Cross-sectional Echocardiography in Assessing the Severity of Valvular Aortic Stenosis

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SUMMARY
Real-time, cross-sectional echocardiograms were recorded in 28 consecutive adult patients with valvular aortic stenosis using a high resolution, mechanical sector scanner. Using the cross-sectional technique, the aortic valve orifice diameter was recorded in each of the 28 patients. With M-mode echocardiographic examination of these same patients, this value could be estimated in only 21 of these 28 patients (75%). The maximum aortic valve diameter recorded during the cross-sectional study averaged 7.9 ± 1.8 mm (range 4–11 mm) in 15 patients with severe aortic stenosis; 11.6 ± 2.3 mm (range 9–15 mm) in five patients with moderate aortic stenosis; 16.9 ± 2.0 mm (range 14–20 mm) in eight patients with mild aortic stenosis; and 20.5 ± 2.8 mm (range 15–26 mm) in 25 patients with no evidence of aortic valve disease. Comparing the means of these groups yielded the following: severe vs moderate P < 0.005; moderate vs mild P < 0.001; and mild vs normal P < 0.001. Although there was some overlap between the individual groups, a clear separation existed between patients with severe and mild aortic stenosis. In addition, the group of patients in whom surgical intervention was recommended was also separated from the other subjects. When the aortic valve orifice was recorded using the M-mode technique, there was also a good correlation with the severity of the stenosis; however, the tendency of the M-mode study to overestimate severity in individual patients with calcific aortic stenosis and to underestimate severity in congenital aortic stenosis was again demonstrated. This study suggests that real-time, high resolution, cross-sectional echocardiography should be valuable in the noninvasive assessment of patients with aortic stenosis.

A number of reports have described the use of M-mode echocardiography in evaluating patients with aortic stenosis. Characteristic echocardiographic findings have been noted in patients with calcific aortic stenosis and congenital bicuspid aortic valve. Attempts have been made to quantitate the severity of aortic stenosis by estimating the echo density within the aortic root in patients with calcific aortic stenosis and by measuring aortic cusp separation in patients with both calcific and noncalcific aortic stenosis. While all of these observations have proven helpful in some cases, it has not been possible reliably and consistently to estimate the severity of aortic stenosis using M-mode echocardiography. There are two common situations in which the narrow M-mode view fails to record reliably the aortic valve orifice and permit measurement of systolic aortic cusp separation. In patients with noncalcific aortic stenosis and systolic doming of the aortic valve, strong echoes will generally be recorded as the ultrasonic beam passes through the base of the dome where the fused leaflets lie perpendicular to its plane. At the apex of the dome where the leaflets are more parallel to the path of the beam, frequently no signal is recorded. In such cases the valve orifice is not appreciated and a severely stenotic aortic valve may appear to have normal cusp separation. In patients with calcific aortic stenosis intense echo production from an area of calcification may obscure leaflet motion and again prevent the aortic valve orifice from being recorded. Cross-sectional echocardiography, by expanding our field of vision and by providing spatial orientation, permits the entire aortic valve to be examined throughout the cardiac cycle and its pattern and amplitude of motion to be more fully appreciated. The following report describes our initial results in examining patients with valvular aortic stenosis using a high resolution, real time, cross-sectional echocardiographic sector scanning system.

Material and Methods
Cross-sectional and M-mode echocardiograms of the aortic valve were recorded in 28 consecutive patients with valvular aortic stenosis. There were 18 females and ten males. The average age was 51.5 years. There were 15 patients with severe stenosis (peak aortic systolic gradient ≥ 75 mm Hg or calculated aortic valve area ≤ 0.75 cm² or

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both), five patients with moderate stenosis (peak systolic gradient 50–75 mm Hg or calculated aortic valve area 0.75 – 1.0 cm$^2$ or both) and eight patients with mild stenosis (peak systolic gradient < 50 mm Hg). The diagnosis and severity of aortic stenosis were determined by standard catheterization and cineangiographic techniques. In one case a catheter could not be passed into the left ventricle. This patient was placed in the severe group on the basis of a very severely stenosed valve at surgery. Patients with both valvular and subvalvular echocardiograms were not included. Cross-sectional echocardiograms were also recorded in 25 subjects with no evidence of aortic valve disease. In this group there were 13 females and 12 males. Average age was 20.5 years. Cardiac catheterization was not performed in these patients.

Cross-sectional echocardiographic examination was performed using a modified Ekoline 20A Echograph with a pulse repetition rate of 4.5 kc/sec. A 2.25 MHz transducer mechanically driven through a 30° sector at a variable rate from 0 to 30 cycles/sec was utilized. The system was routinely operated at a frame rate of approximately 40 frames/sec (20 cycles/sec), which yielded a line density of approximately 120 lines/frame.

The image thus produced was photographed by a standard portable television camera (GBC-CTC-6000) and recorded on half inch video tape using a GBC-TVR-321 recorder. The cross-sectional images could be viewed in real time during the examination or from video tape in real time, slow motion or single frame presentation after the examination. Individual frames were converted to a hard copy presentation using a video converter and a modified Honeywell 1856 Strip Chart recorder. An R-wave triggered electronic counter superimposed on the upper right hand corner of each frame permitted timing of individual frames within the cardiac cycle to one-hundredth of a second. Details of this system have been previously reported.4,8

When performing the examination, patient positioning and transducer placement were similar to those employed in a routine M-mode echocardiographic examination. To record the aortic valve orifice diameter the transducer was initially aligned parallel to the long axis of the aorta. The aortic valve was located and placed in the middle of the 30° sector being examined. A 30° sector scan of the normal aortic valve and surrounding cardiac structures is illustrated in figure 1. The transducer was then moved slowly back and forth in a path perpendicular to the long axis of the aorta maintaining the aortic valve in the center of the 30° sector. The maximum aortic leaflet separation observed during repeated scans across the entire aortic valve was then determined. Figure 2 is a cross-sectional recording of a normal aortic valve. Echoes from the open aortic leaflets are present at the tips of the vertical arrow in the systolic frame on the left. The aortic valve orifice diameter is measured from the inner aspects of these two echoes. The length of the vertical arrow corresponds to this measurement. Figure 3 is a cross-sectional recording from a patient with congenital aortic stenosis. Systolic doming of the valve is apparent in figure 3B. The orifice diameter is measured from the inner aspects of the two dominant echoes at the tips of the vertical arrow representing the anterior and posterior margins of the valve orifice. The length of this arrow again corresponds with this diameter. Figure 3A is a diastolic recording from the same patient. Diastolic inversion of the valve occurs in this case resulting in a diastolic appearance which is almost a mirror image of the systolic doming of the valve seen in figure 3B.

This type of valve is insufficient. In two cases, the aortic valve could not be recorded through the chest and a subxiphoid approach was used.

The probe was then rotated 90° to place the plane of the sector scan perpendicular to the long axis of the aorta and parallel to the orifice of the aortic valve. From this position, a recording of the aortic valve orifice in a short axis was attempted. Each study was recorded on video tape and analyzed following the examination in a slow motion and stop frame presentation. In addition, each patient with aortic stenosis was examined by the conventional M-mode echocardiographic technique. The ability to record the aortic cusps and the diameter of aortic cusp separation measured during the M-mode study were compared with the results obtained during the cross-sectional study in each patient. The normal M-mode values were based on a prior study in our laboratory of 93 normal subjects. The assignment of patients to different groups based on cardiac catheterization data, the analysis and measurement of cross-sectional echocardiograms, and the recording and analysis of M-mode tracings was done independently by three observers. In almost every case both the cross-sectional and

Figure 1

Diagram illustrating a 30° sector scan of the aortic valve and surrounding structures. In this recording the sweep of the transducer is parallel to the long axis of the aortic root. RV = right ventricle; LA = left atrium; AO = aorta; LV = left ventricle; IVS = interventricular septum; AMV = anterior mitral valve; PMV = posterior mitral valve; PLV = posterior left ventricle; PPM = posterior papillary muscle; CW = chest wall; S = sternum.
Figure 2

Cross-sectional echocardiographic recording of a normal aortic valve in a long axis presentation. In the frame on the left recorded during systole, the open aortic leaflets can be appreciated at the tips of the vertical arrow. The diameter of the aortic valve orifice is measured from the inner aspect of the leaflet echoes and corresponds to the length of the arrow. The walls of the aorta (AO) are illustrated by the horizontal arrows. In the right hand diastolic frame the aortic leaflets (AV) appear as a straight line in the center of the aorta (AO). Normally, only the coapted portion of the leaflets are recorded. The cusps themselves, which lie perpendicular to the ultrasonic beam during diastole, do not appear unless leaflet thickening is present. LA = left atrium.
the M-mode echocardiographic studies were performed and interpreted prior to cardiac catheterization.

Results

The aortic valve diameter measured during cross-sectional study and its relationship to the severity of the aortic stenosis are illustrated in figure 4.

In 15 patients with severe aortic stenosis aortic valve diameter (AVD) averaged 7.9 ± 1.8 mm (range 4–11 mm).

In five patients with moderate aortic stenosis AVD averaged 11.6 ± 2.3 mm (range 9–15 mm). In eight patients with mild aortic stenosis AVD averaged 16.9 ± 2.0 mm (range 14–20 mm), and in the 25 normal patients AVD averaged 20.5 ± 2.8 mm (range 15–26 mm). An r value of .92 was achieved when the means of these four groups were correlated. Comparing the means of the groups individually yielded the following: severe vs moderate \( P = < 0.005 \); moderate vs mild \( P = < 0.001 \); mild vs normal \( P = < 0.001 \).

To allow for any effect body size might have on the aortic valve diameter the values were then corrected for body surface area (fig. 5). The corrected aortic valve diameter (AVDc) averaged 4.4 ± 1.0 mm (range 2.5–6.1 mm) in the 15 patients with severe aortic stenosis; 6.1 ± 1.0 mm (range 4.8–7.5 mm) in the five patients with moderate aortic stenosis; 9.3 ± 1.6 mm (range 6.8–11.4 mm) in the eight patients with mild aortic stenosis and 11.9 ± 1.4 mm (range 9.9–14.4 mm) in the normal group. Correlating the means of these four groups gave an r value of .93. The results of statistical comparison of the individual groups were similar to those for the uncorrected data: severe vs moderate \( P = < 0.005 \); moderate vs mild \( P = < 0.001 \); mild vs normal \( P = < 0.001 \).

The ability to record aortic cusp separation by M-mode study and its relationship to the severity of aortic stenosis were also evaluated. These results are illustrated in figure 6. The normal group in this figure is based on data from a prior M-mode study of 93 normal subjects. In 21 of the 28 patients with aortic stenosis, the M-mode recording was adequate to measure aortic cusp separation. In the other seven no measurement could be made either because the aortic cusps were not recorded (one) or because they were obscured by dense masses of echoes from within the aortic root (six). Aortic cusp separation could be determined in ten of 15 patients with severe aortic stenosis, three of five patients with moderate aortic stenosis and eight of eight patients with mild aortic stenosis. In the ten patients with severe aortic stenosis aortic cusp separation averaged 9.3 mm (range 5–12 mm). In the three patients with moderate aortic stenosis aortic cusp separation averaged 13.7 mm (range 8–23 mm).

In the eight cases of mild aortic stenosis M-mode aor-
tic cusp separation averaged 15 mm (range 8–21 mm). In normal patients aortic cusp separation averaged 19.4 ± 21 mm.

Discussion

This study evaluated the ability of cross-sectional echocardiography to visualize the aortic valve orifice in patients with aortic stenosis; the relationship of the diameter measured by this technique to the severity of the stenosis; and the ability of M-mode echocardiography to provide the same information. Using the cross-sectional technique, we were able to record the aortic valve orifice in each of 28 patients with aortic stenosis. The valve orifice could be visualized in only 21 of these 28 patients (75%) using the M-mode technique. The increased ability of cross-sectional echocardiography to record the aortic valve orifice results from the enlarged field of vision and improved spatial orientation this technique permits. In patients with congenital aortic stenosis and systolic doming of the valve, the 30° sector permits visualization of the whole valve. As figure 3 illustrates, when the true geometry of the domed valve is visualized the orifice can be readily distinguished. When calcific aortic stenosis is present, maintaining the aortic valve within the 30° sector while slowly sweeping across the valve permits small or eccentric areas of motion to be appreciated and the valve orifice to be more clearly defined (fig. 7). In two of these 28 patients, the aortic valve could not be recorded through the chest but was successfully recorded using the subxiphoid approach. This suggests that the small, versatile transducer used in this cross-sectional study may provide information in certain areas which is not obtainable using the larger, less maneuverable transducers of other two-dimensional systems.

There was a good correlation demonstrated in this study between the aortic valve orifice diameter measured by the cross-sectional technique and the severity of aortic stenosis. Although some overlap was present among the individual groups, there was a clear separation between patients with mild and severe stenosis. When the clinical condition of the patients was also considered, a further separation of patients occurred. Thus, all patients with an aortic valve diameter of 8 mm or less had severe aortic stenosis. All patients having an aortic diameter of 11 mm or less, and one of two patients with a 12 mm...
Figure 7

Systolic and diastolic recordings from a densely calcified, stenotic aortic valve. The areas of calcification are demonstrated by the long, linear echoes reflected from a major portion of both the anterior and posterior aortic leaflets. The predominant area of calcification, however, is confined to the anterior leaflet. In figure 7A recorded during diastole, several fine echoes can be seen between the two areas of calcification. These echoes represent the limited remaining area of relatively mobile valve tissue. The faint echoes from this area are overshadowed by the strong dominant echoes from the areas of calcification. In the systolic frame, figure 7B, the area between the anterior area of calcification and the posterior leaflet is now clear of faint echoes. It is difficult to appreciate the movement of these echoes in individual frames; in a real-time presentation this echo motion becomes more apparent.

diameter were recommended for aortic valve replacement or commissurotomy based on clinical and hemodynamic considerations. The one patient in the moderate group with a 15 mm valve orifice had aortic stenosis and mild aortic insufficiency, was asymptomatic and was not considered a candidate for valve replacement. This 20-year-old patient was placed in this group because of a peak systolic gradient of 50–55 mm Hg at two successive cardiac catheterizations. Considerable overlap existed between patients with mild aortic stenosis and normal patients. In this area, the direct measurement of aortic valve diameter may not be as helpful as a qualitative assessment of the pattern of valve motion during cross-sectional study. In normal patients, the open aortic leaflet lies parallel to the aortic wall during systole. In patients with mild congenital aortic stenosis, one or both leaflets arch toward the center of the aorta clearly remaining within the stream of flow. In older patients with calcific valves one leaflet is usually poorly moving or fixed while the other moves normally. In either case, the presence of aortic stenosis can be determined by the pattern of leaflet motion and the severity by the orifice diameter.

Comparing these results with those obtained during M-mode study of the same patients (fig. 6) revealed the following: In the ten patients with severe aortic stenosis in whom the aortic cusp separation could be determined by M-mode studies, the results were similar to those recorded on cross-sectional studies. In eight of these ten patients, the results of the two techniques were within 2 mm of each other. In the other two cases, the M-mode measurements were 3 and 4 mm higher. The latter case was a young woman with congenital aortic stenosis and a domed valve. In three of the eight cases of mild aortic stenosis, however, the orifice measurement was also in the severe range. In one case of moderate aortic stenosis, an aortic cusp separation of 23 mm was measured from the M-mode tracing. This was in the upper portion of the normal range and would indicate an absence of stenosis. These results suggest that when the valve orifice itself is measured by both techniques the results will be similar. The inability to determine
when the actual valve orifice has been recorded using the one dimensional M-mode system, however, limits its usefulness.

Using the maximum aortic cusp separation as an indication of aortic valve diameter and thus of aortic valve orifice size presumes that the aortic leaflets are distended maximally. In patients with decreased cardiac output or subvalvular aortic obstruction the leaflets may not open fully, and therefore in these cases this estimate would be incorrect.

The aortic leaflets normally lie against the walls of the circular aorta during systole. The aortic cusp separation at this point reflects the true orifice diameter and hence the valve area. When aortic stenosis is present, the orifice frequently is not circular and the cusp separation is a less exact estimate of the valve area. Measurement of the aortic valve area directly by recording the valve orifice in a short axis presentation would be preferable. Henry et al., using a similar cross-sectional system, reported that they were able to measure the mitral valve orifice directly in patients with mitral stenosis. While we have had similar success in visualizing the larger mitral valve orifice, the lateral resolution of this system appears inadequate to accurately visualize the lateral margins of the aortic valve orifice in the majority of patients. In addition, the opened mitral valve tends to remain in a relatively stable position within the ventricle facilitating short axis localization of the valve orifice. In contrast, the aortic valve moves rapidly in a superior-inferior direction during ventricular systole. As a result, the valve orifice passes rapidly through the plane of the cross-sectional beam and is more difficult to localize and record. We have been able to record clearly an aortic valve orifice in several patients and hopefully with future improvements in engineering and transducer focusing, direct measurement of the aortic valve orifice will be possible.

In this study, we have reported results of long axis, aortic valve diameter measurements in adults only. In these patients, good correlation existed between the directly measured aortic valve diameter and the severity of aortic stenosis. Slight statistical improvement occurred when this measurement was corrected for body surface area although, in general, correction appears unnecessary. We have examined a number of children and found that an aortic valve diameter could readily be determined. Some correction obviously is required in this group to relate aortic valve diameter to body size. Correction for body surface area, however, appears inadequate, since the smaller the child, the greater the ratio of cusp separation to body surface area. We have not examined a large enough group to determine the appropriate correction factor for children and these patients were, therefore, not included.

This study suggests that cross-sectional echocardiography may represent a reliable noninvasive method for estimating the severity of valvular aortic stenosis. It further suggests that cross-sectional echocardiography offers an improvement over conventional M-mode echocardiography in evaluating these patients.

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