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Research Paper

Choice of head circumference formula shifts ultrasound gestational age estimates by more than a week in late pregnancy

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ABSTRACT

Background: Fetal head circumference (HC) is a core obstetric ultrasound measurement for dating and growth monitoring, yet systems and charts calculate it differently and head shape varies. Objective: To quantify the effect of the perimeter formula on HC and dating, describe head shape across pregnancy, and examine image acquisition practice.

Methods: We analysed 999 two-dimensional fetal head ultrasound images from the openly licensed HC18 dataset, each with an expert-annotated skull ellipse, reference HC and pixel spacing. The minor and major axes of fitted ellipses were taken as biparietal (BPD) and occipitofrontal (OFD) diameters. HC was recalculated using the Ramanujan perimeter, $\pi/2 \times (BPD + OFD)$ and $1.62 \times (BPD + OFD)$. Gestational age was estimated with the Hadlock HC equation.

Results: HC ranged from 44 to 346 mm (11.4–40.1 weeks); 70.2% of images were from the second trimester, concentrated at 18–22 weeks (53.5%). Ramanujan HC agreed closely with the reference (bias +0.8 mm), and the $\pi/2$ approximation was within 0.6 mm of it. The 1.62 approximation overestimated HC by 4.8 mm (2.8%), shifting gestational age by +0.9, +2.8 and +7.8 days in the first, second and third trimesters (maximum 11.6 days). Median cephalic index was 79.5; 15.8% of heads were dolichocephalic (<75) and 11.3% brachycephalic (>85), varying by trimester ($p < 0.001$). Pixel size rose with HC ($\rho = 0.81$), indicating that sonographers adjust depth and zoom as the head grows.

Conclusions: The 1.62 approximation can overdate late pregnancies by about a week. Head shape should be considered when BPD alone is used for dating. Reporting the formula used is essential for comparing measurements across systems and charts.

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1. INTRODUCTION

Ultrasound biometry of the fetal head is one of the most frequently performed measurements in medicine. Head circumference (HC) and biparietal diameter (BPD) are used to date pregnancies when the last menstrual period is uncertain or when the first-trimester crown–rump length is unavailable, to monitor growth and to detect abnormalities such as microcephaly [1], [2]. International guidelines define how the transthalamic plane should be obtained and how the calipers should be placed [1], [3], and reference charts for HC have been published from several populations, including the multinational INTERGROWTH-21st standards [4], [5], [6].

Less attention has been paid to how HC is calculated once the head has been outlined. The skull in the transthalamic plane is approximately an ellipse, whose perimeter has no simple exact formula. Ultrasound systems and published charts have used either an ellipse fit with a numerical or series approximation of the perimeter, or simple formulae based on the sum of the two diameters, typically $\pi/2 \times (BPD + OFD)$ or $1.62 \times (BPD + OFD)$ [5]. These approaches give different results, particularly for large heads, and the differences propagate into gestational-age estimates. Head shape adds further variation: dolichocephalic and brachycephalic heads alter the relationship between BPD and gestational age, which is why HC is generally preferred to BPD alone for dating [1], [7].

Many of these questions can be answered with real images. The HC18 dataset, released under an open licence by Radboud University Medical Center, contains ultrasound images of the fetal head in the standard plane across all trimesters, with expert annotations and pixel calibration [8], [9]. This study used it to (i) quantify the agreement between perimeter formulae and their effect on Hadlock gestational-age estimates, (ii) describe fetal head shape across pregnancy using the cephalic index, and (iii) describe acquisition characteristics, such as magnification and the size of the head on the screen, that affect measurement precision.

2. METHODOLOGY

2.1 Data Source

The training set of the HC18 dataset was analysed [8], [9]. It contains 999 two-dimensional ultrasound images of the fetal head in the standard plane, acquired during routine examinations at Radboud University Medical Center (Nijmegen, the Netherlands) by experienced sonographers, with an annotated ellipse outlining the skull and a reference HC in millimetres, together with the pixel size of each image. The dataset is distributed under the Creative Commons Attribution 4.0 licence. The images are de-identified, no clinical information is provided and no new data were collected, so ethical approval was not required. Figure 1 shows real images from each trimester.

2.2 Ellipse Measurements

For each image, the outer contour of the filled annotation mask was extracted and an ellipse was fitted by least squares with OpenCV. The minor and major axes of the fitted ellipse were converted to millimetres with the pixel size and taken as BPD and OFD analogues; because they are measured on the annotated skull ellipse, they correspond to diameters measured along the ellipse outline rather than to the

outer-to-inner caliper convention used clinically for BPD. HC was then calculated in three ways: (1) with Ramanujan's approximation of the ellipse perimeter, $\pi[3(a + b) - \sqrt{((3a + b)(a + 3b))}]$, where a and b are the semi-axes [10], which is accurate to a small fraction of a millimetre for fetal head shapes; (2) as $\pi/2 \times$ (BPD + OFD); and (3) as $1.62 \times$ (BPD + OFD). The cephalic index (CI) was calculated as BPD/OFD × 100 and classified as dolichocephalic (< 75), mesocephalic (75–85) or brachycephalic (> 85) [1], [7]. The fraction of the image occupied by the head and whether the annotation touched the image border were also recorded.

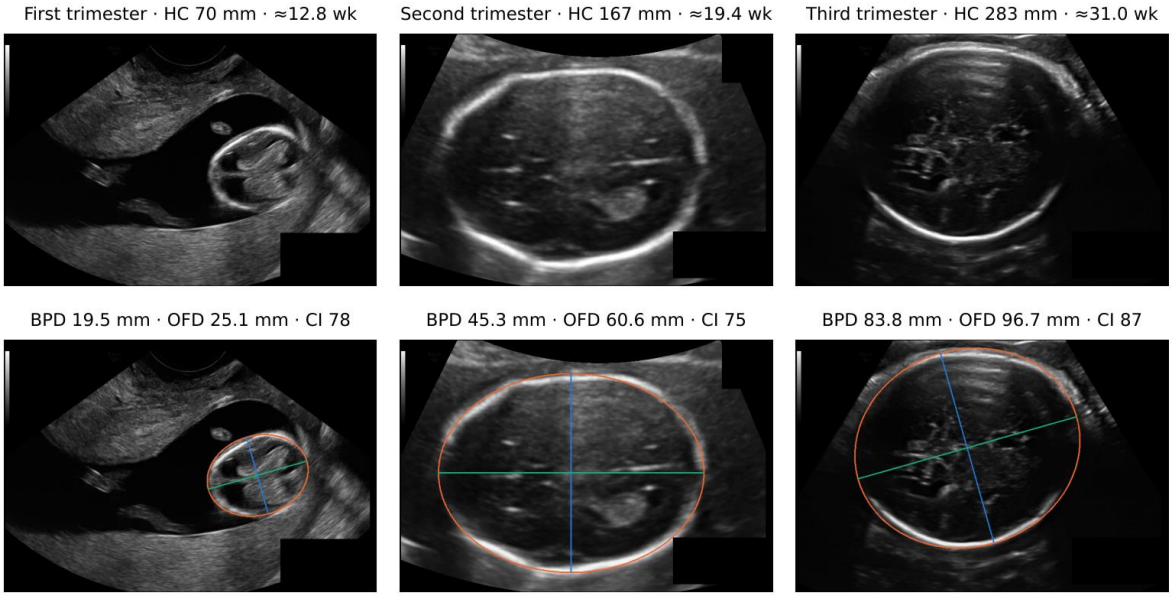


Figure 1. Real Fetal Head Ultrasound Images from the First, Second and Third Trimesters (Top) and the Same Images with the Annotated Skull Ellipse (Orange) and Its Principal Axes (Bottom). HC, Head Circumference; BPD and OFD, Minor and Major Axes of the Ellipse; CI, Cephalic Index. Images from the HC18 Dataset [8], CC BY 4.0

2.3 Gestational Age

Gestational age (GA) was estimated from the reference HC with the Hadlock equation [11]: GA (weeks) = $8.96 + 0.540 \times HC + 0.0003 \times HC^3$, with HC in centimetres. Images were assigned to the first (< 14 weeks), second (14 to < 28 weeks) or third trimester (≥ 28 weeks). The effect of the HC formula on dating was calculated as the difference between the GA derived from each approximation and that derived from the Ramanujan HC, expressed in days.

2.4 Statistical analysis

Agreement between HC methods was assessed with Bland–Altman analysis (bias and 95% limits of agreement) [12]. Associations were assessed with Spearman correlation and differences between trimesters with the Kruskal–Wallis test. Analyses were performed in Python with OpenCV, NumPy, pandas and SciPy.

3. RESULTS AND DISCCUSSION

3.1 Study Images

The reference HC ranged from 44.3 to 346.4 mm (median 174.1 mm), corresponding to a Hadlock GA of 11.4 to 40.1 weeks (median 19.9). There were 154 first-trimester (15.4%), 701 second-trimester (70.2%) and 144 third-trimester images (14.4%) (Figure 2a). More than half of all images (53.5%) fell between 18 and 22 weeks, consistent with the routine mid-trimester anomaly scan [3]. Most images measured 800 × 540 pixels, and the head ellipse touched the image border in only five. Table 1 summarises

the biometry by GA band; BPD and OFD increased in parallel with HC (Figure 2b), and BPD was almost perfectly linearly related to HC (r = 0.996; BPD ≈ 0.280 × HC + 0.2 mm).

Table 1. Fetal Head Biometry by Hadlock Gestational-age Band (Medians)

GA Band, Weeks	Images	HC, Mm	Short Axis (BPD), Mm	Long Axis (OFD), Mm	Cephalic Index	Pixel Size, Mm
10–14	154	75.3	21.7	26.3	82.8	0.077
14–18	90	105.0	30.2	37.4	81.9	0.100
18–22	534	174.5	48.9	62.2	78.4	0.128
22–26	59	219.1	61.1	77.8	78.8	0.163
26–30	50	260.7	73.6	92.5	79.5	0.187
30–34	70	288.5	81.7	102.0	79.8	0.219
34–42	42	316.1	90.0	114.2	80.4	0.232

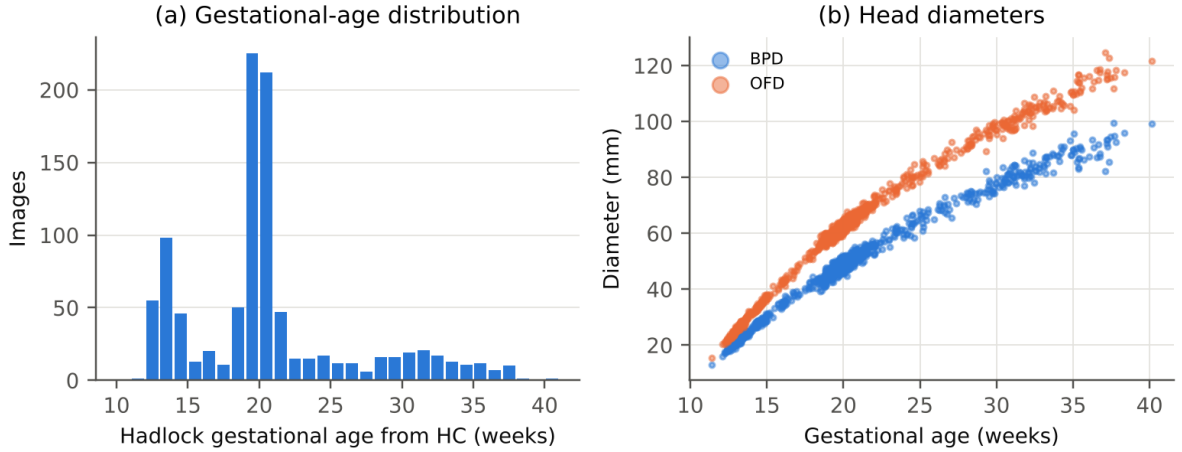


Figure 2. (a) Distribution of Hadlock gestational age estimated from HC. (b) Ellipse minor (BPD) and major (OFD) diameters against gestational age.

3.2 Agreement between HC Formulae

The Ramanujan perimeter of the fitted ellipse agreed closely with the reference HC (bias +0.78 mm; 95% limits of agreement +0.20 to +1.37 mm), and the π/2 × (BPD + OFD) approximation was even closer (bias +0.15 mm; −0.58 to +0.89 mm) (Table 2). In contrast, the 1.62 × (BPD + OFD) formula overestimated HC by 5.6 mm on average relative to the reference (limits +1.5 to +9.7 mm), or 3.3%. Compared with the Ramanujan perimeter, the bias of the 1.62 formula was +4.8 mm (2.8%) and increased proportionally with head size, from +2.2 mm in the first to +8.2 mm in the third trimester (Figure 3a, Table 3).

Table 2. Agreement of Three Head-circumference Formulae with the Reference HC (Bland–Altman, n = 999)

Formula	Bias, Mm	95% Limits of Agreement, Mm	Mean % Bias
Ramanujan perimeter of fitted ellipse	+0.78	+0.20 to +1.37	+0.47
π/2 × (BPD + OFD) = 1.57 × (BPD + OFD)	+0.15	-0.58 to +0.89	+0.12
1.62 × (BPD + OFD)	+5.62	+1.54 to +9.70	+3.25

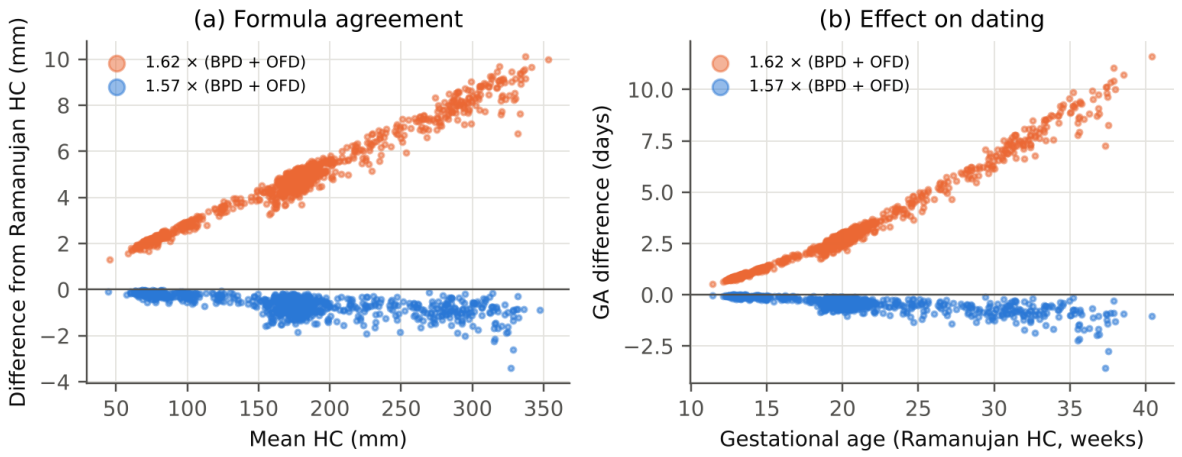


Figure 3. (a) Difference between HC calculated with each simple formula and the Ramanujan ellipse perimeter, against the mean HC. (b) Resulting difference in Hadlock gestational age, in days

3.3 Effect on Gestational Dating

These differences translated into systematic dating errors (Table 3, Figure 3b). Using the 1.62 formula instead of the ellipse perimeter increased the estimated GA by 0.9 days in the first trimester, 2.8 days in the second and 7.8 days in the third, with a maximum of 11.6 days. The π/2 formula reduced the estimated GA by less than one day on average in every trimester (maximum 3.6 days).

Table 3. Formula-related Dating Differences, Cephalic Index and Image Framing by Trimester

Trimester	Images	Median GA, Wk	Median HC, Mm	1.62 Formula – Ramanujan, Mm	Dating Shift, Days (1.62)	Dating Shift, Days (1.57)	Cephalic Index	Head Area, % of Image
First (<14 wk)	154	13.2	75	+2.2	+0.9	-0.1	82.8	16
Second (14–28 wk)	701	19.9	174	+4.7	+2.8	-0.4	78.9	33
Third (≥28 wk)	144	32.0	290	+8.2	+7.8	-0.9	79.7	33

3.4 Head Shape

The cephalic index had a median of 79.5 (interquartile range 76.5–82.4; mean 79.5 ± 4.6). Overall, 72.9% of heads were mesocephalic, 15.8% dolichocephalic and 11.3% brachycephalic (Table 4, Figure 4). Head shape varied with gestation (Kruskal–Wallis $p < 0.001$; ρ with GA = −0.19): first-trimester heads were rounder (median CI 82.8, 27.9% brachycephalic), second-trimester heads were the most elongated (median 78.9, 19.0% dolichocephalic), and third-trimester heads were intermediate (79.7). Figure 5 shows real examples of the three shape categories.

Table 4. Head Shape Categories by Trimester

Trimester	Images	Dolichocephalic (CI < 75), %	Mesocephalic (75–85), %	Brachycephalic (CI > 85), %
First (<14 wk)	154	5.2	66.9	27.9
Second (14–28 wk)	701	19.0	73.0	8.0
Third (≥28 wk)	144	11.8	78.5	9.7
All	999	15.8	72.9	11.3

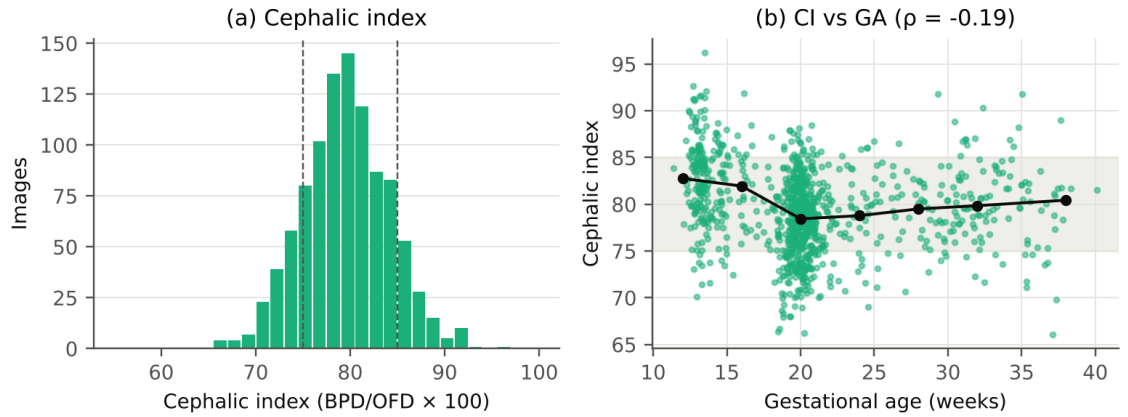


Figure 4. (a) Distribution of the cephalic index; dashed lines mark the conventional limits of 75 and 85. (b) Cephalic index against gestational age with medians by four-week band; the shaded band marks 75–85

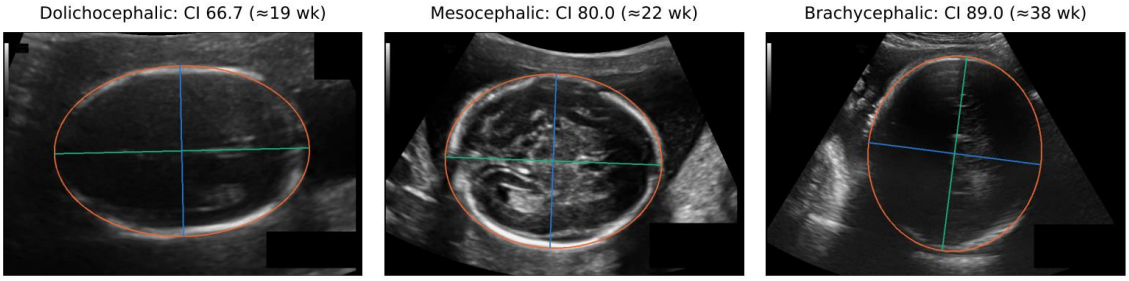


Figure 5. Real Examples of Dolichocephalic, Mesocephalic and Brachycephalic Fetal Heads after 18 Weeks, with the Annotated Ellipse and Its Axes. CI, Cephalic Index. Images from the HC18 Dataset, CC BY 4.0

3.5 Image Acquisition

The pixel size ranged from 0.049 to 0.393 mm and increased strongly with HC ($\rho = 0.81$, $p < 0.001$), from a median of 0.077 mm in the first to 0.221 mm in the third trimester (Figure 6a). The head occupied a median of 31% of the image (5th–95th percentile 10–49%), less in the first trimester (16%) than later (33%) (Figure 6b). Thus, sonographers widened the field of view as the head grew, which kept the head at a similar size on screen after the first trimester but meant that each pixel represented a larger distance late in pregnancy.

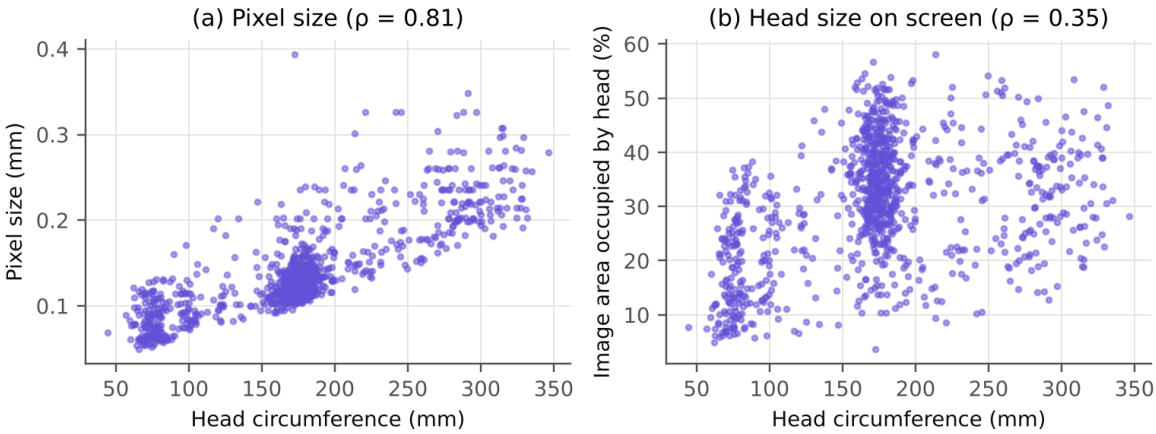


Figure 6. Acquisition Characteristics. (a) Pixel Size against Head Circumference. (b) Percentage of the Image Occupied by the Annotated Head against Head Circumference

3.6 Sensitivity of Dating to Measurement Error

Because the Hadlock equation is non-linear, the same absolute HC error has a larger effect on dating later in pregnancy (Table 5, Figure 7). A 1 mm error in HC changed the estimated GA by 0.42 days at 13 weeks, 0.63 days at 22 weeks and 1.1 days at 39 weeks. Combined with the larger pixel size used late in pregnancy, a one-pixel caliper error in both diameters changed the estimate by about 0.1 day in the first trimester but 0.65–0.86 days near term. For a head of typical shape (CI 80), the 1.62 formula shifted the estimate by +1 day at an HC of 80 mm, +3.6 days at 200 mm and +10.8 days at 340 mm, whereas the π/2 formula shifted it by at most −1.2 days.

Table 5. Sensitivity of Hadlock Dating to the HC Formula and to Measurement Error, for an Ellipse with Cephalic Index 80

HC, Mm	GA, Weeks	BPD / OFD, Mm	Shift with 1.62 Formula, Days	Shift with π/2 Formula, Days	Dating Error per 1 Mm HC, Days	Typical Pixel Size, Mm	Dating Error per 1-pixel Caliper Error, Days
80	13.4	22.6 / 28.2	+0.9	-0.1	0.42	0.079	0.10
100	14.7	28.2 / 35.3	+1.2	-0.1	0.44	0.093	0.13
150	18.1	42.3 / 52.9	+2.2	-0.2	0.52	0.113	0.18
200	22.2	56.4 / 70.5	+3.6	-0.4	0.63	0.157	0.31
250	27.1	70.5 / 88.1	+5.5	-0.6	0.77	0.178	0.43
300	33.3	84.6 / 105.8	+8.1	-0.9	0.94	0.219	0.65
340	39.1	95.9 / 119.9	+10.8	-1.2	1.11	0.246	0.86

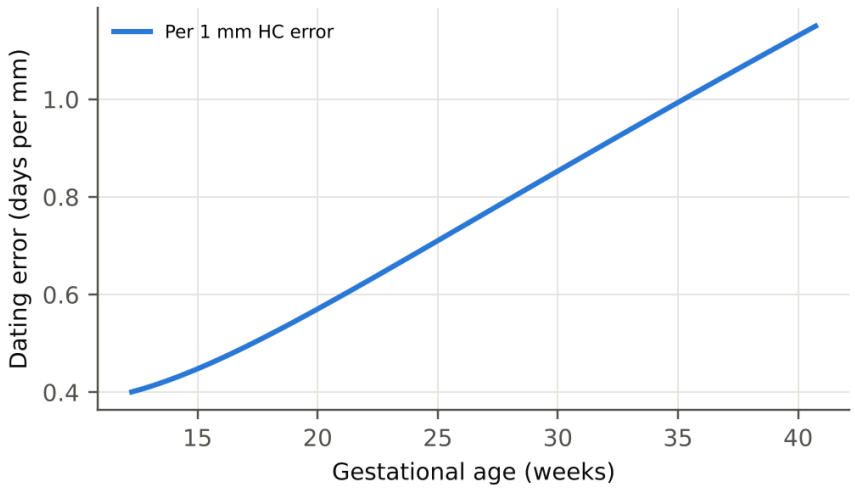


Figure 7. Error in Hadlock Gestational Age Produced by a 1 Mm Error in Head Circumference, across Gestation

3.7 Real Images across Gestation

Figure 8 shows annotated real images at approximately four-week intervals from 12 to 36 weeks. Across gestation, the skull outline and intracranial anatomy become progressively better defined, and the field of view widens, as reflected in the increasing pixel size.

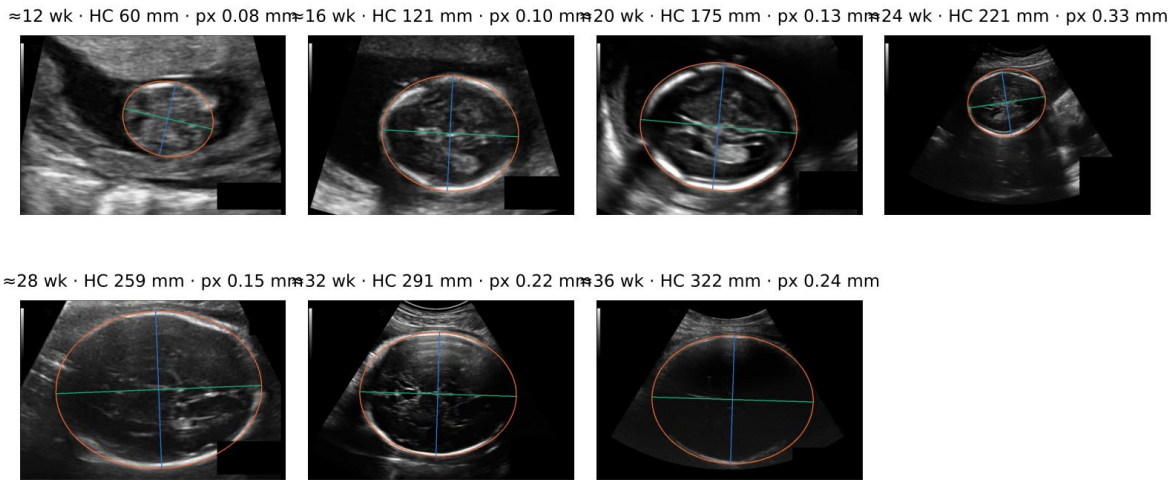


Figure 8. Annotated Real Fetal Head Ultrasound Images at Approximately 12, 16, 20, 24, 28, 32 and 36 Weeks (Hadlock Estimate), with Head Circumference and Pixel Size. Images from the HC18 Dataset, CC BY 4.0

3.8 Discussion

This analysis of 999 real fetal head ultrasound images shows that the method used to compute HC from the skull outline has a measurable effect on dating. The ellipse perimeter and the $\pi/2 \times (BPD + OFD)$ approximation agreed within about a millimetre, but the $1.62 \times (BPD + OFD)$ formula overestimated HC by about 3%, which shifted the Hadlock GA by a mean of 7.8 days, and by up to 11.6 days, in the third trimester.

The reason is geometric. For an ellipse, $\pi/2 \times (BPD + OFD)$ is the perimeter of a circle with the mean of the two diameters and slightly underestimates the true perimeter, whereas a factor of 1.62 overestimates it for any realistic fetal head shape. Because the error is proportional, it is small in absolute terms early in pregnancy, when dating is most accurate and most often performed, but grows with head size. Although HC-based dating is not recommended in the third trimester [1], [2], HC is routinely compared with growth charts at that stage, and a systematic 3% overestimate would shift centiles. Measurements made with different formulae should therefore not be compared directly, and growth charts should be applied with the formula used in their construction [4], [5]. Reports and research articles should state how HC was calculated.

The cephalic index distribution was consistent with established knowledge that the normal fetal head is moderately elongated, with roughly three-quarters of heads in the 75–85 range [1], [7]. The rounder shape in the first trimester and the more elongated shape in mid-pregnancy agree with reports that the CI changes with gestation [13]. About one in four heads fell outside the conventional range. In such heads, BPD alone underestimates (dolichocephaly) or overestimates (brachycephaly) gestational age, whereas HC is relatively independent of shape; this is the main reason for preferring HC to BPD in dating and growth assessment [1], [7]. Breech presentation, oligohydramnios and fetal position can produce dolichocephaly without pathological significance, but persistent or extreme values may warrant a careful look at the skull and brain.

The concentration of images at 18–22 weeks reflects routine practice in many countries, where the mid-trimester anomaly scan is the main scan of pregnancy [3], and suggests that the dataset mirrors real clinical workload rather than a designed uniform sample. The strong increase in pixel size with HC shows that sonographers adjust depth and zoom to keep the head at a similar size on screen. The precision of a caliper placement is limited by pixel size, so a one-pixel error corresponds to about 0.08 mm in the first trimester but 0.22 mm in the third; in practice, observer variability, which is of the order of several millimetres for HC, is far larger [14]. Because the Hadlock equation is steeper late in pregnancy, each millimetre of error costs about two and a half times as many days at term as in the first trimester (1.1 vs

0.4 days; Table 5), which is one reason why dating should be based on the earliest reliable measurement [1], [2].

3.9 Strengths and caveats

The strengths of this study include the use of real clinical ultrasound images with expert annotations and pixel calibration, a large sample across all trimesters, and transparent calculations that can be reproduced from openly licensed data.

Several limitations should be noted. The dataset contains no information on true gestational age, maternal characteristics or outcomes, so GA was estimated from HC itself and the dating differences are relative, not absolute, errors. The BPD and OFD analogues were derived from the annotated ellipse and do not follow the clinical outer-to-inner caliper convention for BPD, so their absolute values differ slightly from clinical measurements, although the CI and the formula comparisons are unaffected. The annotations were made by a small number of experts at one centre, and inter-observer variability could not be assessed. Images from the same pregnancy may appear more than once, and the number of women is not reported in the image-level data. Finally, images were acquired with machines from one manufacturer, so acquisition characteristics may differ elsewhere.

4. CONCLUSION

In 999 real fetal head ultrasound images, the ellipse perimeter and the $\pi/2 \times (BPD + OFD)$ approximation gave nearly identical HC values, whereas the $1.62 \times (BPD + OFD)$ formula overestimated HC by about 3% and shifted gestational-age estimates by up to 11.6 days in late pregnancy. About one in four fetal heads fell outside the conventional mesocephalic range, with rounder heads early and more elongated heads in mid-pregnancy. The HC formula should be reported and matched to the reference chart, and HC rather than BPD alone should be preferred when head shape is atypical.

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Author Contributions Statement

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Zhumanalieva Maksudakan	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓
Omuralieva Gulsana			✓		✓	✓	✓		✓	✓		✓	✓	
Abdykaarova Aigerim	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

Conflict of Interest Statement

The authors declare that there are no conflicts of interest regarding the publication of this article.

Informed Consent

Not applicable. This study analysed publicly available, de-identified data; no participants were recruited.

Ethical Approval

This study is a secondary analysis of de-identified ultrasound images released publicly under an open licence. No new data were collected from human participants, and ethical approval and informed consent were therefore not required.

Data Availability

The HC18 dataset analysed in this study is openly available under the CC BY 4.0 licence (Zenodo, doi:10.5281/zenodo.1327317). The ultrasound images shown in Figures 1 and 2 are from that dataset. The analysis code (Python, OpenCV) is available from the corresponding author on reasonable request.

Use of AI Tools

Generative AI tools were used to assist with code development, statistical analysis and drafting of the manuscript. The authors reviewed and verified all analyses, results and text and take full responsibility for the content of this article.

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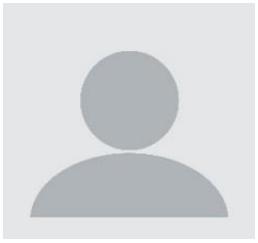
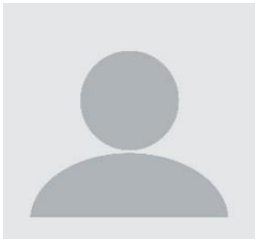
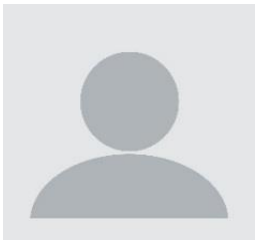
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