Comparison of Preload Recrutable Stroke Work, End-Systolic Pressure-Volume and $dP/dt_{\text{max}}$—End-Diastolic Volume Relations as Indexes of Left Ventricular Contractile Performance in Patients Undergoing Routine Cardiac Catheterization

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The end-systolic pressure-volume relation, the relation between stroke work and end-diastolic volume, termed the preload recruitable stroke work relation, and the relation between the peak of the first derivative of left ventricular pressure ($dP/dt_{\text{max}}$) and end-diastolic volume have been employed as linear indexes of left ventricular contractile performance in laboratory animals. The purpose of this study was to examine the relative utility of these indexes during routine cardiac catheterization in seven human subjects (mean age 48 ± 18 [SD] years) with a normal left ventriculogram and coronary angiogram. Left ventricular pressure was recorded continuously with a micromanometer catheter, and left ventricular volume was derived from digital subtraction contrast ventriculograms obtained at 30-ms intervals. Transient occlusion of the inferior vena cava with a balloon-tipped catheter was employed to obtain beat to beat reductions in left ventricular pressure and volume over 8.7 ± 1.7 cardiac cycles.

Stroke work declined by 49 ± 13% during vena caval occlusion, but end-systolic pressure fell by only 26 ± 11%, and changes in $dP/dt_{\text{max}}$ were small and inconsistent (12 ± 22%). Consequently, the range of data available for determination of the preload recruitable stroke work relation greatly exceeded that for the end-systolic pressure-volume relation and the $dP/dt_{\text{max}}$—end-diastolic volume relation, and much less linear extrapolation from the measured data was required to determine the volume-axis intercept. Preload recruitable stroke work relations were highly linear ($r = 0.95 ± 0.07$), and much more so than end-systolic pressure-volume relations ($r = 0.79 ± 0.23$). The correlation between $dP/dt_{\text{max}}$ and end-diastolic volume was very poor over the limited range examined ($r = 0.30 ± 0.48$). The slopes and volume-axis intercepts of the end-systolic pressure-volume relations in normal hearts were more variable; SD/mean values = 78% and 163%, respectively, compared with 40% and 46% for the preload recruitable stroke work relations. The volume-axis intercepts of the end-systolic pressure-volume relations were spuriously negative in 40% of seven subjects, but those of the preload recruitable stroke work relations were positive in all cases.

Thus, with the limited range of pressure-volume data obtainable during cardiac catheterization in human subjects, the preload recruitable stroke work relation appears to have greater clinical utility than the end-systolic pressure-volume relation or the $dP/dt_{\text{max}}$—end-diastolic volume relation as a linear index of left ventricular contractile performance.

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restricted physiologic range, such as may be obtained during clinical cardiac catheterization.

An alternative, load-insensitive index of left ventricular systolic function is the linear relation between left ventricular stroke work and end-diastolic volume, which was first reported in conscious dog studies in 1985 (12). Over wide ranges of contractility and afterload in the canine heart, this relation exhibits neither significant deviation from linearity nor load dependence (4,12). This linear relation, which has been termed the preload recruitable stroke work relation (12), has not yet been examined in the human heart.

Closely related to the end-systolic pressure-volume relation is the relation between the maximal rate of left ventricular pressure development (dP/dt max) and end-diastolic volume, since both relations can be derived from the time-varying elastance model of ventricular contractile force (13). Recent evidence (14) from studies of conscious dogs indicates that the dP/dt max—end-diastolic volume relation is less reproducible but more sensitive to changes in contractile state than either the end-systolic pressure-volume relation or the preload recruitable stroke work relation, but these relations have not been compared in the human heart.

The first purpose of this study was to verify the linear nature of the relation between left ventricular stroke work and end-diastolic volume in the normal human heart. The second and related purpose was to assess the relative accuracy with which the preload recruitable stroke work relation, the end-systolic pressure-volume relation and the dP/dt max—end-diastolic volume relation could be determined during routine clinical cardiac catheterization procedures.

Methods

Study patients. Seven subjects with atypical chest pain, with a mean age ± SD of 48 ± 18 years, gave written, informed consent to this study before undergoing elective cardiac catheterization, left ventriculography and coronary arteriography that demonstrated normal left ventricular function and normal coronary arteries. The study protocol and consent form were approved by the Duke University Institutional Review Board.

Cardiac catheterization. Routine right and left heart catheterization were performed after percutaneous placement (Seldinger technique) of an 8F introducer sheath into the femoral artery. After completion of routine left ventriculography and coronary arteriography, a 7F pigtail micromanometer catheter (Millar) was passed into the left ventricle, and a balloon-tipped catheter (Meditech, 8F, maximal balloon diameter 40 mm) was passed percutaneously into the right femoral vein and then into the right atrium. The right atrial balloon was inflated by injection of 20 to 25 ml of quarter-strength Iopamidol and suddenly withdrawn until it occluded the inlet of the inferior vena cava (Fig. 1). Vena caval occlusion was continued for approximately 10 s, during which time the patient was asked to maintain a stable inspiration. The balloon was then deflated.

Pressure and volume measurements. Left ventricular pressure was recorded continuously with the micromanometer coupled to a pressure amplifier (Hewlett-Packard 8890B system). Coincident with the onset of left ventricular pressure reduction during vena caval occlusion, an electrocardiographic (ECG)-gated microprocessor-controlled, digital injection system (Liebel-Flarsheim, Angiomat 6000) was activated to deliver 15 ml of half-strength Iopamidol into the left ventricle through the pigtail catheter during each diastole. Digital left ventriculograms were recorded at 30 frames/s in a 256 × 256 8-bit deep matrix throughout the period of contrast injection with an ADAC 4100c computer system coupled to a GE MLX X-ray unit. Physiologic inputs permitted simultaneous acquisition of pressure and radiographic imaging.

After the procedure, each image sequence underwent gated mask-mode digital subtraction to maximize edge enhancement. A semiautomated edge detection algorithm was used to define the left ventricular contours (Fig. 1). Volume was determined with the area-length method (15) with calibration established by imaging a grid. Ventricular volumes were further corrected by a linear regression equation derived from 20 human heart casts of known volume displacement. Analog pressure data were filtered by a 50-Hz low-pass analog filter and digitized in real time along with the image data. Simultaneous display of digital subtraction ventriculograms and digitized pressure was thus available. The right atrial balloon was deflated when there was no further decrease in left ventricular pressure (usually within 10 s of balloon inflation). As reported previously (16), transient occlusion of the inferior vena cava did not result in pain or significant subjective distress in any of the subjects studied.
Table 1. Baseline Data and Hemodynamic Effects of Vena Caval Occlusion in Seven Subjects

<table>
<thead>
<tr>
<th>Pt. No.</th>
<th>Age (yr)</th>
<th>Gender</th>
<th>EF (%)</th>
<th>EDV (ml)</th>
<th>A (%)</th>
<th>ESV (ml)</th>
<th>A (%)</th>
<th>ESP (mm Hg)</th>
<th>A (%)</th>
<th>SW (erg 10^3)</th>
<th>A (%)</th>
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<td>2</td>
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<td>M</td>
<td>58</td>
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<td>36</td>
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<tr>
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<td>M</td>
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<td>10</td>
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\( \Delta \) = percent reduction in a given variable during vena caval occlusion; EDV = end-diastolic volume; EF = ejection fraction; ESP = end-systolic pressure; ESV = end-systolic volume; F = female; M = male; Pt = patient; SW = stroke work.

Data analysis. Subsequent data analysis was performed on a microprocessor (DEC, model PDP 11/23) with interactive programs developed in our laboratory. The first derivative of left ventricular pressure (dP/dt) was computed from the digital pressure waveform as a running 5-point poly-orthogonal transformation (12). End-diastole was defined automatically 40 ms before a positive dP/dt >500 mm Hg/s, and this definition was checked visually for every beat with a videographics display system (12).

Left ventricular stroke work was calculated as the integral of left ventricular pressure and chamber volume over each cardiac cycle (12). The preload recruitable stroke work relation was determined by linear regression analysis of stroke work (SW) and corresponding end-diastolic volume (EDV) data obtained during each inferior vena cava occlusion, according to the formula

$$SW = M_w(EDV - V_w),$$

where \( M_w \) is the slope, and \( V_w \) is the volume-axis intercept of the preload recruitable stroke work relation (12).

For the purpose of determining the end-systolic pressure-volume relation, end-systole was defined as the maximal pressure/volume ratio during each cardiac cycle. The end-systolic pressure-volume relation was determined by linear regression analysis of end-systolic pressure (ESP) and corresponding end-systolic volume (ESV) data obtained during each inferior vena cava occlusion, according to the formula

$$ESP = E_o(ESV - V_o),$$

where \( E_o \) is the slope, and \( V_o \) is the volume-axis intercept of the end-systolic pressure-volume relation.

The dP/dtmax-end-diastolic volume relation was determined by linear regression analysis of dP/dtmax and corresponding end-diastolic volume (EDV) data obtained during each inferior vena cava occlusion according to the formula

$$dP/dt_{max} = M_{dphl}(EDV - V_{dphl}),$$

where \( M_{dphl} \) is the slope, and \( V_{dphl} \) is the volume-axis intercept of the dP/dtmax-end-diastolic volume relation.

When determining all three relations, data were excluded from analysis if the heart rate changed by >10% during the vena caval occlusion. Thus, all three relations were derived from analyses of the same cardiac cycles. Unless stated otherwise, all results are expressed as mean values ± SD.

Results

Hemodynamic data. Individual and mean hemodynamic data from all seven subjects are presented in Table 1. Representative left ventricular pressure and volume data obtained during transient inferior vena cava occlusion are displayed in Figure 2. Vena caval occlusion resulted in progressive beat to beat reductions in both the pressure and the volume of the left ventricle, but the extent of these reductions varied. This variability is demonstrated in Figure 3, in which left ventricular pressure-volume loops are displayed from the subject with the greatest reduction in pressure and volume during vena caval occlusion, and in Figure 4 are shown data from the patient with the least reduction. The number of loops obtained for analysis during each vena caval occlusion averaged 8.7 ± 1.7.

End-systolic pressure-volume and preload recruitable stroke work relations. These relations, derived from the pressure-volume loops in Figures 3 and 4, are shown in

Figure 2. Representative left ventricular (LV) pressure and volume data recorded continuously during vena caval occlusion.
the end-systolic pressure-volume relation were considerably lower and varied widely $(r = 0.79 \pm 0.23)$. The variability (SD/mean) of the slopes and volume-axis intercepts of the end-systolic pressure-volume relation in these normal subjects (78% and 183%, respectively) greatly exceeded that of the preload recruitable stroke work relation (40% and 46%, respectively). Moreover, the volume-axis intercepts of the end-systolic pressure-volume relations were negative in six of the seven subjects, whereas those of the preload recruitable stroke work relations were positive in all cases (Table 2).

One reason for the differences between end-systolic pressure-volume and preload recruitable stroke work relations was the much greater reduction in stroke work than in end-systolic pressure that occurred during vena caval occlusions. Although end-diastolic and end-systolic volumes declined to a similar extent (29 ± 9% and 29 ± 10%, respectively) during vena caval occlusion, stroke work fell by 49 ± 13% but end-systolic pressure decreased by only 26 ± 11%. Consequently, the range of data available for determination of the preload recruitable stroke work relation by linear regression analysis greatly exceeded that available for analysis of the end-systolic pressure-volume relation. Even in Subject 1, who had the smallest overall reductions in left ventricular pressure and end-diastolic and end-systolic volumes during vena caval occlusion and a low linear correlation coefficient ($r = 0.61$) for the end-systolic pressure-volume relation (Fig. 6), stroke work declined by 36% and the preload recruitable stroke work relation was highly linear ($r = 0.98$). In contrast, in Subject 4, who had the largest reductions in left ventricular pressure and volume (Fig. 5), the linear correlation coefficient for the end-systolic pressure-volume relation was high ($r = 0.96$).

Another consequence of the greater reduction in stroke work than in end-systolic pressure during vena caval occlusion was that determination of the volume-axis intercepts of the preload recruitable stroke work relations required far less linear extrapolation from the measured data than did determination of the volume-axis intercepts of the end-systolic pressure-volume relations (Fig. 5 and 6), which varied widely and were negative in most cases (Table 2).

$\frac{dP}{dt_{\text{max}}}$-end-diastolic volume relation. Similarly, the reduction in $\frac{dP}{dt_{\text{max}}}$ with vena caval occlusion was small and erratic: 12 ± 22% from a baseline value of 1,750 ± 728 mm Hg·s$^{-1}$. This may explain, in part, the very poor and sometimes inverse linear correlation demonstrated between $\frac{dP}{dt_{\text{max}}}$ and end-diastolic volume under the conditions of this study (Table 2). The mean linear correlation coefficient for the $\frac{dP}{dt_{\text{max}}}$-end-diastolic volume relation was only 0.30 ± 0.48.

Discussion

Although difficult to define precisely, a practical index of contractility should quantitatively reflect changes in the inotropic state of myocardium independent of preload and
afterload. The quest for such an index has occupied cardiac physiologists for more than a century (17,18). By any definition, ventricular ejection fraction is a poor index of contractility because of its extreme load dependence and its inability to account for the pressure-generating capacity of the ventricle.

End-systolic pressure-volume relation. This relation has been investigated extensively since it was first reported (1) to be a load-independent linear index of contractility in the isolated canine heart. Recent evidence (3-11) has thrown doubt on both the inherent linearity and the afterload independence of this relation. When data are obtained over a sufficiently wide range, the end-systolic pressure-volume relation is seen to be curvilinear, and the precise shape of the relation varies with contractility (3,4,8). In the normal canine heart in situ, the shape of the end-systolic pressure-volume relation is best described by a parabolic relation with concavity to the volume axis (4). This observation explains why the volume-axis intercept \( V_0 \) is frequently found to be negative when determined by linear extrapolation from a narrow range of data at the upper end of the pressure-volume curve (4). In addition, there is now considerable evidence that the end-systolic pressure-volume relation is not independent of afterload in the intact canine heart. Several investigators (5-11) have reported an upward or leftward shift, or both, of the end-systolic pressure-volume relation with increased afterload, which is consistent with counterclockwise rotation of a parabolic relation about a relatively constant \( V_0 \).

In addition to these fundamental concerns about the nature of the end-systolic pressure-volume relation, several statistical problems are related to the limited range of pressure and volume data obtainable in conscious subjects, compared with the range obtainable in the isolated heart, and the need for extensive extrapolation beyond the measured data to determine the volume-axis intercept (11). These limitations are particularly pertinent to the clinical determination of the end-systolic pressure-volume relation. In this study, the average number of pressure-volume loops obtained during vena caval occlusion was only 8.7 ± 1.7, far fewer than are available in conscious dogs (11), and end-systolic pressure decreased by only 26 ± 11%. Linear correlation coefficients were quite low, and extensive linear extrapolation resulted in a negative volume-axis intercept in most cases. Both of these observations might also reflect significant nonlinearity of the end-systolic pressure-volume relation with concavity toward the volume axis (Fig. 4), as observed in dogs (3,4,10), but the small number and narrow
### Table 2. Linear Regression Variables for Preload Recruitable Stroke Work. End-Systolic Pressure-Volume and dP/dt,,,,,-End-Diastolic Volume Relations

<table>
<thead>
<tr>
<th>PRSW</th>
<th>ESPV</th>
<th>dP/dt</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_t )</td>
<td>( M_0 )</td>
<td>( V_0 )</td>
<td>( r )</td>
</tr>
<tr>
<td>No.</td>
<td>(erg/m(^2))</td>
<td>(ml)</td>
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<td>2</td>
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<tr>
<td>3</td>
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<td>7</td>
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<td>92</td>
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<tr>
<td>Mean</td>
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<td>26</td>
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<td>0.067</td>
<td>44</td>
<td>12</td>
</tr>
</tbody>
</table>

\( dP/dt_{max} \) = peak of the first derivative of left ventricular pressure; \( EDV = \) end-diastolic volume; \( ESPV = \) end-systolic pressure-volume; \( M_0, E_r, \) and \( M_{PRSW} \) = slopes of the respective relations; \( PRSW = \) preload recruitable stroke work; \( P_t = \) patient; \( r = \) linear correlation coefficient; \( V_o, V_{PRSW} \) = volume-axis intercepts of the respective relations.

range of the data points measurable in human subjects preclude meaningful application of multiple nonlinear regression analyses to test this hypothesis (3,4).

Similar observations were made by Kass et al. (2) during cardiac catheterization in human subjects. They reported that peak left ventricular pressure declined by an average of 30% during inferior vena cava occlusions lasting 6 to 7 s, during which five to eight pressure-volume loops were obtained for assessment of the end-systolic pressure-volume relation; \( V_o \) determined by linear extrapolation was negative in all six of their normal subjects and varied widely \((-32.5 \pm 18.6 \text{ ml})\). They also reported limited data concerning the reproducibility of end-systolic pressure-volume relations determined based on serial vena caval occlusions in two subjects. There appeared to be considerable variability of the determinations due to linear regression analysis over the narrow range of data obtained.

Comparison with iterative method of determining the end-systolic pressure-volume relation. The linear correlation coefficients for the end-systolic pressure-volume relations in normal human subjects reported by Kass et al. (2) \((0.98 \pm 0.02)\) were considerably higher than those obtained in the present study \((0.79 \pm 0.23)\). Because the range of data obtained in these two reports appears to be similar, the major reason for this difference may lie in the disparate methods used to determine the end-systolic pressure-volume relation. Kass et al. (2) employed repetitive linear regressions in which the first linear estimate of \( V_o \) (as determined in this study) was then used in a second linear regression of "end-systolic" data points defined by the maximal \( P/(V - V_0) \) ratio in each cardiac cycle. This process resulted in a new estimate of \( V_o \), which was then used in a third linear regression of "end-systolic" data defined by maximal \( P/(V - V_0) \) ratios. This process was repeated (usually three to four times) until convergence was achieved for both slope and \( V_o \) estimates (2).

The purported physiologic justification for this iterative process is that the real point of maximal elastance during each cardiac cycle is the point of maximal \( P/(V - V_0) \) ratio rather than maximal \( P/V \) ratio (as employed in this study). If \( P/(V - V_0) \) ratios are to be used validly to determine the end-systolic pressure-volume relation, however, it is imperative that the actual \( V_o \) be determined independently of the linear regression analysis (19). The statistical problem with the iterative method of end-systolic pressure-volume relation determination employed by Kass et al. (2) is that each \( V_o \) estimate is a covariate of the linear regression. Consequently, repetitive substitution of serial \( V_o \) estimates invariably (and artificially) improves the linear correlation. In the present study, for example, application of the iterative method to the data shown in Figure 4 increased the linear correlation coefficient for the end-systolic pressure-volume relation from 0.61 (Fig. 6, left panel) to 0.93. Application of the iterative method to the data for all subjects in this study increased the average linear correlation coefficient for the end-systolic pressure-volume relation from 0.79 \pm 0.23 to 0.86 \pm 0.19. The artificial nature of the iterative method is particularly obvious when the \( V_o \) estimate is a negative number, as it was in all cases studied by Kass et al. (2) and all but one case in the present study. Since the actual \( V_o \) in the normal heart is known to be a relatively small positive number (1,19), it is evident that linear regression of the points of maximal pressure/volume ratio (that is, \( V_o \) assumed to be 0), as employed in the current study, provides a more accurate approximation of the actual end-systolic pressure-volume relation than does substitution of a large and spuriously negative \( V_o \) estimate to determine an unreal \( P/(V - V_0) \) ratio. Put simply, any linear correlation will be improved by repetitive substitution of one of its covariates into subsequent determinations, but doing so is not valid.

The difficulty of obtaining a wide range of pressure-volume data in the human heart has stimulated several attempts to simplify clinical estimation of the end-systolic pressure-volume relation from only two or three beats ob-
tained under different steady state loading conditions achieved by pharmacologic interventions (20,21) or even from a single heat (21). The relatively low linear correlation coefficients for the end-systolic pressure-volume relations obtained under more rigorous measurement conditions and over a wider pressure-volume range in the present study suggest that such attempts at simplification are ill-founded. Moreover, the errors inherent in such simplification have been compounded further by the use of various approximations to end-systolic data, including end-ejection pressure/volume ratios and the ratio of peak ventricular pressure to end-ejection volume (21).

The end-systolic pressure-volume relation, the $dP/dt_{max}$-end-diastolic volume relation can be derived from the time-varying elastance model of ventricular contraction (13). Over the wider range of pressure-volume data obtainable by vena caval occlusion in conscious dogs, this relation is well approximated by a straight line, although it is actually somewhat concave toward the volume axis, as is the end-systolic pressure-volume relation (14). In conscious dogs, the $dP/dt_{max}$-end-diastolic volume relation is more sensitive to changes in contractile state than is either the end-systolic pressure-volume relation or the preload recruitable stroke work relation, but it is also the least reproducible of the three relations (14).

In the present study, however, there was a very poor and sometimes negative linear correlation between $dP/dt_{max}$ and end-diastolic volume (Table 2). Predictably, the correlation was poorest in those subjects with a low linear correlation coefficient for the end-systolic pressure-volume relation, but the correlation for the $dP/dt_{max}$-end-diastolic volume relation was so poor as to render it unusable as an index of contractility under the conditions of the present investigation. Even with the much greater reduction in preload inducible by vena caval occlusion in dogs, the decline in $dP/dt_{max}$ is small when compared with the decline in stroke work, and differentiation enhances any noise inherent in the pressure signal (14). The latter is probably greater when the signal is derived from the chamber pressure during breath holding, as in the present study, because of small fluctuations in intrathoracic pressure. Such small pressure fluctuations may also have influenced correlation coefficients for the end-systolic pressure-volume relation in this study, although to a lesser extent. Measurement of transmural left ventricular pressure would be necessary to obviate this effect (12), but this was not possible under the conditions of this study. Finally, if the $dP/dt_{max}$-end-diastolic volume relation is concave to the volume axis in the human heart, as it is in the canine heart (14), then the portion of the relation obtained during the small reduction in end-diastolic volume in this study would be relatively flat. Thus, it seems likely that the sampling of a small number of $dP/dt_{max}$ data points with fairly large beat to beat variation over the relatively flat initial portion of the $dP/dt_{max}$-end-diastolic volume relation may explain the poor linear correlation coefficients obtained in this study.

The linear preload recruitable stroke work relation. This linear relation between stroke work and end-diastolic volume is a quantifiable expression of Starling's law: "The mechanical energy set free on passage from the resting to the contracted state depends on the . . . length of the muscle fibers" (22). The linear preload recruitable stroke work relation is closely related to the nonlinear relation between ventricular stroke work and preload indexed by end-diastolic pressure, which was described by Sarnoff and Berglund (23) in 1954. The nonlinear nature of the latter relation reflects only the nonlinear characteristics of the end-diastolic pressure-volume curve (12). Thus, when preload is indexed by end-diastolic volume rather than pressure, the relation between stroke work and preload is linear (4,12). In both anesthetized and conscious dogs, the preload recruitable stroke work relation has been shown to remain highly linear despite wide variations in afterload and inotropic state (4,12,14). The relation has also been shown to be afterload insensitive over the range from 100 to 200 mm Hg left ventricular mean ejection pressure, yet it is sensitive to changes in contractility, reflected by variations in slope (12,14). The preload recruitable stroke work relation has been shown to be both more linear and more reproducible than either the end-systolic pressure-volume relation or the $dP/dt_{max}$-end-diastolic volume relation in conscious dogs (14).

This study demonstrates that the preload recruitable stroke work relation is also highly linear in the normal human heart and much more so than the end-systolic pressure-volume relation or the $dP/dt_{max}$-end-diastolic volume relation. The ordinate of the preload recruitable stroke work relation, stroke work, can be determined more reliably because it is determined by integration over the entire cardiac cycle and is insensitive to changes in intrathoracic pressure. In contrast, the ordinates of the end-systolic pressure-volume and $dP/dt_{max}$-end-diastolic volume relations are more difficult to determine accurately because they occur at precise moments in the cardiac cycle and are sensitive to changes in intrathoracic pressure (unless transmural pressure is measured). Moreover, because stroke work is the product of the stroke volume and mean developed ejection pressure, it declines more than end-diastolic pressure or $dP/dt_{max}$ during vena caval occlusion. Therefore, determination of the volume-axis intercept requires far less linear extrapolation from the measured data than does determination of the volume-axis intercept of the end-systolic pressure-volume relation or the $dP/dt_{max}$-end-diastolic volume relation.

Given the limited range of data obtainable during cardiac catheterization, therefore, the slope and volume-axis intercept of the preload recruitable stroke work relation can be determined more reliably by linear regression analysis, and for this reason, this relation appears to have greater utility as a clinical index of contractility than either the end-systolic pressure-volume relation or the $dP/dt_{max}$-end-diastolic vol-
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Lone JACC, primary reason for this difference, particularly in the case of varied more than the ejection fraction (Tables I and 2). The lar dysfunction as a cause of congestive heart failure.

cally altered loading conditions (such as valvular heart

nine relation. This method may be useful in assessing

strates a weaker inverse correlation \( r = -0.59 \). In contrast,

eed-diastolic volume values (independent variable) demon-

ple, linear regression analysis of slope \( E_{0} \) values from

be the variation in cardiac size among subjects. For example, linear regression analysis of the preload recruitable stroke work relation slope \( M_{w} \) values (dependent variable) on baseline end-diastolic volume values from Table 1 (independent variable) demonstrates a strong inverse correlation \( r = -0.98 \). Linear regression analysis of the preload recruitable stroke work relation slope \( M_{w} \) and baseline ejection fraction \( r = -0.59 \). In contrast, the linear correlation between \( E_{0} \) and baseline ejection fraction \( r = -0.76 \) is stronger than that between \( E_{0} \) and ejection fraction \( r = 0.21 \). Consequently, the linear correlation between \( E_{0} \) and \( M_{w} \) in this study is rather weak \( r = 0.59 \).

Because of the dependence of the preload recruitable stroke work relation and the end-systolic pressure-volume relation on ventricular size, both relations are most appropriately employed as indexes of changes in contractility in a given subject. If these relations are to be employed as comparative indexes of contractility in different subjects, then some normalization for differences in ventricular size must be employed, such as conversion of pressure-volume data to stress-strain data (12,20). Normal values for normalized stroke work-end-diastolic strain and end-systolic stress-strain relations (12,20) have yet to be established in human subjects.

Frame by frame analysis of digital subtraction ventriculograms was employed to determine left ventricular volumes by the area-length method in this study. This method of off-line analysis is too time-consuming for routine clinical application and is not applicable to ventricles exhibiting segmental dysfunction. Continuous on-line measurement of left ventricular volume with a conductance catheter, as employed in human subjects by other investigators (2,24), may be a more convenient alternative in future studies; however, adequate validation of the conductance catheter technique for measurement of absolute left ventricular volume remains controversial (2,25).

Limitations. A possible criticism of this and other similar studies (2) is that no attempt was made to attenuate autonomic reflexes during vena caval occlusion. Pharmacologic attenuation of the autonomic nervous system may not always be desirable in patients undergoing cardiac catheterization, particularly those with significant left ventricular dysfunction. Consequently, in evaluating the potential utility of the preload recruitable stroke work, end-systolic pressure-volume and \( dP/dt_{max} \)-end-diastolic volume relations as routine clinical indexes of contractility, it may be more appropriate to do so without autonomic blockade. In an attempt to mitigate possible influences of changing autonomic tone, however, data were excluded from analysis if the heart rate changed by \( >10\% \) during vena caval occlusion. Moreover, the purpose of this study was to compare the three relations derived from the same vena caval occlusions, and the absence of autonomic blockade does not alter the validity of this comparison (4,14). Autonomic blockade may be essential before valid comparisons can be made between contractile indexes derived from serial vena caval occlusions (12), but this issue has yet to be addressed in human subjects.

Conclusions. Estimation of preload recruitable stroke work and end-systolic pressure-volume indexes of cardiac performance is feasible in human subjects during routine cardiac catheterization. By using the method of transient balloon occlusion of the inferior vena cava, a range of left ventricular pressures and volumes can be obtained, allowing linear regression analysis of both relations. The range of data available at present does not appear to be sufficient to permit accurate determination of the \( dP/dt_{max} \)-end-diastolic volume relation. For a number of reasons, the preload recruitable stroke work relation may provide a more valid and practical load-independent estimate of myocardial function in the clinical setting than does the end-systolic pressure-volume relation. Future technologic developments should facilitate data acquisition and could allow such measurements to be made on a routine basis. Quantification of preload recruitable stroke work variables in patients with ventricular dysfunction could improve the physiologic understanding of a variety of clinical cardiac disorders and facilitate decision making and therapeutic timing.

References


