Reduction in the Rate of Diastolic Descent of the Mitral Valve Echogram in Patients with Altered Left Ventricular Diastolic Pressure-Volume Relations

By Miguel A. Quinones, M.D., William H. Gaasch, M.D., Efrain Waisser, M.D., and James K. Alexander, M.D.

SUMMARY

Echocardiographic measurements of the rate of descent of the E wave of the anterior leaflet of the mitral valve during diastole (the mitral valve slope) have been said to correlate with the rate of early left ventricular (LV) filling. Thus, a reduced mitral valve slope in the absence of mitral valve obstruction might be related to impaired LV filling secondary to decreased diastolic compliance. In this study mitral valve slope was compared to several estimates of LV compliance and to the LV end diastolic pressure (EDP) in 32 patients undergoing diagnostic cardiac catheterization: nine normal, 11 coronary artery disease (CAD), seven congestive cardiomyopathy (CC), five left ventricular hypertrophy (LVH). Assuming an exponential relation between pressure (P) and volume (V) at end diastole, and a fixed P intercept at zero V, the following estimates of LV compliance were calculated: (1) the slope of the ln P-V relation (k), which indicates whether a P-V curve is shifted to the left or to the right of normal, (2) an end diastolic distensibility index, (dV/dP)ed, and (3) end diastolic compliance, (dV/VdP)ed.

In every instance of mitral valve slope less than 60 mm/sec an abnormality of the LV P-V relation was found. Of the ten patients with a reduced MVS, four had CAD, one had CC and five had LVH. Correlation was good when mitral valve slope was related to k (r = -0.72, P < 0.001) and to the end diastolic distensibility index (r = 0.59, P < 0.001); but poor (r= NS) when compared to end diastolic compliance or to LVEDP. Thus a reduced mitral valve slope, in the absence of mitral valve obstruction, suggests an alteration in the diastolic properties of the left ventricle.

Additional Indexing Words:
Congestive cardiomyopathy  Left ventricular compliance  Coronary artery disease
Left ventricular diastolic stiffness  Echocardiography  Left ventricular hypertrophy

The rate of descent of the E wave of the anterior leaflet of the mitral valve during early diastole (the mitral valve slope) was one of the earliest measurements obtained in the evaluation of mitral valve motion by echocardiography.1-2 Soon after the development of this technique, it became apparent that patients with mitral stenosis had very low rates of descent.3-7 This reduction in the mitral valve slope was at one time felt to be diagnostic of this disease. However as echocardiography continued to evolve, it became apparent that abnormally low slopes could be observed in conditions other than mitral stenosis (i.e., atrial myxoma, primary pulmonary hypertension, aortic stenosis, aortic insufficiency, and idiopathic hypertrophic subaortic stenosis).8-11 In a study of mitral valve motion, Zaky, Nasser and Feigenbaum suggested that the initial rate of descent of the anterior leaflet (E to Fo) reflects the rate of movement of the mitral ring during early diastole. They felt that the rate of mitral annulus motion during early diastole parallels the rate of ventricular filling. Thus in mitral stenosis, the reduction in mitral valve slope is, at least in part, secondary to a decreased rate of ventricular filling.12 Reduction in the slope observed in conditions such as aortic stenosis and idiopathic hypertrophic subaortic stenosis might be explained on the basis of a reduction in left ventricular diastolic compliance.10

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A noncompliant ventricle, by imposing an increased resistance to left ventricular filling, may reduce the rate of early diastolic filling, and thus reduce the mitral valve slope. The purpose of this study was to investigate the possible relationship between the mitral valve slope, as an indirect measurement of the rate of early ventricular filling, and the diastolic properties of the left ventricle. This has been done by comparing the slope to a series of estimates of left ventricular compliance in a group of patients, none of whom had anatomic mitral obstruction.

Methods

Thirty-two patients (ages ranging from 19–72 years) who underwent diagnostic cardiac catheterization were selected for this study. The patients were divided into four groups (table 1). The first group consisted of nine patients with hemodynamically and angiographically normal left ventricles at rest, in whom cardiac catheterization had been performed for evaluation of chest pain or a heart murmur. The second group consisted of eleven patients with angiographically demonstrated coronary artery disease (CAD) and varying degrees of left ventricular asynergy. The third group consisted of seven patients with congestive cardiomyopathy (CC) as manifested by increase in left ventricular volume, reduction in left ventricular ejection fraction and the presence of normal coronary arteries. Three of these patients had mild degrees of mitral regurgitation (#2, #3, and #7). Group 4 consisted of five patients with inappropriate left ventricular hypertrophy (LVH) as manifested by increased left ventricular wall thickness, low-normal end diastolic volume, and normal ejection fraction. Two of these patients (#3 and #4) had typical hemodynamic, angiographic and echocardiographic findings of idiopathic hypertrophic subaortic stenosis (IHSS). Nonobstructive hypertrophic cardiomyopathy was diagnosed for the other three patients, two of whom (#1 and #5) had echocardiographic evidence of asymmetric septal hypertrophy.

Hemodynamic Measurements

All patients underwent cardiac catheterization in the fasting state following premedication with 10 mg of Diazepam given intramuscularly. Pressures were measured with Statham P23Db pressure transducers from a zero reference point at mid chest level. An Electronics for Medicine DR 8 photographic recorder was utilized. The left ventricular end diastolic pressure (LVEDP) was taken as the junction of the down slope of the "A" wave with the upstroke of the ventricular pressure wave. A cardiac output determination was made in each patient using the Fick principle for oxygen. A left ventriculogram was obtained in each patient in a 35° right anterior oblique projection during normal respiration. Angiographic determinations of left ventricular end diastolic volume and end systolic volume were made using the single plane method of Greene et al. All cineangiographic measurements were corrected for magnification and all volumes were expressed in cc/m² of body surface area. The LVEDP (average of two respiratory cycles) measured immediately before left ventricular angiography was utilized in the calculation of the left ventricular pressure-volume relations.

Formulae and Calculations

Assuming that the pressure-volume relation of the left ventricle at end diastole is exponential, the end diastolic pressure-volume relation may be represented as:

\[ P = b e^{kV} \]  

(1)

where \( P \) = LVEDP in mm Hg, \( V \) = left ventricular end diastolic volume in cc/m², \( b \) = the pressure intercept at zero volume in mm Hg, \( k \) = the slope of the ln P-V relationship, and \( e \) = the base of the natural logarithm (ln). Equation (1) can be expressed as

\[ \ln P = kV + \ln b \]  

(2)

and rewritten as

\[ k = (\ln P - \ln b)/V. \]  

(3)

An index of distensibility (dV/dP) of the left ventricle is defined as the slope of a given part of the pressure-volume curve, or as the change in volume per unit change in pressure.

\[ \text{Since } P = b e^{kV} \]

\[ dP/dV = k b e^{kV} \text{ or } kP \]

\[ dV/dP = e^{kP} \text{ or } 1/kP. \]

(4)

Left ventricular end diastolic compliance [(dV/VdP)ed] is calculated as the end diastolic distensibility index [(dV/dP)ed] normalized for end diastolic volume.\(^{14,15}\)

Thus: \( (dV/VdP)ed = 1/kP \cdot 1/V = 1/kPV. \)

(5)

In order to calculate the index of left ventricular distensibility and compliance at end diastole, the slope of the ln P-V relationship (k) must be determined. If equation #3 is to be used for the calculation of k, a pressure intercept at zero volume (b) must be obtained. An average intercept (b) of 0.43 mm Hg has been found in the in vitro dog heart by extrapolation of serial pressure-volume coordinates assuming the exponential relation previously mentioned.\(^{15}\) This value has been virtually the same in both normal dog hearts and a group of post myocardial infarction dog hearts studied by Hood et al.\(^{15,16}\) Two end diastolic pressure-volume coordinates were obtained by Gorlin et al. in patients with normal left ventricles and in patients with aortic stenosis, by the administration of norepinephrine or isoproterenol.\(^{17}\) These coordinates, plotted as ln P versus V yielded an intercept (b) ranging from 0.31 to 0.46 mm Hg.\(^{15}\) These observations suggest that the pressure intercept (b) varies little when compliance is reduced by experimental myocardial infarction in dogs, and that it is similar in the normal and hypertrophied human left ventricle. If one assumes a pressure intercept (b) of 0.43 mm Hg in all human hearts, k may be calculated as

\[ k = (\ln P - \ln 0.43)/V. \]

(6)
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| 1) 54/M | 1.77     | 90                     | 3.40          | 112/69          | 112/4/6      | 68              | 0.39           | 4.30          | 6.30          | 90           
| 2) 22/M | 2.26     | 62                     | 3.41          | 130/83          | 138/6/11     | 96              | 0.57           | 2.68          | 2.80          | 80           
| 3) 18/M | 1.81     | 100                    | 3.20          | 130/80          | 130/4/6      | 52              | 0.62           | 3.28          | 6.30          | 94           
| 4) 59/M | 1.65     | 89                     | 3.78          | 110/63          | 110/3/5      | 70              | 0.60           | 5.70          | 8.20          | 100*         
| 5) 49/F | 1.66     | 68                     | 3.29          | 110/60          | 110/5/7      | 52              | 0.64           | 2.94          | 5.10          | 60           
| 6) 60/F | 1.72     | 72                     | 3.03          | 153/61          | 153/4/7      | 81              | 0.52           | 4.20          | 5.20          | 88*          
| 7) 23/M | 1.99     | 80                     | 4.07          | 120/65          | 120/6/11     | 70              | 0.77           | 1.98          | 2.83          | 80           
| 8) 40/F | 1.64     | 84                     | 3.30          | 130/84          | 130/4/7      | 56              | 0.73           | 2.86          | 5.10          | 66           
| 9) 72/F | 1.55     | 84                     | 2.93          | 120/63          | 120/3/5      | 64              | 0.67           | 5.27          | 8.20          | 110*         
| Average |          |                        |               |                 | 7.2          | 68              | 0.42           | 3.66          | 5.56          | 85           |
| SEM     |          |                        |               |                 | ± 0.9        | ± 5             | ± 0.83         | ± 0.43        | ± 0.65        | ± 5          |
| **Group II — Coronary Artery Disease** |          |                        |               |                 |              |                |
| 1) 50/F | 1.72     | 60                     | 2.43          | 220/112         | 220/25/35    | 80              | 0.50           | 0.52          | 0.65          | 35           |
| 2) 52/F | 1.87     | 84                     | 1.96          | 165/80          | 165/17/22    | 72              | 0.35           | 0.83          | 1.15          | 36*          |
| 3) 57/M | 2.00     | 65                     | 2.40          | 111/90          | 111/7/14     | 104             | 0.36           | 2.17          | 2.08          | 92*          |
| 4) 46/F | 1.48     | 72                     | 2.05          | 140/80          | 140/9/15     | 154             | 0.29           | 2.90          | 1.88          | 92*          |
| 5) 53/F | 1.52     | 90                     | 2.44          | 102/52          | 102/6/10     | 52              | 0.58           | 1.64          | 3.15          | 46*          |
| 6) 54/M | 1.69     | 68                     | 2.41          | 140/80          | 140/8/17     | 80              | 0.44           | 1.28          | 1.60          | 64           |
| 7) 36/M | 1.78     | 80                     | 3.81          | 125/67          | 125/8/16     | 89              | 0.53           | 1.52          | 1.71          | 110*         |
| 8) 45/M | 2.05     | 80                     | 2.10          | 110/62          | 110/4/8      | 63              | 0.53           | 2.72          | 4.32          | 80*          |
| 9) 52/F | 1.65     | 96                     | 2.99          | 170/75          | 170/20/30    | 104             | 0.38           | 0.81          | 0.78          | 70           |
| 10) 58/F| 1.74     | 105                    | 2.32          | 200/90          | 200/10/20    | 61              | 0.33           | 0.79          | 1.30          | 24           |
| 11) 43/M| 2.26     | 80                     | 2.66          | 141/82          | 141/13/20    | 114             | 0.34           | 1.47          | 1.29          | 80*          |
| Average |          |                        |               |                 | 18.8         | 88              | 0.45           | 1.51          | 1.81          | 66           |
| SEM     |          |                        |               |                 | ± 2.4        | ± 9             | ± 0.04         | ± 0.24        | ± 0.33        | ± 8          |
| **Group III — Congestive Cardiomyopathy** |          |                        |               |                 |              |                |
| 1) 39/M | 1.95     | 72                     | 3.11          | 95/70           | 95/15/23     | 218             | 0.23           | 2.41          | 1.11          | 85*          |
| 2) 45/M | 2.09     | 52                     | 1.97          | 130/73          | 130/10/15    | 169             | 0.37           | 3.17          | 1.88          | 180*         |
| 3) 49/F | 1.53     | 71                     | 2.40          | 169/78          | 169/14/21    | 119             | 0.47           | 1.44          | 1.21          | 60           |
| 4) 19/M | 1.65     | 80                     | 3.22          | 100/65          | 100/10/20    | 103             | 0.38           | 1.35          | 1.32          | 110          |
| 5) 33/M | 1.80     | 76                     | 2.18          | 120/83          | 120/9/12     | 130             | 0.26           | 3.20          | 2.46          | 90*          |
| 6) 30/M | 1.92     | 56                     | 2.41          | 100/54          | 100/10/20    | 104             | 0.43           | 1.35          | 1.30          | 90*          |
| 7) 37/F | 1.57     | 88                     | 1.57          | 145/100         | 145/32/40    | 169             | 0.17           | 0.93          | 0.55          | 45           |
| Average |          |                        |               |                 | 21.6         | 145             | 0.28           | 1.98          | 1.40          | 94           |
| SEM     |          |                        |               |                 | ± 3.4        | ± 14            | ± 0.09         | ± 0.43        | ± 0.23        | ± 16         |
DIASTOLIC DESCENT OF MITRAL VALVE

Since the intercept (b) is assumed to be fixed, k indicates whether a pressure-volume curve is shifted to the left or to the right of normal (a higher k indicates a leftward shift and a lower k indicates a rightward shift).

In each patient, a value for k, \( (dV/dP)_c \)ed and \( (dV/VdP)_c \)ed was determined by the above method.

Echocardiographic Measurements

The ultrasound recording was made in each patient in the supine position with a Smith-Kline Ekolone 20 ultrasonoscope utilizing a transducer with a half-inch crystal focused at 5 cm, with a frequency range of 2.25 MHz and a repetition rate of 1,000 impulses/sec. The transducer was placed in the third, fourth or fifth intercostal space just to the left of the sternum and the ultrasonic beam directed posteriorly and slightly medially until the characteristic motion of the anterior leaflet of the mitral valve was detected. Careful angulation of the probe was made until maximal excursion of the valve was seen. In some of the patients, a recording of the time motion of the valve (m-mode) was displayed on the oscilloscope and a Polaroid film taken of a full oscilloscopic screen sweep. In other patients, the output of the ultrasonoscope was displayed and recorded on an Electronics for Medicine DR 8 multichannel recorder. In both the Polaroid and the strip chart recording, the vertical scale represents distance away from the transducer in centimeters and the horizontal scale represents time in seconds. The echocardiograms of the mitral valve were obtained within 48 hrs of cardiac catheterization in all patients with the exception of four normals. The heart rate at the time the ultrasound recordings were made was less than 100 beats/min in all patients.

The normal echocardiographic motion of the anterior leaflet of the mitral valve has been previously described.6, 12 The E to F segment frequently consists of two distinct slopes, an E to Fo, followed by an Fo to F descent (fig. 1A). The E to Fo segment is believed to represent the movement of the entire mitral valve apparatus (leaflet and ring) away from the transducer during the period of rapid ventricular filling; thus, its slope is believed to reflect the rate of early ventricular filling.12 At the end of rapid filling the anterior leaflet of the mitral valve moves toward a semiclosed position, inscribing a steeper Fo to F descent in the echogram. This type of motion was seen in 17 of the 32 patients (six in group I, four in group II, three in group III, four in group IV). In the remainder of the patients, an E to F descent, without an Fo point, was the only motion recorded (fig. 1B). In the absence of an Fo point the slope of the E to F movement is felt to be an index of the rate of rapid ventricular filling.19 The term mitral valve slope is used in this study to indicate the rate of descent of the E wave (EFO or EF, whichever of the two is recorded).

Statistical analysis of data for comparison between groups was done by using a standard unpaired t-test, or if a significant difference in the variances was detected, an Astin-Welch t-test was used.18, 19 In order to determine the correlation between variables a linear regression analysis was performed.
Figure 1
Examples of two normal echocardiograms of the anterior leaflet of the mitral valve. (A) The E to F segment consists of two distinct slopes, an E to Fo followed by an Fo to F descent. (B) The E to F descent (without a distinct Fo point) is the only motion recorded in this case. Original record in A retouched for illustrative purposes.

Results
The hemodynamic and echocardiographic data for each patient appear in table 1. In the normal group, the average value for the LVEDP was 7 mm Hg, the average value for the end diastolic volume index (EDVI) was 68 cc/m², and the average values for the slope of the In P-V relation (k), for the end diastolic distensibility index [(dV/VdP)ed], and for end diastolic compliance [(dV/VdP)ed] were 0.042 (range 0.034-0.054), 3.66 cc/m²/mm Hg (range 1.98-5.70), and 5.56 mm Hg × 10⁻² (range 2.80-8.20), respectively. These values are in agreement with a previously reported group of normal patients.¹⁵ The average LVEDP in the other three groups was statistically higher than in the normal group (group II-CAD = 19 mm Hg, P < 0.01; group III-CC = 22 mm Hg, P < 0.01; group IV-LVH = 17 mm Hg, P < 0.05). Although the average EDVI in the group with CAD was slightly greater than normal, the difference did not achieve statistical significance. In the group with CC however, EDVI was significantly higher than normal (145 cc/m², P < 0.001). The average EDVI in the group with LVH was only slightly lower than normal (P = NS). The average value for k in the group with CAD was not statistically different from normal; in the group with CC it was significantly lower than normal (k = 0.028, P < 0.01), and in the group with LVH it was significantly higher (k = 0.063, P < 0.01). In the three groups of abnormalities the average value for (dV/dP)ed was significantly lower than normal (group II-CAD = 1.51 cc/m²/mm Hg, P < 0.001; group III-CC = 1.98 cc/m²/mm Hg, P < 0.02; group IV-LVH = 1.11 cc/m²/mm Hg, P < 0.001). The average value for (dV/VdP)ed was also significantly lower in these patients (group II-CAD = 1.81 mm Hg × 10⁻², P < 0.001; group III-CC = 1.40 mm Hg × 10⁻², P < 0.001; group IV-LVH = 1.97 mm Hg × 10⁻², P < 0.01).

The average mitral valve slope in the normal group was 85 mm/sec (range 60-110). These values are somewhat lower than the ones reported by previous investigators.⁴⁻⁶⁻⁷⁻⁸ The reason for this may be that in previous echocardiographic studies, an E to F descent without a distinct Fo point has been most frequently recorded. This may be inferred from the examples of a normal anterior leaflet echogram submitted by most of these investigators in their publications.⁴⁻⁶⁻⁷⁻⁸ In the three normal patients in this study in whom E to F descents were recorded, rates greater than 80 mm/sec were measured. The range for the E to Fo slope in normal patients in our laboratory has been between 60 and 140 mm/sec. Although the average mitral valve slope in the group with CAD was slightly lower than in normals (66 mm/sec) and in the group with CC was slightly greater (94 mm/sec), the differences did not achieve statistical significance. However in the group with LVH, the average slope was 41 mm/sec, a value significantly lower than normal (P < 0.001).

Figure 2
Relationship of the mitral valve slope to (A) the slope, k, of the In P-V relation, and to (B) the LV end diastolic distensibility index, [(dV/dP)ed]. Both correlations are shown to be good. CAD = coronary artery disease; CC = congestive cardiomyopathy; LVH = left ventricular hypertrophy.
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In every instance that a mitral valve slope of less than 60 mm/sec was measured, an abnormality in the left ventricular pressure-volume relation was found. Figures 2A, 2B, 3A and 3B show the correlation between the mitral valve slope and k, (dV/dP)ed, (dV/Vdp)ed, and LVEDP, respectively. Mitral valve slope correlated well with k (r = -0.72, P < 0.001) and with the end diastolic distensibility index (r = 0.59, P < 0.001), but correlated poorly with compliance at end diastole (r = 0.30, P = NS) and with end diastolic pressure (r = 0.34, P = NS).

Of the ten patients who had reduced mitral valve slopes, nine (four with CAD and five with LVH) had pressure-volume curves shifted to the left (high k) and a reduced end diastolic distensibility index. The tenth patient was in the CC group with a pressure-volume curve shifted to the right (low k), but with a markedly reduced end diastolic distensibility index. This patient had a large ventricle with very high filling pressures throughout diastole and an end diastolic pressure of 40 mm Hg. However there were seven patients (four with CAD and three with CC) with normal or low k who also had reduced distensibility index at end diastole but their mitral valve slopes were greater than 60 mm/sec.

Three patients in the group with CC had mitral regurgitation. Patient #2 had a rapid mitral valve slope of 180 mm/sec with a normal end diastolic distensibility index. Patients #3 and #7 had low normal and reduced mitral valve slopes respectively. These two patients had a reduced distensibility index at end diastole.

Figure 4A and B shows examples of two patients with CAD and a reduced mitral valve slope (cases #1 and #10, respectively). Figure 5A and B shows examples of two patients in the LVH group, one of them (fig. 5B, case #4) representing a typical case of idiopathic hypertrophic subaortic stenosis.

Discussion

In this study a correlation has been found between the mitral valve slope and measurements of left ventricular pressure-volume relations at end diastole. Since the slope is determined primarily by

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Figure 3

Relationship of the mitral valve slope to (A) left ventricular end diastolic compliance [(dV/Vdp)ed] and to (B) left ventricular end diastolic pressure (LVEDP). Both correlations are shown to be poor. Abbreviations same as figure 2.

Figure 4

Examples of two patients in the group with CAD with reduced mitral valve slope. (A = case #1, B = case #10). Both patients had pressure-volume curves shifted to the left, as indicated by a high k, and a reduced end diastolic distensibility index.

Figure 5

Examples of two patients in the group with LVH with reduced mitral valve slope (A = case #1, B = case #4). Both patients had pressure-volume curves shifted to the left, as indicated by a high k, and a reduced index of distensibility at end diastole. Example (B) represents a typical case of IHSS. Original record retouched for illustrative purposes.
the rate of early ventricular filling, any alteration in left ventricular compliance resulting in a reduction in the rate of early diastolic filling should also reduce the mitral valve slope. Evidence exists to suggest that the rate of early ventricular filling can be affected by the diastolic properties of the heart. Stewart, Mason and Braunwald described a reduced rate of Y descent of the left atrial pressure curve in patients with idiopathic hypertrophic subaortic stenosis and in patients with valvular aortic stenosis. This finding was ascribed to a reduced rate of filling secondary to diminished ventricular compliance. Miller and associates have described abnormalities of left ventricular compliance in patients with coronary artery disease and left ventricular asynergy. In these patients 25% of diastolic filling occurred in the first one-third of diastole compared to 38% in patients with normal ventricles, suggesting a reduced rate of filling during early diastole.

Ideally it is more appropriate to compare the mitral valve slope with some measurement of left ventricular stiffness obtained during early ventricular filling. This, however, would require simultaneous analysis of pressure and volume during this phase of diastole, a technique not available to us at the time of the study. In spite of this limitation, the mitral valve slope was found to correlate well with the slope of the ln P-V relation (k) and with the end diastolic distensibility index, [(dV/dP)ed]. This suggests that some ventricles that are stiff at end diastole will also be less distensible than normal during early ventricular filling.

The left ventricular pressure-volume relation at end diastole was estimated assuming first, an exponential relationship between pressure and volume and second, a common pressure intercept at zero volume in the human heart. Therefore the slope of the ln P-V relation (k) suggests whether a curve is shifted to the right or to the left (a higher value for k indicating a shift to the left and a lower value indicating a shift to the right). A ventricle with a diastolic pressure-volume curve shifted to the left has higher pressures and is less distensible than a normal ventricle at comparable volumes. It is not unreasonable to postulate that such a ventricle will tend to be less distensible during all phases of diastole, and that this may result in an increased resistance to filling, a reduced rate of early diastolic filling, and thus a reduced mitral valve slope. The opposite can be postulated for a ventricle with a pressure-volume curve shifted to the right; at comparable volumes, it will be more distensible than a normal ventricle. This explains the good correlation (r=0.72) found in this study between the mitral valve slope and k.

An abnormality in the left ventricular end diastolic pressure-volume relation was seen in all the patients with mitral valve slopes of less than 60 mm/sec. All patients with elevated k had reduced end diastolic distensibility index and abnormally low slopes. However, some patients with normal or reduced k had a low end diastolic distensibility index and a normal mitral valve slope. Most of these were patients with enlarged ventricles and elevated left ventricular end diastolic pressures. The reason for elevation in end diastolic pressure in these ventricles (as well as in any ventricle) is a reduction in distensibility at end diastole. In other words, at end diastole these ventricles are operating on a steep portion of their pressure-volume curve. A ventricle with a normal or low k and a reduced end diastolic distensibility index, however, may be normally distensible during early diastole, depending on which portion of its pressure-volume curve the ventricle is operating on during this period.

Of the three patients with mitral regurgitation in the group with CC, case #2 had a rapid mitral valve slope of 180 mm/sec and a normal distensibility index at end diastole. In this normally distensible ventricle, the presence of mitral regurgitation may have contributed to an increase in the rate of early ventricular filling and thus to an increase in the mitral valve slope. The other two patients, cases #3 and #7, had low normal and reduced mitral valve slopes respectively; both had reduced end diastolic distensibility. Thus, in spite of mitral

**Figure 6**

Relationship of the left ventricular end diastolic pressure to the end diastolic volume index for the average of the four groups of patients. On the left a graph of the ln P-V relation is shown. On the right a conceptual diagram of the P-V relation has been drawn.

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regurgitation, the rate of early ventricular filling may have been depressed secondary to reduced ventricular distensibility.

Figure 6 shows a graph of the ln P-V relation and a conceptual diagram of the pressure-volume relation for the average of the four groups of patients studied. It can be seen that the group with LVH lies to the left of the normal group. All the patients in this group have normally contracting ventricles which are stiff because of muscular hypertrophy. The group with CC lies to the right of the normal group. The patients in this group have dilated failing ventricles and, although at comparable volumes they may be more distensible than normal, at end diastole some of them are operating on a steep portion of their pressure-volume curve, therefore having reduced end diastolic distensibility. The group with CAD lies on a curve with a k similar to the normal group but at a steeper portion. This suggests a combination of left ventricular dilatation and increased stiffness possibly secondary to ischemia and/or scar formation. If one examines the individual members of this group, an entire spectrum ranging from low k to elevated k will be seen.

Although the mitral valve slope correlated well with k and with the end diastolic distensibility index, it correlated poorly with end diastolic compliance. As previously defined, end diastolic compliance is the end diastolic distensibility index normalized for end diastolic volume. As suggested by Levine, dV/dP reflects the distensibility of the entire ventricle, while normalized distensibility (dV/VdP) examines the distensibility of the myocardiurn. Since the rate of early ventricular filling, and thus the mitral valve slope, is affected by the resistance offered by the entire ventricle, a poor correlation between the mitral valve slope (a non-normalized velocity) and normalized distensibility is not unexpected.

A reduction in the velocity of opening of the anterior leaflet (D to E slope) has been recently described by Konecke et al. in patients with markedly elevated initial left ventricular diastolic pressures (14 mm Hg or greater). Most of these patients had failing left ventricles with poor ejection fractions and high end systolic volumes. The opening of the mitral valve (DE slope) occurs at a time during early diastole when left ventricular pressure is falling and left ventricular volume is rising. Porter et al. have shown that during this early phase of diastole the ratio of the change in ventricular volume per negative change in ventricular pressure (a ratio which may reflect active ventricular relaxation) may be reduced in enlarged ventricles with large end systolic volumes and reduced ejection fractions. Konecke et al. have also described a prolongation of the A-C interval (from the onset of mitral valve closure to the termination of valve closure as indicated by the junction of the anterior and posterior valve ekggrams) in patients with very high LVEDP caused by a prominent atrial component of the left ventricular pressure. In both of these situations (reduced D to E slope or prolonged A-C interval), a reduction in the mitral valve slope may occur depending on the left ventricular distensibility during early diastolic filling. As can be seen from the data in the present study the mitral valve slope by itself is a poor indicator of left ventricular end diastolic pressure.

In conclusion, a correlation has been found between a reduction in mitral valve slope, as an indirect measurement of the rate of early ventricular filling, and abnormalities of the left ventricular pressure-volume relation at end diastole. Ventricles with pressure-volume curves shifted to the left are most frequently associated with abnormally reduced slopes. A good correlation was also found between the mitral valve slope and the end diastolic distensibility index. Thus, a reduced mitral valve slope in the absence of mitral valve obstruction suggests an alteration in the diastolic properties of the left ventricle.

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