Fetal growth velocity: kinetic, clinical, and biological aspects

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Abstract
With the aim of determining fetal growth kinetics, prenatal data were analysed which had been longitudinally collected in the framework of a perinatal growth survey. The sample comprised 238 singleton normal pregnancies, selected in Genoa and Turin (between 1987 and 1990), and repeatedly assessed by ultrasound scans (five to nine per pregnancy). Five morphometric traits were considered: BPD (biparietal diameter), OFD (occipitofrontal diameter), HC (head circumference), FDL (femur diaphysis length) and AC (abdomen circumference).

Growth rate seemed to increase in the early part of the second trimester, and decrease subsequently: velocity peaks were steeper and earlier for head diameters and circumference (about 18 weeks) than for femur length (20 weeks) and abdomen circumference (22 weeks). Velocity standards were traced using a longitudinal two-stage linear model: this ensures unbiased description of the shape of the growth curve, even when growth kinetics are asynchronous, and efficient estimation of the outer centiles - the most useful for diagnostic purposes.

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Before the development of ultrasonography, there was no harmless and reliable technique available for providing information on physiological fetal growth kinetics, and the so-called intrauterine growth standards were therefore based on anthropometric measures of neonates with different gestational ages. As the assumption that prenatal growth in full term and preterm babies follows the same pattern is hardly tenable,1 these norms are intrinsically a tool for evaluating body size and proportion of neonates, and not true growth standards for monitoring fetal development.

Unfortunately, most ultrasonographic norms derive from cross-sectional surveys,3–5 or from longitudinal surveys involving either a limited number of observations per pregnancy or a limited number of pregnancies.6–10 Even in the case of longitudinal studies, data are generally processed as coming from cross-sectional surveys, so that the specific possibilities of these studies (such as the estimation of growth velocity and the analysis of the pattern of growth) are overlooked and lost.

In this paper we present a new kinetic model for fetal growth and velocity charts computed on a large sample of pregnancies, collected and repeatedly assessed by ultrasound scans in the framework of a prospective perinatal growth longitudinal survey.

Methods
Pregnant women were selected in Genoa and Turin, between 1987 and 1990, in accordance with the restrictive criteria recommended by FIGO,11 so as to include only normal singleton pregnancies. The sample so obtained comprised 238 neonates (123 girls, 115 boys) delivered at term after low risk, uncomplicated pregnancy. Gestational age was estimated from the last menstrual period and was confirmed by an early ultrasound assessment of crown–rump length12 performed within the 12th week: when the difference between the two estimates exceeded seven days, the pregnancy was excluded from the reference set. Informed consent was obtained from each woman participating in the survey.

Individual growth profiles consist of five to nine measures (totalling from 1539 scans for biparietal diameter, to 1237 scans for abdomen circumference), taken between the 12th and the 40th gestational week. All measurements were performed by four trained echographers, using real time scanners (Ansaldo AU920, ATL Ultramark IV, Toshiba SAL 30A) equipped with 3–5 MHz transducers. In accordance with the method described by Campbell,13 BPD (biparietal diameter) was measured at the largest transverse diameter of head at the level of thalamus, from the outer edge of the proximal skull table to the inner edge of the distal skull tables, whereas OFD (occipitofrontal diameter) was obtained from middle to middle measurements on the same plane used for BPD.14 HC (head circumference) was computed from the short and long axes of head taken from the outer contour of skull profile.15 FDL (femur diaphysis length) was determined as the largest of three measures obtained according to Queney et al.16 AC (abdomen circumference) was computed from the antero-posterior and transverse abdomen diameters, measured as two perpendicular axes of the outer contour of abdomen profile at the level of the median portion of porto-umbilical vein passing through the liver, as indicated by Kurjac and Breyer.17

A test-retest experiment was performed to estimate the comparability of measurements. A set of 20 pregnant women with pregnancies...
Fetal growth function

All these above on the decrease of functions and the formation of individual random constants, three prenatal traits of fetuses belonging to the same reference group were simultaneously estimated by an expectation maximisation interactive algorithm (Milani S, Bossi A, Marubini E. Paper contributed to 46th Session of International Statistical Institute, Tokyo, 1987) which leads to generalised least squares estimates. This method allows for the fact that individual growth constants are estimated from observations which differ in number and time location.

Growth velocity charts (the centiles of the distribution of the growth velocity of a given trait conditional on gestational age) were derived from the above average growth constants and interindividual covariance matrix, under the hypothesis that the measurements are taken six weeks apart for BPD, OFD, HC, and FDL, and 10 weeks apart for AC: because of measurement errors, velocity values computed on shorter time intervals are too unreliable to be of practical use (see the appendix for the algebraic details).

**Results**

Figures 1–5 show growth velocity standards for BPD, OFD, HC, FDL, and AC. For all these traits, growth velocity seemed to increase in the early part of the second trimester and decrease subsequently up to the end of pregnancy. Interindividual variability of growth velocity changes remarkably with gestational age: it

**Two-stage models and longitudinal standards**

The fitting of appropriate functions to individual growth profiles may be regarded as the first stage of an explicit two-stage model. In this first stage the individual growth constants were estimated by ordinary least squares method, under the usual assumptions that the intra-individual component of variance (which accounts for both measurement error and biological random fluctuations due to variations of the intrauterine environment and to nutritional factors) is nearly the same over time and subjects, and that repeated measures are uncorrelated. In the case of intrauterine growth these assumptions seem to be sensible and fairly consistent with empirical evidence, provided that a log scale is adopted, homogeneous reference groups are selected, and a flexible growth function (such as the log-Count function defined here) is fitted to data.

In the second stage the average growth constants (which express the mean growth pattern) and the interindividual covariance matrix (which expresses differences between the individual growth patterns of fetuses belonging to the same reference group) were simultaneously estimated by an expectation maximisation interactive algorithm (Milani S, Bossi A, Marubini E. Paper contributed to 46th Session of International Statistical Institute, Tokyo, 1987) which leads to generalised least squares estimates. This method allows for the fact that individual growth constants are estimated from observations which differ in number and time location.

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STATISTICAL METHODS

Growth functions

Most of the mathematical functions used to model prenatal growth of BPD and other one-dimensional traits belong to the same family of three constant linear growth functions:

$$\log y(t) = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \varepsilon(t)$$

Where $y(t)$ is the value of the trait measured on the $i$-th individual at age $t$; $\varepsilon(t)$ is the intra-individual random term associated with $\log y(t)$; $\alpha_0$, $\alpha_1$, and $\alpha_2$ are the growth constants of the $i$-th individual; firstly $f_1(t)$ and $f_2(t)$ are selected functions of age which determine the shape of growth model. If we set $f_1(t) = t$ and $f_2(t) = \log t$ we get a Count function in a log scale (we shall call it log count function). The logarithmic form of Rossavik-Deter18 and Todros et al4 exponential-power functions may be derived by log-Count function if we set $f_1(t) = t \times \log f_2(t)$ and $\alpha_2 = 2$, respectively. All these functions have a point of inflection but do not have an upper horizontal asymptote, thus allowing for the fact that fetal growth velocity increases moderately in the first months of gestation, and then decreases slowly without falling to zero.20

The comparison of the functions mentioned above on the basis of the analysis of residuals and of the precision of the estimates indicated that Todros et al (for AC) and log-Count functions (for the remaining traits) led to the most satisfactory description of fetal growth: the maximum systematic departure of these functions for the growth profile was less than 3%.21 The analysis of fetal growth kinetics and velocity standards presented are based on these functions.
differences in the pattern of growth of the traits under study are shown in figure 6, where the velocity of each trait is expressed as a percentage of its size at 40 gestational weeks. In the same figure the growth velocity of cubic BPD (which is roughly proportional to head volume) is also shown: the peak velocity is sharper and takes place much later (31-1 weeks (0-27)) for computed head volume than for head diameters and circumference.

Only minor differences in the growth pattern of one dimensional traits emerged between sexes: differences seemed to be negligible from a clinical point of view and could be ignored in drawing prenatal growth velocity charts.

**HEAd**

The estimated value of gestational age at peak of velocity was about 17-18 weeks for BPD, OFD, and HC. Lower values were derived from the mixed longitudinal study (13-16 weeks) of Guhard-Costa et al. and from the cross-sectional study (16-4 weeks) of Todros et al. Higher values (20-8 weeks) are reported by Eriksson et al. on the basis of a longitudinal study. Similar velocity values and analogous decrease of velocity after the 17th gestational week were observed by Campbell et al. in a longitudinal study (191 pregnancies, 3-4 scans/pregnancy): however, in their study the age at peak could not be estimated, because of the lack of measurements before the 17th week. Jeanty et al. and Munjanja et al. observed that growth velocity increases after 14-15 gestational weeks. From the longitudinal observation of 30 pregnancies, Fescina et al. in 1994 infer that the maximum growth velocity of intracranial perimeters occurs between the 14th and the 16th gestational weeks. Deter et al. in their first longitudinal study aimed to model fetal growth, and which involved only 20 pregnancies, observed that BPD growth curve has a slight upward convexity which continues up to 38 weeks of gestation, whereas HC is characterised by a linear phase up to 30 weeks and by a subsequent slow down in growth velocity. Ten years later, Deter and Harrist observed that HC growth rate decreases from 14 mm/week (at 14 weeks of gestation) to 9 mm/week (at 30 weeks) and 5 mm/week (at 38 weeks).

Our data indicate that peak growth velocity for BPD, OFD, and HC occurs at the end of the first phase of rapid increase in forebrain cell number, when major neuronal proliferation occurs. The subsequent decrease in growth velocity of these one dimensional traits does not necessarily reflect a contemporary slow down in the weight gain of the brain (which is a complex three dimensional structure and approximates the growth pattern of cubic BPD), whose peak growth velocity seems to be later than those of one dimensional traits.

Our findings agree with those of Meire, who points out that the growth curve of fetal head volume has a shape rather different from that of BPD, with a velocity decrease after 28-32 weeks.
Fetal growth velocity

Figure 4 Standards of FDL (femur diaphysis length) growth velocity (mm/week) as a function of menstrual age (weeks). The chart applies to estimates of growth velocity based on measures taken six weeks apart.

FEMUR

At present there are relatively few data suitable for modelling the growth kinetics of the femur. On the basis of longitudinal observations, Queenan et al.\(^7\) state that growth is linear between 12 and 22 weeks of gestation. In a more recent study Excousos et al.\(^6\) notice that growth is fairly linear from 13 to 28 weeks and then slows down, even if growth velocity cannot be estimated from their cross-sectional data. Cross-sectional data reported by Yeh et al.\(^3\) and longitudinal observations carried out by Elejalde and De Elejalde,\(^9\) suggest that growth of the femur is linear between 10 and 40 weeks of gestation: but such a pattern seems to be unusual for any biological growth process.\(^31\) Longitudinal data reported by O’Brien et al.\(^8\) and Brons et al.\(^9\) display similar growth patterns with a decrease in velocity after 17 and 12 weeks of gestation, respectively. Only Guihard-Costa et al.\(^10\) on the basis of mixed longitudinal data, observe a non-monotonic kinetic pattern, with a peak between 13 and 16 weeks and a subsequent decrease in velocity.

From our longitudinal study it emerged that FDL growth velocity peaks at about 20 weeks when, according to Tanner,\(^33\) the peak of velocity in fetal crown-heel length occurs, which is highly correlated with femur length.

ABDOMEN

As to growth of abdomen circumference, the age at peak estimated from our study (22 weeks) is higher than those reported by Guihard-Costa et al.\(^10\) (from 13 to 16 weeks) and Todros et al.\(^4\) (20 weeks), but lower than that given by Fescina et al.\(^26\) (from 32 to 34 weeks). From a longitudinal analysis of 20 pregnancies Deter et al.\(^27\) concluded that AC growth is essentially linear throughout pregnancy. Ten years later, Deter and Harris\(^28\) asserted that AC growth velocity decreases slightly: from 12 mm/week (at the 14th week
known that fetal growth is characterised by different rates for organ weight and size, limb length and head circumference and volume, so that body shape and proportions change over gestation. On the other hand, differences in fetal growth kinetics of head and abdomen circumferences emerge also from the inspection of preterm and full term babies: preterm neonates have a ratio of head and brain size to body mass that is larger than that of full term neonates, and this may account for their very high glucose turnover. Anoxia affecting fetal development in the first four months of gestation results in generalised growth impairment (weight, length, and head size), while anoxia occurring in the last months of pregnancy affects mainly weight and results in a low birth weight baby with normal head circumference and length.

Discussion
Intrauterine growth velocity has a non-monotonic pattern: it increases in the first part of pregnancy and decreases in the last part. The age at peak velocity as well as the extent of the peak depend on the morphometric traits: peaks are sharper and occur later for three dimensional traits than for one dimensional traits. Furthermore, abdomen circumference reaches maximum growth velocity two weeks after femur length and five weeks after head circumference. The reliability of these conclusions rests on the number of records per longitudinal profile (five to nine, mean=6.5), the size of sample (238 pregnancies), the strictness of criteria adopted to select normal pregnancies resulting in normal outcome, and the relatively good precision of ultrasonographic measurements.

The velocity standards presented here are entirely based on a two-stage linear model. In the first stage the individual intrauterine growth profiles were fitted by a proper growth function: Todros et al.'s function for AC and a new function derived from Count's function for the other fetal traits (log-Count function). The systematic discrepancies which emerged between observed and fitted values (less than 3%) are negligible from a clinical viewpoint. The second stage implied the estimate of the mean constant curve and of the covariance matrix which expresses interindividual variability, required to compute growth centiles. Using this method, the shape of velocity curve can be described without bias, even when growth kinetics are not synchronous among individuals, and efficient estimates are attained even for the outer centiles which are the most useful for diagnostic purposes. Unfortunately, the precision of the current ultrasonographic techniques is still inadequate to obtain reliable measures of individual growth velocity on short time intervals. This drawback restricts the practical use of velocity charts to velocity estimates derived from measures taken at least six (for BPD, OFD, HC, and FDL) or 10 (for AC) weeks apart.

Appendix
Let us consider a morphometric trait \( y \) whose expected growth in a given subject is described by a continuous function of time \( t \). This function is characterised by a vector of individual parameters \( \alpha \) which, in the population from which the subject has been drawn, is a random variable with mean vector \( \beta \) and covariance matrix \( \Sigma \).

\[
E(y|\alpha) = f(\beta \cdot \alpha) = E(Y) = \Sigma \alpha
\]

Therefore, a single measure \( y \) taken on the subject at time \( t \) may be expressed as

\[
y = f(\beta \cdot \alpha) = f(\beta \cdot \alpha) + \epsilon
\]

where random terms \( \alpha - \beta \) and \( \epsilon \) account for interindividual and intra-individual variability. The fetal growth models (log-Count function and Todros et al.'s functions) on which standards here presented are based may be written as:

\[
y = \exp(q \beta + q \alpha + \epsilon)
\]

where \( q = \{1, \log_{e}(t)\} \). Under the usual assumption for random terms (ie, \( V(\epsilon) = \sigma^{2} \), \( \text{Cov}(\alpha, \epsilon) = 0 \), and \( \text{Cov}(\alpha, \beta, \epsilon) = 0 \), the variance of a new observation \( \bar{y} \) at time \( t \), predicted on the basis of an unbiased estimate \( \hat{\beta} \) of \( \beta \), is given by the sum of the interindividual and intra-individual components, and may be computed (approximately) from equation 3 by means of a Taylor series expansion about \( f(\beta \cdot \alpha) \)

\[
V(\bar{y}) = f(\beta \cdot \alpha)^{2} \times \left[ q' \Sigma + V(\hat{\beta}) q \right] + \sigma^{2}
\]

Let us denote the first derivative of vector \( q' \) with respect to time \( t \) as \( dq = \{0, 1, 1/t\} \) and write the expected individual growth velocity as:

\[
E(\epsilon) = \frac{d\epsilon}{dt} = f(\beta \cdot \alpha) \times (dq' \beta + dq' \alpha - \beta)
\]
The variance of a predicted value of velocity $V_\theta$ is given by the sum of an inter-individual component, which does not depend on the time interval $\Delta t$ on which velocity is measured, and of an intra-individual component which does depend on $\Delta t$:

$$V(\theta) = V(\theta) + \frac{1}{\phi} \{ \beta \theta^t \}^2 \times 2 \sigma^2 \Delta t^2$$  \hspace{2cm} (6)

where $V(\theta)$ may be computed (approximately) from equation 5 by means of a Taylor series expansion about $\phi \theta^t$:

$$V(\theta) = \{ \beta \Delta t \} \times (\phi \theta^t)^2 \times \left[ \frac{1}{\psi} \sum \psi \times (\phi \theta^t) \right]^2 + \left[ \frac{1}{\psi} \sum \psi \times (\phi \theta^t) \right]^2 \times \left[ \frac{1}{\psi} \sum \psi \times (\phi \theta^t) \right]^2$$  \hspace{2cm} (7)

The estimate of $V(\theta)$ was obtained by replacement of $\beta$, $\sum \psi$, $V(\theta)$ by their generalised least squares estimates $\hat{\beta}$, $\hat{\sum} \psi$, $\hat{V}(\theta)$, and $\sigma^2$ by the pooled residual mean square error ($s^2$) about the individual growth curves.

For all traits, the distribution of the fitted values of individual growth velocities conditional on gestational age was close to the normal distribution: this is not surprising, as all fetal traits under study are one dimensional. For this reason, the usual parametric estimates of cenciles were computed. As $\Delta t$, we chose an interval of six weeks for BPD, OFD, HC, and FDL and an interval of 10 weeks for AC, the means of which seemed to be affected by relatively large errors. The choice was a compromise between the size of technical error and the obstetrician’s need to have a ready assessment of the normality of fetal growth.

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1 Falkner F. Perinatal growth. Arch Pediatr Fetal Neonatal Ed; first published as 10.1136/fn.74.1.F10 on 1 January 1996. Downloaded from http://fn.bmj.com on February 8, 2021 by guest. Protected by copyright.


