Importance of Atrial Compliance in Cardiac Performance

By Hiroyuki Suga

ABSTRACT
Effects of changes in atrial compliance on cardiac performance were analyzed using a circulatory analog model. The atrium was assumed to be a noncontracting chamber with a constant compliance. It connected the venous return system, which was represented by mean circulatory filling pressure and a venous return resistance in accordance with Guyton's concept, with the ventricle, which was characterized by a time-varying elasticity. Atrial compliance was increased from near zero to a value at which atrial volume was twice ventricular stroke volume, while the parameters of ventricular contractility were kept unchanged. Cardiac output increased from 2,400 to 3,240 ml/min with increases in atrial compliance from 0.1 to 20 ml/mm Hg (venous return resistance 0.1 mm Hg sec/ml), whereas mean atrial pressure simultaneously decreased from 3.0 to 2.2 mm Hg. This result indicates that cardiac performance in terms of the cardiac output-mean atrial pressure relationship was markedly improved by increases in atrial compliance in spite of constant ventricular contractility. The analysis of the model strongly suggests that natural atrial compliance in situ, by pooling venous return flow during systole and supplying it to the ventricle during diastole, facilitates the transformation of the continuous venous return flow into the intermittent ventricular filling flow.

KEY WORDS
ventricular filling cardiac output Starling's law of the heart circulatory analog model atrial function venous return atrial size

The physiological significance of atrial compliance is not well understood, but some indirect evidence does suggest that it is important in hemodynamics. Brighton et al. (1) and Peters et al. (4th Annual Meeting of the Biomedical Engineering Society, 1973) have observed that the addition of a flexible atrium to the inlet of an artificial heart substantially improves the heart's output. However, performance of an artificial heart is not equal to that of the natural ventricle, and doubt still exists about the physiological significance of atrial compliance.

The purpose of the present analysis was to evaluate quantitatively the importance of atrial compliance in natural cardiac performance. In animal experiments, it is difficult to change atrial compliance alone without affecting venous return resistance, and slight changes in venous return resistance sensitively affect cardiac output (2). Therefore, a reasonable analog model of the cardiovascular system based on physiological findings in the literature was used in the present study. Atrial compliance was varied in the model while the other parameters of the venous return system—ventricular contractile state, valve characteristics, and arterial pressure—were kept constant. The results of this analysis suggest that an atrium with an appropriate compliance can increase cardiac output 35-80%.

Methods
Figure 1 shows the electric analog model of the circulatory system used in the present study; the right heart and the pulmonary circulation were purposely eliminated from the model to simplify the analysis. Arterial pressure (Pa) was modeled as if it were held constant and represented by a constant-voltage battery. The venous return system was modeled in accordance with Guyton's concept (2) as a venous return source pressure (Pv), which represents mean circulatory filling pressure, and a venous return resistance (Rv).

The ventricle was represented by a time-varying elasticity (E(t)) (the instantaneous pressure-volume ratio) in accordance with previous experimental findings on the ventricular pressure-volume relationship (3-5); a ventricular model of this type has conventionally been used by others (6-9). The time-varying elasticity of the ventricle increases during systole and reaches its peak value (E_{max}) at the end of systole (3-5). My previous mathematical analysis (3) has shown that the peak value of elasticity determines end-systolic intraventricular volume and hence stroke volume when the end-diastolic volume is given and that the time course per se of time-varying elasticity is not a primary determinant of either end-systolic or stroke volume. Therefore, in the present analysis, a simple time course was assigned to time-varying elasticity as a reasonable approximation of the physiologically observed time course. Elasticity was...
Analog model of the circulatory system. Pa = arterial pressure, Pv = venous return source pressure (mean circulatory filling pressure), Pat = atrial pressure, Vat = atrial volume, Vvt = ventricular volume, Fv = venous return flow, Rv = venous return resistance, Rat = atrioventricular valvular resistance, Rvt = aortic valvular resistance, Cat = atrial compliance, and E(t) = ventricular time-varying elasticity (instantaneous ventricular pressure-volume ratio). See text for further discussion.

Results

Peak systolic and diastolic values (full excursion) of the measured variables and the calculated cardiac output are listed in Table 1. Some sample tracings showing both a large and a small atrial compliance are illustrated in Figure 2. As atrial compliance increased from a value close to zero, the magnitude of the changes in venous return flow and atrial pressure became smaller, the mean level of venous return flow increased, the atrial volume increased, the mean atrial pressure decreased, the ventricular stroke volume increased, and the end-diastolic volume increased; end-systolic volume, however, remained unchanged. Hence, cardiac output (stroke volume x heart rate) increased. Figure 3 shows the marked increases in stroke volume that occurred in response to the increases in atrial compliance.

The increases in atrial compliance from 0.1 ml/mm Hg to 20 ml/mm Hg increased cardiac output logarithmically up to 35% when venous return resistance was 0.1 mm Hg sec/ml and up to 80% when venous return resistance was 0.2 mm Hg sec/ml. At an atrial compliance of 5 ml/mm Hg, cardiac output had already increased significantly; any additional increase in atrial compliance above 5 ml/mm Hg did not affect cardiac output much. Therefore, it seems that a significant improvement in cardiac performance is attained when the atrial compliance is such that atrial volume is more than half of the concomitant stroke volume of the ventricle.

Figure 4 shows the relationship between cardiac output and mean atrial pressure. Increases in atrial compliance caused a considerable improvement in cardiac performance in terms of the cardiac output-mean atrial pressure relationship, since a larger cardiac output was pumped from a lower mean atrial pressure at a higher atrial compliance.

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TABLE 1
Effects of Various Levels of Atrial Compliance on Cardiac Performance

<table>
<thead>
<tr>
<th>Venous return resistance (mm Hg/sec/ml)</th>
<th>Variables</th>
<th>Phase</th>
<th>0.1</th>
<th>0.2</th>
<th>0.5</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0</th>
<th>10.0</th>
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<td>0.2</td>
<td>Fv (ml/sec)</td>
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<td>1</td>
<td>2</td>
<td>5</td>
<td>15</td>
<td>28</td>
<td>34</td>
<td>38</td>
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<td></td>
<td>Vat (ml)</td>
<td>Diastole</td>
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<td>0.5</td>
<td>2.5</td>
<td>4.6</td>
<td>8.5</td>
<td>13.0</td>
<td>18.0</td>
<td>31.0</td>
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<td></td>
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<td>0.1</td>
<td>0.3</td>
<td>0.6</td>
<td>2.0</td>
<td>5.0</td>
<td>9.0</td>
<td>21.0</td>
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<td>Pat (mm Hg)</td>
<td>Diastole</td>
<td>5.0</td>
<td>4.9</td>
<td>4.9</td>
<td>4.6</td>
<td>4.2</td>
<td>2.6</td>
<td>1.8</td>
<td>1.5</td>
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<td></td>
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<td>0.5</td>
<td>0.6</td>
<td>0.6</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
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<td>Vvt (ml)</td>
<td>Diastole</td>
<td>29.0</td>
<td>29.5</td>
<td>31.0</td>
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<td>18.0</td>
<td>18.0</td>
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<td>18.0</td>
<td>18.0</td>
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<tr>
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<td>C.O. (ml/min)</td>
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<td>2340</td>
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<td>2</td>
<td>2</td>
<td>9</td>
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<td>Vat (ml)</td>
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<td>30.0</td>
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<td>0.1</td>
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<td>0.7</td>
<td>1.4</td>
<td>4.0</td>
<td>14.0</td>
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<td>Diastole</td>
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<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
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<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
<td>0.8</td>
<td>1.4</td>
<td>1.5</td>
</tr>
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<td>Diastole</td>
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<td>38.5</td>
<td>39.0</td>
<td>40.0</td>
<td>41.5</td>
<td>44.0</td>
<td>45.0</td>
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<tr>
<td></td>
<td></td>
<td>Systole</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
<td>18.0</td>
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</tr>
<tr>
<td></td>
<td>C.O. (ml/min)</td>
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<td>2460</td>
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<td>2640</td>
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<td>3120</td>
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Fv = venous return flow, Vat = atrial volume, Pat = atrial pressure, Vvt = ventricular volume, and C.O. = cardiac output.

The two rectilinear lines in Figure 4 are the theoretically calculated venous return curves for the two venous return resistances used in the model. The pressure-axis intercept of both lines is the specified venous return source pressure (Pv = 5 mm Hg), and their slopes are the reciprocals of the specified venous return resistances. The data point under a given venous return resistance moves along the corresponding venous return curve as atrial compliance is varied. The effect of increases in atrial compliance on cardiac output is greater with the larger venous return resistance.

Interestingly, the peak and the mean level of atrial pressure during diastole increased with in-
increases in atrial compliance, although the mean level of atrial pressure during the entire cardiac cycle decreased.

Discussion

The results of this analysis suggest that atrial compliance is an important determinant of the performance of the heart as a whole. The natural atrium contracts and, therefore, is not fully consistent with the present assumption of linearity and constancy of atrial compliance. However, more than half of the ventricular filling process occurs during the diastolic period before the atrial contraction (10, 11). Therefore, the present assumption is still a practically reasonable approximation, and the resultant suggestion should hold in the natural situation.

The apparent improvement in cardiac performance with larger atrial compliances can be explained as follows. The smaller the atrial compliance is in the model, the greater are the amplitude and the mean level of atrial pressure. However, simultaneously, the mean level of atrial pressure during the period of ventricular filling, which serves as the effective source pressure of ventricular filling, is smaller. The smaller source pressure causes less filling and a smaller end-diastolic ventricular volume. Moreover, venous return to the atrium decreases because of the higher mean atrial pressure. In contrast, when the atrial compliance is large, the atrial pressure variation is small and the mean level of atrial pressure during ventricular filling is maintained at a relatively high level. Thus, atrial compliance serves to buffer the pressure changes in the atrium during a cardiac cycle and to smooth the transformation of the steady venous return flow into the intermittent ventricular filling flow.

The finding that a larger atrial compliance improves cardiac performance more when the venous return resistance is larger suggests that the natural atrial compliance is more advantageous when the caval veins are partially collapsed. This finding corroborates the importance of a compliant atrium at the inlet of the artificial heart ventricle, because the artificial heart actively sucks blood and collapse of the caval veins would occur without such an atrium.

The observed dissociation of the mean atrial pressure averaged over the entire cardiac cycle and the end-diastolic ventricular volume is physiologically significant. It suggests that mean atrial pressure does not always serve as the source pressure of ventricular filling. Rather, the mean value of atrial pressure averaged only over the period of ventricular filling seems to be the effective, direct source pressure of ventricular filling. The situation is similar for ventricular pressure. Nobody thinks that the mean ventricular pressure averaged over the entire cardiac cycle is the source pressure of aortic flow during ejection. Instead, the ventricular pressure during the ejection period serves as the effective source pressure of ventricular ejection.

References


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