# Birth Weight Prediction by Three-dimensional Ultrasonography

## Fractional Limb Volume

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***Objective.*** To introduce fractional limb volume as a new ultrasonographic parameter, validate reliability of fractional limb volume measurements, develop new birth weight prediction models, and examine their practical utility for estimating fetal weight during late pregnancy. ***Methods.*** Healthy late-third-trimester fetuses were prospectively scanned by two- and three-dimensional ultrasonography within 4 days of delivery. Volume data sets were subsequently used to extract several standard ultrasonographic measurements. Fractional limb volumes of the upper arm and thigh were based on 50% of diaphyseal bone length. Intraclass correlation was used to analyze interobserver and intraobserver reliability of fractional limb volume measurements. Several weight prediction models were developed by linear regression analysis. New prediction models were prospectively compared with the Hadlock formula in 30 healthy late-third-trimester fetuses. ***Results.*** One hundred fetuses were scanned at a mean ± SD menstrual age of 39.2 ± 1.2 weeks. Intraclass correlation indicated a significant degree of interobserver and intraobserver reliability for fractional thigh volume. Fractional thigh volume ($r$ = 0.86), fractional upper arm volume ($r$ = 0.83), abdominal circumference ($r$ = 0.83), and midthigh circumference ($r$ = 0.82) were most highly correlated with birth weight. The best prediction model (abdominal circumference and fractional thigh volume) gave weight estimates that deviated from actual birth weight by –0.025% ± 7.8%. For late-third-trimester fetuses, the Hadlock model yielded errors of 9.0% ± 9.0%. Prospective testing confirmed superior performance of the new prediction model, which gave accuracy of 2.3% ± 6.6% (Hadlock method, 8.4% ± 8.7%). It correctly predicted 20 of 30 birth weights to within 5% of actual weight. By comparison, the Hadlock model predicted only 6 of 30 birth weights to within 5% of actual weight. ***Conclusions.*** A new birth weight prediction model, based on fractional thigh volume and abdominal circumference, is reliable during the late third trimester. It provides a means for including soft tissue evaluation for birth weight prediction. This rapid technique avoids technical limitations that currently hinder the practical implementation of three-dimensional ultrasonography for estimating birth weight. ***Key words:*** birth weight prediction; three-dimensional ultrasonography; fetus; prenatal diagnosis.

**Abbreviations**
AC, abdominal circumference; ArmVol, fractional upper arm volume; BW, birth weight; EFW, estimated fetal weight; FDL, femoral diaphysis length; HDL, humeral diaphysis length; 3DUS, three-dimensional ultrasonography; 2DUS, two-dimensional ultrasonography; TVol, fractional thigh volume

*Received August 2, 2001, from the Division of Fetal Imaging, Department of Obstetrics and Gynecology (W.L., J.D.E., K.B.), and Division of Biostatistics (R.H.), William Beaumont Hospital, Royal Oak, Michigan; Department of Obstetrics and Gynecology, Baylor College of Medicine, Houston, Texas (R.L.D.); and Perinatology Research Branch, National Institute of Child Health and Human Development, Wayne State University, Detroit, Michigan (R.R.). Revision requested September 20, 2001. Revised manuscript accepted for publication October 1, 2001.*

*Project work at William Beaumont Hospital was partially supported by Medison America, Inc, Cypress, California.*

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Fetal growth abnormalities are important causes of increased perinatal morbidity and mortality.[1–4] Poor outcomes can result from delivering macrosomic neonates with shoulder dystocia or growth-restricted neonates with perinatal asphyxia. Despite the widespread use of ultrasonography to estimate fetal size, some commonly used prediction models are known to generate errors as great as 15% from actual birth weight (BW).[5] For example, many formulas tend to overestimate weights in smaller fetuses and to underestimate weights in larger fetuses.[6]

Soft tissue quantification may improve our ability to distinguish intrauterine growth restriction from small but otherwise normally growing fetuses. Pediatric studies suggest that diminished stores of subcutaneous thigh fat commonly occur in malnourished neonates.[7,8] Neonatal fat not only contributes to a significant proportion of BW variance among healthy infants but also may explain the sonographic underestimation of BW for macrosomic neonates.[9,10] Soft tissue, however, is poorly characterized by two-dimensional imaging.[11,12]

Three-dimensional ultrasonography (3DUS) has the potential for allowing more accurate volume measurements compared with two-dimensional ultrasonography (2DUS).[13] In this context, 3DUS may improve BW predictions by allowing clinicians to use fetal volume measurements as an index of soft tissue mass.

Several investigators have measured fetal limb volumes to predict BW by 3DUS.[14–16] At least 2 major problems, however, have delayed the practical implementation of these volume-based prediction models into clinical practice. First, the technique has typically required a large number of manual tracings to calculate upper arm or thigh volumes. Second, it is not always possible to clearly visualize soft tissue borders around the proximal and distal ends of the volume studied, especially if the arm or leg is pressed against the body.

Our study addresses these technical limitations by introducing fractional limb volume as a new sonographic parameter for BW prediction. This approach involves a partial measurement of upper arm or thigh volume by 3DUS as a fixed percentage of total diaphysis length. The primary goals were to determine reproducibility of fractional limb volume measurements and to examine their practical utility for BW prediction during late pregnancy.

## Materials and Methods

Third-trimester pregnancies were prospectively scanned by 3DUS within 4 days of delivery from May 1998 to May 2001. Inclusion criteria consisted of an uncomplicated singleton pregnancy without structural or chromosomal abnormality. Approximately 69% of pregnancies were dated from the first day of the last normal menstrual period. The fetal age was estimated from a sonographic dating study for patients with poor menstrual histories. Each scan sweep (Voluson 530D; Medison Co, Ltd, Seoul, Korea) took approximately 9 seconds, and volume data were stored on removable digital media for subsequent analysis. When feasible, at least 2 volume data sets were collected for each region of interest (fetal arm, abdomen, and thigh) with a mechanical transducer (S-VAW3-5; Kretztechnik AG, Zipf, Austria). Fetal limb volumes were acquired from a sagittal sweep that dynamically displayed both ends of the diaphysis. Abdominal volume data sets also included a transverse plane of fetal stomach and the umbilical portion of the left portal vein.

Volume data were later analyzed for fetal abdominal circumference (AC), femoral diaphysis length (FDL), midthigh circumference, humeral diaphysis length (HDL), and mid-upper arm circumference. The FDL and HDL were defined as the maximal distance between ends of the diaphyseal shaft. Three-dimensional multiplanar imaging was used to identify a midpoint of the upper arm or thigh. Limb circumference measurements were taken at this point, around the outer skin margin, to include skin and subcutaneous fat. Volume data were also reformatted to provide a standardized measurement plane for the AC.[6]

Fractional upper arm volume (ArmVol) and fractional thigh volume (TVol) were measured from stored data sets (3DView software version 4.4; Kretztechnik). Electronic calipers were used to measure the HDL and FDL. The software automatically defined a cylindrical limb volume that was based on 50% of total diaphysis length. Figure 1 illustrates how this region of interest was distributed around the midpoint of each upper limb. The resulting partial limb volume was divided into 5 subsections of equal length to allow manual tracing of surface contours from an axial view. This method eliminated the need for analyzing the proximal or distal end of the diaphysis, where soft tissue boundaries are often poorly visualized (Fig. 2). Each fractional limb volume measurement took only a couple of minutes to determine.

Reliability of blinded fractional volume measurements was evaluated for a single examiner and between 2 different examiners by intraclass correlation.[17] Intraclass correlation coefficients represent the proportion of total variance in measurements due to variation between subjects. For example, intraclass correlation of 0.85 indicates that only 15% of the variance is due to differences in measurements between examiners. This type of analysis provides a more precise evaluation than the Pearson correlation coefficient, because the latter is only a measure of association, not agreement. An intraclass correlation coefficient of greater than 0.80 was considered to represent good agreement.[18]

The quantitative relationship of TVol with total diaphysis volume was also analyzed in late-third-trimester fetuses. Ten thigh volumes were carefully selected for comparison. Both ends of the femoral diaphysis, with surrounding soft tissue borders, had to be clearly visualized for each fetus.

Correlation between single sonographic parameters and BW was evaluated by simple linear regression (StatView 5.0; SAS Institute Inc, Cary, NC). Multiple linear regression (StatView 5.0) was also used to develop several weight estimation functions that included either fractional limb volume alone or a combination of several sonographic parameters. The coefficient of determination was used to indicate the degree of BW prediction variability that could be explained by each model. Stepwise regression (JMP 3.15; SAS Institute) identified the optimal subset of BW predictors with inclusion criteria established at $P = .10$. Statistical significance was set at an $\alpha$ level of $P < .05$.

Sonographic measurements were reported as mean values and their SDs. Systematic error, or accuracy, was evaluated from the mean signed percent error: [(predicted BW – actual BW)/actual BW] × 100. Random error, or precision, was evaluated by the SD of signed percent errors. Each model's predictive performance was assessed from the prediction error (predicted BW – actual BW), mean signed percent error, and SD of the signed percent errors. The relative effect of adding a soft tissue parameter (fractional limb volume) to this weight estimation procedure was

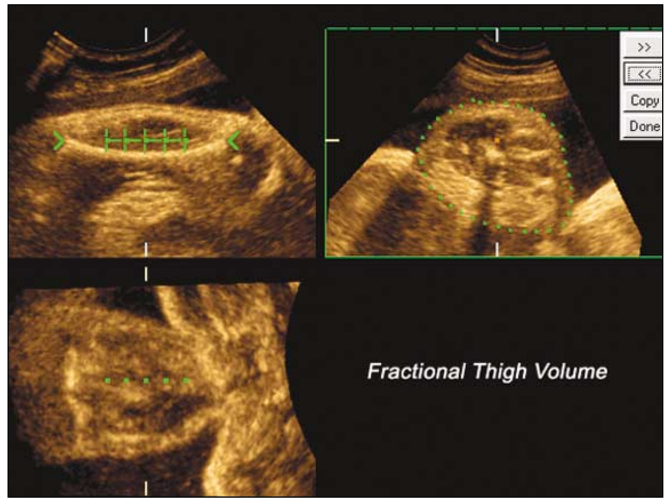
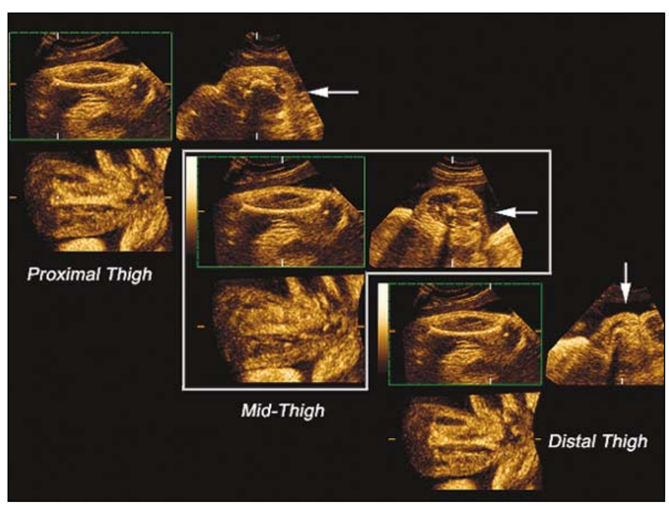



**Figure 1.** Fractional thigh volume in a term fetus. Orthogonal views of the limb are displayed by multiplanar imaging. Green calipers (arrowheads) are placed on either end of the femoral diaphysis (top left). Computer software automatically identifies the limb's midpoint by a green reference dot (top left, third dot from left). A cylindrical volume is generated by sequentially tracing the thigh's surface contours at 5 equally spaced sections from a transverse view of the thigh (top right). Fractional limb volume is based on 50% of diaphysis length.

**Figure 2.** Multiplanar views of the proximal, middle, and distal portions of the fetal thigh. The orthogonal views are layered to illustrate how the soft tissue borders are often indistinct at the proximal or distal ends of the femoral diaphysis (arrows). The middle arrow shows how well the soft tissue borders are usually seen in the axial plane when there is absence of acoustic shadowing.

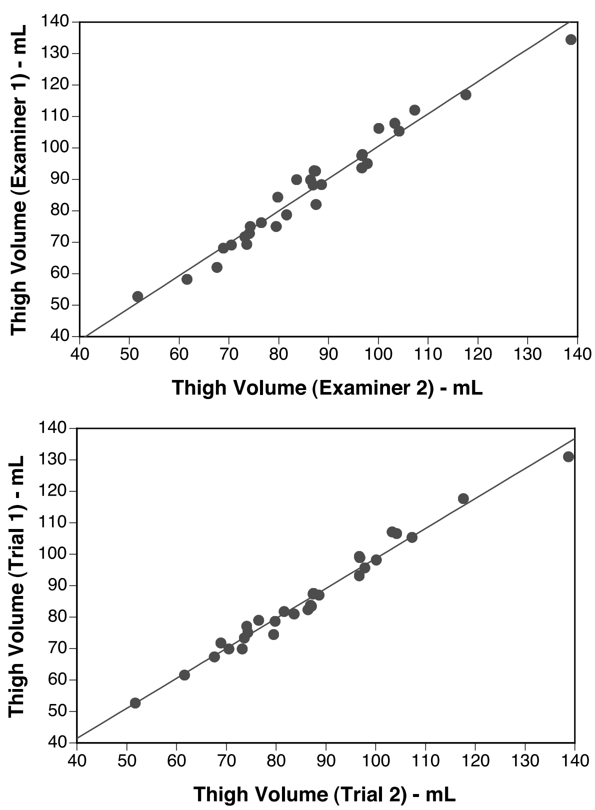


evaluated. Linear regression methods were used to analyze the relationship of the signed percent error with actual BW.

New prediction models were prospectively compared with the formula of Hadlock et al,[5] which included AC and FDL. This weight estimation function was chosen because it does not rely on head circumference, which is often difficult to accurately measure during late pregnancy. Model coefficients for the Hadlock formula were also derived from multiple regression analysis of our own data. In this manner, potential bias in comparing prediction errors for 2 different study populations could be minimized.

A prospective study of new weight prediction functions was subsequently conducted with an independent group of late-third-trimester fetuses that was not previously used to derive these models. An estimated sample size of 30 subjects was established by setting an $\alpha$ level of .05 and statistical power of 0.80 in accepting an 80% coefficient of determination for the relationship between actual BW and BW predictions from 2 sonographic parameters. Prospective results were evaluated by mean signed percent error ± SD of true BW. Prediction accuracy between models, within 5% of actual BW, was also examined for frequency differences by the McNemar test for correlated outcome events (SPSS version 10; SPSS Inc, Chicago, IL).

**Figure 3.** Intraobserver variability (top graph) and interobserver variability (bottom graph) agreement for fractional thigh volume among 30 normal fetuses.




## Results

One hundred fetuses were prospectively scanned once at a mean menstrual age of 39.2 ± 1.2 weeks, 94% of whom were examined at 37 weeks' gestation or later. Mean BW was 3643 ± 574 g. This study population, which had normal fetal growth, consisted of the following racial groups: white (97%), black (5%), and Asian (2%). Forty-nine percent were male fetuses. Intraclass correlation indicated excellent intraobserver ($r = 0.98$) and interobserver ($r = 0.95$) reliability for reproducing TVol measurements from a subset of 30 fetuses (Fig. 3).

The mean ratio of TVol to total diaphysis volume was 0.48 ± 0.06. This finding indicates that TVol, on the basis of 50% of total diaphysis length, represented about half of the total thigh diaphysis volume in late-third-trimester fetuses.

Table 1 summarizes mean values of 7 sonographic parameters and their correlations with BW. The 4 strongest correlations were TVol ($r$ = 0.86), ArmVol ($r$ = 0.83), AC ($r$ = 0.83), and midthigh circumference ($r$ = 0.82; $P <$ .001). Stepwise regression analysis led to a BW prediction model that included 5 sonographic parameters: predicted BW = 9.386 (Tvol) + 48.038 (AC) + 15.239 (ArmVol) + 42.351 (TC) + 51.421 (ArmCirc) – 972.635. This model generated a mean percent

**Table 1.** Sonographic Parameters and Birth Weight Correlation

| Parameter | Value | *r** |
|---|---|---|
| TVol, mL | 87.4 ± 19.3 | 0.86 |
| ArmVol, mL | 39.4 ± 8.3 | 0.83 |
| AC, cm | 36.8 ± 2.4 | 0.83 |
| Thigh circumference, cm | 17.8 ± 1.8 | 0.82 |
| Arm circumference, cm | 12.8 ± 1.4 | 0.74 |
| FDL, cm | 7.43 ± .37 | 0.68 |
| HDL, cm | 6.54 ± .31 | 0.52 |

Values are mean ± 1 SD; all linear regression correlations are significant at $P < .0001$; n = 100 fetuses with normal growth.

*Pearson product moment correlation coefficient for a single sonographic parameter as a function of BW.

error of only 0.4% ± 6.0% from actual BW. Although it explained 83% of predicted BW variability, the inclusion of all 5 parameters did not seem practical for clinical use.

Simplified prediction models were subsequently developed, especially for situations in which the AC measurement could be difficult (e.g., ventral wall defects or suboptimal fetal position). Selection of sonographic parameters was based on the assumption that fractional limb volume already contained information about limb length and circumference measurements. Initial examination of all regression models showed signed prediction errors that were inversely proportional to increasing BW. An empirical correction procedure was used to eliminate this dependence on BW in the following manner (Fig. 4): (1) estimated fetal weight (EFW) was determined by using functions that included various sonographic parameters; (2) prediction errors were determined as the difference between EFW and actual BW; (3) prediction errors (EFW – BW) were plotted against actual BWs, and the relationship between EFW – BW and BW was determined by linear regression; (4) correction for this relationship was obtained by algebraically rearranging the regression equation (EFW – BW) = $a_0 + a_1$ (BW), where $a_0$ is intercept and $a_1$ is slope; and (5) corrected weight estimates were calculated using the following function: corrected EFW = (EFW – $a_0$) / (1 – $a_1$).

Table 2 compares the performance of new BW prediction models with 2 versions of the Hadlock model (Models 1 and 2). The original Hadlock model was associated with the great-

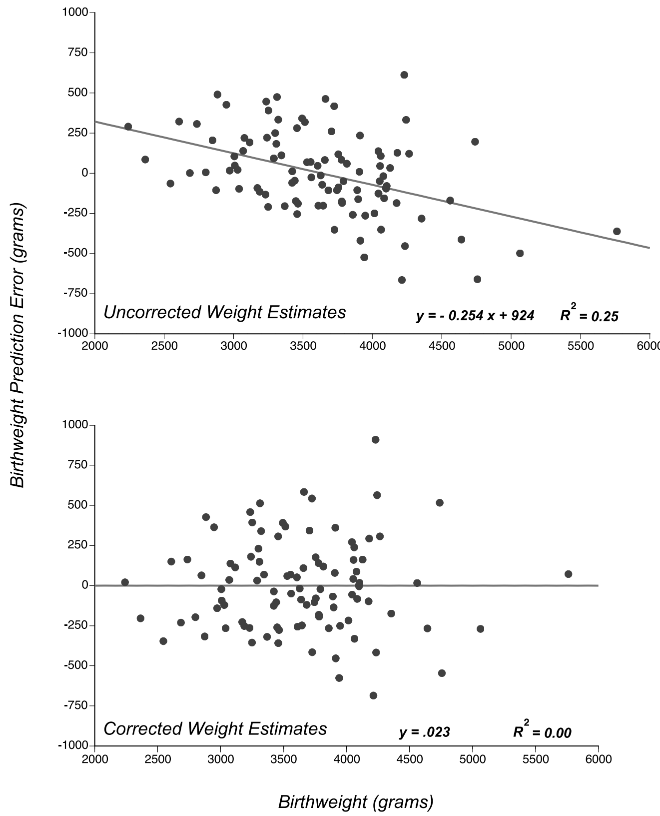



**Figure 4.** Relationship of prediction error to actual birth weight. Top graph, Prediction error that results from a linear regression model that includes abdominal circumference and fractional thigh volume (Model 5; Table 2). A negative slope indicates a tendency for overestimating fetal weight of smaller fetuses and underestimating fetal weight for fetuses who weigh more than approximately 3900 g. Bottom graph, Effect of correcting weight estimates using the slope and intercept of the regression line from the top graph.

**Table 2.** Birth Weight Prediction Functions for 100 Pregnancies With Normal Fetal Growth During the Late Third Trimester

| BW Prediction Function Model | MPE, % | Absolute Error, g | $R^2$ |
|---|---|---|---|
| 1. Abdominal circumference and femur diaphysis length: Hadlock (1985)[5] | | | |
| $\text{Log}_{10}$BW = 1.304 + 0.05281 (AC) + 0.1938 (FDL) – 0.004 (AC × FDL) | 9.0 ± 9.0 | 312 ± 332 | 0.72 |
| 2. Abdominal circumference and femur diaphysis length: modified Hadlock (2001) | | | |
| BW = {10^[0.39939 + 0.07548 (AC) + 0.33141 (FDL) – 0.00761 (AC × FDL)] – 1007.01} ÷ 0.71742 | –0.1 ± 9.8 | 0.02 ± 359 | 0.74 |
| 3. Fractional arm volume | | | |
| BW = 76.837 (ArmVol) + 599.102 | 0.1 ± 9.6 | –0.50 ± 359 | 0.68 |
| 4. Fractional thigh volume | | | |
| BW = 34.649 (TVol) + 604.227 | 0.004 ± 9.3 | –0.02 ± 337 | 0.75 |
| 5. Fractional thigh volume and abdominal circumference | | | |
| BW = 20.953 (TVol) + 113.571 (AC) – 2375.068 | –0.025 ± 7.8 | –0.01 ± 286 | 0.80 |
| 6. Fractional thigh volume, fractional arm volume, and abdominal circumference | | | |
| BW = 13.686 (TVol) + 28.162 (ArmVol) + 68.770 (AC) – 1204.619 | 0.005 ± 6.8 | 0.02 ± 249 | 0.82 |

Error values are mean ± 1 SD; systematic error or mean percent error (MPE) = (predicted BW – true BW) ÷ true BW × 100; random error is defined as ±1 SD of mean percent error. Empiric corrections are applied for models 2 through 6 (see Materials and Methods).

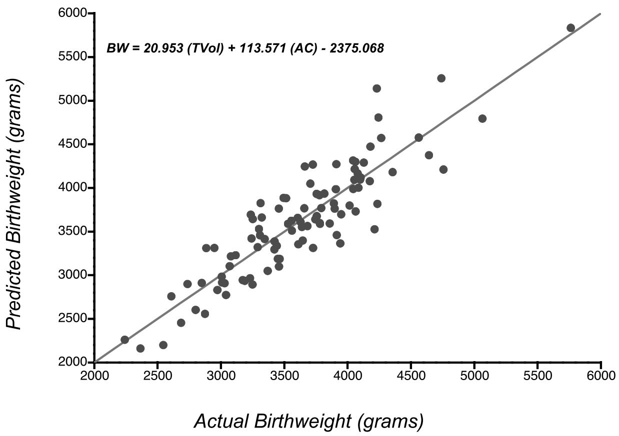



**Figure 5.** Comparison of corrected fetal weight predictions based on AC and TVol as a function of actual birth weight.

est mean signed percent error from actual BW (9.0% ± 9.0%; $R^2$ = 0.72). A modified version of the Hadlock model, derived from our own data, had a mean signed percent error of –0.1% ± 9.8% ($R^2$ = 0.74). Results obtained for other prediction models, using a single fractional limb volume parameter (Table 2, Models 3 and 4), were similar to errors associated with the Hadlock formula.

Weight estimation functions with the best predictive capacity (Table 2, Models 5 and 6) included AC and TVol ($R^2$ = 0.80) and AC, TVol, and ArmVol ($R^2$ = 0.82). The first model had BW prediction accuracy of –0.025% ± 7.8% (Fig. 5). A second model, which added ArmVol to the first model, had a predictive accuracy of 0.005% ± 6.8%, explaining 82% of BW's variability.

Table 3 compares BW predictions from a prospective evaluation of 30 fetuses with normal growth during late pregnancy. Fetuses were scanned at a menstrual age of 39.9 ± 1.4 weeks with a mean BW of 3581 ± 547 g. The original Hadlock formula led to greater systematic error (8.4% ± 8.7%) when compared with the modified version (–0.4% ± 10.2%). Fractional thigh volume, as a single sonographic parameter, gave a similar BW prediction error (5.6% ± 8.4%) when compared with either Hadlock model. The best results were obtained with a weight estimation procedure that used only 2 parameters, AC and Tvol (signed mean percent error, 2.6% ± 6.6%). The mean percent error for this function was not significantly different from zero (1-sample $t$ test, $P < .05$) as opposed to increased systematic errors for Models 1, 3, 4, and 6. Addition of ArmVol did not improve the accuracy or precision over what was already obtained with the simpler Model 5 (AC and TVol). Accordingly, we mainly emphasized statistical comparisons with Model 5 for the remainder of our analysis.

Frequencies in different BW prediction accuracy categories are summarized for Model 1 (original Hadlock model) and Model 5 (AC and TVol) in Table 3. With the use of Model 1, only 20% of BW predictions (6 of 30 fetuses) were within 5% of actual BW. By comparison, with Model 5, 67% of predictions (20 of 30 fetuses) were within 5% of actual BW ($P < .05$, McNemar frequency test). When a 10% accuracy thresh-

**Table 3.** Prospective Comparison of Birth Weight Prediction Functions

| BW Prediction Function Model | MPE, % | Actual BW ±5% | Actual BW ±10% |
|---|---|---|---|
| 1. Abdominal circumference and femur diaphysis length: Hadlock (1985)[5] | | | |
| $\text{Log}_{10}$BW = 1.304 + 0.05281 (AC) + 0.1938 (FDL) – 0.004 (AC × FDL) | 8.4 ± 8.7 | 6/30 | 21/30 |
| 2. Abdominal circumference and femur diaphysis length: modified Hadlock (2001) | | | |
| BW = {10^[0.39939 + 0.07548 (AC) + 0.33141 (FDL) – 0.00761 (AC × FDL)] – 1007.01} ÷ 0.71742 | –0.4 ± 10.2 | 8/30 | 23/30 |
| 3. Fractional arm volume | | | |
| BW = 76.837 (ArmVol) + 599.102 | 10.2 ± 10.5 | 9/30 | 19/30 |
| 4. Fractional thigh volume | | | |
| BW = 34.649 (TVol) + 604.227 | 5.6 ± 8.4 | 16/30 | 26/30 |
| 5. Fractional thigh volume and abdominal circumference | | | |
| BW = 20.953 (TVol) + 113.571 (AC) – 2375.068 | 2.3 ± 6.6 | 20/30 | 29/30 |
| 6. Fractional thigh volume, fractional arm volume, and abdominal circumference | | | |
| BW = 13.686 (TVol) + 28.162 (ArmVol) + 68.770 (AC) – 1204.619 | 5.3 ± 7.0 | 19/30 | 28/30 |

Signed mean percent error (MPE) is reported ± 1 SD; systematic error or mean percent error = (predicted BW –true BW) ÷ true BW × 100; random error is defined as ±1 SD of mean percent error; n = 30 fetuses with normal growth. Empiric corrections are applied for models 2 through 6 (see Materials and Methods).

old was applied, Model 1 categorized 70% of BW predictions (21 of 30 fetuses) compared with 97% of the predictions (29 of 30 fetuses) categorized by Model 5 ($P < 0.05$).

A similar comparison was made between the modified Hadlock function (Model 2) and Model 5 (Table 3). These results also suggested a greater proportion of accurate predictions by Model 5 (±5%, 20 of 30 fetuses; and ±10%, 29 of 30 fetuses) compared with the modified Hadlock formula (±5%, 8 of 30 fetuses; and ±10%, 23 of 30 fetuses). Despite a trend toward a greater proportion of accurate predictions with 3DUS, frequency differences were not statistically significant between groups ($P > .05$, McNemar frequency test).

## Discussion

Birth weight prediction has traditionally relied on anatomic measurements of the fetal head, limbs, and abdomen circumference.[19–22] Hadlock and associates[5] have reported predictive accuracy within 15% (±2 SD) of actual BW using functions containing fetal head circumference, AC, and FDL. Other investigators, however, have suggested that an estimation of soft tissue mass (e.g., skin, fat, and muscle) may improve our ability to evaluate fetal intrauterine nutritional status and growth.[23]

Pediatric studies support the concept that soft tissue, particularly fat mass, contributes significantly to BW. Catalano et al[9] correlated soft tissue mass with BW among 188 newborn infants. Although neonatal fat mass constituted only 14% of BW, it explained 46% of its variance. Another investigation prospectively analyzed the body composition of 52 neonates from diabetic mothers.[24] The percentage of fat mass was strongly correlated with the degree of BW error on 2DUS. Both studies offer a compelling reason to include soft tissue as an index of fetal size and growth. Unfortunately, weight-estimating formulas are presently based on 2DUS measurements that do not consider the contribution of soft tissue to BW.

Fractional limb volume is a new sonographic parameter that allows characterization of fetal soft tissue by 3DUS. It can be reliably used to predict late-third-trimester BW and may be especially helpful when the AC is difficult to measure (e.g., ventral wall defect). Our method has 2 distinct advantages over earlier approaches to BW prediction by 3DUS. Fractional volume measurements require only about 1 to 2 minutes to perform and reduce the amount of time that would otherwise be required to manually trace multiple sections. The examiner no longer needs to manually trace indistinct soft tissue borders that often result from acoustic shadowing at the extreme ends of the diaphysis.

Hadlock and colleagues[5] have validated a widely used prediction model that includes AC and FDL on 2DUS. Their original work was based on 109 fetuses that were prospectively scanned within 1 week of delivery. They reported a mean percent error of 0.3% ± 8.0% for an unselected population of predominantly white fetuses throughout gestation. The systematic error increased to 5.2% when this model was only applied to 19 fetuses (17.4% of the total) with BWs greater than 4000 g.

The Hadlock prediction model was also used for our late-third-trimester fetuses with normal growth and was associated with a systematic overestimation of 9.0%. This study group consisted of a relatively greater proportion (27%) of fetuses with BWs greater than 4000 g. Table 2 summarizes BW prediction functions for 100 late-third-trimester fetuses without abnormalities. The greatest systematic error resulted from the original Hadlock model, although this overestimation was eliminated when model coefficients were derived from our own study population (Model 2). Models 3 and 4, based on the sole use of fractional limb volumes, provided results that were similar to those of the modified Hadlock function (Model 2). The most accurate and precise prediction estimates were provided by a combination of AC and fractional limb volumes (Models 5 and 6).

Prospective testing of Model 5 (AC and TVol) also showed minimal systematic error. Improved precision by this volume model (2 SD = 13.2% mean error), as opposed to the original Hadlock model (2 SD = 17.4% mean error), explains why a greater proportion of prospective BW predictions were more accurate for 3DUS. A similar trend also occurred when a modified version of the Hadlock model was compared with Model 5, although it is possible that our sample size was not large enough to confirm a statistical difference under these conditions.

Earlier reports regarding the use of fetal volume measurements in BW prediction by 3DUS have been encouraging. Chang et al[14] developed a weight estimation function that was based solely on thigh volume in term infants. Prospective validation led to the smallest mean percent error of 1.5% ± 5.6% for 50 Taiwanese infants, as opposed to the Hadlock method, which yielded an error of 4.8% ± 8.9%. Their prediction model (BW = 1080.87350 + 22.44701 × thigh volume) was very similar to our "uncorrected" regression equation for TVol (BW = 1374.211 + 25.837 × TVol) in an American study population. The same research group also showed that accurate BWs were more likely to result from prediction models based on ArmVol (0.35 ± 4.6%) compared with the Hadlock formula (–3.0 ± 9.7%).[14] Their work collectively suggests that fetal limb volumetry can provide important information about the soft tissue contribution to BW.

A major limitation of prior studies has been the increased amount of time required to obtain volume measurements by 3DUS. Circumferential manual tracings may take up to several minutes for each region of interest. To address these concerns, Song et al[25] developed a simplified BW prediction method for 102 Korean fetuses at 37.7 ± 2.2 weeks' gestation. Modified thigh volumes were measured on only 3 cross-sectional images of the upper leg (proximal, middle, and distal parts of the femoral diaphysis). Accuracy of their model was evaluated by analyzing the residual (i.e., absolute value of predicted BW minus actual BW) and SD of the residual. They reported that their simplified method was more accurate than BW estimates generated by 2DUS. Intraobserver variability was evaluated from 30 repetitive measurements of the same fetal thigh volume by 1 examiner. Unfortunately, interobserver variability was not examined for their new technique.

Schild and coworkers[26] recently conducted a multiple regression analysis of several sonographic parameters from both 2DUS and 3DUS. Predictions were based on thigh volume, upper arm volume, abdominal volume, and biparietal diameter measurements. The optimal weight estimation function was derived from a study of 125 fetuses that were scanned at a menstrual age of 36.6 ± 4.4 weeks. In prospective validation of their model, they examined 65 German fetuses (36.4 ± 4.1 weeks' gestation) and gave a systematic prediction error of 1.9% ± 7.6%. Their results were similar to prediction errors from our model that included only AC and TVol (2.3% ± 6.6%). This report also appears to document an inverse relationship between prediction error and actual BW, although this finding was not explained. Intraobserver error for repeated measurements was reported for a single examiner using only 10 cases. Unfortunately, the reproducibility of their technique between different examiners was not evaluated.

Successful application of BW prediction models in clinical practice depends on developing stable model coefficients that generate the least amount of error throughout pregnancy. A relatively small but significant inverse relationship was identified between prediction error and actual BW for all functions that were developed in our investigation. This undesirable characteristic tends to overestimate the weights of small fetuses and to underestimate the weights of large fetuses. To our knowledge, the dependence of prediction errors on BW has not been previously emphasized for regression-based weight prediction models. It is possible that similar results may have been unrecognized in other study populations, although this observation could partially reflect the omission of fetal head measurements in our weight estimation function. If the problem does occur, development of correction methods is strongly encouraged because of inherent problems associated with the need for making clinical decisions over a broad range of fetal weights. Such correction methods are intended to reduce individual errors and to minimize dependence of the prediction error on BW, despite some degradation in model precision.

A new fetal weight prediction model, using fractional limb volume and AC, can be reliably used to estimate BW during the late third trimester of pregnancy. It should be feasible to accurately estimate fetal weight in cases in which the AC measurement is difficult by using the TVol alone. Our initial observations suggest that a volume-based model may provide improved BW predictions when compared with conventional 2DUS. Additional investigations, however, are currently under way to determine the relationship of fractional limb volume to fetal weight over a much broader range of menstrual ages. Future quantitative studies should provide valuable insight into how fractional limb volume measurements can be used to characterize fetal size and growth throughout pregnancy.

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