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ORIGINAL RESEARCH

Femoral artery collapse ratio as an indicator of chest compression quality during cardiopulmonary resuscitation in a porcine cardiac arrest model

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Abstract

Cardiopulmonary resuscitation (CPR) quality is crucial for improving patient survival rates after cardiac arrest. This study aimed to investigate the usefulness of femoral artery collapse ratio (systolic diameter/diastolic diameter ratio) measurement using M-mode ultrasound versus end-tidal carbon dioxide ($ETCO_2$) for the assessment of high-quality CPR in a porcine cardiac arrest model. A total of 10 male mongrel pigs (age range, 16–20 weeks; weight, 45–50 kg) were used. After anesthesia, the carotid artery was dissected and exposed. The animals were instrumented with an arterial catheter in the exposed carotid artery to monitor arterial blood pressure. Cardiac arrest was induced by injecting potassium chloride (KCl, 40 equivalents of weight). The animals underwent chest compression using a mechanical device, and the chest compression depth and $ETCO_2$ were measured using a defibrillator. To obtain hemodynamic information, two investigators performed an ultrasound examination on both femoral arteries. One examiner measured the femoral peak systolic velocity (PSV), while the other measured the diameters of the femoral artery (systolic diameter and diastolic diameter) in a transverse or longitudinal position using the M-mode of the linear ultrasound probe. As the compression depth increased, $ETCO_2$, femoral artery diameter, collapse ratio (systolic diameter/diastolic diameter), and blood flow increased; however, PSV decreased. The $ETCO_2$ and collapse ratio were positively correlated. The femoral artery collapse ratio, measured using the M-mode ultrasound, could be an alternative and simple method to evaluate high-quality CPR.

Keywords

Porcine; Ultrasound; Chest compression; Carbon dioxide; Cardiopulmonary resuscitation

1. Introduction

High-quality cardiopulmonary resuscitation (CPR) is an important factor in improving the survival rate of patients with cardiac arrest. Exhaled end-tidal carbon dioxide ($ETCO_2$) and diastolic arterial pressure monitoring are used to confirm high-quality CPR; therefore, the American Heart Association and European Resuscitation Council guidelines recommend monitoring of these parameters for high-quality CPR after endotracheal intubation [1–3].

If the partial pressure of exhaled end-tidal carbon dioxide ($P_{ET}CO_2$) is maintained at $\geq$10 mmHg or diastolic arterial pressure is maintained at $\geq$20 mmHg during CPR, there is a high chance of return of spontaneous circulation (ROSC) [1, 2].

Currently, $ETCO_2$ measurement is a non-invasive and simple method for estimating organ perfusion during CPR. In addition, $ETCO_2$ reflects cardiac output and the effectiveness of chest compression in CPR and has a positive correlation with the cardiac index, coronary and cerebral perfusion pressure, and ROSC [4–11]. Ultrasound is also useful for differentiating the cause of shock or cardiac arrest during CPR in the intensive care unit (ICU) or emergency department (ED). Therefore, we thought that ultrasound could be an alternative to the quality of CPR and thus compared $ETCO_2$ and ultrasound to evaluate high-quality CPR in a porcine cardiac arrest model. The hypothesis was that the quality of chest compression could be assessed by measuring the hemodynamic parameters in the femoral artery using ultrasound. Moreover, $ETCO_2$ is believed to be correlated with the femoral artery collapse ratio (systolic diameter/diastolic diameter ratio) during chest compressions. Therefore, this study aimed to compare $ETCO_2$ verus hemodynamic parameters (*i.e.*, systolic diameter, diastolic diameter, peak velocity, collapse ratio) measured using ultrasound to evaluate high-quality CPR in a porcine cardiac arrest model. To the best of our knowledge, this is the first study that does not have similar findings; therefore, its findings are novel and of significance.

2. Materials and methods

2.1 Anesthesia/instrumentation

A total of 10 male mongrel pigs (aged 16–20 weeks, weighing 45–50 kg) were premedicated and anesthetized with intramuscular injections of alphaxalone (2 mg/kg) and xylazine (2 mg/kg). After intubation, anesthesia was maintained with isoflurane inhalation (2–3%), and vecuronium (0.1 mg/kg) was injected *via* the auricular vein. Volume-controlled ventilation was provided at a tidal volume (Vt) of 6–7 mL/kg.

After anesthesia, the carotid artery was dissected and exposed. The animals were instrumented with an arterial catheter in the exposed carotid artery to monitor the arterial blood pressure (BeneVision N 15 monitor, Mindray, China). Electrocardiography (ECG) and $P_{ET}CO_2$ were monitored using a monitor defibrillator (X series; ZOLL Medical, Chelmsford, MA, USA). Chest compression depth was measured using a defibrillator with an integral accelerometer-based chest compression sensor. Fasting animals were given an initial fluid bolus of 20 mL/kg warm balanced electrolyte solution and, then, warm normal saline was administered at 5–10 mL/kg/h.

To obtain hemodynamic information, one investigator performed an ultrasound examination of the femoral arteries before cardiac arrest, and ultrasound was maintained during arrest.

2.2 Intervention

Cardiac arrest was induced by injecting potassium chloride (KCl, 40 equivalents of weight). After injection of KCl, the ventilator was disconnected. Arrest was confirmed by ECG monitoring and femoral blood flow using ultrasound performed before cardiac arrest.

The animals underwent mechanical chest compression using the Easy Pulse® device (Schiller, Medizintechnik GMBH, Feldkirchen, Germany). During chest compressions, the pigs were ventilated with a guideline-based ventilation regimen (Vt-8–10 mL/kg, fraction of inspired oxygen (FiO_2)-1.0, and respiratory rate-10 breaths per minute (min)). CPR was continued for 8 min, and 1 mg epinephrine was administered every 4 min. If ventricular fibrillation continued after 4 min, defibrillation (200 J, biphasic) was performed.

2.3 Measurements and statistical analysis

Chest compression depth was measured using a defibrillator with an integral accelerometer-based chest compression sensor (X series; ZOLL Medical, Chelmsford, MA, USA). ECG and $P_{ET}CO_2$ were measured using a monitor defibrillator.

Systolic blood pressure (SBP), mean blood pressure (MBP), and diastolic blood pressure (DBP) were measured using the arterial catheter in the exposed carotid artery. To obtain hemodynamic information, two investigators performed ultrasound examinations of both femoral arteries. One examiner measured the femoral peak systolic velocity (PSV), while the other measured diameters of the femoral artery (diameter during systole (SD) and diastole (DD)) in transverse or longitudinal positions using a 10 M-Hz linear probe and Sonosite brand X-porte model ultrasound. The systolic and diastolic diameters were measured using M-mode ultrasound (Fig. 1). The diameter ratio (SD/DD) was calculated to measure the degree of change in the diameter. Two examiners measured femoral blood flow during cardiac arrest (from 1 min before the arrest). The volume flow rate refers to the volume of fluid that passes per unit time and is defined as the product of velocity and cross-sectional area. Therefore, the blood flow rate was calculated by multiplying the PSV and the cross-sectional area of the femoral artery during systole ($\text{Flow} = \text{PSV} \times (\text{SD}/2)^2$).

PSV, diameter, and $P_{ET}CO_2$ were measured for the first 2 min. The thoracic pressure decreased due to several factors (rib fracture, impaired thoracic expansion, *etc.*) in later cycles of CPR, which may have affected the PSV, diameter, flow, and $P_{ET}CO_2$. CPR was performed for 8 min to check ROSC; however, there was no ROSC.

Sample sizes were calculated based on a correlation analysis between compression depth, PSV, and blood flow rate. The sample size was 138 on calculation with a correlation coefficient of 0.3, α error of 0.5, and power of 0.95, based on previous studies. As chest compressions were performed approximately 200 times and CPR was performed for 2 min, 10 pigs were considered to be a sufficient sample size for verification.

Data were analyzed using the PASW statistical software package for Windows, version 27 (IBM Corp., Armonk, NY, USA), and standard descriptive summaries appropriate for the underlying distribution of the variables were calculated. The normality of the distribution of continuous variables was assessed using the Shapiro-Wilk test. To determine the relationship between compression depth and blood flow, a correlation analysis was performed with PSV, femoral artery diameter, flow rate, and depth. To determine the relationship between $P_{ET}CO_2$ and blood flow, a correlation analysis was performed with PSV, femoral artery diameter, flow rate, and $P_{ET}CO_2$. Multivariate linear regression was performed for the statistically significant variables. As the variables did not have a normal distribution, a correlation analysis was performed using bivariate analysis with Spearman's correlation coefficient. Statistical significance was defined as a two-tailed p-value of < 0.05.

3. Results

A total of 10 experiments were performed. The chest compression depth was 3.29 ± 0.52 cm and SBP, MBP, and DBP were as follows: 88.86 ± 33.03, 41.14 ± 13.16, and 17.67 ± 13.16 mmHg, respectively. $P_{ET}CO_2$ was 33.01 ± 16.77 mmHg. PSV was 59.29 ± 26.46 cm s^{-1}, SD was 2.16 ± 1.02 cm, DD was 1.02 ± 0.92 cm, and collapse ratio (SD/DD ratio) was 2.78 ± 1.55. The blood flow rate was 76.60 ± 65.33 cm^3/s (Table 1).

In the correlation analysis, as the compression depth increased, $P_{ET}CO_2$, femoral artery diameter, femoral artery collapse ratio, and blood flow increased; however, the PSV decreased. Depth affected the diameter and PSV. PSV decreased because of the enlarged systolic diameter (Table 2). As the diameter increased, the PSV decreased; however, the

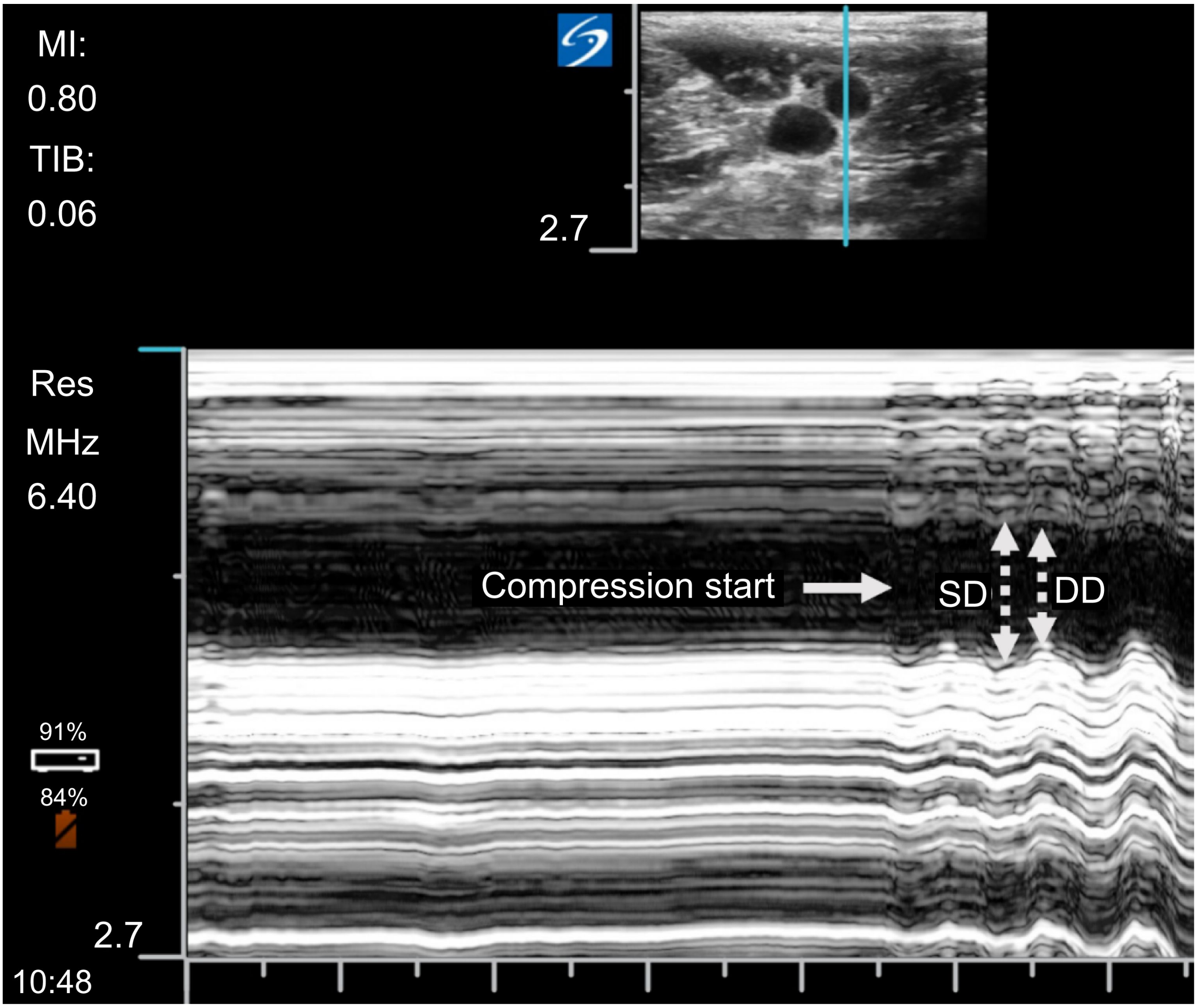

FIGURE 1. Measurement of systolic and diastolic diameter of femoral artery by M-mode ultrasound. SD, systolic diameter; DD, diastolic diameter.

TABLE 1. General characteristics.

Variables	Mean ± SD*
Compression depth (cm)	3.29 ± 0.52
Arterial blood pressure (mmHg)	
SBP	88.86 ± 33.03
MBP	41.14 ± 13.16
DBP	17.67 ± 13.16
$P_{ET}CO_2$ (mmHg)	33.01 ± 16.77
Peak systolic velocity (cm/s)	59.29 ± 26.46
Systolic diameter (SD, cm)	2.16 ± 1.02
Diastolic diameter (DD, cm)	1.02 ± 0.92
Collapse Ratio (SD/DD)	2.78 ± 1.55
Blood flow rate (cm^3/s)	76.60 ± 65.33

SD, standard deviation; SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure; $P_{ET}CO_2$ partial pressure of end-tidal carbon dioxide.*

TABLE 2. Correlation with depth and variables.

Variable	Spearman's correlation coefficient	*p*-value
$P_{ET}CO_2$	0.507	<0.001
Peak systolic velocity	−0.341	<0.001
Systolic diameter (SD)	0.465	<0.001
Diastolic diameter (DD)	0.110	0.002
Collapse ratio (SD/DD)	0.176	<0.001
Blood flow rate	0.125	0.001

$P_{ET}CO_2$, partial pressure of end-tidal carbon dioxide.

TABLE 3. Correlation with $ETCO_2$ and variables.

Variable	Spearman's correlation coefficient	*p*-value
Compression depth	0.507	<0.001
Peak systolic velocity	−0.158	<0.001
Systolic diameter (SD)	−0.026	0.554
Diastolic diameter (DD)	−0.347	<0.001
Collapse ratio (SD/DD)	0.386	<0.001
Blood flow rate	−0.203	<0.001
SBP	−0.210	<0.001
MBP	0.240	<0.001
DBP	0.104	0.048

$ETCO_2$, end-tidal carbon dioxide; SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure.

TABLE 4. Multivariable linear regression for predicting $ETCO_2$.

Variable	B	95% CI	β	*t*	*p*-value
Compression depth	1.898	−0.269–4.065	0.043	1.725	0.086
Peak systolic velocity	−0.018	−0.071–0.0356	−0.020	−0.674	0.501
Systolic diameter (SD)	0.594	−2.798–3.987	0.042	0.345	0.345
Diastolic diameter (DD)	1.096	−2.825–5.017	0.089	0.551	0.582
Collapse ratio (SD/DD)	7.935	7.208–8.662	0.993	21.492	<0.001
SBP	−0.948	−1.275–−0.621	−1.337	−5.713	<0.001
MBP	2.603	1.651–3.556	1.210	5.386	<0.001
DBP	−1.674	−2.336–−1.012	−1.277	−4.981	<0.001

$*R^2_{adj} = 0.916$, $p < 0.001$.
$ETCO_2$, end-tidal carbon dioxide; CI, confidence interval; SBP, systolic blood pressure; MBP, mean blood pressure; DBP, diastolic blood pressure.

blood flow rate increased owing to the enlarged diameter. As $P_{ET}CO_2$ increased, the PSV, systolic diameter, and blood flow rate decreased. As the collapse ratio (SD/DD) and compression depth increased, the $ETCO_2$ increased (Tables 2 and 3).

Multivariable linear regression analysis revealed that the collapse ratio and blood pressure (SBP, MBP, DBP) were correlated with $ETCO_2$ ($R = 0.959$, $R^2_{adj} = 0.916$, $p < 0.001$) (Table 4).

4. Discussion

As mentioned in the Introduction section, $ETCO_2$ measurement is essential for assessing the CPR quality. Several studies have been conducted on $ETCO_2$ during CPR in animal models. In one study, $ETCO_2$ was significantly lower during right lung ventilation than during ventilation of both the lungs and ventilation of the left lung [12]. Another study reported that $ETCO_2$ during extracorporeal cardiopulmonary resuscitation may be predictive of the extent of brain or kidney damage [13, 14].

Several studies have examined the relationship between $ETCO_2$ and ROSC. According to one study, the higher the $ETCO_2$, the higher was the probability of ROSC in patients with out-of-hospital cardiac arrest [15]. Another study reported that the probability of ROSC increases when $ETCO_2$-guided algorithm CPR is performed [16]. However, ROSC was not associated with an increased ventilation rate during CPR, as reported in a previous study [17]. In our study, the association between $ETCO_2$ and ROSC was not evaluated because cardiac arrest takes a long time in the asphyxial model, and porcine vessels tend to collapse easily due to their relatively small diameter compared to human vessels, making it difficult to measure the vessel. Therefore, cardiac arrest was induced by injecting KCl. It was believed that ROSC would not be possible in a model of cardiac arrest caused by KCl administration.

Point-of-care ultrasound (POCUS) is routinely used as a diagnostic screening device in acute care conditions, such as blunt trauma, undifferentiated shock in the ICU or ED, and assessment of reversible causes of cardiac arrest and ROSC during CPR [1, 2, 18, 19]. However, one systematic review reported uncertainty in the diagnostic accuracy of POCUS for identifying reversible causes of cardiac arrest and suggested that further study is needed [20].

Several studies have used the carotid artery to compare CPR quality using POCUS. Two studies reported that sonographic blood flow measurement of the carotid artery is a non-invasive and useful method for ensuring high-quality CPR during chest compression [21, 22]; however, one study reported a weak correlation between PSV and $ETCO_2$ values in CPR [23].

Sonographic measurements of the carotid artery may interfere with CPR to a certain extent. Therefore, we believe that the femoral artery is an appropriate site for sonographic measurement without CPR interruption. Furthermore, as the diameter of the blood vessel changes with the amount of blood flow during chest compression, the femoral artery collapse ratio can be an important method of assessment; thus, it can be used to evaluate high-quality CPR. There is one comparative study on manual palpation and femoral artery Doppler ultrasound as a method to determine ROSC [24]. However, this is the first study to evaluate CPR quality using sonographic measurement of the femoral artery diameter. $ETCO_2$, systolic and diastolic diameter, femoral collapse ratio, and blood flow rate were positively correlated with the compression depth, whereas the PSV was negatively correlated. We judged that there was a negative correlation between the PSV and better chest compression, greater blood flow rate, increased femoral artery diameter, and decreased PSV. The compression depth, collapse ratio, MBP, and DBP were positively correlated with $ETCO_2$ in Spearman's correlation; however, DBP was negatively correlated in multivariable regression. There may be problems with the number of samples and technical measurement of the device, but the exact reason is unknown, and additional research is needed in future.

We used a mechanical chest compression device to maintain regular chest compression rate and depth. The animals underwent mechanical chest compressions using the Easy Pulse® device. This device is a mixed-type combination of piston and compression band. Mean chest compression depth was 3.29 ± 0.52 cm in our study. This is attributed to differences in the anatomy of the chest compared with that of humans and the type of mechanical compression device used. Several CPR guidelines have recommended a chest compression depth of 5–6 cm [1, 25]. The chest compression depth in our study was relatively shallow compared with that mentioned in the recommended guidelines. These guidelines emphasize the role of only compression depth of the sternum for chest compression. In the present study, deeper compression of the sternum may not have increased the intrathoracic pressure or blood flow. Considering this, it may be necessary to discuss only the compression depth of the sternum. One porcine model of cardiac arrest reported that relatively shallow chest compressions have similar hemodynamic effects with fewer complications than standard compression depth [26].

This study has some limitations. First, the results from this study are not directly applicable to patients with clinical cardiac arrest because this study was conducted on animals. Second, spontaneous circulation was not restored because the administration of KCl induced cardiac arrest. However, our study is of great importance because it is the first study to evaluate high-quality CPR using a method that has never been examined before.

5. Conclusions

The femoral artery collapse ratio measured using the M-mode of POCUS could be an alternative and simple method for evaluating high-quality CPR. Further research in humans is needed in the future for its application to clinical settings.

ABBREVIATIONS

DBP, Diastolic blood pressure; DD, Diastolic diameter; ECPR, Extracorporeal cardiopulmonary resuscitation; ED, Emergency department; ICU, Intensive care unit; MBP, Mean blood pressure; POCUS, Point-of-care ultrasound; PSV, Peak systolic velocity; ROSC, Return of spontaneous circulation; SBP, Systolic blood pressure; SD, Systolic diameter.

AVAILABILITY OF DATA AND MATERIALS

The data used to support the findings of this study are available from the corresponding author upon request.

AUTHOR CONTRIBUTIONS

JHR—Conceptualization, supervision; MSC and DSL—methodology; MJL—validation; TKH, MKM and MSC—formal analysis; JHR, MKM, MSC and SWS—investigation; MKM—data curation; MKM and JHR—writing-original draft preparation; SWS and JHR—writing-review and editing. All authors have read and agreed to the published version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study was approved by Pusan National University Yangsan Hospital (PNUYH)'s the Institutional Animal Care and Use Committee (approval no. 2021-031-A1C0(0)).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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