Reducing Ventilation Frequency During Cardiopulmonary Resuscitation in a Porcine Model of Cardiac Arrest

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INTRODUCTION: American Heart Association/American College of Cardiology guidelines recommend a compression-to-ventilation ratio (C/V ratio) of 15:2 during cardiopulmonary resuscitation (CPR) for out-of-the-hospital cardiac arrest. Recent data have shown that frequent ventilations are unnecessary and may be harmful during CPR, since each positive-pressure ventilation increases intrathoracic pressure and may increase intracranial pressure and decrease venous blood return to the right heart and thereby decrease both the cerebral and coronary perfusion pressures. HYPOTHESIS: We hypothesized that reducing the ventilation rate by increasing the C/V ratio from 15:2 to 15:1 will increase vital-organ perfusion pressures without compromising oxygenation and acid-base balance. METHODS: Direct-current ventricular fibrillation was induced in 8 pigs. After 4 min of untreated ventricular fibrillation without ventilation, all animals received 4 min of standard CPR with a C/V ratio of 15:2. Animals were then randomized to either (A) a C/V ratio of 15:1 and then 15:2, or (B) a C/V ratio of 15:2 and then 15:1, for 3 min each. During CPR, ventilations were delivered with an automatic transport ventilator, with 100% oxygen. Right atrial pressure, intratracheal pressure (a surrogate for intrathoracic pressure), aortic pressure, and intracranial pressure were measured. Coronary perfusion pressure was calculated as diastolic aortic pressure minus right atrial pressure. Cerebral perfusion pressure was calculated as mean aortic pressure minus mean intracranial pressure. Arterial blood gas values were obtained at the end of each intervention. A paired *t* test was used for statistical analysis, and a p value < 0.05 was considered significant. RESULTS: The mean ± SEM values over 1 min with either 15:2 or 15:1 C/V ratios were as follows: intratracheal pressure 0.93 ± 0.3 mm Hg versus 0.3 ± 0.28 mm Hg, $p = 0.006$; coronary perfusion pressure 10.1 ± 4.5 mm Hg versus 19.3 ± 3.2 mm Hg, $p = 0.007$; intracranial pressure 25.4 ± 2.7 mm Hg versus 25.7 ± 2.7 mm Hg, p = NS; mean arterial pressure 33.1 ± 3.7 mm Hg versus 40.2 ± 3.6 mm Hg, $p = 0.007$; cerebral perfusion pressure 7.7 ± 6.2 mm Hg versus 14.5 ± 5.5 mm Hg, $p = 0.008$. Minute area intratracheal pressure was 55 ± 17 mm Hg · s versus 22.3 ± 10 mm Hg · s, $p < 0.001$. End-tidal CO_2 with 15:2 versus 15:1 was 24 ± 3.6 mm Hg versus 29 ± 2.5 mm Hg, respectively, $p = 0.001$. Arterial blood gas values were not significantly changed with 15:2 versus 15:1 C/V ratios: pH 7.28 ± 0.03 versus 7.3 ± 0.03; P_{aCO_2} 37.7 ± 2.9 mm Hg versus 37.6 ± 3.5 mm Hg; and P_{aO_2} 274 ± 36 mm Hg versus 303 ± 51 mm Hg. CONCLUSIONS: In a porcine model of ventricular fibrillation cardiac arrest, reducing the ventilation frequency during CPR by increasing the C/V ratio from 15:2 to 15:1 resulted in improved vital-organ perfusion pressures, higher end-tidal CO_2 levels, and no change in arterial oxygen content or acid-base balance. *Key words: cardiopulmonary resuscitation, coronary perfusion pressure, cerebral perfusion pressure, ventilation rate, intrathoracic pressure.* [Respir Care 2005;50(5):628–635.

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Introduction

Recent data have challenged the importance of frequent ventilations during the first minutes of cardiopulmonary resuscitation (CPR) for out-of-the-hospital cardiac arrest.[1–5] Some have advocated for performing only chest compressions without ventilation in the first few minutes after CPR, based upon the challenges associated with the teaching and practicing of mouth-to-mouth ventilation.[6]

Rescuer-assisted ventilations interrupt chest compressions and thereby result in a substantial reduction of compression cycles per minute.[7] With each cessation of chest compressions to provide positive-pressure ventilation, coronary perfusion pressure decreases, requiring additional and critical time to restore coronary flow again.[8] Taken together, frequent ventilations decrease the efficiency of CPR. At present, American Heart Association 2000 Guidelines recommend a compression-to-ventilation (C/V) ratio of 15:2 for 1- and 2-rescuer CPR without a secured airway.[9]

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More recent CPR studies have further examined additional adverse physiologic effects of positive-pressure ventilation on vital-organ perfusion. A recent study demonstrated that by increasing the ratio from 5:1 to 10:1 there is an incremental improvement in hemodynamics and vital-organ perfusion pressures, with and without the use of an inspiratory threshold device.[10] Further support for this mechanical disadvantage associated with ventilation was recently demonstrated in animals and humans receiving excessive ventilation.[11] Those studies showed that hyperventilation is deleterious and can be lethal. Mean intrathoracic pressure was inversely related to arterial pressure, vital-organ blood flow, and survival.[11]

However, our understanding of the relationship between ventilation and vital-organ perfusion during CPR remains incomplete. More recently, a study focused on the decompression phase of CPR showed that the increase of intrathoracic pressure accompanying each positive-pressure breath was immediately associated with an increase of intracranial pressure (ICP).[12] With each positive-pressure ventilation, coronary perfusion pressure and cerebral perfusion pressure was reduced to minimal levels.[12] Building upon these observations, and in consideration of the already known multiple deleterious effects of frequent positive-pressure ventilation, the purpose of this investigation was to determine if the C/V ratio could be further increased without adversely affecting coronary and cerebral perfusion pressures or delivery of oxygen to the vital organs.

We hypothesize that an increase of the C/V ratio from 15:2 to 15:1 will result in a decrease of mean intrathoracic pressure and will enhance venous return and improve arterial pressures and vital-organ perfusion pressures without adversely affecting oxygenation and acid-base balance.

Methods

The study was approved by the Institutional Animal Care Committee of the Minneapolis Medical Research Foundation at Hennepin County Medical Center. The animals received treatment and care in compliance with the 1996 Guide for the Care and Use of Laboratory Animals by the National Research Council, in accord with the United States Department of Agriculture Animal Welfare Act, Public Health Service Policy, and the American Association for Accreditation of Laboratory Animal Care. Anesthesia was used in all surgical interventions to avoid all unnecessary suffering. Experiments were performed by a qualified, experienced team. The study was performed on female farm pigs (28–32 kg).

Preparatory Phase

Initial sedation in each animal was achieved with 7 mL (100 mg/mL) of intramuscular ketamine HCl (Ketaset, Fort Dodge Animal Health, Fort Dodge, Iowa). Propofol anesthesia (PropoFlo, Abbott Laboratories, North Chicago, Illinois) (2.3 mg/kg) was also delivered as an intravenous bolus via the lateral ear vein. While spontaneously breathing, but sedated, the pigs were intubated with a 7.0 French endotracheal tube. Additional propofol (1 mg/kg) was then

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administered, followed by a propofol infusion of 160 μg/kg/min.

While the animals were sedated and mechanically ventilated, under aseptic conditions, a hole was drilled through the skull, for ICP recordings. After identifying the posterior bony prominence of the pig's cranium, a burr hole was made at the middle of the distance between the left eyebrow and the posterior bony prominence. A 3.5 French continuous recording micromanometer pressure transducer (Mikro-Tip Transducer, Millar Instruments, Houston, Texas) was inserted 2 cm into the parietal lobe of the animal and secured in place. The pressure transducer was connected to a signal amplifier (model 13-6615-50, Gould Instrument Systems, Valley View, Ohio) and then to a digital recording system (SuperScope II, GW Instruments, Somerville, Massachusetts) providing real-time ICP tracings. A second hole was drilled in the same way on the right side for a second ICP transducer (Camino, Integra LifeSciences, Plainsboro, New Jersey), which was used to calibrate the micromanometer pressure transducer.

Animals were then positioned supine, and unilateral femoral-artery cannulation was performed under aseptic conditions. Central aortic blood pressures were recorded continuously, with a micromanometer-tipped catheter (Mikro-Tip Transducer, Millar Instruments, Houston, Texas). A similar central venous catheter was placed in the right external jugular vein. All animals were treated with heparin bolus (100 units/kg intravenous) once catheters were in place. During the preparatory phase, animals were ventilated with room air, using a volume-control ventilator (Harvard Apparatus, Dover, Massachusetts), with the tidal volume of 12 mL/kg and rate adjusted to maintain an arterial CO_2 at 40 mm Hg and P_{aO_2} of $>$ 80 mm Hg (oxygen saturation $>$ 95%), based upon analysis of arterial blood gases (IL Synthesis, Instrumentation Laboratory, Lexington, Massachusetts). Electrocardiographic monitoring was recorded continuously. Intratracheal pressure (ITP) was measured continuously, using a micromanometer-tipped catheter positioned 2 cm above the carina. All data were recorded by a digital system (SuperScope II vl.295, GW Instruments, Somerville, Massachusetts) and a Power Macintosh G3 computer (Apple Computer, Cupertino, California). End-tidal CO_2 (P_{ETCO_2}) was measured with a commercial monitor (CO_2SMO Plus, Novametrix Medical Systems, Wallingford, Connecticut).

All the pressures (aortic, right atrial, intratracheal, intracranial, coronary perfusion and cerebral perfusion pressure) were analyzed as follows: (i) the mean values during 4 compression-decompression cycles when ventilations were being delivered, beginning with the onset of the rescuer-assisted positive-pressure ventilation (Fig. 1, line A), and (ii) mean values over a minute. Mean values over 1 min were calculated as follows: electronic data (sampling rate 100/s) from all the measured variables of each animal, from minutes 7 and 10 of CPR, were transferred to a Microsoft Excel (Microsoft, Redmond, Washington) file. Data were averaged to give the mean value over 1 min for each animal. The first measurement (i) is reported as "during ventilation," and the second (ii) as the "mean value over 1 min" during the 15:1 and 15:2 interventions. Electronic data of the ITP for 1 min (minutes 7 and 10 of CPR) were sampled at a rate of 100/s. The ITP area over 1 min was calculated as the integral of ITP over time from 0 to 60 s. The integral ($_0\int^{60}$ Pdt) was calculated by the rim and sum method, representing the minute area under the curve. Minute area ITP was measured in mm Hg · s. Coronary perfusion pressure during CPR was calculated as the difference between the diastolic (decompression phase) aortic pressure and right atrial pressure. ICP was also measured as the area under the curve, as described above (integration, rim and sum method) during the 4 compression-decompression cycles during the positive-pressure ventilations (area ICP). Cerebral perfusion pressure was calculated as the difference between the mean values of aortic pressure and ICP using the mean values over 1 min of our electronic aortic and ICP tracings.

Experimental Protocol

Once the surgical preparations were completed, oxygen saturation was $>$ 90% and P_{ETCO_2} stable between 35–42 mm Hg for 5 min, ventricular fibrillation was induced by delivering direct electrical current via a temporary pacing wire (Daig Division, St Jude Medical, Minnetonka, Minnesota) positioned in the right ventricle. At that time a computer-generated randomization list was used to determine the sequence of the interventions. Once ventricular fibrillation was induced, the ventilator was disconnected from the endotracheal tube and the dose of propofol was reduced to 120 μg/kg/min. After 4 min of untreated ventricular fibrillation, closed-chest standard CPR was performed with a pneumatically driven automatic piston device (Pneumatic Compression Controller, AMBU International, Glostrup, Denmark). The compression rate was 100 compressions/min, uninterrupted, with a 50% duty cycle, and a depth of 25% of the anterior-posterior diameter of the chest wall. The chest wall was allowed to recoil passively and completely as the compression piston was actively pulled upward 0.5 cm off the chest after each compression. Pressure-controlled ventilation was performed with a semi-automatic ventilator (demand valve model L063–05R, Life Support Products, Irvine, California), using 100% oxygen at a constant flow rate (60 L/min). Approximately 400 mL were delivered with each breath (12 mL/kg). Peak airway cut-off pressure was set at 40 mm Hg. Propofol was decreased to 120 μg/kg/min after induction of ventricular fibrillation and during CPR. If return of spontaneous circulation occurred after shocks

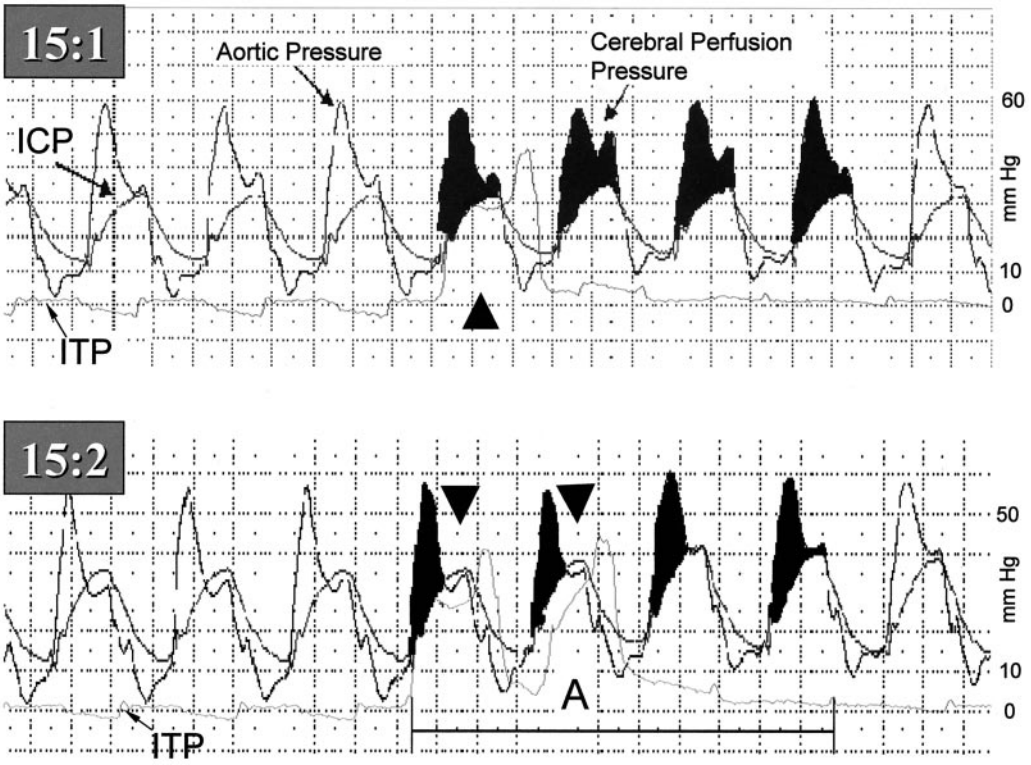

Fig. 1. Representative real-time tracings from a single animal during 15:1 and 15:2 compression-to-ventilation ratios. Aortic pressure and intracranial pressure (ICP) are shown, as well as intratracheal pressure (ITP) at the level of the carina. Black areas represent cerebral perfusion pressure areas. Notice the significant decrease of the area when, instead of one, two breaths are delivered. There is an increase of ICP with positive-pressure ventilation, and it is more pronounced with the 15:2 ratio. Arrowheads show time of positive-pressure breaths. Line A shows where the measurements were made "during the ventilations."

were delivered, it was increased up again to 160 μg/min/kg.

By using 4 min of untreated ventricular fibrillation followed by CPR, we attempted to model clinical practice in many communities. For example, in many cities the 911-to-basic-life-support arrival at the scene time is around 4 min. Once at the patient's side, basic-life-support providers often use 100% oxygen, as used in this protocol. Moreover, after several minutes of CPR, defibrillation is performed. It is important to note that we did not attempt to recreate a model of bystander CPR, as bystander CPR is rarely performed in most cases of out-of-hospital cardiac arrest.

The C/V ratio was randomized so that 4 animals received 15:2 for 4 min, 15:2 for 3 min, and 15:1 for another 3 min, and another 4 animals received 15:2, 15:1, and 15:2 for the same time intervals as the previous group (timeline, Fig. 2). The comparison of the 2 different interventions was done after pooling all values for each specific C/V ratio (15:1 and 15:2) from the 8 animals (4 animals at minute 7 and 4 animals at minute 10 of CPR) and then calculating the mean values for each ratio, as shown on the timeline. With this approach, sequence effects and potential changes in key variables over time were minimized.

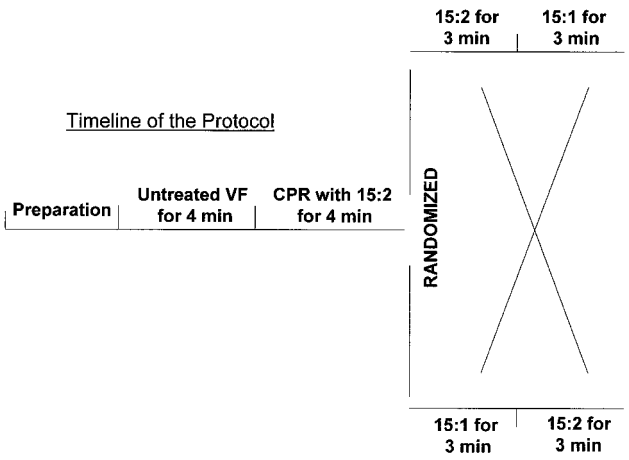

Fig. 2. Protocol timeline. VF = ventricular fibrillation. CPR = cardiopulmonary resuscitation.

CPR was performed continuously for 10 min. Aortic pressure, right atrial pressure, ICP, intratracheal pressure, P_{ETCO_2}, and O_2 saturation were measured continuously. Arterial blood gases were sampled before ventricular fibrillation was induced, immediately before initiation of CPR, and at the end of each intervention, at minutes 3.5,

Table 1. Hemodynamic Variables and Vital Organ Perfusion Pressures With 15:1 Versus 15:2 Compression/Ventilation Ratios

Minute Intratracheal Pressure Area	15:1 Compression/Ventilation Ratio		15:2 Compression/Ventilation Ratio	
	22.3 ± 10 mm Hg × s†		55 ± 17 mm Hg × s†	
	4 Cycles During Ventilation (mean ± SEM mm Hg)	Mean Value Over 1 Min (mean ± SEM mm Hg/min)	4 Cycles During Ventilation (mean ± SEM mm Hg)	Mean Value Over 1 Min (mean ± SEM mm Hg/min)
Intratracheal pressure (mm Hg)	11.1 ± 1.4‡	0.3 ± 0.28*	23.7 ± 2.2‡	0.93 ± 0.3*
Systolic aortic pressure (mm Hg)	56.5 ± 3.8	56.3 ± 5.1*	52.5 ± 3.3	50.7 ± 4.8*
Mean arterial pressure (mm Hg)	39.4 ± 3	40.2 ± 3.6*	35.3 ± 2.8	33.1 ± 3.7*
Diastolic aortic pressure (mm Hg)	22.4 ± 2.8	24.2 ± 2.4*	18.1 ± 3	15.5 ± 3.5*
Diastolic right atrial pressure (mm Hg)	7.2 ± 0.9‡	4.8 ± 1*	8.6 ± 1‡	5.8 ± 0.8*
Coronary perfusion pressure (mm Hg)	15.2 ± 3.2‡	19.3 ± 3.2*	9.5 ± 3.8‡	10.1 ± 4.5*
Mean intracranial pressure (mm Hg)	27.1 ± 2	25.7 ± 2.7	28.2 ± 2	25.4 ± 2.7
Cerebral perfusion pressure (mm Hg)	12.3 ± 4.5‡	14.5 ± 5.5*	7.2 ± 4.6‡	7.7 ± 6.2*

The symbols †, ‡, and * represent statistical significance between values of the same row, with a p value < 0.05.

6.5, and 9.5 of CPR. At the end of 10 min of CPR, animals were defibrillated with a biphasic defibrillator (M Series, Zoll, Chelmsford, Massachusetts), starting at 120 J × 3. If ventricular fibrillation persisted, epinephrine was administered at a dose of 45 μg/kg, and then 3 more shocks (120 J) were delivered. If ventricular fibrillation still persisted, all resuscitation efforts were terminated. When resuscitation was successful, animals were again ventilated with a positive-pressure-cycle Harvard ventilator at a rate of 12 breaths/min with a tidal volume of 15 mL/kg. No further interventions were performed after restoration of spontaneous circulation. At the end of the protocol, after 15 min of observation, the animals were sacrificed, using an intravenous bolus of propofol 60 mg and then 10 M KCl.

Statistical Analysis

Values are expressed as mean ± SEM. The primary end points were coronary and cerebral perfusion pressure and intratracheal pressure. Additional measurements included mean arterial pressures, ICP, arterial oxygen saturation, and P_{aO_2}. A paired *t* test was used to determine statistical significance between different interventions. A p value of < 0.05 was considered statistically significant.

Results

Decreasing the number of positive-pressure ventilations delivered during CPR from 12 to 6 per minute significantly decreased ITP and improved hemodynamics. With C/V ratio increased from 15:2 to 15:1, mean ITP values during positive-pressure ventilations (4 compression-decompression cycles) decreased from 23.7 ± 2.7 mm Hg to 11.1 ± 1.4 mm Hg, p = 0.001. Mean ITP values over 1 min were also decreased significantly, from 0.93 ± 0.3 mm Hg to 0.3 ± 0.28 mm Hg, p = 0.001 (Table 1). The changes were echoed with the calculations of the ITP area over 1 min, which decreased from 55 ± 17 mm Hg · s with 15:2 to 22.3 ± 10 mm Hg · s with 15:1, $p < 0.001$.

Arterial pressures were significantly improved by increasing the ratio from 15:2 to 15:1, as seen by the increase in the arterial systolic and diastolic pressure (see Table 1). The impact on diastolic pressure was notable; diastolic blood pressures were 15.5 ± 3.5 mm Hg with the 15:2 ratio and 24.2 ± 2.4 mm Hg with 15:1, p = 0.001. Thus, the impact of the extra breath resulted in a downstream decrease in diastolic pressure throughout the entire duration of CPR.

Mean coronary perfusion pressure over 1 min increased from 10.1 ± 4.5 mm Hg to 19.3 ± 3.2 mm Hg, p = 0.007. The same effect was also observed during the delivery of positive-pressure breaths (see Table 1). Mean diastolic right atrial pressure over 1 min with the 15:2 ratio was significantly higher, when compared to the 15:1 ratio: 5.8 ± 0.8 mm Hg versus 4.8 ± 1 mm Hg, p = 0.05. Similarly, the right atrial diastolic pressures were 8.6 ± 1 mm Hg and 7.2 ± 0.9 mm Hg with the 15:2 and 15:1 ratios, respectively, p = 0.03 (see Table 1).

ICP was not different between the 2 C/V ratios when calculated over each minute. However, a significant increase in the total ICP area was observed during the time when the positive ventilations were delivered: ICP area was 25.4 ± 1.9 mm Hg · s with 15:1 and 27 ± 1.8 mm Hg · s with 15:2, p = 0.05. Moreover, the combination of higher mean arterial pressure and stable or slightly decreased ICP resulted in a higher cerebral perfusion pressure with 15:1 C/V ratio. Mean coronary perfusion pressure over 1 min increased from 7.7 ± 6.2 mm Hg with 15:2 to 14.5 ± 5.5 mm Hg with 15:1, p = 0.008 (see Table 1 and Fig. 3).

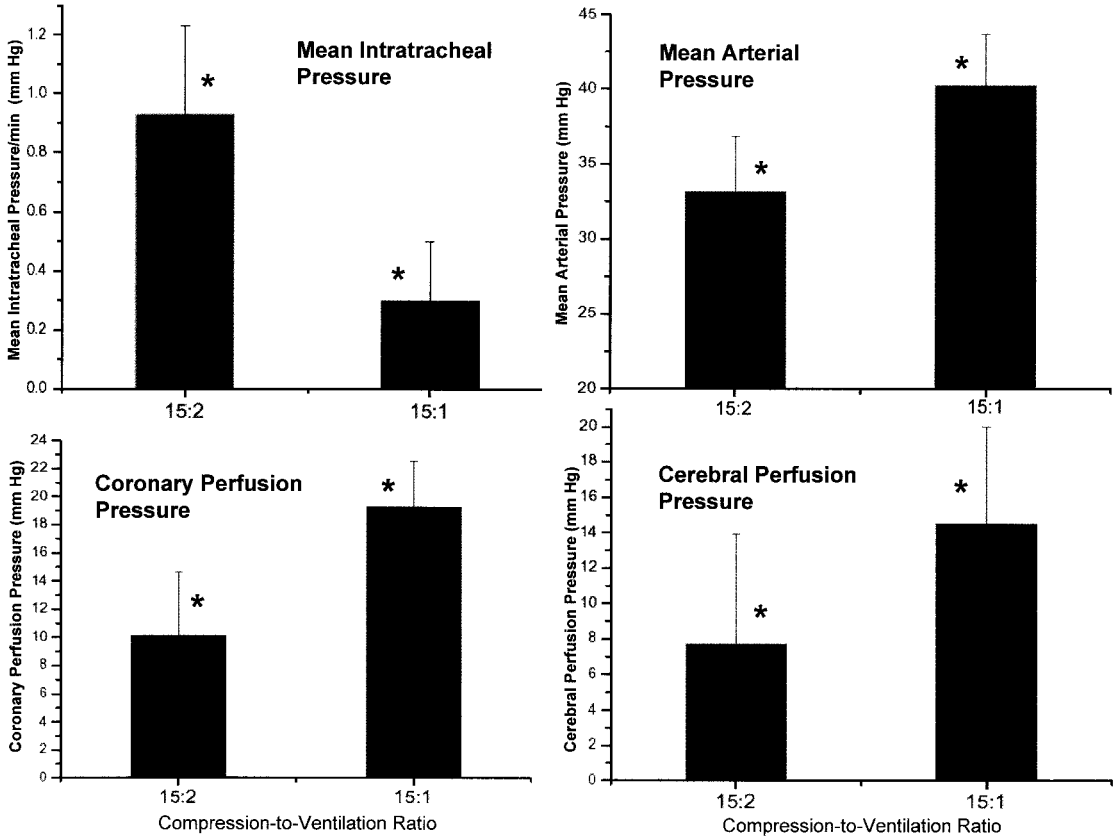

Fig. 3. Differences between 15:1 and 15:2 compression-to-ventilation ratio in mean intratracheal pressure over 1 min (surrogate for intrathoracic pressure), mean arterial pressure, coronary perfusion pressure, and cerebral perfusion pressure. There was an inverse relation between intratracheal pressure and vital-organ perfusion pressures. * $p < 0.01$.

Table 2. Arterial Blood Gas and End-Tidal Carbon Dioxide Values

	Baseline	15:1 C/V Ratio (mean ± SEM)	15:2 C/V Ratio (mean ± SEM)
pH	7.4 ± 0.03	7.3 ± 0.03	7.28 ± 0.03
P_{aCO_2} (mm Hg)	39 ± 2.1	37.6 ± 3.5	37.7 ± 2.9
P_{aO_2} (mm Hg)	98 ± 1	303 ± 51	274 ± 36
P_{ETCO_2} (mm Hg)	38.4 ± 2	29 ± 2.5*	24 ± 3.6*

C/V = compression/ventilation
P_{ETCO_2} = end-tidal carbon dioxide
The symbol * represents statistical significance between values of the same row, with a p value < 0.05.

Arterial blood gas values were not influenced by the different C/V ratios, and oxygenation was always observed to be adequate, with both C/V ratios (Table 2). There was a significant increase in P_{ETCO_2} with the 15:1 intervention, from 24 ± 3.6 mm Hg to 29 ± 2.5 mm Hg, $p < 0.001$.

A total of 6 out of 8 animals returned to spontaneous circulation after delivery of an average of 3 ± 0.5 shocks. Four animals received epinephrine, as was predetermined by the protocol. Two of those animals were not resuscitated after a total of 6 shocks. There were no differences in resuscitation outcomes between the animals that ended with the 15:1 intervention versus those that ended with the 15:2, in the number of delivered shocks, epinephrine requirements, or the number of animals successfully resuscitated (three fourths in each group).

Discussion

The results demonstrated that a reduction in the ventilation frequency, by increasing the C/V ratio from 15:2 to 15:1, improved hemodynamics and vital-organ perfusion pressures without compromising oxygenation and acid-base balance. These findings are consistent with previous observations demonstrating that there is an inverse relationship between intrathoracic pressure and coronary perfusion pressure and survival during cardiac arrest treated with CPR.[10,11]

Aortic pressure increased with a reduction in the ventilation frequency. This increase is due, in large part, to lower intrathoracic pressure, as evidenced by both the lower intratracheal and the diastolic right atrial pressure. Lower mean intratracheal pressure, an intrathoracic pressure surrogate, results in a more efficient coupling between the

thoracic pump output generated by the compression force and the venous return input to the chest, leading to improved hemodynamics. These effects last over the ventilation cycle and extend into the compression-decompression cycles between ventilations. The improvement in hemodynamics during the ventilation cycles with the 15:1 ratio persisted between positive-pressure ventilations, as it can be seen by the improvement of the mean values over 1 min of all the hemodynamic variables. The finding that diastolic blood pressure is reduced throughout the entire period of CPR when the 15:2 ratio is used, is analogous to automobile traffic flow patterns. Inhibition of venous return by the additional breath resulted in a substantial and persistent downstream effect manifesting as a decrease in diastolic pressures. Like traffic speed, which can take a substantial amount of time to recover from the slowing of a single automobile, the diastolic blood pressures never recovered between breaths. The impact of this single additional breath is remarkable and provides further strong support for decreasing the number of individual breaths delivered during CPR per minute.

These results support the contention that a persistent elevation in intrathoracic pressure is the major physiologic factor resulting in the increased coronary and cerebral perfusion pressure gradients. Two consecutively delivered breaths have a similar effect on hemodynamics to the intermittent discontinuation of chest compressions during CPR. In both situations there is a disruption of continuous blood flow and suboptimal generation of vital-organ perfusion pressures.[8] As such, we believe that these results may have important clinical implications.

A direct relation between intrathoracic pressure and ICP was observed in this study.[12] We observed that there was a direct and immediate transfer of the increase and decrease in intrathoracic pressure to the cranial cavity with each positive-pressure ventilation. This was particularly pronounced when positive-pressure ventilation was delivered simultaneously with each chest compression. Most importantly, with a 15:1 C/V ratio, ICP returned to the pre-breath level after 1–2 compression-decompression cycles, but with 15:2 the time required for the ICP to return to pre-breath levels doubled, thereby reducing the cerebral perfusion pressure. This observation was made in all the animals. The increase in ICP was best quantified by calculating ICP as the integral (area measurement) of the ICP over time, as seen in Figure 1. The mean ICP area was lower in the 15:1 C/V group. The lower mean arterial pressure in combination with the higher ICP observed with the 15:2 ratio underlie the lower cerebral perfusion pressures, when compared with the 15:1 ratio. This finding, that there was a direct correlation between the rise of ICP following an increase in intrathoracic pressure in CPR, is consistent with the work of Guerci et al, who have shown that the transfer of pressure to the brain is mediated, at least in part, by the cerebrospinal fluid and the nonvalvular spinal cord veins.[13] In our study each positive-pressure breath increased intrathoracic pressure and thus ICP, together and in addition to the increase in ICP produced by each CPR chest compression.

By decreasing the number of delivered breaths by 50%, oxygenation remained adequate and acid-base balance remained unaltered. Pseudo-respiratory-alkalosis is a persistent finding in the arterial blood gases of very-low-cardiac-output states when the red blood cell alveolar-capillary transit time is prolonged.[14] In the current study, 2 consecutive breaths, delivered closely together in time, had no additional beneficial effect on gas exchange: the delivery of 100% oxygen with the first breath saturated the lung alveoli, and the diminished blood flow caused the hemoglobin to become fully saturated during the first pass of red cells through the alveolar capillaries. In addition, CO_2 elimination is continuous during CPR where air is expelled during the compressions, and, then, to some degree, passively inhaled during the elastic recoil of the chest wall, assuming that the airway is open. There is a relative increase in the ventilation-to-perfusion ratio during CPR.[14–16] During CPR, pulmonary blood flow is reduced and the transit time through the lungs is prolonged. Thus, CO_2 removal from the pulmonary circulation during CPR is enhanced, resulting in a decrease in partial pressure of arterial CO_2, but the total amount of CO_2 removed from the body is reduced as a result of the overall decreased pulmonary blood flow. This, in turn, causes severe venous hypercapnic acidemia, as previously described by Weil et al.[15] Thus, the elimination of CO_2 is limited by the total amount of pulmonary blood flow during CPR, and there is no additional CO_2 exchange by delivering 2 consecutive breaths instead of one.

The results from this study demonstrate that by decreasing the number of breaths delivered during CPR, coronary and cerebral perfusion pressures are increased. The significant increase in P_{ETCO_2}, with no concomitant change in the P_{aCO_2} with the 15:1 ratio, suggests an increase in pulmonary blood flow (ie, better cardiac output and circulatory blood volume). Increased P_{ETCO_2} during CPR has been associated with increased survival and successful resuscitation.[17] Taken together, these results support the hypothesis that a 50% reduction in the number of ventilations improves blood flow during CPR. It is possible that by further increasing the ratio to, for example, 20:1 or 30:1, there may be further hemodynamic benefit. However, at some point the benefits of hypoventilation are outweighed by the generation of hypoxemia, hypercarbia, and acidosis.

An intravenous anesthetic was specifically used in the current investigation to maintain a continuously adequate level of anesthesia through the study. The animals did not gasp spontaneously. Our experience is that spontaneous gasping is common with use of inhaled agents such as

isofluorane, as inhaled anesthetics cannot be delivered continuously when the positive-pressure ventilation is reduced or absent altogether.

This study has several limitations. Only 2 ratios were compared and all studies were done in healthy farm pigs. Further studies are needed to determine if the hemodynamic benefits associated with the 15:1 C/V ratio will benefit animals by improving rates of resuscitation, survival, and neurological status. Surrogates, rather than direct blood flow to vital organs, were measured. Based upon our prior studies, the calculated increases in coronary and cerebral perfusion pressures often grossly underestimate the true perfusion impact of changes in intrathoracic pressure.[18,19] In our study we controlled only one of the several variables that can influence the intrathoracic pressure (number of ventilations). We believe that similar benefits may be observed by delivering smaller tidal volumes or by using lower positive pressures to deliver the breaths. Furthermore, because of prolonged time of CPR (10 min), the study design and the analysis of the data (minutes 7 and 10 were analyzed) most likely overstated the differences in hemodynamics. Finally, we did not measure pulmonary capillary blood flow, which may have been decreased by increased alveolar pressures. We speculate that increased resistance at the level of pulmonary capillary blood flow may contribute to the harmful effects of the additional breath associated with the 15:2 C/V ratio.

Conclusions

Increasing the C/V ratio from 15:2 to 15:1 decreases mean intratracheal pressure, improves systolic and diastolic aortic pressures, augments cerebral and coronary perfusion pressures, and does not compromise oxygenation and acid-base balance in a porcine model of cardiac arrest. A 15:1 C/V ratio is simple, safe, and better than 15:2, and warrants further research and evaluation in animals and humans.

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