracic pressure, which promotes blood flow out of the chest to the brain. The second is direct cardiac compression, which also forces blood out of the heart to the rest of the body. The third mechanism is the decrease in intrathoracic pressure that occurs each time the chest wall recoils, after each chest compression. The small vacuum created within the thorax relative to the rest of the body draws blood back into the heart, thereby refilling the heart in advance of the next compression phase. It is also during the recoil or decompression phase that blood flows into the heart itself. Research has shown that to be effective any CPR approach must optimize both the promotion of blood out of the thorax and the refilling of the heart with blood after chest compression. Although these mechanisms seem simple, each has taken over a decade to become established. Moreover, the current understanding of these mechanisms remains limited because of the complex heart-lung interactions and regulatory processes which govern gas exchange in the lungs, pulmonary blood flow, coronary blood flow and venous return, and cardiac metabolism and function immediately after the heart stops beating. In addition, there are many technical, ethical, and legal challenges that have hampered the understanding of the mechanisms of blood flow during CPR.

For many years, direct cardiac compression was thought to be the principal operative mechanism of closed chest cardiac massage. In the presence of competent cardiac valves, compression of the arrested heart between the sternum and the spine increases intracardiac pressures and forces blood out of the aorta. This has been observed by transesophageal echocardiography in humans and in animals undergoing CPR [3]. In the late 1970s, Weisfeldt and colleagues attempted to resuscitate a patient in the cardiac care unit after a cardiac arrest (M. Weisfeldt, MD, 2001 personal communication). The patient had had recent cardiac surgery. Despite the obvious compression of the heart with each chest compression, the blood pressure observed on the monitor remained nearly flat. Weisfeldt noticed that the lateral walls of the chest bellowed outward with each sternal chest compression. This prompted him to wrap his own belt around the patient's chest and then proceed with chest compressions. The result was a dramatic increase in arterial blood pressure. This case led to the discovery of the "thoracic pump" mechanism of CPR, and ultimately in a vestlike device for resuscitation [4]. It would take nearly a decade for the seminal observation of Weisfeldt and colleagues—that a rise in intrathoracic pressure in the absence of direct cardiac massage improves the efficiency of CPR—to be accepted as an important mechanism during resuscitation. Today, it is believed that both the thoracic pump mechanism and the direct cardiac compression mechanism propel blood from the heart to the vital organs, particularly the brain, during closed chest CPR.

But what about blood flow back to the heart during CPR? This mechanism has been elusive until recently. It had always been assumed that blood would flow back to the empty heart, once blood flow out of the heart had occurred. Recent data, however, suggest that the cardiac cavities become increasingly smaller over time, once closed chest cardiac massage has started, as there is no strong driving force to propel venous blood return to the heart in the setting of a cardiac arrest [5]. Consequently, cardiac output decreases, and without sufficient venous blood return, it becomes impossible to maintain even minimally viable levels of vital organ blood flow. In some patients, the natural recoil of the chest, as it is allowed to rise after each compression phase, results in a small vacuum within the thorax, which draws blood back into the heart; however, the benefits of the vacuum can only be realized if the chest is allowed to recoil.

The rediscovery of the importance of chest wall recoil in the promotion of blood flow during cardiac arrest began after an anecdotal report of a patient who was resuscitated by family members who desperately applied a toilet plunger to his chest during cardiac arrest [6]. This case stimulated further elucidation of the mechanism of venous blood flow back to the heart after each chest wall compression. It is now clear that the small vacuum created with the recoil of the chest during CPR is essential for the maintenance of venous blood return back to the heart [7]. By using new devices to increase this vacuum effect to refill the heart after each compression phase, it is possible to maintain near-normal blood pressures for prolonged periods of time in patients in cardiac arrest [8].

In addition to creating a vacuum within the thorax to draw blood back to the heart, it is possible to push blood back into the heart by compression on the abdomen in an alternating manner with the chest after each chest compression. This approach, termed "interposed abdominal counterpulsation," promotes venous blood back to the right side of the heart and increases arterial blood pressures [9]. Venous return is clearly increased during the chest wall decompression phase; however, this may not translate into an increase in cardiac output. This approach is complicated by the need to balance, from a mechanistic standpoint, increasing venous return and optimizing cardiac perfusion. It is during the relaxation phase or chest recoil phase of CPR that blood flow to the heart takes place. The driving force for cardiac perfusion during the decompression is the pressure difference between the aorta and the left ventricle. The coronary perfusion pressure can be calculated mathematically by the difference between the diastolic or decompression phase aortic pressure and right atrial pressure. When the interposed abdominal counterpulsation technique is used, the rise in right atrial pressure associated with pushing venous blood back into the chest can decrease the gradient needed for coronary perfusion. From this perspective, the chest wall should be allowed to recoil before pushing on the abdomen during interposed abdominal counterpulsation. The coordinated timing of such a procedure can be a challenge.

At present, no device or technique is available to optimize all of these mechanisms simultaneously [10]; however, it may only be necessary to optimize some of these mechanisms to provide adequate blood flow to the vital organs to significantly improve the chances for survival.

Cardiopulmonary resuscitation with the vest

The circumferential vest for CPR has been tested in animals and in humans (Fig. 1). The hemodynamic improvements in patients are striking [11]. The bladderlike device looks like a large blood pressure cuff. It is rapidly wrapped around the chest of the patient and connected to a pneumatically driven pump. It can also be connected to a defibrillator and physiologic monitoring system. By rapidly compressing the chest at rates of 60 times per minute or more, the increased intrathoracic pressure generated by repetitively squeezing the thorax increases systolic and diastolic arterial blood pressure and coronary perfusion pressure. One small-scale study, which focused on the hemodynamic effects of the vest, demonstrated that use of the vest significantly increased systolic and diastolic blood pressures compared with the Kouwenhoven technique [11]. These data were used to support the AHA's recommendation (Class IIB) of this approach [2]. Although these changes were statistically significant, and more patients treated with the vest

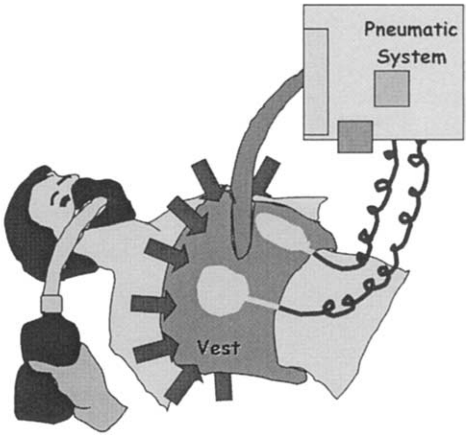

Fig. 1. This illustration shows how a vest device is applied to the chest. The device compresses the chest in a circumferential manner at a rate of 60 to 100 times per minute.

had an immediate return of spontaneous circulation, there was no difference in hospital discharge rates in this pilot study. Further efforts are underway to design a more compact vest device and to test the vest in patients in cardiac arrest.

Interposed abdominal counterpulsation

To increase venous return back to the heart, interposed abdominal counterpulsation was introduced to enhance the return of venous blood to the thorax after each chest compression [9]. This method is performed by having one person compress the chest during the chest compression phase; as the chest is recoiling, a second person compresses the abdomen (Fig. 2). This technique has been studied in animals and in humans in cardiac arrest [10–14]. Animal studies and hemodynamic studies in patients have demonstrated that when compared with standard manual CPR, interposed abdominal counterpulsation CPR results in increased systemic blood pressures.

Randomized clinical trials have demonstrated improved outcomes when interposed abdominal counterpulsation CPR was compared with standard CPR for in-hospital resuscitation, but have shown no survival benefit for out-of-hospital cardiac arrest [9,12,13]. Two randomized clinical trials of interposed abdominal counterpulsation CPR for patients with an in-hospital cardiac arrest from the same site showed statistically significant improvement of outcome measures, whereas an out-of-hospital study failed to demonstrate a benefit. Both in-hospital studies showed that use of interposed abdominal counterpulsation CPR results in a marked increase in survival rates [9,12]. Pooled data from these studies demonstrated that there was

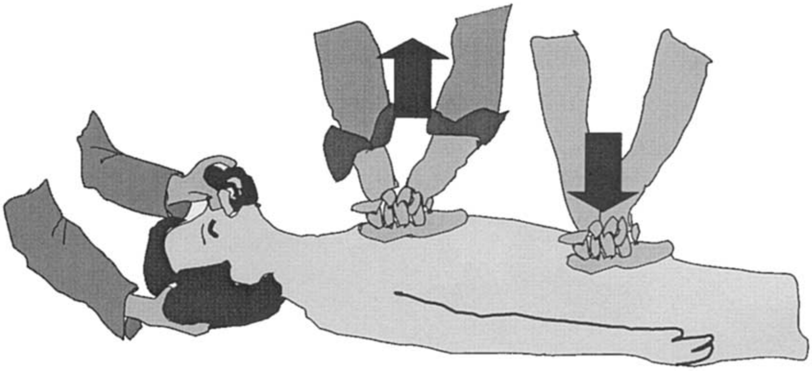

Fig. 2. Interposed abdominal counterpulsation CPR is performed by having one person perform chest compression and decompression while a second person performs, in an alternating manner, abdominal compression and decompression.

a 33% versus 13% improvement in 24-hour survival. The larger randomized out-of-hospital study showed no difference in outcome or in complications [13]. CPR-related injuries do not appear to be more common with interposed abdominal counterpulsation CPR than with standard CPR.

With the positive hemodynamic findings, lack of complication rates, and positive yet limited in-hospital results, the use of interposed abdominal counterpulsation CPR for in-hospital resuscitations was recommended by the AHA as an alternative intervention to standard CPR, when sufficient personnel are available who are trained in the technique (Class IIB). Interposed abdominal counterpulsation CPR was not recommended for patients with out-of-hospital cardiac arrest.

Active compression-decompression cardiopulmonary resuscitation

The case of the patient resuscitated with the plunger led rapidly to the development of a hand-held suction cup device [15]. The device includes a handle, a suction cup, and a force gauge (Fig. 3) [16]. By placing the device over the sternum and actively compressing the chest, as in the Kouwenhoven technique, blood is propelled out of the chest. Active chest wall decompression is performed by pulling upward on the handle of the active compression-decompression device, rather than allowing the chest to recoil on its own, as with the Kouwenhoven technique. Both animal and clinical studies have demonstrated that arterial pressures, coronary perfusion pressures, and vital organ blood flow are increased with active compression-decompression CPR [15,16]. No device has been more extensively studied in patients in cardiac arrest. Long-term survival rates, including 1-year survival, have been reported to increase by more than 100% with the use of the

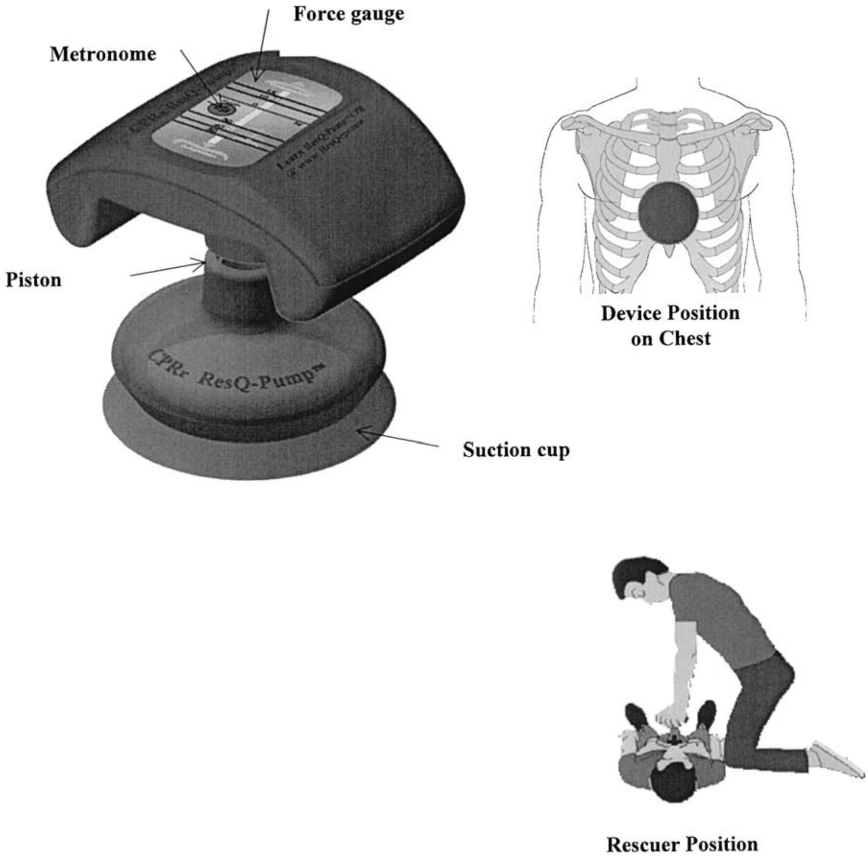

Fig. 3. The active compression-decompression device is applied to the midsternal region during cardiopulmonary resuscitation. The force gauge is used to guide the rescuer in the proper amount of force needed to compress and actively decompress the chest. The metronome provides guidance on the correct compression-decompression rate. The suction cup helps to maintain the position of the device on the chest and allows for active decompression.

active compression-decompression device [17]. Although training had been a major concern when the device was first introduced, the survival study by Plaisance et al [17] was performed after the rescue personnel had been performing active compression-decompression for several years as part of the standard of care where the study was performed. The positive results from this study resulted in the recent recommendation by the AHA (IIB) of this technique and device [2].

Not all clinical studies have shown a superior effect with the active compression-decompression device [18]. Several studies have shown only a small or no benefit when compared with the Kouwenhoven technique [15,17,18]. There are many potential reasons for the differences in outcomes, but training and competency in using the device have been major concerns [18]. Other study differences included differences in the overall efficiency of the emergency medical service systems, fatigue associated with the technique, concurrent use of drug therapies, and the duration of CPR during the clinical trial [15,17–19]. As with the Kouwenhoven technique, training is paramount and often overlooked. Only recently have the major challenges related to training and retention of skills with standard CPR been addressed [20].

At present, the active compression-decompression CPR technique is practiced widely in France and to a lesser extent in other European and Asian countries. There are some rescue systems that use this technique routinely in Canada, but most systems have not yet adapted the technique.

Mechanical piston devices for cardiopulmonary resuscitation

Recognizing the fatigue associated with performing prolonged chest compressions, several mechanical piston devices have been developed to try to improve the manner in which the Kouwenhoven technique is delivered. Only one device, the Michigan Instruments Thumper (Grand Rapids, Michigan), has achieved widespread use. The body is placed under a mechanical piston and the device can be programmed to compress the chest at a set depth and rate. This class of devices has been recently reviewed by Wik et al [21]. There are no studies that confirm the clinical efficacy of this approach, in terms of a survival benefit. Moreover, the combination of chest wall trauma, including rib and sternal fractures, with the poor survival rates associated with this kind of device, has led to the abandonment of this approach by many clinicians. The fundamental mechanical problem is that the current models of this device do not allow the chest to recoil after each compression cycle. The compression piston remains in contact with the chest, preventing the natural recoil of the chest. Therefore, the weight of the compression piston prevents the generation of the small vacuum needed in the thorax after each compression cycle to augment venous return back to the heart. Generation of the small vacuum is critical for the success of any closed chest cardiopulmonary technique. The use of the current Michigan Instruments Thumper results in a decrease in blood pressures in patients in cardiac arrest when compared with the Kouwenhoven technique [16]. At present, the rationale for consideration of the mechanical piston devices in the recent AHA guidelines stems not from the efficacy of this device but from the potential for performing CPR with only one or two medical personnel [2]. The device does reduce the number of people needed to perform CPR for prolonged periods of time, but the poor results, from a perfusion and survival viewpoint, have resulted in an overall decrease in its utilization. Despite the lack of efficacy of the current mechanical devices, in improving key hemodynamic parameters and survival rates, this kind of mechanical piston device may be valuable. If there were a mechanical piston device that allowed for the natural recoil of the chest, or a mechanical device that combined both active compression and decompression, such a device could be of hemodynamic and clinical benefit.

The impedance threshold valve

An impedance threshold valve was recently developed to improve venous return to the heart during the decompression phase of CPR [7]. A small vacuum is created within the chest relative to the rest of the body every time the chest wall recoils back to its resting position. This draws venous blood back into the right side of the heart during the CPR decompression phase. The impedance threshold valve is a small (35 mL) disposable valve that is attached to the endotracheal tube or face mask, or other protective airway device (Fig. 4). It allows the rescuer to freely ventilate the patient. When the rescuer is not actively ventilating the patient, the valve impedes inspiratory

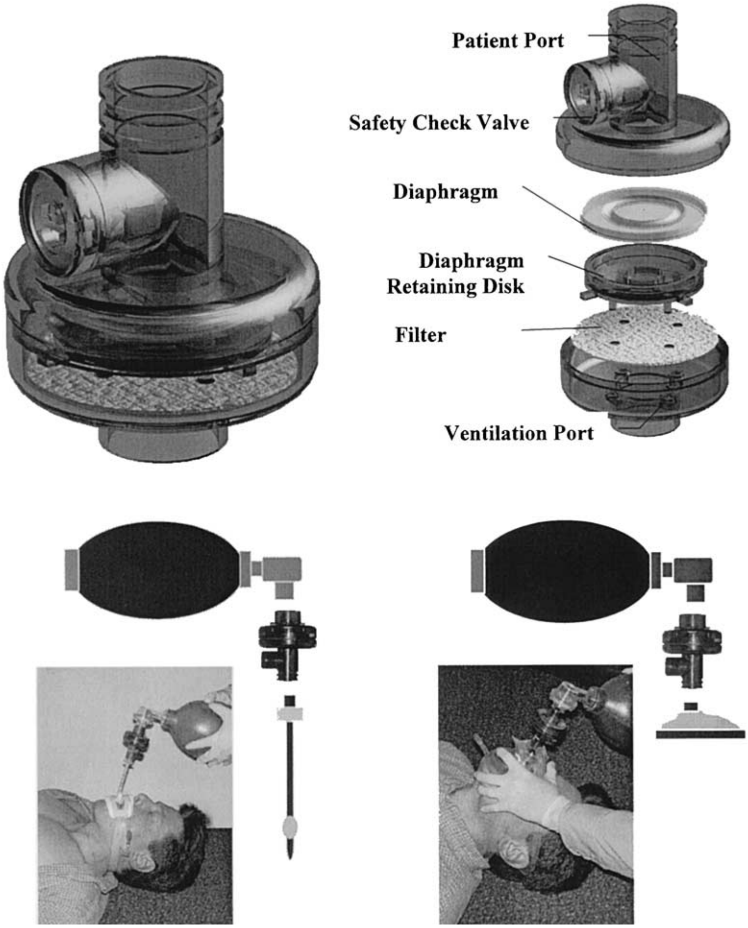

Fig. 4. The impedance threshold valve is shown attached to both a face mask and an endotracheal tube. It should only be used in patients in cardiac arrest. It does not interfere with active rescuer ventilation or exhalation of respiratory gases by the patient. It regulates the inspiration of respiratory gases when the rescuer is not actively providing ventilation.

airflow during the decompression phase of CPR (Fig. 5). This creates a small vacuum within the chest to further enhance venous return. A recent study has shown that the impedance valve is effective when ventilating patients through a face mask or an endotracheal tube [22].

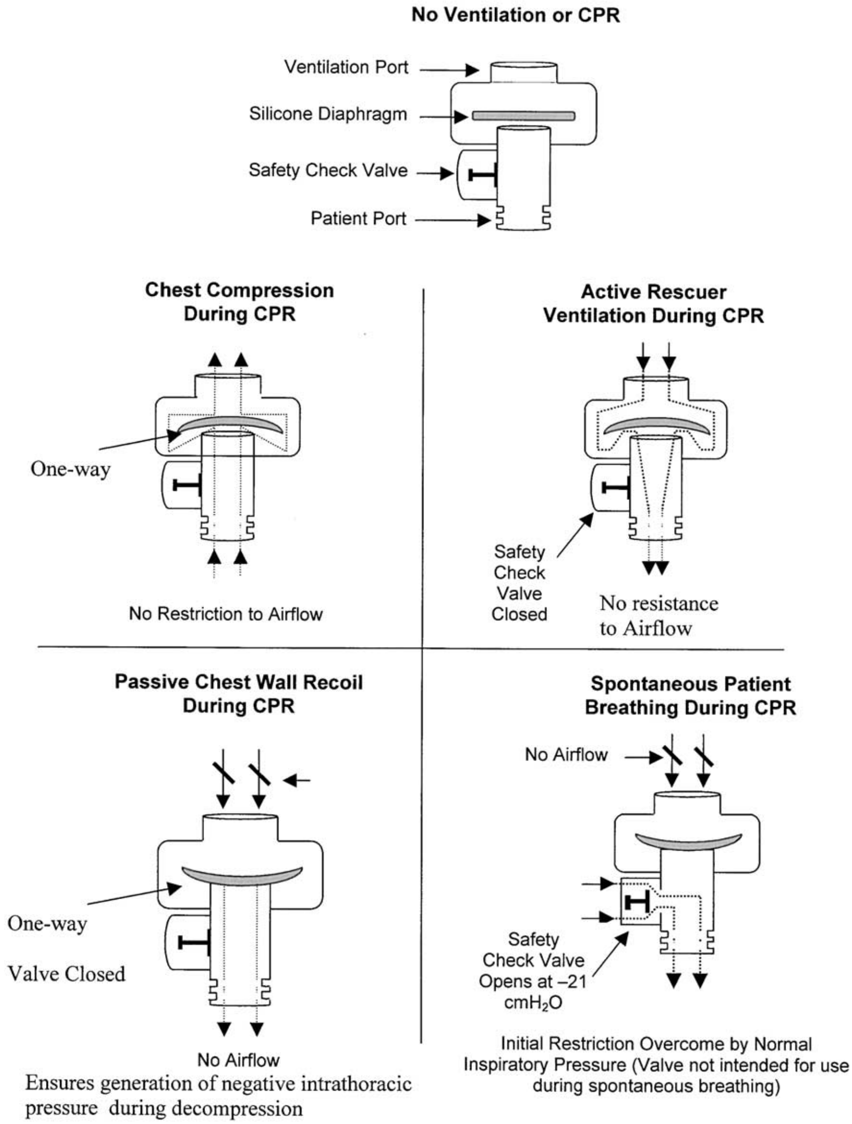

Fig. 5. This illustration shows the movement of respiratory gases in and out of the patient during active rescuer ventilation, chest compression without ventilation, chest decompression without ventilation, and active patient inspiration. The safety check valve opens when pressure within the thorax is <21 cm H_2O. The impedance valve must be removed as soon as the patient begins to breathe spontaneously.

In animals, use of the impedance valve results in a nearly twofold increase in blood flow to the brain and the heart when used with the Kouwenhoven technique [23,24]. In addition, 24-hour survival rates and neurologic outcomes are significantly improved with the use of the impedance valve with the Kouwenhoven approach [25]. In animals, use of the impedance valve with active compression-decompression CPR results in a 300% increase in blood flow to the brain and a 400% increase in blood flow to the heart when compared with the Kouwenhoven approach [26]. In patients in cardiac arrest, the combination of active compression-decompression CPR and the impedance valve results in nearly normal blood pressures (≈110/60 mmHg) during prolonged cardiac arrest [8]. These data have led to the recent AHA recommendation (IIB) of the use of the impedance valve during performance of active compression-decompression CPR [2].

More recently, there have been two larger clinical trials with the impedance valve. A study with 400 patients from France showed that the combination of active compression-decompression CPR and the impedance valve results in a doubling of 24-hour survival in patients with out-of-hospital cardiac arrest [27]. In that study, patients were treated with either a sham or an active valve. The neurologic function in the survivors was significantly better at hospital discharge in patients treated with the valve. A second study in Germany comparing manual closed chest CPR versus the combination of active compression-decompression CPR and the impedance valve also found a marked improvement in survival rates. In this study of 210 patients, there was a 100% increase in 24-hour survival in patients with a witnessed cardiac arrest treated with the impedance valve and active compression-decompression CPR, and brain function in the survivors was also better with the new approach [28]. A large clinical study is presently underway in Milwaukee, Wisconsin, to examine the potential clinical value of the impedance threshold valve used with the Kouwenhoven technique.

Phased thoracoabdominal compression-decompression cardiopulmonary resuscitation

This approach combines the potential benefits of active compression-decompression CPR and interposed abdominal counterpulsation [29]. It can be performed with a device designed to compress and decompress both the chest and abdomen. The rescuer alternates chest compression with one hand and abdominal decompression with the other hand, followed immediately by chest decompression and abdominal compression. This technique has been shown to improve hemodynamics and 24-hour outcome in animals; in addition, a small-scale study with humans has shown improved coronary perfusion pressure [29–31]. A recent clinical trial in patients randomized to either phasedthoracoabdominal compression-decompression CPR or closed chest manual CPR found no difference in outcomes [32]. Because of limited clinical outcome data, the AHA did not recommend this approach in their 2000 guidelines [2].

Summary

Despite the promise and universal use of the Kouwenhoven technique for closed chest cardiac massage, this method has been shown repeatedly to suffer from lack of clinical efficacy. Although the Kouwenhoven technique can clearly save lives, the inherent inefficiency of this approach and the challenges related to teaching and retaining the skills needed to perform the technique correctly have limited its overall effectiveness. This has prompted the development of newer lifesaving CPR techniques and devices. Some of the advances, such as the vest approach, active compression-decompression, and the impedance threshold valve, offer a benefit when compared with the Kouwenhoven technique. It is clear, however, that challenges related to implementation of these newer approaches will determine their ultimate utility. It is not sufficient to have a better technique or device available. Challenges to implementation of the newer approaches include overcoming the inertia of a universal mindset on the already-familiar Kouwenhoven technique and creating a cost-effective justification for change. Each year, approximately 10 million people in the United States are trained in the Kouwenhoven technique. Americans spend nearly $500,000,000 annually on this form of CPR training and retraining. Given the less than 5% survival rate for the 300,000 patients who experience out-of-hospital cardiac arrest each year in the United States, the prudence of this societal investment when compared with other ways health care dollars are spent should be questioned. It is hoped that this mismatch between costs and benefits will be recognized and will lead to the adoption of more effective means to resuscitate patients.

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