

Quantitative Real-time Cross-sectional Echocardiography in the Developing Normal Human Fetus and Newborn

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SUMMARY New high-resolution real-time ultrasound cross-sectional imaging systems have enabled us to demonstrate detailed fetal cardiac anatomy in the second half of pregnancy. We studied normal fetal cardiac development quantitatively by echocardiography in the second half of pregnancy in 69 normal pregnancies of healthy mothers. Eighteen of the fetuses were followed serially before birth. The estimated gestational ages were 20–41 weeks (mean 31.7 ± 0.5 weeks [SEM]) of pregnancy. Calculated fetal weights were 500–3100 g (mean 1590 ± 83 g). Fetuses were reexamined within 36 hours after birth by real-time cross-sectional echocardiography to provide comparative data for the assessment of circulatory changes that take place at birth. Measurements of the right and left ventricles at the atrioventricular valve level were taken from four-chamber plane images of the heart before and after birth, and measurements of the aorta and pulmonary artery were taken in the short-axis view. All measurements were taken at end-diastole and were related to calculated fetal or actual newborn body weight. Statistical analysis for fetal cardiac dimension, right (RV) and left ventricular (LV) dimension and great artery size showed good correlation to calculated fetal weight, and growth curves for fetal cardiac structures were derived. Physiologic changes in the circulation at birth affected RV size considerably compared with measurements before birth. The RV/LV dimensional ratio was 1.18 ± 0.01 before birth and decreased to 0.99 ± 0.03 ($p < 0.001$) within 36 hours of birth. The pulmonary artery-to-aortic dimensional ratio did not change significantly after birth. Our findings about cardiac growth and the major adjustments of the circulatory system for extrauterine life are similar to those previously reported in humans and animals.

EARLIER STUDIES of human fetal cardiac measurements determined with ultrasound techniques have provided only preliminary quantitative data for assessing fetal cardiac growth.^{1–4} The structural details obtained in fetal echocardiograms from a previous study from our laboratory⁵ encouraged us to try a quantitative evaluation of the fetal heart in order to derive information about normal fetal cardiac growth. The same fetuses were imaged again in the newborn period, so we hoped that this study could also provide physiologic data for the assessment of circulatory changes that take place at and after birth.

Methods

Patient Group 1

We reviewed two-dimensional echocardiographic studies of 69 pregnancies of healthy mothers who were referred for routine fetal scanning or who wanted information about fetal cardiac anatomy because of earlier birth histories of cardiac malformations. Eighty-seven examinations were performed before birth. Fifty were adequate for three of four measurements, and 18 fetuses were examined serially. Ten fetuses had two adequate examinations for measurements. After a routine clinical B-scan

procedure for determination of fetal size and lie, the patients underwent a real-time cross-sectional analysis of the fetal heart and great arteries. The examination was performed under a human subjects approved protocol after informed written consent was obtained from the mother.

Patient Group 2

Three mothers with RH incompatibility were examined to evaluate possible alterations of fetal heart size. Two of these fetuses were hydropic at birth and had required in utero transfusion.

Patient Group 3

All fetuses were followed after birth to confirm cardiac anatomy by physical examination and cross-sectional echocardiography. For the quantitative follow-up study, 19 newborns from group 1 had satisfactory examinations prenatally and postnatally for quantitation. These 19 subjects make up group 3.

B-scan Examination

The patients underwent a standard B-scan procedure to determine the fetal lie and maturation. Either a single transducer-type scanner with gray scale (Unirad Sono II with GZD), or a large, multiple-crystal, computerized, waterbed-based B-scanner (Octoson) were used. Gestational age was determined from biparietal diameter.⁶ The fetal weight was calculated by using the biparietal diameter and abdominal circumference as described by Warsof et al.⁶ Fetal echo measurements were performed with a computerized digitizing system (Numonics).

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Real-time Cross-sectional Examination of the Fetal Heart

The real-time echocardiographic examinations were performed with a 3.5-MHz, electronically focused, linear-array ultrasonic scanner (Toshiba SAL 10A), or a 3.5-MHz, dynamically focused, experimental phased-array ultrasonic scanner. Beam profiles of both systems performed in our laboratory suggest that lateral resolution at 6 db down was about 1.5–2 mm and axial resolution was 0.2 mm, at a depth of 6–10 cm from the transducer.

We preferred the linear-array format prenatally, as it has constant line density over the whole depth of view, and used it in 92% of prenatal examinations. Moreover, the large transducer was easy to manipulate on the abdominal wall of the mother and more of the fetus could be imaged at any one time with the rectangular format image.

During the examination, the mother lay in a comfortable supine position and was occasionally turned to either side to influence the fetal lie. The fetal lie was determined using images of the fetal head, spine and liver.

We then attempted to reproduce commonly used cross-sectional view equivalents: long-axis, short-axis, apical four-chamber and subxiphoid four-chamber. Our success rate for achieving these views prenatally was 100% for the four-chamber and 95% for the great-artery view.⁵ Postnatally our success rate was 100% for all views. While these views could be obtained on most examinations, there were only 50 prenatal examinations, 10 from fetuses with two serial examinations each, which were adequate for three of four measurements. In 19 cases, both a prenatal and a postnatal examination were judged adequate for quantitation.

Follow-up Newborn Examinations

The cross-sectional echocardiographic examinations of the newborns were performed within 36 hours after delivery with the same linear-array system used prenatally, with a 2.4-MHz, wide-angle, phased-array system (Toshiba SSH 10A) with variable electronic focusing, or with the experimental 3.5-MHz, phased-array scanner. The high-resolution, phased-array at 3.5 MHz was used in 18 of the 19 quantitated postnatal exams. We could obtain the four-chamber views much more easily with a sector scanner.

Five newborns had measurable images on both the linear array and the phased array. There was no difference between the measurements on the two systems by paired *t* test (NS). A complete examination included the precordial long-axis, precordial short-axis and four-chamber views. Emphasis was placed on imaging a true four-chamber view so that both atrioventricular (AV) valves could be seen opening and closing at the same time, assuring that the cross section passed close to the center of the heart.⁷ This cross section provided the largest diameter of both ventricular chambers and therefore comparative

measurements and ratios of ventricular size could be obtained from the newborn infants.

Display and Recording

All studies were recorded in real time on videotape interfaced with the echograph via a video camera. Video tapes could be reviewed in real time or slow motion, or by frame-by-frame analysis. Still-frame images were stored either on Polaroid prints during the examination or photographed afterward from video tapes. Frequently, problems arise in illustrating real-time cross-sectional observations with selected still frames. The actual examinations observed in real-time on videotapes are more impressive than any individual still-frame illustration.

Specific Alterations in Examination Technique for Quantitation and Measurement Techniques

All measurements were performed with a computerized digitizing system (Numonics). B-scan still frames were measured from x-ray film. A peripheral digitizer could be mounted in front of a video screen and allowed measurements directly from videotape still frames of real-time cross-sectional images. Biparietal diameters were measured by the leading-edge method. Abdominal circumference was measured from the abdominal wall echogram. Estimated fetal weight was determined from B-scan images as described by Warsof et al.⁸ (fig. 1). Fetal and newborn cardiac measurements were obtained from views showing the four cardiac chambers and the spiral orientation of the great arteries (figs. 2 and 3).

Figure 2 shows a typical four-chamber presentation at end-diastole. The AV valves have just closed. Measurements from such a still frame were taken just inferior to the AV valves for the evaluation of right ventricular (RV) and left ventricular (LV) diameters. (The valves were used for timing of end-diastole as there were no fetal ECGs available. End-diastolic measurements were obtained from the frame before or the frame just after closure of the AV valves.) The total diameter of the heart (total cardiac dimension) was measured as the distance from the RV epicardial surface to the epicardial surface of the LV posterior wall. The RV and LV inner diameters were measured as the same level. The thickness of the echo lines was excluded from all measurements for inner cavity dimensions or great artery dimensions.

As stated, attempts were made to optimize four-chamber views so that the maximum diameter of both ventricles was imaged. Bommer et al. suggested that measurement of the right ventricle on four-chamber apical views at the level just below the tricuspid valve correlates closely with maximum RV short-axis dimension measured from anatomic casts.⁷ Axial resolution is always superior to lateral resolution in pulsed ultrasound devices, so we attempted to obtain four-chamber views oriented as closely as possible so as to allow measurement in a more axial direction (figs. 2 and 3).

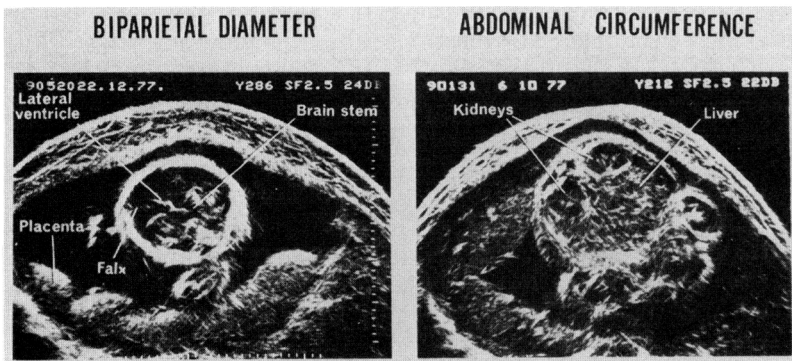


FIGURE 1. The calculation of estimated fetal weight (EFW) was based on the biparietal diameter (left) and the abdominal circumference (right) using the algorithm of Warsof et al.⁶

Figure 3 shows fetal great artery orientation as imaged for measurement. In this figure, for instance, the aorta can be measured in a purely axial plane. Measurements were made from inner edge to inner edge of each vessel at the level of the aortic and pulmonary valves at end-diastole in this view. End-diastole was considered the frame just before opening of the semilunar valves. We measured pulmonary artery diameter only when two leaflets of the pulmonary valve were imaged.

Statistical Analysis

Multiple regression models were evaluated for expressing the fetal cardiac measurements as a function of estimated gestational age or estimated (calculated) fetal weight. The best correlations were obtained to the fetal weight estimate reported herein. While correlations of the measurements were evaluated to various functions of fetal weight (log, linear, square root, cube root), the best correlations were obtained to a power function of body size ($Y = ax^n$, where n was close to $1/3$ (cube root; see table 1). All data are therefore regressed to a power function of estimated fetal weight and are displayed as the regression line along with the 5% and 95% confidence limits for the regression relationship. Paired and unpaired t tests were used for other statistical comparisons.

The analyses of these data are intended to test whether the fetal cardiac measurements obtained by the techniques described above relate to each other

and to other information in logically consistent and useful ways. Two analytic phases are involved. The first phase focuses on the fetal measurements and on their variation with estimated fetal weight, used as a criterion of overall development. In the second phase, the relationship between fetal and postnatal measurements are considered. Gold⁸ observed that physical dimensions of many biologic structures are related to each other by power functions of the general form, $M_2 = aM_1^b$, where M_1 and M_2 represent two such dimensions while a and b are parameters estimable from data. The parameter a serves as a scaling factor and b may be interpreted, cautiously, as indicative of the relative rate of development of the two structures measured. Such a power function model was the basis of our explanation of the relationships among the fetal cardiac measurements and their dependence on fetal weight. This model is computationally convenient in that the measurements for such a model can be estimated by applying linear regression analysis to the logarithms of the measurements. It is also possible to derive 5% and 95% confidence limits for additional observations from such a linear regression by using techniques described by Draper and Smith.⁹ These limits are interpretively equivalent to the percentile traces for developmental profiles based on more extensive data.

In the second phase of analysis, we considered the relations between the fetal measurements and the set of subsequent postnatal measurements. If data were available for all 50 fetal subjects, an ideal procedure

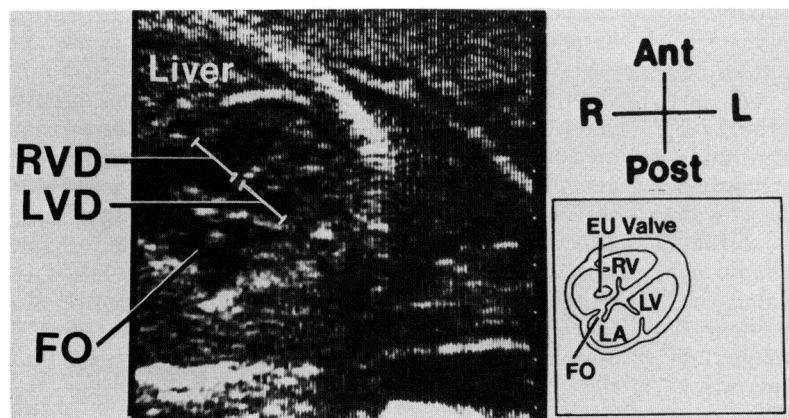


FIGURE 2. Four-chamber view oriented so that ventricular measurements may be made along oblique lines in a more axial direction as shown in this picture. This results in better resolution (see text) of the endocardium and more accurate measurements. The movements of the foramen ovale (FO) flap could also be demonstrated in an axial direction. Fetal ventricular measurements were taken from four-chamber views at end-diastole directly inferior to the atrioventricular valves, as shown. RVD = right ventricular dimension; LVD = left ventricular dimension; LA = left atrium; EU VALVE = eustachian valve.

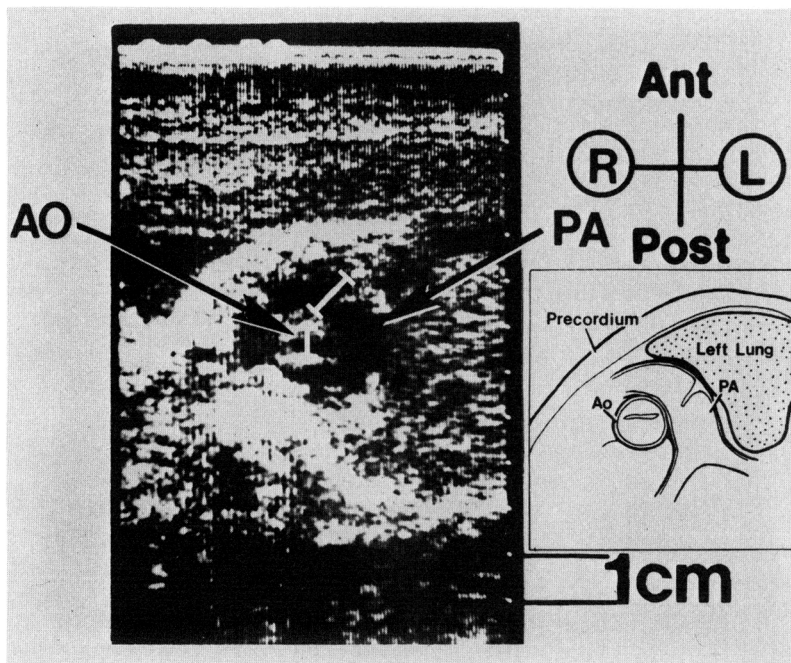


FIGURE 3. Great-vessel orientation view for the fetus. Measurements (inner dimension) were taken at the valvular level at end-diastole as indicated. AO = aorta; PA = pulmonary artery.

would be to carry out a similar examination of the postnatal data for internal consistency and weight dependence and then to relate the derived pattern to those of the fetal data. With only 19 of the 50 subjects followed up after birth with adequate measurements, we have too few postnatal data for such an approach to be reliable. However, an alternative approach is viable: If the postnatal data are such that they represent a continuation of the developmental pattern indicated by the fetal data, then the postnatal measurements, plotted against weight, will fall within an extrapolation of the confidence limits for the fetal data. The extent to which a particular postnatal measurement deviates from the fetal expectation can be quantified simply by calculating a weight-adjusted score for it using its birth weight in the adjustment formulas defined for the fetal data. If the same developmental pattern is appropriate for the postnatal data as for the fetal data, then the means of the adjusted postnatal scores for the 19 subjects should not differ significantly by *t* test from those of the fetal adjusted scores for those same subjects. Should the means differ significantly, it would indicate a change in developmental pattern between the fetal and postnatal measurements.

If evidence for a change in pattern is not found by this test, the predictability of the postnatal measurements from the fetal ones may be assessed by examining the correlations between corresponding weight-adjusted scores. High positive correlations indicate good predictability in the cases shown to be deviated from the mean in the same direction prenatally and postnatally.

Results

Despite potential difficulties in measurement, our fetal data provided acceptable correlations of cardiac

dimensions to fetal weight. Additionally, if the fetal measurements are to be judged logically consistent, certain relations among them should be demonstrable. First, there should be fairly strong positive correlations among all of the cardiac dimensions, corresponding to overall consistent growth of the entire fetus (table 1). Second, all of the cardiac dimensions should correlate positively with fetal weight, corresponding to growth of the heart, consistent with overall development. Third, if the relative position of a subject in one of the growth profiles is to be useful as an index of that subject's degree of abnormality, then there should be positive correlation between weight-adjusted scores on related structures.

Table 1 is a summary of the analysis of the fetal measurements. The correlations among the cardiac dimensions before adjustment for weight dependence are displayed in section A. All are quite strong and positive. Their detailed pattern indicates that, within this overall pattern of positive correlation, there is some independence between the great arteries and the three measurements of cardiac chamber size.

Section B of table 1 displays regression statistics from the dependence under a power function model, of the cardiac dimensions on fetal weight. Again, all correlations are fairly strong and positive. Plots of the raw data, including the estimated regression line, with 5% and 95% confidence limits, are presented as figures 4-6. Curvature toward the origin, consistent with a power function model, is apparent in each of them. The raw data were converted to weight-adjusted scores by using the expected value from the regression equations and the conditional standard deviations upon which the confidence bounds are based. Under this transformation, any case lying exactly on the upper confidence boundary would yield an adjusted score of 1.96, regardless of its weight. Thus, the adjusted scores represent the extent to which the subjects

TABLE 1. *Fetal Data Analysis Summary*

Section	Dimension	TCD	RV	LV	PA	AO	Statistics shown
A	TCD	—	0.93	0.94	0.75	0.73	Correlations for unadjusted data (see text for details)
	RV	—	—	0.93	0.70	0.72	
	LV	—	—	—	0.72	0.74	
	PA	—	—	—	—	0.93	
	AO	—	—	—	—	—	
B	Scale factor a	0.356	0.128	0.099	0.137	0.096	Regression statistics: dimensions on fetal weight: $n = aWt^b$
	Component b	0.284	0.315	0.329	0.224	0.253	
	r	0.86	0.83	0.81	0.68	0.66	
C	TCD	—	0.74	0.80	0.45	0.42	Correlations for weight-adjusted data (see text for details)
	RV	—	—	0.79	0.35	0.39	
	LV	—	—	—	0.40	0.44	
	PA	—	—	—	—	0.87	
	AO	—	—	—	—	—	
	n	50	47	47	47	50	

*All coefficients significant at $p < 0.05$.

Abbreviations: AO = aorta; PA = pulmonary artery; TCD = total cardiac dimension; RV = right ventricle; LV = left ventricle.

deviate from the overall "normal" pattern of the group. The correlations among these adjusted scores are displayed in section C of table 1. Although they are consistently smaller than those among the unadjusted dimensions, all are positive and significant. This indicates that a subject found to be relatively large or small on one cardiac dimension tends also to be

relatively large or small on the others. The detailed pattern of contrast between the great artery measurements and the three cardiac chamber dimensions is stronger here than in the unadjusted data, as the compounding effect of weight has been removed.

Figure 4 documents the growth of the total cardiac dimension of the heart measured in a four-chamber

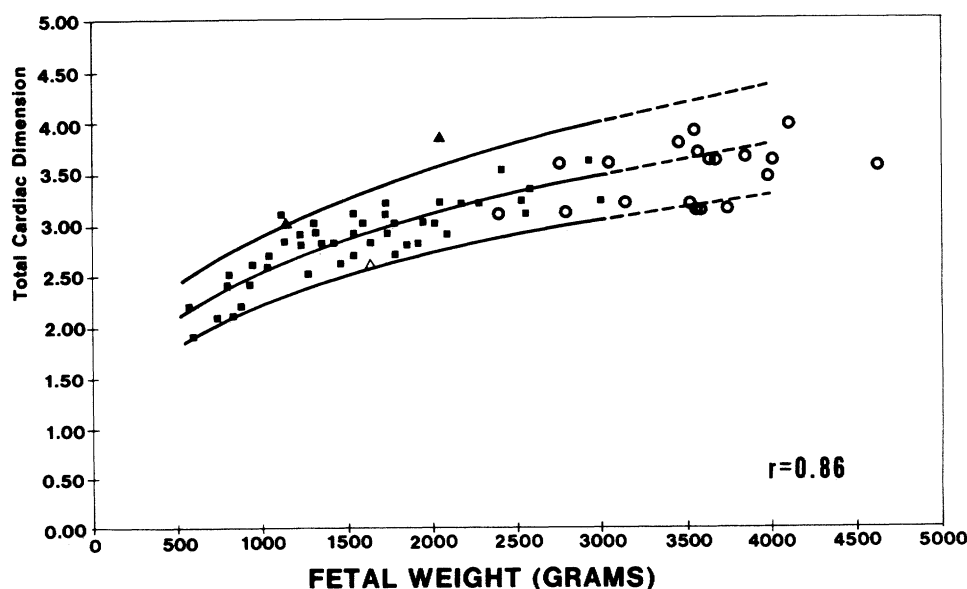


FIGURE 4. The growth of the fetal total cardiac dimension (cm) taken from a four-chamber presentation is plotted against calculated fetal weight. Statistical analysis refers only to the fetal data (squares). The central line is the regression line. The other lines represent the 5% and 95% confidence limits of the regression relationships. The regression lines and confidence limits are valid for the region over which they are drawn as solid lines. They have been extrapolated as dotted lines to allow a visual comparison of the postnatal data. Postnatal measurements from apical four-chamber views are marked as circles. Closed triangles represent data from two hydropic fetuses. The open triangle refers to an unaffected RH fetus. See tables 1 and 2.

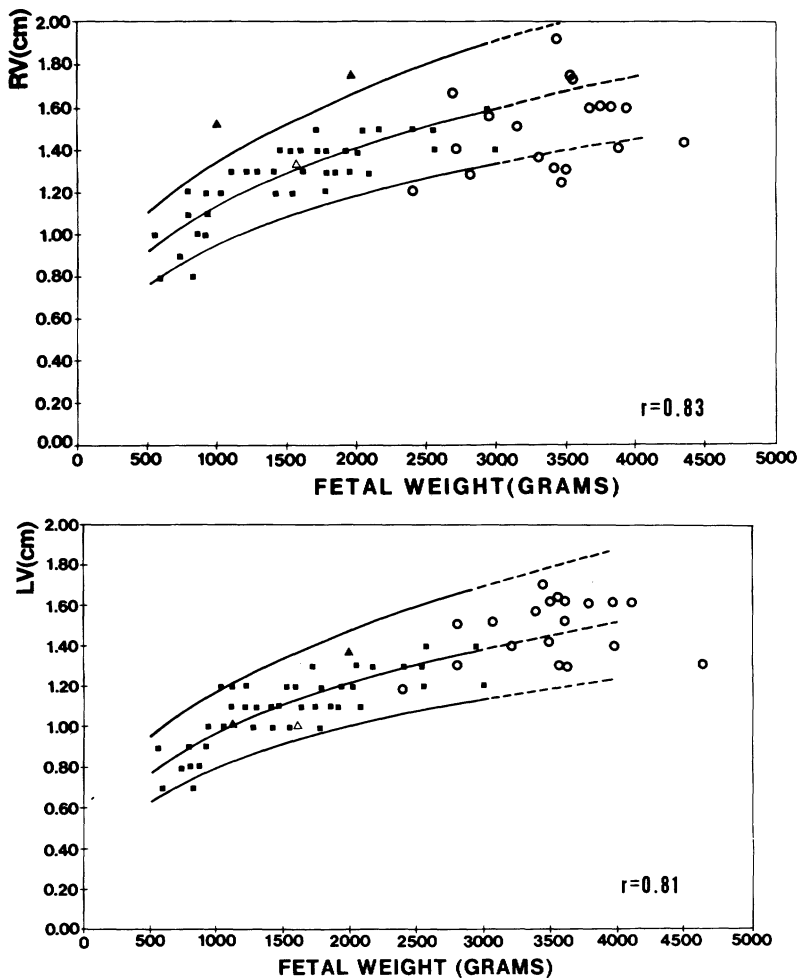


FIGURE 5. The growth of (A) the right ventricular diameter (RV) and (B) the left ventricular diameter (LV) from a four-chamber view are plotted against calculated fetal weight. Statistical analysis and display are the same as in figure 4.

presentation. The statistical regression analysis uses fetal data only. Table 1 shows the regression analyses for all curves.

Figure 5 is a comparison of the growth of the RV (A) and LV dimension (B) in relation to calculated fetal weight. These data are plotted as in figure 4. As seen for total cardiac dimension, a power function of fetal weight provided the best correlation. All correlation coefficients are comparable, but slightly lower than for total cardiac dimension.

Superimposed on these diagrams are the three RH fetuses. The nonhydropic fetus exhibits measurements within the 95% confidence limits. The two hydropic fetuses have normal LV diameter but lie above the confidence limits with respect to the RV diameter, thus demonstrating RV dilatation, associated with clinical hydrops fetalis.

Figures 6A and B are a comparison of the growth of the great arteries in relation to a calculated fetal weight. The data are displayed as in figure 4. The correlation coefficient was considerably lower than for the ventricular measurements $R(\text{PA}) = +0.68$, $R(\text{AO}) = +0.66$. The magnitude of growth and absolute size of the great arteries is considerably less than for the ventricles or total cardiac dimension, thus presenting difficulties for quantitation of growth and reflected in the poorer correlations.

Table 2 displays the results of the analysis of the postnatal data in relation to the fetal developmental patterns for both of the great artery dimensions and for the cardiac chamber dimension. The significant t values comparing the means of fetal and postnatal weight-adjusted scores permits rejection of the hypothesized common developmental pattern. Thus, the artery dimensions are both significantly larger after birth than they would be expected to be on the basis of the extrapolated fetal pattern, while the RV dimension is smaller. The total cardiac dimension and LV dimension show insignificant deviations from the fetal patterns; however, the t value for total cardiac dimension is marginal ($p = 0.055$), just short of the significance cutoff. None of the dimensions shows a significant correlation between fetal and prenatal weight-adjusted scores, indicating low predictability. Technically, only those for total cardiac dimension and left ventricle should be considered at all predictable, but with very poor correlations. The differences in postnatal measurement could result from a difference in technique or plane of imaging. The fact that these differences affect the aorta, a circular, easily imaged structure, suggests that they may be real.

Figure 7 shows the dimensional ratios of the pulmonary artery to the aorta (PA/AO) and right ventricle to left ventricle. It also provides regression

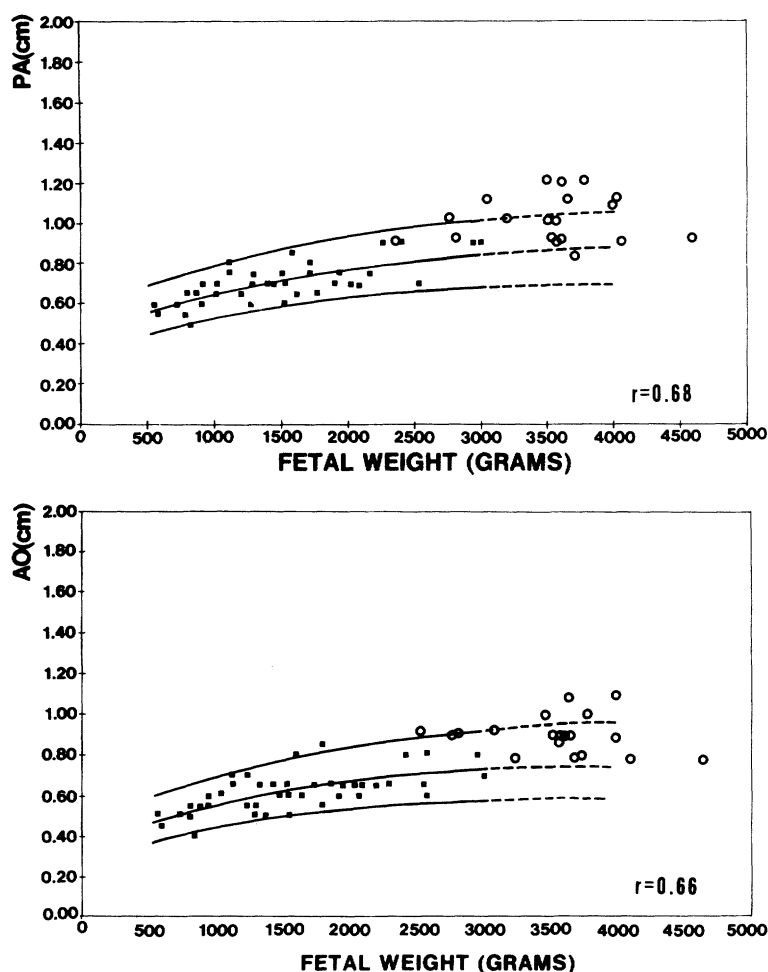


FIGURE 6. Growth of (A) the pulmonary artery (PA) and (B) the aorta (AO) taken from great artery views are plotted against calculated fetal weight. Statistical parameters and display are the same as in figure 4.

lines for each ratio of right- to left-sided structures plotted with respect to estimated fetal weight. The PA/AO ratio appears to be relatively constant throughout gestation. (All ratios were rounded off to two significant figures.) While slightly lower ratios appear more common later in gestation and after birth, no significant difference occurred between the prenatal and postnatal ratios for the PA/AO. In contrast, the RV/LV ratio is also relatively fixed before

birth with respect to estimated fetal weight but is significantly lower in postnatal measurements.

Figure 8 demonstrates grouped data of PA/AO and RV/LV ratios regardless of estimated gestational age or weight. The ratio between the dimensions of great arteries before and after birth is unchanged, and shows a slightly larger diameter of the pulmonary artery compared with the aorta. Differences between the prenatal and postnatal ratios are within the limits of accuracy. On the other hand, the RV/LV dimensional ratio changes considerably after birth.

TABLE 2. Analysis of Postnatal Data

Dimension	Mean fetal Z	Mean postnatal Z	t	r	n
TCD	0.25	-0.49	2.05	0.40	19
RV	-0.32	-1.95	3.82*	0.02	19
LV	-0.14	0.07	-0.47	-0.20	19
PA	-0.02	1.63	-3.41*	-0.31	19
AO	-0.17	1.61	-4.86*	-0.04	19

*Significant at $p < 0.05$ by two-tailed paired t .

Abbreviations: Z = weight adjusted score expressed as a number of standard deviations; t = t test value; TCD = total cardiac dimension; RV = right ventricle; LV = left ventricle; PA = pulmonary artery; AO = aorta.

Discussion

This quantitative study of cardiac measurements provides fetal cardiac growth curves for the second half of pregnancy. Cross-sectional cardiac measurements can be obtained serially prenatally and postnatally. Our fetal measurements derived from four-chamber views are not comparable to measurements of premature infants which have been published using M-modes.¹⁰ The same is true for the measurement of the great vessels, because we measured the inner dimension of the aorta and pulmonary artery from two-dimensional images. The exact positions of the outer edge of the pulmonary artery are difficult to define on echo images. Ad-

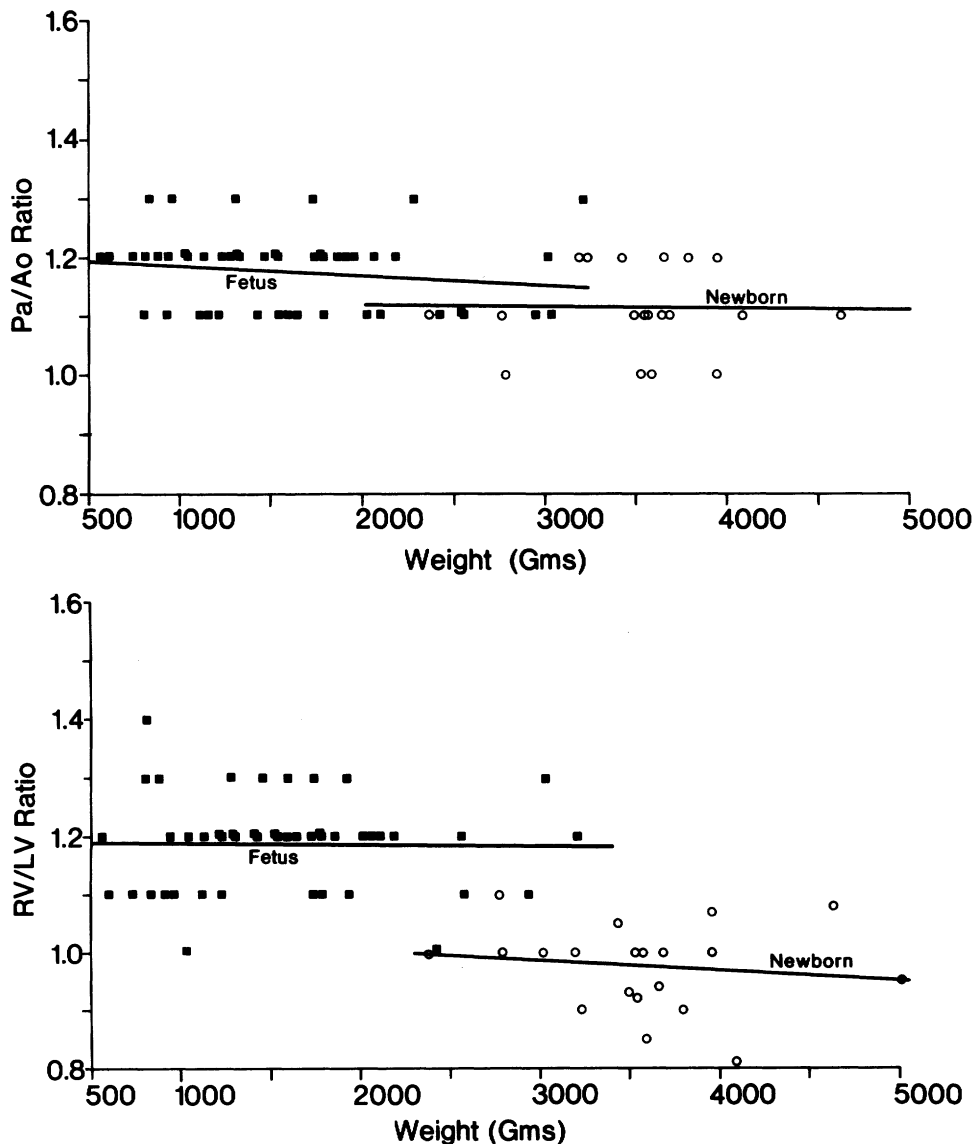


FIGURE 7. Comparison of (A) the pre- and postnatal dimensional ratio of pulmonary artery/aorta (PA/AO) and (B) the right ventricle/left ventricle (RV/LV) plotted with respect to estimated fetal weight by linear regression analysis.

ditionally, pulmonary artery measurements are difficult to obtain by M-mode and cannot be compared to our data. At present, measurements of cross-sectional images are not standardized. Validation of quantitative measurements of the anatomic views we obtained are just beginning to be reported.⁷

Measurement factors, such as the thickness of the lines, may differ from instrument to instrument. We optimized them by using minimum gain in order to get echo lines as thin as possible and used very high resolution systems. Another measurement problem is that as soon as the "real-time" integration of the eye performed on the moving image is lost, any still frame is difficult to measure.

Aside from the problems involved in the measurement of the still frame, the great arteries represent smaller structures which grow only about 5 mm dur-

ing the second half of pregnancy. Changes in size of ± 1 mm can hardly be detected by our echo method, especially in structures measured laterally side-to-side rather than in an axial direction. This results in a relatively large error for the slow-growing vessels and may explain the poorer correlations obtained for these measurements vs estimated fetal weight.

Difficulties also arise from our reference standard, the calculated fetal weight, which, although it is a relatively accurate method, has a standard deviation of at least ± 100 g.^{11, 12}

Resolution limitations in present diagnostic instruments obviously limit the absolute accuracy of the data we present. A large-aperture, high-frequency, 5–7-MHz dynamically focused scanner with fetal ECG (or Doppler signals for timing) and directionally oriented TM-mode would be best for the studies we

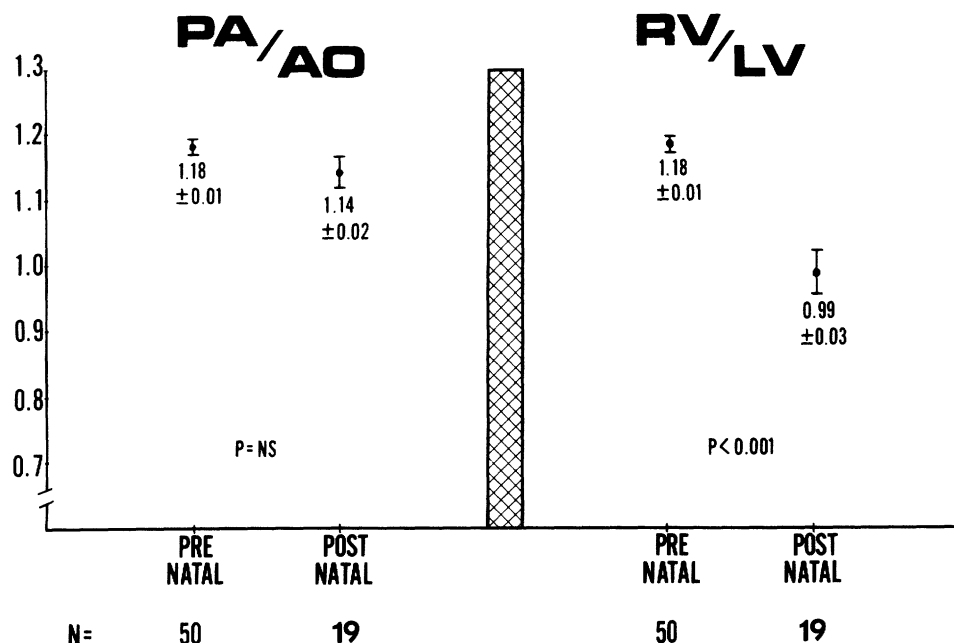


FIGURE 8. Grouped data for pre- and postnatal dimensional ratios as in figure 7. The mean (circle) and ± 1 SEM (brackets) are shown. Statistical analysis is by unpaired *t* test.

have described. Image rate should be at least 60 frames/sec.

The physiologic changes of the circulation at birth affect ventricular size considerably. The size of the great arteries appears less affected (figs. 5, 7 and 8). Our preliminary data suggest that the total dimension of the heart stays constant (fig. 4), but left ventricular dimension may become slightly larger and right ventricular dimension becomes significantly smaller, resulting in an equalization of ventricular size after birth. These findings confirm earlier ultrasound research on fetal cardiac chamber size by Winsberg,² but are contrary to work reported by Garrett and Robinson.¹ Recent data reported in abstract form by Voster et al.¹³ in fetuses older than 32 weeks estimated gestational age show measurements similar to ours in a smaller series. Finally, our data are also similar to an older radiographic study on aborted fetal and newborn heart size performed by Lind and Wegelius.¹⁴

In recent years, efforts have been made to understand physiologic changes in the circulation before and after birth by study of chronically instrumented fetal lambs.¹⁵⁻¹⁷ Findings in these studies about chamber size in utero and changes after birth are also similar to the data we report in the present study.

Conclusions

The resolution capabilities of new ultrasonic instruments allow detailed quantitative analysis of the development of the fetal heart during the second half of pregnancy. This study, therefore, provides a new method for evaluating fetal development. It also enables us to investigate noninvasively the circulatory changes which take place perinatally. These data con-

firm previous work using highly sophisticated, chronic animal preparations which provide observations about the major adjustments of the circulatory system for extrauterine life.

Quantitative data should not only be of use in evaluating functional abnormalities in the abnormal fetus, but the chamber and great vessel patterns should also be useful as baseline data for attempts at prenatal diagnosis of congenital cardiac malformations⁵ because, for instance, in tricuspid atresia, gross abnormalities of chamber size may be present and may be detectable early in utero. As such, the normal quantitative data published herein may be of use as an adjunct for prenatal cardiovascular diagnosis by echocardiography.

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References

- Garrett WJ, Robinson DE: Fetal heart size measures *in vivo* by ultrasound. *Pediatrics* 46: 25, 1970
- Winsberg F: Echocardiography of the fetal and newborn heart. *Invest Radiol* 7: 152, 1972
- Suzuki K, Minei LJ, Schnitzer LE: Ultrasonic measurement of fetal heart volume for measurement of birth weight. *Obstet Gynecol* 43: 867, 1976
- Egeblad H, Bang J, Northeved A: Ultrasonic identification and examination of fetal heart structures. *J Clin Ultrasound* 3: 95, 1975
- Lange LW, Sahn DJ, Giles H, Anderson C, Allen HD, Goldberg SJ: Quantitative real-time cross-sectional echocardiography in the developing human fetus. (abstr) *Am J Cardiol* 43: 365, 1979
- Warsof SL, Gohari P, Berkowitz RL, Hobbins JC: The estima-

- tion of fetal weight by computer-assisted analysis. *Am J Obstet Gynecol* 128: 831, 1977
7. Bommer W, Weinert L, Neumann A, Neef J, Mason DT, DeMaria A: Determination of right atrial and right ventricular size by two-dimensional echocardiography. *Circulation* 60: 91, 1979
 8. Gold HJ: *Mathematical Modeling of Biological Structures*. New York, Wiley, 1977, ch 3
 9. Draper NR, Smith H: *Applied Regression Analysis*. New York, Wiley, 1966, p 24
 10. Lange L, Fabecic-Sabadi V, Bein F: Echocardiographic normal data for premature and normal newborn infants. *Z Kardiol* 67: 534, 1978
 11. McCallum WD, Brinkley JF: Estimation of fetal weight from ultrasonic measurements. *Am J Obstet Gynecol* 133: 195, 1979
 12. Naeye RL, Dixon JB: Distortions in fetal growth standards. *Pediatr Res* 12: 987, 1978
 13. Vosters R, Wladimiroff JW, Vletter W: Assessment of fetal and neonatal cardiac geometrics by means of real-time ultrasound. In *Echocardiology*, edited by Lancee CT. The Hague, Martinus Nijhoff, 1979, p 355
 14. Lind J, Wegelius C: Human fetal circulation: changes in the cardiovascular system at birth and disturbances in the postnatal closure of the foramen ovale and ductus arteriosus. *Quant Biol* 19: 109, 1954
 15. Born GVR, Dawes GS, Mott JC, Widdicombe JG: Changes in the heart and lungs at birth. *Quant Biol* 19: 102, 1954
 16. Rudolph AM, Heymann MA: Circulatory changes during growth in the fetal lamb. *Circ Res* 26: 289, 1970
 17. Rudolph AM: *Congenital Diseases of the Heart. Clinical-Physiological Considerations in Diagnosis and Management*. Chicago, Year Book Medical Publishers Inc, 1974, ch. 1, 2

The Blalock-Taussig Anastomosis in Infants Younger Than 1 Week of Age

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SUMMARY Thirty-one newborns 7 days of age or younger had a Blalock-Taussig subclavian-pulmonary arterial anastomosis for hypoxia and acidosis secondary to cyanotic congenital heart disease. Seven infants (23%) died within 30 days of operation, four of shunt thrombosis and three of sepsis. Six newborns died 1-44 months after operation, two of respiratory insufficiency and sepsis, two at reoperation and two of unknown causes. Eighteen (58%) are alive an average of 38 months after operation.

The lowest preoperative arterial PaO_2 increased from a mean of 21 torr to 34 torr after the shunt was opened. Postoperatively 13 infants had one or more arterial PaO_2 of 25 torr or less, but only nine were also acidotic. The shunt was patent in three of these infants and thrombosed in six (19%). The mean diameter of thrombosed shunts (2.3 mm) was significantly less than that of patent shunts (2.9 mm). Seventy-eight percent of successful shunts remained open 4 years or longer and none closed abruptly after hospital discharge.

In newborns, early mortality of the Blalock-Taussig anastomosis is nearly four times that for infants 1 week to 2 years of age. However, the use of prostaglandin E_1 to dilate the ductus arteriosus should reduce early mortality caused by shunt thrombosis or stenosis. The presence of a partially patent ductus in newborns makes clinical determination of shunt patency difficult. Although the results of the Blalock-Taussig anastomosis in cyanotic newborns are unsatisfactory, other procedures have not produced better results. Long-term advantages of the Blalock-Taussig anastomosis make it useful when the subclavian artery is 2.5 mm in diameter or greater.

MANY NEWBORNS with cyanotic congenital heart disease are dependent on the ductus arteriosus for all or almost all of their pulmonary blood flow. Most of these infants have lesions that cannot be corrected in the neonatal period,¹⁻⁷ and therefore require a systemic-pulmonary arterial shunt for survival. In older infants and children, the Blalock-Taussig subclavian-pulmonary arterial anastomosis is preferred and has many advantages over alternative shunts.^{8, 9-11} However, in newborns, the question of which shunt is best is not settled. Newborns younger than 1 week of

age have unique hemodynamic and anatomic considerations that make shunt construction more difficult than in infants only a few weeks older. Early mortality of systemic-pulmonary arterial shunts in newborns is more than twice that of older infants.⁴

In this report we analyze the early and late results of the Blalock-Taussig anastomosis in 31 newborns ages 7 days or younger.

Methods

Between August 1971 and August 1979 31 consecutive newborns 7 days of age or younger had a Blalock-Taussig anastomosis and no other procedure for severely cyanotic congenital heart disease. Twenty-four patients (77%) were admitted within 1 day of birth, and 25 had operation within 3 days of birth. All infants had severe cyanosis and hypoxia, and all infants had cardiac catheterization before opera-

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