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NOTE

Physiology

Magnitude of mitral valve closure plays a pivotal role in enhancing the forward blood flow during cardiac massage in dogs with ventricular fibrillation

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ABSTRACT. Motion of mitral valve during cardiac massage was examined using beagle dogs with ventricular fibrillation (n=4). Active compression-decompression cardiac massage (ACD-CM) exhibited greater peak aortic pressure than standard cardiac massage (S-CM), reverse of which was true for peak pulmonary capillary wedge pressure in each animal. Accordingly, peak aortic pressure was greater than peak pulmonary capillary wedge pressure with ACD-CM, whereas its reverse was true with S-CM. Transesophageal echocardiography revealed that mitral valve was incompletely closed with S-CM with showing regurgitation. The valve was more effectively closed during ACD-CM. These results indicate that effective closure of mitral valve during cardiac massage may increase forward blood flow, supporting "cardiac pump theory" rather than "thoracic pump theory" as a principle in dogs.

KEYWORDS: active decompression, cardiac massage, cardiac pump theory, mitral valve closure, transesophageal echocardiography

Both "cardiac pump theory" [8, 9] and "thoracic pump theory" [3, 15] have been proposed to explain the efficacy of external cardiac massage for cardiopulmonary resuscitation (CPR). In the former theory, the heart would be compressed between the sternum and the vertebral body in human subjects, which could increase the intraventricular pressure making the mitral valve closed and the aortic valve open to develop forward blood flow [9]. In the latter, chest compression would uniformly increase the pressure in whole intrathoracic compartment. Since retrograde venous flow is believed to be inhibited by collapse of veins at the thoracic inlet and/or by closure of venous valves unlike arteries, "antegrade" blood flow could develop through the opened mitral and aortic valves during compression phase [9]. However, it remains elusive which of the two hypotheses would better correctly explain the blood flow mechanism during CPR in dogs.

In this study, we tried to answer the question in dogs which had developed the ventricular fibrillation by ventricular electrical stimulation. Aortic pressure and pulmonary capillary wedge pressure were continuously monitored, whereas the motion of mitral valve was examined during cardiac massage using the transesophageal echocardiography. The dogs received standard cardiac massage (S-CM) and active compression-decompression cardiac massage (ACD-CM). Since ACD-CM has been shown to increase the negative intrathoracic pressure during active decompression phase, augmenting venous return and cardiac filling, which will effectively increase the cardiac output as well as improve neurological outcome [1, 2, 10, 11, 14, 16], we propose that comparison of hemodynamic and echocardiographic findings between S-CM and ACD-CM would be an effective way to better understand the pump mechanisms during CPR.

The experiment was performed using 1 female and 3 male beagle dogs weighing 6.0–13.5 kg, which were obtained through

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Kitayama Labes Co., Ltd. (Nagano, Japan). The experiment was reviewed and approved by the Toho University Animal Care and User Committee (No. 12-52-152) and performed in accordance with the Guidelines for the Care and Use of Laboratory Animals of Toho University and ARRIVE guidelines [7, 13]. The dogs were initially anesthetized with thiopental sodium (30 mg/kg, i.v.) (Ravonal® 0.5 g for Injection, Mitsubishi Tanabe Pharma Co., Osaka, Japan). After intubation, anesthesia was maintained by inhalation of halothane (1% v/v) (Fluothane®, Takeda Pharmaceutical Co., Ltd., Osaka, Japan) vaporized in oxygen with a volume-limited ventilator (SN-480-3; Shinano Manufacturing Co., Ltd., Tokyo, Japan). Tidal volume and respiratory rate were set at 20 ml/kg and 15 breaths/min, respectively.

A standard 6-French quad-polar electrodes catheter (Cordis-Webster Inc., Baldwin Park, CA, USA) was positioned at the right ventricle for electrical stimulation under the monitoring of intracardiac electrogram obtained from the distal electrode pair. For hemodynamic assessment, the tip of a pig-tail catheter was placed at the ascending aorta through the right femoral artery to measure the aortic pressure, whereas a thermodilution catheter (132F5; Edwards Lifesciences, Irvine, CA, USA) was positioned at the pulmonary artery through the right femoral vein to measure the pulmonary capillary wedge pressure. We confirmed the location of tips of each catheter by using their pressure waveforms. The aortic pressure and pulmonary capillary wedge pressure, and surface lead II electrocardiogram were monitored with a polygraph system (RM-6000, Nihon Kohden Corp., Tokyo Japan), which were saved and analyzed with a data analysis system (Power Lab and Lab Chart 7; AD Instruments Ltd., Dunedin, New Zealand). Echocardiographic images were obtained using the ultrasound system (GE Vivid i; GE Healthcare Japan, Tokyo, Japan) equipped with a 4.0–10.0 MHz of multiple phased array transducer for transesophageal echocardiography (9T-RS, GE Healthcare Japan). The motions of aortic and mitral valves, and the blood flow within the heart were continuously monitored with the B-mode echocardiogram with color Doppler.

After the ventricular fibrillation was induced by burst electrical stimulation, the dogs were started to be ventilated twice every 20 sec using a resuscitation bag with a tidal volume of 20 ml/kg. Meanwhile, the dogs received 3 min of S-CM followed by 3 min of ACD-CM with an interval of 2 min in a left lateral recumbent position [4, 6, 12], which was repeated 4 times for each dog to obtain the highest peak aortic pressure. During S-CM, the chest is not manually decompressed. ACD-CM is an alternative method to compress the chest, then decompress the chest after each compression [1, 2, 10, 11, 14, 16]. S-CM as well as ACD-CM was performed with a custom-made, pneumatically driven automatic piston device [1]. The chest compression rate was set at 70 per minute with a depth of 3–5 cm, and the duration of compression was 50% of the total cycle time. The velocity of compression was fixed during S-CM and ACD-CM in the sequence of cardiac massage protocol. Data are presented as mean ± standard error of the mean (S.E.M.) (n=4). Statistical analysis was performed with paired *t*-test. A P value <0.05 was considered to be significant.

Typical tracings of aortic pressure and pulmonary capillary wedge pressure during S-CM and ACD-CM are shown in Fig. 1, indicating that peak and trough aortic pressures with ACD-CM were greater than those with S-CM, and that its reverse was true for peak and trough pulmonary capillary wedge pressures. The peak values of aortic pressure and pulmonary capillary wedge pressure were 49 ± 13 and 57 ± 17 mmHg during S-CM, whereas those were 55 ± 15 and 46 ± 9 mmHg during ACD-CM, respectively (n=4). The peak value of aortic pressure was significantly greater during ACD-CM than S-CM (P=0.04, n=4); whereas that of pulmonary capillary wedge pressure tended to be smaller during ACD-CM than S-CM, which did not achieve a statistical significance (P=0.37, n=4). Accordingly, the peak pulmonary capillary wedge pressure was greater than the aortic pressure during S-CM (Fig. 1, left panel), whereas its reverse was true during ACD-CM (Fig. 1, right panel). The same trend was observed in all dogs, except in the one with the lowest peak aortic pressure. In this dog, the highest peak aortic pressure was lower than the highest peak pulmonary capillary wedge pressure during both ACD-CM and S-CM. The highest peak aortic pressure in other dogs was higher than 40 mmHg during both ACD-CM (44.5–91.8 mmHg) and S-CM (41.5–80.2 mmHg). Peak aortic pressure higher than 40 mmHg is considered critical for successful CPR [5, 10]. The highest peak aortic pressure in these dogs was higher than the peak pulmonary capillary wedge pressure by 18.0 ± 7.6 mmHg during ACD-CM, whereas the highest peak aortic pressure was lower than the highest peak pulmonary capillary wedge pressure by 8.1 ± 7.8 mmHg during S-CM.

Transesophageal echocardiography revealed the aortic valve was kept closed, but the mitral valve was left open, during ventricular fibrillation in each experiment (Supplementary Movie 1 and Supplementary Text 1). Typical echocardiograms during compression and recoil phases of S-CM, and those during compression and active decompression phases of ACD-CM are shown in Fig. 2 and Supplementary Movie 2. During compression phase with S-CM, the closure of the mitral valve was incomplete, whereas the mitral valve was effectively closed during compression phase with ACD-CM, suggesting that larger "dynamic pressure" developed with ACD-CM may have helped the mitral valve close. The aortic valve was well opened with either S-CM or ACD-CM. During recoil phase of S-CM or active decompression phase of ACD-CM, the aortic valve got closed with the mitral valve opened. It should be noted that during S-CM, spontaneous echo contrast, a marker of stasis of blood flow, was recorded in the left ventricle with showing slow and continuous mitral regurgitation, which during ACD-CM disappeared for the most part with giving rise to color doppler flow signal (Supplementary Movie 2 and Supplementary Text 1), suggesting that ACD-CM could have enhanced the forward blood flow. The same tendency was observed in all the examined dogs.

In conclusion, effective closure of mitral valve with ACD-CM might increase the peak aortic pressure and decrease the peak pulmonary capillary wedge pressure, possibly enhancing the forward blood flow during cardiac massage, although further study needs to be done to demonstrate this hypothesis. These findings may also support "cardiac pump theory" rather than "thoracic pump theory" in dogs as a prevailing principle during cardiac massage. The current study would at least in part provide a basic knowledge to further improve the clinical utility of cardiac massage of dogs.

CONFLICT OF INTEREST STATEMENT. The authors declared no potential conflict of interest.

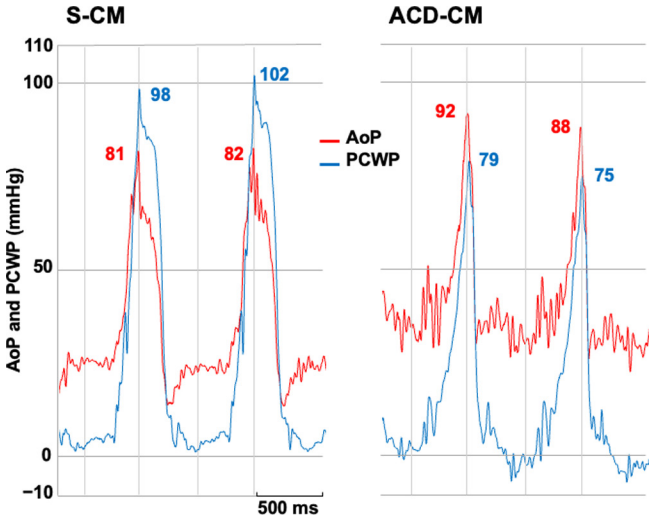

Fig. 1. Typical tracings of the aortic pressure (AoP: red) and pulmonary capillary wedge pressure (PCWP: blue) during standard cardiac massage (S-CM; left) or active compression-decompression cardiac massage (ACD-CM; right) following ventricular fibrillation.

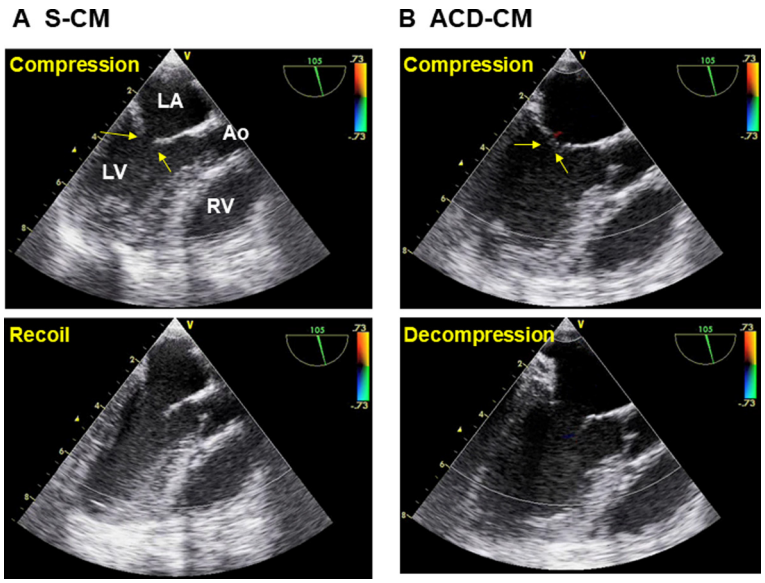

Fig. 2. Representative long-axis views of the aortic bulb and mitral valve (yellow arrows) obtained by transesophageal echocardiography for a dog with ventricular fibrillation. (**A**) During compression (top) and recoil (bottom) phases of standard cardiac massage (S-CM). (**B**) During of compression (top) and decompression (bottom) phases of active compression-decompression cardiac massage (ACD-CM). Note that in compression phase, the mitral valve was incompletely closed with S-CM, which was more effectively closed during ACD-CM. LA: left atrium; LV: left ventricle; RV: right ventricle; and Ao: aorta.

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