The Left Ventricular dP/dtmax-End-Diastolic Volume Relation in Closed-Chest Dogs

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SUMMARY. I investigated the relation of the maximum rate of left ventricular pressure rise to the end-diastolic volume and the comparison of the maximum rate of left ventricular pressure rise-end-diastolic volume relation to the end-systolic pressure-volume relation, using the time-varying elastance model. These studies were performed in 11 dogs chronically instrumented to measure left ventricular pressure and determine left ventricular volume from three orthogonal dimensions. During vena caval occlusions, the relations between the maximum rate of left ventricular pressure rise and end-diastolic volume were described by straight lines (r = 0.97 ± 0.01, mean ± SD). Dobutamine increased the slope of the maximum rate of left ventricular pressure rise-end-diastolic volume relation to 358 ± 94% of control. This increase was greater than the 244 ± 61% increase in the slope of the end-systolic pressure-volume relation (P < 0.005). The volume intercepts of the maximum rate of left ventricular pressure rise-end-diastolic volume relation and end-systolic pressure-volume relation were similar and were not significantly altered by dobutamine. The ratio of the slope of the maximum rate of left ventricular pressure rise-end-diastolic volume relation to the slope of the end-systolic pressure-volume relation divided by the time from end-diastole to end-systole was similar before (2.2 ± 0.7) and after dobutamine (2.3 ± 0.7, P = NS). Angiotensin II did not significantly alter the maximum rate of left ventricular pressure rise-end-diastolic volume relation generated by caval occlusion. Thus, consistent with the predictions of the time-varying elastance model, the maximum rate of left ventricular pressure rise-end-diastolic volume relation generated by caval occlusions is linear, and its slope may be a sensitive load-independent measure of left ventricular contractile performance. (Circ Res 56: 808–815, 1985)

It has been proposed that left ventricular (LV) systolic pump function can be modeled as a time-varying elastance (Suga and Sagawa, 1974; Sunagawa and Sagawa, 1982). In this model, the left ventricle is considered to behave as an elastic structure that stiffens in a predictable manner during systole. The LV pressure, P(t), at any time after the onset of contraction, t, is described by:

\[ P(t) = E(t) (V(t) - V_o), \]

where \( E(t) \) is the LV elastance at \( t \), \( V(t) \) the LV volume at \( t \), and \( V_o \) the minimal volume required for the LV to generate supra-atmospheric pressure. The LV elastance, \( E(t) \), reaches a maximum value, \( E_{\text{max}} \), at time \( t_{\text{max}} \), which has been termed end systole. This end-systolic pressure-volume relation,

\[ P_{\text{ES}} = E_{\text{max}} (V_{\text{ES}} - V_o), \]

has been the subject of much investigation. \( E_{\text{max}} \), the slope of the \( P_{\text{ES}}-V_{\text{ES}} \) relation, is a measure of the global inotropic state, and is relatively insensitive to changes in loading conditions in isolated canine hearts (Suga et al., 1973; Suga and Sagawa, 1974; Suga and Yamakoshi, 1977; Suga et al., 1979; Sagawa, 1978, 1981), conscious dogs (Sodums et al., 1984), and man (Grossman et al., 1977; Mehmel et al., 1981).

In isolated canine hearts, Suga and Sagawa (1974) demonstrated that \( E(t) \) can be normalized by considering \( E_{\text{max}} \) and \( t_{\text{max}} \), so that:

\[ E_N(t_N) = E(t) / E_{\text{max}}, \]

where \( t_N = t/t_{\text{max}} \) and \( E_N(t_N) \) is a normalized elastance function that is similar for all ventricles. Thus, the LV elastance can be expressed as:

\[ E(t) = E_{\text{max}} E_N(t_N). \]

Although the \( P_{\text{ES}}-V_{\text{ES}} \) relation has been the subject of intense investigation, the more general time-varying elastance model has not been as widely studied in preparations other than the isolated heart. In addition to the \( P_{\text{ES}}-V_{\text{ES}} \) relation, the time-varying elastance model also has implications concerning the relation between the maximum rate of rise of LV pressure (dP/dtmax) and the end-diastolic volume (VED).

Derivation of the dP/dtmax-VED Relation from the Time-Varying Elastance Model

The time derivative of LV pressure (dP/dt) can be expressed in terms of LV elastance, as suggested by Sunagawa and Sagawa (1982), by differentiating Equation 1:

\[ \frac{dP}{dt} = \frac{d}{dt}(E(t)(V(t)-V_o)). \]

Under normal conditions, dP/dt reaches its maxi-
LITTLE/LEFT VENTRICULAR DP/dt\textsubscript{MAX}-V\textsubscript{ED} RELATION

The time-varying elastance model of the LV predicts that the \( \text{dP/dt}_{\text{max}}-V_{\text{ED}} \) relation should be linear (Eq. 3). Furthermore, the slope of this relation, or \( \text{dE/dt}_{\text{max}} \), should be proportional to \( E_{\text{max}}/t_{\text{max}} \) (Eq. 4). Since \( E_{\text{max}} \) and \( t_{\text{max}} \) are both assumed to be independent of loading conditions, this relation should also be load independent. Since \( E_{\text{max}} \) increases in response to positive inotropic stimuli, while \( t_{\text{max}} \) decreases (Suga et al., 1973), the slope of the \( \text{dP/dt}_{\text{max}}-V_{\text{ED}} \) relation, which is proportional to their ratio, should be highly sensitive to changes in contractile function. The model also predicts that the volume intercept of the \( \text{dP/dt}_{\text{max}}-V_{\text{ED}} \) relation should be the same as the volume intercept (\( V_0 \)) of the LV \( P_{\text{ES}}-V_{\text{ES}} \) relation.

This study was thus undertaken to evaluate the above predictions of the time-varying elastance model in intact, chronically instrumented dogs.

**Methods**

Data Collection

All studies were performed after full recovery from the thoracotomy (10 days to 2 weeks), with the dogs lying on their right sides in a sling. The LV catheter was connected to a pressure transducer (Statham P23DB) calibrated with a mercury manometer. The signal from the micromanometer was adjusted to match that of the catheter. The transit time of 5 MHz sound between the crystal pairs was determined and converted to distance assuming a constant velocity of sound in blood of 1.55 m/msec. The first derivative of LV pressure (dP/dt) was obtained by electronically differentiating the micromanometer signal using an RC circuit with a linear frequency response to above 70 Hz. The analog signals were recorded on an eight-channel oscillograph (Beckman Instruments) and digitized with an on-line analog-to-digital converter (Dual Control Systems) at 100 Hz and stored on a floppy disk memory system utilizing a computer system (Zobex).

Experimental Protocol

The dogs were sedated with fentanyl (0.03-0.06 mg/kg) in combination with droperidol (1.5-3.0 mg/kg) and intubated. To prevent reflex changes in heart rate, the dogs were treated with atropine sulfate (0.2 mg/kg, iv) and were ventilated with room air. To minimize the effect of fluctuations in intrathoracic pressure, all data were recorded during 12-second periods while the dogs were apneic, with the glottis held open by the endotracheal tube (Little et al., 1984).

The effect of dobutamine (10 \( \mu \)g/kg per min, iv) was assessed in six dogs. Data were recorded during a steady state, non-intervention period to obtain baseline values. The \( P_{\text{ES}}-V_{\text{ES}} \) and \( \text{dP/dt}_{\text{max}}-V_{\text{ED}} \) relations were then generated by sudden occlusion of the cavae. This caused a progressive fall in LV end-systolic pressure, volume, and \( \text{dP/dt}_{\text{max}} \) over a 12-second recording period (Fig. 1). Immediately after the recording period, the caval occlusion was released. After all parameters had returned to their baseline level, the caval occlusion was repeated. Then dobutamine was infused until a steady state had been achieved, and the caval occlusions were repeated.

In seven dogs, the effect of arterial vasoconstriction produced by the infusion of angiotensin II (0.5-2.5 \( \mu \)g/min) was assessed. In addition to atropine, these animals were also pretreated with propanolol (2 mg/kg, iv) to block \( \beta \)-adrenergically mediated changes in contractility. Two caval occlusions were performed before, and again after, the infusion of angiotensin II sufficient to raise the systolic arterial pressure by at least 40 mm Hg (Sodums et al., 1984).

**Data Analysis**

The stored digitized data were analyzed by computer algorithm (Sodums et al., 1984; Little et al., 1984). Baseline

\begin{align*}
\text{dP/dt}_{\text{max}} &= \left[ \text{dE(t)/dt}_{\text{max}} \right] (V_{\text{ED}} - V_o) \quad (3) \\
\text{dE(t)/dt}_{\text{max}} &= (E_{\text{max}}/t_{\text{max}}) \cdot (\text{dE/n/dt}_{\text{Nmax}}) \\
\end{align*}

Since \( E_{\text{n}(t)} \) appears to be relatively constant in all ventricles (Suga and Sagawa, 1974; Sunagawa and Sagawa, 1982), the maximum value of its derivative should also be a constant, \( k \). Thus,

\[ \text{dE/dt}_{\text{max}} = k E_{\text{max}}/t_{\text{max}}. \quad (4) \]

Analog recording following caval occlusion. \( P_{\text{LV}} \) = LV pressure in mm Hg, \( D_{\text{ap}} \) = anterior-posterior LV dimension in mm, \( D_{\text{sl}} \) = septal-lateral LV dimension in mm, \( D_{\text{la}} \) = long axis dimension in mm.

FIGURE 1.
hemodynamic values in each dog were obtained by averaging the data obtained during the 12-second steady state, non-intervention recording periods. End systole was defined as the time when the ratio of LV pressure to volume reached its maximum (Suga and Yamakoshi, 1977). End diastole was defined as the relative minima following the "a" wave of the high-fidelity LV pressure tracing. The time from end diastole to end systole was defined as t. End ejection was defined as peak negative dP/dt (dP/dt^e). The LV volume was calculated as a modified general ellipsoid using the equation:

\[ V_{LV} = \frac{\pi}{6} D_{AP} D_{SL} D_{LA} \]

where \( V_{LV} \) = LV volume, \( D_{AP} \) = the anterior-posterior LV dimension, \( D_{SL} \) = the septal-lateral LV dimension, and \( D_{LA} \) = the long axis LV dimension. This method of volume calculation has been validated in our laboratory (Little et al., 1984; Sodums et al., 1984; Little and O'Rourke, 1985) and is similar to that used and validated by others (Olson et al., 1983), except that we determined endocardial dimensions directly; thus, the subtraction of LV wall thickness or volume was not necessary. This method gives a consistent measure of LV volume (r > 0.97, see < 2ml) despite changes in LV loading conditions and configuration.

Only caval occlusions that produced a fall in LV systolic pressure of at least 40 mm Hg, and that produced no extra systoles, were analyzed. The LV end-systolic pressure-volume data during the fall of LV pressure produced by the caval occlusions were fit to

\[ P_{ES} = E_{max} (V_{ED} - V_o), \]

using the linear least square technique. The LV V_{ED} and dP/dt^e were fit to

\[ dP/dt^e = (dE/dt_{max}) (V_{ED} - V_o), \] (3a)

where dE/dt_{max} is the slope of the relation and V_o is the volume intercept.

All results are summarized as the mean ± 1 SD, and the level of significance was \( P < 0.05 \). Multiple comparisons were performed by analysis of variance. Intergroup comparisons were performed by paired t-tests with an appropriate correction for the performance of multiple comparisons using the Bonferroni inequality (Glantz, 1981).

**Postmortem Studies**

At the conclusion of the experiments, the animals were killed and the hearts were examined to confirm the proper positioning of the instrumentation.

**Results**

A typical analog recording during a caval occlusion is shown in Figure 1. The LV pressure, dP/dt_{max}, and the three LV dimensions decline to-

![Figure 3. Simultaneously determined LV P_{ES}-V_{ES} (left) and dP/dt_{max}-V_{ED} relations (right) during control and after dobutamine. Both relations are linear, and their slopes increase with dobutamine. The increase in slope of the dP/dt_{max}-V_{ED} is greater.](image-url)
Effect of Dobutamine on the LV End-Systolic Pressure-Volume Relation

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Mean 7.7 12.9 18.6 14.5 ±SD 2.9 6.3 7.7 7.9

$E_{max} = \text{slope of } P_{ES}\text{-}V_{ES} \text{ relation in mm Hg/ml, } V_o = \text{volume intercept of } P_{ES}\text{-}V_{ES} \text{ relation in ml.}$

gather following caval occlusion. An example of the LV pressure-volume loops generated by the caval occlusion is shown in Figure 2. The infusion of dobutamine increased LV dP/dt max and decreased VED and VES (Table 1). The response of typical LV $P_{ES}\text{-}V_{ES}$ and dP/dt max-VED relations to the infusion of dopamine are shown in Figure 3. The individual regression information is shown in Tables 2 and 3. Both the $P_{ES}\text{-}V_{ES}$ and dP/dt max-VED relations were described by straight lines during control and after administration of dobutamine ($r = 0.97 ± 0.01$). Dobutamine markedly increased the slopes of both the LV $P_{ES}\text{-}V_{ES}$ and dP/dt max-VED relations. The increase in the slope of the dP/dt max-VED relation (dE/dt max) (358 ± 94% of control) was greater than the increase in the slope of the $P_{ES}\text{-}V_{ES}$ relation (244 ± 61% of control, $P < 0.005$) (Fig. 4). The ratios of dE/dt max, to E max/ t max were similar, 2.2 ± 0.7 during control and 2.3 ± 0.7 after dobutamine (P = NS). The volume intercepts of the control $P_{ES}\text{-}V_{ES}$ and dP/dt max-VED relations were similar (12.9 ± 6.3 and 9.4 ± 5.1 ml, P = NS) and were not altered significantly by dobutamine (14.5 ± 7.9 and 14.5 ± 8.9 ml, respectively, P = NS); although $V_o$ increased in five of six animals.

Angiotensin II increased $P_{ES}$ from 105 ± 23 to 191 ± 19 mm Hg ($P < 0.05$) and also increased VED, VES, dP/dt max, and dP/dt min (Table 4). Because of the autonomic blockade, the heart rate was not altered, and t max remained nearly constant. Consistent with our previous observations (Sodums et al., 1984), the infusion of angiotensin II shifted the $P_{ES}\text{-}V_{ES}$ relation to the left, as manifest by a decrease of the volume intercept from 18.0 ± 7.9 to 11.7 ± 7.6 ml (Fig. 5; Table 5). The slope of the $P_{ES}\text{-}V_{ES}$ relation also decreased somewhat in response to angiotensin II (9.5 ± 4.1 to 6.3 ± 2.2 mm Hg/ml, $P < 0.05$). In contrast, the dP/dt max-VED relation was not altered as much by angiotensin II (Fig. 5; Table 6). Although the slope and volume intercept of the dP/dt max-VED relation were slightly, but not significantly, decreased in response to angiotensin II, a single line described the dP/dt max-VED relation before and after angiotensin II ($r = 0.982 ± 0.010$) more adequately.
FIGURE 4. Comparison of the effect of dobutamine on the slope of the $P_{ES}-V_{ES}$ and $dP/dt_{max}-V_{ED}$ relations.

dobutamine, the slope of the $dP/dt_{max}-V_{ED}$ relation is markedly increased (more so than the increase in $E_{max}$, the slope of the $P_{ES}-V_{ES}$ relation), while the volume intercept of the relation is relatively unchanged. Also, consistent with the time-varying elastance model, the volume intercept of the $dP/dt_{max}-V_{ED}$ relation is similar to the volume intercept of the $P_{ES}-V_{ES}$ relation.

The simple time-varying elastance model of LV function does not account for any effect of the characteristics of ejection on the LV systolic pressure generated at any LV volume (Suga and Sagawa 1974; Sunagawa and Sagawa, 1982). However, the LV pressure generated at any volume may be reduced somewhat when the stroke volume, ejection fraction, maximal velocity of ejection, or flow at end-systole are markedly altered (Suga and Yamakoshi, 1977; Suga et al., 1977; Hunter et al., 1983; Weber et al., 1982; Shroff et al., 1983; Maughan et al., 1984). These factors may account for the shift of the LV $P_{ES}-V_{ES}$ relation observed in this study and seen previously (Sodums et al., 1984) after the infusion of a vasoconstrictor. Interestingly, the LV $dP/dt_{max}-V_{ED}$ relation was not shifted as much by

FIGURE 5. Simultaneously determined $P_{ES}-V_{ES}$ (left) and $dP/dt_{max}-V_{ED}$ (right) relations before and after infusion of angiotensin II. Angiotensin II shifts the $P_{ES}-V_{ES}$ relation to the left, decreasing the volume intercept. The $dP/dt_{max}-V_{ED}$ relation is well described by a single line both before and after angiotensin II. Data from Dog 5, restudied 1 week after data reported in Table 5 were obtained.
vasoconstriction. This may indicate that the simple
time-varying elastance model is a better descriptor
of the isovolumic phase of LV contraction than
during ejection, and that the dP/dtmax-VED relation
may be affected less by alterations of the arterial
input characteristics than the PES-VES relation. Under
conditions different than those employed in this
study, the predictions of the time-varying elastance
model may not be as accurate. For example, if the
stroke volume and rate of LV ejection were increased
due to a slow heart rate or vasodilation, the simple
time-varying elastance model may not be adequate
because of a much greater deactivating effect of
dobutamine). However, the values obtained for
dE/dtmax* and Emax/tmax from Figure 3 of Suga and
Sagawa's earlier study (1972) indicate that this ratio
is approximately 2, in closer agreement with the
observations of this study. The relationship between
dE/dtmax* and Emax/tmax* and the similarity of the
volume intercepts of the dP/dtmax-VED and PES-VES
relations indicate that the time-varying elastance
model provides a conceptual link between the events
occurring during isovolumic contraction and at end
ejection.

The observation that the slope of the dP/dtmax-
VED relation (dE/dtmax) showed a greater increase in
response to a positive inotropic stimulation than Emax

### Table 5

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Abbreviations as in Table 1.

### Table 6

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* Determined simultaneously with Table 5. Abbreviations as in Table 2.
† In animal 7, the LV dp/dtmax-VED relation became nonlinear at high VED (see Fig. 5). Only data
from the linear portion (VED <33 ml) were analyzed.
is consistent with a previous observation of Suga et al. (1976). They compared the effects of baroreflex inotropic interventions on $E_{\text{max}}$ and $dP/dt_{\text{max}}$ in open-chest canine LV preparations contracting isolomically at a constant volume. In their study, $dP/dt_{\text{max}}$ showed greater changes than $E_{\text{max}}$ in response to changes in contractility.

The results of this study are consistent with previous observations that $dP/dt_{\text{max}}$ is preload dependent (Mason, 1969; Mahler et al., 1975; Wallace et al., 1963; Schmidt and Hoppe, 1978). These earlier studies assessed LV preload, using the LV end-diastolic pressure and not $V_{\text{ED}}$. Due to the nonlinear relation of LV end-diastolic pressure and $V_{\text{ED}}$, the $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relation cannot be directly deduced from these studies. Also, consistent with the observations of this study, Reeves et al. (1960) found in open-chest dogs that the relation between $dP/dt_{\text{max}}$ and a measure of LV end-diastolic stretch was approximated by a straight line, whose slope was increased by epinephrine. Similarly, Quinones et al. (1976) reported that the ratio of $dP/dt_{\text{max}}$ to the LV end-diastolic circumference increased in response to isoproterenol.

Most previous studies have found that $dP/dt_{\text{max}}$ increases somewhat in response to elevations of arterial pressure. This increase in $dP/dt_{\text{max}}$ can usually be attributed to an increase in the LV end-diastolic pressure and, thus, presumably, $V_{\text{ED}}$ (Mason, 1969). However, Wallace et al., (1963) found, in a canine right-heart bypass preparation, that a sudden increase in aortic pressure increased $dP/dt_{\text{max}}$ before the end-diastolic pressure increased. Others (Wildenthal et al., 1969; Furnival et al., 1970) have found that such sudden increases in aortic diastolic pressure do not alter $dP/dt_{\text{max}}$ when it occurs prior to aortic valve opening.

Suga and Sagawa (1972) have derived the force-velocity relation from the time-varying elastance model. The force-velocity relation is related by appropriate scaling factors to the relation of $E(t)$ to $dE(t)/dt|_{E_{\text{t}}}$. Figure 3 of their paper shows an analog recording of $dE(t)/dt$ obtained in an isolated heart as an intermediate step toward constructing a force-velocity relation. The peak value of $dE(t)/dt$ or $dE/dt_{\text{max}}$ in their figure is relatively constant during an increase in LV systolic pressure or an increase in $V_{\text{ED}}$, but increases in response to the infusion of positive inotropic agent, epinepherine. Since $dE(t)/dt_{\text{max}}$ is the slope of the $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relationship, our results are consistent with these observations of Suga and Sagawa (1972).

In one animal in this study, the $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relation became nonlinear at high $V_{\text{ED}}$. This may be a manifestation of the flat portion of the Frank-Starling relationship. The time-varying elastance model treats the ventricle as a perfectly elastic structure in which pressure and volume are linearly related at all volumes. It is clear that the real LV must have a limit above which further increase in volume will not result in a continued linear increase in $dP/dt_{\text{max}}$ or LV systolic pressure. The $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relation may reach this limit sooner than the $P_{ES}$-$V_{ES}$ relation, since $V_{ED}$ is larger than $V_{ES}$. The observations of the linearity of the $P_{ES}$-$V_{ES}$ relation and the data in the other animals in this study indicate that this limit is not usually reached in the physiological range of LV volumes.

The derivation of the $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relation described in the introduction depends on several assumptions that may not be completely accurate. First, LV volume may not be constant during isovolumic systole, as some volume is ejected into outwardly bulging mitral and aortic valves. Second, the volume correction factor ($V_o$) may not be constant early in systole (Suga and Sagawa, 1974). Finally, $dP/dt_{\text{max}}$ may not always occur during isovolumic systole, but instead may in some circumstances be reached shortly after aortic valve opening. This is most likely to occur after vasodilation or when the LV systolic performance is depressed (Wildenthal et al., 1969; Quinones et al., 1976). However, the agreement of our results with the predictions of the time-varying elastance model (i.e., equations 3 and 4) suggests that these factors do not have a substantial effect under the conditions of this study.

The results of this study suggest that the LV $dP/dt_{\text{max}}$-$V_{\text{ED}}$ relation is a sensitive, load-independent index of LV performance. However, before this can be applied, several limitations of this study must be considered. First, this study was performed after
opening of the pericardium. Second, although the study was performed in close-chest animals, the conditions were carefully controlled. Measurements were obtained during periods of apnea to avoid the confounding influences of changes in intrathoracic pressure. The animals were treated with atropine to avoid the influences of alterations in heart rate during caval occlusion, and with atropine and propranolol to prevent reflex changes in contractility during angiotensin II administration. Finally, the $dP/dt_{\text{max}} - V_{\text{ED}}$ relations were generated by acute preload reduction. The effect of changing loading conditions, after other methods and the variability of the relation over time remain to be determined.

In conclusion, this study demonstrates that in chronically instrumented dogs LV $dP/dt_{\text{max}}$ and the $V_{\text{ED}}$ are linearly related during caval occlusions. The relation is not altered by arterial vasoconstriction, and the slope of the $dP/dt_{\text{max}} - V_{\text{ED}}$ relation appears to be more sensitive to positive inotropic stimulation than $E_{\text{max}}$ the slope of the $P_{\text{ES}} - V_{\text{ES}}$ relation. These results are consistent with predictions of the time-varying elastance model of the LV and support its use as a conceptual framework for the understanding of LV systolic performance.

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