Reflected Ultrasound as a Diagnostic Instrument in Study of Mitral Valve Disease*

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The refinement of phonocardiography, apex cardiography, electrocardiography, vectorcardiography, cardiac catheterization, and cine-angiography in the post-war years has contributed considerably toward enhancing the clinical acumen of physicians. These techniques have become standardized and widely used as diagnostic aids, particularly in the study of valvular heart disease. In the evaluation of patients as candidates for surgical correction it is customary to employ as many diagnostic procedures as is feasible. But in many instances reliance on catheterization and cine-angiographic information has been necessary to establish the type and degree of abnormality. Unfortunately, the latter two techniques are not without complications, particularly in those who are seriously ill.

The development of an ultrasound technique to evaluate mitral and tricuspid valve motion with some degree of precision has provided an important additional tool to this armamentarium. By definition, ultrasound is composed of sound waves with a frequency above 20,000 cycles per second exceeding the limits audible to the human ear. The physical characteristics of the transmission of ultrasound through liquid or solid matter are similar to light in many respects, including the occurrence of reflection and refraction through medium having different acoustical impedance. Acoustical impedance is a value determined by the product of the velocity times the density of the medium. The portion of ultrasound that is reflected at any interface is directly related to change in

acoustical impedance at the interface of the two media, i.e. between cardiac tissue and intracavitary blood. The amount of reflected energy will depend upon this difference in acoustical impedance and also upon the angle of incidence, so that maximum reflection will occur from an interface positioned at right angles to the ultrasonic waves.

In 1881, the Curie brothers discovered the piezoelectrical effect. A piezo-electric crystal when activated by an alternating electric field of appropriate frequency may generate a resonance in the crystal which will invoke mechanical vibrations which may then be transmitted as ultrasound waves. This same crystal may be used as a detector for reflected ultrasound waves, since the latter cause mechanical vibrations in the crystal which in turn generate electric charges suitable for recording. It is this reflected ultrasound technique which has become useful in diagnostic medicine. Its most useful clinical application outside of cardiology has been the detection of space-occupying lesions within the skull by locating shifts of a distinctive midline echo (Leksell, 1956; Jeppsson, 1961; Taylor, Newell, and Karvounis, 1961). It has been evaluated as a possible adjunct in the diagnosis of abdominal cysts, solid tumours, and in the location and measurement of the fetal head *in utero* (Donald and Brown, 1961). Experimentally it has been applied to the location of gall-stones and foreign bodies in dogs (Ludwig and Struthers, 1949), to study tumours of the breast (Wild and Reid, 1952), and to define soft tissue structures of the extremities, neck, liver, spleen, and kidneys (Holmes *et al.*, 1955).

In 1954, Edler and Hertz introduced this method for recording cardiac motion. In a beautiful series of studies, motion of the left atrial wall, interventricular septum, outflow tract of the left ventricle, mitral, and tricuspid valves was demonstrated

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(Edler and Gustafson, 1957; Edler *et al.*, 1961). A characteristic pattern for motion of the anterior leaflet of the mitral valve located about 6–8 cm. from the anterior chest wall with a range of motion of about 2 cm. in the anterior–posterior plane was evolved. This pattern of motion was consistently distorted in the presence of mitral stenosis. Subsequent confirmatory studies were forthcoming from Europe from Effert, Erkens, and Grosse-Brockhoff (1957), Effert *et al.* (1964), Gässler and Samlert (1958), Schmitt and Braun (1960), and Wirth (1966). In 1963, Joyner and Reid from Philadelphia published their first confirmatory report in the United States. Curiously, the technique has not gained wide acceptance in the United States despite the very substantial contributions it may provide in the assessment of mitral and tricuspid valve disease. The usefulness of ultrasound in the diagnosis of pericardial effusion is also now well established (Feigenbaum, Waldhausen, and Hyde, 1965; Soulen, Lapayowker, and Gimenez, 1966), and its application in the study of prosthetic valvular function has been described (Winters, Gimenez, and Soloff, 1967; Gimenez *et al.*, 1965). The present report describes our experience with this technique in the study of mitral valve function and its relative value when compared to the other standard diagnostic cardiologic procedures.

SUBJECTS AND METHODS

Two hundred adult patients were studied in this series. Seventy-five were without valvular disease and were representative of normal mitral valve motion. One hundred and twenty-five patients had rheumatic valvular heart disease with mitral and/or aortic valve dysfunction. Forty-four patients in this latter group had predominant mitral stenosis without significant mitral insufficiency.

The reflected ultrasonic method employed in this study used a Smith, Kline Instrument Company Ekoline 20 unit, with a 2.5 megacycle crystal to transmit and receive an ultrasound signal pulsed at 200 a second. The penetrating power of sound diminishes with an increase in frequency. This in turn diminishes the angle of divergence of the beam, resulting in greater resolution. Edler and Hertz demonstrated in 1954 that echo signals could be obtained from the deeper parts of the thorax in adults using a frequency of 2.5 megacycles per second. At this frequency a sound beam is cylindrical for a distance of 60 mm. from the crystal. The diameter of the beam increased twofold at about 100 mm. from the crystal with 3.5° divergence. Hertz's experience, however, indicated that when carrying out examinations of the heart and chest in man, echo signals could be recorded from structures up to 150 mm. from the crystal. In patients with emphysema or obesity, difficulty in obtaining a reflected echo is occasionally encountered with a 2.5 megacycle crystal because of scattering and refraction of the transmitted echoes. Reducing the frequency

response to 1 megacycle per second may increase penetrating power in such patients, but the greater angle of divergence may adversely alter the ability to "focus" the ultrasound beam. Thus, the frequency 2.5 megacycle/sec. has been used exclusively in this study.

The transducer was placed in the third, fourth, or fifth left intercostal space 1–4 cm. lateral to the midsternal line with the patient supine, left lateral or right lateral oblique position. The transducer was directed generally in a posterior direction and slightly to the right. The tricuspid valve may on occasion be located with the transducer close to the midsternal line, but with the echo recorded considerably closer to the anterior chest wall. No discussion of tricuspid valve motion will be included in this presentation. This unit contains an electronic gate enabling the operator to select for direct recording a returning echo for some particular intracardiac structure, in this case the anterior leaflet of the mitral valve (Fig. 1). The isolated signal was recorded on an Electronics for Medicine DC channel simultaneously with an electrocardiogram, phonocardiogram, and apex cardiogram. The Ekoline unit is calibrated so that each hairline on the horizontal grid represents 2 mm. distance, with the left side of the screen representing the anterior chest wall. Calibration of the direct recorder was accomplished by adjustment of the DC amplifier sensitivity control, so that 1 cm. deflection on the Ekoline unit equalled 1 cm. deflection on the recorder.

The phonocardiogram was obtained with a piezo crystal supplied by Electronics for Medicine, and the apex cardiogram obtained with a Sanborn Model 374 pulse wave attachment. Parameters were recorded at a paper speed of 50 or 100 mm./sec. with all measurements made at the latter speed. On other occasions, the ultrasound signal was recorded on a Schwarzer multichannel direct writer with an electrocardiogram lead II and a phonocardiogram exhibiting four frequency ranges of sound; 250–500 cycles, 140–280 cycles, 70–140 cycles, and 20–90 cycles/sec. Velocity of valve motion was determined by measurement of the slope of the ultrasound curves occurring after peak mitral valve opening.

Right heart catheterization was performed according to standard techniques. Cardiac output was determined by the direct Fick principle or dye dilution technique utilizing Cardiogreen injected into the pulmonary artery and sampled from a peripheral systemic artery. Left atrial catheterization was performed by the transseptal approach and left ventricular catheterization by percutaneous femoral artery catheterization with retrograde passage of the catheter through the aortic valve into the left ventricle. Cine-angiograms were obtained following injections of Renovist into the pulmonary artery, left atrium, or left ventricle. Mitral valve area was calculated from catheterization data according to the Gorlin formula (Gorlin and Gorlin, 1951). Analysis of mitral valve function from the cine films was determined independently by two of the authors (W.L.W. and J.G.), with an estimation of the degree of valvular stenosis by estimation of valvular mobility, size of jet through valve, and opacification time of left atrium.

Thirty-seven patients reported in this series have undergone open-heart operation for correction of a

FIG. 1.—The relation between ultrasound transducer (left) on anterior chest wall and the anterior leaflet of mitral valve. Intervening echoes are rejected by the analogue gate permitting direct recording of desired echo (e) in a pattern depicted on the right, simultaneously with phonocardiogram and electrocardiogram. Normal motion and that of mitral stenosis are shown.

FIG. 2.—Normal mitral valve. ACG=apex cardiogram; US=ultrasound recording; MVO=mitral valve opening; A=deflection on US and ACG resulting from atrial contraction; E=time of opening of aortic valve; F=rapid filling wave on ACG; SFW=slow filling wave on ACG; O=maximum mitral valve opening on ACG. Note mitral valve begins to close after A point on ultrasound recording considerably before point of onset of ventricular contraction marked on the apex cardiogram by the sharp upstroke occurring after the point A. Time=0.04 sec.

valvular defect. In each instance, the degree of mitral valve stenosis, regurgitation, chordæ shortening, and location of calcification was estimated by the surgeon.

RESULTS

The echocardiogram of a normal mitral valve is depicted in Fig. 2. This ultrasound signal is reflected from a normal adult mitral valve at a depth of 5.5 to 8 cm., with an anterior posterior motion range of from 2.5 to 4.0 cm. Motion of the ultrasound signal toward the top of the tracing represents motion of the anterior leaflet of the mitral valve as it opens toward the anterior chest wall. Conversely, downward motion represents closure of the anterior leaflet. In the normal mitral valve, two upward deflections are noted. The first, representing initial mitral valve opening, occurs on an average of 0.12 sec. after the second heart sound and initiates the period of rapid filling of the left ventricle. In Fig. 2 the mitral opening occurs 0.10 sec. after S_2 . This may be correlated on the apex cardiogram with the O point which coincides with peak mitral valve opening and is followed by the period of rapid ventricular filling. This peak opening on the ultrasound record is followed by a rapid descent during ventricular filling with flotation of the mitral valve toward its closed position. There follows a period of relatively little motion of the mitral valve during the slow filling phase of ventricular filling. The second upward deflection follows the P wave of the

electrocardiogram and represents motion of the mitral valve away from the atrium during atrial contraction. This is followed by a rapid downward motion preceding the onset of ventricular contraction and represents the closing movements of the valve. This appears to occur following atrial systole and *before* isovolumetric contraction of the left ventricle. Closure of the mitral valve is coincident with the major deflections of S_1 . This A wave is absent in the presence of atrial fibrillation or if the P wave is engulfed by a premature nodal or ventricular beat. During ventricular contraction the baseline of the ultrasound tracing is pulled toward the anterior chest wall representing motion of the atrial ventricular ring toward the ventricular apex during systole. The descent of the ultrasound tracing after its maximum opening measured in mm./sec. varied from 65 to 210 mm./sec. in patients with normal mitral valves. The magnitude of this wave varied from 2.5 to 4.0 cm. The measurement of this slope during ventricular filling is the key to mobility of the anterior leaflet and deviations from this normal range indicate impaired function.

In mitral stenosis, the contour of the ultrasound tracing is significantly altered. Fusion of the commissures, fibrosis, and calcifications of the leaflets, and chordae fusion shortening, reduce the mobility of the mitral valve, thereby decreasing the slope and amplitude of the ultrasound signal following peak mitral valve opening. Fig. 3 illustrates the ultrasound recording of a patient with a tight mitral stenosis, a very slow slope, absence of the "a" wave normally seen in patients with sinus rhythm, and a much reduced total amplitude of excursion. In 35 patients with predominant mitral stenosis, the slope of the ultrasound recording was compared to mean pulmonary artery pressure, mean left atrial pressure, left atrial-left ventricular end-diastolic pressure gradient, and mitral valve area. No correlation between the first three parameters and the slope was found. However, the correlation between the calculated mitral valve area and the ultrasound slope is shown in Fig. 4. It can be seen that in all patients with a calculated area of less than 1 sq. cm. the slope did not exceed 25 mm./sec. In 5 other patients with calculated areas of 1.5 cm., the slope did not exceed 35 mm./sec. Four other patients showed little relation between calculated valve area and slope. In each instance the clinical impression was that of a mild mitral stenosis, raising the question of accuracy of the mitral valve area calculation. In 8 patients with normal mitral valves with calculated areas in excess of 3 sq. cm., the slope of the ultrasound tracing was in the normal range, exceeding 70 mm./sec. The open circles and open squares represent patients in whom

FIG. 3.—Typical pattern of a tight mitral stenosis. Normal sinus rhythm slope is 8 mm./sec. Amplitude of excursion 10 mm. Time = 0.04 sec.

the severity of the stenosis was subsequently estimated at operation (Fig. 5).

In 32 patients a similar correlation was found when relating the surgeon's estimate of the degree of stenosis with the ultrasound slope (Fig. 5). A very tight stenosis (i.e. less than 1 sq. cm.) was associated with a slope of less than 20 mm./sec., intermediate degrees of stenosis with slopes to 45 mm./sec., and a normal mitral valve with slopes in excess of 65 mm./sec. There was some overlap between the lower range of "moderate" stenosis and the upper range of "severe" stenosis, as might be expected in such a subjective estimation. There was likewise overlap between the upper and lower ranges of moderate and slight stenosis, respectively. Nevertheless, a distinct relation exists between the

FIG. 4.—Slope of ultrasound compared to calculated mitral valve area.

FIG. 5.—Slope of ultrasound compared to surgeon's estimate of orifice size, at operation or necropsy.

severity estimated by the surgeon and that measured from ultrasound recording.

In 26 patients, considerable agreement was evident between the amplitude of the ultrasound tracing and the degree of chordæ shortening as

FIG. 6.—Amplitude of ultrasound compared to surgeon's estimate of chordæ shortening, at operation.

estimated by the surgeon (Fig. 6). Severe shortening was associated with amplitudes less than 13 mm., intermediate degrees of shortening with amplitudes of 13–25 mm., and normal chordæ with amplitudes greater than 25 mm.

In Fig. 7 is shown a correlation between the ultrasound slope and degree of stenosis estimated from the cine-angiograms in 38 patients. A close relation between the ultrasound slope and degree of stenosis is evident. Severe stenosis occurred with slopes of less than 15 mm./sec.; moderate stenosis with slopes of 10–28 mm./sec., with two patients in

FIG. 7.—Slope of ultrasound compared to estimate of valvular stenosis by cine-angiography.

this category having slopes of 38 and 40 mm./sec.; slight stenosis generally with slopes from 28 to 45 with two exceptions at 62 and 70. These latter two with low normal ultrasound slopes were judged to have slight restriction of valvular motion and were without clinical evidence of mitral stenosis. They were included in what was anticipated as cine studies of normal mitral valves, as were the other 9 patients (Fig. 7). The open circles, squares, and triangles represent studies in which the mitral orifice size was subsequently estimated by the surgeon. There is good correlation between cine estimation and surgeon's estimation.

In Fig. 8 a comparison between the measured slope and amplitude is illustrated. It can be seen that in general there is a tendency for the amplitude of the excursion to decrease as the slope decreases.

Fig. 8.—Relation of ultrasound slope to amplitude of excursion.

No patient with mitral stenosis was found with an amplitude of greater than 27 mm. No patient with a normal mitral valve was found with an amplitude of less than 25 mm. The five patients whose amplitude ranges fell outside the general trend were patients with moderate to severe valvular stenosis, but with chordæ apparatus which was found at operation to be well preserved.

In patients with clinical evidence of mitral insufficiency, mitral valve motion is unpredictable, and valvular motion ranging from a degree seen with advanced mitral stenosis to that seen in normal patients may be found. The determining factor is the degree of valvular thickening and immobilization. It is apparent that a reduction in slope and amplitude may occur with chordæ shortening and valvular thickening associated with mitral regurgitation, as well as from a tight valvular stenosis with or without chordæ involvement. Patients with severe mitral insufficiency associated with a destroyed, fixed, widely patent mitral valve are not uncommon. Contrariwise, mitral insufficiency may result from rupture of papillary muscle or chordæ, torn leaflet, or other defect resulting in a flail leaflet with great mobility. Such is the case in Fig. 9. The slope in this patient is 118 mm./sec. with a normal amplitude of 26 mm. Notice the flutter

type wave seen in a prolonged diastole as though atrial fibrillatory movements were in some way affecting its motion. In contrast, Fig. 10 demonstrates valvular restriction of a mild degree with a slope of 44 mm. but a normal amplitude of 26 mm. in a patient with clinical evidence for mitral regurgitation. There is a well-preserved rapid filling wave immediately following the O point on the apex cardiogram. This patient died of subacute bacterial endocarditis and at necropsy was found to have thickened leaflets with vegetations, but without valvular stenosis or chordæ fusion. Fig. 11 demonstrates a young patient with massive mitral regurgitation without clinical evidence of mitral stenosis. The slope of 17 mm. is in the range of that seen with moderate valvular stenosis. The amplitude of 16 mm. is distinctly abnormal. At operation the leaflets were very thickened and calcified, and the chordæ were greatly shortened with slight fusion of commissures resulting in a regurgitant mitral orifice with a smaller than normal opening with little ability to either open or close properly.

DISCUSSION

The reflected ultrasound technique provides a simple reproducible atraumatic method for the detection of mitral valve stenosis and for the estima-

FIG. 9.—Severe mitral insufficiency with highly mobile leaflet. Slope 118 mm./sec. Amplitude 25 mm. Atrial fibrillation with flutter type movement of mitral valve seen in first complex. Time=0.04 sec.

tion of valvular immobility in the presence of mitral insufficiency. The technique can be quickly and easily learned and by the direct writing method may be combined with simultaneous recordings of the phonocardiogram, electrocardiogram, apex cardiogram, and carotid or intracardiac pressure curves. The direct recording technique has the disadvantage

of being unable to record the thickness of the interface surface. Joyner, Reid, and Bond (1963) and Segal, Likoff, and Kingsley (1966) have reported that an estimation of valvular thickening may be obtained by measurement of the thickness of the line representing valvular motion during diastolic filling of the ventricle. The direct recording method of utilizing an analogue gate permits the recording only of the echoes reflected from the surface of the valve and deletes those coming from the valve substance. The presence of emphysema, which increases sound absorption and refraction, or chest deformities, may occasionally offer difficulties in locating the anterior leaflet. Normal mitral valve motion is exceedingly rapid and positioning of the patient in the right or left anterior oblique position is occasionally necessary to record the reflected signal. Discouragement is frequently encountered in the early experience of the operator, but with some practice the great majority of normal valve movements may be recorded without difficulty. However, the slow motion of the anterior leaflet in mitral stenosis provides an easy mark for even the inexperienced in recording an acceptable tracing.

Our series confirms earlier reports that mitral stenosis is associated with a decreased motion of the mitral anterior leaflet with velocities under 45 mm./sec. and usually under 35 mm./sec. We have found no patient with the murmur of mitral stenosis with a slope exceeding 45 mm./sec. even in the presence of a coexistent mitral insufficiency. However, Segal *et al.* (1966) reported 18 patients with valve areas calculated to be greater than 1.7 sq. cm., with slopes ranging from 40 to 79 mm./sec. In the present study, a diastolic slope of less than 25 mm./sec. correlated closely with a calculated valve area of less than 1 cm.² from catheterization data and with the surgeon's estimate of a tight mitral steno-

FIG. 10.—Mitral insufficiency with slight restriction of mitral valve motion (S=slope, 44). MVO=mitral valve opening. MVC=mitral valve closing. Well-preserved rapid diastolic filling wave after point O on apex cardiogram. A=mitral valve motion resulting from atrial contraction.

FIG. 11.—Mitral insufficiency with severe restriction of mitral valve motion (slope 17, amplitude 16), atrial fibrillation. Co-existent abnormal left ventricular filling as demonstrated by persistence of slow diastolic filling wave (SFV) on apex cardiogram.

sis. A less severe degree of stenosis with slopes between 25–35 mm./sec. was found with valve areas up to 1.5 sq. cm. Intermediate degrees of stenosis estimated by the surgeon were found with slopes between 25–45 mm./sec.

Of considerable interest was the close relation between the degree of mitral valvular stenosis as estimated from cine-angiography when compared to the diastolic slope of the ultrasound tracing. The estimation of mitral valve narrowing and loss of valvular mobility from cine-angiography could be accurately predicted from the ultrasound tracing. It is recognized that estimation of orifice size from a single plane cine study is hazardous. The resulting correlation was a pleasant surprise, particularly when justified by the surgeon's subsequent estimate at operation.

Further, there is a general correlation between the amplitude of the ultrasound tracing and the degree of subvalvular chordæ fusion as estimated by the surgeon. A wide range for all slopes exists, but generally the higher the amplitude, the less subvalvular fusion. It is interesting to note that five patients with low diastolic slopes exhibited nearly normal amplitudes. At operation, these patients were found to have tight valvular fusions with fairly well-preserved chordæ structure. It is thus apparent in mitral stenosis with an impaired diastolic ultrasound slope that the amplitude of valvular motion may be restricted because of leaflet immobility and/or chordæ shortening; or it may approach normal limits if the chordæ system is intact. Low amplitude may also result from failure of the operator to locate and record the signal with the largest amplitude.

The ease of direct recording of the ultrasound signal provides a means to complement other graphic methods used in the evaluation of the cardiac patient. We have found its addition to the phonocardiogram and/or apex cardiogram helpful.

The measure of the corrected Q-1 minus 2-OS interval has been proposed to quantitate the degree of mitral stenosis (Wells, 1954). A figure from 0 to +7 indicates increasingly severe valvular stenosis. In many instances a relation is present, but in the presence of atrial fibrillation, the correction factor is an estimate at best resulting in occasional confusion as to the significance of a finding. Addition of the ultrasound study to phonocardiography may supply confirmatory evidence. In Fig. 12 excellent correlation is evident. The Q-1 minus 2-OS combination of +5 suggests a very tight mitral stenosis, as does the ultrasound slope of 5 mm./sec. In patients who may be suspected of having mitral stenosis but in whom no murmur can be heard or recorded, an ultrasound study may quickly and easily settle the issue. In Fig. 13 is pictured the ultrasound curve of a 17-year-old boy with atrial fibrillation in whom a murmur of mitral stenosis was suspect. The slope of this tracing is normal (170 mm./sec.), as is the amplitude (29 mm.), before and after conversion to normal sinus rhythm by cardioversion.

The ultrasound technique offers a simple method for detecting mitral valve impairment associated with aortic valve disease, and particularly the clarification of a suspected Austin Flint murmur. This is illustrated in Fig. 14. This 53-year-old man exhibited severe aortic insufficiency with an apical pansystolic murmur and an early apical diastolic rumble of uncertain significance. The ultra-

FIG. 12.—Tight mitral stenosis. Slope=S; OS=opening snap; DM=diastolic murmur; MVO=mitral valve opening; MVC=mitral valve closing. (Q-1) interval of 0.10 sec. less (S₂—OS) interval of 0.05 sec. confirmatory evidence for tight stenosis.

FIG. 14.—Aortic insufficiency with coexistent apical pansystolic murmur and early apical diastolic rumble. Normal mitral valve mobility with slope of 135 mm./sec. Normal rapid filling wave on apex cardiogram (follows point O). Note absence of "a" wave on ultrasound with premature ventricular contraction (PVC).

FIG. 13.—Normal mitral valve motion. Atrial fibrillation. Slope 170 mm./sec. Amplitude 29 mm. Normal valve motion on cine-angiography.

FIG. 15.—Severe mitral stenosis. Ultrasound slope diminished. A wave of ultrasound diminished in size. Apex cardiogram confirmatory with absent rapid diastolic filling wave after point O with prolonged slow filling wave.

sound tracing clearly identifies normal mitral valve mobility, thus eliminating structural mitral stenosis from consideration. Note the absence of the ultrasound “a” waves with the premature ventricular beat.

In the presence of mitral insufficiency, the ultrasound technique provides an atraumatic method of assessing the degree of mitral valve mobility. Many patients with mitral regurgitation will exhibit normal or faster than normal slopes. In the presence of clinical signs of mitral insufficiency, a slope of less than 35 mm./sec. strongly suggests severely damaged valve leaflets with fibrosis, with or without calcification, and some narrowing of the orifice with little of the normal ability to close. Slopes intermediate between 35 and 70 mm./sec. indicate lesser degrees of mitral fixation. The addition of a simultaneously recorded apex cardiogram in individual situations may be of additional assistance. Benchimol *et al.* (1960) have described the characteristic abnormalities of this technique in the presence of mitral stenosis and regurgitation and combinations of both. In the presence of mitral stenosis or predominant mitral stenosis if regurgitation is also present, the characteristic finding was the absence of a rapid filling wave. It is easily

determined by ultrasound analysis whether this impairment to ventricular filling is the result of mitral stenosis. In Fig. 15 the absent rapid filling wave and decrease of the ultrasound slope point decidedly to mitral stenosis. The “a” wave of the ultrasound trace is visible but greatly reduced in amplitude.

Conversely, in the presence of a predominant mitral regurgitation, the apex cardiogram inscribes a normal or accentuated rapid filling wave. In Fig. 16 is shown a patient with severe mitral regurgitation. The apex cardiogram is compatible and exhibits a sharply written rapid filling wave. However, mitral valve mobility is considerably reduced with a slope of 39 mm./sec. Such a finding is strongly suggestive of rheumatic heart disease as the ætiology of the valvular disease, since such valvular immobility would be unexpected in the presence of a papillary muscle or pure chordæ rupture, leaflet tear, or other causes of mitral regurgitation.

Tavel *et al.* (1965) reported an inconsistent relation of mitral valve opening to the O point on the apex cardiogram in some patients with mitral stenosis and insufficiency. Confirmation of this finding is apparent from 16 of our simultaneous ultrasound

FIG. 16.—Severe mitral insufficiency with decreased mitral valve mobility (slope 39 mm./sec.). Preservation of sharp rapid diastolic filling wave on apex cardiogram (RFV) culminating in prominent S_3 . Slow filling wave normal.

FIG. 17.—Mitral stenosis. Atrial fibrillation. Mitral valve opening (MVO) occurs regularly 0.03–0.04 sec. before O point on apex cardiogram.

and apex cardiogram recordings. In Fig. 17 the ultrasound records the opening of the mitral valve 0.03 sec. before the O point of the apex cardiogram. In the 16 tracings suitable for study it was apparent that this occurred not only in mitral stenosis and in some patients with mitral insufficiency, but that in all patients this interval varied slightly from beat to beat in an unpredictable manner by as much as 0.02–0.03 sec. This was never seen in any of the 75 normal valves in which the O point and mitral valve opening were always within 0.01 sec. of each other.

Previous investigators have reported improvement in the slope of the ultrasound trace following mitral commissurotomy either by the closed or open method. All but five of our patients undergoing operation had valve replacement. Four of these five demonstrated improved slopes and amplitudes (S_{24} , A18 to S_{34} , A21; S_{17} , A24 to S_{33} , A26; S_{18} , A23 to S_{67} , A27; S_{14} , A12 to S_{37} , A25); and the last was a patient with mitral insufficiency (Fig. 18). She was found to have normal valve leaflets with a defect at the angle of the medial commissure. This was sutured and plicated. After operation, a typical murmur of mitral stenosis appeared. The ultrasound tracing demonstrated a change in the slope from a normal 75 mm./sec. to a slow 29 mm./sec. No significant change occurred following conversion to normal sinus rhythm. It is well

established that the slope is not significantly different whether the rhythm be normal sinus or atrial fibrillation.

Most simply the ultrasound technique offers a sensitive and reproducible method for quickly determining the presence of mitral stenosis whenever there may be a question as to its presence, as occurred in the patient in Fig. 13. At the other end of the spectrum, the physiology of mitral and tricuspid valve motion may be studied under a wide variety of physiological and pathological conditions.

SUMMARY

Analysis of mitral valve motion in 200 patients revealed 75 normal, 44 with predominant mitral stenosis, and 81 with mixed mitral and aortic disease. Comparison with results from catheterization data, cine-angiography, surgery, apex cardiography, and phonocardiography was made.

In patients with mitral stenosis, an ultrasound diastolic slope of less than 25 mm./sec. correlated well with a calculated mitral valve area of under 1 sq. cm., moderately severe stenosis on cine-angiography, and a finger tip orifice at operation. Lesser degrees of stenosis were associated with slopes up to 45 mm./sec. No patient with the murmur of mitral stenosis with or without mitral insufficiency exhibited a slope of greater than 45 mm./sec.

FIG. 18.—Pre-operative mitral insufficiency. Normal slope 75 mm./sec. Post-operative mitral valvuloplasty slope significantly reduced in atrial fibrillation as well as subsequent normal sinus rhythm (31 and 35 mm./sec.).

Normal mitral valve motion was accompanied by slopes in excess of 65 mm./sec.

Amplitude of excursion generally diminished directly with the slope though with a wide scatter. A nearly normal amplitude was found in several patients with advanced mitral stenosis in whom the chordæ apparatus was nearly intact.

In mitral insufficiency, the diastolic slope varied from that seen with severe restriction (17 mm./sec.) to that seen with normal valves (over 65 mm./sec.). The determining factor appeared to be degree of fibrosis, calcification, and chordæ fusion present. Flail valves with high mobility were less likely to be the result of rheumatic involvement. In the presence of clinical signs of mitral insufficiency, a slope of less than 35 mm./sec. suggests severely damaged leaflets with fibrosis, with or without calcification, and some narrowing of the orifice with little of the normal ability to close. Slopes intermediate between 35 and 70 mm./sec. indicate lesser degrees of fixation.

Simultaneous recording with apex cardiography with special reference to the diastolic filling waves, and with phonocardiography with calculation of the Q-1, 2-OS intervals, may provide additional information as to type and severity of the valvular abnormality.

The technique provides a simple and reproducible method for evaluating mitral valve function in

patients with other valvular disease, patients with suspect mitral valve function, or patients with other types of heart disease. It may provide also a useful method for studying the physiology of mitral valve function in the normal as well as abnormal state.

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