Cardiopulmonary Resuscitation With a Novel Chest Compression Device in a Porcine Model of Cardiac Arrest

Improved Hemodynamics and Mechanisms

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OBJECTIVES

The goal of this study was to determine the magnitude and mechanisms of hemodynamic improvement of an automated, load-distributing band device (AutoPulse, Revivant Corp., Sunnyvale, California) compared with conventional cardiopulmonary resuscitation (C-CPR).

BACKGROUND

Improved blood flow during cardiopulmonary resuscitation (CPR) enhances survival from cardiac arrest.

METHODS

AutoPulse CPR (A-CPR) and C-CPR were performed on 30 pigs (16 ± 4 kg) 1 min after induction of ventricular fibrillation. Aortic and right atrial pressures were measured with micromanometers. Regional flows were measured with microspheres; A-CPR and C-CPR were performed with 20% anterior-posterior chest compression, with (n = 10) and without (n = 10) epinephrine. A pressure transducer was advanced down the airways during chest compressions (n = 10), and magnetic resonance imaging (MRI) was performed.

RESULTS

AutoPulse CPR improved coronary perfusion pressure (CPP) (aortic – right atrial pressure) without epinephrine (A-CPR 21 ± 8 mm Hg vs. C-CPR 14 ± 6 mm Hg, mean ± SD, p < 0.0001) and with epinephrine (A-CPR 45 ± 11 mm Hg vs. C-CPR 17 ± 6 mm Hg, p < 0.0001). AutoPulse CPR improved myocardial flow without epinephrine and cerebral and myocardial flow with epinephrine (p < 0.05). AutoPulse CPR also produced greater myocardial flow at every CPP (p < 0.01). With A-CPR, high airway pressure was noted distal to the carina, which corresponded to an area of airway collapse on MRI, and which was not present with C-CPR.

CONCLUSIONS

AutoPulse CPR improved hemodynamics over C-CPR in this pig model. AutoPulse CPR with epinephrine can produce pre-arrest levels of myocardial and cerebral flow. The improved hemodynamics with A-CPR appear to be mediated through airway collapse, which likely impedes airflow and helps maintain higher levels of intrathoracic pressure. (J Am Coll Cardiol 2004;44:2214–20) © 2004 by the American College of Cardiology Foundation

Of the estimated 460,000 victims of cardiac arrest each year in the U.S. (1), only 5% to 15% survive (2). Fewer than half of cardiac arrests are due to ventricular fibrillation (VF), where strategies that may provide early defibrillation may improve overall mortality (3). In addition, most patients do not receive early defibrillation (3).

Survival in subjects who failed defibrillation, or had non-VF arrests, is related to the amount of blood flow generated to the heart and brain during cardiopulmonary resuscitation (CPR) (4–6). In addition, circulation before defibrillation may improve the outcome of patients with prolonged VF (7). Blood flow itself is related to the amount of sternal displacement and compression time during CPR (8,9). Airway mechanisms may also be important in generating flow (10). Because manual CPR is often done incorrectly (11,12), especially during transportation, automated devices may eliminate the variability and fatigue inherent in manual CPR, decrease interruptions, augment airway mechanisms, and improve blood flow and survival.

It was previously shown that chest compression with a pneumatic vest generates more blood flow and survival in animals than standard CPR and improves coronary perfusion pressure (CPP) in patients (5,13). These improvements are likely mediated by increased intrathoracic pressure generation from airway collapse (10). The pneumatic system, however, had a size that precluded a portable resuscitation device. An improved, portable device has been developed that uses an automated, load-distributing band (LDB) to compress the anterior and anterior-lateral chest. This study is the first experimental comparison of the magnitude and mechanisms of hemodynamics generated by the device (AutoPulse, Revivant Corp., Sunnyvale, California) (A-CPR) versus conventional CPR (C-CPR), using a porcine model of cardiac arrest.

METHODS

Preparation. Studies were approved and performed at Johns Hopkins University. A total of 30 pigs (16 ± 4 kg)
received ketamine 22 mg/kg intramuscularly. After endotracheal intubation and mechanical ventilation, anesthesia was maintained with isoflurane (1% to 2.5%) in 100% oxygen. Pigs were placed in the supine position and were given normal saline intravenously to maintain a mean right atrial pressure of 3 to 5 mm Hg. From bilateral femoral cutdowns, micromanometers (PC-470; Millar, Houston, Texas) were placed into the right atrium and ascending aorta, a pigtail catheter was placed into the descending aorta, and a pacing catheter was placed into the right ventricle. From a carotid cutdown, a pigtail catheter was placed into the left ventricle.

Neutron-activated microspheres (Biophysics Assay Lab, Wellesley, Massachusetts) were used to measure regional blood flows with methods previously validated for CPR (6,8,14). Each injection was 6.3 million spheres. Reference samples were withdrawn at 3.9 ml/min for 3 min. The first flow measurement was made immediately before cardiac arrest. Isoflurane was then reduced to 0.5%, and VF was induced with a 60-Hz current applied to the pacing catheter and left untreated for 1 min. Two protocols compared hemodynamics generated by A-CPR and C-CPR, with (n = 10) and without (n = 10) epinephrine. In a third protocol (n = 10), a fluid-filled catheter was placed into the airway (10); the catheter was connected to a pressure transducer (Gould-Statham, Oxnard, California), and chest compressions were performed during catheter pullbacks. Magnetic resonance images were also obtained.

**Protocols**

**Hemodynamics without epinephrine.** The first CPR treatment was started with either A-CPR or C-CPR chosen using a random number generator (Fig. 1A). AutoPulse CPR and C-CPR were both performed with 20% anterior-posterior sternal displacement (80/min); C-CPR was performed with a pneumatic piston (Thumper, Michigan Instruments, Grand Rapids, Michigan). Ventilation was performed asynchronously (12/min). The first CPR treatment was continued for 4 min while pressures and regional blood flows were measured. Coronary perfusion pressure was aortic – right atrial pressure during chest decompression, averaged over 10 cycles.

Immediately after completing treatment 1, all animals were crossed-over to the other method (C-CPR or A-CPR) for 4 min of treatment 2. Pressures and regional blood flows were measured again. After completion of the crossover method, the first method was performed again for 2 min (treatment 3 = 1), and pressures were recorded. After completion of the three treatments, manual CPR was performed for 2 min while pressures were recorded.

**Hemodynamics with epinephrine.** The first treatment was started with either A-CPR or C-CPR chosen randomly (Fig. 1B). Epinephrine was started simultaneously with the first treatment with a 0.5 mg intravenous bolus, followed by a 4-μg/kg/min intravenous infusion. The treatment sequence was similar to that described for the protocol without epinephrine, but omitting manual CPR.

**Airway collapse.** The fluid-filled catheter was advanced down the airway while airway pressures were recorded. Advancement of the catheter was stopped if there was a sudden increase in airway pressure or any significant increase in resistance to advancing the catheter. The catheter was then withdrawn in increments of 1 to 2 cm as pressure was recorded.

**Figure 1.** (A) Timeline for protocol without epinephrine. For blood flow measurements, blood is withdrawn during the times indicated. (B) Timeline for protocol with epinephrine. CPR = cardiopulmonary resuscitation; VF = ventricular fibrillation.
Pressures were recorded similarly during A-CPR, C-CPR, and manual CPR. Equivalency of starting positions for the with-drawals was confirmed with fluoroscopy.

The animals were then placed in a nonmagnetic A-CPR device, and positioned in a 1.5-T magnetic resonance imaging (MRI) scanner (General Electric, Signa, Waukesha, Wisconsin). T2-weighted fast spin echocardiography sequences (TE: 68 ms; TR: 1,000 ms; slice: 7 mm) were performed during A-CPR, covering the entire thorax.

AutoPulse device. The AutoPulse device is built around a backboard that contains a motor to retract an LDB under microprocessor control. As the motor turns, the band is tightened or loosened around the chest (Fig. 2). The device adjusts the LDB to the size of the subject being resuscitated, while the LDB distributes the compressive load over the anterior chest to reduce local stresses.

The AutoPulse device used in the present study incorporated an LDB that was scaled down from the device designed for human use. This porcine-sized LDB allowed an analogous proportion of the porcine thorax to be compressed by the LDB.

**Figure 2.** Operation of the AutoPulse. During compression (left) the band is tightened by the motor, and compression force is directed inward. During relaxation (right), the band is released, and the chest expands.

**Hemodynamics without epinephrine.** Aortic pressures improved with A-CPR over C-CPR and manual CPR (Table 1). Right atrial peak and mean pressures were also increased with A-CPR, but the diastolic (decompression phase) right atrial pressure was not increased with A-CPR. The CPP, therefore, was also increased with A-CPR over C-CPR and over manual CPR. The pressures generated by manual CPR were equivalent to those generated by C-CPR (p = NS).

Blood flow to the myocardium was increased with A-CPR over C-CPR (Fig. 3A). Flow to the brain was similar between A-CPR and C-CPR (Fig. 3B). Overall, blood flow to the myocardium was 36% of pre-arrest flow with A-CPR, and 13% with C-CPR, whereas flow to the brain was 36% with A-CPR and 28% with C-CPR.

**Hemodynamics with epinephrine.** Aortic pressures improved with A-CPR over C-CPR (Table 2). The right atrial peak and mean pressures were increased similarly, but the diastolic right atrial pressure was not increased with A-CPR; CPP, therefore, was also increased with A-CPR over C-CPR.

There was some change in pressures between the 1- and 4-min A-CPR measurements, but there was no differential

### Table 1. Blood Pressures (mm Hg) Pre-Arrest and Without Epinephrine

<table>
<thead>
<tr>
<th></th>
<th>A-CPR</th>
<th>C-CPR</th>
<th>Manual</th>
<th>Mixed Effects Model Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-Arrest</td>
<td>1 min</td>
<td>4 min</td>
<td>1 min</td>
</tr>
<tr>
<td>Peak Ao</td>
<td>124 ± 18</td>
<td>88 ± 18</td>
<td>85 ± 17</td>
<td>45 ± 11</td>
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<tr>
<td>Diastolic Ao</td>
<td>90 ± 17</td>
<td>31 ± 9</td>
<td>27 ± 8</td>
<td>25 ± 7</td>
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<tr>
<td>Mean Ao</td>
<td>101 ± 17</td>
<td>50 ± 11</td>
<td>47 ± 10</td>
<td>31 ± 8</td>
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<tr>
<td>Peak RA</td>
<td>9 ± 3</td>
<td>88 ± 20</td>
<td>83 ± 17</td>
<td>32 ± 9</td>
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<tr>
<td>Diastolic RA</td>
<td>3 ± 3</td>
<td>10 ± 3</td>
<td>10 ± 2</td>
<td>11 ± 4</td>
</tr>
<tr>
<td>Mean RA</td>
<td>5 ± 3</td>
<td>36 ± 8</td>
<td>34 ± 6</td>
<td>18 ± 4</td>
</tr>
<tr>
<td>CPP</td>
<td>87 ± 18</td>
<td>21 ± 8</td>
<td>18 ± 7</td>
<td>14 ± 6</td>
</tr>
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</table>

A-CPR and C-CPR results have two measurements (replicates) during each treatment period (1 and 4 min of treatment). Mixed effects model results describe the relative improvement in pressure with A-CPR over C-CPR and the associated confidence interval (CI) and probability of difference. Period effect indicates pressure alteration in repeated crossover and is accounted for in the mixed effect model for p < 0.05. During CPR, diastolic refers to the chest decompression phase.

A-CPR = Autopulse cardiopulmonary resuscitation; Ao = aortic; C-CPR = conventional cardiopulmonary resuscitation; CPP = coronary perfusion pressure; RA = right atrial.

### Statistical analysis

Data are presented as mean values ± SD. Pressures recorded at the beginning and end of treatment periods are referred to as replicates (1 and 4 min for treatments 1 and 2, and 1 and 2 min for treatment 3). Pressures and flows were compared using a repeated measures linear mixed effects model that incorporated predictor terms for treatment and period effects. Treatment effect is defined as the first versus the second treatment period. Period effect is defined as the first versus third treatment period. Independent variables with low predictive power were eliminated from the model by a backward deletion selection process until all predictor terms in the model were significant by F-test. All calculations were performed using SAS statistical software (SAS Institute, Cary, North Carolina). A p value <0.05 was considered significant.
crossover effect. The same pressures that had a period effect without epinephrine demonstrated a significant period effect with epinephrine ($p < 0.05$). This indicates that the third treatment period was different from the first. There was also a significant replicate effect in both diastolic pressures and CPP. This may reflect a time-dependent alteration in the pressor effect of epinephrine, as this effect was not seen without epinephrine.

Blood flow to the myocardium and brain improved with A-CPR over C-CPR (Fig. 3). A differential carryover effect was not present. Overall, blood flow to the myocardium was 127% of pre-arrest flow with A-CPR and 29% with C-CPR, whereas blood flow to the brain was 129% with A-CPR and 31% with C-CPR.

**Pressure-flow relationships.** There were strong linear relationships between CPP and blood flow both in the left ventricle and brain (Fig. 4). The differences between treatment with A-CPR and C-CPR were examined in a repeated measures linear mixed effects model with CPP as the independent variable, and left ventricular and brain flows as dependent variables. There was a significant increase noted in the CPP-flow slopes for A-CPR over C-CPR (Fig. 4), indicating that, at equivalent CPPs, A-CPR produced more myocardial flow and brain flow than C-CPR.

**Airway collapse.** Figure 5A shows the decrease in phasic pressure changes during A-CPR measured by the airway catheter as it is withdrawn in one pig. With the catheter advanced approximately 2 to 4 cm beyond the carina (confirmed with fluoroscopy), large increases in airway pressure are noted (Fig. 5A, distal). When the catheter was withdrawn approximately 6 cm, smaller changes in pressure were recorded (Fig. 5A, proximal). Similar results were noted in all 10 pigs.

Figure 5B shows recordings with a similar protocol as in Figure 5A, but during C-CPR. With the catheter starting at the same distal position as for A-CPR, there were no areas of high airway pressure recorded. Similar results were noted in all 10 pigs for C-CPR and manual CPR.

The MRI obtained during A-CPR showed the trachea widely patent in the uncompressed state, but collapsed during chest compression at the level of the carina (Fig. 6).

**DISCUSSION**

AutoPulse CPR improved myocardial flow, aortic pressure, and CPP without epinephrine, and improved myocardial flow, cerebral flow, aortic pressure, and CPP with epinephrine in a porcine model of cardiac arrest. In addition, A-CPR produced higher levels of flow than C-CPR at all levels of CPP. AutoPulse CPR with epinephrine early in the course of cardiac arrest produced levels of myocardial and cerebral flow that are comparable to those measured before arrest. AutoPulse CPR caused the airways just distal to the carina to collapse during chest compression. Distal to the collapse site, high airway pressures were noted. No such high airway pressures were noted with C-CPR.

**Survival related to blood flow.** Numerous studies in animals, and confirmatory studies in patients, have shown a strong correlation between restarting the heart and higher levels of coronary blood flow (5,6,15). Because blood flow is produced by chest compression, it is not surprising that survival is also related to the amount of chest compression, with improved survival produced by “correct CPR” (1.5 to 2 inches of sternal displacement) (16).

A recent study showed, however, that fewer than 20% of the compressions performed by the students, even immediately after the courses, were correct (17). This was true even
of health care professionals, who performed CPR incorrectly after the first minute.

Mechanisms of blood flow generation. Elucidation of the mechanisms of blood flow may help optimize flow. It has been well-described that blood moves during CPR chest compression because of some combination of direct cardiac compression and intrathoracic pressure manipulation (8,10,18–20). This intrathoracic pressure model was instrumental in developing vest CPR (5,13), which could generate normal levels of flow during CPR, likely mediated by collapse of medium-sized airways, trapping air in the lungs (10).

Both A-CPR and C-CPR caused a 20% reduction in the anterior-posterior dimension of the chest. The similar sternal displacements should, therefore, cause cardiac compression to the same degree with either technique. Compressions with A-CPR, however, additionally produce collapse of the airways (Figs. 5 and 6), likely because of the larger compression area of A-CPR. Similar airway collapse did not occur, however, with C-CPR. This airway collapse during A-CPR could maintain intrathoracic pressure higher during A-CPR, by reducing the amount of air that was expired from the lungs during compression. Any expired air during chest compression would reduce the level of intrathoracic pressure generated.

Limitations of the present study. The hemodynamic effects of A-CPR and C-CPR were evaluated after only 1 min of untreated VF. Although evaluations of hemodynamics are described frequently in this manner, they may not be predictive of hemodynamics generated with longer untreated periods, especially in patients. Although there is a well-described relationship between improved hemodynamics and increased survival (4–6), the actual survival rate with A-CPR remains to be demonstrated. In addition, the details of the relationship between airway collapse and vascular pressure generation remain to be determined.

Conclusions. AutoPulse CPR improved myocardial flow, aortic pressure, and CPP over conventional CPR with and without the use of epinephrine. AutoPulse CPR also improved cerebral blood flow with the use of epinephrine. Additionally, A-CPR produced higher levels of heart and brain flow than C-CPR at every level of CPP. In this pig

<table>
<thead>
<tr>
<th></th>
<th>Pre-Arrest</th>
<th>1 min</th>
<th>4 min</th>
</tr>
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<tbody>
<tr>
<td>Peak Ao</td>
<td>119 ± 8</td>
<td>134 ± 36</td>
<td>121 ± 34</td>
</tr>
<tr>
<td>Diastolic Ao</td>
<td>89 ± 7</td>
<td>56 ± 11</td>
<td>42 ± 10</td>
</tr>
<tr>
<td>Mean Ao</td>
<td>99 ± 7</td>
<td>82 ± 17</td>
<td>69 ± 16</td>
</tr>
<tr>
<td>Peak RA</td>
<td>8 ± 4</td>
<td>153 ± 64</td>
<td>151 ± 57</td>
</tr>
<tr>
<td>Diastolic RA</td>
<td>2 ± 2</td>
<td>11 ± 3</td>
<td>12 ± 4</td>
</tr>
<tr>
<td>Mean RA</td>
<td>4 ± 2</td>
<td>59 ± 21</td>
<td>58 ± 20</td>
</tr>
<tr>
<td>CPP</td>
<td>86 ± 8</td>
<td>45 ± 11</td>
<td>30 ± 9</td>
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</table>

A-CPR and C-CPR comparisons are as described in Table 1. Replicate effect indicates a difference in measurements at 1 and 4 min within each period.

Abbreviations as in Table 1.

Figure 4. Correlations between left ventricular (LV) and brain flows, and coronary perfusion pressure (CPP), for AutoPulse cardiopulmonary resuscitation (A-CPR) and conventional (piston) cardiopulmonary resuscitation (C-CPR). For both the LV and brain, A-CPR produced more flow at given levels of CPP than C-CPR (p < 0.05).
model of cardiac arrest, A-CPR, with the use of epinephrine early in the course of cardiac arrest, produced levels of myocardial and cerebral flow that are comparable to those measured before arrest. These improved hemodynamics appear to be mediated by airway collapse that occurs during A-CPR and is not present during C-CPR. Because survival from cardiac arrest, when defibrillation fails or is not indicated, is related to the amount of blood flow generated

![Figure 5](image_url)

**Figure 5.** (A) Recordings during AutoPulse cardiopulmonary resuscitation (A-CPR) before and after airway catheter withdrawal. The catheter was advanced down the airway until high airway pressure was recorded (distal). The catheter was then withdrawn 6 cm, and the lower airway pressure was recorded (proximal). (B) Recordings during conventional (piston) cardiopulmonary resuscitation before and after airway catheter withdrawal. The catheter was manipulated as with A-CPR. All pressures in mm Hg. AO = aortic; RA = right atrial.

![Figure 6](image_url)

**Figure 6.** Magnetic resonance imaging of the thorax during AutoPulse cardiopulmonary resuscitation. The trachea is widely patent in the uncompressed state (A, arrow) but is nearly fully collapsed during peak compression (B, arrow).
by CPR (4,5,12), it is likely that A-CPR, if used early enough in the course of cardiac arrest, could improve survival. Further study quantifying neurologically intact survival after cardiac arrest is indicated.

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