AN INDEX $(dP/dt)/(P/t)$ FOR THE ASSESSMENT OF LEFT VENTRICULAR FUNCTION

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The ascending limb of left ventricular pressure curve and its first derivative obtained by the routine cardiac catheterization were carefully analyzed in 74 patients with varying heart diseases.

The ratio of an instantaneous rate (dP/dt) , to the mean rate (P/t) , of left ventricular pressure rise, for a given patient was reasonably constant during the pre-ejection phase (coefficient of variable = 10.1 ± 4.5 (sd) %).

The value of the ratio $(dP/dt)/(P/t)$ obtained in each patient was compared to the cardiac function assessed by routine hemodynamic data. Patients with normal cardiac function (60 cases) and those with abnormal one (14 cases) had the ratio of 2.49 ± 0.39 sd and 1.84 ± 0.33 sd, respectively, and the difference between two patient-group was statistically significant ($p < 0.001$).

The usefulness of the ratio $(dP/dt)/(P/t)$ as an indicator for evaluating the LV performance was emphasized. The theoretical significance of the ratio was also discussed, suggesting that the LV pressure rises with increasing acceleration or decreasing one when the ratio is greater, or smaller than "2", respectively.

IT HAS been demonstrated that the rate of rise of left ventricular pressure reflects the fundamental property of the contracting myocardium and provides a measure for evaluating the left ventricular performance.¹⁻⁹ The maximum rate of pressure rise, however, has been found to be of limited value as an independent measure because of its dependence on heart rate and loading conditions to the ventricle.³

The left ventricular pressure curve always moves upwards concavely in its ascending limb¹⁰ while the corresponding portion of the first

derivative curve appears to run upwards concavely or convexly in various inotropic interventions. This fact leads us to attempt to investigate the mode of left ventricular pressure rise in the pre-ejection period.

MATERIALS AND METHODS

Seventy four patients, 34 females and 40 males, 13 to 55 years in age, were studied. They were diagnosed as having mitral valvular disease (MS 19, MI 5), aortic valvular disease (AS 3, AI 3), combined valvular disease (18, primary myocardiopathy (3), hypertensive or ischemic heart disease (11), atrial septal defect (10), and ventricular septal defect (2). Fifty seven patients were with normal sinus rhythm while the rest were with atrial fibrillation.

The patients were divided into two groups

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Fig.1. Analysis of left ventricular pressure and its derivative. (Left) Original tracing. ECG, LV pressure, and its first derivative (dP/dt) are simultaneously recorded. (Right) Schematic representation of the original recording. Timing (t), LV pressure (P), and the magnitude of LV dP/dt (dP/dt) are measured for every 5 mmHg increment, up to 50 mmHg of LV pressure. dP/dt , P and t so obtained are used for calculating $(dP/dt)/(P/t)$ ratios.

S.O. 16y.(f) Sinus Rhythm

Fig.2. The phasic values of $(dP/dt)/(P/t)$ in a representative case with sinus rhythm.

(Left) $(dP/dt)/(P/t)$ ratios obtained from a cardiac cycle are plotted versus LV developed pressure. The ratio is reasonably constant from 5 to 50 mmHg of LV pressure (mean 2.65 ± 0.1). (Right) Beat to beat change in the phasic ratio is demonstrated for five consecutive cycles. Overall deviation from the mean value is small and the coefficient of variable is 6.7%. Beat to beat change of the ratio is 4.6%.

according to the status (left ventricular (LV) function): group A with normal LV function, 60 cases; and group B with abnormal LV function, 14 cases. The LV function was regarded as abnormal in cases with the ejection fraction less

than 50%, and with one or more of the following: the left ventricular end-diastolic pressure greater than 12 mmHg, the cardiac index less than 2.3 L/min/M^2 , and the clinical findings of left ventricular failure.

Fig.3. A representative case with atrial fibrillation. K value, expressed as mean $(dP/dt)/(P/t)$ ratio from one cardiac cycle, is compared to the preceding RR interval. The ratio is not greatly affected by the RR interval and seems independent from it (coefficient of variable = 6.7%).

Fig.4. K value $((dP/dt)/(P/t))$ ratio is compared with the LV function assessed by the routine hemodynamic data. Horizontal lines and vertical lines with bars represent mean and 1 standard deviation, respectively. Dotted line at K value 2 separates well the two patient groups. Open circles with arrow show improvement of K value after surgery. Double circles represent the cases who had excellent postoperative course. Triangles represent death after surgery.

Left heart catheterization was performed by the retrograde arterial technique. Pressure was measured from a zero reference to mid-chest by means of P23Db Statham strain gauge and a fluid filled catheter system, and was recorded on a photographic recorder (Electronics for Medicine DR 12 Recorder). The recording speed was 75 to 200 mm/sec. The rate of rise of the LV pressure (dp/dt) was obtained by SGM Resistance Capacitance differentiating circuit (time constant 1.0 msec). Damping characteristics of the catheter system used in our laboratory has been reported elsewhere!¹

For the analysis of the LV pressure upstroke, an instantaneous LV developed pressure (P), the magnitude of its first derivative (dP/dt) and timing (t) were measured for every 5 mmHg increment, up to 50 mmHg of LV pressure, as shown in Fig. 1. Values for P, dP/dt , and t so obtained from each cardiac cycle were used for calculating $(dP/dt)/(P(t))$ ratios. This procedure was done for five consecutive cycles in cases with sinus rhythm and for fifteen with atrial fibrillation, and the mean value of the ratios was determined for every patient.

The maximum velocity of contractile element shortening at zero load (V_{max}) was obtained by a straight line extrapolation from phasic plots of $(dP/dt)/32P$ versus P, using developed pressure!¹² The LV volume and ejection fraction were calculated angiographically as reported elsewhere!¹

RESULTS

In any given LV pressure and the corresponding first derivative, the instantaneous $(dP/dt)/(P/t)$ ratio was reasonably constant throughout the pre-ejection phase, at least up to 50 mmHg of the LV developed pressure. Representative cases were shown in Fig. 2 and 3. The percentile variation of ten figures of $(dP/dt)/(P/t)$ values obtained from one cardiac cycle was 10.1 ± 4.5 (sd) % averaged for all cases studied. The beat to beat variation in the ratio was also considerably small, with coefficient of variable of 5.5 ± 3.1 (sd) %. The change was slightly larger in cases with atrial fibrillation than with sinus rhythm, the coefficient for which was 9.9 ± 2.7 (sd) % and 4.6 ± 2.3 (sd) %, respectively.

The $(dP/dt)/(P/t)$ ratio for each patient was compared to the cardiac function (Fig. 4). Patients with normal LV function (group A) had a $(dP/dt)/(P/t)$ ratio of 2.49 ± 0.39 sd, while those with abnormal function (group B), that of

Fig. 5. K values and some "contractility indices" in patients with normal and abnormal LV function. Student "t" value is greater for $(dP/dt)/(P/t)$, $(dP/dt)/P_{50}$, V_{max} , and $max dP/dt$ in this order ($t = 6.27$, 4.06 , 4.00 , and 1.34 , respectively).

1.84 ± 0.33 sd. The difference between the two groups was highly significant ($p < 0.001$).

In Fig. 5, the $(dP/dt)/(P/t)$ ratio as well as some of the currently proposed "contractility indices" (V_{max} , $(dP/dt)/P_{50}$, and $max dP/dt$) obtained in every patient studied were summarized for the purpose of comparison. As for the ability of these indices to differentiate LV function as normal, $(dP/dt)/(P/t)$ ratio was appeared superior to V_{max} or $(dP/dt)/P_{50}$ according to the value of student "t".

MATHEMATICAL CONSIDERATION

Since the ratio $(dP/dt)/(P/t)$ is proved in this study to be reasonably constant during the pre-ejection phase of LV contraction, or at least up to 50 mmHg of the pressure, it may be formulated as

$$(dP/dt)/(P/t) = K \text{ (constant)}$$

or

$$(1/P)dP = (K/t)dt$$

Accordingly, $\log P = K(\log t) + \log A$ ($\log A =$ constant of integral), or

$$P = At^K \text{ follows.}$$

This equation describes the ascending portion of the left ventricular pressure pulse.

The first and second derivatives of P are given by

$$dP/dt = AKt^{K-1}$$

$$d^2P/dt^2 = AK(K-1)t^{K-2}$$

As far as the rate of LV pressure rise (dP/dt) during the pre-ejection phase is increasing, d^2P/dt^2 is positive, and K is greater than 1.

The third derivative is described as

$$d^3P/dt^3 = AK(K-1)(K-2)t^{K-3}$$

This equation determines the pattern of the dP/dt curve. When the d^3P/dt^3 is positive, or K is greater than 2, the dP/dt curve moves upwards concavely, and when negative, or K is inbetween 1 and 2, runs upwards convexly (Fig. 6, left). In another words, when K is above 2, or inbetween 1 and 2, the magnitude of d^2P/dt^2 increases, or decreases, respectively, with time (Fig. 6, right).

DISCUSSION

Recently, ventricular contractility has been evaluated on the basis of the heart as a muscle by the application of concepts of myocardial fiber mechanics which describe force, velocity, and length characteristics of performance.^{8,9,13-15} However, application of these concepts to the evaluation of performance of the heart presents many problems.¹⁶⁻¹⁹ The fibers constituting the LV wall do not contract isometrically during isovolumic contraction. The different strands of myocardial fibers contract in sequence rather than simultaneously^{20,21} and there is the simultaneous passive distension of others.²²⁻²⁴ The nonhomogenous, nonsimultaneous contraction of the individual myocardial fibers sums up all together to raise the intraventricular pressure.^{10,22-24,25-27} Furthermore, the intraventricular pressure is determined not only by the ventricular wall-tension, but also by the ventricular cavity size, as explained by Laplace's law. Therefore, it is reasonable to consider that a quantitative analysis of the LV pressure curve in

Fig. 6. (Left) LV dp/dt upstroke and K value. Assuming LV pressure is determined by K value: convex, straight, or concave upwards, as shown in the schema. (Right) d^2P/dt^2 of LV pressure, or acceleration mode of LV pressure development. Acceleration of LV pressure increases, is constant or decreases, according to the K value.

the pre-ejection phase would provide information for evaluating the LV performance as a whole. The same idea would be applicable to the LV dp/dt , which is found to be a complex function dependent principally on the contractile state and loading conditions on the myocardium.^{1,3-6,28}

In this study, the pre-ejection portion of LV pressure could be described by a simple equation $P=At^k$, since the K , determined by $(dP/dt)/(P/t)$, was proved constant during the LV pre-ejection phase. The first and the second derivatives of the pressure, velocity and acceleration, respectively, could be given similarly by: $\dot{P}=AKt^{K-1}$ and $\ddot{P}=AK(K-1)t^{K-2}$. According to these equations, the modes of LV pressure development could be described as follows: when K is in between 1 and 2, the velocity curve of the LV pressure moves upwards convexly and the corresponding acceleration of the pressure decreases during the pre-ejection phase, and when K is above 2, the velocity curve runs upwards concavely and the acceleration increases. As shown in Fig. 4, eighty seven percent of 60 patients with normal LV function had a K value of more than 2, while sixty four percent of 14 patients with abnormal function had less than 2. Six patients with abnormal function underwent valvular surgery. Four of them, having a K value of more than 2 preoperatively, revealed excellent clinical improvement after surgery, while 2 patients, having a K value of less than 2 pre-operatively, proved to have severe papillary muscle fibrosis at the time of surgery, and died later in their postoperative course. Though the materials are too few to make a definite conclusion, they would suggest that the ratio $(dP/dt)/(P/t)$ is more sensitive and useful in evaluating the overall ventricular func-

tion than a set of the routine hemodynamic data (ejection fraction, LVEDP, and CI) as used in this study.

V_{max} has been considered most reliable and theoretical among the currently available "contractility indices". The ratio $(dP/dt)/(P/t)$ was compared to the V_{max} with regard to the ability to separate LV function into normal or abnormal categories as shown in Fig. 5 and the former seemed to be superior to the latter in this regard. The relationship between the ratio and V_{max} will be discussed in detail elsewhere.²⁹

The biophysical or physiological significance of the ratio remains unknown. It may be, however, of great interest to make a speculation here as to how the mode of the left ventricular pressure rise would relate to the pumping capability of the left ventricle. In the initial phase of myocardial contraction every myocardial fiber begins to activate in sequence, but the fibers would reserve their forces within the myocardium for forthcoming synergic discharge in the later phase of the pre-ejection period. Acceleration for the resultant LV pressure development may be increasing towards the time of aortic valve opening. Pressure development with such an increasing acceleration may result in more effective ejection of blood in the aorta. On the other hand, the ventricle whose pressure develops only with the convex upwards movement of the dp/dt , could not reserve its force within the myocardium, but would consume it dyssynergically, due to the overstretching of myocardial fibers or the unbalanced summation of individual fiber tensions²⁷ or the interruption of the coordinated effort of fibers,³⁰ and thus may no longer attain the concentration of individual fiber forces in the pre-ejection period.

Fig. 7. Practical method in computing K value. $K = (dP/dt)/(P/t) = \max(dP/dt)/(P_m/t_m)$.

Instead, acceleration of the pressure development in such a case decreases. Such decreasing acceleration for pressure development is obviously at a disadvantage for ejecting blood effectively. In summary, the K value or the ratio $(dP/dt)/(P/t)$ would be determined by the acceleration state of the LV pressure development.

Finally, it would be convenient and important for clinical use to obtain the K value or $(dP/dt)/(P/t)$ ratio in an easy and simple way. Since $(dP/dt)/(P/t)$ is assumed constant during the pre-ejection period, one can calculate it at any instant in the period. When LV dP/dt reaches the maximum with LV developed pressure P_m at the instant t , the ratio is $\max(dP/dt)/(P_m/t_m)$, as shown in Fig. 7. If one does not need the K value itself, but only needs to know how the K value deviates from "2", all that is needed is to examine the LV dP/dt curve at about the concavity of its upstroke (Fig. 6, left).

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