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Ultrasonographic estimation of fetal weight: development of new model and assessment of performance of previous models

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KEYWORDS: birth weight; estimated fetal weight; fetal biometry; systematic review

ABSTRACT

Objectives *To develop a new formula for ultrasonographic estimation of fetal weight and evaluate the accuracy of this and all previous formulae in the prediction of birth weight.*

Methods *The study population consisted of 5163 singleton pregnancies with fetal biometry at 22–43 weeks' gestation and live birth of a phenotypically normal neonate within 2 days of the ultrasound examination. Multivariable fractional polynomial analysis was used to determine the combination of variables that provided the best-fitting models for estimated fetal weight (EFW). A systematic review was also carried out of articles reporting formulae for EFW and comparing EFW to actual birth weight. The accuracy of each model for EFW was assessed by comparing mean percentage error, absolute mean error (AE), proportion of pregnancies with AE ≤ 10% and Euclidean distance.*

Results *The most accurate models, with the lowest Euclidean distance and highest proportion of AE ≤ 10%, were provided by the formulae incorporating ≥ 3 rather than < 3 biometrical measurements. The systematic review identified 45 studies describing a total of 70 models for EFW by various combinations of measurements of fetal head circumference (HC), biparietal diameter, femur length (FL) and abdominal circumference (AC). The most accurate model with the lowest Euclidean distance and highest proportion of AE ≤ 10% was provided by the formula of Hadlock* et al.*, published in 1985, which incorporated measurements of HC, AC and FL; there was a highly significant linear association between EFW and birth weight (*r *= 0.959;* P *< 0.0001), and EFW was within 10% of birth weight in 80% of cases. The performance of the best model developed in this study, utilizing HC, AC and FL, was very similar to that of Hadlock* et al.

Conclusion *Despite many efforts to develop new models for EFW, the one reported in 1985 by Hadlock* et al.*, from measurements of HC, AC and FL, provides the most accurate prediction of birth weight and can be used for assessment of all babies, including those suspected to be either small or large. Copyright © 2018 ISUOG. Published by John Wiley & Sons Ltd.*

INTRODUCTION

Ultrasonographic estimation of fetal weight is an essential part of fetal medicine and prenatal care, allowing the identification of appropriately grown (AGA), and small- (SGA) and large- (LGA) for-gestational-age fetuses. Estimated fetal weight (EFW) is derived from various combinations of measurements of fetal head circumference (HC), biparietal diameter (BPD), femur length (FL) and abdominal circumference (AC). However, there is no universally accepted formula for EFW and, in the last six decades, > 60 formulae have been reported, which were mainly derived from the study of a very small number (< 300) of fetuses.

The objective of this study, of 5163 pregnancies with fetal biometry at 22–43 weeks' gestation and live birth of a phenotypically normal neonate within 2 days of the ultrasound examination, was to develop a new formula for EFW and evaluate the accuracy of this and all previous formulae in the prediction of birth weight.

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METHODS

Study population

The data for this study were derived from ultrasound examinations of women attending the fetal medicine units at King's College Hospital, London, UK and Medway Maritime Hospital, Gillingham, Kent, UK (between January 2006 and December 2017). The fetal databases were searched to identify pregnancies fulfilling the following criteria: singleton pregnancy, dating by fetal crown–rump length at 11–13 weeks' gestation, ultrasound examination at 22–43 weeks' gestation and available measurements of fetal HC, BPD, AC and FL, live birth of phenotypically normal neonate, and birth within 2 days of the ultrasound examination.

The ultrasound scans were carried out by sonographers who had the Fetal Medicine Foundation Certificate of Competence in Fetal Abnormalities. BPD and occipitofrontal diameters (OFD) were measured at the level of the transventricular plane from the outer to inner bone margin and HC was calculated [$HC = \pi \times (OFD + BPD)/2$]. The fetal abdomen was measured in a cross-sectional view with visible stomach bubble and umbilical vein in the anterior third at the level of the portal sinus; the transverse (ATD) and anteroposterior (APD) diameters were measured and AC was calculated [$AC = \pi \times (ATD + APD)/2$]. FL was measured with calipers placed on the outer borders of the diaphyses.

Maternal demographic characteristics, obstetric and medical history, and fetal biometry were stored in a fetal database. Pregnancy outcomes, including indication for and method of delivery, birth weight and findings from examination of the neonate, were obtained from computerized records in each labor ward.

Identification of formulae for estimated fetal weight

A systematic review was carried out of articles reporting formulae for EFW and comparing EFW with actual birth weight. The inclusion criteria were singleton human pregnancy, ultrasound measurements of fetal HC, BPD, AC and FL, individually or in combination, and interval between ultrasound examination and birth of ≤ 15 days. The term 'fetal weight' was searched through PubMed and Cochrane CENTRAL library from 1964, when the first paper was published[1], to January 2018, and in references of other systematic reviews. No language restrictions were applied.

All citations were examined to identify potentially relevant studies; the abstracts of these were then reviewed by two independent reviewers (A.H. and A.M.Z.) who selected eligible studies for full assessment of the complete article. Any disagreements were resolved by discussion and the opinion of a third party (K.H.N.).

Table 1 Characteristics of study population of 5163 normal singleton pregnancies

Characteristic	*Median (range) or* n *(%)*
Maternal age (years)	31 (16–52)
Maternal height (cm)	165 (122–198)
Maternal weight at ultrasound (kg)	80 (43–175)
Maternal racial origin	
White	3579 (69.3)
Black	1104 (21.4)
South Asian	268 (5.2)
East Asian	62 (1.2)
Mixed	150 (2.9)
Conception	
Spontaneous	4990 (96.6)
Assisted	173 (3.4)
Cigarette smoker	630 (12.2)
Parity	
Nulliparous	2503 (48.5)
Parous	2660 (51.5)
Gestational age (weeks)	
At ultrasound	39.3 (22.3–43.3)
At delivery	39.4 (22.6–43.4)
< 28 weeks	95 (1.8)
28 to 33 + 6 weeks	370 (7.2)
34 to 36 + 9 weeks	677 (13.1)
37 to 39 + 6 weeks	1738 (33.7)
≥ 40 weeks	2283 (44.2)
Birth weight (g)	3200 (440–5688)
< 2500 g	1148 (22.2)
2500–3999 g	3404 (65.9)
≥ 4000 g	611 (11.8)
Interval between ultrasound and delivery (days)	1 (0–2)
Indication for delivery	
Spontaneous	2435 (47.2)
Iatrogenic	2728 (52.8)
Preterm	
SGA, PE, PIH or CH	521 (10.1)
LGA, polyhydramnios, DM or GDM	44 (0.9)
Maternal medical condition or cholestasis	10 (0.2)
Previa, accreta, vasa previa, abruption or APH	45 (0.9)
Poor obstetric history	4 (0.1)
Red blood cell or platelet alloimmunization	19 (0.4)
Reduced FM, abnormal Doppler or CTG	20 (0.4)
Term	
Breech or unstable lie	90 (1.7)
SGA, PE, PIH or CH	613 (11.9)
LGA, polyhydramnios, DM or GDM	253 (4.9)
Maternal medical condition or cholestasis	70 (1.4)
Maternal request, age, IVF or previous CS	139 (2.7)
Previa, accreta, vasa previa, abruption or APH	33 (0.6)
Poor obstetric history	29 (0.6)
Red blood cell or platelet alloimmunization	6 (0.1)
Reduced FM, abnormal Doppler or CTG	269 (5.2)
Postdates	563 (10.9)

APH, antepartum hemorrhage; CH, chronic hypertension; CS, Cesarean section; CTG, cardiotocography; DM, diabetes mellitus; FM, fetal movements; GDM, gestational diabetes mellitus; IVF, *in-vitro* fertilization; LGA, large-for-gestational age; PE, pre-eclampsia, PIH, pregnancy-induced hypertension; SGA, small-for-gestational age.

Table 2 New formulae for estimated fetal weight developed in study population of 3000 pregnancies from measurements of biparietal diameter (BPD), head circumference (HC), abdominal circumference (AC) and femur length (FL), using combinations of fractional polynomial terms. Reported performance applies to validation dataset of 2163 pregnancies.

Model	*Adjusted* R^2	*Residual SD*	*RMSE*	*MPE*	*AE*	*AE* $\leq$ *10%*	*ED*
AC							
$2.22857 + (0.03754 \times AC)$	0.91	344.78	0.0516	0.87	8.33	68.84	10.99
$1.23636 + (0.10475 \times AC) - (0.00111 \times AC^2)$	0.94	276.93	0.0428	0.55	6.63	77.48	8.58
FL							
$1.27801 + (0.43698 \times FL) - (0.01792 \times FL^2)$	0.86	430.66	0.0629	−1.49	10.30	56.91	13.05
$3.76793 + (-0.82298 \times FL) + (0.18904 \times FL^2) - (0.01109 \times FL^3)$	0.87	422.29	0.0618	−1.10	10.16	56.87	12.98
AC and FL							
$1.34493 + (0.02431 \times AC) + (0.31364 \times FL) - (0.01779 \times FL^2)$	0.95	258.89	0.0382	0.09	6.03	81.04	7.61
$1.33647 + (0.04951 \times AC) - (0.00038 \times AC^2) + (0.20222 \times FL) - (0.01014 \times FL^2)$	0.95	255.66	0.0378	0.47	6.00	81.51	7.58
HC and AC							
$1.16299 + (0.03706 \times HC) - (0.00033 \times HC^2) + (0.06305 \times AC) - (0.00057 \times AC^2)$	0.95	258.43	0.0387	1.38	6.13	82.02	7.80
$1.35336 + (0.01600 \times HC) + (0.07192 \times AC) - (0.00071 \times AC^2)$	0.95	258.64	0.0388	0.11	6.02	82.43	7.61
HC, AC and FL							
$1.21633 + (0.06076 \times HC) - (0.00075 \times HC^2) + (0.02107 \times AC) + (0.05261 \times FL)$	0.95	247.40	0.0361	−0.66	5.71	84.65	7.12
$1.42482 + (0.01165 \times HC) + (0.03949 \times AC) - (0.00028 \times AC^2) + (0.14147 \times FL) - (0.00662 \times FL^2)$	0.96	243.39	0.0357	−0.20	5.61	84.93	7.02
BPD and AC							
$0.98904 + (0.29764 \times BPD) - (0.01347 \times BPD^2) + (0.02677 \times AC)$	0.94	266.93	0.0399	1.39	6.30	80.77	8.05
$1.10450 + (0.14816 \times BPD) - (0.00574 \times BPD^2) + (0.06410 \times AC) - (0.00057 \times AC^2)$	0.95	256.68	0.0388	1.47	6.10	81.92	7.78
BPD, AC and FL							
$1.27303 + (0.20358 \times BPD) - (0.00912 \times BPD^2) + (0.02168 \times AC) + (0.05366 \times FL)$	0.96	247.49	0.0363	0.61	5.74	85.53	7.23
$1.31192 + (0.08652 \times BPD) - (0.00300 \times BPD^2) + (0.03839 \times AC) - (0.00025 \times AC^2) + (0.12769 \times FL) - (0.00559 \times FL^2)$	0.96	242.33	0.0358	0.57	5.62	85.71	7.05
BPD, HC, AC and FL							
$1.87409 + (0.01783 \times BPD) + (0.01088 \times HC) + (0.02000 \times AC) + (0.05837 \times FL)$	0.95	257.08	0.0369	0.65	6.05	82.99	7.57
$1.43237 + (0.01660 \times BPD) + (0.00745 \times HC) + (0.03876 \times AC) + (0.14005 \times FL) - (0.00027 \times AC^2) - (0.00663 \times FL^2)$	0.96	240.71	0.0354	0.35	5.57	85.39	6.97
BPD, HC, AC, FL and GA							
$1.85735 + (0.01583 \times BPD) + (0.01028 \times HC) + (0.01966 \times AC) + (0.04836 \times FL) + (0.00051 \times GA)$	0.95	252.47	0.0365	0.69	5.98	83.31	7.52
$1.542676 + (0.014694 \times BPD) + (0.007436 \times HC) + (0.037447 \times AC) + (-0.000257 \times AC^2) + (0.169354 \times FL) + (-0.009406 \times FL^2) + (-0.001519 \times GA) + (0.000004 \times GA^2)$	0.96	243.02	0.0350	3.43	6.39	80.44	8.02

In each section, the second of the two models was considered to be superior and was analyzed further (Table 3). Models are compared for adjusted R^2, residual SD, root mean square error (RMSE), mean percentage error (MPE), absolute mean error (AE), proportion of pregnancies with AE $\leq$ 10% and Euclidean distance (ED). GA, gestational age.

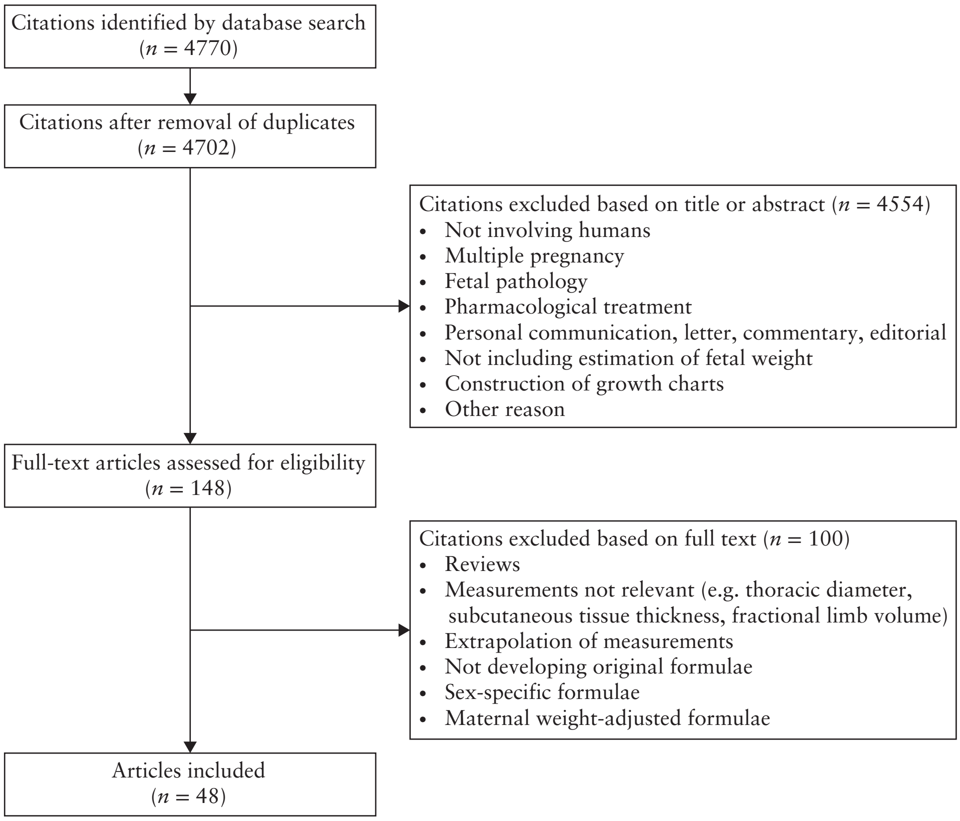

Figure 1 Selection tree for included articles.

Statistical analysis

Development of new model for estimated fetal weight

The potential variables for prediction of birth weight were measurements of BPD, HC, AC and FL in cm, and gestational age in days. The data for birth weight were transformed logarithmically to achieve Gaussian normality which was assessed by inspection of histograms and probability plots. The study population was divided into a testing dataset ($n = 3000$) and a validation set ($n = 2163$). In the testing dataset, multivariable fractional polynomial analysis was used to determine the combination of variables that provided the best-fitting equation using a combination of powers ranging from −3 to 3. We examined each biometric parameter using a combination of linear and fractional polynomial terms and identified formulae that provided a significant contribution in the regression analysis. For each group, we selected the two best models based on the model's R^2, root mean square error (RMSE), residual SD, mean percentage error (MPE), absolute mean error (AE), proportion of pregnancies with AE $\leq$ 10% and Euclidean distance[2].

MPE provides a measure of the systematic deviation of EFW from birth weight: MPE = 100 × ((EFW − birth weight)/birth weight). AE measures the absolute value of the deviation of EFW from actual birth weight. SDs of MPE and AE provide measures of the variation of the prediction error and reflect precision of the formula in calculation of EFW. Euclidean distance, calculated from $\sqrt{(\text{MPE}^2 + \text{MPE SD}^2)}$, provides a measure of accuracy of prediction of the model.

Assessment of accuracy of published models for estimated fetal weight

All models were compared for accuracy in prediction of birth weight by assessing MPE with 95% limits of agreement (mean ± 1.96 × SD of MPE), AE, proportion of pregnancies with AE $\leq$ 10% and Euclidian distance. We also examined the proportion of pregnancies with AE $\leq$ 10% and Euclidian distance in cases in which birth weight was < 2500 g and those with birth weight > 4000 g.

The statistical software package SPSS Statistics 24.0 (IBM Corp., Armonk, NY, USA) and StatsDirect version 3.1.11 (StatsDirect Ltd, Altrincham, UK) were used for data analyses.

RESULTS

Study population

The entry criteria were fulfilled by 5163 pregnancies. Pregnancy characteristics and indications for delivery are summarized in Table 1. The ultrasound examinations were performed by 419 examiners.

New model for estimated fetal weight

The new models for EFW were derived from the testing dataset and assessed in the validation set of the study population and are shown in Table 2. The most accurate models, with the lowest Euclidean distance and highest proportion of AE ≤ 10%, were provided by the formulae incorporating ≥ 3 rather than < 3 biometrical measurements.

Literature search

The literature search identified 4770 citations and 148 of these were selected for further evaluation (Figure 1). There were 48 articles reporting formulae for EFW and comparing EFW to actual birth weight[1,3–49]. However, in three cases, AE was > 50%; it is possible that in these articles there was an error in the formula and they were not included in further analysis of data[47–49]. Details of the 45 included studies on a total of 70 formulae for EFW are provided in Table S1[1,3–46]. In 33 (73.3%) of the 45 studies, the number of patients used for development of the formulae was < 200 and, in most cases, the populations examined were unselected, but a few studies were confined to the examination of small or large fetuses. In most studies, the interval between ultrasound examination and birth was ≤ 7 days, but in one it was < 14 days[30] and in another ≤ 15 days[34].

Accuracy of estimated-fetal-weight formulae

The accuracy of each published model for EFW in the prediction of birth weight in our 5163 pregnancies, assessed by comparing MPE, AE, proportion of pregnancies with AE ≤ 10% and Euclidean distance, is shown in Table 3.

Overall results

The most accurate models, with the lowest Euclidean distance and highest proportion of AE ≤ 10%, were provided by the formulae of Hadlock *et al.*, which incorporated measurements of HC, AC and FL, with or without the addition of BPD[15]. There was a highly significant linear association between birth weight and EFW derived by the measurement of HC, AC and FL ($r = 0.959$; $P < 0.0001$; Figure 2), and EFW was within 10% of birth weight in 80% of cases.

The performances of the best models developed in this study, utilizing HC, AC and FL, with or without BPD, were very similar to those of Hadlock *et al.*[15]. High performance was also achieved by the models of Ott *et al.*[38], which incorporated measurements of HC, AC and FL, Sabbagha *et al.*[46], which incorporated measurements of BPD, HC, AC, FL and gestational age, and Ben-Haroush *et al.*[19], which incorporated measurements of AC and FL, with or without the addition of BPD or BPD and HC.

In papers reporting models for different combinations of measurements, inclusion of HC and/or BPD improved the accuracy provided by measurement of AC and/or FL alone[8–10,12,15,16,19]. There are four papers reporting models for different combinations of measurements with and without FL; inclusion of FL improved the accuracy of the models in two[26,29], and produced similar results in the other two[16,27].

Small babies

In the subgroup of babies with birth weight < 2500 g, the most accurate models of EFW, with the lowest Euclidean distance and highest proportion of AE ≤ 10%, were provided by the formulae of Hadlock *et al.*[15], Dudley *et al.*[40] and Scott *et al.*[41], all of which used measurements of HC, AC and FL. However, the model of Scott *et al.*[41] was developed specifically for the assessment of small babies and performed poorly in the whole population and especially in the subgroup of large babies. The performance of the model of Dudley *et al.*[40] was poorer than that of Hadlock *et al.*[15] in the whole population and especially in large babies. In the model of Hadlock *et al.*[15], EFW was within 10% of birth weight in 73% of cases of small babies, compared with 80% for the whole population.

Large babies

In the subgroup of babies with birth weight ≥ 4000 g, the most accurate prediction was provided by the models of Ferrero *et al.*[18], which used measurements of AC and FL, Merz *et al.*[12], which used measurements of BPD and AC, and Chen *et al.*[44] and Souka *et al.*[45], which used measurements of BPD, HC, AC and FL. However, these models performed poorly in the whole population and especially in the subgroup of small babies. The models reported by Hadlock *et al.*[15], were among the best ones also for the prediction of large babies; however, in common with our models, the accuracy of the model combining BPD, AC and FL was superior to that combining HC, AC and FL. In the model of Hadlock *et al.*[15] using HC, AC and FL, EFW was within 10% of birth weight in 76% of cases of large babies, compared with 80% for the whole population.

Two-stage screening

In this study, the model with the highest performance for babies with birth weight < 2500 g was that of Scott *et al.*[41], which used measurements of HC, AC and FL, and the best model for babies with birth weight ≥ 4000 g was that of Ferrero *et al.*[18], which used measurements of AC and FL. First-line screening was carried out by the model of Hadlock *et al.*[15] using HC, AC and FL, and, on the basis of EFW, the population was divided into three groups. In the group with EFW < 2500 g, the model of Scott *et al.*[41] was applied to derive a new EFW, in the group with EFW ≥ 4000 g, the model of Ferrero *et al.*[18] was applied to derive a new EFW, and, in the group with EFW 2500–3999 g, the values obtained from the model of Hadlock *et al.*[15] were retained. The accuracy of the new combined EFW in the prediction of birth weight was then examined (Table 3).

Table 3 Performance, in our population of 5163 pregnancies, of models for estimated fetal weight in prediction of birth weight (BW) reported in literature and those developed in this study

	All pregnancies				*BW < 2500 g*		*BW ≥ 4000 g*	
Study	*MPE (%) (95% CI)*	*AE ± SD (%)*	*AE ≤ 10%*	*ED*	*AE ≤ 10%*	*ED*	*AE ≤ 10%*	*ED*
BPD								
Willocks (1964)[1]	−3.2 (−42.9 to 36.6)	14.3 ± 14.7	44.6	20.5	25.0	35.0	13.1	20.9
Thompson (1965)[3]	8.7 (−43.2 to 60.6)	17.9 ± 21.3	41	27.9	11.9	51.4	59.1	12.2
Kohorn (1967)[4]	9.0 (−41.3 to 59.3)	18 ± 20.3	43.6	27.2	2.8	52.7	12.8	18.5
Hellman (1967)[5]	9.7 (−32.5 to 51.8)	16.6 ± 16.8	45	23.6	6.4	43.7	34.7	15.2
AC								
Campbell (1975)[6]	1.4 (−18 to 20.9)	7.8 ± 6.3	70.0	10.0	50.9	14.1	52.7	11.2
Higginbottom (1975)[7]	−1.9 (−23.7 to 19.9)	9.0 ± 6.8	63.2	11.3	53.1	13.4	65.6	10.6
Warsof (1977)[8]	8.0 (−8 to 23.9)	10.0 ± 5.4	48.3	11.4	8.6	15.4	75.3	9.4
Jordaan (1983)[9]	−3.9 (−27.4 to 19.5)	10.1 ± 7.5	56.1	12.6	49.7	16.4	9.7	17.8
Hadlock (1984)[10]	2.7 (−16 to 21.4)	7.8 ± 6.2	70.1	9.9	53.7	13.2	78.4	8.1
Hill (1985)[11]	2.2 (−19.8 to 24.2)	8.5 ± 7.7	68.2	11.4	39.1	18.7	59.1	10.5
Merz (1988)[12]	20.2 (−6.5 to 47)	21.0 ± 12.4	21.7	24.4	36.1	19.8	14.6	26.6
Pedersen (1992)[13] (large)	5.1 (−15.4 to 25.6)	9.2 ± 7.2	63.2	11.6	44.9	15.8	81.5	7.6
This study	0.3 (−18 to 18.6)	7.4 ± 5.7	72.5	9.3	60.8	11.9	70.2	9.3
FL								
Warsof (1977)[8]	2.0 (−26.7 to 30.7)	11.4 ± 9.4	53.0	14.8	34.6	21.7	14.7	17.7
Honarvar (2001)[14]	1.5 (−30.6 to 33.7)	12.6 ± 10.6	49.5	16.5	21.7	26.3	10.1	19.6
This study	0.2 (−26.9 to 27.3)	10.8 ± 8.7	55.5	13.8	47.1	17.7	27.5	16.9
AC, FL								
Hadlock (1985)[15]	1.9 (−14.6 to 18.4)	6.9 ± 5.2	75.7	8.6	67.5	10.0	79.9	7.7
Woo (1985)[16]	13.9 (−8.4 to 36.3)	15.5 ± 9.2	31.9	18.0	40.1	17.2	45.5	14.1
Warsof (1986)[17]	6.4 (−12.3 to 25.2)	9.0 ± 7.2	63.5	11.5	45.6	15.6	75.9	9.0
Ferrero (1994)[18]	9.5 (−9 to 28)	10.9 ± 7.8	52.8	13.4	39.0	17.0	91.5	5.8
Ben-Haroush (2008)[19]	0.7 (−16.4 to 17.8)	6.9 ± 5.4	76.0	8.7	62.7	11.6	66.3	9.4
Akhtar (2010)[20]	−5.7 (−40.8 to 29.5)	13.1 ± 13.5	52.0	18.8	31.2	31.8	0.8	24.5
This study	0.6 (−15.6 to 16.8)	6.6 ± 5	77.2	8.3	69.8	9.6	74.5	8.5
BPD, AC								
Warsof (1977)[8]	2.3 (−15.8 to 20.4)	7.4 ± 5.9	72.5	9.5	64.1	11.8	77.3	8.4
Shepard (1982)[21]	7.5 (−11.8 to 26.9)	9.8 ± 7.6	58.6	12.4	45.4	15.7	75.0	9.0
Jordaan (1983)[9]	7.7 (−13.5 to 28.9)	9.9 ± 8.8	61.5	13.3	28.0	21.9	81.2	7.8
Thurnau (1983)[22] (small)	−10.0 (−35.9 to 15.9)	14.3 ± 8.3	32.0	16.6	60.5	15.8	0.5	24.4
Hadlock (1984)[10]	7.0 (−10.7 to 24.8)	9.1 ± 6.9	62.4	11.5	47.1	15.0	84.6	7.3
Weinberger (1984)[23] (small)	−11.4 (−32.2 to 9.4)	13.6 ± 7.6	34.2	15.6	73.4	10.2	0.7	23.7
Campbell (1985)[24]	16.8 (6.1 to 39.7)	17.5 ± 10.6	27.1	20.4	37.3	19.0	29.3	19.9
Tamura (1985)[25] (large)	23.1 (−9.1 to 55.3)	23.5 ± 15.8	20.7	28.3	2.4	44.6	76.8	8.4
Woo (1985)[16]	−3.1 (−20.7 to 14.5)	7.6 ± 5.7	71.3	9.5	69.2	11.0	46.0	12.4
Woo (1986)[26]	5.1 (−20.5 to 30.6)	9.9 ± 9.9	61.8	14.0	36.5	23.2	82.5	7.5
Merz (1988)[12]	10.5 (−15 to 36)	12.9 ± 10.6	46.3	16.7	15.8	27.0	90.5	6.1
Hsieh (1987)[27]	7.3 (−12.5 to 27.1)	9.7 ± 7.9	60.6	12.5	36.2	18.2	76.6	8.7
Vintzileos (1987)[28]	13.8 (−8.8 to 36.5)	14.8 ± 10.3	37.0	18.0	40.3	17.3	35.4	19.6
Akhtar (2010)[20]	47.7 (12.6 to 82.8)	47.9 ± 17.4	3.0	50.9	12.7	38.8	0	53.2
This study	0.9 (−15.7 to 17.5)	6.7 ± 5.2	76.8	8.5	69.2	10.4	74.6	8.3
HC, AC								
Jordaan (1983)[9]	5.7 (−15.4 to 26.9)	9.4 ± 7.8	62.0	12.2	35.5	18.2	73.5	8.9
Hadlock (1984)[10]	0.6 (−16.2 to 17.5)	6.8 ± 5.2	75.9	8.6	67.3	10.6	66.4	9.4
Weiner (1985)[29] (small)	−14.2 (−32.8 to 4.3)	15.0 ± 8.1	29.5	17.1	49.2	13.0	13.4	21.2
Stirnemann (2017)[30]	−3.3 (19.5 to 12.9)	7.2 ± 5.3	73.2	8.9	66.7	10.0	55.6	11.0
This study	−0.3 (−16.7 to 16.1)	6.7 ± 5	77.2	8.4	71.5	9.8	69.1	9.2
BPD, AC, FL								
Hadlock (1985)[15]	4.3 (−11.6 to 20.2)	7.3 ± 5.5	73.3	9.2	64.2	10.8	84.9	7.1
Woo (1985)[16]	5.1 (−12.8 to 23)	8.2 ± 6.5	68.5	10.4	49.2	14.5	83.6	7.1
Hill (1986)[31]	5.4 (−15.9 to 26.8)	9.3 ± 7.9	63.1	12.2	39.0	17.4	78.9	8.2
Woo (1986)[26]	−4.9 (−21.5 to 11.7)	7.7 ± 6	69.5	9.8	65.9	11.4	38.8	13.5
Benson (1987)[32] (large)	10.1 (−8.4 to 28.7)	11.5 ± 7.8	48.5	13.9	38.7	17.1	85.3	7.2
Hsieh (1987)[27]	7.5 (−13.1 to 28.2)	9.8 ± 8.4	60.3	12.9	39.9	19.7	82.8	7.6
Shinozuka (1987)[33] (small)	7.0 (−12.1 to 26.1)	9.4 ± 7.6	61.9	12.0	29.5	18.6	83.6	7.3

Continued over

Table 3 *Continued*

Study	All pregnancies				BW < 2500 g		BW ≥ 4000 g	
	MPE (%) (95% CI)	AE ± SD (%)	AE ≤ 10%	ED	AE ≤ 10%	ED	AE ≤ 10%	ED
Nzeh (1992)[34]	8.1 (−14.6 to 30.8)	10.4 ± 9.5	60.5	14.1	12.9	25.1	81.8	7.2
Halaska (2006)[35]	4.7 (−20 to 29.4)	10.0 ± 9	61.8	10.5	19.3	23.3	46.3	12.1
Ben-Haroush (2008)[19]	2.8 (−13.9 to 19.4)	7.0 ± 5.6	75.6	8.9	54.1	12.9	74.6	8.1
Siemer (2009)[36] (small)	−11.1 (−35 to 12.8)	14.3 ± 8.2	32.7	16.5	66.6	11.8	0.0	26.9
Akhtar (2010)[20]	−21.2 (−48.5 to 6.1)	21.7 ± 13.2	19.4	25.4	40.5	28.2	0.3	37.1
Kehl (2012)[37] (small)	21.9 (−4 to 47.8)	22.2 ± 12.6	19.1	25.6	45.7	16.8	8.5	30.0
This study	0.4 (−14.8 to 15.6)	6.2 ± 4.7	80.3	7.8	75.4	8.9	75.0	8.2
HC, AC, FL								
Hadlock (1985)[15]	0.7 (−14.5 to 16)	6.3 ± 4.7	79.9	7.8	72.8	9.1	76.4	8.2
Weiner (1985)[29] (small)	−8.1 (−23.5 to 7.2)	9.5 ± 6.2	57.0	11.3	57.4	11.1	45.7	13.3
Ott (1986)[38]	2.1 (−14.3 to 18.6)	6.8 ± 5.3	76.4	8.7	57.1	12.1	72.0	8.6
Combs (1993)[39]	0.6 (−16.9 to 18.1)	7.0 ± 5.5	74.7	9.0	54.0	12.7	56.8	10.6
Dudley (1995)[40]	−4.0 (−19.1 to 11.1)	7.1 ± 5	73.7	8.7	75.2	8.7	53.8	11.1
Scott (1996)[41] (small)	−12.3 (−29.6 to 5)	13.3 ± 7.2	34.7	15.1	77.8	8.3	0.7	23.2
Schild (2004)[42] (small)	−18.1 (−33.9 to −2.2)	18.3 ± 7.5	14.5	19.8	51.5	11.7	0	27.4
This study	−0.3 (−15.4 to 14.8)	6.2 ± 4.6	80.3	7.7	75.8	8.5	72.2	8.7
BPD, HC, AC, FL								
Hadlock (1985)[15]	2.7 (−12.8 to 18.1)	6.7 ± 5	77.7	8.3	69.8	9.8	82.8	7.4
Roberts (1985)[43] (small)	15.3 (−5.9 to 36.5)	15.9 ± 9.9	31.6	18.8	41.6	16.5	35.7	18.8
Ben-Haroush (2008)[19]	2.8 (−13.8 to 19.4)	6.9 ± 5.6	75.6	8.9	53.8	12.9	74.8	8.1
Chen (2011)[44]	12.9 (−6 to 31.7)	13.6 ± 8.5	38.1	16.1	26.0	19.5	66.0	10.7
Chen (2011)[44] (small)	−12.6 (−39.4 to 14.2)	15.7 ± 10.1	33.4	18.6	66.0	11.4	0.7	29.3
Chen (2011)[44] (large)	35.6 (−27.7 to 98.9)	36.5 ± 31.3	18.4	48.0	0	87.9	89.4	6.3
Souka (2014)[45]	0.2 (−30.6 to 30.9)	8.5 ± 13.2	73.9	15.7	46.8	30.3	71.4	8.7
Souka (2014)[45] (large)	4.5 (−40.1 to 49.1)	12.3 ± 19.7	57.4	23.2	30.8	45.1	89.4	6.2
Souka (2014)[45] (small)	−19.4 (−60 to 21.3)	21.1 ± 19	27.7	28.4	66.9	36.9	0	41.9
This study	0.2 (−14.9 to 15.2)	6.2 ± 4.6	80.4	7.7	75.2	8.6	74.3	8.3
BPD, HC, AC, FL, GA								
Sabbagha (1989)[46]	−1.3 (−18.7 to 16.1)	7.1 ± 5.5	74.9	9.0	62.8	11.7	41.1	12.4
Sabbagha (1989)[46] (large)	4.3 (−28.7 to 37.2)	9.4 ± 14.5	71.5	17.3	36.3	34.0	64.8	9.6
Sabbagha (1989)[46] (small)	−2.8 (−18.8 to 13.3)	6.9 ± 5.1	75.4	8.6	73.2	9.4	44.5	12.4
This study	0.6 (−15.2 to 16.4)	6.5 ± 4.9	79.0	8.1	76.3	8.9	77.6	8.2
Two-stage screening								
Hadlock (1985)[15] (HC, AC, FL), Scott (1996)[41] (HC, AC, FL), Ferrero (1994)[18] (AC, FL)	0.2 (−16.1 to 16.5)	6.5 ± 5	77.3	8.3	70.5	9.4	77.1	8.2

Only first author of each study is given. Models are compared for mean percentage error (MPE), absolute mean error (AE), proportion of pregnancies with AE ≤ 10% and Euclidean distance (ED). Some models were developed specifically for assessment of large or small fetuses; these are indicated by '(large)' or '(small)' in first column. AC, abdominal circumference; BPD, biparietal diameter; FL, femur length; GA, gestational age; HC, head circumference.

DISCUSSION

Principal findings of the study

This study has demonstrated that, first, there is a strong association between EFW and birth weight, and, second, the most accurate model for prediction of birth weight is one that includes measurements of the fetal head as well as AC and FL. This study has also demonstrated that there are large variations in the accuracy of 70 previously reported models of EFW in the prediction of birth weight. The most accurate model was that of Hadlock *et al.*[15], and it is rather disappointing but impressive that the prediction of a model reported from the study of 276 patients in 1985[15] could not be improved upon by our study of several thousand patients in 2018. In both the model of Hadlock *et al.*[15] and the one developed in this study, EFW, derived from measurements of HC, AC and FL, was within 10% of birth weight in 80% of cases.

On assessment of small or large babies, some models were better than that of Hadlock *et al.*[15]. However, a two-stage strategy in which the model of Hadlock *et al.*[15] is first applied in the whole population and then those with EFW below or above certain cut-offs have their EFW recalculated using other models, failed to improve the accuracy of prediction of birth weight either in the whole population or in subgroups of small or large babies.

Strengths and limitations of the study

Strengths of our study include the large population examined covering a wide range of gestational ages and birth weights, pregnancy dating based on fetal crown–rump length, proximity of the ultrasound examination to delivery, and trained sonographers that carried out fetal biometry according to a standardized protocol. We adopted the pragmatic approach of utilizing all measurements obtained from a large number of appropriately trained

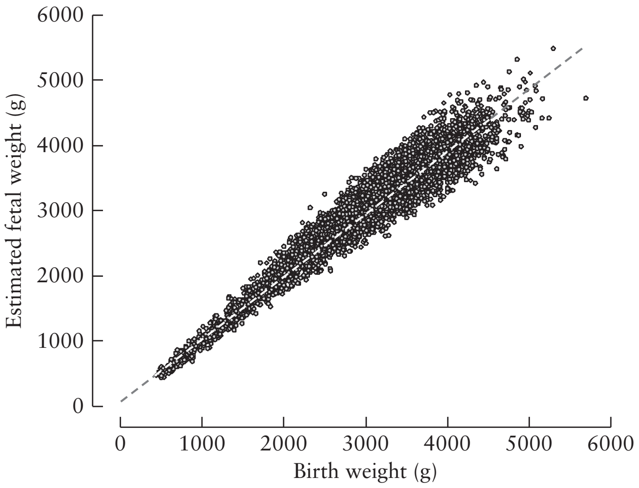

Figure 2 Association between birth weight and estimated fetal weight derived from model of Hadlock *et al.*[15] using measurements of head circumference, abdominal circumference and femur length in study population ($r = 0.959$; $P < 0.0001$).

sonographers providing a routine clinical service rather than a small number of highly skilled specialists. Another strength is the systematic review of the literature that identified a large number of previously reported models for EFW, derived from fetal HC, BPD, AC and FL, individually or in combination, and assessment of the accuracy of these models for the prediction of birth weight both in the whole study population and in small and large babies.

A potential limitation is the retrospective nature of the study, which inevitably introduces bias in favor of high-risk pregnancies; this is, for example, reflected in the high proportion of babies with birth weight < 2500 g. However, the large sample size included a high number of appropriately grown, small and large fetuses to allow adequate assessment of the EFW models for such pregnancies. Although the precise performance of each model would vary with the characteristics of a given study population, our study allows comparison of the relative performances between the different models.

Comparison with previous studies

Studies describing new models have often reported that their model was superior to previously published ones, but this is an inevitable consequence of deriving and testing a model in the same population. In general, previous studies assessing the accuracy of different models for EFW in the prediction of birth weight have reached the conclusion that either the most, or among the most, accurate models were those reported by Hadlock *et al.*[15] in all pregnancies, including those with a small or large baby[50–57].

There is controversy as to whether use of FL in models for EFW improves the accuracy of prediction of birth weight[16,26,27,29]. We found that the models providing the most accurate prediction included measurements of HC and/or BPD, as well as AC and FL. A small study investigating 43 SGA fetuses with abnormal umbilical artery Doppler that were born at < 33 weeks' gestation reported that, although symmetrical smallness models using FL were more accurate than those without, the opposite was true in the case of asymmetrical smallness[58].

Attempts at improving the prediction of birth weight by the addition of maternal characteristics, such as height, weight, parity and racial origin, to fetal biometry[59] have not been found to be successful[60]. A study of over 9000 singleton pregnancies investigated the effect of maternal age, weight, height, parity, diabetes, fetal sex, presentation, amniotic fluid index and sonographer experience; it was concluded that, although some of these factors had a significant effect on EFW, their contribution was small and of questionable clinical significance[61]. There is some contradictory evidence for whether the precision of EFW can be improved by three-dimensional (3D) ultrasound volumetry[62–64]. Recent evidence suggests that EFW using magnetic resonance imaging (MRI) may be more accurate than ultrasound in the prediction of both SGA and LGA neonates[65,66]. Assessments of the value of 3D ultrasound and fetal MRI were beyond the scope of our study.

Conclusions

Despite many efforts to develop new models for EFW, the one reported in 1985 by Hadlock *et al.*[15] from measurements of HC, AC and FL provides the most accurate prediction of birth weight and can be used for assessment of all babies, as well as those suspected to be either small or large.

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SUPPORTING INFORMATION ON THE INTERNET

The following supporting information may be found in the online version of this article:

Table S1 Articles reporting formulae for estimated fetal weight (EFW) derived from various combinations of ultrasonographic measurements of fetal head circumference (HC), biparietal diameter (BPD), femur length (FL) and abdominal circumference (AC)