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Phase-controlled intermittent intratracheal insufflation of oxygen during chest compression-active decompression mCPR improves coronary perfusion pressure over continuous insufflation

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Abstract

Purpose: It has previously been shown that continuous intratracheal insufflation of oxygen (CIO) is superior to intermittent positive pressure ventilation (IPPV) regarding gas exchange and haemodynamics. The purpose of this study was to investigate gas exchanged and haemodynamics with a new technique of phase-controlled intermittent insufflation of oxygen (PIIO) compared to CIO.

Method: Twenty (20) pigs were used, stratified into two groups (CIO, PIIO), with 10 animals each. Upon induction of ventricular fibrillation, standard ventilator support was replaced by either of CIO or PIIO ventilation. Chest compressions were delivered by the LUCAS I mCPR device. Following 20 min of CPR in normothermia, defibrillation was attempted.

Results: Return of spontaneous circulation (ROSC) occurrence was not significantly higher (P<0.16) in the PIIO (9/10) than in the CIO (6/10) group. During the decompression phase the PIIO group showed significant increases in mean (P<0.01), maximal (P<0.02) and end-decompression (P<0.01) coronary perfusion pressure (CPP), compared to the CIO group. PIIO resulted in increased compression phase aortic pressure (P<0.03). Intratracheal pressure was 5–30 cmH_2O within both groups during mCPR, with a significantly lower (P<0.02) mean for the PIIO group. Arterial and venous blood gas analysis showed comparable results between the groups, when taking base line values into account. An exception was that PIIO resulted in significantly higher (P<0.05) oxygen partial pressure during mCPR, and lower (P<0.05) arterial lactate following ROSC.

Conclusion: PIIO results in significantly higher CPP and compression phase aortic pressure during mCPR in a porcine population. Further studies are needed to validate these findings in humans.

Study protocol conforming with ethic approval M174-15, issued by the Malmö/Lunds regionala djurförsöksetiska nämnd (REB).

Keywords: Mechanical chest compression; Mechanical chest decompression; LUCAS; PIIO; CIO

Introduction

It has previously been shown that continuous intratracheal insufflation of oxygen (CIO) has haemodynamic benefits over intermittent positive pressure ventilation (IPPV), when co-administered with active-decompression mechanical cardiopulmonary resuscitation (mCPR) [3]. Specifically, CIO results in improved coronary perfusion pressure (CPP)—the difference between ascending aortic pressure (AP) and right atrial pressure (RAP) during the decompression phase[1], and the best known haemodynamic predictor of ROSC [2]. In the current study, CIO was compared to a novel ventilation regimen, based on the phase of the compression cycle, as outlined below under *Phase controlled insufflation of oxygen*, with the specific aim of facilitating CPP.

Synchronizing insufflation with the chest compression cycle has previously been reported in [4] and [5]. In [4] IPPV and bi-level ventilation were comparted to a regimen introduced as chest compression synchronized ventilation (CCSV). The comparison showed a slight (9 % mean) decrease in ROSC frequency, when using CCSV. Arterial oxygen partial pressure was significantly improved (140 % mean increase), as compared to IPPV. An increase (17 % mean) in mean aortic (arterial) pressure (MAP) during CPR was also reported, compared to IPPV. While increased MAP is desirable, the computation of MAP was performed as a true average over the compression cycle. The measure is hence affected by the AP during compression, and the presented data does not reveal how CPP differed between the ventilation regimens. The method studied in [5] resembles CCSV, in that insufflation flow is synchronized with the compressions. The reported porcine study featured an increase in CPP from 20±7 mmHg using manual ventilation to 25±9 mmHg using the better of two investigated synchronized gas delivery variants.

The novelty of the current work lies in the introduction of phase-controlled insufflation of oxygen (PIIO), being a phase shifted version of CCSV. The particular focus of this study was to compare the effects of CIO and PIIO on CPP during mCPR.

Methods

Phase controlled insufflation of oxygen

Herein, we introduce a variant of compression controlled synchronized ventilation – phase-controlled insufflation of oxygen (PIIO) – in which the onset of oxygen insufflation is phase shifted with respect to the active compression-decompression cycle, as illustrated in Fig. 1.

It was hypothesized, and verified through pilot experiments (data on file), that PIIO has two substantial benefits:

- Turning off oxygen insufflation prior to the active decompression results in a lower intratracheal pressure during the active decompression, facilitating right ventricular preload;
- Adding gas to the lungs prior to compression results in an increased pressure on the heart during the subsequent compression, facilitating cardiac output.

[1] Compression phase and decompression phase correspond to systole and diastole during CPR.

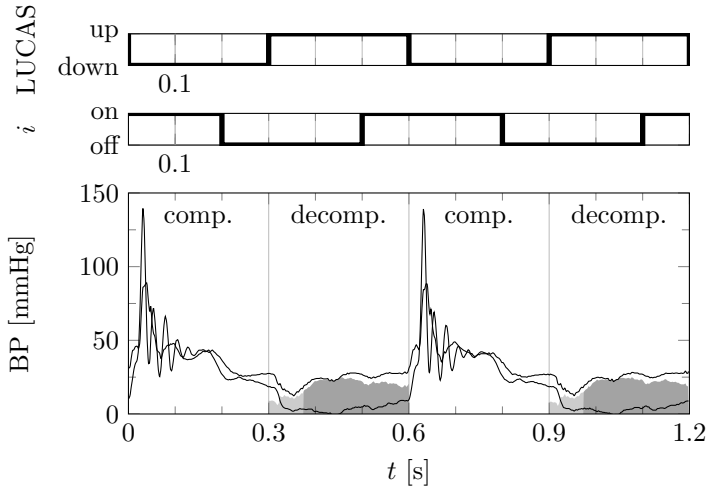

Figure 1 Top panel shows timing diagram for one compression cycle with phase-controlled intermittent intratracheal insufflation of oxygen (PIIO). Two full compression cycles are shown with phase shifted synchronization between the chest compression device (LUCAS) state and oxygen insufflation (*i*). Bottom panel shows resulting blood pressure (BP)—the right atrial pressure (RAP) and aortic pressure (AP) response from one of the study cases (solid lines); coronary perfusion pressure (CPP) during decompression (light grey); and CPP≥15 mmHg (dark grey).

The purpose of the phase shift is to take the dynamics of the lungs and thorax into account. There is a lag between start and stop of insufflation and the lungs reaching a corresponding steady state in terms of pressure and volume. The phase shift hence results in the compression downstroke occurring with the lungs near the steady state corresponding to CIO, and the decompression upstroke occurring with the lungs near the steady state corresponding to an open airway in absence of forced oxygen insufflation. During PIIO, oxygen was administered through an endotracheal (E.T.) tube of Boussignac type (Boussignac E.T. tube for cardiac arrest, VYGON Ecouen, France) with a 7.0 mm diameter main lumen. Oxygen is delivered through secondary lumina in the wall of the tube, giving an advantage over conventional intratracheal tubes in that the volume of the main lumen does not contribute to the anatomic dead space. The Boussignac tube has two additional capillary tubes. These can be used for drug administration into the trachea, or, as in this study, to measure intratracheal pressure.

A pressure regulator (Festo LRP-1, Festo, Esslingen am Neckar, Germany) was used in series with a 605 ml buffer tank to maintain a steady pressure driving the gas delivery. A direct valve (Festo MHE4, Festo, Esslingen am Neckar, Germany), with a switching time of 3.5 ms and nominal maximal flow of 400 l/min was used to gate oxygen insufflation. The pressure controller was set to 4.5 bar, being a common supply pressure in ambulances. This corresponded to an oxygen flow of 23 l/min into the Boussignac tube, as measured by rotameter (Medimeter-30, Mediline, Saint Helens, England), and a cease of gas flow through the tube if ambient (i.e. intratracheal) pressure exceed 20 cmH_20[2]. This is well below the plateau and peak airway pressures (PAP) of around 50 cmH_20 associated with an increased risk of barotrauma [6].

Due to the high flow resistance of the gas delivery channels inside the wall of the Boussignac tube, as compared to that of the respiratory system, mCPR causes no noticeable fluctuations

[2] This was determined by lowering the Boussignac tube into a water column and registering the depth corresponding to zero flow.

in oxygen delivery through the channels, nor in driving pressure while the valve is open. Furthermore, the buffer tank prevents pressure fluctuations otherwise caused by valve opening and closing.

Active compression-decompression mCPR (also known as mechanical or automated CPR) was provided by a LUCAS (first generation pneumatic device, Jolife AB, Lund, Sweden), configured to run at 50 % duty cycle and a frequency of 100 compressions per minute. The ventilator control circuit paced both the LUCAS device and the oxygen valve, to assure accurate timing according to Fig. 1.

The 23 l/min oxygen insufflation flow corresponds to an addition of 115 ml per “breath”, i.e., compression cycle. To this is added approximately 80 ml per “breath”, entering the lungs via the main lumen of the Boussignac tube, due to Venturi effect during each active decompression [3].

Continuous insufflation of oxygen

Continuous insufflation of oxygen (CIO) was administered by the same type of Boussignac tube as used in the PIIO group. The pressure regulator was set to 2.5 bar (gauge pressure), corresponding to a constant insufflation flow of 15 l/min, which has been shown to provide adequate oxygenation and excellent ventilation [7]. See [3] for further details.

Study design

The study was performed on 20 Swedish domestic pigs, upon exclusion of two animals – one where the protocol was breached when commencing CPR; one where a technical issue was encountered with the data acquisition system.

Animals of 25–30 kg were used, to comply with the Utstein guidelines for CPR research. The animals were stratified into one CIO and one PIIO group, each comprising 10 animals. Upon each of the two mentioned exclusions, the remainder of the study was re-stratified.

All animals received humane care in compliance with [8] guidelines. The experiments were run under ethic approval M174-15, issued by the Malmö/Lunds regionala djurförsöksetiska nämnd (REB).

The study groups were stratified with respect to time of day when experiments were performed, as large animal experiments during the development and verification of LUCAS indicated that there might exist a correlation between the circadian cycle and the outcome of mCPR experiments (and also fluctuations correlated with time of year).

The study was blinded with respect to the physician performing the experiments.

Protocol

The anaesthesia and preparation protocol has been previously described in [3].

Individual catheters (Secalon-T-over-needle central venous catheter, 16G/1.70.130mm) for blood gas samples were inserted via direct puncture into the right carotid artery and right internal jugular vein. Catheters were also inserted into the ascending aorta and the right atrium for continuous invasive blood pressure measurement and connected to a data acquisition system (DAQ) described in [9]. A flow sensor (REF 6710; Novametrix Medical Inc., Wallingford, CT) was fitted to the proximal end of the Boussignac tube and connected to the same DAQ. Upon placement of the catheters, a baseline arterial and central venous blood gas sample pair (BG1) was drawn and analysed. Air-filled plastic tubing with non-flexible walls was fitted between a pressure transducer and two of the secondary lumina in the wall of the Boussignac tube to enable intratracheal pressure measurement.

Defibrillation pads (LifePak 12, Medtronic, Minneapolis, MN) were placed upon shaving the attachment areas to improve skin conductivity. The animals, placed in supine position, were fitted with the LUCAS mCPR device, as described in [3] and [10].

Ventricular fibrillation (VF) was induced with a 5–20 mA, 6 Hz and 30 V alternating current delivered to the epicardial surface via a needle electrode. Cardiac arrest was confirmed by abrupt decrease in aortic blood pressure, and an ECG showing VF.

Upon confirming cardiac arrest, the servo ventilator was disconnected from the proximal end of the Boussignac tube, leaving the main lumen of the latter open to the atmosphere. The LUCAS device was started and, depending on the stratification, either CIO or PIIO was maintained for 20 min. A second arterial and venous blood gas sample pair (BG2) was drawn and analysed 19 min after initiation of mCPR.

After 20 min of continuous mCPR under normothermic conditions, a 360 J defibrillation was given and the LUCAS turned off to investigate ROSC. A maximum of three (3) 360 J attempts, with 0.2 mg i.v. adrenaline given between the second and third attempt, were provided, with LUCAS mCPR provided between the attempts. Lack of ROSC was registered, as defined in [2], for animals, which did not develop sinus rhythm and a systolic AP of $\geq$60 mmHg two minutes after defibrillation.

Animals which developed ROSC were put back on positive pressure ventilation, with the same settings as during preparation, but with FiO_2=1.0, and kept under observation for 20 min, at the end of which a third blood gas sample pair BG3) was drawn and analysed, prior to termination of the experiment through euthanasia.

Comparison endpoints

The primary endpoint of the study was to investigate the hypothesized CPP improvement of PIIO over CIO. Several metrics were computed, to provide both insight and comparability with previous works:

1. End-decompression CPP, CPP_{ED}, being the measure reported in [3], was averaged over 0.05 s at the end of each decompression, as described in [10].
2. Maximal CPP, CPP_{max}, computed during the mCPR decompression phase. This metric is motivated by e.g. [2], identifying max CPP as a strong outcome predictor for CPR;

3. Mean CPP, CPP_{mean}, being the time normalized area under the curve during decompression;
4. Mean CPP, CPP_{mean15}, for episodes of CPP $\geq$ 15 mmHg. This metric is motivated by myocardial blood flow showing a linear correlation with CPP [1], and CPP$\geq$15 mmHg being a requirement for successful CPR [2];
5. Time in range, T_{IR}, defined as percentage of time during each decompression where CPP$\geq$15 mmHg.

The following secondary end-points were additionally compared between the study groups:

6. ROSC frequency;
7. Range of intratracheal pressure during mCPR. A combination of low maximal pressure and positive minimal pressure are desired to avoid barotrauma and oedema formation, respectively;
8. Arterial and venous blood gas. Further details are provided in the *Results* and *Discussion* sections.
9. Compression phase AP during mCPR – the mean over the 20 min period was considered. Compression phase AP is a good indicator of cerebral perfusion.
10. Systolic AP development following ROSC – the maximal and mean systolic AP values during the 20 min observation phase, were considered. (Animals which did not develop ROSC were excluded.)

Data collection and processing

Blood pressures and intratracheal pressure were sampled and time aligned with a period of 0.001 s (1 kHz). The data was exported to MATLAB (R2016a, MathWorks, Natick, MA), segmented into preparation, mCPR and ROSC (observation) datasets for each animal, and subsequently saved to file for analysis. Blood gas samples were manually collected.

A 3 min (acausal) median filter was applied to all signals, to remove outlier artefacts caused foremost by flushing of pressure transducer channels. Individual signals were removed from the dataset during elongated episodes of sensor occlusion.

Statistical analysis

Statistics are reported in terms of mean $\pm$SEM. SEM, the standard error of the mean, scales variance with sample size, motivating its use when the number of measurements vary.

The single-sided Mann-Whitney U-test was used for investigating inferiority differences in measurement ensemble medians between the CIO and PIIO groups. Differences were deemed statistically significant if the test null hypothesis could be discarded with $P<0.05$.

The haemodynamic (1–5) and respiratory (7) measurement signals mentioned under *Comparison endpoints* are defined once per cardiac (compression) cycle. In order to arrive at a scalar measurement for each individual animal – and thereby enable comparison between the study groups, in terms of mean and SEM – the average of these measurements was computed for each animal over the mCPR experiment phase.

Results

Coronary perfusion pressure

Table 1 shows the CPP metrics described above under *Comparison endpoints*. The rightmost column shows the confidence level by which PIIO values exceed their CIO counterparts. The time evolution of CPP_{ED}, is shown for both study groups in Fig. 2.

Table 1 CPP statistics for both groups. See Comparison endpoints under Materials and Methods for definition of the considered metrics.

	CIO	**PIIO**	***P***
CPP_{ED}	14.3 ± 2.1 mmHg	25.9 ± 3.6 mmHg	≤ 0.01
CPP_{max}	19.6 ± 2.6 mmHg	30.4 ± 4.3 mmHg	≤ 0.02
CPP_{mean}	10.1 ± 1.8 mmHg	18.1 ± 3.3 mmHg	≤ 0.01
CPP_{mean15}	21.1 ± 2.0 mmHg	26.9 ± 3.4 mmHg	≤ 0.03
T_{IR}	26.9 ± 9.0 %	52.9 ± 8.0 %	≤ 0.03

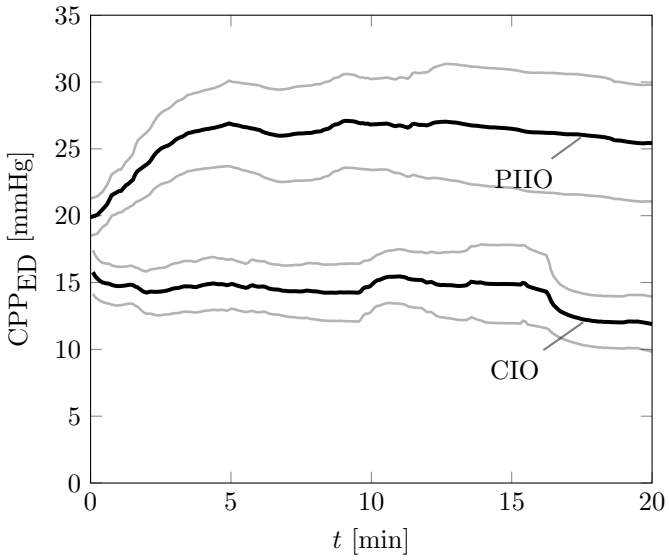

Figure 2 Coronary perfusion pressure (CPP). Time evolution of end-decompression CPP, CPP_{ED} (mean ± SEM), during mCPR of the two study groups. Means are shown in black; standard error of the mean (SEM) in grey.

Return of spontaneous circulation

Nine of ten (9/10) animals in the PIIO group achieved ROSC, and were stable (systolic AP≥60 mmHg) throughout the 20 min observation period, following defibrillation. This was not significantly higher (P<0.16) than for the CIO group, where six of ten (6/10) achieved ROSC. Animals that did not develop ROSC were subject to autopsy to inspect for atrial septal defect (ASD) and signs of barotrauma. No cases of barotrauma or ASD were present.

Airway pressure

Intratracheal pressure remained positive (≥8 cmH_2O) and below harmful levels (≤32 cmH_2O) within all animals in both groups. The minimal, mean and maximal intratracheal pressure measurements are shown in in Fig. 3. During mCPR, the maximal intratracheal pressure averaged 27 cmH_2O in both groups. PIIO resulted in significantly (*P*<0.04) lower minimum intratracheal pressure than CIO (average 12 vs 20 cmH_2O). Consequently, mean intratracheal

pressure was also significantly (P<0.02) lower than within the CIO group (average 18 vs 24 cmH_2O).

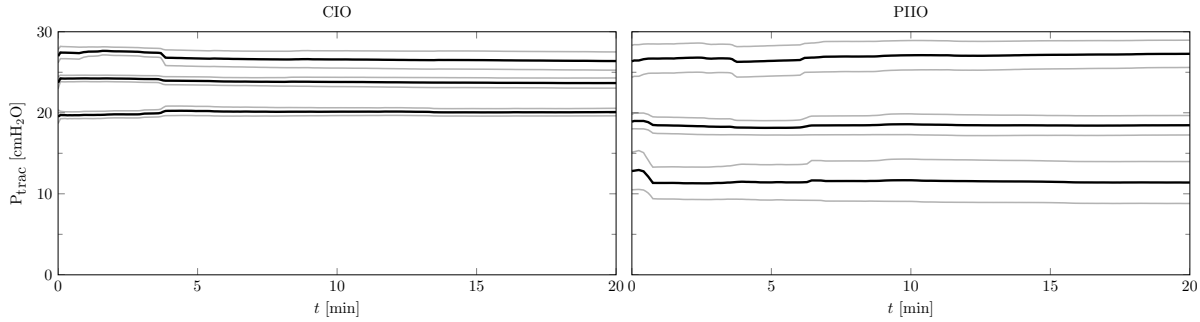

Figure 3 Intratracheal pressure. Minimal (bottom), mean (middle), and maximal (top) values across the study groups during mCPR (mean ± SEM) are shown. The mean of each mentioned value is shown in black; SEM in grey. Left pane shows CIO; right pane PIIO.

Blood gases

Arterial and venous blood gas values for both groups, drawn at time described under *Protocol*, are shown in Table 2. Arterial and venous blood gas analysis showed comparable results between the groups, when taking base line values into account. Statistically significant differences were observed in: arterial and venous PO2; arterial and venous lactate; lactate; baseline glycogen, as per the considered statistical significance test. All significant differences except arterial PO2 BG3 favour PIIO over CIO.

Table 2 Arterial and venous blood gas values for the continuous (CIO) and phase-controlled (PIIO) insufflation of oxygen groups. BG1 are base line values, BG2 were collected after 19 min of mCPR, BG3 were collected 19 min following ROSC. Measurements with significant difference between the PIIO and CIIO groups are marked by asterisk (*).

		CIO			**PIIO**		
		BG1	**BG2**	**BG3**	**BG1**	**BG2**	**BG3**
Arterial	Hb	120.6 ± 1.9 g/l	120.3 ± 6.1 g/l	125.7 ± 5.1 g/l	116.5 ± 3.9 g/l	124.4 ± 4.8 g/l	121.6 ± 4.0 g/l
	PO_2	18.0 ± 3.4 kPa	40.3 ± 4.4 kPa	65.5 ± 4.1 kPa	*15.3 ± 3.0 kPa	*24.7 ± 5.4 kPa	*50.7 ± 6.3 kPa
	PCO_2	5.0 ± 0.3 kPa	2.3 ± 0.4 kPa	5.2 ± 0.2 kPa	5.3 ± 0.3 kPa	3.6 ± 0.7 kPa	5.3 ± 0.5 kPa
	pH	7.36 ± 0.03	7.42 ± 0.04	7.29 ± 0.03	7.35 ± 0.03	7.42 ± 0.06	7.29 ± 0.04
	ABE	-4.0 ± 1.3 mmol/L	-9.3± 2.2 mmol/L	-7.5 ± 1.3 mmol/L	-3.9 ± 1.4 mmol/L	-8.0 ± 1.7 mmol/L	-7.7 ± 1.4 mmol/L
	Lac	2.4 ± 0.3 mmol/L	5.6 ± 0.5 mmol/L	6.6 ± 1.0 mmol/L	2.0 ± 0.4 mmol/L	4.5 ± 0.4 mmol/L	*3.8 ± 0.4 mmol/L
	Glu	7.9 ± 0.5 mmol/L	8.6 ± 1.7 mmol/L	8.5 ± 1.6 mmol/L	*6.2 ± 0.8 mmol/L	9.7 ± 2.0 mmol/L	10.4 ± 2.1 mmol/L
Venous	Hb	121.0 ± 3.0 g/l	121.9 ± 3.0 g/l	116.8 ± 8.5 g/l	116.0 ± 4.1 g/l	124.0 ± 3.1 g/l	118.8 ± 7.3 g/l
	PO_2	5.2 ± 0.4 kPa	2.7 ± 0.1 kPa	6.0 ± 0.6 kPa	4.9 ± 0.2 kPa	*3.8 ± 0.7 kPa	6.1 ± 0.5 kPa
	PCO_2	6.4 ± 0.2 kPa	6.7 ± 0.4 kPa	6.8 ± 0.4 kPa	6.7 ± 0.3 kPa	6.7 ± 0.6 kPa	8.0 ± 0.8 kPa
	pH	7.30 ± 0.03	7.22 ± 0.03	7.20 ± 0.02	7.29 ± 0.03	7.27 ± 0.04	7.16 ± 0.04
	ABE	-3.4 ± 1.2 mmol/L	-7.6 ± 1.2 mmol/L	-8.6 ± 1.2 mmol/L	-3.4 ± 1.2 mmol/L	-5.2 ± 1.4 mmol/L	-8.8 ± 1.6 mmol/L
	Lac	2.7 ± 0.3 mmol/L	5.8 ± 0.4 mmol/L	6.3 ± 1.0 mmol/L	2.5 ± 0.4 mmol/L	*4.3 ± 0.4 mmol/L	*4.3 ± 0.6 mmol/L
	Glu	7.1 ± 0.5 mmol/L	7.8 ± 1.2 mmol/L	6.7 ± 1.3 mmol/L	5.9 ± 0.7 mmol/L	9.0 ± 1.7 mmol/L	9.2 ± 1.9 mmol/L

Haemodynamics

Fig. 4 shows AP and RAP for the two groups during the preparation, mCPR, and ROSC phases of the experiment.

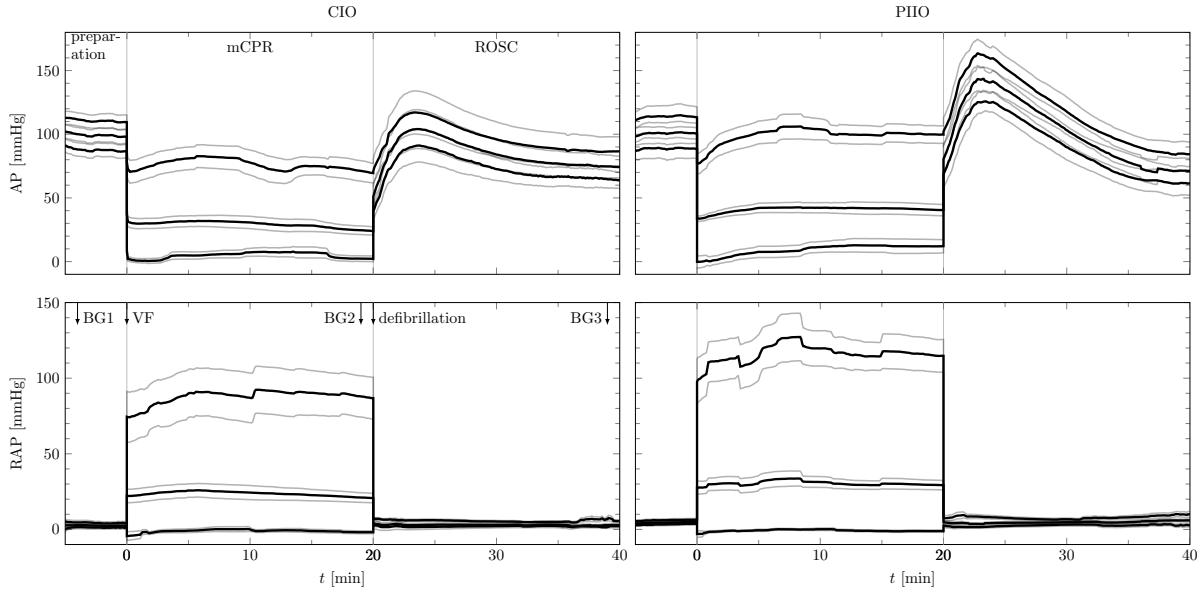

Figure 4 A pressure (AP) and right atrial pressure (RAP). Top panes show AP, bottom panes show RAP. Minimal (bottom), mean (middle), and maximal (top) values across the study groups during mCPR (mean ± SEM) are shown. (The reported means are computed as the true averages over the entire mCPR cycle.) The mean of each mentioned value is shown in black; SEM in grey. Continuous insufflation of oxygen (CIO) results are in the left panes; phase-controlled insufflation of oxygen (PIIO) results in the right. Experiment phases (preparation; mCPR treatment; observation following ROSC) are indicated in the top left pane. Time instances for blood gas samples (BG1–3); induction of ventricular fibrillation (VF); defibrillation are indicated in the bottom left pane.

Mean AP during the compression phase of the mCPR cycle was higher in the PIIO group (average 53 vs 39 mmHg in the CIO group), however not significantly (P<0.06). During decompression, the corresponding difference (average 29 vs 19 mmHg) was significant (P<0.02). Mean AP, over the compression and decompression phases combined, as shown in Fig. 4, was significantly (P<0.01) higher with PIIO (average 41 vs 29 mmHg in the CIO group).

Mean RAP was significantly higher (P<0.04) in the PIIO group during compression (average 50 vs 38 mmHg in the CIO group). During decompression, mean RAP was higher in the PIIO group (average 11 vs 10 mmHg in the CIO group), but the difference was not significant (P<0.16).

Discussion

Myocardial blood flow (MBF) has an instrumental impact on the outcome CPR [1]. While not directly measurable during CPR, MBF through coronary perfusion is driven by CPP. Whereas a gradient, AP > RAP, may also exist during the compression phase, the high pressure across the heart during mCPR compression prohibits antegrade MBF [1].

A linear relation between CPP and MBF exists, whenever CPP exceeds a closing pressure, which has been reported to be around 5–10 mmHg during cardiac arrest [1]. A clinical study

involving 100 cardiac arrest patients [2] concluded that a compression cycle-wise maximum CPP≥15 mmHg was necessary to achieve return of spontaneous circulation (ROSC) upon defibrillation, and that the cycle-wise maximal CPP is the best-known haemodynamic predictor of ROSC.

This study has demonstrated that PIIO has a significant positive effect on CPP, as compared to CIO, as visualized in Fig. 2. Blood gas analysis (Table 2), intratracheal pressure measurement (Fig. 3) and autopsy have confirmed that PIIO does not have a negative impact on ventilation, oxygen delivery, or risk of barotrauma.

Although the insufflation flow is higher with PIIO (23 l/m) than with CIO (15 l/min), the minute volume of insufflated oxygen is lower due to the 50 % PIIO duty cycle. As observed in our pilot PIIO experiments, and confirmed by data herein, 23 l/min PIIO flow results in good oxygenation and ventilation. In particular, Table 2 shows the lower PIIO oxygen minute volume did not result in worse pCO_2. There is thus no reason to increase the PIIO flow beyond 23 l/min, while doing so would likely result in PIIO yielding a higher maximal intratracheal pressure than CIO (cf. Fig. 3).

The intratracheal pressure measurements presented herein are reliable for maximum pressures. The measured minimum pressures are likely somewhat higher than the actual ones for both groups, due to a combination of Pitot tube effect and compressibility of the gas in the measurement channels. Using water-filled channels as in [3] eliminates this problem. Indeed, the measured intratracheal pressures are lower in [3]. However, the higher inertia of the water column limits temporal resolution of the pressure measurements, which is why gas-filled measurement channels were employed in this study.

Another measurement artefact is seen in Fig. 1, where at least parts of the transient pressure spikes following each LUCAS downstroke, and subsequent ringing in both the AP and RAP waveforms, are an effect of the catheter tips being displaced by the compression impact force, rather than the result of actual high frequency pressure variations in the aorta and right atrium. Care should therefore be taken when using this part of the data sets. This is the reason for the use of mean values when computing and comparing compression phase blood pressure statistics.

Limitations

The herein investigated form of the PIIO method requires tracheal access and hence relies on emergency responders with competence to intubate. The availability of this competence varies widely between countries and individual regions.

In the study, as well as in the previous study comparing CIO and IPPV [3], a Boussignac endotracheal tube was used. Results might not translate to other types of endotracheal tubes.

The PIIO method has been investigated in the context of LUCAS mCPR. Synchronization between insufflation and chest compressions was performed by pacing both the ventilator and the LUCAS. Controlling insufflation based on detected compressions has not been

investigated. Relatedly, the efficiency and safety in conjuncture with manual chest compressions is hitherto unknown.

While adhering to the Utstein protocol to ensure similarity in thorax mechanics, further research is needed to investigate to what extent reported results translate to adult humans.

Conclusion

PIIO ventilation had a positive effect on CPP during mCPR in the studied porcine population, which was chosen to adhere to the Utstein guidelines.

Conflicts of interest

The PIIO ventilation method has been patented by members of the research group. The authors have no commercial associations to the content of the manuscript.

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