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ORIGINAL RESEARCH

Forward blood flow provoked by changing intravascular pressure using an extracorporeal circulation during cardiopulmonary resuscitation

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Abstract

Since both "cardiac pump" and "thoracic pump" theories have been proved during cardiopulmonary resuscitation (CPR), the mechanism of forward blood flow during closed chest compression still remains open to question. The cardiac pump seems to work by the direct compression of the cardiac ventricles between the sternum and vertebral column. A pressure gradient created between the ventricle and aorta generates systemic blood flow. However, the thoracic pump mechanism presumes chest compression causes a rise in intrathoracic pressure which generates a blood flow from the thoracic cavity to the systemic circulation. Retrograde blood flow from the right heart into the systemic veins is prevented by a concomitant collapse of veins at the thoracic inlet. We hypothesize that the intrinsic decrease of vascular resistance from the aorta to peripheral arteries and the existence of competent venous valves enable blood to flow unidirectionally by the fluctuation of intravascular pressures during closed chest compression. The purpose of this study is to prove an antegrade arterial blood flow without cardiac compression and intrathoracic pressure changes in an animal cardiac arrest model. We demonstrate that arterial pulses can be developed by using an extracorporeal circuit, resulting in forward blood flow from the aorta through the systemic vasculature. It can be suggested that changes in intravascular pressure provoked by either cardiac or thoracic pump generate systemic blood flow during closed chest compression, while systemic vascular patency and valve function may be required for successful CPR.

Keywords

Cardiopulmonary resuscitation; Blood flow; Chest compression; Vascular resistance

1. Introduction

The mechanism of forward blood flow during cardiopulmonary resuscitation (CPR) remains controversial. The "cardiac pump" theory is supported by echocardiographic images of left ventricular chamber deformation and mitral valve closure during precordial compression [1]. However, a "thoracic pump" mechanism has also been suggested, which is associated with equal increases in right atrial and systemic arterial pressures with veins at the thoracic inlet collapsed [2]. Moreover, rhythmic coughing was found to produce pulsatile arterial blood pressures and antegrade flow during ventricular fibrillation without cardiac compression [3]. Other studies have shown that the mitral valve can close or remain open during the compression phase of CPR [4] and that a longer time from collapse to CPR is associated with an open mitral valve during precordial compression [5]. Forward blood flow in patients with severe hypothermia has been recognized to occur with an open mitral valve during external chest compression [6].

It is hypothesized that an innate difference between vascular resistance from the aorta to the periphery and the presence of competent venous valves may both play an important role in the genesis of unidirectional systemic blood flow when an intravascular pressure change is present. We aim to demonstrate that a forward blood flow can be generated by changing intravascular pressure using an extracorporeal circulation without closed chest compression in a cardiac arrest model.

2. Materials and methods

The study was approved by the animal care and use committee of Seoul National University Hospital (No. 03-0073). To develop a Y-shaped extracorporeal circuit, two 3/8" by 1m PVC tubes were prepared, and their distal ends were fitted with 3/8" straight connectors containing a capped side hole. Their proximal ends were connected to two arms on the same side of a 3/8" Y connector. The remaining end of the Y connector was connected with a 25cm long PVC tube fitted with a straight 3/8"-1/4" connector to allow the fitting of a 1/4" by 5cm PVC

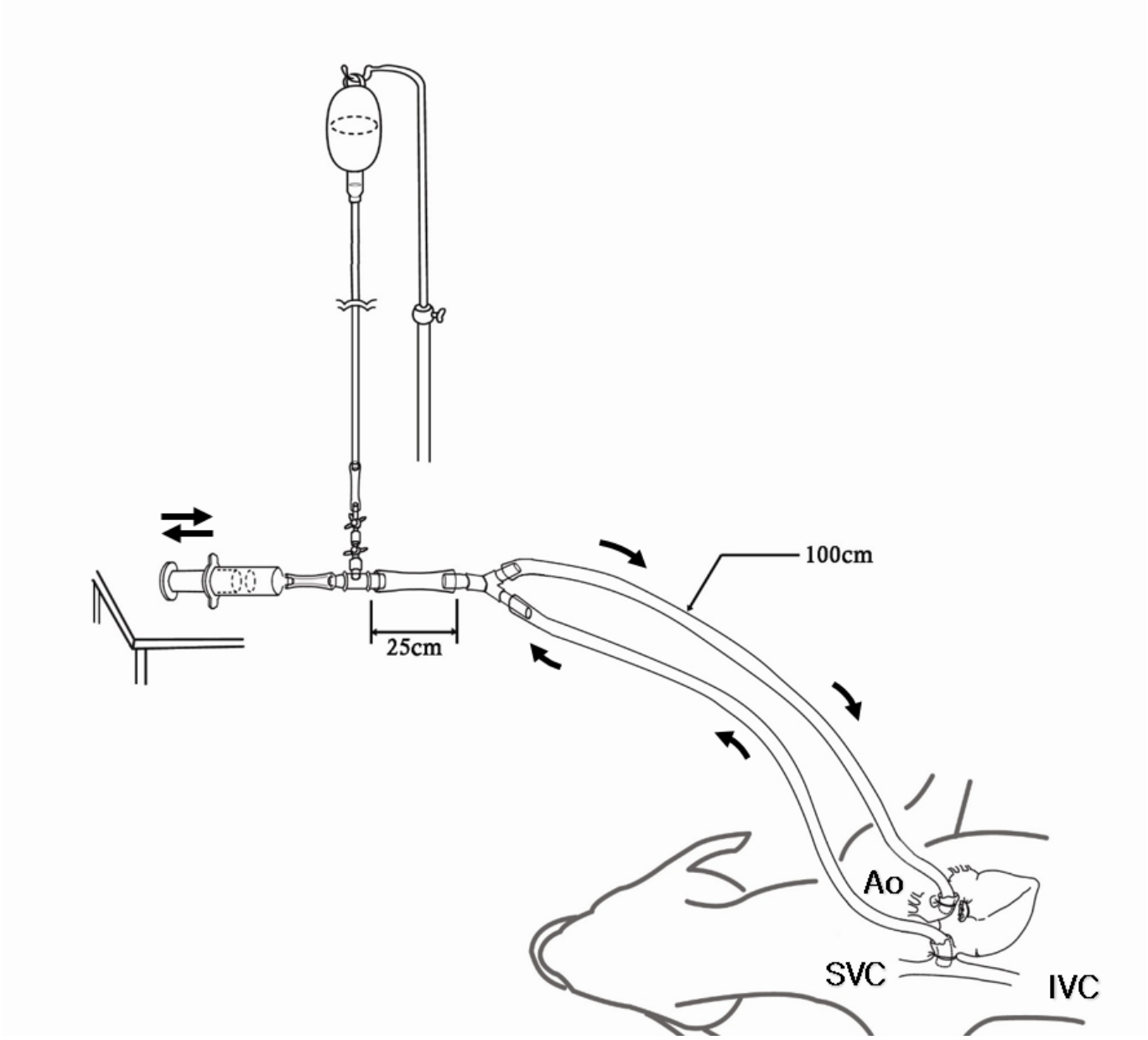

FIGURE 1. A diagram for an extracorporeal circulation. A Y-shaped extracorporeal circuit was composed of tubes, connectors containing a side hole (for dye injection), and a 50 cc enema syringe. Two 3/8" by 1 m PVC tubes bearing two 3/8" straight connectors were inserted into their distal ends, and their proximal ends were connected to the two equivalent arms of a 3/8" Y connector. The other end of the Y connector was connected to a 3/8" by 25 cm long PVC tube and the free end of this tube was fitted with 3/8"- 1/4" adapter to allow a 1/4" by 5 cm PVC tube containing the syringe to be fitted. One of the 1 m long tubes was then introduced via the right atrium to the junction of the vena cava and the right atrium. The aorta was transected above the aortic valve and the 3/8" connector of the other 1 m long tube was introduced directly into the aorta. Extracorporeal circulation was initiated with pull/push movements of the syringe, positioned at the midline level of the heart, after declamping the circuits. SVC, superior vena cava; IVC, inferior vena cava; Ao, aorta.

tube and the terminal 50 ml enema syringe (Shinchang medical Co, Kumi, Korea) (Fig. 1). This extracorporeal circuit which was primed with 300 mL of normal saline containing heparin 5000 U beforehand and warmed in a water chamber at 38 °C.

A male mongrel dog of 23 kg was anesthetized with an intravenous (IV) pentobarbital sodium (15 mg/kg), followed by a continuous infusion (5 mg/kg/hr) and vecuronium (0.2 mg/kg initially and 0.02 mg/kg at 30-min intervals) IV. The animal was tracheally intubated and mechanically ventilated with 30 % O_2 under the ventilator setting of tidal volume 10 mL/kg and respiratory rate of 15/min. Normal saline was infused to maintain normovolemia and body temperature (BT) was kept at 37-38 °C with a warming pad. A right femoral arterial catheter was positioned to continuously monitor arterial pressure. A double lumen catheter was introduced via the right external jugular vein to measure central venous pressure (CVP) and to infuse medication. Cardiac rhythm and heart rate were monitored using a standard lead II ECG. After performing a midline thoracotomy, pulmonary artery and aorta were isolated by cotton tapes positioned beneath the origin of both vessels.

TABLE 1. BT, SBP, CVP, and ABGA values before cardiac arrest and during piston pumping using an extracorporeal circuit for 30 min.

	Before Arrest	Just before pumping	Pumping for 5 min	Pumping for 15 min	Pumping for 30 min
BT (°C)	37.4	36.8	36.2	35.4	34.8
SBP (mmHg)	110	8	36	36	18
CVP (mmHg)	7	8	8	8	8
PH	7.32	7.26	7.03	6.96	6.92
$PaCO_2$ (mmHg)	40	51	61	63	65
PaO_2 (mmHg)	141	55	48	43	39
HCO_3^- (mEq/L)	21	18	16	13	11

BT; body temperature, SBP; systolic blood pressure, CVP; central venous pressure, ABGA; arterial blood gas analysis.

After infusing heparin (300 U/kg) through the jugular vein, KCL 20 mEq IV was injected to induce cardiac arrest followed by the cessation of mechanical pulmonary ventilation.

One terminal connector of the extracorporeal circuit was inserted into the junction of superior and inferior vena cavae via the right atrium. Pulmonary artery was ligated with a suture silk to stop the pulmonary blood flow. The aorta was transected above the aortic valve after ligating the aortic root, and the 3/8" connector of the other tube was introduced into the aorta directly. Indocyanine green dye was injected into the connector at the right atrium. Extracorporeal circulation was initiated with pull/push movements of the syringe, positioned at the midline level of the heart, after declamping the circuits (Fig.1).

We observed the dye direction and blood flowrates in the circuit over 30 minutes, while moving the syringe plunger in and out manually to produce a volume change of 30 mL per stroke. Arterial and external jugular blood pressures and BT were also recorded. Arterial blood gas analysis (ABGA) were performed before inducing cardiac arrest, just before syringe pumping, at 5 minute after pumping and every 15 minute during the experiment.

3. Results

After injecting KCL intravenously, the ECG showed P-R interval prolongation progressing to P wave loss, widening of the QRS complex, and peaking of the T wave, which resulted in an immediate cardiac standstill without intervening ventricular tachycardia or ventricular fibrillation (Fig. 2).

When the syringe movement was initiated by withdrawing blood, the indocyanine green dye moved from the venous connector to the piston side and the aortic blood drained to the piston side at the same time. By pushing the plunger of the syringe, the dye returned to the venous direction at a lesser degree than the aortic blood returned into the aorta. By repeating the syringe pull/push movement, the dye flowed subsequently from vena cavae to the aortic side while showing an oscillatory to and fro advance into the aorta. It took about 12 seconds for the dye from the venous connector to reach the aortic connector along the 2 m long 3/8" tube (volume 142 mL), which meant the bypass flowrate would be about 710 mL/min. Subsequently, venous blood flowed from both vena cavae to aorta as the indocyanine dye.

BT, systolic BP (SBP), heart rate (HR), CVP, and ABGA values before arrest and during extracorporeal circulation for 30 min were summarized in Table 1. Repetitive piston movement generated a femoral arterial pressure of 36/8 mmHg (mean BP 18 mmHg) and a CVP of 7 mmHg at a rate of 62 strokes/min with the flowrate of 710 mL/min. Systemic vascular resistance (SVR = (MBP- CVP) / CO × 80) approximately calculated with mean BP (MBP), CVP and bypass flowrate which meant cardiac output (CO) would be 1240 $dyn \bullet s \bullet cm^{-5}$. The femoral arterial blood pressure and ECG changes before and after arrest were shown in Fig. 2 We terminated pumping after 30 min due to a reduced amount of blood drained from the vena cavae.

4. Discussion

The “cardiac pump” theory for the CPR assumes that external precordial cardiac compression squeezes the heart between the sternum and the spinal column to generate forward blood flow [1]. However, pure intrathoracic pressure changes were found to cause mitral valve closure with accompanying lung deflation, and lung inflation alone opens the mitral valve in dogs [7]. The “thoracic pump” theory postulates that the left heart is a conduit, not a pump, that atrioventricular valves may be irrelevant [2, 8]. Pressures in cardiac chambers and in the thoracic aorta increase proportionally with increased intrapleural pressure during chest compression [9].

Dog models of human CPR introduce the problem of a different thoracic anatomy [10]. During sternal compression in dogs, the heart moves dorsally and rotates clockwise when viewed from apex, and forward flow was observed in a dog model without apparent distortion or compression of the left ventricle [2]. In human echocardiographic studies, it seems that airway pressure [7, 11], applied compressive force [10], rate of compression [12], and cardiac rhythm [2] might affect blood flow through the heart during CPR, and that both cardiac and thoracic pump may operate during different phases of prolonged resuscitation under positive-pressure ventilation [10, 13].

We hypothesize that the vascular system itself appears to actively direct blood flow in the veno-arterial direction when changes in intravascular pressure are applied. Arterial vascular trees are known to display a dichotomous branching pattern, which increases the total cross section areas of subsequent

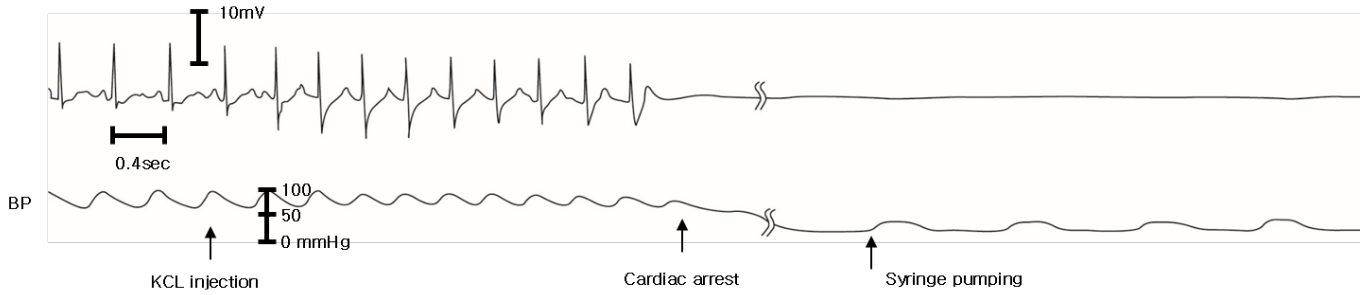

FIGURE 2. ECG and femoral arterial blood pressure recording. Mean blood pressure (MBP) was 80 mmHg, heart rate 134/min, and the CVP 6 mmHg before cardiac arrest. After KCL injection, the ECG showed P-R interval prolongation and subsequently progressed to P wave loss, QRS complex widening, and T wave peaking, which resulted in immediate cardiac arrest. Syringe movement began immediately after extracorporeal circulation was established. When the syringe plunger was initially depressed, femoral arterial blood pressure was 36/8 mmHg (MBP 18 mmHg), CVP 8 mmHg at 62 beats/min.

arterial levels from the aorta to peripheral arteries, and which results in a physiologic decrease in vascular resistance from the aorta to the periphery [14]. In addition, the arterial system is intrinsically stiffer than the venous system, and the capacity of the extrathoracic arterial system is less than that of the venous system [9]. Peripheral veins, as capacitance vessels with a large vascular compliance, receive blood flow from the arterial side via capillaries and contain many intravenular valves to prevent blood from flowing backwards.

In a pilot canine study from our group, blood clots began to appear into the extracorporeal circuit from the venae cavae about 1 hour after the cardiac arrest without the injection of heparin. The bypass flow was reduced to the extent of MBP less than 10 mmHg at 15 min of bypass. Therefore, heparin was administered into the circuit and to the animal beforehand. This study revealed retrograde aortic flow and antegrade venous flow towards the syringe when its plunger was withdrawn, as was mentioned when precordial compression was released [2, 9]. Repetitive piston movement generated a femoral arterial pressure of 36/8 mmHg and a flowrate of about 710 mL/min, which were comparable to the pressure increase in the aorta and flowrate obtained during chest compression alone in dogs [2], indicating that the amount of blood flow was very low comparing with prearrest flow in the present study.

Hypoxia has been known to act on the vasculature by the disruption of vascular tone, enhancement of inflammatory responses and activation of coagulation pathways. Vascular response to hypoxia can be a transient vasoconstriction followed by a potent vasodilatation [15]. Hypercapnic acidosis causes vasodilatation [16]. In this experiment, a decrease of systemic vascular resistance after the cardiac arrest might cause a reduction of changes in intravascular pressures, resulting in a subsequent decrease of forward blood flow as time passed.

The limitations of this study might be one animal study without statistical comparisons of the data during the experiment. Hypoxemia, hypothermia and acidosis might influence SVR. Coronary perfusion pressure might be important for return of spontaneous circulation [17]. In addition, formation of clots might also influence the distribution of blood flow. Though drugs are extensively used to control vascular tone during clinical CPR, we eliminate the effects of pharmacologic agents on this experiment. However, once the nature of vascular resistance and function of venous valves in the central venous circulation are understood, the results of this experiment seem obvious. Notwithstanding which mechanism of blood flow contributes more during clinical CPR remains questionable, this demonstration has shown that one of the important mechanisms of blood flow generation during CPR is associated probably with changes in intravascular pressure with adequately functioning venous valves.

5. Conclusions

Though this experimental design never will reflect the scenario of human CPR, it can be concluded that forward blood flow can be generated by changing intravascular pressure without cardiac compression and intrathoracic pressure changes. In addition to the movement of cardiac valves or the collapse of intrathoracic great veins, patency of the vascular physiology may be required for successful CPR. Further experimental studies are recommended to elucidate the effect of the systemic vascular tone and valve functions on the blood flow during CPR.

AUTHORS' CONTRIBUTIONS

Lee KH designed the research study. Jung CW and Kim JT performed the research. Kang BC helped and advised the humane animal care. Lee KH wrote the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this article.

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