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Two new models for the estimation of foetal weight more than a week before delivery: An MRI study☆

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ABSTRACT

Purpose: To develop and evaluate new formulas to determine the magnetic resonance imaging (MRI)-based estimated foetal weight (EFW) more than a week before delivery.

Methods: The study included 153 women with singleton pregnancies who gave birth to live, normal neonates within 15–21 days of the MRI examination for whom foetal body volume biometry data were available at term. All foetuses were randomly divided into a testing group (102) and a validation group (51). Regression analysis was used to determine the single volume or the combination of volume and MRI-to-delivery interval that determined the EFW. The accuracy of the two new models and the primary existing model developed by Baker et al. were evaluated in validation group.

Results: The two new models had similar mean percentage errors (MPEs) (3.9% vs 3.9%) and proportions of pregnancies with an MPE < 10% (92.2% vs 90.2%); the model incorporating volume and MRI-to-delivery had relatively higher proportions of pregnancies with an MPE < 5% (72.5% vs 64.7%) and EFWs in agreement with the birth weights. The error in the Baker model was almost twice that in the new models.

Conclusion: The accuracy of foetal weight estimation more than one week before delivery using the model developed by Baker et al. was poor and was significantly improved by the new models. A combination of the foetal body volume and MRI-to-delivery interval will enable the more accurate determination of the EFWs.

1. Introduction

Estimated foetal weight (EFW) at term is an important variable in obstetrical clinical practice, allowing the identification of abnormal foetal growth and the prediction of delivery outcomes, thus improving the clinical management of labour and delivery [1,2]. However, an inaccurate EFW might lead to disappointing outcomes; for example, the overestimation of the foetal weight increases the possibility that a caesarean section will be performed that is not necessitated by the actual foetal weight [3,4]. Ultrasound is the main method of predicting foetal weight in clinical practice, but there is a large variability in the accuracy of the estimations [5]. Therefore, efforts are being made to improve the accuracy of foetal weight estimation using ultrasound [6].

Since 1994, magnetic resonance imaging (MRI) has been used to predict foetal weight via an equation generated by Baker et al., and a growing body of evidence has demonstrated that MRI is superior to ultrasound for foetal weight estimation [7–17]. MRI has a mean percentage error (MPE) of 2.6%–3.9% compared to 6.3%–6.8% for ultrasound in the same population [7,10,11,17]. However, in all but two existing studies, the interval between MRI examination and birth was no more than 7 days. The two studies with relatively longer MRI-to-birth intervals had small sample sizes and a wide range of birth weights and gestational ages [14,15]. In the clinic, there are administrative difficulties in arranging MRI examinations, and not all women have planned deliveries or are in labour a short time after undergoing the MRI examination. In addition, previous studies demonstrated that the late-term birthweight was underestimated by the equation developed by Baker et al. [8,10,17]. Therefore, we speculated that the term birth weight is also underestimated by the Baker equation, with a large error for foetal weights estimated more than 7 days before delivery; thus, it is necessary to develop new formulas for EFWs for this population. Therefore, the aim of the present study was to develop new formulas to

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estimate foetal weight more than 7 days before birth.

2. Methods

This is a secondary analysis of a prospective study that was performed to predict the delivery model using an MRI-based 3D model of the pelvis and foetus. This study was conducted in a single teaching hospital and approved by the institutional medical ethics committee. Between Jan 2014 and Jan 2017, subjects before labour at ≥37 weeks of gestation were recruited to participate in our prospective study. The inclusion criteria and exclusion criteria were as previously described [17]. Women were eligible if they had a singleton pregnancy without major foetal malformations, with a vertex presentation and a plan to deliver vaginally. Women were excluded if they had multiple pregnancies, non-vertex presentations, contraindications for vaginal delivery or MRI examination, and a plan to undergo a caesarean delivery. The gestational age, which was determined by the time of the last menstrual period and confirmed by first or second trimester biometry, was given in exact weeks. Written informed consent was obtained from all subjects.

Maternal demographic characteristics and relevant clinical information, including delivery data and neonate sex and birth weight, were obtained from the medical records.

2.1. Ultrasound examination

All ultrasound scans were performed by sonographers who had been trained for at least five years and had the ability to detect foetal abnormalities; transabdominal sonography (RAB 2-5-D, Voluson E8; GE Medical Systems, Milwaukee, WI) was used. Foetal weight was estimated using the formula developed by Hadlock et al. in 1985, incorporating head circumference (HC), abdominal circumference (AC) and femur length (FL) [18].

2.2. Magnetic resonance imaging

Detailed information on foetal MR image acquisition has been described elsewhere [17]. All subjects underwent the MRI examination with a 1.5 or 3.0 T GE Signa magnet (Signa HDxt system and Signa EXCITE HD System, GE Company, USA) using a torso coil or an abdominal coil, respectively. Fast imaging employing steady-state acquisition (FIESTA) images in the foetal sagittal plane were acquired for full uterine coverage. The acquisition parameters were as follows: 1.5 T system with TR 4.0 ms, TE 1.7 ms, FOV 40 cm, 4-mm slice thickness, matrix 192 × 256, and NEX 1 or the 3.0 T system with TR 4.2 ms, TE 1.4 ms, FOV 40 cm, 4-mm slice thickness, matrix 224 × 224, and NEX 1. Each image had a 4-mm slice thickness without a gap, and 40–50 consecutive images were acquired. The foetal scan time was approximately 2 min, and the total imaging time was no more than 10 min.

2.3. Three-dimensional reconstruction and volume calculation

The details of the 3D reconstruction and calculation of the foetal volume have also been described elsewhere [17]. In short, the primary foetal MRI data were imported into Mimics software (Materialise's Interactive Medical Image Control System, Version 10.01, Materialise Company, Belgium), and manual segmentation was performed to reconstruct a 3D foetal model (Fig. 1a and b).

The foetal body volume was calculated automatically (Fig. 1c). All foetal reconstructions were performed by one senior researcher with 3 years of experience in foetal image post-processing who was blinded to the birth weights, and the average time required for reconstruction and volume calculation was 25 min.

The EFW was calculated using the equation 0.12 + 1.031 x foetal volume (litre) = MRI weight (kg), developed by Baker et al. [7]

2.4. Statistical analysis

To develop new equations for EFWs more than 7 days before delivery, two-thirds of the foetuses were randomly selected using statistical software and assigned to the testing group, and the remaining one-third of the foetuses were assigned to the validation group. FBV at the time of the MRI examination and birth weight were correlated by a best-fit curve, and the combination of FBV at the time of the MRI examination and the MRI-to-delivery interval were correlated with birth weight with a best-fit curve.

The potential effects of confounding variables on the accuracy of the MRI-EFW based on the new formulas were evaluated with multiple regression analysis.

The accuracy of the foetal weight estimation was assessed by calculating (a) mean percentage error (MPE) = (|birthweight - EFW|/ birthweight)·100%; (b) absolute error(AE) = |birthweight - EFW|; (c) the percentage of EFWs within 5% and 10% of the birth weight.

The general demographic characteristics of the testing and validation groups were compared using independent sample t tests and Mann-Whitney U tests for continuous numerical variables and the Chi-square test for categorical data. Bland-Altman plots were used to assess the bias in the predictions made by each method in the validation group.

Statistical software packages (SPSS, version 20.0, SPSS, Chicago, IL; Excel, version 9.0, Microsoft, Redmond, WA; MedCalc, version 7.4; MedCalc, Mariakerke, Belgium) were used for the data analysis.

3. Results

Of the 301 women who participated in our study, 162 women gave birth more than 7 days after the MRI examination. Among the 162 foetuses, 8 foetuses moved during the MRI examination, and 1 was delivered more than 21 days after the MRI examination. All 9 foetuses were excluded to avoid foetal volume calculation bias and interval bias, so only 153 women were included in the present study. Their general characteristics are shown in Table 1.

To determine whether the widely used model, which includes the Baker and Hadlock formulas, can accurately predict birthweight more than 7 days before birth, foetal weight estimations were performed with both formulas for all foetuses with ultrasound and MRI examinations more than 7 days before delivery. There were 92 foetuses undergoing ultrasound examinations. Table 2 shows that the use of the Hadlock formulas and the Baker equation resulted in large errors in the EFW, with an MPE of more than 8.0%, a mean AE of approximately 0.3 kg, approximately 70% of EFWs with an MPE ≤ 10%.

To develop new equations for foetal weight estimation more than 7 days before delivery, 153 foetuses were divided randomly into a testing group (102) and a validation group (51). The general demographic data of the testing and validation groups are shown in Table 3. There were no significant differences in characteristics between the groups ($P > 0.05$).

The two new models derived from the testing dataset are shown in Table 4. The FBV at the time of MRI examination and the birth weight were significantly correlated according to the following linear equation: birthweight = 0.992*V + 0.507. The combination of FBV and the MRI-to-delivery interval were also significantly correlated with the birth weight according to the following linear equation: birthweight = 1.057*V + 0.029*d, where V is foetal body volume, and d is the MRI-to-delivery interval.

The model based on the volume and MR-to-delivery interval had a better fit than did the one involving only body volume, with a larger correlation coefficient (0.945 vs 0.916) and a larger coefficient of determination (0.894 vs 0.838).

The analysis of accuracy of the newly developed formulas are shown in Table 5 and Fig. 2. Table 5 shows that the MPEs and the proportions of pregnancies with MPEs ≤10% for the MRI-EFWs based on the two new equations were almost the same and were both significantly

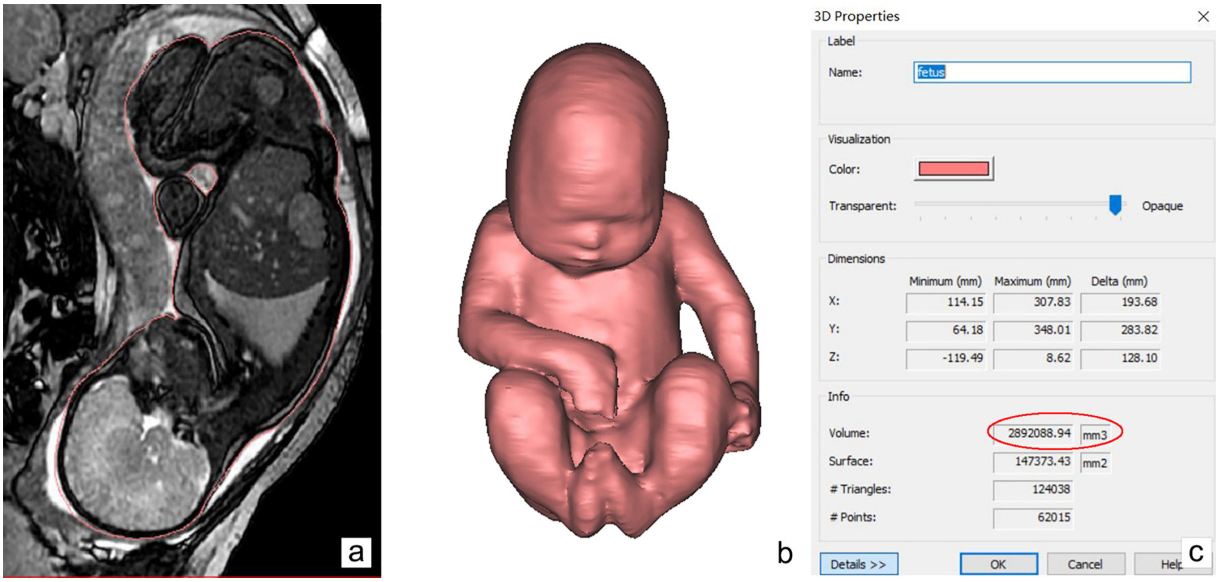

Fig. 1. Cross-sectional image, 3D model and volume calculation of a foetus. (a) Sagittal T2-weighted MR image shows a foetal boundary. (b) A foetal 3D model (c) foetal volume is 2892088.94 mm^3.

Table 1
General characteristics of the 153 subjects.

Characteristic	Mean ± SD
Maternal age (years)	27.7 ± 3.5
Maternal BMI (kg/m^2)	26.2 ± 3.1
Birth weight (kg)	3.375 ± 0.399
Gestational age at MRI (days)	272.9 ± 2.2
Gestational age at delivery (days)	284.9 ± 3.3
MRI-to-delivery interval (days)	12.1 ± 3.5
Ultrasound-to-delivery interval (days)	9.9 ± 5.3

Table 2
Comparison of the accuracy of the widely used models based on ultrasound and MRI for predicting foetal birth weight.

Model	AE (kg)	Mean ± SD of MPE (%)	Percentage of predictions within	
			≤5%	≤10%
Ultrasound	0.294	8.6 ± 5.1	26 (28.2%)	59 (64.1%)
Baker model	0.276	8.1 ± 4.2	40 (26.1%)	108 (70.6%)

smaller than that of the MRI-EFWs based on the Baker equation, MPEs were 3.9%, 3.9%, and 7.7%, respectively, and the proportions of pregnancies with MPEs ≤10% were 92.2%, 90.2% and 72.5%, respectively.

Table 4
New models for predicting birth weight more than seven days before birth.

Model	R	R^2	F	P value
Birthweight = 0.992*V + 0.507	0.916	0.838	518.4	< 0.001
Birthweight = 1.057*V + 0.029*d	0.945	0.894	416.7	< 0.001

V body volume, d interval between examination and delivery.

Table 5
Comparison of the accuracy of the different equations for predicting the birth weight in validation group.

Model	AE (kg)	Mean ± SD of MPE(%)	Percentage of predictions within	
			≤5%	≤10%
MR1	0.266	7.7 ± 4.4	27.5	72.5
MR2	0.128	3.9 ± 3.6	64.7	92.2
MR3	0.125	3.9 ± 2.9	72.5	90.2

AE absolute error, MPE mean percentage error, SD standard deviation.
MR1 Baker equation.
MR2 birthweight (kg) = 0.992 (kg/litre)*V (litre) + 0.507.
MR3 birthweight (kg) = 1.057 (kg/litre)*V (litre) + 0.029 (kg/days)*d (days).

Bland-Altman scatter plots of the differences between the estimates and the actual birth weights in Fig. 2 shows that the MRI-EFW

Table 3
Comparison of general data between the testing and validation groups.

Characteristic	Testing group (n = 102)	Validation group (n = 51)	P value
Maternal age (years)*	28.0 ± 3.7	27.2 ± 3.1	0.201
Maternal BMI (kg/m^2)#	26.1 ± 3.2	26.3 ± 3.2	0.738
Birth weight (kg)#	3.399 ± 0.396	3.327 ± 0.405	0.315
Gestational age at MRI (days)#	272.8 ± 2.3	273.1 ± 2.1	0.526
Gestational age at delivery (days)#	284.7 ± 3.2	285.4 ± 3.5	0.198
MRI-to-delivery interval (days)#	12.0 ± 3.4	12.4 ± 3.6	0.558
Sex			0.865
Female	54 (52.9)	28 (54.9)	
Male	48 (47.1)	23 (45.1)	

BMI body mass index, MRI magnetic resonance imaging.
Data are expressed as the mean ± standard error, except for sex, which is expressed as a percentage (number).
* Two sample t test, #Mann-Whitney U test, Pearson Chi-squared test for sex.

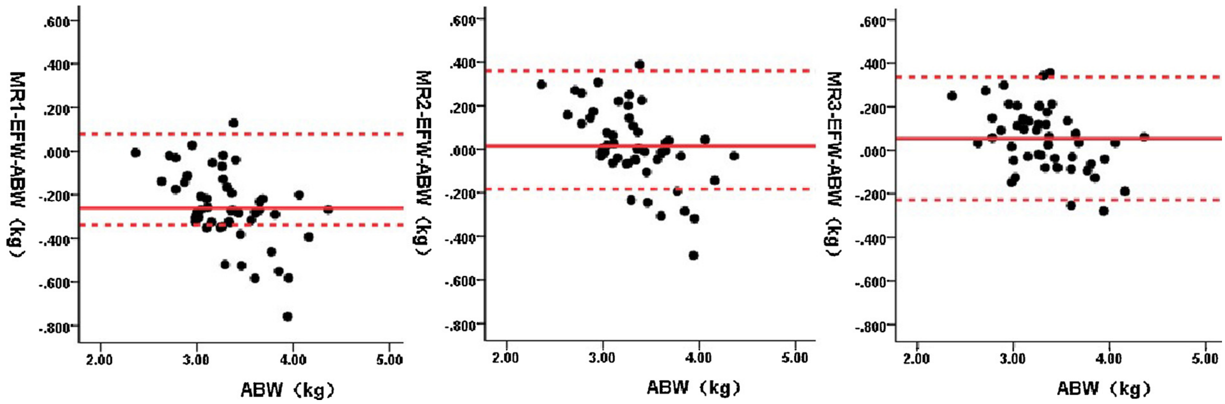

Fig. 2. Bland-Altman scatter plots of the differences between the estimates and the ABWs. The dotted lines represent the mean ± 1.96 SD (95% confidence interval) of the differences, and the solid line represents the mean difference between the EFWs and the birthweights. The plots show the narrowest limits of agreements but the largest proportion of estimates outside the 95% agreement limits and the largest range of differences for estimates made with the Baker equation.
ABW actual birth weight,
MR1 Baker equation,
MR2 birthweight (kg) = 0.992 (kg/litre)*V (litre) + 0.507,
MR3 birthweight (kg) = 1.057 (kg/litre)*V (litre) + 0.029 (kg/days)*d (days)

calculated with the Baker equation had the narrowest 95% limits of agreement and the largest proportion of estimates outside of the 95% limits of agreement, 21.6%, and the largest range of estimate error, −0.758 to 0.129 kg. The two newly developed equations had similar 95% limits of agreement but the equation involving only volume had a slightly higher proportion of estimates outside of the limits of agreement (15.6% versus 7.8%) and a slightly higher estimated error range (−0.487 kg to 0.388 kg vs −0.279 kg to 0.355 kg).

To investigate the potential effects of confounding variables including foetal sex, birth weight, gestational age at the time of MRI examination, and MRI-to-delivery interval on the accuracy of the MRI-EFW, multiple regression analysis was performed. The results in Table 6 shows that the MPE of the EFW calculated with the equation incorporating only volume was not associated with the studied variables. However, the EFW calculated with the equation incorporating volume and MRI-to-delivery interval was significantly correlated with the birth weight, with a relatively smaller birth weights associated with a larger error.

4. Discussion

Our study first demonstrated that the Baker equation significantly underestimated foetal weights when the birth occurred more than 7 days after the MRI examination; however, the two newly developed formulas significantly improved the estimations of those foetal weights, with an MPE of 3.9% and 90.2% of estimates within 10% of the birth weight. The equation incorporating the foetal volume and the MRI-to-delivery interval performed slightly better than the one incorporating only volume. Furthermore, we did not find that the MPE of the equation involving only the body volume was significantly associated with any variables including foetal sex, birth weight, gestational age or the MRI-to-delivery interval. The MPE of the formula involving a combination of volume and the MRI-to-delivery interval was only significantly associated with the foetal weight. The smaller the foetal weight was, the larger the error.

We were not surprised to find that the foetal weight estimated more than 7 days before birth was significantly underestimated by the Baker equation and ultrasound. A large number of studies on the ultrasound-based estimation of foetal weight have shown that the equation determines the accuracy of the estimate [6]. However, to the best of our knowledge, while there have been four equations used in the existing studies on MRI-EFW, only the one developed by Baker et al. has been validated [7,11,14,17]. Furthermore, all the equations currently used were derived from births within a week after examination, which means that they are better suited for the estimation of foetal weight within seven days of birth. Moreover, prior studies have demonstrated that the best accuracy of sonographic weight prediction with most of the commonly used formulas was achieved within one week before delivery, the longer time delay between delivery and examination was, the larger error [19,20]. Additionally, the estimated error by using ultrasound and MRI in the present study are larger than our previous study (MPE, 8.6% vs 6.7% for ultrasound, 8.1% vs 3.9% for MRI) [17]. Therefore, it was necessary to develop new formulas for the estimation of foetal weight more than seven days before birth.

Table 6
Regression analysis of the effect of variables on the EFW generated with the new equations.

Characteristic	MR1 model		MR2 model	
	Regression coefficient (95%CI)*	P value	Regression coefficient (95%CI)*	P value
Sex	−0.003 (−0.044 to 0.010)	0.816	0.001 (−0.015 to 0.018)	0.874
Male				
Female				
Birthweight (kg)	−0.017 (−0.044 to 0.010)	0.202	−0.024 (−0.044 to −0.004)	0.021
Gestational age at MRI (days)	−0.002 (−0.007 to 0.004)	0.549	−0.002 (−0.006 to 0.003)	0.448
MRI-to-delivery interval (days)	1.838E–0.005 (−0.003 to 0.003)	0.991	0.001 (−0.002 to 0.003)	0.498

*Data in parentheses are the 95% confidence intervals.
MPE mean percentage error. SD standard deviation. BMI body mass index.
MR1 birthweight (kg) = 0.992 (kg/litre)*V (litre) + 0.507.
MR2 birthweight (kg) = 1.057 (kg/litre)*V (litre) + 0.029 (kg/days)*d (days).

Foetal body volume is the only independent factor in the existing MRI-EFW equations, and it is a convenient variable to use for estimating the foetal weight. The reason for choosing foetal body volume as the independent factor instead of other anatomic measurements is that volume contains both bone and soft tissue and does not change significantly in a short time. However, the MRI-to-delivery interval was found to have a marginal effect on the MPEs of EFWs made within a week of birth in our previous study, so we postulated that it would have an effect on the estimates of birth made more than a week before birth, with a wide range of MRI-to-delivery interval, and a regression formulas involving volume and MRI-to-delivery interval was developed [17]. Our results demonstrated that there was a slightly higher coefficient of determination (R^2) for the model incorporating volume and MRI-to-delivery interval than for the one incorporating only volume, which indicates that the former model explains a slightly higher percentage of the observed variability. We think this difference is clinically significant. The results of the validated analysis also showed that both newly developed formulas accurately predict foetal weight, but the formula involving a combination of volume and MR-to-delivery was slightly superior to the other formula, resulting in a higher proportion of EFWs within the 95% agreement limits and with MPEs within 5%. Therefore, the inclusion of the MRI-to-delivery interval can improve the accuracy of the EFW.

By far, apart from our present study, only two studies have evaluated the accuracy of weight estimation by using MRI for fetus remote from delivery. Both studies were reported by Kadji et al [14,15]. The first one included 37 fetus for weight estimation by using the formula developed by Kacem et al. with large ranges of gestational ages (31.1 weeks to 36.9 weeks), time delays between examination and delivery (mean 6 weeks) and neonatal birth weights (1920–4830 g). The authors found that the MPE was 4.11% (0.20–13.24) [14]. The second one evaluated 83 fetuses with a mean MRI-to-delivery of 3 weeks by using Baker equation [15]. In the second study, the authors aimed to detect the rate of the large-for-dates neonates by comparing the areas under the curve between MRI and ultrasound performances, and the MPE, which taking systematic and random errors into consideration, and the percentage of estimated foetal weights within 5% and 10% of the birth weight, are the fundamental types of prediction error, were not evaluated. Therefore, these findings are not directly comparable to our present results.

Although we attempted to develop a new model that was highly accurate at estimating the foetal weight based on MRI, approximately 10% of the estimates were not within 10% of the birth weights. Multiple regression analysis showed that only the birth weight had a significant effect on the MPE in the model incorporating volume and the MRI-to-delivery interval; the smaller the birth weight was, the larger the estimated error. This finding might be explained by the fact that small babies grow more slowly than do large babies, which means that changes in the regression coefficient cannot completely explain the weight change. Furthermore, the effect of birth weight is very small, with every increase of a kilogram explaining one percentage of error, which also explains why the precise model is more susceptible to this effect.

There are some strengths in our study, including a large population examined between 2 and 3 weeks before delivery with small ranges of gestational ages and birth weights. Another strength is that two new equations were developed and validated in a different population, which is very important for determining the performance of the new model. Last, multiple regression analysis was performed to investigate the potential effect of confounding variables on the accuracy of the estimated weights.

There are also some limitations in our study, including its retrospective nature and focus on normal term pregnancies, as reflected in the fact that there were only eleven abnormal birth weights, with ten infants with macrosomia and one with a low birth weight. Another limitation is that the volume calculation is time consuming, which might limit its clinical use. In the present study, we performed manual segmentation to obtain the foetal body volume because manual segmentation is the standard method of image segmentation. Furthermore, manual segmentation is simple and does not require advanced knowledge of anatomy because of the good contrast between the foetal surface and surrounding tissues. Last, the software used for manual segmentation is readily available on the open market; thus, this method is suitable for hospitals without advanced image post-processing software and technology and for studies requiring accurate segmentation. The primary purpose of this study was to develop a new formula to estimate foetal weight more than a week before birth, and an accurate volume calculation was required. There is no doubt that the semi-automatic volume calculation reported by Kadji et al. is more suitable for clinic practice [13]. We believe that with the advancement of science and technology and the popularity of software, many hospitals can also use the semi-automatic volume calculation method.

5. Conclusion

In conclusion, the MR-EFWs generated with the Baker formulas were not accurate more than seven days before birth, but the estimates made with the newly developed equations were significantly improved. It should therefore be appropriate to use the new formulas for fetuses more than 7 days before delivery and thus improve the fetal weight estimation for fetuses in this condition.

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