Intact Chordae Tendineae Increase Ventricular Volume Measurement Error by the Balloon Method

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Summary

We assessed the accuracy of the intraventricular balloon method of left ventricular volume measurement with all chordae tendineae intact and then severed. The space between the endocardium and the balloon is the source of the volume measurement error. We assessed the volume errors at different intra-balloon pressures between 50 and 250 mmHg, using formalin fixed canine left ventricles. The volume error with all chordae tendineae intact was significantly greater than with all chordae tendineae severed at any balloon pressure. The difference of the volume errors under these two conditions amounted to 1.9-3.3 ml regardless of intra-balloon pressures. We visually confirmed that this difference predominantly originated from the space behind the tense chordae tendineae.

Additional Indexing Words:
Dog Left ventricle Volumetry Pressure-volume relation

When one assesses the left ventricular performance in terms of the pressure-volume relationship, left ventricular volume must be measured accurately. To measure the absolute volume of the left ventricular lumen in an isolated beating heart, a thin latex balloon has conventionally been fitted in the lumen after cutting all chordae tendineae and the intraballoon water volume has been measured directly with a variety of volumetric systems. Recently, Hansen et al reported that intact chordae tendineae contributed to normal left ventricular contractility. They assessed the left ventricular contractility by Emax (the slope of the end-systolic pressure-volume relationship), in cardiopulmonary bypassed hearts. They measured left ventricular volume by the intraventricular balloon method,

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using a compliant latex balloon with all chordae tendineae intact and then all chordae severed. Their results showed that ventricular contractility (in terms of Emax) decreased after all chordae tendineae were cut.

We have been using the left ventricular balloon method in our laboratory. We always cut all chordae tendineae to fit the balloon within the left ventricular lumen. From our experience, we suspected that the accuracy of left ventricular volume measurement would decrease considerably with the chordae tendineae intact.

Suga and Sagawa have already reported an accuracy of the intraventricular balloon method with all chordae tendineae severed in formalin fixed hearts. We now compared the accuracy of the intraventricular balloon method between before and after all chordae tendineae were severed in similar formalin fixed hearts.

**METHODS**

Nine mongrel dogs (13–15 kg) were anesthetized with pentobarbital sodium (25 mg/kg, i.v.) and the hearts were arrested with a 20 ml bolus i.v. injection of KCl (3 mEq/L). The chest was opened and the heart was excised. The ascending aorta and the right auricle of the excised heart were cannulated with polyethylene tubes. Ten-percent formalin was injected into the ascending aorta to fill all the cardiac chambers and coronary vessels to an arbitrary left ventricular volume. The hearts were immersed in 10% formalin for 2–5 days. The fixed hearts had widely different intraventricular volumes as listed in Table I.

We assessed the volume error by the balloon method in these fixed hearts as described previously. We defined the volume error as the volume of the residual space between the intraventricular latex balloon and the endocardial surface. We assumed that the formalin fixed hearts would mimic beating hearts at end systole.

We prepared a balloon apparatus similar to that of Hansen et al. The balloon apparatus in this study consisted of three elements: 1) a thin

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**Table I. Materials**

<table>
<thead>
<tr>
<th>Dog No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>mean±SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW (kg)</td>
<td>13</td>
<td>13</td>
<td>14</td>
<td>15</td>
<td>13</td>
<td>15</td>
<td>13</td>
<td>13</td>
<td>15</td>
<td>13.8±1.0</td>
</tr>
<tr>
<td>LVW (g)</td>
<td>67.6</td>
<td>89.2</td>
<td>93.5</td>
<td>110.1</td>
<td>89.9</td>
<td>74.6</td>
<td>67.3</td>
<td>59.7</td>
<td>112.3</td>
<td>84.9±18.9</td>
</tr>
<tr>
<td>LVV (ml)</td>
<td>14.0</td>
<td>15.2</td>
<td>21.5</td>
<td>46.5</td>
<td>36.3</td>
<td>53.0</td>
<td>39.0</td>
<td>27.2</td>
<td>22.3</td>
<td>30.6±13.8</td>
</tr>
</tbody>
</table>

Abbreviations: BW=body weight of the dog; LVW=left ventricular weight after fixation with formalin; LVV=volume of the left ventricular lumen.
latex balloon (Qualatex #9; kept stretched overnight to have an unstressed volume greater than the fixed left ventricular volume, 2) an acrylic disk (22 mm in diameter), and 3) a polyethylene connecting tube (4.15 mm OD, 3.15 mm ID), as shown in Fig. 1. Figure 1 also shows the heart preparation. The right and left atria were removed. First, to measure the volume error with all chordae tendineae intact, we held the heart vertically and filled the left ventricular lumen with water up to the mitral annulus. We then positioned the balloon in the left ventricle by placing the acrylic disk in the mitral annulus with two threads tightened with forceps. These threads had been passed behind the chordae tendineae. The balloon was then filled with water to different pressures between 50 and 250 mmHg in 50 mmHg steps. Water flowed over the mitral annulus and a small amount of water remained in the residual space between the ventricular chamber and the inflated balloon. We measured this residual water volume with a syringe after the balloon was deflated. This procedure was repeated 3 times for each intra-balloon pressure in each heart.

Second, after all chordae tendineae were severed, we repeated the same procedure to measure the residual water volume. Since the valves were free, we positioned the balloon in the left ventricle by manually holding the acrylic disk in the mitral annulus.

To compare the volume errors with and without chordae tendineae at each pressure, we used the paired t-test. To examine the dependence of the volume error with or without chordae tendineae on the pressure, we used analysis of variance (ANOVA) and F-tests. We also applied ANOVA to the difference of the volume error between with and without chordae tendineae.
Statistical significance was assumed at $p<0.01$.

**RESULTS**

Table I lists the body weight of the dogs from which the hearts were excised, left ventricular weight after the atria and the right ventricular free wall were removed, and left ventricular volume attained after fixation. The volume range of the fixed left ventricle was 14.0–53.0 ml, covering most of the normal working range of beating left ventricles.1)-8)

We found that the volume error of either measurement condition decreased with increases in intra-balloon pressure in each heart. At a given intra-balloon pressure, the volume error with chordae tendineae intact was always greater than that with chordae tendineae severed in each heart. The mean volume error before and after severing the chordae tendineae and their mean differences at different pressures are summarized in Fig. 2. The mean of the coefficients of variation of the volume error among different intra-balloon pressures and hearts was 32% with chordae tendineae intact and 31% with chordae tendineae severed. The volume error with chordae tendineae intact was significantly ($p<0.01$) greater than that with chordae tendineae severed at any intra-balloon pressure of 50–250 mmHg. The difference of the volume errors ($\Delta$ volume error) before and after severing the chordae

![Figure 2](image_url)

Fig. 2. (A) Mean volume errors as a function of intra-balloon pressure with chordae tendineae intact (■) and severed (○). Data are expressed as mean±SD (n=9). * indicates statistically significant difference by paired t-test $p<0.01$. (B) Means of differences of the volume errors ($\Delta$ volume error) between chordae intact and severed. Data are expressed as mean±SD.
tendineae did not significantly change with the intra-balloon pressure ($F > 0.05$).

To study the location of the residual space with chordae tendineae intact, we bored holes (10 mm in diameter) through the left ventricular wall above the heads of two papillary muscles. We found considerable residual space behind the intact tense chordae tendineae. The space decreased after all chordae tendineae were cut. These holes were plugged with rubber stoppers when the residual volume was measured. Although we could not directly quantify the residual space behind the tense chordae tendineae, it appeared not to decrease with increasing intra-balloon pressure.

**Discussion**

The absolute values of the volume errors in this study were slightly greater than those reported previously by Suga and Sagawa, despite the use of similar formalin fixed dog left ventricles and balloons in both studies. These differences may be partly due to differences in the shape and structure of the balloon connector. Because Suga and Sagawa used a larger-bore balloon connector, which fitted directly into the mitral annulus, their preparation probably had a smaller residual volume near the mitral annulus.

We used 10% formalin to obtain fixed hearts which were stiff enough to withstand 50–250 mmHg intra-balloon pressures without marked dilatation. The fixation enabled us to obtain different sized rigid left ventricles resembling end-systolic left ventricles. Although the fixation may have also stiffened the chordae tendineae, limiting their distensibility, the natural chordae tendineae are also very stiff. Therefore, we assume that severing the formalin fixed chordae tendineae reasonably simulates the severing chordae tendineae in situ.

We consider that the $J$ volume error as seen in Fig. 2 was mainly due to the space behind the tense chordae tendineae, as we confirmed visually. The $J$ volume error did not significantly change with intra-balloon pressure.

What then is the origin of the volume error after all chordae tendineae are severed? Given a spherical balloon for example, the balloon volume $V$ is

$$V = \frac{4}{3} \pi r^3,$$

where $r$ is radius of the balloon.

- When $r = 2\text{ cm}$, $V = \frac{4}{3} \pi 2^3 = 33.5 \text{ ml}$.
- When $r = 2.05\text{ cm}$, $V = \frac{4}{3} \pi 2.05^3 = 36.1 \text{ ml}$.
- When $r = 2.1\text{ cm}$, $V = \frac{4}{3} \pi 2.1^3 = 38.8 \text{ ml}$.

The volume difference between $V_{r=2}$ and $V_{r=2.05}$ is 2.6 ml, and the volume
Fig. 3. Schematic diagram of the end-systolic pressure-volume relation (ESPVR) considering the volume error. (A) The broken line shows the true ESPVR without any volume measurement error. Its slope is $E_{\text{max-t}}$. (B) The chained line simulates the ESPVR with volume error when all chordae tendineae are intact. Its slope is $E_{\text{max-i}}$, which will be smaller than $E_{\text{max-t}}$ because ventricular volume underestimation (black arrow) is greater at a lower pressure. The volume axis intercept of the chained line will be much smaller than that of the broken line. (C) The solid line simulates the ESPVR when all chordae tendineae are severed. Its slope is $E_{\text{max-s}}$, which will be the same as $E_{\text{max-i}}$ because $J$ volume error (white arrow) is pressure-independent. The volume axis intercept of the solid line will be greater than that of line B by $J$ volume error.

difference between $V_{r=2.05}$ and $V_{r=2.1}$ is 2.7 ml. This example suggests that even a 1 mm thick residual space around the balloon corresponds to the volume error of 2–3 ml in this range of radius. No natural left ventricle has a residual space of a uniform thickness of 0.5 mm or 1 mm, because the endocardial surface displays 0.5–2 mm deep trabeculae in the middle volume range. However, the balloon probably fits better to the endocardium with increasing intra-balloon pressure, decreasing an average thickness of the residual space and hence its volume. Therefore, the magnitude of the volume error observed after severing all chordae tendineae and its decrease with pressure may be explained by this simple model.

Let us compare the effect of the volume error on $E_{\text{max}}$ with all chordae tendineae intact ($E_{\text{max-i}}$) and severed ($E_{\text{max-s}}$), based on the results of this study and the assumption that the intraventricular pressure is not affected by the chordae tendineae. First, we must compare $E_{\text{max-i}}$ relative to true $E_{\text{max}}$ ($E_{\text{max-t}}$), which is assumed to be obtained when there is no volume error. We will underestimate the intraventricular volume by the volume error. The volume error at a lower pressure will be greater than that at a higher pressure (Fig. 2A). Therefore, $E_{\text{max-i}}$ will be smaller than $E_{\text{max-t}}$ as shown in Fig. 3. Second, we may compare $E_{\text{max-i}}$ and $E_{\text{max-s}}$. Ac-
ccording to the results in this study, the Δ volume error is independent of intraventricular pressure (Fig. 2B). Therefore, Emax-s will be the same as Emax-i although the volume axis intercept with all chordae tendineae severed will be greater than that with all chordae tendineae intact (Fig. 3). However, it remains unknown whether or not this situation holds in the intact beating heart.

Finally, ventricular contractility of the beating heart decreases when all chordae tendineae are severed because of the loss of their traction. However, Salter et al more recently showed that absence of chordal attachment after mitral valve replacement does not adversely affect ventricular geometry and systolic left ventricular function. This finding seems inconsistent with Hansen et al’s findings. Nevertheless, severing all chordae tendineae seems to be a prerequisite for reliable assessment of intraventricular volume and Emax by the balloon method, a possible Emax depression notwithstanding.

REFERENCES