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Only Two-Phase Models, Computed Independently for Males and Females, Are Appropriate to Describe Fetal Head Growth

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Key Words

Ultrasound · Fetal growth · Mathematical model · Biparietal diameter · Head circumference

Abstract

Objective: To establish an accurate mathematical model describing fetal head growth, taking into account gender differences and changes in growth rate during gestation. ***Methods:*** Ultrasound measurements of head circumference and biparietal diameter were made on 1,336 normal fetuses (684 males and 652 females) in the Maternité Régionale de Nancy (France). A new two-phase model, taking into account an alteration in growth kinetics at 30 gestational weeks, was computed independently for male and female data. The accuracy of this model was tested and compared with three current mathematical models: a linear-quadratic, a linear-cubic, and the Rossavik and Deter (1984) models. ***Results:*** In all models, including ours, the coefficients of determination (R^2) were high (≥ 0.999), so long as male and female data were computed separately. However, the standard error estimates (SEE) of our two-phase model were much lower ($0.13 \leq$ SEE ≤ 0.57) than the SEE of the three other models when computed over the whole gestational period ($0.49 \leq$ SEE ≤ 2.69); nevertheless, when these three other models were computed for these two successive periods, their SEE decreased, and data fitting was improved. ***Conclusion:*** Only two-phase mathematical models, computed independently for male and female data, accurately describe the kinetics of fetal head growth. They should be used to calculate growth standards and to perform an exact diagnosis of impaired growth.

Introduction

In clinical practice, the diagnosis of growth impairment is largely dependent on the accuracy of standard curves. Concerning the fetal head, accurate standards of biparietal diameter (BPD) and head circumference (HC) are of particular interest. Unlike other measurements, such as abdominal parameters or femoral length, which are altered early by insufficiencies of placental supply, the brain dimensions present a relative tolerance to environmental stress. Consequently, only accurate standard curves may detect small deviations from normal head growth, which can reflect disturbances in cerebral development.

Numerous growth charts of BPD and HC have already been published, but they often differ significantly from each other. Such discrepancies between growth standards reflect great diversity in study methodology, sample selection as well as data fitting. More particularly, the choice of the mathematical model to estimate the mean curve and/

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or centiles is of great importance, since inadequate fitting may lead to erroneous estimation of 'normal' range of growth.

Various mathematical models have been proposed to fit fetal BPD and HC data: second- or third-order polynomial regressions, logistic-logarithmic function, or more sophisticated models, such as the Deter and Rossavik model [1]. Fitted curves were computed from cross-sectional data [2–8], or from longitudinal data [9–13].

In addition, although gender differences in head growth have been observed by several authors [7, 14, 15], no specific charts of BPD and HC have been published. Furthermore, despite the obvious slowing of head growth in late gestation [15], only in one study concerning BPD [11], was it suggested to use two different mathematical models for the early and late gestational periods.

Therefore, in this study, we searched for a mathematical model as close as possible to the raw data, in order to detect any possible change in growth rate in the course of gestation. We established an equation describing the relationship between the successive mean values of each variable and gestational age, taking into account the extent of variation around the average curve. In order to take into account gender differences in head growth, the model was computed independently for male and female data. Its accuracy was tested and compared with three mathematical models currently used: a linear-quadratic model, a linear-cubic model [9] and the 'Rossavik' model [16]. In a further study, we shall publish accurate centile charts of BPD and HC, computed from this new model.

Subjects and Methods

Subjects

This study included 1,336 subjects (684 males and 652 females) born between 1995 and 1997 at the Maternité Régionale de Nancy (France). They ranged from 12 to 38 gestational weeks (GW). Gestational age was determined from the date of the last menstrual period and confirmed at the first ultrasound examination.

All scans were performed as part of the routine screening perinatal program including all pregnancies, and were not clinically indicated. Fetuses with malformations, and premature babies were excluded retrospectively from the study. Multiple pregnancies and pathological pregnancies (including maternal diabetes, maternal hypertension and severe infections) were also excluded. Due to the maternity program of ultrasound examinations (at determined gestational weeks), the distribution of cases was uneven throughout gestation.

Measurements

Each fetus was included only once (cross-sectional data). Therefore, only one ultrasound examination was selected at random among the several examinations performed during pregnancy.

BPD was measured on a transaxial plane at the widest portion of the skull, the thalamus positioned in the midline, from the first echo of the closest temporoparietal calvarial table to the first echo of the furthest temporoparietal table. The HC was measured on the same plane, by electronic determination of the ellipse circumference. The measurements were made using a Toshiba SSH 140A, SSA250A (Tokyo, Japan).

Mathematical Method

The means for each GW were calculated separately for males and females. Student's t test was performed between male and female means for each age interval. Gender differences in BPD were significant ($p < 0.05$) from 22 GW for most age intervals (table 1). Gender differences in HC were significant from 21 GW (table 2). Therefore, before 22 GW (BPD) or 21 GW (HC), we did not compute distinct models for males and females. Afterwards, separate models were calculated for males and females.

The mathematical model computed in this study was developed by Pineau [17]. In this model, the determination of the relationship between two variables is based on the estimation of their variability around the mean. Let us consider an interval of variation around the mean corresponding to a percentage $\pm k \cdot \sigma$ of the standard deviation σ. This interval was arbitrarily chosen in order to include a reasonable proportion of experimental data, but this choice has no bearing on the final equation fitting the mean values. At each time t, the dispersion of the data in this interval is Δy, which changes in relation to time (fig. 1).

The relationship between y and Δy is: $\Delta y = a \cdot f(y)$, where a = constant. A similar relationship exists between Δt and t: $\Delta t = b \cdot f(t)$, b = constant. For each point (y,t) of the curve, we have $\Delta y / a \cdot f(y) = \Delta t / b \cdot f(t)$ so: $\Delta y / f(y) = c \cdot \Delta t / f(t)$, where $c = a/b$ = constant.

The corresponding differential equation is: $dy/f(y) = c.dt/f(t)$. This differential equation can also be written: $dy/y^{\alpha} = k\ dt/t^{\beta}$ where α and β are constants. To resolve this equation, the relationships between Δt et t, and then between Δy et y should be successively quantified. A decimal logarithmic transformation is applied: X = log t and Y = log Δt. The same transformation is applied to Δy et y. So: $\log \Delta t = \beta \log t + d \rightarrow \Delta t / k_1\ t^{\beta} = 1$ and $\log \Delta y = \alpha \log y + v \rightarrow \Delta y / k_2 y^{\alpha} = 1$, where k_1, k_2 are constants. Therefore:

$$\Delta t / k_1\ t^{\beta} = \Delta y / k_2 y^{\alpha}. \quad (1)$$

In practice, a linear relationship $y = a\ t^{\gamma} + b$ (where γ = constant) between y and t is searched for. By integrating equation 1, a fairly accurate value of γ is obtained, which is optimized by applying small fluctuations around this value.

As an example, the calculation of the equation of the model for BPD is detailed in the Appendix.

Concerning BPD and the HC, we observed that dt increased regularly and slowly during the two first gestational trimesters, and much more quickly afterwards. The change in the slope of log Δt versus log t occurred at 30 GW in both males and females for the two variables. This observation is illustrated for HC in figure 2. This abrupt increase of dt corresponds to a decrease in the head growth rate after 30 GW.

Therefore, we computed the model in two successive phases: the first phase included data between 12 and 29 GW, and the second, data between 30 and 38 GW. These two successive phases were characterized by two mathematical equations with distinct constants, which intersect at about 29.5 GW. Impreciseness in Δt estimation for extreme data precluded computing beyond 38 GW.

Furthermore, to take into account the significant gender difference in BPD and HC in the second half of gestation (see above), we computed distinct two-phase models for males and females. Until 21GW (DBP) or 20GW (HC), the mean values of BPD and HC are not significantly different in both genders, so the mean of each age group, without distinction of gender, was introduced in the model (tables 1, 2). Afterwards, the means for males and females were computed separately in the models.

Consequently, for each variable, four mathematical equations were computed: the first concerned males between 12 and 29 GW; the second, males between 30 and 38 GW; the third, females between 12 and 29 GW, and the fourth, females between 30 and 38 GW.

Statistical Analysis

To test our two-phase models, we utilized the SYSTAT software to calculate the coefficient of determination R^2, and the standard error of the estimate: SEE = $\sigma\sqrt{(1 - R^2)}$. We used the same mean values of BPD and HC (table 1) to calculate the parameters and to test three other mathematical models: a linear-quadratic model: $a + bt + ct^2$; a linear-cubic model, corresponding to the model used by Deter et al. [9] to fit longitudinal data: $a + bt + ct^3$ and the Rossavik equation [16].

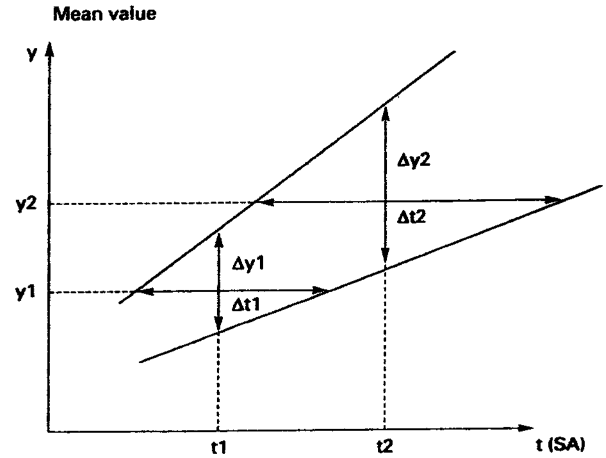

Fig. 1. Variation of the dispersion Δy around the mean in relation to time t.

Table 1. Gender difference in BPD according to GW

GW	Males			Females			Student's test p
	n	M	SD	n	M	SD	
12	24	21.8	1.4	19	21.1	1.8	0.552
13	30	25.1	2.2	28	25.1	1.5	1
14	23	28.1	1.9	31	28.4	1.9	0.551
15	26	32.2	1.7	14	32.9	1.8	0.237
16	28	36.1	2.0	16	35.3	2.4	0.277
17	21	39.8	2.4	20	38.8	2.3	0.169
18	20	42.9	2.0	16	41.9	2.6	0.202
19	11	45.9	1.9	16	45.7	2.2	0.767
20	25	49.0	2.0	14	49.0	2.6	1
21	18	52.1	2.0	16	50.9	2.6	0.143
22	27	55.3	1.8	27	54.0	2.7	0.040
23	33	58.5	2.4	42	56.5	2.3	<0.001
24	28	61.3	2.6	41	59.8	2.4	0.019
25	32	64.5	2.7	25	62.7	3.4	0.032
26	26	67.5	3.5	25	65.8	2.3	0.041
27	25	69.9	2.1	17	68.0	3.0	0.027
28	18	72.8	3.2	16	71.7	2.6	0.279
29	23	75.9	3.1	16	74.5	2.5	0.118
30	24	78.0	3.6	12	76.8	2.6	0.279
31	18	80.8	2.5	24	79.3	2.4	0.050
32	32	83.5	3.9	30	81.3	3.1	0.015
33	37	85.4	3.1	41	83.4	3.3	0.006
34	35	87.3	3.5	36	84.8	3.3	0.003
35	28	88.8	3.5	31	86.4	3.6	0.012
36	16	90.0	3.5	25	87.4	3.9	0.033
37	21	91.0	3.5	21	88.4	3.8	0.027
38	13	91.8	2.5	7	89.1	4.5	0.151

n = Sample size; M = mean; SD = standard deviation.

Table 2. Gender difference in HC according to GW

GW	Males			Females			Student's test p
	n	M	SD	n	M	SD	
12	20	78.1	5.1	18	76.7	6.3	0.488
13	29	91.1	7.9	26	90.7	6.2	0.842
14	23	103.2	7.9	31	103.8	7.3	0.765
15	25	116.5	8.3	11	115.6	4.0	0.691
16	25	130.2	7.1	14	126.4	10.6	0.238
17	18	142.1	7.5	18	139.6	7.3	0.324
18	18	153.0	8.0	16	154.1	7.7	0.968
19	11	164.6	4.7	14	164.4	8.1	0.921
20	25	177.2	7.7	20	176.0	7.4	0.619
21	25	190.3	5.2	27	187.4	4.9	0.041
22	25	201.4	5.9	27	198.9	6.0	0.139
23	33	212.4	8.3	41	210.0	7.7	0.198
24	28	223.0	8.9	22	220.2	7.8	0.236
25	31	234.5	6.9	23	230.7	6.3	0.041
26	26	245.5	7.4	24	241.3	6.7	0.041
27	25	256.0	6.9	17	251.0	7.0	0.027
28	16	267.2	8.2	14	261.1	8.0	0.045
29	23	277.0	9.8	16	270.8	9.2	0.051
30	25	283.0	7.6	13	278.0	7.4	0.050
31	17	291.5	8.1	21	286.0	7.9	0.043
32	30	298.7	9.6	28	292.7	9.0	0.015
33	30	306.1	10.5	38	299.1	10.9	0.009
34	35	311.5	11.4	35	305.0	10.8	0.019
35	26	317.0	12.4	31	310.0	13.1	0.040
36	16	321.7	9.5	24	314.3	11.5	0.034
37	22	325.5	10.4	20	318.0	10.5	0.027
38	12	329.0	12.1	6	322.2	11.1	0.247

n = Sample size; M = mean; SD = standard deviation.

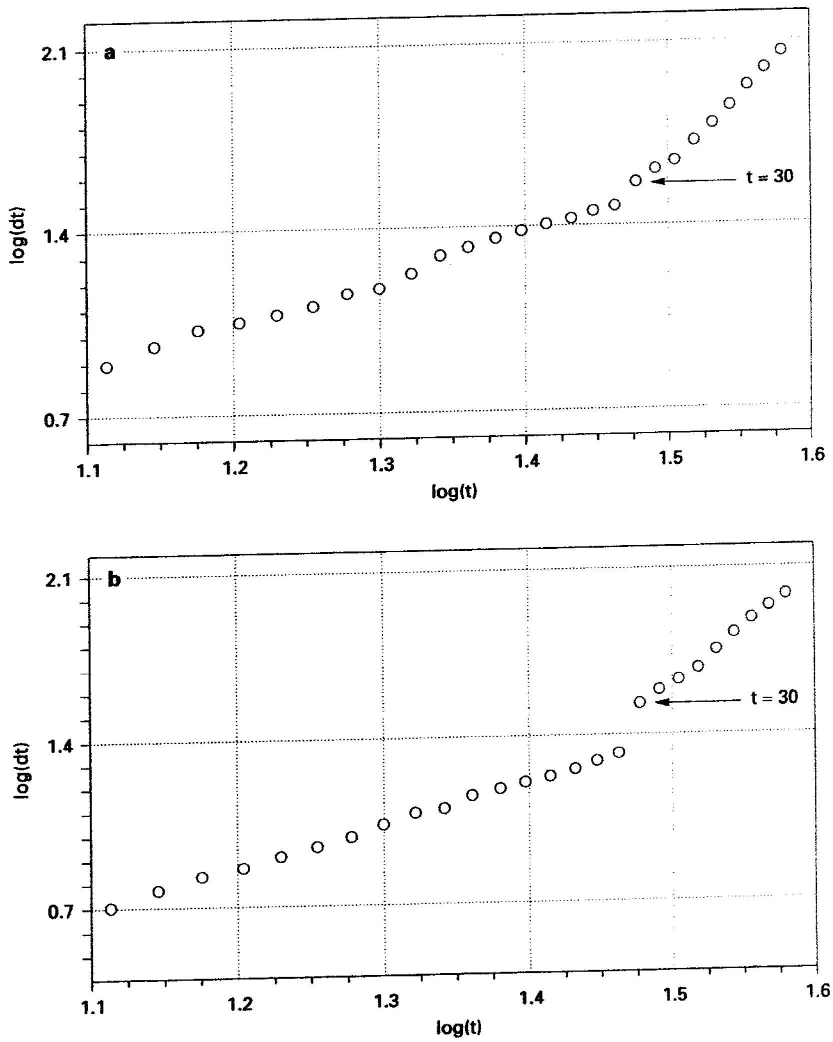

Fig. 2. HC growth: the change in the slope of log (dt) versus log (t) corresponds to a decrease of the head growth rate after 30 GW. **a** Males. **b** Females.

We first computed these three models on the whole period of gestation (12–38 GW), as in previous studies. We then computed the three models for the two successive periods: 12–29 GW and 30–38 GW, in order to allow an accurate comparison with our two-phase model. Distinct equations were computed for male and female data. The R^2 and SEE were calculated for each of these mathematical equations. The residuals (real values-predicted values) versus the predicted values of the mean were plotted for the two models that had the smallest SEE.

Results

The constants, R^2, and SEE for each mathematical model fitted to the BPD and HC mean data are reported in table 3 (BPD) and table 4 (HC).

Models Fitting BPD (table 3, fig. 3)

All models have high values of R^2 ($R^2 \geq 99.9$). Nevertheless, there are large differences in SEE among the four models. In males and females, the SEE of our two-phase model are lower ($0.13 \leq SEE \geq 0.44$) than the SEE of the three other models computed on the whole gestational period ($0.49 \leq SEE \geq 0.85$). However, when the linear-quadratic, linear-cubic and Rossavik models are computed for two successive periods (12–29 GW and 30–38 GW), like our two-phase model, their SEE are notably lower (table 3). They are similar to the SEE of our model for the 30–38 GW period (SEE = 0.10), but remain higher in the 12–29 GW period ($0.25 \leq SEE \geq 0.83$). In that case, the most accurate of the three models is the linear-quadratic one (SEE = 0.25 in males and 0.50 in females).

Table 3. Accuracy of the four mathematical models applied to BPD data

Mathematical models				R^2, %	SEE
Two-phase model: $a\,t^{\gamma} + b\,dy/y^{\alpha} = k\,dt/t^{\beta}$					
	a	γ	b		
M (12–29 GW)	15.32	0.63	–52.04	99.99	0.19
M (30–38 GW)	-80.40×10^{6}	–4.45	99.50	99.93	0.13
F (12–29 GW)	16.88	0.60	–53.42	99.93	0.44
F (30–38 GW)	19.20×10^{7}	–4.75	95.15	99.91	0.14
Linear-quadratic model: $a + bt + ct^2$					
	a	b	c		
M (12–38 GW)	–33.59	5.06	-4.50×10^{-2}	99.90	0.70
F (12–38 GW)	–31.67	4.92	-4.50×10^{-2}	99.80	0.85
M (12–29 GW)	–26.14	4.29	-2.70×10^{-2}	99.99	0.25
M (30–38 GW)	–143.77	11.89	-14.97×10^{-2}	99.98	0.11
F (12–29 GW)	–25.10	4.26	-2.92×10^{-2}	99.95	0.50
F (30–38 GW)	108.54	9.85	-12.24×10^{-2}	99.98	0.09
Linear-cubic model: $a + bt + ct^3$ [9]					
	a	b	c		
M (12–38 GW)	–25.83	4.0	-6.02×10^{-4}	99.95	0.53
F (12–38 GW)	–23.99	3.87	-5.95×10^{-4}	99.89	0.71
M (12–29 GW)	–22.79	3.76	-4.39×10^{-4}	99.98	0.26
M (30–38 GW)	–86.65	6.81	-1.47×10^{-3}	99.97	0.12
F (12–29 GW)	–21.47	3.68	-4.75×10^{-4}	99.95	0.54
F (30–38 GW)	–61.86	5.70	-1.20×10^{-3}	99.98	0.10
Rossavik model: $c.t^{(k+st)}$ [16]					
	c	k	s		
M (12–38 GW)	0.152	2.11	-91.94×10^{-4}	99.95	0.49
F (12–38 GW)	0.167	2.08	-91.34×10^{-4}	99.89	0.73
M (12–29 GW)	0.118	2.22	-108.2×10^{-4}	99.96	0.48
M (30–38 GW)	1.5×10^{-3}	3.80	-2.04×10^{-2}	99.98	0.11
F (12–29 GW)	0.116	2.25	-1.15×10^{-2}	99.88	0.83
F (30–38 GW)	-8.35×10^{-3}	3.18	-1.67×10^{-2}	99.98	0.09

Distinct equations were calculated for males (M) and females (F). The new two-phase model was computed for two periods (12–29 and 30–38 GW). The other models were computed over the whole gestational period (12–38 GW) and also for the former periods (12–29 and 30–38 GW).

The difference in accuracy between the one-phase and the two-phase computations is illustrated in figure 3. Residuals versus predicted values of the mean are plotted for males and females for the two-phase model (fig. 3a), for the linear-cubic model computed over the whole gestational period (fig. 3b), and for the linear-cubic model computed for two successive periods (fig. 3c). The range of residuals is smaller in the two-phase model: [(–0.3 to +0.4) in males; (–0.6 to +0.9) in females] than in the linear-cubic model computed in the whole gestational period [(–1.3 to +1.4) in males; (–1.4 to +2.2) in females]. Nevertheless, when the linear-cubic model is calculated for two successive periods (fig. 3c), the range and the pattern of the residuals are very similar to the residuals of our two-phase model. It is noteworthy that all the models are less accurate in females than in males.

Models Fitting HC (table 4, fig. 4)

All models have high values of R^2 ($R^2 \geq 99.9$). As observed for BPD, the SEE of our two-phase model are lower ($0.26 \leq \text{SEE} \geq 0.57$) than the SEE of the three other models computed for the whole gestational period ($1.09 \leq \text{SEE} \geq 2.69$), the Rossavik model being the best of them (SEE = 1.09 in males and females).

Table 4. Accuracy of the four mathematical models applied to HC data

Mathematical models				R^2, %	SEE
Two-phase model: $at^{\gamma} + b\ dy/y^{\alpha} = k\ dt/t^{\beta}$					
	a	γ	b		
M (12–29 GW)	36.45	0.728	−145.3	99.99	0.57
M (30–38 GW)	-1.79×10^6	−2.9	376.4	99.97	0.30
F (12–29 GW)	57.10	0.62	−189.5	99.99	0.33
F (30–38 GW)	-6.6×10^5	−2.6	374.0	99.99	0.26
Linear-quadratic model: $a + bt + ct^2$					
	a	b	c		
M (12–38 GW)	−132.78	19.42	-18.78×10^{-2}	99.89	2.69
F (12–38 GW)	−127.04	19.02	-18.69×10^{-2}	99.92	2.12
M (12–29 GW)	−93.20	15.14	-8.27×10^{-2}	99.99	0.52
M (30–38 GW)	−295.84	30.02	-35.75×10^{-2}	99.98	0.23
F (12–29 GW)	−97.09	15.87	-11.0×10^{-2}	99.99	0.26
F (30–38 GW)	−226.56	25.80	-29.92×10^{-2}	99.97	0.28
Linear-cubic model: $a + bt + ct^3$ [9]					
	a	b	c		
M (12–38 GW)	−100.47	14.99	-25.04×10^{-4}	99.95	1.80
F (12–38 GW)	−94.88	14.61	-24.92×10^{-4}	99.97	1.25
M (12–29 GW)	−82.07	13.51	-13.45×10^{-4}	99.99	0.52
M (30–38 GW)	−159.49	17.91	-3.50×10^{-3}	99.98	0.26
F (12–29 GW)	−83.40	13.70	-17.95×10^{-4}	99.99	0.38
F (30–38 GW)	−112.41	15.66	-2.93×10^{-3}	99.96	0.31
Rossavik model: $c.t^{(k+st)}$ [16]					
	c	k	s		
M (12–38 GW)	0.459	2.19	-100.7×10^{-4}	99.98	1.09
F (12–38 GW)	0.487	2.17	-101.2×10^{-4}	99.98	1.09
M (12–29 GW)	0.452	2.19	-101.9×10^{-4}	99.96	1.32
M (30–38 GW)	0.139	2.63	-130.5×10^{-4}	99.98	0.23
F (12–29 GW)	0.417	2.24	-111.5×10^{-4}	99.95	1.43
F (30–38 GW)	0.344	2.29	-109.8×10^{-4}	99.97	0.28

Distinct equations were calculated for males (M) and females (F). The new two-phase model was computed for two periods (12–29 and 30–38 GW). The other models were computed over the whole gestational period (12–38 GW) and also for former periods (12–29 and 30–38 GW).

When computed for two successive periods (12–29 GW and 30–38 GW), the linear-quadratic and linear-cubic models have low values of SEE, similar to the SEE of our model for the two periods. The Rossavik model is much less accurate for the 12–29 GW period (SEE = 1.32 in males and 1.43 in females).

The study of the residuals confirms the best accuracy of the two-phase computation of HC data (fig. 4a, c). The range of residuals is smaller in the two-phase model [(1.2 to +1) in males; (−0.6 to +0.6) in females] than in the linear-cubic model computed over the whole gestational period [(−4 to +3) in males; (−2.5 to +2) in females]. Nevertheless, when the linear-cubic model is calculated for two successive periods (fig. 4c), the range and the pattern of the residuals are very similar to the residuals of the two-phase model (fig. 4a). Unlike the models for BPD, those for HC are not less accurate in females than in males.

The advantage of a two-phase, gender-dependent model to fit HC means is illustrated in figure 5. The same mathematical model – the linear-cubic one [9] – is used to fit the HC mean curve in two ways: firstly, computing the model over the whole gestational period, without distinction of genders, as currently published in the literature; secondly, computing the model for two successive periods

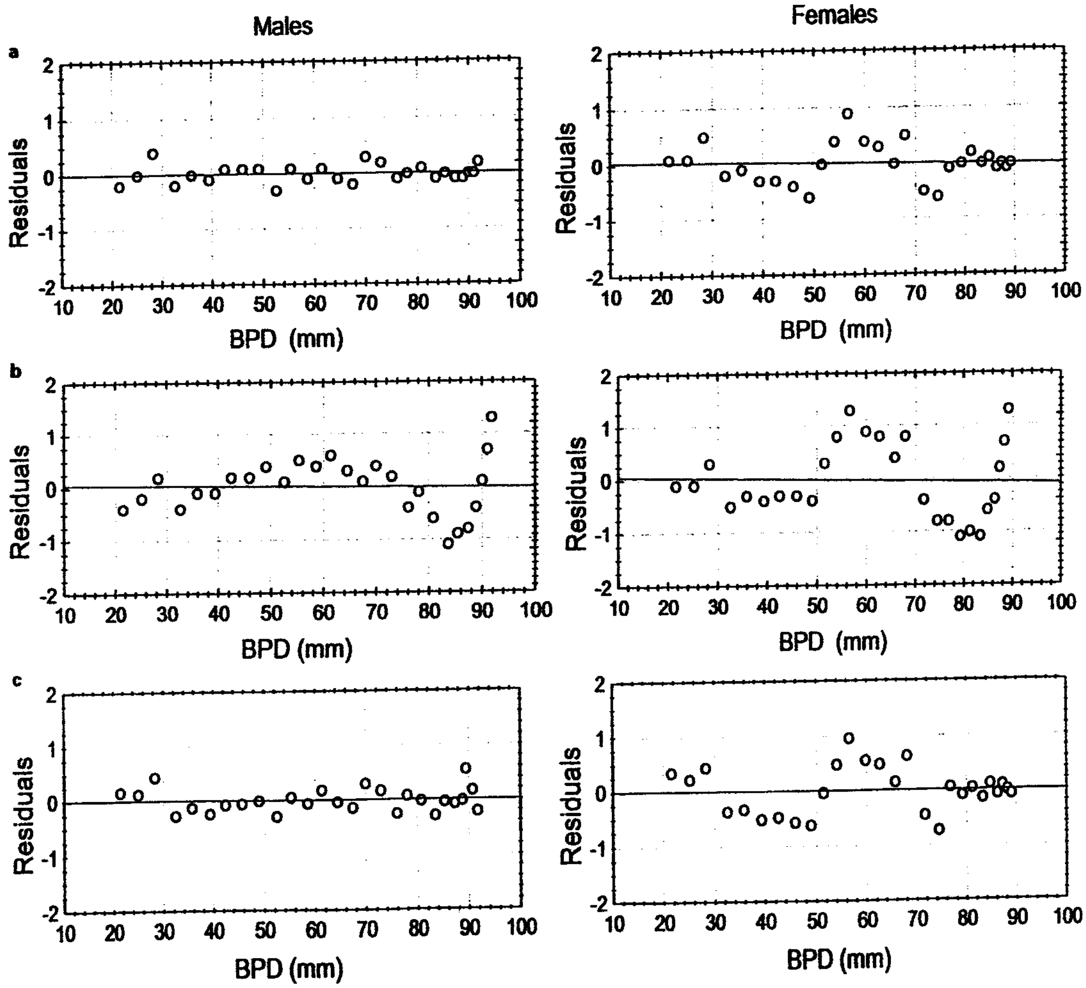

Fig. 3. Residuals versus DBP values for the two-phase model (**a**), the linear-cubic model [9] computed over the whole gestational period (**b**) and the linear-cubic model [9] computed for two successive periods (**c**).

(two-phase model), separating male and female data. Important discrepancies between the three resulting curves are observed. The one-phase, undifferentiated curve is positioned far from the male two-phase curve, and more closely to the female two-phase curve. This observation implies that HC standard curves must be fitted by two-phase, gender-dependent models.

Discussion

In this study, we applied a new method to fit cross-sectional data of fetal BPD and HC. Male and female data were processed separately. Mathematical computing has shown a change in growth kinetics at 30 GW, so that separate equations were calculated before and after this age. We then compared this two-phase model with three usual one-phase models: a linear-quadratic model, a linear-cubic model [9], and the Rossavik model [16]. The last two models have been devised from longitudinal data. Nevertheless, they may be compared with our model, since, as observed by Deter and Harrist [10] 'there is a good agreement between the predicted values specified by functions derived from the cross-sectional data sets and the mean values obtained from the longitudinal data sets'.

If we compare our two-phase model with the three other models computed over the whole period of gestation (12–38 GW), the former appears much more accurate

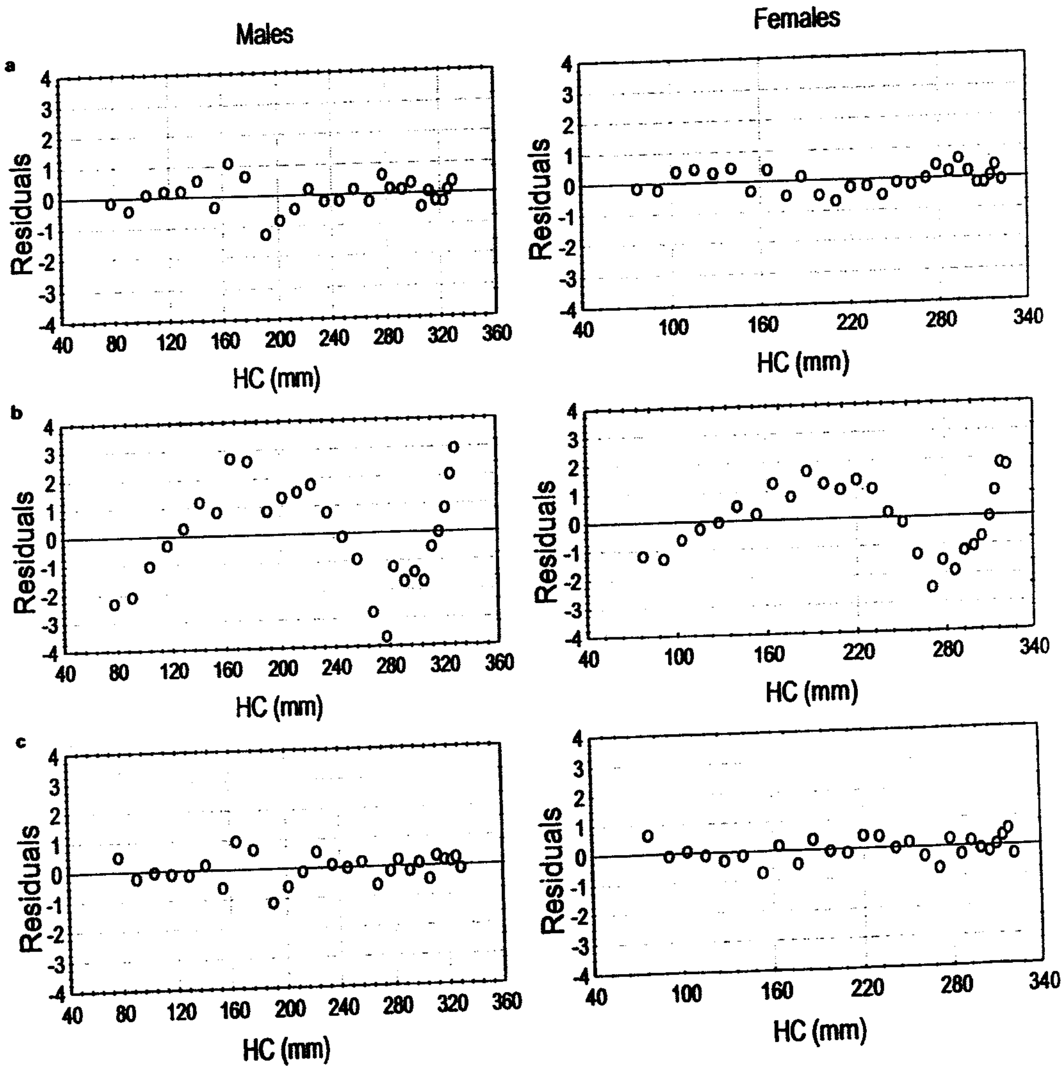

Fig. 4. Residuals versus HC values for the two-phase model (**a**), the linear-cubic model [9] computed over the whole gestational period (**b**) and the linear-cubic model [9] computed for two successive periods (**c**).

than the others, for both BPD and HC. However, when the three other models are computed for the two successive periods corresponding to our two-phase model (12–29 GW and 30–38 GW), their accuracy is greatly improved. For BPD, our two-phase model remains the most accurate in the 12–29 GW period. For HC, the linear-quadratic and linear-cubic models become as accurate as the two-phase model. Thus, whatever the mathematical model fitting BPD or HC data, computing the data for two successive periods greatly enhances the accuracy of the model. Moreover, differences between models become insignificant when computed in that way. Consequently, many mathematical models can be used to fit BPD and HC data, so long as the models are computed independently for two periods: 12–29 and 30–48 GW.

This model reflects the specific pattern of head growth, which slows down at the beginning of the third gestational trimester. We know that most fetal biometrical parameters reflect a decreased growth rate later in gestation, after 35 GW [5]. Therefore, two-phase models may not be the most appropriate to fit other measurements than BPD and HC. This hypothesis should be further tested.

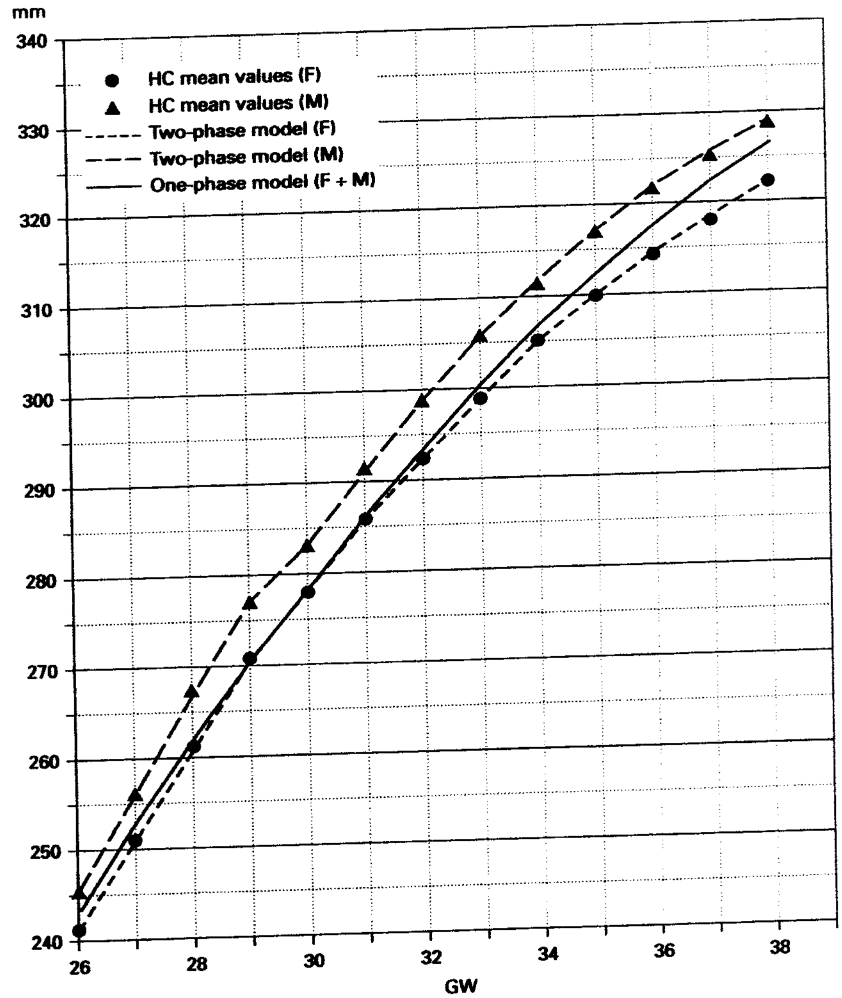

Fig. 5. Mean HC growth curve fitted by the Deter model [9], in one phase or two phases. The one-phase model was computed without distinction of genders. The two-phase model was computed separately for males (M) and females (F).

Two-phase models are uncommon in the literature. Concerning BPD, Nitzan et al. [11] previously proposed a 'sectioned polynomial' model, including a linear growth model until 28 weeks, and a second-order polynomial model afterwards. This 'sectioned polynomial' model is less accurate than our two-phase model, since its average SEE is 1.27, with a standard deviation of 1.02. This difference may be explained by the fact that, unlike Nitzan et al., we computed the two genders separately. Separate mathematical computing of male and female data greatly improves the precision of the models, as confirmed by the comparison of the SEE. For example, Nitzan et al. [11] report an SEE value of 1.81 for the Rossavik model when computed without distinction of genders. However, when the same model is computed separately for males and females, we obtain lower SEE values (0.49 in males and 0.73 in females). Thus, to provide a correct description of fetal head growth, it is essential to compute male and female data separately.

In conclusion, we proposed a two-phase, gender-dependent model which agrees better with HC and BPD cross-sectional data. Moreover, we established that the accuracy of other usual models is greatly improved when they are computed as our model, namely, dividing gestation into two periods and modeling male and female data separately. We think that only two-phase models should be used to compute accurate centile charts of fetal HC and BPD. In a further study, we shall give these centile charts and the better accuracy of these models to predict head growth by comparing the observed measurement on normal fetuses at a given time with the corresponding value predicted by the model.

Appendix: Computing the equations of the Pineau model for BPD [17]

An interval including 5–95% of the variation of theBPD data is chosen, and the curves corresponding to the limits of this interval are drawn. For each mean value y, the value of Δy, and of Δt at the same mean point are measured in the interval defined above (fig. 1). Then the decimal logarithm of t, Δt, y and Δy are computed. The results are reported in the table opposite.

The variation of Δt in relation to t shows a breakpoint at 30 GW (as observed in fig. 2 for HC) which corresponds to a change in the analytic form of the growth function. Therefore, we computed two models: the first one between 12 and 29 GW, the second one between 30 and 38 GW.

The relationship between Δt and t in the 12–29 GW interval is: $\log \Delta t = 0.803 \log t + 0.394. \rightarrow dt/t^{0.8} = \text{Cte}$. Similarly, the relationship between Δy and y is: $\log \Delta y = 0.415 \log y + 0.265 \rightarrow dy/y^{0.415} = \text{Cte}$. For each point of the mean curve, we have: $dy/y^{0.415} = dt/t^{0.8}$. By integrating this differential equation, we have: $y^{0.585} = f(t^2)$. So $y = f(t^{0.615})$. We optimized this relationship by applying small fluctuations around the value 0.615. We obtained various equations, and we chose the best equation with the largest R^2, and consequently the smaller SEE:

$$y = 15.32\, t^{0.63} - 52.04, \quad (1)$$

with $R^2 = 0.99994$ and SEE = 0.19.

We proceeded in the same way to establish a relationship between y and t in the 30–38 GW interval. The equation was:

$$y = -80.40 \times 10^6\, t^{-4.45} + 99.50 \quad (2)$$

At t = 29.5 SA (point of intersection of the two models), y = 77.16 cm with equation 1, and y = 76.35 cm with equation 2, an insignificant difference of 0.81 cm (≠ 1% of the y value).

T	log t	Δt	log Δt	Y	log y	Δy	log Δy
12	1.079	19.0	1.279	21.5	1.332	7.0	0.845
13	1.114	20.0	1.301	25.1	1.400	7.0	0.845
14	1.146	20.5	1.312	28.3	1.452	7.0	0.845
15	1.176	21.0	1.322	32.5	1.512	7.6	0.881
16	1.204	22.0	1.342	35.8	1.554	7.9	0.898
17	1.230	23.5	1.371	39.3	1.594	8.6	0.934
18	1.255	25.0	1.398	42.5	1.628	9.0	0.954
19	1.279	26.5	1.423	45.8	1.661	9.0	0.954
20	1.301	28.0	1.447	49.0	1.690	9.0	0.954
21	1.322	29.0	1.462	52.5	1.720	10.0	1.000
22	1.342	30.0	1.477	55.3	1.743	10.0	1.000
23	1.362	31.0	1.491	58.5	1.767	9.0	0.954
24	1.380	32.0	1.505	61.3	1.788	9.5	0.978
25	1.398	33.0	1.518	64.5	1.810	10.0	1.000
26	1.415	34.0	1.531	67.5	1.829	11.0	1.041
27	1.431	35.0	1.544	69.9	1.844	11.0	1.041
28	1.447	36.0	1.556	72.8	1.862	11.0	1.041
29	1.462	37.0	1.568	75.9	1.880	11.7	1.068
30	1.477	41.0	1.613	78.0	1.8920	11.7	1.068
31	1.491	46.0	1.663	80.8	1.907	13.0	1.114
32	1.505	55.0	1.740	83.5	1.922	13.0	1.114
33	1.518	68.0	1.833	85.4	1.932	13.0	1.114
34	1.531	80.6	1.906	87.3	1.941	12.5	2.565
35	1.544	97.8	1.990	88.8	1.948	12.5	2.565
36	1.556	121.1	2.083	90.0	1.954	12.5	2.565
37	1.568	144.4	2.160	91.0	1.959	13.0	2.565
38	1.580	167.7	2.225	91.8	1.963	12.3	2.565

References

1 Deter RL, Rossavik IK: A simplified method for determining individual growth curve standards. Obstet Gynecol 1987;70:801–806.
2 Campbell S, Newman GB: Growth of the fetal biparietal diameter during normal pregnancy. J Obstet Gynaecol Br Commonwealth 1971;78:513–519.
3 Todros T, Ferrazzi E, Groli C, Nicolini U, Parodi L, Pavoni M, Zorzoli A, Zucca S: Fitting growth curves to head and abdomen measurements of the fetus: A multicentric study. J Clin Ultrasound 1987;15:95–105.
4 Chitty LS, Altmann DG, Henderson A, Campbell S: Charts of fetal size. 2. Head measurements. Br J Obstet Gynaecol 1994;101:35–43.
5 Guihard-Costa AM, Larroche JC: Fetal Biometry: Growth charts for practical use in fetopathology and antenatal ultrasonography. Fetal Diagn Ther 1995;10:215–278.
6 Guihard-Costa AM, Droullé P: Standards échographiques de croissance fœtale: De la population à l'individu. Ann Méd Nancy Lorraine 1998:37:261–268.
7 Moore WMO, Ward BS, Jones VP, Bamford FN: Sex difference in fetal head growth. Br J Obstet Gynaecol 1988;95:238–242.
8 Kurmanavicius J, Wright EM, Royston P, Wisser J, Huch R, Huch A, Zimmermann R: Fetal ultrasound biometry. 1. Head reference values. Br J Obstet Gynaecol 1999;106:126–135.
9 Deter RL, Harrist RB, Hadlock FP, Poindexter AN: Longitudinal studies of fetal growth with the use of dynamic image ultrasonography. Am J Obstet Gynecol 1982;143:545–554.
10 Deter RL, Harrist RB: Growth standards for anatomical measurements and growth rates derived from longitudinal studies of normal fetal growth. J Clin Ultrasound 1992;20:381–388.
11 Nitzan M, Tadmor OP, Skomorowski Y, Rabinowitz R, Diamant Y: Mathematical models for fetal growth: Application for biparietal diameter measurement. Fetal Diagn Ther 1994;9:321–326.
12 Marubini E, Bossi A, Milani S: Fetal growth by echography. Acta Med Auxol 1996;28:7–16.
13 Di Battista E, Bertino E, Benso L, Fabris C, Aicardi G, Pagliano M, Bossi A, De Biasio P, Milani S: Longitudinal distance standards of fetal growth. Acta Obstet Gynecol Scand 2000;79:165–173.
14 Levi S, Keuwez J: Biométrie fœtale: Revue et application de la détermination du sexe. Ultrasound Med Biol 1984;10:51–59.
15 Guihard-Costa AM, Droullé P: Croissance du diamètre bipariétal, du diamètre abdominal transverse et de la longueur du fémur chez le fœtus. Influence du sexe. Cah Anthrop Biom Hum 1990;8:49–69.
16 Rossavik IK, Deter RL: Mathematical modeling of fetal growth. I. Basic principles. J Clin Ultrasound 1984;12:529–534.
17 Pineau H: La croissance et ses lois. Cah Anthrop Biom Hum 1991:9:1–307.