EQUALIZATION RATE: A HÆMODYNAMIC METHOD FOR EVALUATION OF MITRAL STENOSIS*

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The presently accepted methods for the estimation of the diastolic area of the mitral orifice have been based on either the pressure gradient (Gorlin and Gorlin, 1951) or the contour of the left atrial pressure pulse (Marshall, Woodward, and Wood, 1958). In 1961 a formula was presented in which we attempted to combine the two methods (Gunnar *et al.*, 1961); however, the calculations had the disadvantage of producing a nondescript number which appeared to be proportional to the size of the mitral orifice as found at operation or necropsy but was without dimensions. We have now enlarged our series and modified the formula to provide dimensions which relate directly to the valve area, and the results of the analysis of this method comprise the basis of this report.

SUBJECTS AND METHODS

This series consists of 74 patients with their detailed surgical reports and data from combined heart catheterization. Of these, 73 had rheumatic mitral valve disease, and one had a congenital cleft of the mitral valve associated with a previously repaired persistent ostium primum defect.

(1) *Estimates of Orifice Area at Surgery.* It became apparent early in our study that surgical estimates of orifice size were relatively inaccurate. In "closed" procedures, the amount of a precisely measured "finger" which can be partially or completely passed through an orifice is a crude measurement and depends upon the delicacy of the initial examination. The surgeon may apply more pressure than the atrio-ventricular gradient, and adhesions may be severed by the examining finger. In "open" procedures and at necropsy the ragged edges of a deformed mitral valve and the uneven planar apposition of the mitral leaflets make estimations difficult despite direct observation (Richter, 1963). Recognizing these limitations, we divided all the surgical estimates of orifice size into four categories.

Group I included cases with "tight" stenosis or orifices measuring 1 cm.² or less.

Group II included cases with "moderate" stenosis or orifices measuring 1.1 to 2.0 cm.²

Group III included cases of "mild" stenosis or orifices measuring 2.1 to 3.0 cm.²

Group IV consisted of cases in which the orifice measured more than 3 cm.²

(2) *Catheterization Techniques.* Combined heart catheterization was performed in all cases. A modification (Bougas, Musser, and Goldberg, 1956) of the Björk (Björk, Malmström, and Uggla, 1953) technique was used. A Cournand catheter was inserted in a peripheral vein and advanced into the right pulmonary artery. The patient was turned into the prone position and two 18-gauge, thin-walled cardiac needles were inserted transthoracically under fluoroscopic guidance into the left atrium. Two polyethylene

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FIG. 1.—Pressure pulse curves from left atrium and left ventricle. The pressure difference is measured at the opening snap time (P_1) and again 0.2 sec. later (P_2). Time lines are 0.02 sec. The pressure tracings are set on the same baseline and same sensitivity.

catheters (PE-50) 25 cm. in length were passed through the needles into the left atrium and left ventricle. In most cases an external crystal microphone was placed beneath the patient in the left lower sternal position. The left atrial and left ventricular catheters were connected to identical P 23 G Statham or 267 B Sanborn Transducers set on the same baseline and at the same sensitivity. Using a multi-channel photographic recorder, pressures were recorded at paper speeds of 75–100 mm./sec. together with a standard limb-lead electrocardiogram and the phonocardiogram. Immediately thereafter blood and gas samples were collected to calculate cardiac output by the Fick Principle. When appropriate, the transthoracic needles were removed, leaving the polyethylene catheters in place; the patients were exercised, and all studies were repeated.

(3) *Calculation.* All data utilized in these calculations are mean values from measurement of a minimum of three representative, simultaneous left atrial–left ventricular pressure-pulse contours.

(A) *Indices.* *Ry.* The rate of the descent of the atrial pressure from the peak of the V wave to the nadir of the Y descent.

Ry/V. The rate of the descent of the atrial pressure from the peak of the V wave to the nadir of the Y descent divided by the V wave peak (Owen and Wood, 1955).

Ry/LA (m). The rate of the descent of the atrial pressure from the peak of the V wave to the nadir of the Y descent divided by the left atrial mean pressure (Morrow *et al.*, 1957).

Ry 0.1 sec./LA (m). The rate of the descent of the atrial pressure from the peak of the V wave to a point 0.1 sec. later divided by the left atrial mean pressure (Morrow *et al.*, 1957).

(B) *Mitral orifice area* was calculated by the Gorlin Formula utilizing the simultaneously recorded left atrial and left ventricular pressures to determine the mean mitral diastolic gradient (Gorlin and Gorlin, 1951). The constant used was 0.85 since this was found to be more consistent with the surgical assessment of the orifice area than the traditional 0.7.

(C) *Equalization rate.* A straight line was drawn along the left atrial pulse from the opening snap time or the point that left ventricular pressure falls below left atrial pressure, to the nadir of the Y descent. A second line was drawn to fit best the left ventricular diastolic pressure pulse. The pressure difference was then measured at the time of the opening snap or the cross-over (P_1) and again 0.2 sec. later (P_2) (Fig. 1). The time of measuring P_2 was chosen to be 0.2 sec. after P_1 , since this was the longest interval at which the gradient could actually be measured in most cases. Where the actual pressure difference at P_2 could not be used because of the superimposition of atrial contractions, the distance between the extrapolated lines was used

TABLE I
COMPARISON OF MITRAL VALVE AREA FOUND AT OPERATION OR NECROPSY WITH ESTIMATED AREA CALCULATED BY GORLIN EQUATION AND EQUALIZATION RATE FORMULA IN FIRST 24 PATIENTS USED TO DERIVE EQUALIZATION RATE FORMULA

Patient	Gorlin formula	Equalization rate	Degree of error	
			Gorlin formula	Equalization rate
<i>Group I—1.0 cm.² or less</i>				
L.N.	0.4	0.3	—	—
M.R.	0.9	0.7	—	—
E.G.	0.5	0.4	—	—
H.J.	0.6	0.5	—	—
E.W.	0.5	0.3	—	—
G.B.	0.7	0.5	—	—
M.H.	0.6	0.5	—	—
J.S.	0.7	0.7	—	—
M.R.	1.2	1.2	+1	+1
H.R.	0.6	0.5	—	—
J.B.	0.7	0.6	—	—
A.D.	0.8	0.5	—	—
L.L.	1.0	0.8	—	—
A.R.	1.0	1.0	—	—
Total	13 correct	13 correct	1	1
<i>Group II—1.1 to 2.0 cm.²</i>				
M.K.	0.8	0.7	−1	−1
J.W.	0.9	1.3	−1	—
G.W.	0.9	0.9	−1	−1
E.F.	2.4	1.3	+1	—
N.R.	0.5	0.8	−1	−1
F.L.	1.0	1.3	−1	—
E.B.	0.7	1.3	−1	—
Total	0 correct	4 correct	7	3
<i>Group III—2.1 to 3.0 cm.²</i>				
A.C.	3.0	3.6	—	+1
Total	1 correct	0 correct	0	1
<i>Group IV—3.0 cm.²</i>				
W.S.	0.7	∞	−3	—
M.C.	1.5	7.1	−2	—
Total	0 correct	2 correct	2	0
Total for Groups I-IV	14 correct	19 correct	10	5

for P_2 . The mean diastolic gradient (MDG) and diastolic filling period were calculated as in the Gorlin method. The mitral valve area was calculated as:

$$A = \frac{\text{Flow in ml./diastolic second}}{C \cdot \log \frac{P_1}{P_1 - P_2} \cdot \sqrt{2g \text{ MDG}}} = \frac{\text{Flow in ml./diastolic second}}{100 \log \frac{P_1}{P_1 - P_2} \cdot \sqrt{\text{MDG}}}$$

This equation is an empirical adjustment of the constant in the Gorlin formula. It was derived in the first 24 cases (Table I) by trial of various methods to include an expression of the pressure pulse contour in the calculation of orifice area (*vide infra*). Statistical analysis of these cases revealed the most accurate constant to be 2.2. The 100 in the denominator of the equalization rate formula is $2.2\sqrt{2g}$. This constant was used to estimate the diastolic size of the mitral valve in the subsequent 50 patients (Table II).

TABLE II

COMPARISON OF MITRAL VALVE ORIFICE AREA FOUND AT OPERATION OR NECROPSY WITH ESTIMATED AREA CALCULATED BY GORLIN EQUATION AND EQUALIZATION RATE FORMULA IN 50 CASES USED TO TEST FORMULAS

Patient	Gorlin formula	Equalization rate	Degree of error	
			Gorlin formula	Equalization rate
<i>Group I—1.0 cm.² or less</i>				
F.J.	0.4	0.3	—	—
J.P.	1.1	1.1	+1	+1
P.S.	0.5	0.4	—	—
G.W.	0.5	0.4	—	—
J.P.	0.8	0.5	—	—
M.C.	0.4	0.3	—	—
V.G.	0.3	0.3	—	—
G.D.	0.4	0.4	—	—
G.C.	0.7	0.4	—	—
L.L.	0.5	0.8	—	—
E.C.	0.8	1.0	—	—
F.H.	0.7	0.6	—	—
C.S.	0.8	0.9	—	—
R.P.	0.8	0.6	—	—
A.M.	0.8	0.9	—	—
C.B.	0.5	0.9	—	—
J.D.	0.4	0.4	—	—
P.C.	0.6	0.4	—	—
C.B.	0.7	0.5	—	—
L.M.	1.0	0.7	—	—
M.F.	1.0	2.1	—	+2
A.B.	0.6	0.5	—	—
J.B.	0.7	1.0	—	—
A.H.	0.8	0.7	—	—
W.P.	0.5	0.5	—	—
G.K.	1.0	Indeterminate	—	Indeterminate
M.R.	0.6	0.5	—	—
M.C.	1.4	2.4	+1	+2
D.C.	0.8	0.9	—	—
D.B.	1.2	2.2	+1	+2
J.Z.	0.7	0.6	—	—
B.M.	0.6	1.0	—	—
C.T.	0.9	1.3	—	+1
Total	30 correct	27 correct	3	6
<i>Group II—1.1 to 2.0 cm.²</i>				
B.C.	1.2	1.4	—	—
H.C.	1.1	1.3	—	—
T.W.	1.2	1.4	—	—
J.C.	1.1	1.9	—	—
C.T.	0.6	0.9	-1	-1
J.B.	0.8	1.2	-1	—
B.D.	0.9	1.4	-1	—
M.C.	1.0	1.0	-1	-1
C.C.	1.1	1.4	—	—
Total	5 correct	7 correct	4	2
<i>Group III—2.1 to 3.0 cm.²</i>				
D.F.	4.7	2.5	+1	—
D.J.	0.7	2.3	-2	—
B.Y.	0.7	2.2	-2	—
R.H.	1.0	2.7	-2	—
Total	0 correct	4 correct	4	0
<i>Group IV—3.0 cm.²</i>				
M.M.	0.7	7.4	-3	—
A.A.	3.6	18.7	—	—
A.B.	0.9	3.1	-3	—
C.H.	1.6	6.2	-2	—
Total	1 correct	4 correct	3	0
Total for Groups I-IV	36 correct	42 correct	14	8

In one case the equalization rate could not be calculated because the diastolic filling period was entirely occupied by a large "a" wave as a result of tachycardia and first degree heart block. Since the Gorlin equation was correct in predicting the valve area, this patient (G.K.) is carried in the results as a correct prediction for the Gorlin formula and incorrect for the equalization rate.

The cross-sectional area of the mitral orifice in diastole estimated by each of the above methods was compared with the area found at operation or necropsy. In order to compare the Gorlin formula with the equalization rate modification, the 24 cases used in deriving the constant in the latter were dropped from both series. Since we wished to relate only to the mitral diastolic orifice size, the amount of regurgitation was noted but not accounted for.

RESULTS

All calculated indices were assessed for their reliability in predicting the size of the mitral orifice by plotting calculated values against the estimate obtained during operation or at necropsy.

A. *Indices* Ry/V (Fig. 2), Ry/LA (m) (Fig. 3), and $Ry\ 0.1\ sec./LA$ (m) (Fig. 4) correlated poorly with observed estimates in all 74 cases.

B. *The Gorlin formula* accurately classified the orifice size in 30 of 33 patients in Group I, in 5 of 9 patients in Group II, in none of the 4 patients in Group III, and in 1 of the 4 patients in Group IV (Fig. 5). In Group I the estimates, when inaccurate, were all of necessity too large, and all three were estimated to be in Group II. In Group II the four cases inaccurately assessed were thought to be in Group I. In Group III one was estimated to be in Group IV, while the three classified too small were all thought to be in Group I. In Group IV all the inaccuracies were of necessity too small an estimate of the valve area with two classified in Group I and one in Group II. Of the 50 cases, the grouping was correct in 36.

C. *Equalization Rate.* This formula accurately predicted the grouping in 27 of 33 patients in Group I, 7 of 9 patients in Group II, all 4 patients in Group III, and all 4 patients in Group IV (Fig. 6). In all, the grouping was correct in 42 of the 50 patients. In only three patients was the classification inaccurate by more than one group. In Group I, where inaccurate estimates were by

FIG. 2.—The relation of Ry/V to observed mitral orifice size in all 74 cases.

FIG. 3.—The relation of Ry/LA (m) to observed mitral orifice size in all 74 cases.

FIG. 4.—The relation of $Ry\ 0.1\ sec./LA$ (m) to observed mitral orifice size in all 74 cases.

FIG. 5.—The relation of the Gorlin formula calculation of orifice size to the observed orifice size in the 50 cases used to test the equalization rate formula.

FIG. 6.—The relation of the equalization rate formula calculation of orifice size to the observed orifice size in the 50 cases used to test the formula.

necessity too great, two were estimated to be in Group II, three in Group III, and in one, the equalization rate could not be calculated. The two Group II patients inaccurately assessed were all assigned to Group I. In five cases when both the Gorlin formula and the equalization rate were inaccurate, they tended to vary in the same direction, suggesting the possibility that the surgeon's estimate may have been inaccurate.

In Group I the equalization rate formula provided an incorrect prediction three times when the Gorlin formula was correct, and in no case was the reverse true. In Groups II, III, and IV the equalization rate was correct in nine cases when the Gorlin formula was inaccurate, and in no case in these groups was the reverse true (Table II). A test of the significance of the difference between the methods for the entire series gives a *p* value less than 0.05. It must be noted, however, that on looking at the specific values the Gorlin formula is excellent for valve orifice areas of 1.0 cm.² or less, while for areas above 1.0 cm.² the equalization rate formula appears to be much more reliable.

DISCUSSION

It is not surprising that all of the indices which depend upon the slope of the Y descent beginning at the peak of the V wave were inadequate in predicting the diastolic area of the mitral orifice. It has been pointed out that the peak of the V occurs before mitral opening and is more closely related to aortic closure than mitral opening (Gunnar *et al.*, 1961; Nixon, 1961). Shortly after the ventricular pressure falls below atrial pressure, the opening snap occurs, and this is often accompanied by an abrupt change in the rate of the Y descent (Fig. 1). The early portion of the Y descent, from the V peak to the cross-over, must represent something other than emptying of the left atrium into the ventricle, since it occurs when there is no forward flow across the valve. This early portion of the Y descent which figures prominently in all the indices probably represents the decline of the transmitted ventricular pressure in patients with significant mitral insufficiency and the relaxation of the atrio-ventricular ring in patients without such a systolic atrio-ventricular communication.

The formula devised by Gorlin is a modification of the hydraulic formula of Bernoulli utilizing Torricelli's theorem to calculate velocity. Gorlin's modification has been deemed to be quite adequate for clinical purposes when used to evaluate semilunar valvular stenosis but has been often in serious error when used to evaluate atrio-ventricular valvular lesions. The most serious objections to the use of Gorlin's modification in evaluating valvular disease are as follows.

(1) Bernoulli's formula applies to steady, not pulsatile, flow; (2) inaccuracy of the flow measurement (since only net forward flow can be measured); (3) Burger, van Brummelen, and Dannenburg (1956) have pointed out that the dimensions of the heart do not fit the ideal conditions for application of this formula; (4) Rodrigo (1953) calls attention to the relationship of the orifice shape to the coefficient of contraction; (5) the fluid in the chamber cannot turn immediately into the axis of the jet when it reaches the orifice and thus the cross-section of the jet of flow does not necessarily coincide with the orifice shape; and (6) the stagnation pressure, which may not obtain for gas, may in the case of a liquid involve a different pressure just at the orifice as compared to the main body of fluid, and this would be of particular influence in pulsatile flow. In the series here presented, the Gorlin formula was a good predictor of orifice sizes of 1 cm.² or less, but for larger orifices was a poor measure, and in regurgitant valves was usually misleading.

In attempting to increase the accuracy of the Gorlin formula for measuring valve orifice area, it seemed reasonable to take into account the contour of the pressure gradient during diastole. Since the equalization rate formula is essentially a modification of the Gorlin formula, it is subject to the objections enumerated above; however, these studies demonstrate that estimates by this modification are probably more accurate. The increased accuracy can be attributed to our alteration of the constant to give weight to the change in pressure gradient per unit time. For this purpose, the log of the ratio $\frac{P_1}{P_1 - P_2}$ was used to correct the constant C. This modification tended to minimize the influence of regurgitant flow by undercorrecting the denominator in the face of rapid equilibration of pressure early in diastole.

We have tried other modifications of the formula such as the reciprocal of the percentile change $\left(\frac{P_1}{P_1 - P_2}\right)$, the absolute change in pressure ($P_1 - P_2$), and the square root of the reciprocal of the percentile change in pressure $\sqrt{\frac{P_1}{P_1 - P_2}}$, but none of these has been helpful in separating the data into their respective groups. Thus, we have empirically justified but not explained our formula. In searching for an explanation, we have found that little is actually known about the flow characteristics across the diseased mitral valve, and therefore it is almost impossible to give an accurate mathematical description of the flow and pressure relationships. It is probable that no formulation is possible for all valves, since the pressure-flow characteristics will vary with the shape and thickness of the orifice as well as the size. We hope that others may find our modification useful in the clinical assessment of diastolic mitral orifice size.

SUMMARY

We have presented an "equalization rate" formula for estimation of the diastolic area of the mitral orifice. This formula modifies that of Gorlin by including an expression of the change in the pressure gradient per unit time. Seventy-four patients were studied, the first 24 for derivation of the formula. In 50 patients our modification was compared with the Gorlin formula, using the area found at operation or necropsy as the reference standard. There was little difference between the Gorlin formula and the equalization rate formula when estimating valve areas measuring 1 cm.² or less, but in 17 valves measuring more than 1 cm.², the equalization rate formula was accurate nine times when the Gorlin formula was inaccurate, and in no patients was the reverse true.

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