Analysis of ventricular shape by echocardiography in normal fetuses, newborns, and infants

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ABSTRACT Qualitative and quantitative changes in left ventricular shapes were analyzed in 14 normal fetuses, 29 normal newborns, and 12 normal infants. Qualitative observations demonstrated that most fetuses and newborns with dominant right ventricles had flattened or even indented interventricular septae, which changed left ventricular shape into an ellipse. In contrast, left ventricular shapes in infants were round, similar to shapes described in older children and adults. When changes in shape or septal distortions were gross, interobserver agreement was 100%; when changes were less altered from a circular shape, interobserver agreement was 78%. To avoid subjective misinterpretations, quantitative analyses were performed, including M mode echocardiographic comparisons of right ventricular/left ventricular dimensions and left ventricular cavity anterior-posterior/lateral diameters, as well as Fourier analysis of digitized tracings of the entire left ventricular shape. The right ventricular/left ventricular ratio, determined by M mode echocardiography, showed significant differences between fetuses (1.07 ± 0.07) and newborns (0.62 ± 0.12) (p < .001). Infants had a significantly lower right ventricular/left ventricular ratio (0.45 ± 0.01) when compared with newborns (p < .01). Ratios of left ventricular anterior-posterior/lateral diastolic diameters were significantly lower (p < .001) in newborns (0.66 ± 0.08) when compared with those of infants (0.82 ± 0.10). All diameters tended to increase (toward roundness) with systole and with aging. Fourier analysis allowed evaluation of the entire left ventricle, including that portion of the septum that qualitatively appeared most indented and could not be analyzed by either of the above techniques. Shape factor derived from idealized shapes ranging from a circle to an indented ellipse allowed comparison with digitized left ventricular tracings. This technique allowed accurate quantitation of the observed changes in shape. Fetuses had the highest diastolic shape factor (7.47 ± 0.92), whereas infants’ shape factors were lowest (2.12 ± 0.41). A tendency toward roundness and loss of distortion occurred with aging. Systolic shape factor was lower with aging in each group studied. The Fourier technique used in this study allows evaluation of an arbitrarily large number of components of a shape, and thus a complete description of that shape is permitted. Comparisons of right ventricular/left ventricular diastolic dimensions and left ventricular anterior-posterior/lateral comparisons are subsets of this technique, which allow evaluation of only two points (circular component—first harmonic) or four points (elliptical component—second harmonic) of an overall shape. Left ventricular geometric changes were similar to shapes seen in various pathologic conditions of right ventricular pressure or volume overload. Accordingly, quantitation of left ventricular shape in normal subjects is necessary before comparison can be made with abnormal subjects. The Fourier method used in this study helps to achieve an enhanced understanding of right and left ventricular interdependence in normal fetuses, newborns, and infants. Through this information, comparison can be made with observations in patients with congenital heart disease.

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TWO-DIMENSIONAL echocardiographic studies and experimental cineangiographic studies using radiopaque markers have shown that left ventricular shape remains generally circular and that septal contour is convex throughout the entire cardiac cycle in
normal humans and animals. Flattened or even concave septal shapes have been noted in conditions associated with right ventricular volume overload and in conditions associated with right ventricular pressure overload. Fetal anatomic and echocardiographic studies in women having normal pregnancies have demonstrated flattened septal shapes and similar right and left ventricular dimensions when the volume-loaded right heart faces a common resistance resulting from a patent ductus arteriosus, high pulmonary vascular resistance, and a low placental systemic vascular resistance.

Septal shape reflects ventricular interdependent geometric configurations. Since normal neonates are in a transitional circulatory phase of falling pulmonary resistance and increasing systemic resistance, methods for quantification of dynamic shape changes in normals will be necessary before comparison with abnormal conditions can be made.

In this study we present prospective serial qualitative and quantitative two-dimensional echocardiographic findings in normal fetuses, newborns, and infants. The study emphasizes computerized Fourier shape analysis, which compares idealized shapes and allows mathematical expression of serial changes in dynamic shape.

**Materials and methods**

**Patients.** All studies were performed after informed consent was obtained according to a protocol approved by the human subjects committee of our institution.

**Group 1: fetuses.** Studies were performed on 14 women having normal pregnancies, and the gestational ages ranged
from 17 to 37 weeks. Age was confirmed by measurement of biparietal diameter and abdominal circumference. Normalcy of pregnancy was confirmed by its course and by postpartum evaluation of the newborn infant (table 1).

**Group 2: newborns.** Twenty-nine normal newborns were studied. Five of these were from the fetal group. All Apgar scores were 7 or higher. Mean gestational age was 39.5 ± 1.2 (1 SD) weeks, and mean weight was 3.44 ± 0.43 kg (table 1).

Group 2 was subdivided as follows: subgroup 2 — ≤ 0.5 days of age (n = 12), three newborns were examined within 2 hr of birth; subgroup 2 — 0.5 to < 3 days of life (n = 17). Six of these were serially studied from subgroup 2A. Sixteen studies were performed on the 12 subgroup 2A patients and 23 studies were performed on the 17 subgroup 2B patients. Physical examination by a neonatologist and by one of the investigators, the subsequent course of the newborn, and the echocardiogram itself helped rule out congenital cardiac disease (table 1).

**Group 3: infants.** Twelve newborns were restudied 15 to ≤ 90 days postnatally (table 1). Mean weight at the time of study was 5.4 ± 1.2 kg. Sixteen echocardiograms were obtained from these 12 patients.

**Echocardiographic examination.** Fetal studies were performed with three two-dimensional echocardiographic instruments, including a SmithKline EkoSector I mechanical sector scanner with a 3.5 MHz 30 degree angle transducer, a 3.5 MHz linear array General Electric SRT, and a 3.5 MHz linear array, electronically focused ultrasonic scanner (Toshiba SSH 10A). Before examination with any of the instruments, gestational age was determined from B-scan evaluation of biparietal diameter and abdominal circumference by a single transducer-type gray-scale scanner (Unimar Sono II with GZD).

Fetal studies were conducted according to the technique described by Sahn et al., that allows reproduction of commonly used echocardiographic views used during standard examinations. Fetal cardiac position was confirmed by appropriate valve motion and location of great vessels during examination. After
Newborns and older infants were studied with one and sometimes two cross-sectional echocardiographic systems. A mechanical sector scanner (SmithKline EkoSector I) with a 5 MHz 30 degree transducer was most commonly used. Some examinations were performed with a Toshiba SSH 10A phased-array sector scanner device with a 2.4 MHz electronically focused transducer. Six newborns were studied with both instruments for purposes of comparison. Throughout this study, accuracy of the sector angle for each instrument was periodically verified with a protractor.

Studies on newborns and infants were performed according to usual techniques. Images were obtained from standard long-axis, short-axis, apical four-chamber, subcostal, and suprasternal planes. Subjects were either in the supine or left lateral recumbent position. No sedation was used.

Although complete examinations were performed on each patient, only short-axis views were subsequently evaluated for analysis in this study. Distinction between papillary muscle and the level of the chordae could not be achieved in all fetuses; therefore, optimal frames for analysis were considered those of the largest left ventricular diastolic diameter just below mitral level. Systolic evaluation was not possible because echocardiographic images of the fetal left ventricle were nearly obliterated during systole.

In newborns and infants, special care was taken to image the entire left ventricle in the short-axis view. This was especially necessary during 30 degree angle sector scanning. Short-axis imaging and subsequent evaluation were performed at the mitral valve level because internal anatomic landmarks allowed reproducible quantitative measurements. Visualization of lateral attachments of the mitral valve in the center of the echocardiographic frame was required before an examination was

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**FIGURE 1.** Diagram of left ventricle at mitral valve level. An anterior-posterior chord is drawn through the midportion of the ventricle and is intersected by a perpendicular lateral line intersecting the mitral valve attachments. See text for details. RV = right ventricle; IVS = interventricular septum; AML = anterior mitral valve leaflet; PML = posterior mitral valve leaflet; PW = posterior wall.

Verification of cardiac location, standard equivalent views (long-axis, short-axis, apical four-chamber, and subcostal four-chamber) were derived. M mode echocardiographic tracings were then obtained from short-axis views.

**FIGURE 2.** Algorithm for Fourier spectrum. Idealized shapes are demonstrated on the left, ranging from a circle to an indented ellipse. The middle diagram demonstrates a vector plot of those shapes comparing change in direction to path length. The right column demonstrates derived Fourier spectra for these shapes. Amplitude is on the ordinate and frequencies (from low frequency on the left to high frequency on the right) are on the abscissa. Note that a circle has very low Fourier spectral amplitudes with highest amplitudes in the low harmonics. In comparison, an ellipse has higher amplitudes with higher peaks in higher frequencies. A distorted ellipse has different high amplitude peaks in low frequencies and higher amplitude peaks in the higher frequencies.
considered acceptable. Initially, four time frames were used for purposes of analysis at the mitral valve level: (1) early diastole, first opening of mitral valve; (2) late diastole, "A" point of mitral valve (second opening of valve); (3) end-diastole, just after mitral valve closure; (4) end-systole, frame just before mitral valve opening.

This method required frame-by-frame analysis of several cardiac cycles; 1500 frames were analyzed and 425 frames met the above criteria and were kept for future analysis.

**Qualitative observations.** Two-dimensional images were visually evaluated by three different observers for presence of deviations from normal round left ventricular shape in both diastole and systole. This was accomplished by frame-by-frame analysis and observation in real time. Deviations from normal round left ventricular shapes were characterized by flatness, presence and timing of septal indentation into the left ventricle, and degree of apposition of the anterior mitral valve leaflet to the septum during diastole. Interobserver variability in qualitative analysis was tested by the chi-square technique.

**Quantitative analyses**

**M mode echocardiography**

**FETUSES.** End-diastolic right and left ventricular dimensions were measured with a computerized light-pen graphics tablet system on fetal M mode echocardiograms derived from two-dimensional images at the level of moving mitral leaflets, as near the posterior leaflet as could be resolved on the image. Since fetal electrocardiograms were not always available for timing purposes, the widest ventricular excursion was chosen. This is in accord with the method of Kleinman et al.⁹

**NEWBORNs AND INFANTS.** Right and left ventricular end-diastolic dimensions from derived M mode echocardiograms were measured according to standard criteria.¹¹ Dimensions were then expressed as a ratio (right ventricle/left ventricle; RV/LV). Statistical analysis was performed with an unpaired Student's t test that compared intergroup RV/LV ratios.

**Two-dimensional echocardiography.** Real-time recordings were kept on video tape. Preliminary viewing of the sequence in real-time, slow-motion, and frame-by-frame analysis with reference to the frame counter facilitated best single-frame selection and allowed tracing of areas where endocardial outlines were not complete in any single frame. After single-frame images were obtained, they were photographed on Polaroid film and stored for future analysis. Fetal pictures were enlarged.

Because of uncertainty about absolute location of landmarks such as papillary-chordal muscle and occasionally the mitral valve edge in fetal left ventricular images, they were excluded from two-dimensional anterior-posterior and lateral diameter measurements. However, the left ventricle was clearly seen. The largest diastolic left ventricular cross-sectional image just below the mitral valve was used for subsequent two-dimensional Fourier analysis. Measurements of two-dimensional echocardiograms were performed in newborns and infants as follows:

(1) Left ventricular cavity: anterior-posterior vs lateral axis (AP/LAT). Left ventricular anterior-posterior internal diastolic dimension was measured from septal internal wall to left ventricular posterior wall in the posterior mitral valve leaflet plane, intersecting the mitral "fishmouth" orifice. A perpendicular line to this line was drawn at its midpoint and intersected mitral valve attachments at the left ventricular lateral walls. This was used as the lateral axis in this particular analysis (figure 1). Measurements were made with a computerized light-pen graphics tablet system. Left ventricular systolic analysis was performed in the same plane at the frame taken just before the mitral valve opened.
FIGURE 4. Method of analysis. A, Digitized shape from a short-axis image in a newborn. Note the area of septal distortion. B, After mathematical smoothing, a reconstructed shape is displayed. C, The reconstructed shape is then analyzed with reference to path length and change in direction of a vector tangent to the path. Positive signs indicate a clockwise deflection, zero no deflection, and negative deflections are demonstrated by a counterclockwise vector. D, The change in vector direction versus path length is then plotted. The ordinate represents vector direction change in degrees (in this case, from −3 to 25 degrees), and the abscissa represents normalized path length in radians (here from 0 to 4.1 radians). This is now available for Fourier analysis (E), which demonstrates the amplitude Fourier spectrum for this particular image. The ordinate represents the amplitude of the Fourier components (here from 0 to 6 degrees), and the abscissa represents various frequencies (from 0 to 4 radians). The numbers 1, 25, and 50 represent frequency points distributed along this spectrum.

Data were statistically analyzed by paired and unpaired Student's t tests for intragroup and intergroup comparisons, respectively.

(2) Left ventricular Fourier shape analysis. Left ventricular short-axis images of fetuses, newborns, and infants were independently digitized by two of the authors. The entire left ventricular inner contour was traced with an electromagnetic HiPad digitizer. Digitization started at the left attachment of the mitral valve and proceeded clockwise in newborns and infants. Fetal left ventricular image digitization started at a 3 o'clock location on the cross-sectional image. When images had some signal dropout, the outlines were nonetheless clear, and minimal visual interpolation was necessary during the digitization process. Separate tracings were performed by two observers when this was the case. Ten tracings of single Polaroid images were performed at different times by each of two observers.
These tracings were randomized and analyzed for interobserver and intraobserver variability. Variability tested by this technique was not significant (p < .01). Still-frame calibration dots were digitized to provide 1 cm reference points for ensuing computer analysis. Sampling resolution in this computer system was 0.66 points/mm, and an average of 40 points per tracing were taken. As the operator digitized, data were graphically displayed on a computer terminal for visual image cross-checking. Data were processed in both interactive and batch modes by a DEC-10 32-bit time-sharing computer and a CDC CYBER 175 60-bit computer.

Digitized tracings were independently reviewed by three of the investigators. Subjective visual analysis of overall left ventricular shape and of septal distortion were assigned values of 1 to 4 (round to elliptical and normal to severely indented). These data were then compared for qualitative interobserver agreement.

Figure 2 demonstrates the background for Fourier analysis used in this study. Sine (or cosine) curves derived from Fourier analysis can be described in terms of frequency and amplitude. Low-order Fourier frequencies provide information about gross shapes, whereas high-order frequencies carry information about abrupt changes in direction on a shape’s surface (distortion). This information can be further enhanced by analyzing separate portions of the shape (figure 3). In this study, the septal portion of the left ventricle showed the greatest degree of distortion and shape change, whereas the left ventricular posterior portion of the shape showed the least degree of change. Accordingly, although we applied the analysis technique described below to the whole left ventricular shape, the left ventricular posterior wall, and septal portions separately, only data from the septal portion were used for purposes of emphasis.

After visual inspection confirmed that digitized shapes (figure 4, A) were the same as the original shapes, the digitized shapes were smoothed to remove scatter induced by the digitizing process. After the mathematical smoothing process was applied, the curve was redisplayed for visual reinspection (figure 4, B). The shape was then converted into a vector diagram, which presents instantaneous change in direction of the path vs. accumulated path length from an arbitrary origin (mitral attachment) on the shape (figure 4, C and D). Total circumference scale was then normalized to a unit axis ellipse that nominally fit the overall shape. This last step removed most variation caused by different ventricular sizes. Fourier analysis was then applied to the vector diagram by means of discrete frequency harmonic analysis. Resultant Fourier frequency amplitude spectra were then displayed (figure 4, E). Phase spectral analysis was not necessary in this study.

When all Fourier spectra were collected, specific frequency bands displaying requisite sensitivities were selected and integrated into band averages. In this study, three band averages were calculated from each septal shape spectrum. Band I ranged from points 1 to 6 (midpoint 3), band II from 7 to 14 (midpoint 10), and band III from 15 to 21 (midpoint 18) of 50 points available for evaluation. These represented low-frequency harmonics of the Fourier spectrum. Subsequently we found that only two (bands I and II) were necessary for evaluation of the shape changes seen in this population.

To form a single parameter that would change monotonically within increasing septal shape changes and distortion from a true circle, a numerical model specific to range and type of distortion observed in this population was generated (figure 5). Idealized shapes that progressed from a circle to an ellipse to an indented ellipse allowed generation of a mathematical function. This was accomplished by using a multiple regression technique that calculated a function that transformed band averages into a single factor. This function, called shape factor, allows visual comparisons and a standard for statistical analyses.

Results

Qualitative. Fetuses and newborns had right ventricles that appeared more dominant than those of infants. The septum was flattened during diastole, a pattern described in patients with atrial septal defects.1-2 Most fetuses and some newborns showed septal flattening during systole and diastole. Their septae buckled into their left ventricles, which were shaped like an ellipse. Most concavity existed in the septal area between the tricuspid valve and the anterior interventricular septum (figure 6, A). In these, the anterior mitral valve leaflet was in apposition with the interventricular septum throughout diastole.

In infants left ventricular shape was round, with the septum convex in both systole and diastole. Right ventricular cavities were small and crescent shaped. The anterior mitral valve leaflet was not in prolonged contact with the interventricular septum during any phase of the cardiac cycle (figure 6, B).

Overall interobserver agreement was 77% for obser-
FIGURE 6. A. Short-axis echocardiogram from diastole and systole in a normal newborn. Note the septal indentation into the left ventricle, which tends to round with systole. IVS = interventricular septum; MV = mitral valve; PW = posterior wall. B. Short-axis diastolic and systolic images from a normal infant. Note that septal and left ventricular shapes are round in both phases of the cardiac cycle. AML = anterior mitral valve leaflet; PML = posterior mitral valve leaflet.

...vations of qualitative overall left ventricular shape and 78% for septal distortion. One hundred percent agreement among three observers existed on shape in 63/129 observations and on distortion when none was present or when it was gross in 72/129 observations.

Quantitative

M mode echocardiographic RV/LV ratio. A significant decrease of the RV/LV ratio was noted between fetuses (mean 1.07 ± 0.07 cm [± SD]) and newborns (mean 0.62 ± 0.12 cm) (p < .001). RV/LV ratio was not significantly different in the two newborn groups (0.60 ± 0.05 and 0.63 ± 0.02 cm). Infants showed a significant decrease in RV/LV ratio (0.45 ± 0.01) when compared with newborns (p < .01) (figure 7).

Two-dimensional echocardiographic AP/LAT diameter.

INTERGROUP. At the mitral valve level, three diastol-
ic frames (early, late, and end) were not significantly different from one another in the newborn subgroups (2A and 2B). However, significant differences existed in early diastolic LV AP/LAT dimension between newborns (mean 0.66 ± 0.08) and infants (mean 0.82 ± 1.0) (p < .001).

Intergroup comparison showed that all diameter measurements tended to become rounder (ratio closer to 1.0) with systole and with aging (figure 8).

Intragroup. Although major differences were noted between newborns and infants, little change in shape as reflected by the left ventricular AP/LAT ratios occurred throughout the cardiac cycle within a given group, with the exception of newborns, who showed significant differences between early and end-diastole (mean difference 0.15 ± 0.01; p < .001) in frames from the mitral valve level.

Fourier analysis of digitized shapes with comparison to idealized figures. The shape factors for the ventricular imaging data were calculated and are listed in table 2. The table entries are in order of age ranging from fetuses to infants. Since the different diastolic phases were similar, only the early phase, which displays the strongest effect, was considered in this analysis. Fetuses with flattened left ventricles showed the highest shape factors during diastole, whereas infants showed more circular diastolic shape factors (figure 9, A). When the same technique was applied to systole (figure 9, B), left ventricular shapes were rounder and the curve was accordingly flatter. Newborns had greater systolic septal alterations than infants. Fetuses were not included because the two-dimensional images obtained during systole were filled with echoes and were thus beyond the interpretive and measurement capabilities of this study.

When these data were statistically analyzed, interobserver Fourier agreement was at the 95% confidence level. No differences in Fourier results existed when tracings from separate echocardiographic instruments were evaluated (p < .05). Differences in diastolic shape factors between each age group (fetuses, newborns, and infants) in systolic shape factors of newborns and infants were significant (p < .01). Further-
fore, to communicate these observations objectively, various mathematical models were applied to shape changes. Fourier characterization and comparison to idealized shapes proved the best method of those tested for describing these changes. M mode echocardiographic comparisons of RV/LV diameter demonstrated dominance of the right ventricle in fetuses and newborns, whereas left ventricles were more dominant in infants. Left ventricular AP/LAT ratio demonstrated that left ventricles were compressed into an elliptical shape in newborns and became round in infants. However, each of these methods of mathematical analysis did not allow evaluation of that portion of the left ventricle that visually demonstrated the greatest distortion, the septum between the tricuspid valve and the anterior left ventricle. This area was easily analyzed by the Fourier technique, and its analysis was enhanced when it was separated from that of the posterior left ventricle.

The Fourier technique used in this study allows evaluation of an arbitrarily large number of components of a shape and thus a complete description of that shape is permitted. Comparisons of RV/LV diastolic dimension and left ventricular AP/lateral dimensions are subsets of this technique, which allow evaluation of only two points (circular component—first harmonic) or four points (elliptical component—second harmonic), respectively, of an overall shape.

Shape changes seen in this study are expected because of the changes in circulatory dynamics between fetuses, newborns, and infants, which have effects on interdependent ventricular geometric configurations. Newborn ventricular shapes resembled those described by Weyman et al. in patients with right ventricular volume overload and those seen in patients with right ventricular pressure overloading conditions. Other studies have demonstrated that left ventricular shape and diastolic pressure are affected by alterations in right ventricular volume and pressure. These alterations can make echocardiographic assessment of left ventricular contractility and volume based on standard geometric models unreliable. This is especially true in conditions of right ventricular pressure overload such as simple transposition of the great vessels with intact ventricular septum and no subpulmonic or pulmonic stenosis, in which a reversed pressure relationship exists between the ventricles.

Since we have demonstrated that newborns have altered left ventricular geometric shapes when compared with those of infants and that newborn left ventricular shapes are similar to shapes seen in various pathologic conditions of right ventricular volume or

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**FIGURE 9.** Septal shape factor with comparison to age in days. Newborns are subgrouped as shown in table 2. F = indicates fetuses. Note that fetuses and newborns have significantly higher shape factors (less round, more distorted ventricles) than infants. Furthermore, a significant difference exists between systole (A) and diastole (B).

more, systolic shape factors were significantly smaller than diastolic shape factors (p < .01), indicating that left ventricles become rounder in systole regardless of age.

**Discussion**

This study describes left ventricular and septal shape changes in children ranging from the prenatal period to infancy. Qualitative observations show that fetuses have dominant right ventricles and that newborns have similar patterns, with an elliptical left ventricular shape and an asymmetrically flat septum. Diastolic mitral valve apposition to the flattened septum was frequently observed in newborns. During qualitative analysis, when shape changes and distortion were gross, all observers agreed. However, when shapes were less altered, subjective observations varied, with only 78% agreement among three observers. Therefore, to communicate these observations objectively, various mathematical models were applied to shape changes. Fourier characterization and comparison to idealized shapes proved the best method of those tested for describing these changes. M mode echocardiographic comparisons of RV/LV diameter demonstrated dominance of the right ventricle in fetuses and newborns, whereas left ventricles were more dominant in infants. Left ventricular AP/LAT ratio demonstrated that left ventricles were compressed into an elliptical shape in newborns and became round in infants. However, each of these methods of mathematical analysis did not allow evaluation of that portion of the left ventricle that visually demonstrated the greatest distortion, the septum between the tricuspid valve and the anterior left ventricle. This area was easily analyzed by the Fourier technique, and its analysis was enhanced when it was separated from that of the posterior left ventricle.

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pressure overload, quantitative comparison of shape factors seen in abnormal conditions to shape factors of normal infants is necessary before quantitative description of these conditions can be made. Additionally, calculation of left ventricular and right ventricular areas and volume must take these geometric alterations into consideration.

The Fourier method used in this study helps to achieve an enhanced understanding of right and left ventricular interdependence and of right and left ventricular shape and function interrelationships in normal subjects and patients with congenital heart disease.

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