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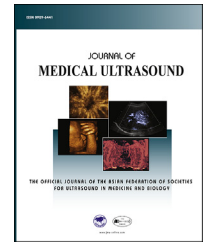

ORIGINAL ARTICLE

A Systematic Evaluation of Ultrasound-based Fetal Weight Estimation Models on Indian Population

Sujitkumar S. Hiwale

Philips Research India, Philips Innovation Campus, Manyata Tech-Park, Nagavara, Bengaluru, Karnataka, 560045, India

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Abstract *Background:* The purpose of this study was to systematically evaluate ultrasound-based fetal weight estimation models on Indian population to find out their performance across different weight bands and ability to correctly categorize low birth weight (LBW) and high birth weight (HBW) fetuses.
Methods: We used retrospectively collected data of 154 cases for the study. Inclusion criteria were a live singleton pregnancy, gestational age $\geq$34 weeks and ultrasound scan to delivery duration $\leq$7 days. Cases with fetal growth restriction or malformation were excluded. The cases were divided into standard weight bands of 500 g each based on newborns' actual birth weights (ABW). For each weight band, performance of 12 different models based on abdominal circumference (AC), biparietal diameter (BPD), head circumference (HC) and femur length (FL) was evaluated by mean percentage error (MPE) and its standard deviation (random error). Sensitivity and positive predict value (PPV) of models to categorize LBW (ABW $\leq$ 2500 g) and HBW (ABW $>$3500 g) neonates were also evaluated.
Results: We observed a significant variation in MPE of the 12 models with no single model being consistently superior across all the weight bands. For the cases with birth weight $\leq$3000 g, the Woo (AC-BPD) model was found to be more appropriate, whereas for the cases with birth weight $>$3000 g the Woo (AC-BPD-FL) model was found more appropriate. In general, models had a tendency to overestimate fetal weight in LBW neonates and underestimate it in HBW neonates. Overall, the models showed poor sensitivity and PPV to categorize LBW and HBW neonates. The highest sensitivity (57.1%) for LBW identification was observed with the Woo (AC-BPD) model; the highest PPV (50%) for HBW neonate identification was observed with the Hadlock (AC-HC), Warsof (AC-BPD) and Combs (AC-HC-FL) model.
Conclusion: We found that the existing fetal weight estimation models have high systematic and random errors on Indian population, with a general tendency of overestimation of fetal weight in the LBW category and underestimation in the HBW category. We also observed that

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E-mail address: Sujit.hiwale@philips.com.

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these models have a limited ability to predict babies at a risk of either low or high birth weight. It is recommended that the clinicians should consider all these factors, while interpreting estimated weight given by the existing models.
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Introduction

The ultrasound-based weight estimation is a well-established and routinely practiced method for intrauterine fetal well-being assessment. The ultrasound-based methods have evolved over a period of time with researchers proposing a number of models with different combinations of fetal biometry parameters. However, these models are shown to have high systematic and random errors associated with them; moreover, due to difference in population characteristics no single model has been shown to applicable for all populations [1,2]. Therefore, thorough validation studies are required before application of these models in routine practice [3].

For the existing ultrasound-based models, apart from Hebbar [4] and Hiwale et al. [2] not many validation studies have been carried on Indian population. These studies have observed that the existing models have high errors on Indian population. Both of these studies have evaluated performance of different models on an entire range of birth weights without any categorization in weight bands. However, it is known that the ultrasound-based models behave differently in different weight bands with high errors at the extreme ends of a birth weight range [1,5,6]. This behavior can introduce errors in fetal weight estimation leading to either missed or unnecessary interventions in low birth weight (LBW) or high birth weight (HBW) fetuses. Therefore, it is very important to have a reliable information on accuracy of existing models across standard weight bands in addition to information on the entire range of birth weights.

The high error associated with the existing models coupled with a lack of information on their accuracy across weight bands put Indian practitioners at a disadvantage. This study is an attempt to address this gap in the literature with in an objective to systematically evaluate performance of the existing models across the weight bands.

Material and methods

Study population

For the study, de-identified records of pregnant women were obtained from an archival (year 2013) of a tertiary care hospital in Bengaluru (Bangalore), India. These records were then scrutinized for inclusion and exclusion criteria. Inclusion criteria for the study were a live-birth singleton pregnancy, gestational age more than or equal to 34 weeks, and the last ultrasound scan to delivery duration less than equal to seven days. All the cases with pre-gestational or gestational diabetes, suspected fetal malformation or anomaly were excluded to avoid any bias in weight estimation. The cases with small for gestational age (SGA) newborns were also excluded due to sub-optimal performance of routine ultrasound-based models on theses fetuses [6]. All the cases with complications other than the exclusion criteria were included in the study.

For inclusion, gestational age was determined using the date of last menstrual period (LMP) or by the earliest ultrasound scan when LMP dates were not available. All ultrasound scans were performed by experienced radiologists using standard protocols. Weights of all newborn babies were measured immediately after birth. The SGA cases (birth weight $<$ 10th percentile for gestational age) were excluded using customized percentile charts by Mikolajczyk et al. for Indian population [7].

The retrospective data used for the study was obtained in accordance with local regulations after approval of an ethical committee in writing.

Selection of the models

For the study, we selected only those models, which on Indian population have shown systematic error within $\pm$10% in earlier studies. We selected 10% as a threshold because any model with more than $\pm$10% variation in estimated fetal weights is likely to be of a limited use in clinical practice [1]. To find out the relevant models a comprehensive literature search was conducted on the databases of Medline, Google scholar, general internet sources and reference lists of relevant papers. Selection was restricted to models based on combinations of four routinely used biometry parameters, such as abdominal circumference (AC), biparietal diameter (BPD), head circumference (HC) and femur length (FL).

All the selected 12 models (Table 1) were implemented in MATLAB® (MATLAB 9. 0.0.341360, The MathWorks Inc., Natick, MA, 2016). For each case, fetal weight was estimated by all the selected models using ultrasound parameters from the last week of pregnancy.

Categorization of cases in weight bands

To evaluate performance of the models across weight bands, all the cases were divided based on newborns' birth weights into standard weight bands of 500 g each. In each of these weight bands, performance of the different models was evaluated by comparing actual birth weights (ABW) with estimated fetal weights (EFW) given by the different models. Accuracy information provided by this approach is useful for comparative analysis of the models; therefore

Table 1 Details of selected ultrasound-based fetal weight estimation models.

Model	Model (Parameters)	Equation
1	Higginbottom (AC) [8]	$EFW = 0.0816(AC)^3$
2	Jordaan (AC) [9]	$Log_{10}\ EFW = 0.6328 + 0.1881(AC) - 0.0043(AC)^2 + 0.000036239(AC)^3$
3	Hadlock (AC-HC) [10]	$Log_{10}\ EFW = 1.182 + 0.0273(HC) + 0.07057(AC) - 0.00063(AC)^2 - 0.0002184(HC)\ (AC)$
4	Hsieh (AC-BPD) [11]	$Log_{10}\ EFW = 2.1315 + 0.0056541(AC)\ (BPD) - 0.00015515(BPD)\ (AC)^2 + 0.000019782(AC)3 + 0.052594(BPD)$
5	Warsof (AC-BPD) [12]	$Log_{10}\ EFW = -1.599 + 0.144(BPD) + 0.032(AC) - 0.000111(BPD)^2\ (AC)$
6	Woo (AC-BPD) [13]	$Log_{10}\ EFW = 1.63 + 0.16(BPD) + 0.00111(AC)^2 - 0.0000859(BPD)\ (AC)^2$
7	Hsieh (AC-BPD-FL) [11]	$Log_{10}\ EFW = 2.7193 + 0.0094962(AC)\ (BPD) - 0.1432(FL) - 0.00076742(AC)\ (BPD)^2 + 0.001745(FL)\ (BPD)^2$
8	Woo (AC-BPD-FL) [13]	$Log_{10}\ EFW = 1.54 + 0.15(BPD) + 0.00111(AC)^2 - 0.0000764(BPD)\ (AC)^2 + 0.05(FL) - 0.000992(FL)\ (AC)$
9	Combs (AC-HC-FL) [14]	$EFW = 0.23718(AC)^2(FL) + 0.03312(HC)^3$
10	Hadlock-3 (AC-HC-FL) [15]	$Log_{10}\ EFW = 1.326 - 0.00326(AC)\ (FL) + 0.0107(HC) + 0.0438(AC) + 0.158(FL)$
11	Ott (AC-HC-FL) [16]	$Log_{10}\ EFW = 0.04355(HC) + 0.05394(AC) - 0.0008582(HC)\ (AC) + 1.2594(FL/AC) - 2.0661$
12	Hadlock-4 (AC-HC-BPD-FL) [15]	$Log_{10}\ EFW = 1.3596 + 0.0064(HC) + 0.0424(AC) + 0.174(FL) + 0.00061(BPD)\ (AC) - 0.00386(AC)\ (FL)$

AC = abdominal circumference; BPD = biparietal diameter; EFW = estimated fetal weight; FL = femur length; HC = head circumference.

most of the researchers have used this method for categorization of cases in different weight bands.

Statistical analysis methodology

The EFW by the different models were compared with ABW by means of: (1) mean of percentage errors (MPE) (a measure of systematic error), for an individual case, percentage error was calculated using following equation,

$$Precenatge\ Error = \left(\frac{EFW - ABW}{ABW}\right) * 100$$

(2) standard deviation of percentage errors (a measure of random error) (3) analysis for proportions of EFW, which are within ±5%, ±10% and ±15% of ABW.

For a particular ABW based band, a model with the lowest absolute MPE was judged as the best model for that band. MPE was used as a primary mean for comparison as it denotes a magnitude of systematic error in fetal weights estimation. The models were compared with each other using one-way Analysis of Variance (ANOVA) test. For a pairwise comparison of systematic errors between the models Tukey's honest significance test was used. The Levene's test was used to assess the equality of random errors of the models. A p value < 0.05 was considered as a statistically significant difference for all comparisons.

In addition to this, sensitivity and positive predictive value (PPV) of a model to correctly identify fetal weight band with ABW band as a ground truth was also calculated.

All statistical analyses were performed in MATLAB ®.

Results

In total, 154 cases met the inclusion and exclusion criteria. The important demographic characteristics of the study population are summarized in Table 2. The nulliparous women constituted 47% of the study population. The mean gestational age of the study population was 38.35 weeks with 82% cases having it in the range of 37–42 weeks. About 61% cases had their last ultrasound scan done within three days before delivery. Based on the selection criteria, 12 models were selected for analysis. The models of Warsof (AC-BPD) and Ott (AC-HC-FL) provide fetal weight in kilogram, it was converted in gram before analysis.

Performance of the models as per the weight bands

All the cases were divided into the weight bands of 500 g each starting from 2500 g and performance of each model was evaluated in these bands. We observed a wide variation in systematic error (as measured by MPE) of the different models across all the birth weight bands (Table 3). In the LBW category (ABW $\leq$ 2500 g), most of the models had their systematic errors in excess of 10%. The difference in

Table 2 Demographic characteristics of the study population.

Characteristic	Mean (±SD)
Maternal age (Year)	23.57 (±3.36)
Gestational age (Week)	38.35 (±1.49)
Biparietal diameter (cm)	8.98 (±0.38)
Abdominal circumference (cm)	32.79 (±1.48)
Head circumference (cm)	32.31 (±1.01)
Femur length (cm)	7.14 (±0.27)
Actual birth weight (g)	2745.63 (±380.40)
Mean duration between ultrasound scan and delivery (day)	2.86

SD = Standard deviation.

systematic error between the models was found statistically significant by one-way ANOVA test. The subsequent pairwise comparison revealed that the Woo (AC-BPD) model had statistically significant less systematic error (3.2%) compared to all other models except the Warsof (AC-BPD) model (7.16%). In category two (ABW $>$ 2500 g to ABW $\leq$ 3000 g), the Woo (AC-BPD) model was found to have statistically significant less systematic error (0.48%) compared to all other models; this was also the lowest error observed with any model in all categories. In category three (ABW $>$3000 g to ABW $\leq$ 3500 g), despite of statistically significant difference among the models, no single model was found to be superior in a pairwise comparison; the lowest error in this category was observed with the Woo (AC-BPD-FL) model (0.52%).

In the HBW category (ABW $>$ 3500 g), no statistically significant difference among the models was observed, with the Hsieh (AC-BPD-FL) model having the least error (−4.04%). However, due to a small sample size it is difficult to comment on the results from this category. The ranks of the models as per their systematic error in the individual weight bands are summarized in Table 3.

In regard to precision (as measured by random error), no statistically significant difference was observed among the models in the different weight bands by Levene's test. The lowest random error was observed with the Jordaan (AC) model (5.1%) in the category three. Overall, the Jordaan (AC) model was found to be the most consistent with the least random error across all the weight bands. Fig. 1, shows the systematic and random error of the models across the weight bands.

As per proportion of EFW within certain limits of ABW (Table 4), we observed that in the LBW category all the models had a tendency to overestimate the fetal weight considerably, evident by a fact that nine models had overestimated the fetal weight by more than 10% in more than 50% of total cases. This tendency of overestimation reduced with increase in birth weight; however, at higher birth weights ($>$3000 g) the models started showing an increasing tendency of underestimation. Overall the highest proportion of EFW within $\pm$10% of ABW was observed with the Jordaan (AC) model (90.9%) in the category three. Fig. 2, shows the overestimation and underestimation tendencies of the models in the different ABW categories.

Accuracy for LBW and HBW categorization

We observed a significant variation in sensitivity of the models to accurately categorize LBW and HBW neonates with ABW band as a ground truth. Among the studied models, the Woo (AC-BPD) model was found to have the highest sensitivity (57.1%) for accurate categorization of LBW babies. For accurate categorization of HBW babies, the highest PPV (50%) was observed with the models of Hadlock (AC-HC), Warsof (AC-BPD) and Combs (AC-HC-FL). The sensitivity and PPV of the models for categorization of the different weight bands are summarized in Table 5.

Discussion

Given a fact that the ultrasound based fetal weight estimation is often taken as a proxy for actual birth weight, it is paramount important that clinicians should have a precise information on accuracy of such estimation. In current Indian scenario, due to lack of information on models' performance across the weight bands, clinicians often refer to accuracy information of a model based on the entire birth weight range; this could result in an erroneous assessment as the models have different error margins in different weight bands. This study attempts to provide systematic information to the clinicians in this regard.

In this study, we observed a significant variation in systematic error of the existing models across the weight bands with no single model being consistently superior across all the weight bands. We found the Woo (AC-BPD) model more appropriate for the cases with ABW below 3000 g as it had statistically significant less systematic error in these categories. For the cases with ABW more than 3000 g, the Woo (AC-BPD-FL) model was found to be more appropriate as it had the low systematic and random error in these categories. However, barring these models most of

Table 3 Ranks of the models in the different ABW categories as per their MPE.

Model	ABW ≤ 2500 g (n = 35)		2501 g–3000 g (n = 79)		3001 g–3500 g (n = 33)		3501 g–4000 g (n = 7)	
	MPE (SD)	Rank	MPE (SD)	Rank	MPE (SD)	Rank	MPE (SD)	Rank
1	8.21 (11.4)	3	7.17 (8.75)	4	0.86 (8.66)	3	−6.56 (9.29)	7
2	11.76 (7.11)	4	4.98 (5.69)	2	−4.68 (5.1)	11	−14.08 (4.87)	12
3	12.52 (9.93)	8	9.39 (7.49)	6	1.83 (7.6)	6	−8.45 (8.64)	8
4	12.24 (10.76)	7	9.73 (8.37)	8	0.88 (10.13)	4	−5.05 (6.84)	3
5	7.16 (10.8)	2	5.22 (8.53)	3	−3.42 (11.07)	10	−8.68 (6.51)	10
6	3.20 (9.65)	1	0.48 (7.3)	1	−7.96 (8.59)	12	−13.91 (5.67)	11
7	11.77 (11.42)	5	9.89 (9.36)	9	0.57 (13.51)	2	−4.04 (7.07)	1
8	11.87 (10.68)	6	9.45 (8.15)	7	0.52 (9.78)	1	−5.55 (6.47)	4
9	13.05 (8.89)	10	8.97 (6.75)	5	0.98 (7.62)	5	−8.50 (7.44)	9
10	13.04 (9.87)	9	10.36 (7.49)	10	2.93 (8.46)	7	−5.89 (8.03)	5
11	14.32 (9.43)	12	10.76 (7.14)	11	2.94 (8.01)	8	−6.55 (8.0)	6
12	13.61 (10.1)	11	11.01 (7.55)	12	2.95 (8.43)	9	−4.81 (7.43)	2

ABW = Actual birth weight; MPE = Mean percentage error; SD = Standard deviation.

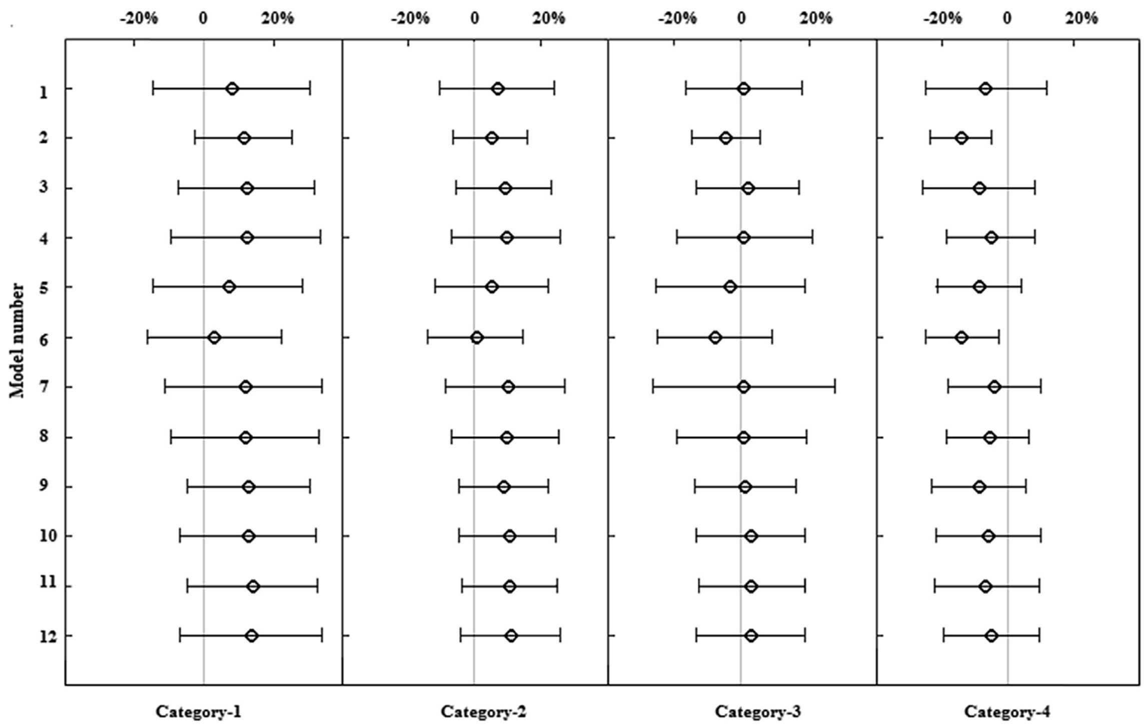

Figure 1 Systematic and random error (±2 SD) of the models in the different ABW categories. Category-1 = ABW <2500 g; Category-2 = ABW >2500 g to ABW ≤ 3000 g; Category-3 = ABW >3000 g to ABW ≤ 3500 g; Category-4 = ABW >3500 g. The x-axis indicate MPE, whereas y-axis indicate a model number.

Table 4 Percentage of EFW within a certain range of ABW for the different models.

Model	ABW ≤ 2500 g			ABW 2501 g–3000 g			ABW 3001 g–3500 g			ABW 3501 g–4000 g		
	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
1	25.7	57.1	74.3	34.2	65.8	79.7	60.6	78.8	90.9	57.1	57.1	71.4
2	20.0	45.7	68.6	49.4	79.7	94.9	48.5	90.9	97.0	0.0	14.3	57.1
3	28.6	45.7	62.9	22.8	55.7	82.3	54.5	84.8	93.9	57.1	57.1	71.4
4	22.9	48.6	62.9	17.7	48.1	75.9	42.4	69.7	90.9	57.1	71.4	85.7
5	37.1	60.0	77.1	39.2	70.9	87.3	45.5	72.7	84.8	28.6	57.1	71.4
6	34.3	68.6	82.9	60.8	84.8	93.7	36.4	72.7	84.8	0.0	28.6	57.1
7	22.9	48.6	62.9	17.7	45.6	74.7	39.4	69.7	81.8	57.1	71.4	100.0
8	22.9	48.6	62.9	20.3	50.6	81.0	45.5	72.7	90.9	57.1	71.4	85.7
9	17.1	42.9	65.7	24.1	60.8	84.8	57.6	84.8	93.9	57.1	57.1	71.4
10	22.9	37.1	62.9	15.2	51.9	77.2	54.5	72.7	90.9	57.1	57.1	71.4
11	17.1	37.1	51.4	15.2	44.3	77.2	54.5	72.7	90.9	57.1	57.1	71.4
12	20.0	40.0	57.1	15.2	44.3	73.4	57.6	75.8	90.9	57.1	57.1	100.0

ABW = Actual birth weight; EFW = Estimated fetal weights.

the other models had high systematic error associated with them. The possible reasons for these high errors could be differences in anthropometric, nutritional, socio-economic and genetic factors between Indian and other populations as stated by the earlier studies [2,17]. Although less variations were observed in random error, most of the models had it in excess of 7%, with the Jordaan (AC) model being the most precise.

We also observed that the models behave differently at the extreme ends of birth weight range, with a tendency to overestimate fetal weigh in LBW babies and underestimate it in HBW babies. We observed a transition zone between 2600 g and 3200 g, where results from most of the model were fairly accurate with the low systematic and random error, and without a tendency of significant over- or underestimation of fetal weight. Although many theories have been put forth to explain this peculiar behavior of the models [1,18], none of the existing theory has been able to explain it convincingly. One possible explanation could be limitations of regression equations based methods to

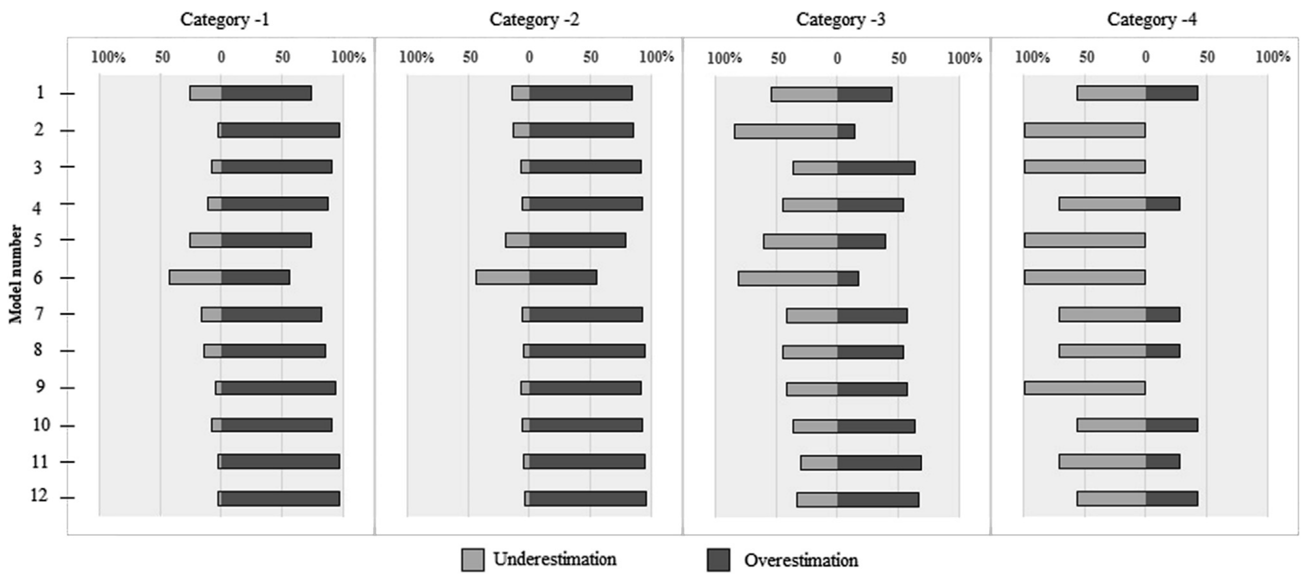

Figure 2 Percentage of under- and overestimated cases by the models in the four actual birth weight (ABW) based categories. Category -1 = ABW ≤ 2500 g; Category -2 = ABW > 2500 g to ABW ≤ 3000 g; Category -3 = ABW >3000 g to ABW ≤ 3500 g; Category -4 = ABW > 3500 g. The x-axis indicate percentage of cases, whereas y-axis indicate a model number.

Table 5 Sensitivity and PPV of the models to categorize the different weight bands.

Model	EFW ≤ 2500 g				2501 g—3000 g				3001 g—3500 g				3501 g—4000 g			
	Total cases	TP	Sen.	PPV	Total cases	TP	Sen.	PPV	Total cases	TP	Sen.	PPV	Total cases	TP	Sen.	PPV
1	19	15	42.9	78.9	60	38	48.1	63.3	68	24	72.7	35.3	7	3	42.9	42.9
2	9	7	20.0	77.8	103	59	74.7	57.3	42	19	57.6	45.2	0	0		
3	11	9	25.7	81.8	64	37	46.8	57.8	73	26	78.8	35.6	6	3	42.9	50.0
4	15	12	34.3	80.0	58	36	45.6	62.1	71	22	66.7	31.0	10	4	57.1	40.0
5	22	17	48.6	77.3	70	46	58.2	65.7	60	22	66.7	36.7	2	1	14.3	50.0
6	32	20	57.1	62.5	90	55	69.6	61.1	32	13	39.4	40.6	0	0		
7	16	13	37.1	81.3	57	36	45.6	63.2	70	22	66.7	31.4	11	4	57.1	36.4
8	16	12	34.3	75.0	58	35	44.3	60.3	71	23	69.7	32.4	9	4	57.1	44.4
9	12	10	28.6	83.3	64	37	46.8	57.8	74	27	81.8	36.5	4	2	28.6	50.0
10	11	9	25.7	81.8	56	31	39.2	55.4	77	24	72.7	31.2	10	4	57.1	40.0
11	8	7	20.0	87.5	58	30	38.0	51.7	79	25	75.8	31.6	9	4	57.1	44.4
12	9	8	22.9	88.9	56	31	39.2	55.4	77	23	69.7	29.9	12	4	57.1	33.3

EFW = Estimated fetal weights; MPE = Mean percentage error; PPV = positive predictive value; Sen. = Sensitivity; SD = Standard deviation; TP = True positive (total number of cases correctly categorized by a model with actual birth weight band as a ground truth).

accurately model intrauterine fetal growth pattern throughout pregnancy, especially at the extreme ends. Due to this differential behavior of the models, it is recommended that the clinician should have some educated guess about the expected weight band of a fetus before applying the ABW category based error margins; however, such information is less likely to be available in routine scenarios. Nevertheless, the clinicians should exert caution in interpretation when estimated fetal weight is at the extreme end of the weight range.

One very important application of ultrasound-based fetal weight estimation is to identify fetuses, which are likely to be in LBW or HBW category. For a reliable prediction of LBW, it is desirable that the model should have high sensitivity to provide opportunities for early identification and subsequent management, if required. However, we observed that most of the models had low sensitivity for accurate LBW categorization. On the other hand, it is desirable to have a high PPV for prediction of large babies to avoid unnecessary interventions such as caesarean sections. Although we studied a small number of large babies, we observed that all the models had low PPV for this prediction, with none of the models having PPV more than 50%. The poor sensitivity and PPV of the existing models to correctly categories LBW and large babies further limits their applicability in clinical practice without due diligence. This also highlights a need of specialized weight estimation models for these categories.

The retrospective design and a small sample size from a single center are two important limitations of our study.

Other limiting factor is that we did not study impact of other factors like maternal ethnicity, socio-economic status, nutritional factor, geographic factors etc., which could have an impact on fetal weight. This makes it difficult to generalize finding of this study for the entire country. Furthermore, as we wanted to evaluate the general purpose models without any prior categorization, we did not study the models, which are specifically designed for low birth weight or macrosomic fetuses.

To conclude, we found that the existing fetal weight estimation models have high systematic and random errors on Indian population, with a general tendency of overestimation of fetal weight in the LBW category and underestimation in the HBW category. We also observed that these models have low sensitivity and PPV to correctly predict fetuses at a risk of either low or high birth weight. This observations makes it very important that clinicians should be aware of these limitation and their possible implications. The strength of our study lies in being the first study on Indian population, where accuracy and error margins of the existing models are analyzed according to standard weight bands. Having such information is likely to help the doctors to take informed decisions in a timely manner. However, given the importance of accurate fetal weight estimation in clinical management and associated medico-legal issues, we recommend that more research is required in this filed with large scale studies.

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