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Fetal Weight Estimation from Lengths and Volumes Found by Three-dimensional Ultrasonic Measurements

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A custom-built computer system combined with a commercial real-time ultrasonic scanner was used to predict fetal weight. A special three-dimensional (3D) locating system provided 3D coordinates of fetal surface points imaged on multiple ultrasound scans. The 3D coordinates were used to develop length and volume variables that are not available with commercial instruments. Multiple regressions were used to compare these lengths and volumes with more conventional diameters and circumferences for their ability to predict fetal weight. Measurements were made on 41 live fetuses within 48 hours prior to delivery (weight range 1,985–4,734 g, mean weight 3,421 g). Combinations of 19 measured variables were analyzed against birth weight and the natural log of birth weight. The correlation between log birth weight and combinations including lengths from 3D measurements was R = .93, SE = 73 g/kg. When volumes from 3D measurements (which are much more difficult to obtain) were added, the correlation was R = .94, SE = 69 g/kg. These results suggest that lengths from 3D measurements have the potential to improve fetal weight prediction by 25–30 per cent over current methods, which have an approximate error of 100 g/kg. The relative lack of improvement with volumes from 3D measurements is probably the result of technical problems which may be overcome with further research. (Key words: fetal weight, three-dimensional ultrasound, computers, computer graphics)

Knowledge of fetal weight is important in the management of premature labor, the growth-retarded fetus (IUGR), and breech presentation if vaginal delivery is contemplated. The clinical utility of accurate weights has prompted several authors to examine the potential of ultrasonic methods of weight prediction.[1–7] These methods estimate weight by using regression analysis to correlate a few one- or two-dimensional fetal measurements with birth weight. The accuracy of most of these methods is on the order of 100 g/kg (1 SE), which is not accurate enough to allow monitoring of weekly growth rates for a fetus with suspected IUGR.

In a previous publication[3] we demonstrated a small but statistically significant improvement in weight prediction when a longitudinal variable was added to head and trunk diameters. The longitudinal variable, acquired from a static B-scan, had a relatively high repeatability error. We also analyzed a volume formula based on the sum of a series of parallel scans. This formula gave poorer predictability than simpler measurements, partly because of a higher repeatability error and partly because of an inadequate mathematical volume model. Therefore, improvement in fetal weight estimation should come as more repeatable methods are found to measure length and volume, and as more accurate three-dimensional volume models are developed.

Recently[8] we demonstrated on a series of 26 dead neonates that volume, measured by displacement, correlates closely with measured weight (r = .99). This close relationship implies that precise volume measurements will eventually lead to highly accurate weight estimates. A method was described for obtaining three-dimensional (3D) positions of fetal

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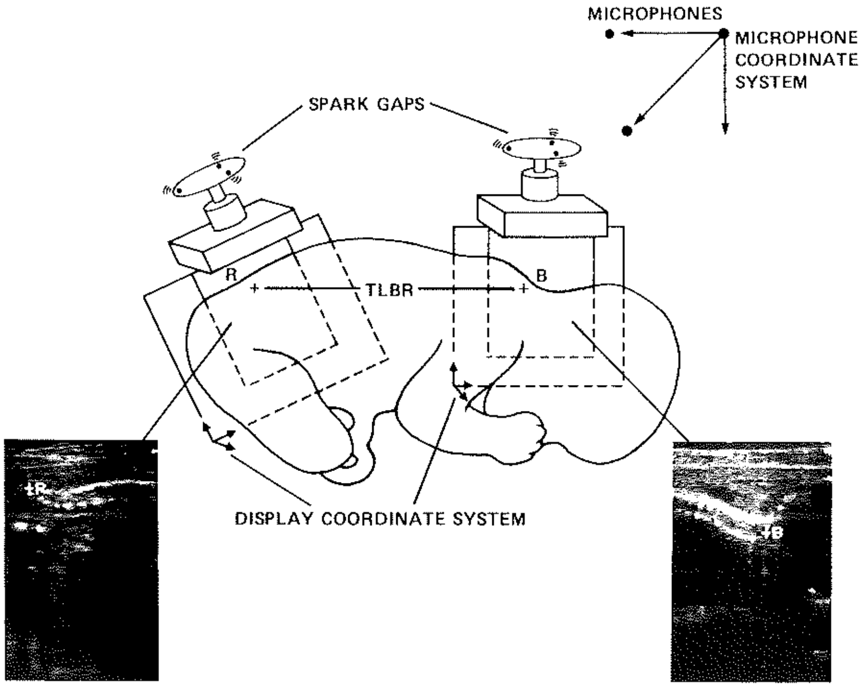


Figure 1. Locations of points in three dimensions. A point (such as the *B*ase of the head) was indicated in the display coordinate system with a light pen, then converted to three-dimensional microphone coordinates by means of three spark gaps mounted on the scan head. A second point, such as the *R*ump end of the spine, could be determined in the same way. The three-dimensional distance between these two points formed a length (variable TLBR) that could be acquired without requiring complete trunk visualization on a single scan.

surface points in terms of a fixed external reference coordinate system.[8–10] The technique utilizes a special position-locating system which allows points acquired from different individual scans to be related in three dimensions.[11] Length and volume variables calculated from these 3D "points" are not obtainable from most commercial real-time instruments because the entire fetus does not always fit on a single ultrasound scan. These variables are referred to as "3D lengths" and "3D volumes" throughout the remainder of this paper.

In vitro tests on the dead neonates showed that 3D head and trunk volumes correlated closely with weight (r = .98). The primary advantage of 3D volumes is that they reflect the underlying shape of the object being imaged. Therefore, they can give more accurate volumes for irregular shapes. However, these volumes, in the current state of development, are cumbersome to obtain. Length measurements acquired with the locator are more practically available. The present paper has two purposes: to assess the utility of the easily acquired 3D length measurements in the in utero prediction of fetal weight, and to assess the utility of the more complicated but theoretically more accurate 3D volumes in the prediction of fetal weight.

METHODS

Patient Population

A population of 41 women were scanned within 48 hours of delivery. Thirty-three of the women were admitted for elective cesarean section; the other eight were in early labor during the scans. Two complete ultrasound examinations, obtained within a half-hour interval, were performed on 36 of the patients. The other five, who were in early labor, had only one scan each.

Lengths from Three-dimensional Measurements

Figure 1 is a schematic diagram of the way points taken from separate ultrasound scans were related to each other in order to form the 3D length and volume variables. The position-locating system consisted of a set of three fixed hemispherical microphones arranged at right angles to each other as a three-dimensional microphone coordinate system. The microphones were mounted directly over the maternal abdomen. A flat plexiglas plate containing three small spark gaps was fixed in a known way to a Toshiba 3.5-MHz linear-array scan head. The position and orientation of the scan plane with respect to the microphone coordinate system was established by firing each spark gap in turn. The transit time of the acoustic shock wave produced by each spark was measured between the spark gap and each of the microphones. These transit times were converted to distance from the known speed of sound in air; the distances were used to calculate the three-dimensional coordinates of each spark gap with respect to the microphone coordinate system. Since three points are required to define a plane, the coordinates of the three spark gaps were enough to completely specify the position and orientation of the ultrasound scan plane in space.

A point on the fetus (such as the *B*ase of the head) was indicated with a light pen on the two-dimensional ultrasonic display (in the same manner as the cursor on commercial real-time scanners is used to indicate points). The outputs of the light pen were the two-dimensional XY display coordinates of the indicated point. These coordinates were converted to three-dimensional XYZ microphone coordinates by means of the spark gap locations and the known relationship between the spark gaps and the scan plane.

Once points on the fetus were described as three-dimensional XYZ coordinates it was possible to relate points to each other, even if they were obtained from separate two-dimensional scans. For example, after the location of the *B*ase of the head had been determined, the ultrasound transducer could be moved to the fetal rump and the *R*ump end of the fetal spine located, also with respect to the fixed microphones. The distance between these points could be calculated from the formula for the distance between two points in three dimensions, producing a long axis measurement without requiring complete fetal trunk visualization on any one scan.

Volumes from Three-dimensional Measurements

When a series of points was indicated with the light pen, as for example around the borders of a trunk cross section (fig 2), the resulting XYZ coordinates of these points formed a "slice" through the fetus which could be related to slices found from other arbitrarily oriented ultrasound scans. The combination of a large number of such slices through the fetal head and trunk formed a reconstruction of the fetal head and trunk geometry. Three-dimensional head and trunk volumes were found from this reconstruction by linear interpolation.[8] Figure 3*A* is a computer plot of the head and trunk reconstruction for a live term fetus. Figure 3*B* shows results of the interpolation process used to find three-dimensional head and trunk volumes.

Ultrasonically Measured Variables

On each patient, 19 ultrasonic variables were measured, including the 3D lengths and volumes. For the patients with paired observations the mean value for the two observations was used, and a repeatability measure was calculated as the absolute difference of the two observations divided by the mean. Overall repeatability for each of the 19 variables was estimated from the mean of the individual repeatability measures. Fetal weight was measured at birth.

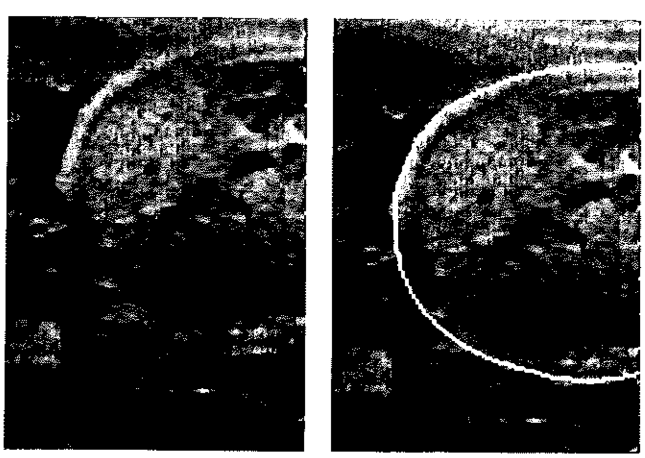
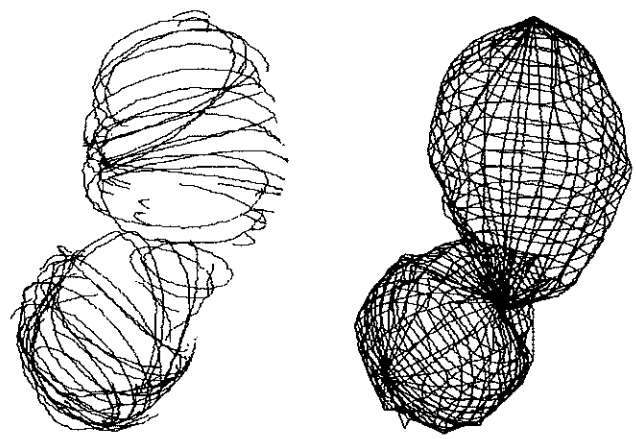


Figure 2. Abdominal cross section. *Left,* before being outlined with a light pen. *Right,* after being outlined. Partial outlines were allowed. The three-dimensional microphone coordinates of the outlined scan formed a "slice" through the fetus. A large number of such slices acquired throughout the head and trunk formed the three-dimensional reconstruction.



A B

Figure 3. Computer-generated reconstruction of the head and trunk of a live term fetus in utero. *A*, original ultrasound slices. Each contour in the computer plot is a single light pen outline (as in fig. 2) displayed in its three-dimensional relationship to all the other slices. *B*, longitudinal and cross-sectional interpolated scans. Volume was found from these scans.

The left portion of table 1 summarizes the ultrasonically measured variables. The variables are named to reflect their origins: the entire *B*ody, the *H*ead alone, or the *T*runk alone. The type of measurement is also indicated: a longitudinal *L*ength, a transverse *D*iameter, a *CIR*cumference, or a *V*olume. The 3D head and trunk volumes are called HV3D and TV3D in this table. Although several of the variables could have been measured by conventional calipers (for example, the BPD), others could not, since it was impossible to include the entire area on a single scan with our real-time scanner. Those variables that would always require a position locator are indicated in the table.

All the independent variables (except the 3D volumes) were derived from the three-dimensional location of 12 fetal landmarks (fig. 4). Each landmark was located in 3D by means of the position-locating system. Various lengths and diameters were derived from the distances between these points in the manner indicated in figure 1. These lengths and diameters were then manipulated to create the independent variables shown in table 1.

Crown–rump length (variable BLCR in table 1) is the linear distance between the crown and rump, rather than a curvilinear distance along the spine.

Head *C*ircumference (variable HCIR in table 1) was derived from the biparietal and fronto-occipital diameters by assuming an elliptical cross section. Trunk *C*ircumference (TCIR) was similarly derived from two transverse trunk diameters.

A *H*ead *V*olume *FOR*mula (HVFOR) was derived from the product of the two transverse head di-

Table 1. Relative Repeatabilities of Independent Variables

Independent Variables	Site	Description	Repeatability (Per Cent)
BLCR*	*Body*	*L*ength from *C*rown of head to *R*ump end of spine	5.8
BLMR*	*Body*	*L*ength from *M*idline echo to *R*ump end of spine	5.5
BSHE	*Body*	After *SHE*pard: HDST × TCIR	6.4
HCIR	*Head*	*CIR*cumference of cross section in plane of BPD	3.2
HCIR2	*Head*	*CIR*cumference squared	6.4
HDST	*Head*	*D*iameter, biparietal (BPD)	3.5
HDUV	*Head*	*D*iameter, fronto-occipital	4.8
HLCM	*Head*	*L*ength from *C*rown to *M*idline echo	18.0
HLCB	*Head*	*L*ength from *C*rown to *B*ase	8.3
HLMB	*Head*	*L*ength from *M*idline echo to *B*ase	16.6
HVFOR	*Head*	*V*olume *FOR*mula: HLCB × HDST × HDUV	11.5
HV3D*	*Head*	*V*olume by *3D* reconstruction	9.5
TCIR	*Trunk*	*CIR*cumference of cross section at umbilical vein	4.4
TCIR2	*Trunk*	*CIR*cumference squared	8.8
TDWX	*Trunk*	*D*iameter, transverse	6.4
TDYZ	*Trunk*	*D*iameter, anteroposterior	6.2
TLBR*	*Trunk*	*L*ength from *B*ase of head to *R*ump end of spine	6.5
TVFOR*	*Trunk*	*V*olume *FOR*mula: TDBR × TDWX × TDYZ	10.9
TV3D*	*Trunk*	*V*olume by *3D* reconstruction	8.9

* Requires 3D locator.

ameters and a head longitudinal length. A *T*runk *V*olume *FOR*mula (TVFOR) was similarly derived from the product of the two transverse trunk diameters and a trunk longitudinal length. These products are called volumes because they are related to volume formulas for cylinders and ellipsoids.

Regressions

Multiple linear regressions were performed to determine which combination of independent variables was the best predictor of birth weight or natural log of birth weight. The regressions included both the standard method, in which the user selects the combination of variables to be included, and stepwise regression, in which the computer automatically selects the best combination.[12] In the stepwise procedure the dependent variable and a group of potential independent variables are given as input to the computer. At each stage that variable is chosen which can do the most to explain the variance in the dependent variable, after taking into account already included variables. A variable is only added if it explains a statistically significant amount of the remaining variance. Multiple runs of the stepwise procedure were performed with different groups of independent variables as input. These multiple runs were done in order to determine the best combination of variables not requiring a locator (standard variables), the best combination including 3D length variables, and the best combination including 3D length and 3D volume variables. The program STATPACK[13] was used for this analysis.

RESULTS

The population of 41 infants was normally distributed, with mean weight 3,421 g, standard deviation (SD) 607 g, and range 1,985 to 4,734 g. Two infants weighed less than 2,500 g, 19 weighed 2,500–3,500 g, and 20 weighed more than 3,500 g.

The right column of table 1 shows the repeatability for each of the 19 independent variables.

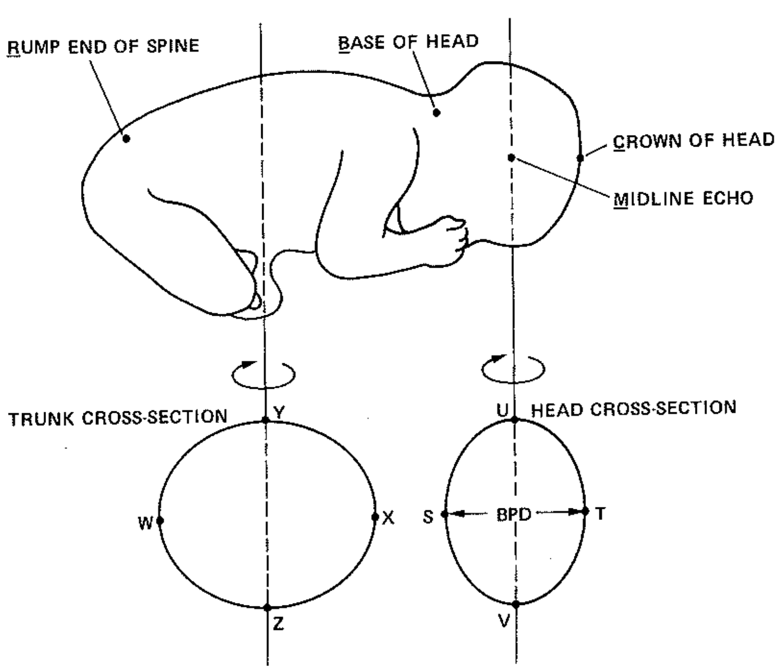


Figure 4. Fetal landmarks. Distances between the three-dimensional locations of these landmarks were used to create all the independent variables except the three-dimensional head and trunk volumes.

Table 2 shows the results of multiple regressions on the data from the 41 fetuses.

Regression equations for the two best formulas (regressions 1 and 2 in table 2) are:

Regression 1:

$$\text{Ln(weight)} = 0.000364(\text{HVFOR}) + 0.000195(\text{TVFOR}) + 0.000222(\text{TV3D}) + 7.183$$

$R = 0.941$, $SE = 69$ g/kg

Regression 2:

$$\text{Ln(weight)} = 0.000429(\text{HVFOR}) + 0.000283(\text{TVFOR}) + 7.150$$

$R = 0.932$, $SE = 73$ g/kg

DISCUSSION

One of the problems with comparing different weight prediction methods is that the distribution of weights in the population greatly influences the results. If a new formula is statistically produced from a given population then all formulas against which it is being compared should also be statistically produced from the same population. Otherwise the new formula will be optimized to the current data while the previous formula will not. If both are optimized to the same data then any differences will be due to the underlying model and method of acquiring measurements.

The fact that only two infants in our population weighed less than 2,500 g means that our formulas are valid only for infants weighing more than 2,500 g. The fairly large constant terms of 7.18 and 7.15 in the best two regressions demonstrate that these formulas are not valid for small fetuses. Thus, comparisons of the relative predictabilities of different models tested in our population are valid only for larger fetuses.

However, our results are similar to those previously found when the same models were used. Thus, we expect that results from new methods found in our small population will extrapolate to larger populations.

For example, regression 6 employs the model reported by Campbell and Wilkin.[1] Their reported prediction error for a population of 140 fetuses was 91 g/kg, compared with our error of 106 g/kg.

Regression 5 employs the model reported by Shepard and associates (BPD, abdominal circumference, and BPD times abdominal circumference).[6] Their reported error for a population of 73 fetuses was 106 g/kg, compared with our error of 102 g/kg.

The Utility of Lengths from Three-dimensional Measurements

Regression 2 is the computer-chosen best combination of variables that includes a 3D length (trunk length) but no 3D volumes. Regression 5 is one of the currently accepted standard models.[6]

Table 2. Regressions, n = 41, Mean Weight = 3,421 Grams

Independent Variables	Regression	Weight (g) R	Weight (g) SE	Ln (weight) (g/kg) R	Ln (weight) (g/kg) SE
1. HVFOR TVFOR* TV3D*	Stepwise†	.949	199	.941	69
2. HVFOR TVFOR*	Stepwise‡	.934	223	.932	73
3. HV3D* TV3D*	3D volumes	.904	266	.892	91
4. TCIR HVFOR	Stepwise§	.881	295	.886	94
5. HDST TCIR BSHE	Shepard et al.[6]	.868	313	.871	101
6. TCIR TCIR2	Campbell and Wilkin[1]	.844	334	.853	106

(Dependent Variables: Weight (g); Ln (weight) (g/kg))

* Requires 3D locator.

† Computer-chosen best combination from among all possible independent variables.

‡ Computer-chosen best combination from among variables including 3D lengths but not 3D volumes.

§ Computer-chosen best combination of variables not requiring a 3D locator.

The addition of longitudinal variables improves the standard error (the most important single measure of predictability) by 28 g/kg, or 28 per cent. When compared with the computer-chosen best combination not requiring a position locator (regression 4) the improvement is 21 g/kg, or 22 per cent. These results are in accord with those of other authors, who report increased predictability when longitudinal variables are included.[3,14,15]

The variables in regression 2 could easily be obtained either by using a locator to acquire the 3D positions of various landmarks on the fetus or by making the measurements directly using a scanner with a very wide field of view. It seems reasonable that if simple limb length measurements were also included further improvements in weight prediction could be expected.

The Utility of Volume from Three-dimensional Measurements

The regression results show that although head and trunk 3D volumes (regression 3) are somewhat more accurate weight predictors than most methods reported in the literature, they are not the most accurate of the weight prediction models we examined. As in our previous study,[3] combinations of simply measured variables did as well as or better than 3D head and trunk volumes. Only when 3D trunk volumes were added to the head and trunk volume formulas was there a small (but statistically significant, $P < 0.05$) improvement (regression 1 versus regression 2).

These results again show that statistically optimized formulas, based on one- or two-dimensional measurements, do about as well as our best method for computing volume. Since the method for finding 3D volume is cumbersome (about 90 minutes for the head and trunk[8]) the volume methods are not yet ready for practical use. However, the close empirical relationship between volume and weight[8] implies that better methods for finding volume will eventually lead to more accurate estimates of weight.

The current volume method shows definite improvement over that reported previously (sum of a set of parallel scans).[3] For the earlier method even a single circumference measurement gave better results. The current method works when non-parallel, incomplete scans are used, thus allowing much better definition of the fetal endpoints. Also, the real-time scanner makes the patient examination time much shorter, thus reducing the effects of movement.

Nevertheless, the 3D volume method employed in this study has many technical limitations which prevent it from accurately measuring true fetal volume. These limitations include the continuing effects of fetal movement, the absence of fetal limb measurements, and the continuing difficulty in defining the endpoints of the fetal trunk.

The data acquisition system employed in this study was designed to minimize the effects of movement by allowing all the scans to be recorded on videotape before being outlined with the light pen.[10] The time required to obtain the scans for a reconstruction of the head and trunk was about 1–2 minutes. Although the fetus often has 1–2 minute periods of immobility, there are still small movements which contribute to errors. The effects of movement could be greatly reduced with the advent of a three-dimensional real-time scanning device.

One of the reasons limbs were not included is that limbs move more than the head and trunk. In addition, the time required to outline scans for complete limb reconstructions was too great even for research use. Future studies might approximate limb volume with geometric models. However, these models are not likely to be better than the statistical techniques unless they are accurate reflections of limb geometry.

The inability to completely define the fetal endpoints is due to the fact that a term fetus is naturally curled up, making it difficult to obtain clear images of the neck and rump regions. Given the physical limitations of ultrasound, there will always be portions of the fetus that are not easily visualized. Since the computer currently does not have any knowledge of fetal shape it is unable to make reasonable guesses in the absence of data. In the future it may be possible to teach the computer the expected shape of the fetus, then to have the computer utilize this knowledge to fill in areas of missing data.[16]

CONCLUSION

The results of this study suggest that, given the availability of a 3D locator or a scanner with a wide field of view, easily acquired longitudinal trunk measurements may improve fetal weight prediction by about 20–30 per cent. Because of the small sample size this potential will have to be tested on much larger populations. The study has also demonstrated the application of 3D volume models, which, though not yet ready for practical use, represent a further step in the direction of accurate 3D fetal reconstructions for precise monitoring of growth.

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REFERENCES

1. Campbell S, Wilkin D: Ultrasonic measurement of fetal abdomen circumference in the estimation of fetal weight. Br J Obstet Gynecol 82:689, 1975
2. Lunt R, Chard T: A new method for estimation of fetal weight in late pregnancy by ultrasonic scanning. Br J Obstet Gynaecol 83: 1, 1976
3. McCallum WD, Brinkley JF: Estimation of fetal weight from ultrasonic measurements. Am J Obstet Gynecol 133: 195, 1979
4. Deter RL, Hadlock FP, Harrist RB, et al: Evaluation of three methods for obtaining fetal weight estimates using dynamic image ultrasound. J Clin Ultrasound 9:421, 1981
5. Warsoff SL, Gohari P, Berkowitz RL, et al: The estimation of fetal weight by computer-assisted analysis. Am J Obstet Gynecol 128:881, 1977
6. Shepard MJ, Richards VA, Berkowitz RL, et al: An evaluation of two equations for predicting fetal weight by ultrasound. Am J Obstet Gynecol 142:47, 1982
7. Eik-Nes SH, Grottum P, Andersson NJ: Estimation of fetal weight by ultrasound measurement. II. Clinical application of a new formula. Acta Obstet Gynecol Scand 61: 307, 1982
8. Brinkley JF, McCallum WD, Muramatsu SK, et al: Fetal weight estimation from ultrasonic three-dimensional head and trunk reconstructions: evaluation in vitro. Am J Obstet Gynecol 144: 715, 1982
9. Brinkley JF, Moritz WE, Baker DW: Ultrasonic three-dimensional imaging and volume from a series of arbitrary sector scans. Ultrasound Med Biol 4:317, 1978
10. Brinkley JF, Muramatsu SK, McCallum WD, et al: In vitro evaluation of an ultrasonic three-dimensional imaging and volume system. Ultrasonic Imaging 4: 126, 1982
11. Moritz WE, Shreve PL: A system for locating points, lines and planes in space. IEEE Trans Instrum Meas IM-26: 5, 1977
12. Draper N, Smith H: Applied Regression Analysis. Second edition. New York, John Wiley & Sons, 1981
13. Western Michigan University, STATPACK Statistical Package, 1974
14. Neilson JP, Whitfield CR, Aitchison TC: Screening the small-for-dates fetus: a two-stage ultrasonic examination schedule. Br Med J 280: 1203, 1980
15. Wittman BK, Robinson HP, Aitchison T, et al: The value of diagnostic ultrasound as a screening test for intrauterine growth retardation: comparison of nine parameters. Am J Obstet Gynecol 134: 30, 1979
16. Brinkley JF: Artificial intelligence and ultrasonic imaging: the use of learned shape knowledge to analyze 3D data. Proceedings, 28th Annual Meeting, American Institute of Ultrasound in Medicine, New York, October 1983