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Research article

A modified model can improve the accuracy of foetal weight estimation by magnetic resonance imaging☆

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ABSTRACT

Purpose: To determine whether birth weight can be reliably estimated using three-dimensional (3D) magnetic resonance imaging (MRI) foetal body volume at term.

Method: Foetuses between 37^{+5} weeks and 41 weeks of gestation were delivered within 7 days after MRI and ultrasound (US) examinations. 3D foetal models were reconstructed from MRI data, and body volume was calculated. The MRI-based weight estimations were calculated using the Baker equation and the modified Baker equation with a higher density coefficient. The US-based weight estimations were determined using the formula by Hadlock. Estimations based on MRI and US were compared with the birth weights.

Results: Among 22 foetuses that underwent both US and MRI evaluations within 48 h before labour, the mean random errors for the estimated weight based on US, the Baker equation and the modified Baker equation were 6.5%, 4.8%, and 4.8%, respectively, and these methods correctly estimated the weights of 77.3%, 86.4% and 100% of the foetuses to within 10% of the actual birth weight. The weights of 95.5% of the foetuses were underestimated by the Baker equation. Similar findings were observed among 103 estimations based on both US and MRI within 7 days before delivery. The mean relative error of the MRI-determined estimate of foetal weight using the modified Baker equation was not significantly associated with foetal sex, birth weight, gestational age at MRI examination, the MRI-to-delivery interval or the type of MRI scanner.

Conclusion: A modified Baker equation with a high-density coefficient can improve the accuracy of foetal weight estimation based on 3D MRI foetal volume at term, and its accuracy was not significantly affected by foetal characteristics or the type of MRI scanner among births occurring within 7 days after examinations.

1. Introduction

Foetal weight is a major indictor for evaluating foetal growth and is an important factor in management decisions regarding delivery mode and timing [1,2]. Ultrasound (US) is the main imaging modality for foetal weight estimation, as it is portable, inexpensive and easy to perform. However, US measurements may be hindered by factors such as maternal obesity, oligohydramnios, and foetal posture, resulting in a mean percentage error of 6–20% [3–7]. Magnetic resonance imaging (MRI) was introduced to obstetrics in 1983 and has played an important complementary role in antenatal diagnosis, as it provides a larger viewing field, safety and high soft tissue contrast with no radiation exposure [8–10].

All prior studies have demonstrated that MRI is more accurate than US in foetal weight estimations, with a mean percentage error of 3.0% [11–18]. However, foetal weight at term was underestimated by the widely used equation developed by Baker et al., and the use of a high foetal density was suggested for term foetuses [12,14]. Nevertheless, to date, no prospective trial has been conducted to test the accuracy of the new equation. In addition, the US-to-delivery interval has been found to be associated with estimate of foetal weight-birth weight (EFW-BW) error [19]; however, whether it applies to magnetic resonance-estimated foetal weight (MR-EFW) remains unclear. Baker et al. developed the formula for MRI-estimated foetal weight based on births within 7 days after MR examination, but almost all subsequent studies included foetuses with a shorter interval between evaluation and delivery

☆ This is a single-institution study conducted at NanFang Hospital, Southern Medical University.

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[11–12,14–18]. Furthermore, two studies concerning the effect of various factors on the accuracy of MRI-based foetal weight estimates had small sample sizes [12,20].

Therefore, in the present study, by using foetal body volume calculated from a three-dimensional (3D) foetal model, we sought to determine whether a modified Baker equation with a high foetal density coefficient would improve the accuracy of foetal weight estimates for term foetuses and to explore the effect of possible variables on the accuracy of MRI estimates.

2. Methods and materials

This was a secondary analysis from a single-institution observational study, which was conducted to predict cephalic delivery outcomes based on digital 3D pelvic and foetal models. This study was approved by the institutional medical ethics committee. We retrospectively included cases that satisfied the entry criteria for this study.

Between Jan 2014 and Dec 2016, pregnant women were prospectively recruited to participate in the study from the clinic at a teaching hospital. Women with a singleton pregnancy at ≥37 weeks of gestation, a vertex presentation, suspected macrosomia and cephalopelvic disproportion (CPD), a contracted pelvis, and a planned vaginal delivery without indications for caesarean section were included. The exclusion criteria were a non-vertex presentation, multiple pregnancies, planned caesarean section, major foetal malformations and contraindications on MRI examination. All the subjects provided their written informed consent.

In the present study, women who delivered a live-born infant within 7 days after MRI and US examinations were included in the analysis. For all patients, gestational age was based on the last menstrual period and/or confirmed with first or second trimester US scans.

2.1. Ultrasound examination

Ultrasounds were performed as part of routine clinical practice in the clinic for women at term (37–40 weeks). All US examinations were performed using transabdominal sonography (RAB 2-5-D, Voluson E8; GE Medical Systems, Milwaukee, WI) by maternal-foetal medicine specialists with at least five years of training. Foetal weight was estimated using the formula developed by Hadlock et al. in 1985, which is currently widely used in clinical practice [21].

2.2. Magnetic resonance imaging

Foetal MR images were acquired in the supine position in a 1.5 or 3.0 Tesla GE Signa magnet (Signa HDxt system and Signa EXCITE HD System, GE Company, USA) with a torso coil or an abdominal coil, respectively. Fast imaging employing steady-state acquisition (FIESTA) in the foetal sagittal plane was performed with the following parameters: for the 1.5 Tesla system, the field of view (FOV) was 400 mm, repetition time (TR) was 4.0 ms, echo time (TE) was 1.7 ms, matrix was 192 × 256, and NEX was 1; for the 3.0 Tesla system, the FOV was 400 mm, TR was 4.2 ms, TE was 1.4 ms, matrix was 224 × 224, and NEX was 1. Each image had a 4-mm slice thickness without a gap. The FIESTA sequence incorporated the entire gravid uterus and pelvis, and an average of 40–50 images were acquired. The FIESTA scan time was approximately 2 min, and the total imaging time was 10 min or less without requiring patients to hold their breath or be sedated.

2.3. Three-dimensional reconstruction and volume calculation

The FIESTA data were imported into Mimics 10.01 (Materialise's Interactive Medical Image Control System, Version 10.01, Materialise Company, Belgium) for 3D reconstruction. On the Mimics software interface, foetal boundaries were identified clearly and segmented in a cross-sectional image layer by layer to generate a new foetal mask (Fig. 1a). Then, the foetal mask was translated into 3D models (Fig. 1b). The foetal body volume was calculated automatically (Fig. 1c). All 3D reconstructions were completed by one senior maternal-foetal researcher who was trained in maternal-foetal image post-processing and blinded to the US estimations and birth weights, and the total time required to create a 3D reconstruction was approximately 25 min.

Foetal weight estimations were calculated with the equation 0.12 + 1.031 x foetal volume (mL) = MRI weight (g), developed by Baker et al., and with the modified Baker equation of 0.12 + 1.07 x foetal volume (mL) = MRI weight (g) with a foetal density of 1.07, as proposed by Utiol et al. [11,12].

2.4. Statistical analysis

To determine whether the modified Baker equation can improve the accuracy of MRI foetal weight estimates, the estimated foetal weight was compared with the actual birth weight. The accuracy of the foetal weight estimation was examined by calculating the mean percentage error (MPE) as follows: (|BW - EFW|/BW)·100%, where EFW is the estimate of foetal weight and BW is the birth weight.

Differences in estimations by different methods were assessed by comparing MPE, absolute error (AE) and the percentage of estimated foetal weights within 5% and 10% of the birth weight in each group (group 1 was defined as estimations made by both US and MRI within 2 days prior to delivery, and in group 2, the estimations were made within 7 days before delivery). Nonparametric tests for continuous numerical variables and the chi-square test and Fisher's exact test for categorical data were used. Bland-Altman plots were used to assess the bias of the predictions of each method in both groups.

Multiple regression analysis was used to further evaluate the effect of the following variables on the accuracy of MRI-based foetal weight estimates by the equation with the better accuracy made within seven days before delivery: foetal gender (male, female), birth weight, and gestational age at MRI, time delay between MRI examination and delivery, and the type of MRI scanner (1.5 T, 3.0 T).

The data were analysed with statistical software packages (SPSS, version 20.0, SPSS, Chicago, IL; Excel, version 9.0, Microsoft, Redmond, WA; MedCalc, version 7.4; MedCalc, Mariakerke, Belgium). A two-sided P value less than 0.05 indicated a statistically significant difference.

3. Results

A total of 301 foetuses underwent prospective MRI scanning, all scans were reconstructed into 3D models, and the averaged post-processing time was approximately 25 min. Of 139 MRI examinations performed within 7 days before delivery, 4 (Fig. 2) presented different degrees of discontinuity and dislocation resulting from foetal movements; these subjects were excluded to avoid potential volume calculation errors. Of the remaining 135 subjects, 103 were delivered within 7 days of both the MRI and US examinations and 22 were delivered within 2 days of both examinations. The demographic data for the women and foetuses are summarized in Table 1. No foetus had any congenital malformations.

Using the Baker equation, 95.5% and 96.1% of the EFWs were less than the birth weights of infants born within 2 days and 7 days after MRI examination, respectively, and 59.0% and 71.8% for the modified Baker equation. Table 2 shows that the predicted MPE within 2 days before delivery did not differ significantly from the US-EFW, MR-EFW by the Baker equation and MR-EFW by the modified Baker equation (6.5%, 4.8%, and 4.8% respectively, $p = 0.701$), and there was a significant difference in the AE between the US-EFW, MR-EFW by the Baker equation and MR-EFW by the modified Baker equation (0.213 kg, 0.154 kg, and 0.093 kg, respectively, $p = 0.043$). A larger proportion of estimates was within 5% and 10% of the actual birth weight (ABW) using the MR-EFW than with the US-EFW, and the modified Baker equation had the best performance. Analysis of the predictions within 7

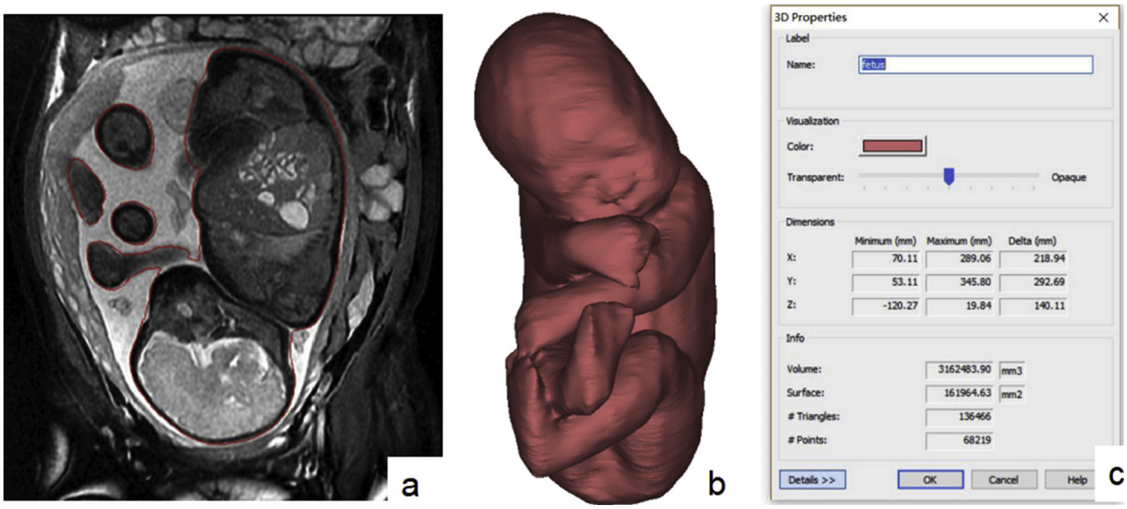

Fig. 1. Cross-sectional image, 3D model and volume calculation of a foetus. (a) Sagittal T2-weighted MR images show a foetal boundary. (b) A foetal 3D model (c) foetal volume 3,162,483.9 mm3.

days before delivery showed that there were significant differences in MPE and AE between US-EFW, MR-EFW by the Baker equation and MR-EFW by the modified Baker equation (MPE 6.7%, 6.4%, 3.9%, $P < 0.001$; AE 0.223 kg, 0.215 kg, 0.131 kg, $P < 0.001$). US-EFW and MR-EFW by the Baker equation had a similar proportion of estimates within 5% and 10% of the ABW, and the MR-EFW by the modified equation had the largest proportion (68.0% and 94.1%, respectively).

In Fig. 3, the Bland-Altman scatter plots show narrower limits of agreement for MRI estimates compared with those for US-EFW, regardless of whether the Baker equation or the modified Baker equation was used and whether the examinations were performed within 2 days or 7 days of delivery.

Above all, the modified Baker equation provided a more accurate estimate than the Baker equation and was thus selected for further analysis of the effect of factors on the accuracy of MR-EFW. In 135 foetuses delivered within 7 days of MRI examination, the mean MPE was 3.9%. The multiple regression analysis in Table 3 showed that the MPE of MR-EFW by the modified Baker equation was not significantly associated with foetal gender, birth weight, gestational age at MRI, the MRI-to-delivery interval and the type of MRI scanner, all p values were greater than 0.05.

Although foetal gender has been widely demonstrated to be associated with US-EFW, no previous studies found differences in MR-EFW between males and females. Therefore, we performed a post hoc power analysis with 90% power to detect a 5% difference in MPE between males and females based on the differences and the standard deviation of the MPE that were found between the foetal gender subgroups. Our results showed that 10,688 males and 10,688 females are needed to detect a difference between males and females.

Table 1
Demographic characteristics of two groups of women and foetuses.

	≤2 days (n = 22)	≤7 days (n = 103)
Maternal age (years)	26.4 ± 3.1	27.3 ± 3.4
Maternal body mass index (kg/m^2)	25.6 ± 3.0	25.7 ± 2.5
Birth weight (kg)	3.203 ± 0.376	3.293 ± 0.360
Gestational age at birth (weeks)	277.0 ± 5.2	279.1 ± 4.4
MRI-to-delivery interval (days)	1.4 ± 0.6	4.1 ± 2.0
US-to-delivery interval (days)	1.0 ± 0.5	2.8 ± 2.1
Male foetus	36.4%(8)	52.4%(54)

Data are expressed as the mean ± standard error, except for Male foetus as percentage (number).

4. Discussion

To our knowledge, this is the largest study of late-term foetal weight prediction based on volume calculated from a 3D MRI model. There are some key findings of our study. First, MRI was more accurate than US in foetal weight estimation. Second, the Baker equation tended to underestimate foetal weight in the late term, and the modified Baker equation

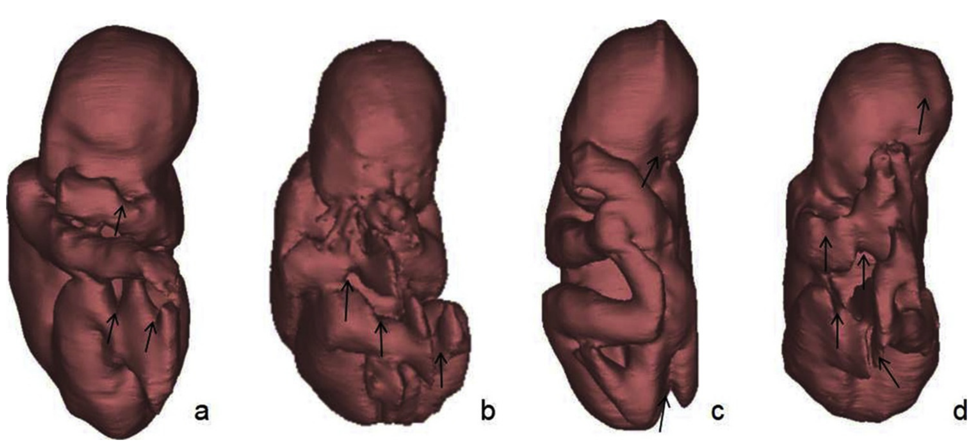

Fig. 2. Cases with varying degrees of foetal motion. a and b show a foetal foot with discontinuity, indicating a minor motion; c and d show the foetal body, head and foot with an obvious discontinuity, indicating a large motion. The arrows point to positions of fetal movement.

Table 2
Comparison of the accuracy of foetal weight estimations by various methods performed within two or seven days before delivery.

Model	AE (kg)		Mean ± SD of MPE (%)		Percentage of predictions within			
					5%		10%	
	≤2 days	≤7 days	≤2 days	≤7 days	≤2 days	≤7 days	≤2 days	≤7 days
US	0.213	0.223	6.5 ± 5.5	6.7 ± 4.7	54.5	46.5	77.3	75.7
MR1	0.154	0.215	4.8 ± 3.5	6.4 ± 3.9	63.6	42.7	86.4	75.7
MR2	0.093	0.131	4.8 ± 3.5	3.9 ± 3.1	81.8	68.0	100	94.1
P	0.043	< 0.001	0.701	< 0.001	0.148*	< 0.001*	0.083#	< 0.001*

AE: absolute error, MPE: mean percentage error, SD: standard deviation.
MR1: foetal weight estimation by the Baker equation, MR2: foetal weight estimation by the modified Baker equation.
≤2 days: estimations made by both US and MRI within 2 days prior to delivery.
≤7 days: estimations made by both US and MRI within 7 days prior to delivery.
Nonparametric tests were used for AE and MPE. *chi-square tests, # fisher exact test.
P indicates comparisons performed between different models in each group.

improved the accuracy of weight estimates. Third, the MPE of weight estimations by the modified Baker equation was not significantly associated with foetal sex, birth weight, gestational age at MRI, the examination-to-delivery interval or the type of MRI scanner.

It took approximately 25 min to produce the 3D foetal model and volume, a dramatically shorter time than the 3 h reported in a previous similar study [13]. Additionally, in a large number of foetuses, we found that foetal motion can be more easily identified in 3D models than in cross-sectional images because foetal movement can be frozen with the use of fast MRI sequences. In 4 cases, motion artefacts were not detected on the 2D images, but obvious discontinuities were present in the 3D models. However, there was no evidence that the error of the estimate increased for these foetuses.

In this study, we confirmed that the foetal weight was underestimated by the Baker equation and that a modified equation with a higher foetal density coefficient could improve the accuracy of estimates in term foetuses. The eleven foetuses included in Baker's study covered a wide range of gestational ages (35.0–41.9), and the formula developed based on these cases had a foetal density coefficient of 1.031 [11]. However, in Uotila and Zaretsky's studies, foetal weight was underestimated when the Baker equation was used for foetuses over 39 weeks of gestational age. The higher foetal density of 1.07 proposed by Uotila helped to explain these underestimations [12,14]. In the present study, we first validated that the modified Baker equation, with a foetal density of 1.07, performed better than the original Baker formula for foetal weight estimations. Although foetal density has been demonstrated to vary with gestational age and was higher in near-term than in term foetuses [15], previous results and our findings indicated that a higher density was more appropriate for late-term foetuses. Further studies are needed to address this problem.

Similar to previous studies, we found that MRI was better than US in foetal weight estimates when performed within 2 days before delivery [11–18], but only the modified Baker equation was obviously more accurate than US in weight predictions in examinations performed within 7 days before delivery. This result may be explained by the effect of continued foetal growth. The wider the examination-to-delivery interval, the greater the increased weight. Therefore, the relative error created from the Baker equation, which underestimated the foetal weight in 96.1% of cases, was larger than that from the modified equation. Another interesting finding was that MRI was more accurate than US in weight estimation despite a longer MRI-to-delivery interval. It is possible that the increased foetal weight at a late gestational age mainly depends on the accretion of soft tissue, while body volume that includes soft tissue is more likely to reflect the foetal growth at term than the diameters and circumference measurements can [22]. In addition, MRI volumetry is not affected by maternal BMI, foetal gender, operator experience, etc., which have been demonstrated to pose effects on US biometry [20,24,25]. Although the examination-to-delivery interval is associated with the accuracy of the weight estimation, the systematic error in predicting foetal weight is not significantly affected by weight gain during a short time when the systematic error is relatively small. That reasoning also explains that why the modified equation is better than Baker equation is in weight estimations when the births occur within 7 days after examination.

The effect of the MRI-to-delivery interval on the measurement error of estimates is also of concern for clinicians when making decisions. Almost all previous validation studies included foetuses delivered by elective caesarean or induction with an MRI-to-delivery interval of no more than 48 h [12,14,15,17,18]. However, in clinical practice, most births do not occur soon after MRI examinations. Information regarding the accuracy of estimates in foetuses with a relatively wide range of intervals is more important for clinical practices. Our results indicated that estimates obtained by the modified Baker equation and not by the Baker equation were more accurate than those obtained by US in births occurring within 7 days after both examinations, with a 3.9% MPE, and 94.1% of cases had a relative error of less than 10% (6.7% and 75.7%, respectively, for US). Therefore, the modified equation is suggested to be applicable to weight estimates in births occurring within 7 days after MRI examination.

Although the modified Baker equation was better than US in foetal weight estimations, the MPE (3.9%) was still slightly higher than that in the primary study (3.0%). However, a few studies exist in the literature concerning factors affecting the accuracy of the MRI foetal weight estimate. Zito et al. performed foetal weight estimations in 20 births occurring within 3 days after MRI examination and found that the mean relative error was associated with the women's BMIs but not with any other variables, including foetal gender, gestational age at delivery, birth weight and maternal diabetes, or even operator experience and MRI sequence [20]. In this study, variables including foetal gender, birth weight, gestational age at MRI, the MRI-to-delivery interval and the type of MRI scanner were not significantly associated with the mean relative error of MR-EFW by the modified Baker equation. However, we have to pay attention to the effect of the MRI-to-delivery interval and the type of MRI scanner on estimations because both p values showed marginal significance in the multiple regression analysis. This suggested that there was potential effect of foetal growth on estimations, as well as explained why previous validation studies including births occurring within 2 days of MRI yielded a smaller MPE than that in the present study.

To our surprise, the type of MRI scanner (1.5 T, 3.0 T) might have potential effect on MPE. In this study, all examinations were performed with the same slice thickness and slice gap to avoid the confounding effects of these factors. Additionally, as discussed above, we created foetal 3D models to ensure that we included cases with satisfactory MRI data for analysis, which helped us reduce the bias of volume calculation caused by incorrect segmentations and potential foetal and maternal

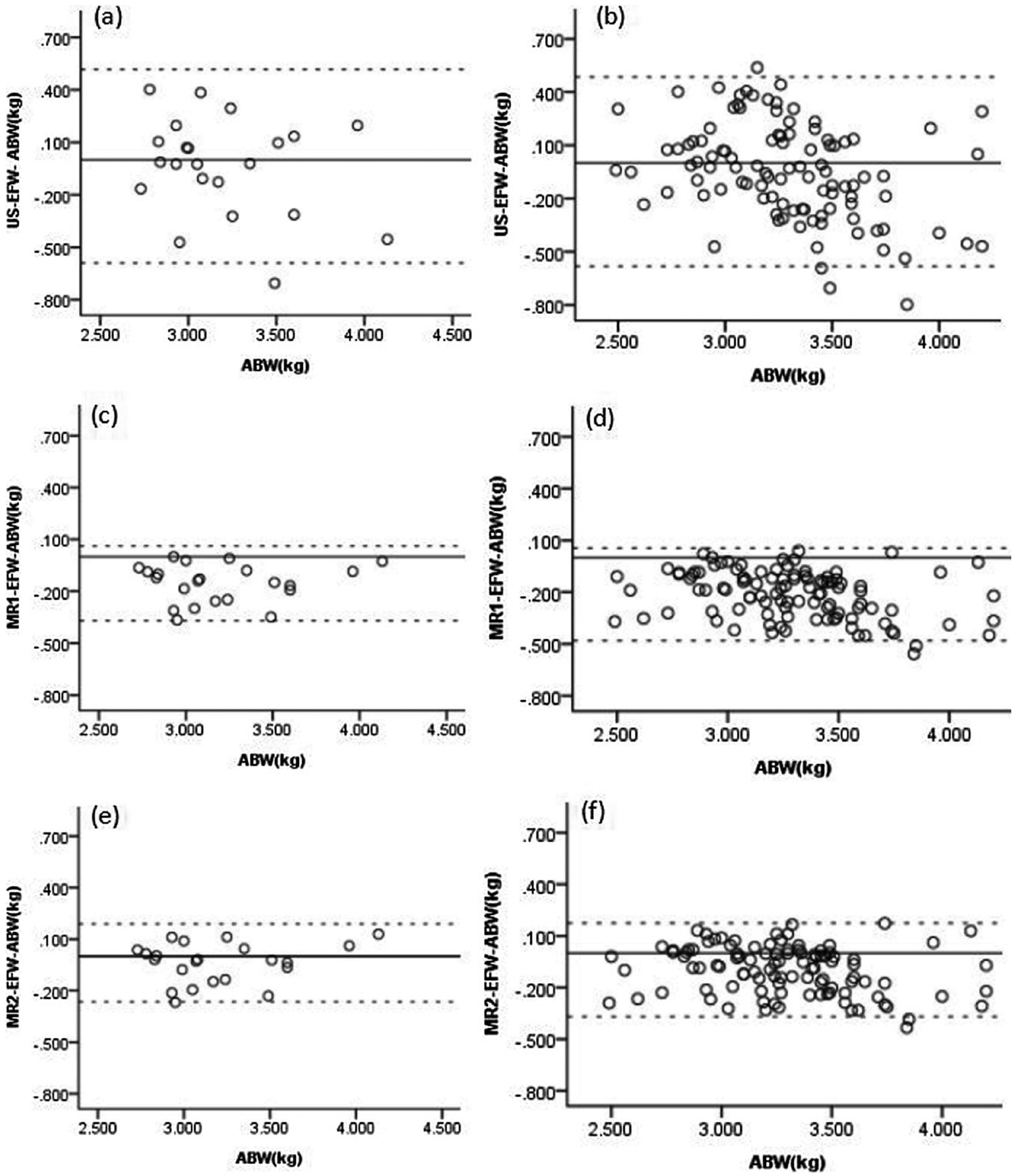

Fig. 3. Bland-Altman scatter plots of the difference between estimates and ABW. The dotted lines represent the mean ± 1.96 SD (95% confidence interval) of difference, the solid line represents zero. The plots show narrower limits of agreements for MR estimates, whether with the Baker equation or modified Baker equation, whether within 2days or 7days, compared with US-EFW. (a) US-EFW within 2days of delivery. (b) US-EFW within 7days of delivery. (c) MR1-EFW within 2days. (d) MR1-EFW within 7days. (e) MR2-EFW within 2days. (f) MR2-EFW within 7days.
ABW actual birth weight; EFW estimate fetal weight. MR1-EFW EFW by Baker equation; MR2-EFW EFW by the modified Baker equation.

motion. The only difference was that the gestational age at MRI in the 1.5 T group was significantly greater than that in the 3.0 T group (276 days vs 273 days, P < 0.001). However, the gestational age at MRI was not associated with MPE of MR-EFW. Therefore, whehter the type of MRI scanner has effect on accuracy of MR-EFW remains to be evaluated in further studies.

Inconsistent with the US-EFW results, our results showed that foetal gender, birth weight, and gestational age at examination were not associated with MR-EFW accuracy [23–25]. This may be because 95.6% of the birth weights ranged from 2.5 kg to 4.0 kg and because the gestational ages at examination were all over 38 weeks in our population. The gender differences in foetal growth patterns and body composition impact weight estimates obtained by measurements of certain diameters with ultrasound [24]. Estimating weight by volume, which considers changes in body volume caused by fat and soft tissue, may reduce these differences and explain why both Zito et al. and our group detected that foetal gender was not related to the relative error of MR-EFW.

Our new findings add to the literature, but there are also some limitations of our study. First, our population consisted primarily of foetuses with normal birthweights; only one foetus weighed less than 2.5 kg and 5 weighed more than 4.0 kg, making it unclear whether our results are applicable to foetuses with extreme birth weights. As we obtain more data, it may be possible to assess the MR-EFW in detail.

Table 3
Regression analysis of the effect of variables on EFW using the modified Baker equation.

Characteristic	No. of foetuses (MPE%) or mean ± SD	Multiple regression analysis	
		Regression Coefficient (95%CI)[a]	p
Gender		−0.003 (−0.011 to 0.005)	0.400
Male	65 (3.8)		
Female	70 (3.7)		
Birth weight (kg)	3.265 ± 0.36	−0.006 (−0.017 to 0.005)	0.292
Gestational age at MRI (days)	274.9 ± 3.9	0.001 (−0.001 to 0.002)	0.310
Time delay between MRI and delivery (days)	4.1 ± 1.9	−0.002 (−0.004 to 0.000)	0.055
Type of MRI scanner		0.008 (0.000 to 0.017)	0.051
1.5 T	75 (4.2)		
3.0 T	60 (3.3)		

MPE, mean percentage error. SD standard deviation. BMI body mass index.
[a] Data in parentheses are 95% confidence intervals.

Second, compared with the time required for the latest reported semi-automated segmentation techniques, it is time consuming to manually perform foetal segmentation [17,18]. The semi-automated segmentation via a home-built user interface programmed in the MATLAB (matrix laboratory) environment includes the following: first, the voxels that potentially represent the foetal skin were automatically searched by selecting the low-intensity pixels surrounded by two layers of higher intensity. Second, when a point on the foetal border is selected, the program automatically searches for a path of skin pixels connected to the selected points and adds new points along it, which can be copied to the adjacent slice automatically, thus reducing the manual operation. Last, incorrect segmentation can be automatically corrected at each step [17]. The greatest strength of this new semi-automated method is the shorter time for segmentation and its more likely acceptability in clinical practice. However, in the first step, the key to pixel extraction in foetal skin is having a large pixel difference between the foetal skin and surrounding tissues, while the decrease in amniotic fluid in late-term pregnancy increases the parts of the foetus without amniotic fluid surrounding. This phenomenon may affect the formation of subsequent skin paths and increase the possibility of correction. So far, there are no data from other centres to validate the effectiveness of the method. In fact, we have also tried to perform segmentation semi-automatically, but this method requires further improvement. However, we believe that evolving computer technology will help us achieve such segmentation in the near future. Furthermore, it is undeniable that the 3D model has a wider range of applications, including weight prediction, individualized virtual delivery, and finite element analysis.

Overall, for term foetuses, birth weights were underestimated by the Baker equation but improved with the modified Baker equation. Additionally, the accuracy of foetal weight estimates based on the modified Baker equation was not related to the foetal gender, birth weight, gestational age at MRI, MRI-to-delivery interval or the type of MRI scanner. However, it is necessary to determine which patients require MR-EFW because MRI is expensive and time consuming. Except for growth-restricted neonates, foetuses with a 2D US-based abdominal circumference > 35 cm have been suggested as candidates for MRI [16], as MRI can provide not only accurate weight estimation but also information on the bony pelvis and soft tissues, which can be used to predict the delivery modality. Therefore, women with suspected CPD, a contracted pelvis, a breech pregnancy and macrosomia appear to be better candidates for MRI estimation of foetal weight, facilitating optimization of obstetrical management.

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