Cyclic Elevation of Intrathoracic Pressure Can Close the Mitral Valve During Cardiac Arrest in Dogs

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Mitral valve closure during cardiopulmonary resuscitation may result from direct cardiac compression. An alternative hypothesis is that with a rise in intrathoracic pressure, mitral valve closure can occur but may be influenced by whether the lungs are inflated or deflated. To test this hypothesis, we placed a large-bore cannula into the thoraces of 11 dogs. Intrathoracic pressure was changed by inflating and deflating the thorax through the cannula while the airway was open, as well as by inflating and deflating the lungs with the thoracic cannula clamped. Mitral valve motion was observed with two-dimensional echocardiography from the right chest wall or esophagus in eight of the dogs. With a rise in intrathoracic pressure from thoracic inflation, all eight dogs showed closure of the mitral valve, while with thoracic deflation, all showed mitral valve opening. With lung inflation and deflation alone, however, the mitral valve remained open throughout the cycle. In seven dogs, with thoracic inflation, the peak gradient from the left ventricle to the left atrium was (mean ± SEM) 18 ± 4 mm Hg and the average gradient was 7 ± 3 mm Hg, while with lung inflation alone, the average gradient was −1 ± 1 mm Hg (p<0.01 vs. thoracic inflation). Thus, mitral valve closure, with concomitant retrograde pressure gradients, can be produced by intrathoracic pressure changes with accompanying lung deflation. With lung inflation alone, however, the mitral valve remains open, and there are no significant transmural pressure gradients. We conclude that intrathoracic pressure changes can cause the mitral valve to close or to remain open, depending on how intrathoracic pressure is generated. (Circulation 1988;78:754–760)

The mechanisms of blood flow during cardiopulmonary resuscitation (CPR) remain controversial. In 1960, it was proposed that blood moved because of direct compression of the heart between the sternum and vertebral column.1 It was not until 1980, however, that compelling evidence was provided that blood moves during chest compression because of phasic changes in intrathoracic pressure.2 According to this model, chest compression produces a rise in the pressure in all intrathoracic vascular structures. This pressure is transmitted from intrathoracic to extrathoracic arteries. Competent venous valves3,4 and the large extrathoracic venous compliance prevent the full transmission of pressure to the extrathoracic veins. The difference in pressure between extrathoracic arteries and veins causes blood to move from the thorax into the extrathoracic arterial system. With blood movement by intrathoracic pressure changes, it was thought that the mitral valve was open during chest compression, so that the heart was a passive conduit for blood flow.4–7

Since 1980, some studies have supported the theory of blood movement by direct cardiac compression,8,9 while others have supported the theory of blood movement by intrathoracic pressure changes.10,11 It has recently been shown that mitral valve closure occurred during short duration (200–250 msec/cycle) manual chest compression.12 These data were interpreted as indicating that mechanical cardiac compression was the mechanism responsi-
ble for blood movement because the mitral valve closure showed that the heart was not a passive conduit.12

Mechanical compression of the heart is, however, only one possible mechanism of mitral valve closure during chest compression. We hypothesized that during a rise in intrathoracic pressure with accompanying lung deflation, the mitral valve may close because the left atrial pressure may rise less than the left ventricular pressure. Under CPR conditions, left atrial pressure may be influenced by alveolar pressure, which could rise less than intrathoracic pressure.13 The lower left atrial pressure would cause the mitral valve to close. With lung inflation alone, however, the mitral valve should remain open.

**Materials and Methods**

**Preparation**

Eleven mongrel dogs weighing 20–32 kg were anesthetized with pentobarbital sodium (15 mg/kg i.v.). Supplemental pentobarbital was administered as needed. An endotracheal tube was inserted, and the dogs were ventilated with room air by a volume-cycled respirator (Model 607, Harvard Apparatus, South Natick, Massachusetts). A limited thoracotomy was performed in the fourth left intercostal space in nine of the dogs and in the fourth right intercostal space in the remaining two dogs. The middle mediastinal pleura was removed to allow free movement of air throughout the thorax. In seven of the dogs, a micromanometer-tipped catheter (Model PC-470, Millar Instruments, Houston, Texas), set at zero and calibrated at 37° C, was placed through a small incision in the pericardium, through the left atrial appendage, and advanced into the left atrium. An inflation-deflation port (Figure 1) was secured in the intercostal space, and the chest was closed in layers. The chest was then wrapped circumferentially with 2-in. wide adhesive tape at the level of the sixth rib to limit expansion. From a femoral cutdown, a pacing catheter was placed into the right ventricle, and micromanometer-tipped catheters were placed into the right atrium, ascending aorta, and, in dogs with left atrial catheters, the left ventricle. The vascular pressures did not change significantly after the tape was applied, and all vascular pressures were recorded after the tape was applied. All dogs were studied in the supine position. Sodium heparin (200 units/kg i.v.) was administered. Cardiac arrest was induced by applying 60 Hz alternating current (6.3 V) to the pacing catheter.

**Mitral Valve Motion and Directional Flow**

After induction of ventricular fibrillation, intrathoracic pressure changes were induced by cyclically inflating and deflating the thorax through the inflation-deflation port with a programmable pneumatic generator14 in eight dogs. The left ventricular and left atrial catheters were present in four of the dogs. With the programmable pneumatic generator, air moved into the thorax from a high pressure source under computer control. The amount of time that air moved into the thorax (30–250 msec) determined the peak pressure. The inflation-deflation cycle rate was 40–60/min. High intrathoracic pressure was maintained for 20–50% of the cycle by clamping the pressure source after the desired peak pressure was obtained. During the initial 200–400 msec of deflation, negative pressure (−100 mm Hg) was applied to the inflation-deflation port to facilitate movement of air out of the thorax. For the remainder of the deflation phase of the cycle, the port was open to atmosphere. Ventilation was as before arrest, except that the trachea was open to atmosphere during intervals when data were recorded. Intrathoracic pressure changes were also induced by lung ventilation alone through the endotracheal tube with the inflation-deflation port clamped.

Echocardiographic images and color Doppler flow maps were recorded from the right chest wall or esophagus with a two-dimensional ultrasonic imaging–Doppler system (Model 77020A, Hewlett-Packard) with 5-MHz transducers (both standard and transesophageal). Two-chamber views were used with transesophageal imaging, and long-axis modified parasternal views were used with external chest wall imaging. The timing of the ultrasonic images with respect to inflation and deflation of the thorax or lungs was determined by two independent methods. First, the sounds of the pneumatic generator were recorded on the audio channel of the ultrasonic system, and inflation or deflation could easily be identified by characteristic sounds. Second, aortic pressure was recorded directly on the images. Images and flow maps, along with the simultaneous audio and pressure signals, were recorded on 1/2-in. video tape (Panasonic AG6300).

**Left Ventricular-to-Left Atrial Pressure Gradient**

Intrathoracic pressure changes were generated as in the previous protocol. Left ventricular and left atrial pressures were measured in seven dogs. Four
of the dogs were common to the previous protocol. Pressure signals were recorded on an eight-channel oscillographic recorder (Gould, Cleveland, Ohio) and were digitized and stored by a microcomputer-based data acquisition system. After completion of each study, the micromanometer-tipped catheters were connected to a common pressure source to verify that their calibrations were identical.

Statistical Analysis

Differences between paired data were tested with the paired t test. p<0.05 was considered statistically significant. Data are mean ± SEM.

Results

Mitral Valve Motion and Directional Flow

Representative long-axis images from the right chest wall of three dogs during thoracic inflation and deflation are shown in Figure 2. The mitral valve leaflets were approximated in a manner similar to that seen during left ventricular systolic contraction during the inflation phase of the cycle (upper panels) but separated widely during the deflation phase of the cycle (lower panels). Similar images were obtained in all eight dogs, showing clear mitral valve closure during thoracic inflation and opening during deflation. With lung ventilation alone, however, the mitral valve leaflets remained separated during both inspiration and expiration.

Color-flow maps from the right chest wall were obtained in four dogs but were inadequate for analysis because of the motion artifact produced by sudden expansion of the chest wall. High-quality color-flow images that were free of significant artifact were obtained from the transesophageal approach in three dogs. Images from one such dog during thoracic inflation and deflation are shown in Figure 3. As the mitral valve leaflets closed during thoracic inflation (upper panel), there was a jet of regurgitant mitral flow (red). This retrograde flow ceased after the mitral valve leaflets were fully coapted. As the mitral valve leaflets separated during deflation (lower panel), there was an antegrad mitral flow jet (blue) indicating flow from the left atrium to the left ventricle. Similar flow maps were obtained in all three dogs.

Left Ventricular-to-Left Atrial Pressure Gradient

With thoracic inflation, the left ventricular pressure was higher than the left atrial pressure for most of the high-pressure portion of the cycle in all seven dogs in which it was recorded. Recordings from one dog are shown in Figure 4. The peak left ventricular-to-left atrial pressure gradient during the high-pressure portion of the cycle was 18 ± 4 mm Hg, and the average pressure gradient was 7 ± 3 mm Hg. The maximum left ventricular pressure generated was 84 ± 11 mm Hg.
With lung ventilation alone, the left ventricular-to-left atrial pressure gradient averaged $-1 \pm 1$ mm Hg ($n=7$, $p<0.01$ vs. thoracic inflation), but the maximum left ventricular pressure generated was only $41 \pm 9$ mm Hg. Peak pressure gradients were not analyzed because of the oscillatory nature of the gradient (Figure 5).

**Discussion**

Even if there were regional differences in intrathoracic pressure produced by thoracic inflation, pressure would equilibrate very shortly after airflow ceased. The left ventricular-to-left atrial pressure gradients were present even after airflow into the thorax ceased because air flowed into the thorax only during the upstroke of the high-pressure phase of the cycle (Figure 4). Thus, the pressure gradients were not an artifact of air movement into the thorax.

If lung volume were to remain constant as intrathoracic pressure rises, then the pressure surrounding pulmonary vessels would rise by the same amount as the increase in intrathoracic pressure. Under these circumstances, the pressures in the pulmonary vasculature and left heart would rise in tandem, and retrograde flow would not occur. In the current studies, however, the airway was open during thoracic inflation (Figure 6). Air could be compressed and flow out of the lungs as intrathoracic pressure was raised, thereby decreasing lung volume. Previous workers have shown that the pulmonary circulation contains two types of vessels that are defined by the way their surrounding pressures change when lung volume changes.$^{16,17}$ Lung deflation causes the pressure surrounding alveolar vessels to decrease relative to pleural pressure. In contrast, deflation causes the pressure surrounding extra-alveolar vessels to rise relative to pleural pressure. Under most circumstances, the effect on alveolar vessels is predominant.$^{18,19}$ This could allow the pressure in the pulmonary circulation and left atrium to fall relative to left ventricular pressure, resulting in a retrograde pressure gradient and mitral valve closure.

The effects of increases in lung volume on pulmonary vascular pressures were also apparent when CPR was performed by lung inflation without thoracic inflation (Figure 5). Lung inflation caused the pressure surrounding alveolar vessels to rise relative to pleural pressure. This caused the pressure in the pulmonary circulation to increase relative to the pressure in the left heart, resulting in a small forward pressure gradient.

Mitral valve closure during short duration (200–250 msec/cycle) manual external CPR has been reported.$^{12}$ The mitral valve closure and concomitant pressure gradients were taken as evidence that the mechanism of blood movement during chest
compression is mechanical compression of the heart. Because there was no evidence of entrapment of the heart between the sternum and vertebral column, it was reasoned that the inertia of the heart held it fixed while the momentum applied to the chest wall was transferred to the heart and compressed it directly. The present study shows, however, that pure intrathoracic pressure changes can produce left ventricular-to-left atrial pressure gradients (Figure 4) and cause the mitral valve to close (Figures 2 and 3) in the absence of any mechanical cardiac compression. Closure of the mitral valve during chest compression, therefore, does not allow one to distinguish whether blood moves because of mechanical compression of the heart or because of changes in intrathoracic pressure. In the present study, the chest wall moved away from the heart as the mitral valve closed, making it impossible for any momentum to be transferred from the chest wall to the heart directly.

The intracardiac pressure gradients produced by the highest-force compression technique in the study

\[ \text{Figure 4. Plot of intracardiac pressures during thoracic inflation and deflation in one dog. Left ventricular (LV) pressure is higher than left atrial (LA) pressure during most of high-pressure phase, and difference in those pressures (LV-LA) is shown separately.} \]

\[ \text{Figure 5. Plot of intracardiac pressures during lung ventilation alone in one dog. Left ventricular (LV) pressure is nearly identical to left atrial (LA) pressure during entire cycle, and difference in those pressures (LV-LA) is shown separately.} \]
FIGURE 6. Schematic representation of thorax during rises in intrathoracic pressure (ITP). Alveolar vessels are, by definition, exposed to alveolar pressure (P_{alv}). Extra-alveolar vessels (E.-A.) are not exposed to alveolar pressure, but their effect on pulmonary vascular pressure is less than that of the alveolar vessels (see text). If alveolar pressure rises less than intrathoracic pressure because of compression and movement of alveolar air out of the lungs, pulmonary venous pressure will be at some intermediate level between alveolar pressure and intrathoracic pressure. Left atrial (LA) pressure could, thereby, be less than intrathoracic pressure. Because the left ventricle (LV) would be subjected to intrathoracic pressure, the left ventricular pressure would be greater than the left atrial pressure, thereby producing a pressure gradient that could cause the mitral valve to close.

of manual CPR\textsuperscript{12} were higher than those produced by thoracic inflation in the current study (peak, 38.5 ± 4 vs. 18 ± 4 mm Hg; mean, 13.5 ± 2.9 vs. 7 ± 3 mm Hg). These higher gradients were probably due to the higher left ventricular peak pressures generated in those studies (129 ± 10 vs. 84 ± 11 mm Hg for thoracic inflation). In addition, manual chest compression may have produced a nonuniform rise in intrathoracic pressure that would favor generation of the pressure gradient, or there may have been some degree of cardiac compression contributing to the gradients. A lower-force manual technique in the studies of manual CPR\textsuperscript{12} still produced mitral closure but produced peak left ventricular pressures of 75 ± 7 mm Hg and pressure gradients that were less (peak, 13 ± 4 mm Hg; mean, 5.1 ± 2 mm Hg) than those produced by thoracic inflation.

Previous studies with nuclear flow and angiographic techniques in dogs have shown that blood moved through the heart during chest compression,\textsuperscript{4,5} suggesting that the heart is a passive conduit for blood flow caused by generalized rises in intrathoracic pressure. Although those data seem to contradict our present study, there are important differences between the ventilation patterns that must be considered. In the nuclear flow study,\textsuperscript{5} there was high pressure ventilation simultaneous with the chest compression. This could have increased the pressure in the pulmonary circulation relative to intracardiac pressures, resulting in forward flow across the mitral valve. In the cineangiographic study,\textsuperscript{4} antegrade flow across the mitral valve increased markedly only when simultaneous ventilation was added to chest compression, again likely increasing the pressure in the pulmonary circulation relative to intrathoracic pressure. Additional factors that have been shown to affect blood flow through the heart during CPR are the rate of chest compression and the vascular volume status.\textsuperscript{13} Low rates and increased intravascular volume are associated with more antegrade flow through the heart during compression, while higher rates and decreased intravascular volume are associated with elimination of antegrade flow during compression.\textsuperscript{13}

Echocardiographic studies of CPR in humans have also shown that the mitral valve is open during chest compression.\textsuperscript{5,7} In those studies, it is not known whether the level of intrathoracic pressure generated was insufficient to produce significant intracardiac pressure gradients, whether the heart simply was a passive conduit for flow produced by intrathoracic pressure changes, whether the degree of cardiac compression was insufficient to produce mitral valve closure, what effects the duration of cardiac arrest had on the observed findings, or what effects the rate of compression or the intravascular volume status had.

In summary, pure rises in intrathoracic pressure with accompanying lung deflation can produce higher pressures in the left ventricle than in the left atrium and cause the mitral valve to close. With intrathoracic pressure changes from lung inflation alone, however, the mitral valve remains open. We conclude that intrathoracic pressure changes can cause the mitral valve to close or to remain open, depending on how intrathoracic pressure is generated.

References


**KEY WORDS** • cardiopulmonary resuscitation • blood flow • echocardiography
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