Original Article

Impact of Head-Up Position on the Efficacy of Cardiac Massage Assessed by the Physical Heart Simulator Dock-kun

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ABSTRACT

Introduction: Cardiac massage with head-up position is known to achieve higher cardiac output than that with the supine one by enhancing venous return. We explored unknown mechanisms of cardiac massage with head-up position including its impact on the motion of mitral and aortic valves.

Methods: We assessed impacts of cardiac massage with head-up position on the cardiac output, stroke volume and pressure waves of aorta, left ventricle and left atrium in comparison with those of that with supine position using a physical heart simulator (n = 5). Cardiac massage was performed at a rate of 105 strokes/min with a depth of 5 cm using the mechanical device with the head-up-simulating position (+30 cm), the results of which were compared with those with supine-mimicking position (0 cm).

Results: Cardiac massage with head-up position increased the cardiac output and stroke volume by 23%. Cardiac massage with head-up and supine positions induced the mitral valve regurgitation during the compression phase and aortic valve regurgitation during the recoil phase, resulting in a lack of isovolumetric contraction and relaxation phases, respectively. Cardiac massage with head-up position shortened the open duration of aortic valve in the recoil phase by 12%.

Conclusions: Cardiac massage with head-up position increased the forward blood flow partly by shortening of the time window for aortic valve regurgitation in the recoil phase. These experimental findings may add insight into clinical practice of cardiac massage with head-up position.

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KEYWORDS: cardiac massage, head-up position, heart simulator

Introduction

Cardiopulmonary resuscitation with head-up position has been shown to improve the outcomes of patients with out-of-hospital cardiac arrest.[1–3)] In animal experiments using a pig model of ventricular fibrillation, head-up position can enhance the venous return from cerebral circulation and the cardiac filling, and decrease the intracranial pressure during cardiac massage, which may increase the cerebral forward blood flow, improving neurologically in-

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tact survival.[4–6] During the compression phase of cardiac massage, the blood is thought to be propelled from the heart to the body by both cardiac compression and a rise in thoracic pressure, which squeezes the blood out of the ventricles into the systemic and pulmonary circulations, forces the mitral and tricuspid valves to close, and facilitates opening of the aortic and pulmonary valves.[7,8] However, in previous studies using the transesophageal echocardiogram, chest compression can induce regurgitation flow through the mitral valve during cardiac massage.[9–11] In this study, we tried to clarify how the addition of head-up position alters the function of mitral and aortic valves during cardiac massage. In order to better estimate the state of mitral and aortic valves during cardiac massage, we adopted a mechanical model of cardiopulmonary circulation as shown in Fig. 1,[12] enabling to measure the cardiac output, stroke volume and pressure waves of the aorta (AoP), left ventricle (LVP) and left atrium (LAP), which would also be of interest from its reproducibility and animal ethics point of view. Using that model, we compared hemodynamic variables associated with the performance of cardiac massage during head-up position with those during supine and head-down positions to better understand the underlying favorable mechanisms of cardiac massage with head-up position.

Methods

Experimental system

The physical heart simulator (Dock-kun™, Sakai Sangyo Co., Ltd., Shizuoka, Japan) consists of the compression apparatus, inlet tube (=left atrium), inlet valve (=mitral valve), BB-type air pump (=left ventricle), outlet valve (= aortic valve) and outlet tube (=aorta) (Fig. 1A).[12,13] The experimental system consisted of a custom-made, motor-driven, cardiac massage device; the physical heart simulator; two buckets as cerebral arterial and venous vascular beds; the pressure transducers to measure the aortic, left ventricular and left atrial pressures; the connecting tubes of 10 mm in inner diameter; and water as the blood (Fig. 1B).[12] The bottom face of air pump was fixed to the base metal panel using Velcro tape (Fig. 1C). The ends of inlet and outlet tubes were positioned at the same height to the base of physical heart simulator (Fig. 1B, Supine), at 30 cm above the base of physical heart simulator (Fig. 1B, Head-up), or at 30 cm below the base of physical heart simulator (Fig. 1B, Head-down). The tip of outlet tube was not dipped into water of the bucket to prevent a gradual increase of the afterload.

Experimental protocol

The physical heart simulator was driven by the cardiac massage device at a rate of 105 strokes/min with a stroke amplitude of 5 cm according to our previous study.[14,15] Two different strengths of coil springs were prepared for the heart simulator: 5 cm/30 kg (5 cm shortening at 30 kg) and 5 cm/15 kg (5 cm shortening at 15 kg), which could reflect stiffness of the chest in adults and children, respectively. The latter was adopted in this study, since the motor-driven cardiac massage device was used, with which the strength of the coil spring would not affect the compression or dilation of the pump. The AoP, LVP and LAP during cardiac massage were simultaneously measured and recorded with polygraph system (RM-6000; Nihon Kohden Corporation, Tokyo, Japan), and analyzed with Power Lab and Lab Chart 7 (ADInstruments Pty Ltd., NSW, Australia). The cardiac output was measured by the amount of water pumped out into the bucket. The experiment was performed for 1 min for each of the head-down, supine and head-up positions using five physical heart simulators (n = 5 for each position).

Definition of the compression and recoil phases in a cardiac cycle

The compression panel of cardiac massage device kept moving up-and-down, whereas recoil speed of the air pump was much slower than upward movement of the compression panel due to relatively lower spring constant of the pump than that of the coil spring. In this way, fully recoiled condition of the air pump was not attained during upward movement of the compression panel (Fig. 1C, left). In other words, the pump mimics impaired myocardial relaxation, hampering the filling of the heart during recoil phase, and thereby reflecting the clinical manifestation of cardiac massage. As the air pump was actually compressed by the panel only during the latter phase of downward movement (Fig. 1C, right), a cardiac cycle of the pump was divided into two phases; namely, the compression phase and recoil phase (Fig. 1C and Fig. 2, top). The compression phase was defined as a time period that the compression panel moved downward with compressing the air pump, whereas the recoil phase consisted of a time period that the compression panel moved upward and moved downward without compressing the air pump (Fig. 1C and Fig. 2, top).

Assessment of state of the mitral and aortic valves

The pressure differences between AoP and LVP (AoP-

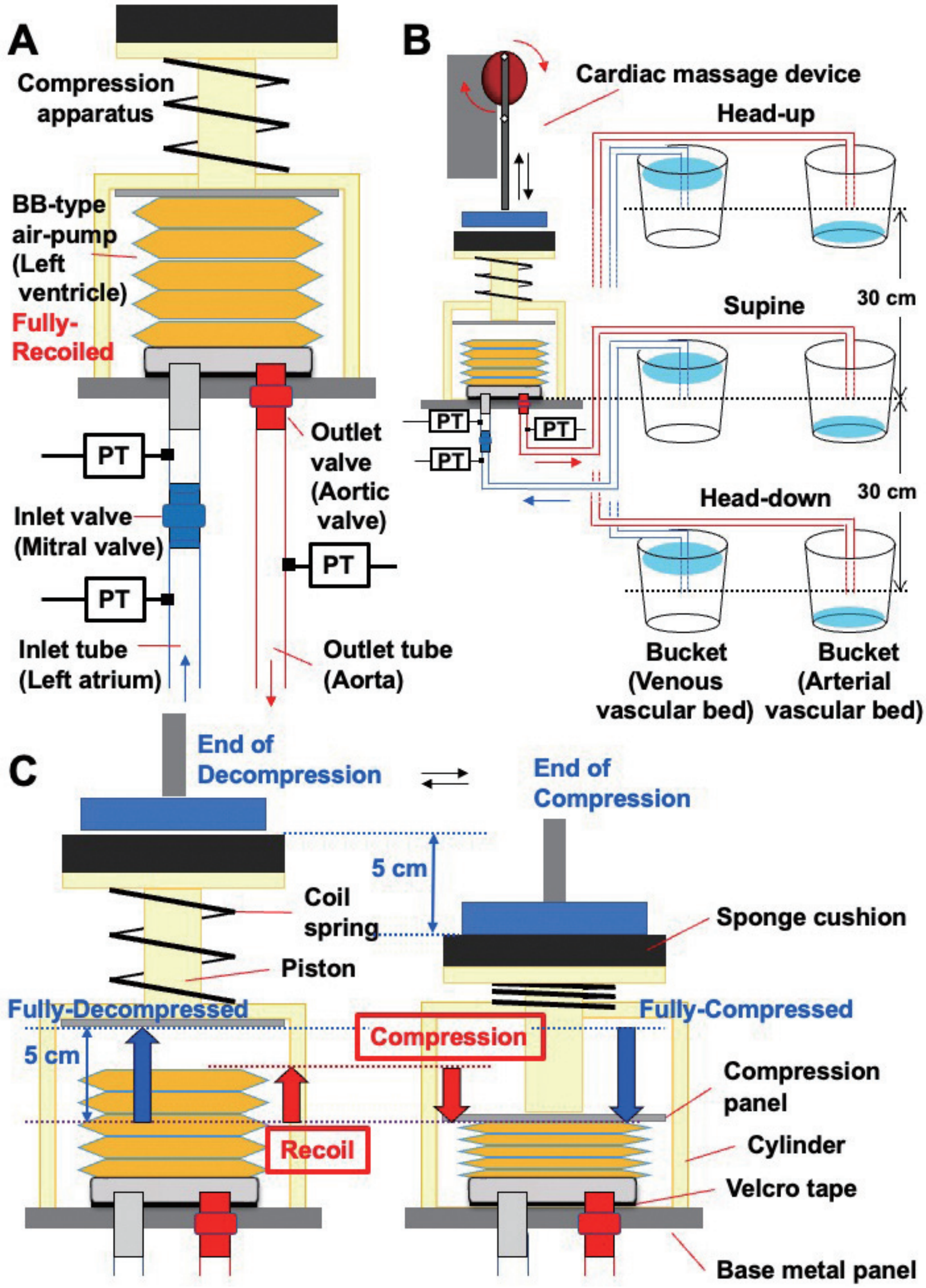

Fig. 1

Schematic representation of the experimental system. (A) The physical heart simulator with a fully recoiled condition, consisting of the compression apparatus; inlet tube (Left atrium); inlet valve (=Mitral valve); BB-type air pump; a commercially available, portable and lightweight foot pump (=Left ventricle); outlet valve (=Aortic valve); outlet tube (Aorta); and pressure transducers (PTs) to measure the left atrial, left ventricular and aortic pressures. A plastic, circular mono-leaflet, check valve with an inner diameter of 14 mm was used for the mitral and aortic valves. (B) The whole experimental system, consisting of the motor-driven automatic cardiac massage device and physical heart simulator along with two buckets simulating arterial and venous vascular beds at 3 different positions of head-up (+30 cm), supine (0 cm level) and head-down (−30 cm). (C) Condition of the pump during cardiac massage at the end of decompression and that of compression. Note that fully recoiled condition of the pump was not attained during cardiac massage. Bottom face of the pump was fixed to the base metal panel using Velcro tape.

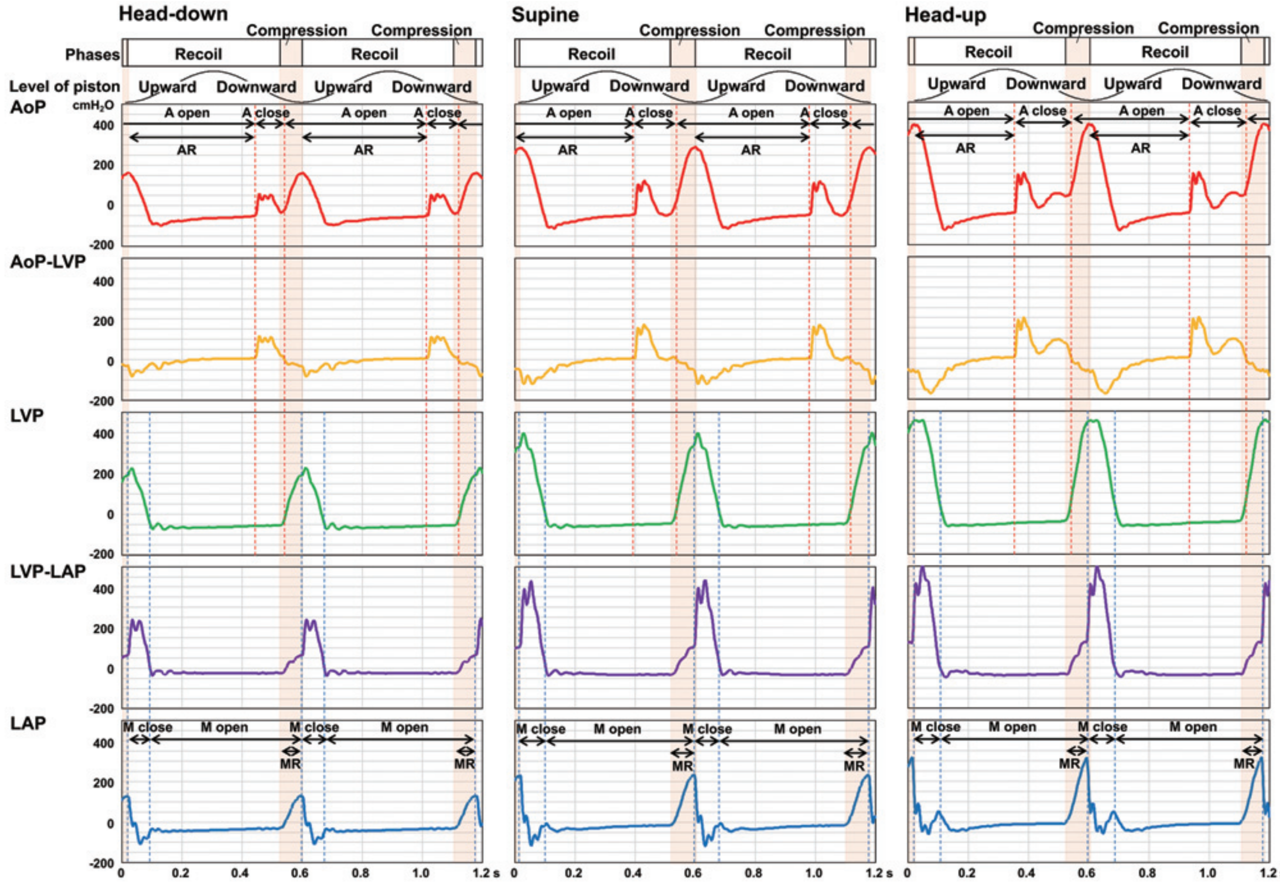

Fig. 2

Typical tracings of the aortic (AoP), left ventricular (LVP) and left atrial (LAP) pressures along with their pressure differences between AoP and LVP (AoP-LVP) as well as between LVP and LAP (LVP-LAP) during cardiac massage with head-down, supine and head-up positions. The cardiac cycle was divided into 2 phases; namely, compression phase and recoil phase of the pump. Note that AoP-LVP was below zero-pressure line during the early recoil phase, reflecting the magnitude of suction by the ventricle, which was greater in the order of head-up, supine and head-down positions. A: aortic valve; AR: aortic valve regurgitation; M: mitral valve; and MR: mitral valve regurgitation.

LVP) as well as between LVP and LAP (LVP-LAP) were calculated to estimate the state (open or closed) of mitral and aortic valves. When there was actually no difference in the pressure between the two consecutive chambers, the valve between the chambers was judged to be open. Meanwhile, when an apparent difference in the pressure waveforms was observed between them, the valve was considered to be closed. Using these criteria, the state of mitral and aortic valves was estimated (Fig. 2).

Statistical analysis

Data are presented as mean±SD (n = 5). Statistical differences in the measured values among three positions were examined by one-way, repeated-measures analysis of variance (ANOVA) followed by a post-hoc test for multiple comparisons (Bonferroni's test) to determine the statistical significance among the head-up, supine and head-down positions. A p-value < 0.05 was considered to be statistically significant.

Results

Effects of head-position change on the cardiac output and stroke volume

Cardiac output and stroke volume during the cardiac massage with head-down, supine and head-up positions are summarized in Table 1. The cardiac output and stroke volume increased to 1.23 times with head-up position from those with supine position, whereas those decreased to 0.65 times with head-down position from those with supine position. These results indicated that head-up position significantly increased the net forward blood flow during cardiac massage, and its reverse was true for head-down position.

Table 1 Cardiac output, stroke volume and time windows for the state of mitral and aortic valves

			Head-down	Supine	Head-up
Cardiac output (L/min)			1.65 ± 0.01 **	2.52 ± 0.00	3.10 ± 0.01 ** ††
Stroke volume (mL)			15.7 ± 0.1 **	24.0 ± 0.0	29.5 ± 0.1 ** ††
Compression phase		Total duration (ms)	73 ± 2 **	80 ± 2	80 ± 1 ††
	Mitral valve	Closed duration (ms)	0 ± 0 **	4 ± 1	6 ± 1 ** ††
		Open duration (ms)	73 ± 2 *	77 ± 2	74 ± 1 *
	Aortic valve	Closed duration (ms)	18 ± 2	19 ± 1	22 ± 2 †
		Open duration (ms)	54 ± 2 **	61 ± 2	58 ± 1
Recoil phase		Total duration (ms)	507 ± 2 **	500 ± 2	500 ± 1 ††
	Mitral valve	Closed duration (ms)	74 ± 1 **	83 ± 1	87 ± 2 ** ††
		Open duration (ms)	433 ± 2 **	417 ± 2	413 ± 1 ††
	Aortic valve	Closed duration (ms)	80 ± 6 **	118 ± 3	164 ± 1 ** ††
		Open duration (ms)	427 ± 6 **	382 ± 2	336 ± 1 ** ††

Data are presented as mean ± SD (n = 5). *$p < 0.05$ vs. Supine; **$p < 0.01$ vs. Supine; †$p < 0.05$ vs. Head-down; and ††$p < 0.01$ vs. Head-down

Effects of the head-up and head-down positions on the pressure waveforms

Typical tracings of the AoP, LVP and LAP from the simulation model along with those of AoP-LVP and LVP-LAP during cardiac massage with head-down, supine and head-up positions are depicted in Fig. 2. Durations of each state (open or closed) of the mitral and aortic valves during the compression and recoil phases are summarized in Table 1. The durations of a cardiac cycle were 580 ± 0, 580 ± 1 and 580 ± 1 ms for head-down, supine and head-up positions, respectively, among which no significant difference was observed.

Compression phase

The total duration as well as the open and closed durations of the mitral and aortic valves during the compression phase are summarized in Table 1. Head-up position hardly altered the total duration compared with supine position, whereas head-down position shortened it from 80 to 73 ms, indicating that the start of compression was delayed, since recoil speed of the pump with head-down position was slower than that with supine or head-up position, leading to less sufficient diastole during the recoil phase (Fig. 1C, left and Fig. 2, left). As for the mitral valve, head-up position prolonged the closed duration compared with supine position, but head-down one shortened it, indicating that head-up position hastened closure of the mitral valve, and that its reverse was true for head-down position. Open duration of the mitral valve reflected the difference between the total duration and closed time. Meanwhile, as for the aortic valve, head-up position tended to prolong the closed duration compared with supine position ($p = 0.12$), but head-down one hardly altered it, indicating that head-up position delayed the opening of the aortic valve. Open duration of the aortic valve reflected the difference between the total duration and closed time.

Recoil phase

The total duration as well as the open and closed durations of the mitral and aortic valves during the recoil phase are summarized in Table 1. Head-up position hardly altered the total duration compared with supine position, whereas head-down position prolonged it, indicating that recoil speed of the pump with head-down position was slower than that with supine or head-up position as already described (Fig. 1C, left and Fig. 2, left). As for the mitral valve, head-up position prolonged the closed duration compared with supine position, but head-down one shortened it, indicating that head-up position delayed the opening of the mitral valve, and that its reverse was true for head-down position. Open duration of the mitral valve reflected the difference between the total duration and closed time. Meanwhile, as for the aortic valve, head-up position markedly and significantly prolonged the closed duration compared with supine position, but head-down one shortened it, indicating that head-up position hastened closure of the aortic valve, and its reverse was true for head-down position. Open duration of the aortic valve reflected the difference between the total duration and closed time.

Discussion

We studied how the level of head position during cardiac massage affects the cardiac output, stroke volume, AoP, LVP and LAP using the physical heart simulator to explore unknown beneficial mechanisms of head-up position. We confirmed that head-up position can significantly increase the net forward blood flow during cardiac massage. Meanwhile, cardiac massage may induce regurgitation through the mitral and aortic valves during the compression and recoil phases, respectively, which would limit the effectiveness of cardiac massage.

Lack of isovolumetric contraction and relaxation

The regurgitation of mitral and aortic valves induced characteristic changes in the pressure waveforms in each chamber (Fig. 2). The mitral valve closed around the end of compression phase, whereas the aortic valve shut at late in the recoil phase. Namely, when the ventricle started to be compressed, the mitral valve remained open, resulting in a lack of isovolumetric contraction. In addition, when the ventricle started to recoil, the aortic valve was left open, resulting in a disappearance of isovolumetric relaxation. Such mechanically unfavorable situation could occur in patients and animals receiving cardiac massage, since the arrested heart is flaccid and is just compressed and recoiled, making the mitral and aortic valves unable to exert their physiologically sound function.[9–11]

Intracardiac hemodynamics

Although the increase of cardiac output during cardiac massage with head-up position has been considered to depend on the increase of venous return,[1–6] the mitral and aortic valve regurgitations occurring during cardiac massage should have attenuated its efficiency. Those regurgitations have been qualitatively confirmed in patients and dogs during cardiac massage, of which quantitative analysis remains limited.[9–11] Given a lack of such information, we tried to understand the intracardiac hemodynamics during cardiac massage using the developed pressures in each chamber, with which kinetics of the mitral and aortic valves could be estimated (Table 1 and Fig. 2). Namely, head-up position hastened closure of the mitral valve during the compression phase, which could be explained by larger "dynamic pressure" that was developed by greater upstroke velocity of the LVP. Meanwhile, head-up position delayed the opening of the mitral valve during the recoil phase, which could be partly explained by longer downstroke period of the LVP derived from its higher peak pressure. Conversely, head-up position tended to delay the opening of the aortic valve during the compression phase, which could be partly explained by larger afterload produced by head-up position. More importantly, head-up position hastened closure of the aortic valve during the recoil phase, markedly and significantly abbreviating the time window for aortic valve regurgitation, which would be brought about by greater dynamic pressure from the aorta to the left ventricle. These intracardiac hemodynamic changes associated with head-up position may partly contribute to the increase of cardiac output, whereas their reverse mechanisms would be possible for head-down position.

Clinical implication

In the current mechanical model of cardiopulmonary circulation, cardiac massage with head-up position produced a pressure gradient of 30 cm H_2O between the left ventricle and the brain, which could increase venous return from the brain to the heart during the recoil phase, possibly contributing to the decrease of intracranial pressure.[4, 5] The increased venous return along with the shortened time window for aortic valve regurgitation will elevate the net cardiac output during following compression phase, although such beneficial effects of head-up might be partly offset by the expansion of vascular beds in the lower extremities. When the left ventricle is postulated to be set in the lowest position with lower extremity elevated in the current model, similar responses in the intracardiac hemodynamics could occur. However, the intracranial pressure in such position would increase, since venous return from the brain will not increase rather decrease during the recoil phase, and the cardiac output may increase during the compression phase. In effects, head-up position may have potential to improve the prognosis of patients undergoing cardiac massage.

Study limitation

There are several limitations in this study. First, the right side of the heart was not considered in this experiment. During cardiac massage, pulmonary arterial pressure becomes almost equal to aortic pressure,[11] causing significant changes in the pulmonary circulatory system including the onset of pulmonary edema, which are not taken into account. Second, the results can be highly dependent on the mechanical properties of the valves of the heart simulator. We adopted plastic, circular mono-leaflet, check valves with an inner diameter of 14 mm for the mitral and aortic ones, which may not necessarily mimic the properties of biological ones. However, they may at least in part estimate the impact of head position on the state of the mitral and aortic valves during cardiac massage.

Third, tap water was used to simulate the blood. As the water exerts smaller viscosity compared with that of the blood, it would produce less great "dynamic pressure" on the valves than the blood. As a result, in this study, we observed longer open time of the mitral valve during the compression phase and that of the aortic valve during the recoil phase compared with those expected from our previous in vivo canine study with the fibrillating hearts.[11] Forth, the tube was too hard to simulate the compliance of aorta. The vascular compliance in a living body may elevate the dynamic pressure of blood flow toward the left ventricle during the recoil phase via Windkessel effect,[16] which can hasten closure of the aortic valve, further abbreviating the time window for the aortic valve regurgitation.

Conclusion

Mechano-physiological analyses using the physical heart simulator indicate that cardiac massage with head-up position can markedly and significantly hasten closure of the aortic valve during the recoil phase, partly contributing to the effective augmentation of forward blood flow. These experimental findings may add insight into clinical practice of cardiac massage with head-up position.

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Authors' contribution: A.G., R.K., and A.S. conceived and designed research. A.G., R.K., K.C., and Y.N. conducted experiments. A.G., R.K., and A.S. analyzed data and wrote the manuscript. All authors read, discussed and approved the manuscript.

Conflicts of interest: None declared.

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