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Cardiopulmonary Resuscitation

Effect of CPAP on Gas Exchange during Chest Compressions

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Background: **Conventional cardiopulmonary resuscitation (CPR) includes 80–100/min precordial compressions with intermittent positive pressure ventilation (IPPV) after every fifth compression. To prevent gastric insufflation, chest compressions are held during IPPV if the patient is not intubated. Elimination of IPPV would simplify CPR and might offer physiologic advantages, but compression-induced ventilation without IPPV has been shown to result in hypercapnia. The authors hypothesized that application of continuous positive airway pressure (CPAP) might increase CO_2 elimination during chest compressions.**

Methods: **After appropriate instrumentation and measurement of baseline data, ventricular fibrillation was induced in 18 pigs. Conventional CPR was performed as a control (CPR_C) for 5 min. Pauses were then discontinued, and animals were assigned randomly to receive alternate trials of uninterrupted chest compressions at a rate of 80/min without IPPV, either at atmospheric airway pressure (CPR_{ATM}) or with CPAP (CPR_{CPAP}). CPAP was adjusted to produce a minute ventilation of 75% of the animal's baseline ventilation. Data were summarized as mean ± SD and compared with Student *t* test for paired observations.**

Results: **During CPR without IPPV, CPAP decreased Pa_{CO_2} (55 ± 28 *vs.* 100 ± 16 mmHg) and increased Sa_{O_2} (0.86 ± 0.19 *vs.* 0.50 ± 0.18%; $P < 0.001$). CPAP also increased arteriovenous oxygen content difference (10.7 ± 3.1 *vs.* 5.5 ± 2.3 ml/dl blood) and CO_2 elimination (120 ± 20 *vs.* 12 ± 20 ml/min; $P < 0.01$). Differences between CPR_{CPAP} and CPR_{ATM} in aortic blood pressure, cardiac output, and stroke volume were not significant.**

Conclusions: **Mechanical ventilation may not be necessary during CPR as long as CPAP is applied. Discontinuation of IPPV will simplify CPR and may offer physiologic advantage. (Key words: Artificial circulation; artificial ventilation; CPR; continuous positive airway pressure.)**

RECOMMENDATIONS by the American Heart Association for cardiopulmonary resuscitation (CPR) of an unintubated patient performed by two rescuers include precordial compressions at a rate between 80–100/min with a 1.5- to 2.0-s pause after every five compressions to allow sufficient time for intermittent positive pressure ventilation (IPPV).[1] Suspension of chest compressions during the delivery of IPPV is indicated to avoid high inflation pressures and to reduce the risk of gastric inflation and subsequent aspiration. IPPV is performed asynchronously during advanced life support without interruption to chest compression. Elimination of IPPV during CPR would simplify the process, and it might also improve outcome by making uninterrupted chest compressions possible during basic life support.[2,3]

There are conflicting reports regarding the efficiency of ventilation effected by precordial compression during CPR without mechanical ventilation. Some investigators have proposed that compression-induced ventilation and gasping may cause adequate pulmonary gas exchange and obviate the necessity for IPPV during CPR.[4–11] However, over time, compression-induced ventilation and gasping alone lead to a decline in minute ventilation, hypercapnia, and acidosis.[12–15]

We hypothesized that application of a continuous positive airway pressure (CPAP) would increase the CO_2 elimination produced by precordial compressions.

Methods

Animal Preparation

The study protocol was approved by the Institutional Animal Use and Care Committee. Animals were treated according to the recommendations of the Declaration of Helsinki.[16] Eighteen pigs (23 ± 2 kg) were anesthetized

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with ketamine hydrochloride (25 mg/kg) by intramuscular injection followed by an intravenous injection (15 mg/kg) and infusion (during instrumentation, 45 mg · kg^{-1} · h^{-1}, and after instrumentation, 30 mg · kg^{-1} · h^{-1}). Neuromuscular blocking agents were not used so that gasping during the investigational procedure was permitted. Subcutaneous needle electrodes were placed to monitor the electrocardiogram. The trachea was intubated through a tracheotomy. The injection port of the modified tracheal tube (EMT Tracheal Tube #85592, Mallinckrodt Anesthesiology Division, St. Louis, MO) was connected to a calibrated pressure transducer for airway pressure (P_{aw}) measurement. A 16-gauge catheter was inserted into the left hemithorax at the midaxillary level as described by Downs[17] for pleural pressure (P_{pl}) measurement. A 7.5-French, thermistor-tipped catheter was inserted into the right internal jugular vein and advanced into a main pulmonary artery. A separate polyethylene catheter was placed alongside to measure central venous pressure. Another catheter was inserted into the left carotid artery and advanced into the descending aorta. All lines were hydraulically linked to separate pressure transducers.

Measurements and Calculations

Aortic, pulmonary artery, central venous, airway, and pleural pressures were recorded on a polygraph (Gould TA 2000, Gould Electronics, Orlando, FL) for at least 10 consecutive cardiac cycles or precordial compressions. Cardiac output was determined in triplicate with a thermodilution technique. Aortic and pulmonary artery blood were sampled in duplicate to measure respiratory gas tensions and *p*H with the appropriate electrodes (IL 1301, Instrumentation Laboratories, Lexington, MA). Hemoglobin concentration and oxyhemoglobin saturation were assayed spectrophotometrically (Co-oximeter IL 282, Instrumentation Laboratories). Then, a computer program developed by Ruiz *et al.*[18] was used to convert oxyhemoglobin saturation values to reflect the oxygen-combining characteristics of adult pig hemoglobin.[19] Oxygen utilization coefficient was quantified as the quotient of the difference in arterial and venous oxygen content divided by the arterial oxygen content [$C(a\text{-}\bar{v})O_2/Ca_{O_2}$].[20] Carbon dioxide elimination ($\dot{V}CO_2$, STPD) was calculated from minute ventilation ($\dot{V}_E$) and CO_2 concentration in mixed exhaled gas. Transpulmonary pressure (P_L) was calculated as the difference between airway and pleural pressures. Expired gas volume (BTPS) was measured with a waterseal spirometer (Warren Collins Inc., Braintree, MA). Accuracy of the spirometer was confirmed with sequential volume injections from a calibrated super-syringe (Hamilton Medical, Reno, NV) and a stop-watch.

Investigative Procedures

Baseline data were recorded 30 min after instrumentation when animals were stable. Ventricular fibrillation was induced with a transthoracic electric shock of 400 J. Two minutes later, animals underwent conventional CPR (CPR_C), including a 1.5-s pause after every fifth compression for IPPV and an intravenous infusion of phenylephrine (40 mg · kg^{-1} · min^{-1}).[21] One hundred percent oxygen was supplied with a tidal volume of 12 ml/kg during IPPV. Precordial compression force was adjusted to produce a sternal depression of 4 cm 80/min (Programmable Thumper,[7] model 1016, Michigan Instruments Inc., Grand Rapids, MI). A compression–relaxation ratio of 1:1 resulted in a 0.225-s compression. Data were collected 5 min later. Then, mechanical ventilation was discontinued, and animals were assigned randomly to receive alternate trials of uninterrupted compressions at atmospheric pressure (CPR_{ATM}) and CPAP (CPR_{CPAP}) for 5 min each with 100% oxygen. Compression was extended to 0.375 s to maintain 80 compressions per minute with a compression-to-decompression ratio of 1:1. The level of CPAP (Evita, North-American Drager, Chantilly, VA) was set to 15 cm H_2O initially and adjusted during the first minute of CPR_{CPAP} to produce ventilation equal to 75% of the animal's measured spontaneous minute ventilation. Data were collected at the completion of each 5-min trial.

Statistical Assessments

Data were summarized as mean ± SD. To assess the possibility of a treatment-period interaction, we applied Student *t* test for independent observations to compare the differences between the two treatment sequences. We found no significant treatment-period interaction. Therefore, response variables obtained during CPR_{ATM} and CPR_{CPAP} were compared with Student *t* test for paired observations. Statistical assessments were performed using SigmaStat software (Version 2.0, Jandel Scientific, San Rafael, CA).

Results

Variables reflecting pulmonary mechanics, gas exchange, and cardiovascular function during baseline and the various treatment trials are summarized in tables 1

Table 1. Variables Reflecting Pulmonary Mechanics and Gas Exchange during Normal Spontaneous Breathing (Baseline) and during Ventricular Fibrillation and Conventional CPR, with Intermittent Positive Pressure Ventilation, and CPR at Atmospheric Pressure (CPR_{ATM}) and with CPAP (CPR_{CPAP})

	Baseline	Conventional CPR	CPR_{ATM}	CPR_{CPAP}
Minute ventilation (L/min)	10.0 ± 3.0	4.7 ± 1.1	0.69 ± 0.90	7.57 ± 2.7*
Gasping (L/min)	NA	NA	0.43 ± 0.81	0.10 ± 0.20
Airway pressure (cmH_2O)				
Inspiration	−3 ± 3	18 ± 4	NA	NA
Exhalation/compression	7 ± 3	8 ± 4	9 ± 7	26 ± 6*
Relaxation	NA	−2 ± 2	0 ± 4	16 ± 6*
Pleural pressure (cmH_2O)				
Inspiration	−3 ± 4	10 ± 6	NA	NA
Exhalation/compression	6 ± 3	15 ± 7	17 ± 9	28 ± 11*
Relaxation	NA	1 ± 6	1 ± 6	7 ± 7*
Transpulmonary pressure (cmH_2O)				
Inspiration	7 ± 3	8 ± 4	NA	NA
Exhalation/compression	−3 ± 3	−2 ± 2	−7 ± 11	−3 ± 12
Relaxation	NA	NA	−1 ± 5	8 ± 7*
Change	10 ± 3	10 ± 4	6 ± 11	11 ± 15
Pa_{CO_2} (mmHg)	51 ± 9	44 ± 6	100 ± 16	55 ± 28*
Sa_{O_2} (%)	97 ± 1	92 ± 7	50 ± 18	86 ± 19*
*p*Ha	7.37 ± 0.08	7.30 ± 0.08	6.2 ± 2.0	7.14 ± 0.17*
$P\bar{v}_{CO_2}$ (mmHg)	60 ± 10	84 ± 12	106 ± 9	93 ± 16*
$S\bar{v}_{O_2}$ (%)	77 ± 7	10 ± 5	6.2 ± 2.0	13.8 ± 9.2*
*p*H$\bar{v}$	7.33 ± 0.07	7.12 ± 0.08	6.95 ± 0.04	6.99 ± 0.10
$C(a\text{-}\bar{v})_{O_2}$ (mL/dl)	2.5 ± 0.9	11.7 ± 2.0	5.5 ± 2.3	10.7 ± 3.1*
$C(a\text{-}\bar{v})_{O_2}/Ca_{O_2}$ (ml/dl)	0.21 ± 0.07	0.89 ± 0.06	0.84 ± 0.12	0.83 ± 0.13
$\dot{V}_{CO_2}$ (STP, ml/min)	203 ± 70	80 ± 22	12 ± 20	120 ± 47*

Data are mean ± SD.

NA = not applicable.

* $P < 0.05$ *versus* CPR_{ATM}.

and 2. Data reflecting cardiopulmonary function during CPR_C were not compared with CPR_{ATM} and CPR_{CPAP} because CPR_C was always the first treatment and was followed by CPR_{ATM} and CPR_{CPAP} in random order. Thus, the effects of time-related decompensation in cardiopulmonary function could not be controlled for comparisons with CPR_C.

Ventilation that resulted from gasping was not significantly different between CPR_{ATM} and CPR_{CPAP}. Application of CPAP increased airway and pleural pressures,

Table 2. Variables Reflecting Cardiovascular Function during Normal Spontaneous Breathing (Baseline) and during Ventricular Fibrillation and Conventional CPR, with Intermittent Positive Pressure Ventilation, and CPR at Atmospheric Pressure (CPR_{ATM}) and with CPAP (CPR_{CPAP})

	Baseline	Conventional CPR	CPR_{ATM}	CPR_{CPAP}
Cardiac output (L/min)	4.72 ± 0.98	0.75 ± 0.16	0.63 ± 0.22	0.63 ± 0.30
Stroke volume (ml)	31 ± 7	9 ± 2	8 ± 3	8 ± 4
Aortic blood pressure (mmHg)				
Systolic/compression	123 ± 12	76 ± 21	72 ± 44	64 ± 30
Diastolic/relaxation	91 ± 9	27 ± 58	7 ± 11	13 ± 11
Central venous pressure (mmHg)				
Systolic/compression	10 ± 2	86 ± 26	100 ± 42	80 ± 33
Diastolic/relaxation	4 ± 2	16 ± 3	14 ± 5	16 ± 7
Pulmonary artery pressure (mmHg)				
Systolic/compression	30 ± 7	83 ± 22	99 ± 40	96 ± 41
Diastolic/relaxation	12 ± 7	20 ± 7	21 ± 8	21 ± 10

Data are mean ± SD.

which were increased further during chest compression ($P < 0.001$). P_L, during the relaxation phase, was higher during CPR_{CPAP} than CPR_{ATM} ($P < 0.001$). The change in P_L during the compression–relaxation cycle (ΔP_L) was not different between CPR_{CPAP} and CPR_{ATM}. CPR_{CPAP} increased Sa_{O_2} and $S\bar{v}_{O_2}$ and decreased Pa_{CO_2} and $P\bar{v}_{CO_2}$ compared with CPR_{ATM} ($P < 0.05$). CPR_{CPAP} increased the arterial O_2 content and $C(a\text{-}\bar{v})O_2$ ($P < 0.05$) but not the oxygen utilization coefficient compared with CPR_{ATM}. CPR_{CPAP} produced a significantly higher CO_2 elimination than CPR_{ATM} ($P < 0.001$). Arterial blood *p*H was significantly lower during CPR_{ATM} than during CPR_{CPAP} ($P < 0.001$). Mixed venous blood *p*H was similar during the two treatments.

A significantly higher CPAP level was required (27.8 ± 8.7 cm H_2O) when CPR_{ATM} preceded CPR_{CPAP} than with the opposite order (18.9 ± 3.3 cm H_2O; $P < 0.02$). There were nine animals in each sequence group.

Cardiac output and stroke volume statistically were similar during CPR_{ATM} and CPR_{CPAP}. Aortic, pulmonary artery, and central venous blood pressures also were similar during both treatments.

Discussion

The modern era of advanced cardiac life support began with the concept that precordial compressions would produce adequate circulation until spontaneous cardiac activity was restored.[22] Today the goal of CPR is maintenance of adequate tissue perfusion with oxygenated blood and sufficient carbon dioxide elimination to maintain near physiologic *p*H until spontaneous circulation is reestablished. The currently accepted technique of closed cardiac massage and IPPV has changed minimally since first introduced in the 1960s.[23]

Several attempts have been made to improve ventilation during CPR. Ruben *et al.*[24] demonstrated that an airway pressure of more than 19 cm H_2O is likely to produce gastric inflation during ventilation with a mask. The initially recommended 0.5 s of inspiratory time after every five compressions was replaced by a 1.5- to 2-s pause during basic life support. This pause allows for a decreased inspiratory flow rate to decrease inspiratory airway pressure and the likelihood of gastric distension, regurgitation, and subsequent aspiration during two-rescuer CPR of unintubated patient.[25] Consequently a longer inspiratory time occurred at the expense of time spent delivering chest compressions to provide artificial circulation.

Improvement of circulation was the focus of several studies. Rudikoff *et al.*[26] observed an increase in carotid blood flow when intrathoracic pressure was increased during chest compression. Application of an abdominal binder was suggested by Chandra *et al.*[27] to increase intrathoracic pressure during precordial compressions. Similarly, simultaneous lung inflation and chest compression were recommended to increase stroke volume and blood pressure.[28] The technique of interposed abdominal compressions was developed by Coletti *et al.*[29] to increase cardiac filling and increase circulation during relaxation. None of these mechanisms has been incorporated in the recommended standard CPR guidelines because of their limited effect on the rate of successful resuscitation.

It has been suggested that agonal gasping of the subject and compression-induced ventilation might be adequate for gas exchange.[4–11] However, elimination of positive pressure breathing has been shown to produce arterial hypoxemia and hypercapnic acidosis.[12–15] We hypothesized that application of a CPAP during precordial compressions would increase CO_2 elimination and might provide adequate gas exchange, even without mechanical ventilation.

The animals were intubated to allow for continuous distal airway pressure measurement and eliminate individual differences in airway patency during CPR. Vasopressor infusion was used in our model to slow the rapid hemodynamic deterioration that is seen in untreated animals. Phenylephrine was chosen to avoid the deleterious effects of epinephrine on matching of ventilation and pulmonary perfusion.[21]

Application of CPAP increased P_{aw} and P_{pl} throughout the compression–relaxation cycle, but it did not increase ΔP_L compared with that observed during CPR_{ATM}. Thus, the higher tidal and minute ventilation recorded during CPR_{CPAP} resulted from increased respiratory system compliance. Increased ventilation improved CO_2 elimination and decreased Pa_{CO_2} and P_{CO_2} compared with CPR_{ATM}.

Assuming a decreased metabolic rate during cardiac arrest, CPAP was adjusted during CPR_{CPAP} to produce a ventilation equal to 75% of the animals measured spontaneous minute ventilation. $\dot{V}CO_2$ during CPR_{CPAP} was found to be about 60% of baseline. The predetermined minute volume during CPR_{CPAP} resulted in a Pa_{CO_2} similar to baseline, indicating that dead space ventilation was not dramatically increased even during cardiac arrest and CPR_{CPAP}. This finding contrasts greatly with values of $\dot{V}CO_2$, $\dot{V}_E$, and Pa_{CO_2} obtained during CPR_{ATM}. Despite low $\dot{V}CO_2$ (10% of CPR_{CPAP} value) and $\dot{V}_E$ (9% of

CPR_{CPAP} value), Pa_{CO_2} was higher during CPR_{ATM}, indicating much less efficient alveolar ventilation.

Continuous positive airway pressure decreased pulmonary venous admixture by an improved matching of ventilation and pulmonary perfusion.[30] Thus, this well-known effect of CPAP increased Sa_{O_2} and arterial O_2 content compared with that observed during CPR_{ATM}. Oxygen utilization coefficient was similarly high during CPR_{CPAP} and CPR_{ATM}. This finding, and the low $S\bar{v}O_2$ measured during both treatment periods, suggests a delivery limited oxygen consumption. Therefore, the increase in arterial oxygen content during CPR_{CPAP} permitted a marked increase in oxygen consumption, as reflected in a higher $C(a\text{-}\bar{v})O_2$. This finding may explain the significantly greater $\dot{V}CO_2$ observed during CPR_{CPAP} and likely is a reflection of increased aerobic metabolism. Clearly this interesting observation and speculation deserves further investigation.

Progressive metabolic acidosis was observed from the time of cardiac arrest throughout the resuscitation trials. As expected, *p*Ha and *p*H$\bar{v}$ were higher during CPR_C than during the other two trials because CPR_C was the first treatment mode in all the animals. Arterial acidemia was more profound during CPR_{ATM} than during CPR_{CPAP} caused by a greater degree of hypercapnia, resulting from relative hypoventilation during CPR_{ATM}.

Aortic, pulmonary artery, and central venous blood pressures and stroke volume and cardiac output were similar during CPR_{ATM} and CPR_{CPAP}. Aortic blood pressure during relaxation was significantly higher during CPR_C than during the two subsequent treatment trials. In addition to the progressive deterioration of the cardiovascular function, the duration of relaxation phase was significantly longer during CPR_{CPAP} and CPR_{ATM} than during CPR_C (0.375 *vs.* 0.225 s). Prolongation of the compression and relaxation duration was necessary to maintain a compression rate of 80/min during latter treatments. Had we compressed the animals' chest with the same duty cycle as that used during CPR_C, the rate of uninterrupted chest compression would have been increased, and aortic relaxation pressure might have been better sustained.

The authors acknowledge the questionable accuracy of the thermodilution technique and fluid-filled catheters for cardiac output and intravascular pressure measurement in such an extreme low-flow state, but the primary objective of the study was to evaluate the effect of CPAP on compression-induced ventilation and variables relevant to that. Similarly we used various invasive monitors, tracheal intubation, mechanical compression device, and vasopressor infusion, which are not part of standard basic life support, to create a reproducible model for measurements.

Further studies are needed to compare CPR_{CPAP} with standard basic and advanced CPR and to determine how uninterrupted chest compressions, with increased intrathoracic pressure, will affect cerebral blood flow, coronary perfusion, pulmonary and myocardial integrity, duration of viability, and incidence of successful conversion to spontaneous circulation. Additional studies are needed to define the appropriate level of CPAP, compression rate, and compression-to-decompression ratio.

Reevaluation of the need for tracheal intubation during advanced life support is also indicated. As long as the airway pressure is less than 19 cm H_2O during relaxation, elimination of the IPPV may decrease the incidence of gastric distention, regurgitation, and pulmonary aspiration during mask ventilation.[24] Pressure increases equally in the intrathoracic structures driven by the increased P_{pl} during compression; therefore, the P_{aw} is not likely to exceed the force compressing the esophagus, even with high P_{aw} that might be generated during chest compression. Based on these data, the CPAP level necessary to provide adequate gas exchange is likely to be lower if CPR_{CPAP} is applied early in the resuscitation process and is not preceded by conventional CPR or chest compressions at atmospheric pressure.

We observed that CPR_{CPAP} increased CO_2 elimination and arterial oxygen content compared with CPR_{ATM}. IPPV may not be necessary during CPR as long as continuous positive pressure is applied to the airway opening. Elimination of IPPV, as will occur when CPAP is applied to increase ventilation during chest compressions, could not only simplify CPR but also might improve outcome during basic life support by making uninterrupted chest compression possible.

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