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BAILLIÈRE'S BEST PRACTICE & RESEARCH

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Recent advances in active compression-decompression cardiopulmonary resuscitation

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In an attempt to improve upon the currently poor outcomes for patients in cardiac arrest, new methods and devices have been developed to enhance the efficiency and efficacy of standard cardiopulmonary resuscitation (CPR). One new approach, active compression-decompression (ACD) CPR was developed to lower the intrathoracic pressure during the decompression phase of CPR, thereby enhancing venous blood return to the thorax. Over the past decade the ACD CPR device has been extensively evaluated in animals and humans. ACD CPR is the only new approach for improving CPR efficacy with a mechanical device that has achieved clinical relevance. More recently, an inspiratory impedance threshold valve (ITV®) has been developed that causes a further reduction in intrathoracic pressures, augmenting the efficiency of both standard and ACD CPR. Consequently, ACD CPR and the impedance valve were recently recommended by the American Heart Association. Clinical trials are underway to determine the long-term, potential value of these new technologies.

Key words: cardiopulmonary resuscitation; CPR; active compression-decompression; ACD CPR; inspiratory impedance valve; ITV; CPR techniques; CPR devices; cardiac arrest; ventricular fibrillation.

BACKGROUND

Despite the widespread practice of basic and advanced life support, the vast majority of patients in cardiac arrest do not survive to hospital discharge.[1–3] While the differences

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in outcomes between regions are due to many factors (e.g. response times, patient population), the inherent mechanical inefficiencies of standard cardiopulmonary resuscitation (CPR) limit the potential of even the most highly skilled rescuers. During optimal standard CPR myocardial perfusion is as low as 10–20% of baseline, depending upon the arrest to CPR time, and cerebral perfusion is only 20–30% of baseline. At best, standard CPR can only serve as a bridge to more effective and more definitive therapy. As such, even in the most efficient emergency medical systems less than 20% of patients with out-of-hospital cardiac arrest survive to hospital discharge in the USA.[1–3] As a result several new techniques and devices have been developed during recent years to improve the efficiency and efficacy of standard CPR.

ACTIVE COMPRESSION-DECOMPRESSION

Active compression-decompression (ACD) CPR has been developed as an alternative to standard CPR. ACD CPR is based on the concept that lowering the intrathoracic pressure during the decompression phase of CPR enhances venous blood return to the thorax, thus 'priming the pump' for the subsequent compression. Minute ventilation is similarly increased by the bellows-like action of the chest. ACD CPR is performed using a hand-held device equipped with a suction cup to actively lift up the chest during decompression (Figure 1).

Despite its fundamental role in the efficiency of CPR, for many years the decompression phase of CPR was largely ignored. Research had focused on the compression phase. Over the past decade ACD CPR has been extensively evaluated in animals and humans and the importance of the decompression phase has become more greatly appreciated.[4–21] Animal studies have consistently shown a clear improvement in vital organ perfusion with ACD CPR. Results in clinical studies have been less favourable or neutral. Important determinants in patient outcomes include training[7], where and how the device was used, concurrent use of low rather than high dose epinephrine[19], utilization of the force gauge[7] and performance of CPR for a sufficient duration of 'prime the pump'.[7] Evidence has shown that the use of ACD CPR can benefit patients in cardiac arrest if performed by well-trained rescuers in efficient emergency medical service (EMS) systems.[7,14] The purpose of this chapter is to describe experimental and clinical studies related to the use of ACD CPR. In addition, we review the development and potential benefits of a small inspiratory impedance threshold valve (ITV®) which, like ACD CPR, also functions to decrease intrathoracic pressure during the decompression phase of CPR.

PHYSIOLOGY

During standard CPR the 'bellows-like' action of the chest depends on the active compression and passive relaxation of the chest wall. When the chest is compressed there is an increase in intrathoracic pressure as well as some indirect cardiac compression. During this phase blood is forced out of the chest to the brain and other vital organs. With decompression blood returns to the thorax and heart. Promotion of venous blood return to the heart during the decompression phase is a fundamental aspect of CPR. During standard CPR there is a natural recoil of chest muscles that causes a decrease in intrathoracic pressure and subsequent blood return to the chest. By contrast, with ACD CPR the chest is actively lifted up during the decompression

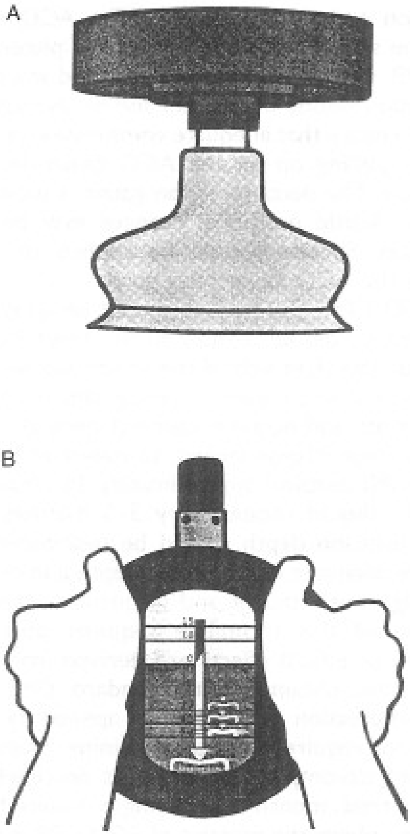

Figure 1. Active compression-decompression (ACD) CPR is performed using a small hand-held device (A) comprised of a suction cup, handle and force gauge. The gauge (B), located in the midportion of the handle, is used to guide the operator during both chest compression and decompression. A built-in metronome functions to maintain correct compression/decompression frequency. By actively pulling the chest up after each compression phase, the intrathoracic pressure is decreased. This decrease in intrathoracic pressure enhances venous return, increased blood flow to the heart and 'primes the pump' for the next compression.

phase, creating a greater pressure gradient between intra- and extrathoracic organs. This increases venous blood return to the heart when compared to that generated by the natural recoil of the chest during standard CPR. Consequently, ACD CPR leads to significantly higher coronary perfusion pressures and vital organ perfusion than standard CPR. Minute ventilation is also increased. Building upon this concept, it has been shown more recently that occlusion of the airway during the decompression phase of CPR improves overall CPR efficiency by promoting increased blood flow back into the chest during decompression.

ACD CPR TRAINING

ACD CPR is performed using a small hand-held device. Rigorous and thorough training is an essential for effective ACD CPR.[7,20] A pressure gauge incorporated into the handle is used to assist the operator in determining the proper degree of force to apply during compression and decompression. The ACD device is placed in the midsternal position in the same location as is used for placement of the palm of the hand during standard CPR. Compressions are performed at a rate of 80–100 times per minute with a compression depth of 5–6 cm for an average size adult. The compression gauge is used to ensure that adequate compression is applied. Decompression is performed by actively pulling up on the ACD device until just prior to loss of suction of the ACD device. The decompression gauge is used to make sure sufficient upward force is applied. Subtle positional changes may be necessary in order to maintain adequate suction. Suction should be applied to −20 pounds using the decompression gauge on the ACD device as a guide.

When performing ACD CPR, the patient should be lying on the back on a firm surface. Ideally, the patient should be treated on the ground. The rescuer performing ACD CPR should kneel on the right side of the victim and be positioned directly over the patient. Rocking back and forth while kneeling, the weight of the rescuer can be used to facilitate compression and decompression (Figure 2). Some rescuers prefer to perform ACD CPR with their elbows locked, to minimize the work load.

Performance of ACD CPR requires approximately 25% more energy than standard CPR.[20] As such, rescuers should rotate every 3–5 minutes to avoid fatigue. Both compression and decompression depth should be monitored on a continuous basis using the gauge to ensure adequate compression depth and decompression excursion.

ACD CPR must be rigorously taught and frequent retraining is critical. As with standard CPR, retention of this technique requires continuous practice. When incorrectly performed no beneficial effects are derived from ACD CPR and overall results are similar to those obtained with standard CPR.[8] Skogvolle and Wik[22] reported that correct compression frequency was applied by only 20% of rescuers in their system, which did not require rigorous retraining. Moreover, only 20% of their rescuers applied sufficient decompression force, as specified in the manufacturer's instructions for use. In contrast, monthly retraining is required for the fire department personnel in Paris, France, where the practice of ACD CPR is the standard of care and has more than doubled long-term survival rates.[7] No study in patients has shown any significant increase in adverse events associated with the use of ACD CPR.

PRIOR STUDIES AND TESTING OF ACD CPR

Many studies have been performed to investigate the mechanisms and potential benefits of ACD CPR. The enhanced decrease in intrathoracic pressure associated with ACD CPR during recoil causes more blood to return to the chest and acutely improves haemodynamics and vital organ perfusion. In some clinical trials, ACD CPR has improved both short-term clinical end-points and neurological outcome.[7–9] The largest and most comprehensive study evaluating long-term end-points comes from Paris, France.[7] In Paris, 1-year survival doubled with the use of ACD CPR. However, in other clinical trials, the short-term outcomes such as hospital admission rates or 1-hour survival were similar between patients receiving ACD CPR and those who received standard CPR.[8] The reasons for the neutral findings may be caused by the fundamental differences in the ACD CPR training that rescuers received and the overall efficiency of the EMS systems from one study site to the next. Below we discuss two key ACD CPR studies: a combined analysis and a recent study from Paris, France.

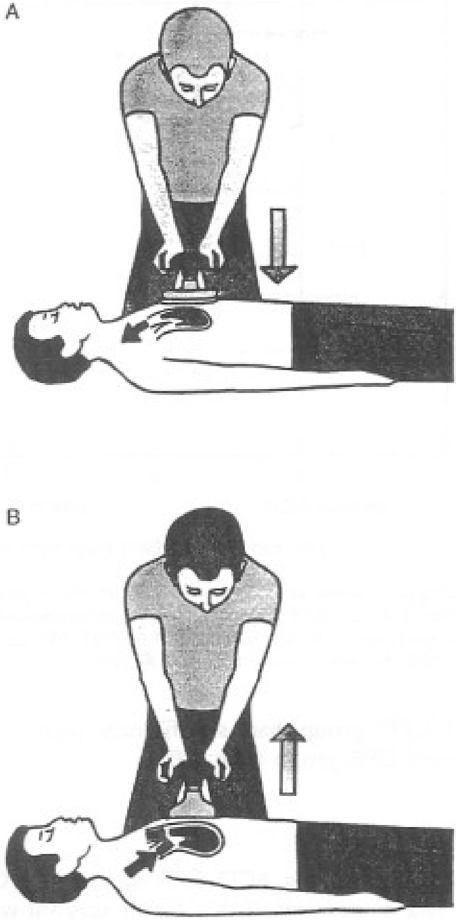

Figure 2. The ACD CPR device is placed in the midsternal position (A); the same location as is used for placement of the palm of the hand during standard CPR. Decompression is performed by actively pulling up on the ACD CPR device (B) until just prior to loss of suction of the ACD CPR device. The force applied during compression and decompression should be monitored using the pressure gauge located in the handle of the device.

Combined Analysis

Mauer et al[8] performed a combined analysis which included data from 2866 patients from seven different prehospital prospective studies conducted at seven separate sites. All of the studies had short-term end-points such as 1-hour survival or return of spontaneous circulation (ROSC) as the primary end-point. All patients with out-of-hospital cardiac arrest were randomized to receive either ACD CPR or standard CPR.

The analysis revealed that 1-hour survival was significantly greater in patients receiving ACD CPR ($n = 1410$) compared to standard CPR ($n = 1456$) (odds ratio (OR) = 0.83; confidence interval (CI) = 0.695–0.99, $p < 0.05$: Figure 3). Although there was no significant difference in hospital discharge rates between the two treatment groups versus the combined analysis, a χ^2 test for trend in overall survival

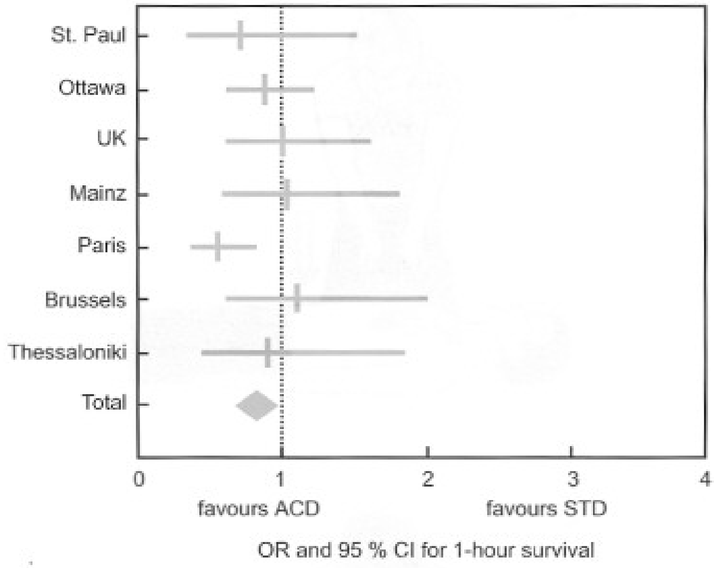

Figure 3. In a combined analysis of seven separate study sites, in which patients in cardiac arrest were randomized to receive standard (STD) CPR versus active compression-decompression (ACD) CPR, a significant improvement was observed in 1-hour survival (OR $= 0.83$, 95% CI $= 0.695$–0.99, $p < 0.05$) for patients that received ACD CPR. An odds ratio < 1 favours ACD CPR.

found that the ACD CPR group had significantly higher overall survival rates compared to the standard CPR group ($p < 0.05$).

Paris Study

The most positive results comparing ACD CPR to standard CPR come from Paris, France, where recent data demonstrated that 1-year survival was more than doubled with the use of ACD CPR compared to standard CPR.[7] In that study, 750 patients were randomized, when the advanced life support team arrived at the scene, to receive either standard CPR or ACD CPR. When ACD CPR was used, 24-hour survival, hospital discharge rates and 1-year survival increased by $> 100\%$.

When comparing ACD versus standard CPR, hospital discharge without neurological impairment was 5.6% versus 1.9%; $p = 0.01$, and 1-year survival was 4.6% versus 1.9%; $p = 0.03$, respectively. Neurological outcome was similar in both groups since 12/17 (71%) of patients after ACD CPR returned to their baseline neurological status versus 3/7 (43%) after standard CPR ($p = 0.34$: Figure 4). This study resulted in the American Heart Association recommending ACD CPR as an alternative to standard CPR in the 2000 guidelines.

STUDY COMPARISONS

No study has shown a worse outcome when using ACD CPR compared with standard CPR. However, differences in results from one study site to the next have led clinicians and scientists to question if and how this technique should best be utilized. Some of

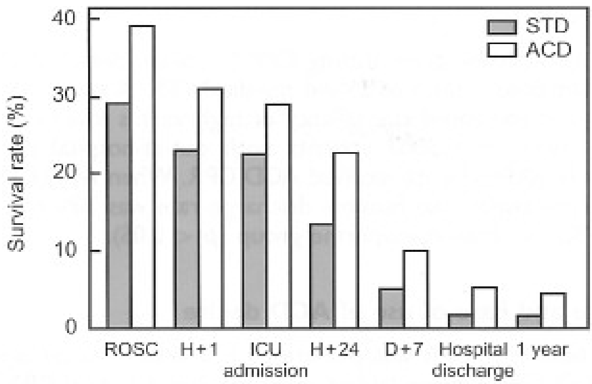

Figure 4. Short and long-term survival rates (% overall survival) from a prehospital study in Paris, France are shown. Patients in cardiac arrest were randomized to receive active compression-decompression (ACD) CPR versus standard (STD) CPR when the mobile intensive care unit (ICU) vehicle arrived at the scene. Odds ratio and confidence intervals (CI) were: 1.5 (CI = 1.14–2.08) for return of spontaneous circulation (ROSC); 1.5 (CI = 1.09–2.08) for 1-hour survival (H + 1); 1.4 (CI = 1.02–1.97) for ICU admission; 1.9 (CI = 1.29–2.76) for 24-hour survival (H + 24); 2.0 (CI = 1.16–3.6) for 7-day survival (D + 7); 3.2 (CI = 1.32–7.51) for hospital discharge; 2.5 (CI = 1.03–6.16) for 1-year survival (1 year).

the reasons for the disparity in study site results can be attributed to inadequate or improper training, rescuer fatigue with the use of the ACD device, overall efficiency of the EMS system, duration of CPR performance, whether or not ACD CPR was performed in a moving vehicle and study size. In Paris, training was rigorous and repeated monthly, CPR was performed continuously for 30 minutes by the advanced cardiac life support (ACLS) team, regardless of rhythm, and only low dose epinephrine was used. Thus, despite the relative inefficiencies typical of large EMS systems such as that in Paris, France, 1-year survival rates were doubled with the use of ACD CPR.[7]

Training

Probably the most important determinant in associated improvements with ACD CPR over standard CPR relates to training. Investigators have learned that training is fundamental for this new technique and many have underestimated the challenges involved in the training of rescue personnel to perform ACD CPR appropriately. In some studies ACD CPR was introduced to the rescue personnel just weeks prior to initiating the clinical studies. By contrast, the French professional rescuers had used or were familiar with the new approach for more than 2 years prior to beginning the present study. Moreover, training by all the personnel in both ACD CPR and standard CPR was frequent, rigorous and focused on the gauge for compression and especially decompression. Emergency medical technicians were retrained every 4 months and paramedics were retrained every 3 months in ACD CPR. This level of intensive training is essential for the proper performance of this new technique. Additionally, the value of using the gauge on the device to assist in consistently applying the correct force during both compression and decompression can not be overstated: in at least one large trial, where use of the gauge was not considered important, no benefit from ACD CPR was observed.[10]

Epinephrine levels

The amount of epinephrine given during CPR has been identified as a critical factor influencing the outcome of both ACD and standard CPR. A recent multicentre trial in France and Belgium compared the efficacy of high versus low doses of epinephrine during CPR in more than 3000 patients with out-of-hospital cardiac arrest.[19] A subgroup of nearly 1000 patients received ACD CPR. When ACD CPR was combined with low dose epinephrine the hospital discharge rate was 50% higher compared to the standard CPR, low dose epinephrine group ($p < 0.05$).

Rescuer fatigue and ease of use of ACD device

Where and for how long CPR was performed is another critical aspect for effective resuscitation. ACD CPR is more labour intensive than standard CPR. It requires 25% more energy than standard CPR. In an effort to decrease rescuer fatigue the handle of the ACD device was recently redesigned for easier and more efficient use. In addition, all ACD CPR should be performed at the scene, not in a moving vehicle. Other studies have shown that standard and especially ACD CPR are much more difficult to perform in a moving vehicle.

CPR duration

If medical personnel staffing the mobile intensive care units believe that resuscitation efforts should continue once they arrive at the scene, then CPR is routinely performed in Paris for at least 30 minutes after the arrival of the mobile intensive care unit, regardless of the initial rhythm. This may be the most important difference between the practice of ACD CPR in Paris and that in other studies comparing standard with ACD CPR. The Paris study comparing ACD CPR with and without the impedance valve demonstrated how long it takes to 'prime the pump' adequately to enhance the benefits of ACD CPR. The duration of CPR may be particularly important for patients found in asystole.[7] In other studies patients in asystole received 10–15 minutes of CPR and if they were not revived all further rescue efforts were often terminated.

Sample size

Finally, another difference between studies relates to sample size. The principal study end-points for several studies were all short-term and those studies did not have sufficient statistical power to demonstrate differences between the two most meaningful end-points: hospital discharge rates and 1-year survival.

ACD CPR CONCLUSIONS

ACD CPR improves haemodynamics acutely in patients in cardiac arrest, yet many studies have consistently failed to show a benefit compared with standard CPR. The reasons for these discrepancies appear to be multifactorial. Given the observations from a number of different investigators that there is a measurable improvement in blood pressure with ACD CPR compared with standard CPR and that clinical long-term results are favourable or neutral, the performance of ACD CPR using a hand-held suction device has recently been recommended by the American Heart

Association (recommendation level 2b) as an alternative technique to standard CPR when it is used by properly trained personnel during CPR. ACD CPR has been approved for use in many countries but is not currently available in the USA. However, ACD CPR is used widely in France and Japan and its use has become increasingly common in those countries as the result of the recently published positive findings from Paris, France.

THE IMPEDANCE THRESHOLD VALVE

During ACD CPR, active decompression decreases the intrathoracic pressure and enhances blood return to the chest. Building on this concept, it has been shown that intermittent occlusion of the airway during chest wall decompression with a small impedance valve improves overall CPR efficiency. An inspiratory threshold valve (ResQ-Valve®, CPRxLLC, Minneapolis, MN) has been recently developed[23–25] to selectively block inspiratory gas exchange during the decompression phase of CPR thereby augmenting venous return. The impedance threshold valve (ITV®) harnesses the kinetic energy of the chest wall recoil, thereby augmenting its 'bellows-like' action. Ventilation is performed, every five compressions as usual, without any resistance from the ITV®. The impedance valve is easily inserted into any standard respiratory circuit between the ventilation bag and endotracheal tube, facemask, laryngeal mask airway or Combitube® (Figure 5). As such, the impedance valve does not interfere with CPR performance and can be used with any generally accepted method of CPR.

Research has shown that the benefits of standard[24] and ACD CPR can be significantly improved by the use of the impedance valve. With standard CPR, use of the impedance valve doubles blood flow to the brain and heart. The combination of

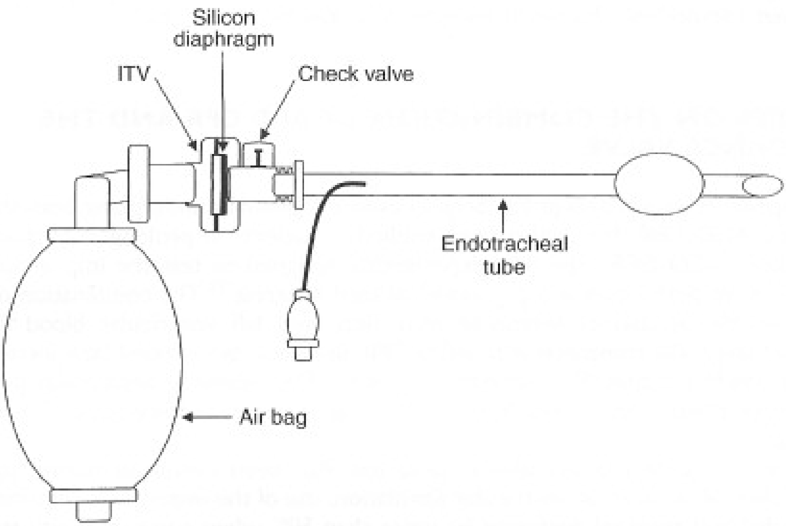

Figure 5. The impedance valve (ITV®) (ResQ-Valve®, CPRxLLC, Minneapolis, MN) is inserted into the respiratory circuit between an airway assist device (facemask, endotracheal tube, laryngeal mask airway or Combitube®) and the ventilation bag. This device intermittently occludes inspiratory gas exchange during decompression enhancing CPR efficiency. The impedance valve functions to enhance CPR efficiency by decreasing intrathoracic pressure during decompression and thereby enhancing venous return to the chest.

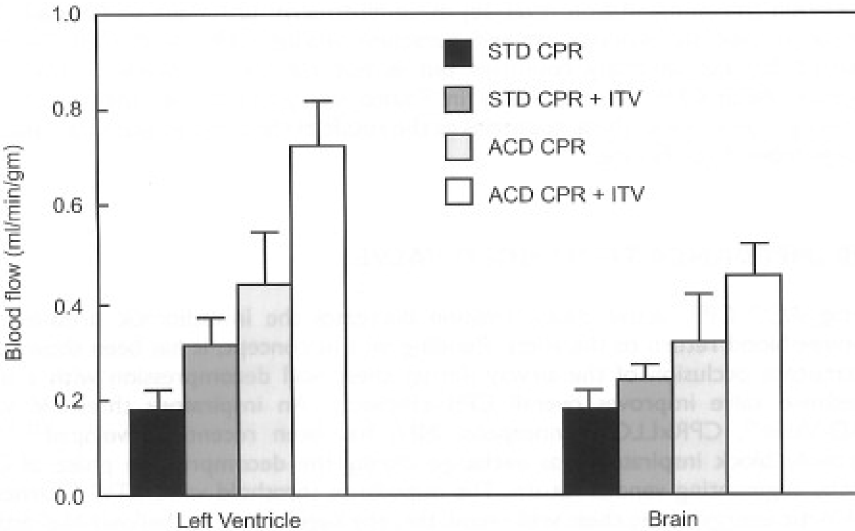

Figure 6. Blood flow during performance of CPR in a porcine model of ventricular fibrillation is shown. Both left ventricular and brain blood flow, measured using radiolabelled microspheres, increased with the addition of the impedance threshold valve (ITV®) with standard (STD) CPR and when the ITV was used during active compression-decompression (ACD) CPR.

ACD CPR plus the valve markedly improved vital organ perfusion and decreased defibrillation thresholds in animals compared with ACD CPR alone.[23] In patients in prolonged cardiac arrest the addition of the valve to ACD CPR resulted in significantly improved haemodynamics when compared to standard CPR alone.[25]

STUDIES ON THE COMBINATION OF ACD CPR AND THE IMPEDANCE VALVE

The impedance valve concept has been evaluated in animals undergoing both standard CPR and ACD CPR. It has also been studied in patients in prolonged cardiac arrest undergoing ACD CPR. The first experiments designed to test the impedance valve concept were performed in a pig model of cardiac arrest.[23] The combination of ACD CPR plus the impedance threshold valve improved left ventricular blood flow by approximately 50% compared with ACD CPR alone and brain blood flow increased to normal baseline values (0.35 ml/min: Figure 6). The enhanced myocardial perfusion with the combined devices resulted in a decrease in energy required to defibrillate the animals.

The potential of the impedance valve has also been evaluated during standard CPR.[24] After 4 minutes of ventricular fibrillation, use of the impedance valve increased myocardial and cerebral perfusion by more than 50% when compared with standard CPR alone. Each time the impedance valve was removed from the respiratory circuit, the coronary perfusion pressure and vital organ perfusion decreased while perfusion pressures stabilized or increased when the valve was placed back in the circuit. This pattern was reproducible regardless of which treatment the animal received: standard

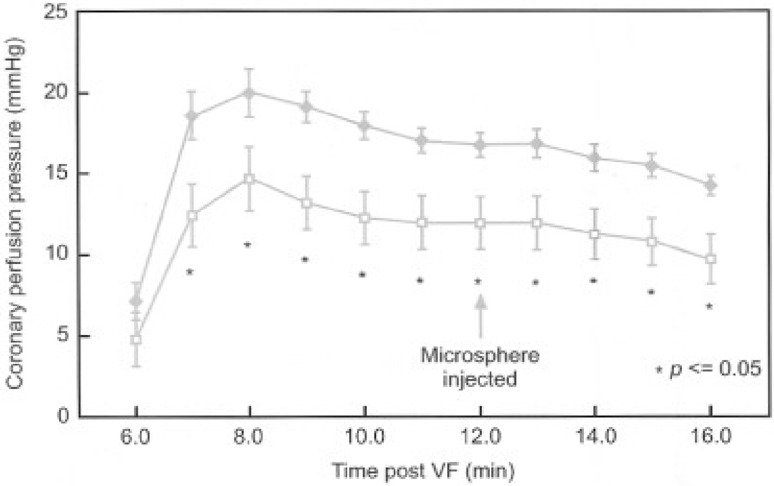

Figure 7. Coronary perfusion pressure (CPP) in animals receiving standard (STD) CPR plus the impedance threshold valve (ITV®) (—◆—, $n = 9$) versus standard CPR alone (—□—, $n = 9$) are shown. Two groups of animals received standard CPR for 11 minutes after a 6 minute period of cardiac arrest without CPR. Addition of the active impedance valve resulted in a significant improvement in coronary perfusion

CPR or standard CPR plus the impedance valve initially. More recently, similar studies were conducted using the same pig model with a 6 minute arrest time. All study animals in both groups received standard CPR for 11 minutes after a 6 minute period of cardiac arrest without CPR. Addition of the active impedance valve resulted in a marked improvement in coronary perfusion pressures (Figure 7). With the impedance valve, both left ventricular and cerebral blood flow increased by nearly 100% and there was a near normalization of flow to the brain. After a total of 17 minutes of ventricular fibrillation and 11 minutes of CPR, 3/12 pigs in the sham group and 6/11 pigs in the active impedance valve group were resuscitated by direct current shock. Despite the 6 minute arrest time, 24 hour neurological outcome in survivors of 6 minutes of ventricular fibrillation followed by standard CPR with the impedance valve was excellent. In many ways the 6 minute arrest time prior to the start of CPR more closely resembles clinical field experience, where the time from arrest to start of CPR ranges between 4–8 minutes in the USA cities having highly efficient emergency medical systems. In this regard, the impedance valve represents the first adjunctive standard CPR device found to significantly improve the efficacy of standard CPR.

At present, experience with the new impedance valve in humans remains limited to the measurement of acute haemodynamic parameters on patients undergoing ACD CPR.[25] In 21 patients in Paris, France in prolonged cardiac arrest, the combination of ACD CPR with the impedance valve resulted in a greater than 50% increase in end tidal CO_2 and diastolic blood pressure (Figure 8). Patients were randomized in a blinded prospective fashion to a functional or non-functional sham valve after approximately 18 minutes of cardiac arrest. The mean arterial systolic and diastolic pressures were 108($\pm$3.1) and 56.4($\pm$1.7)mmHg in patients receiving ACD CPR plus the valve versus 90($\pm$6.4) and 36.5($\pm$1.5)mmHg with ACD CPR alone ($p < 0.01$ comparing systolic and diastolic blood pressure between groups). No adverse effects were observed with the use of the impedance valve in this study including failure of the device, secondary respiratory failure, pulmonary complications, or barotrauma.

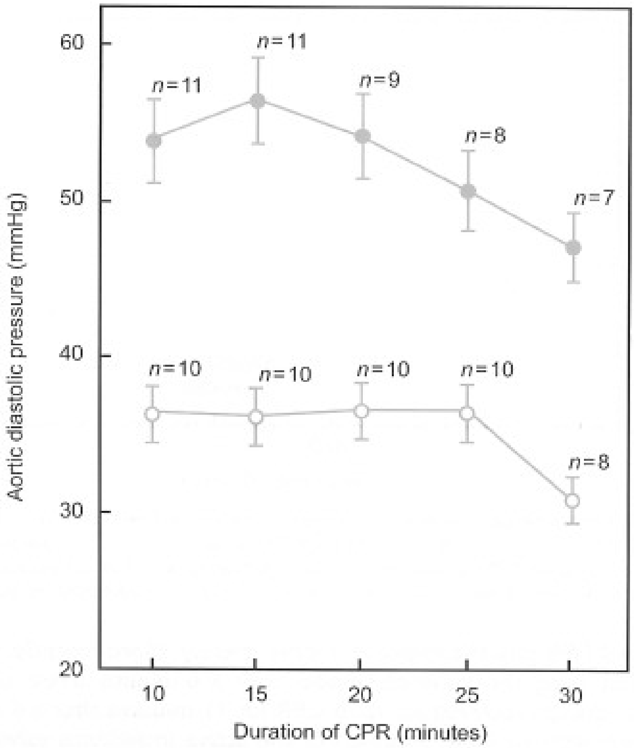

Figure 8. Diastolic arterial pressures (DAP) in patients randomized to receive active compression-decompression (ACD) CPR plus the impedance valve (ITV[19]) (—●—) versus ACD CPR alone (—○—) are shown. Upon arrival of the mobile intensive care unit, patients underwent endotracheal intubation and placement of invasive arterial catheters within 10 minutes after intubation. DAP were markedly higher in the ACD plus impedance valve treatment group compared to those who received ACD CPR alone ($p < 0.001$ for peak values).

The impedance valve has not yet been evaluated with standard CPR in humans. However studies are underway to determine if addition of the valve significantly improves CPR efficiency. Results from the most recent porcine model study comparing standard CPR plus valve versus standard CPR alone indicate promise for the effectiveness of the impedance valve with standard CPR. In addition, the ease of use of this device and its ability to be incorporated into mask and other airway devices suggest the impedance valve may be a favourable new device for improving CPR efficiency.

CONCLUSION

ACD CPR and the ITV have been recently developed to improve the efficiency of standard closed-chest CPR. Individually, both show promise in numerous animal and clinical studies, but the most exciting results emerge when the two devices are used in combination. In combination, diastolic blood pressures and coronary perfusion pressures are nearly normal in patients undergoing CPR. Practical issues associated with ACD CPR include the need for rigorous and extensive training; however, when

Practice points

- when treating patients in cardiac arrest, use of an ACD CPR device and an impedance valve will triple blood flow to the vital organs and reduce defibrillated thresholds. The ACD CPR technnique requires training and retraining. However, when combined with the impedance valve, ACD CPR is recommended by the American Heart Association and the International Consensus Panel because of the superior haemodynamics associated with this device combination

Research agenda

- recent studies showing a marked benefit of the impedance valve with the standard CPR suggest that the valve may significantly improve long-term results with standard CPR. Clinical trials are underway to assess short- and long-term effects of the impedance valve with standard and ACD CPR

used properly by trained personnel, the benefits of ACD CPR alone over standard CPR have been demonstrated in clinical trials. The impedance valve is easy to use and provides promise as an effective adjunct for several CPR techniques including standard and ACD CPR. As a result of the improvement in blood pressure in patients treated with ACD CPR combined with the impedance valve, the American Heart Association has recently recommended these devices as an alternative to standard CPR.[26] Widespread acceptance of ACD CPR and the concept of the impedance valve as valuable new CPR tools continues to grow as researchers and physicians search for better ways to treat victims of cardiac arrest.

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