Comparative Study of Five Growth Models Applied to Weight Data From Congolese Infants Between Birth and 13 Months of Age

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ABSTRACT Five growth models are compared using weight data from 95 rural Congolese infants between birth and 13 months of age. The objective is to find the best model in terms of goodness of fit and distribution of parameter estimates. The Infancy component of the Karlberg model, the Count model, and the Kouchi model, which are all three-parameter models, are tested together with the four- and five-parameter versions of the Reed model. The closest fits are obtained using the Reed models, followed by the Karlberg model, while the Count and Kouchi models provide poor fits. The five-parameter Reed model is not superior to the four-parameter version. Examination of mean residuals by age shows a systematic bias in neonatal weight estimation with the three-parameter models. Mean within- and between-individual correlations are especially high for the Kouchi and Reed models. Extreme skewness is observed for some parameters of the Kouchi model and of the five-parameter Reed model. Despite its high degree of collinearity, the four-parameter linear Reed model should be preferred on weight data between birth and 1 year. The I-component of the Karlberg model could be used between ages 2 and 12 months.

In developing countries almost 30% of preschool children suffer from impaired growth (Keller and Fillmore, 1983) due to local ecological conditions, mainly improper nutrition and infections (Martorell et al., 1988). Growth during infancy is thought to be especially important because of high growth velocity and sensitivity to external factors in that age range (Waterlow, 1988; Forman et al., 1990). Food supplementation has been shown to have the largest effect on weight and height growth prior to 1 year of age and virtually no effect after 2 years in children from Guatemala (Lutter et al., 1990). Furthermore, nutritional status (in terms of weight, length, or length for age) at 12 months is more predictive of the child's preschool status than is status at birth or during the first months of life (Scholl et al., 1983; Simondon et al., 1991), suggesting that a child's preschool nutritional status is largely determined by growth during infancy. Therefore, research on growth impairment should focus on the infancy, i.e., the first year of life.

The modelling approach is a powerful tool for the study of growth. It provides smooth curves of status and velocity, even from irregularly spaced measurements. Furthermore, the comparison between families of curves can be done using parameter estimates. Several models have been used for the modelling of infant growth, but no general evaluation of existing models is available as it is for growth from 3 months to 6 years (Berkey, 1982), for pubertal growth (Marubini et al., 1971; Hauspie et al., 1980), and for total lifetime growth (Preece and Baines, 1978; Jolicoeur et al., 1988). The present research compares the models currently used for infancy or preschool growth using weight data from Congolese infants between birth and 13 months of age.

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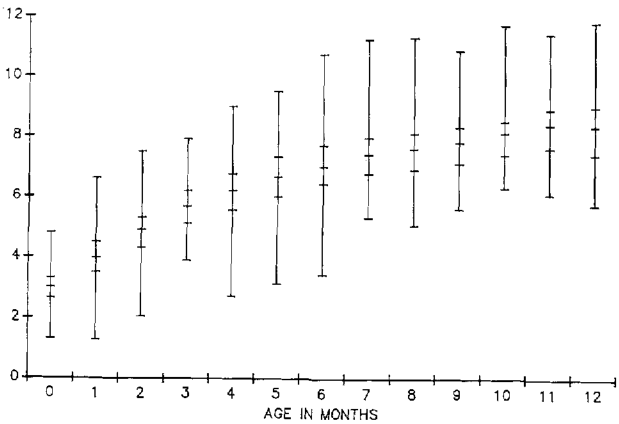

Fig. 1. Means, maxima, minima, and quartile values of the original weight data (in Kg) by age.

MATERIALS AND METHODS

Study population and data

The data were taken from the 1987 National Survey of Nutrition in The People's Republic of Congo, Central Africa (Cornu et al., 1990). Briefly, a sample of 2,429 children under 5 were selected using a stratified cluster sampling design. Their nutritional status and the potential risk factors of protein–energy malnutrition were assessed. Weight measurements taken at the local health centers during infancy were copied from the children's health cards when these were available in their homes, and the corresponding ages noted. The objective was to study the relationship between growth in infancy, nutritional habits, and subsequent nutritional status. These routine weight measurements were used for the present study. Weights were recorded to the nearest 20 g.

Ninety-five children who had been monitored until 13 months of age were selected. They were all weighed before 1.5 months and between 12 and 13.5 months of age, and they were measured during at least 7 different examinations. Birth weight was also included in the analysis whenever it was available (79% of the children).

The nutritional status of most children was poor, but a broad spectrum of growth patterns was represented in the sample. Mean weight by age is given in Figure 1 together with maxima, minima, and quartile values of the distributions.

Models

The following five growth models were compared: the Count model, the Kouchi model, the first- and second-order Reed models, and the I-component of the Karlberg model.

The Count model (1943) is linear in its three parameters:

$$y = A + Bt + C\ln(t)$$

and it was proposed for modelling anthropometric variables such as weight, height, and head circumference. Berkey (1982) compared it to the Jenss model on weight and height data for children between 3 months and 6 years and concluded that it had severe age-related biases.

The Kouchi model was developed by Kouchi et al. (1983a,b), who applied it to weight (Kouchi et al., 1983a) and length (Kouchi et al., 1983b) data for children from the Fels Longitudinal Growth Study between birth and 2 years. This three-parameter nonlinear model is

$$y = A + Bt^C$$

The two linear Reed models (Berkey and Reed, 1987) are extensions of the Count model. The first-order model is

$$y = A + Bt + C\ln(t) + D/t$$

a four-parameter model, which is more flexible than the Count model since it allows an inflexion point. The second-order model is

$$y = A + Bt + C\ln(t) + D/t + E/t^2$$

where the fifth parameter allows a second inflexion point. The first-order version was shown to perform well on height between 3 months and 6 years: only a few children needed the second order version (Berkey and Reed, 1987).

The Karlberg or ICP model (Karlberg, 1987) is a combination of three components describing, respectively, infancy, childhood, and pubertal growth. It is analytical rather than descriptive. The infancy component is

$$y = A + B[1 - \exp(-Ct)]$$

It was used to study length data from healthy Swedish children (Karlberg et al., 1987) and from nutritionally at-risk Pakistani children (Karlberg et al., 1988; Jalil et al., 1989). The fit of the infancy component (I-component) was good up to 9 months, on average, in the Swedish sample, and up to 1 year in the Pakistani sample. The I-component of the Karlberg model has previously been used on the Congolese infancy weight data reported here. The objective was the estimation of individual weights and quarterly weight increments for the prediction of linear growth retardation in preschool children (Simondon et al., 1991). The goodness of fit was satisfactory. Only the I-component, named the Karlberg model for convenience, will be considered here.

Modelling

The Count and Reed models are not defined at age = 0. One of the aims of this study was to find a model which properly fits the neonatal period. Therefore, it was important to include birth weight in the modelling.

The linear models were modified as follows:

Count: $y = A + Bt + C\ln(t + 1)$

Reed 1: $y = A + Bt + C\ln(t + 1) + D/(t + 1)$

Reed 2: $y = A + Bt + C\ln(t + 1) + D/(t + 1) + E\,(t + 1)^2$

Another solution would have been to shift the age scale using t = age + 1 (in months). In this case, the parameter estimates and correlations would not be the same as in the present study, but goodness of fit would remain unchanged.

Fitting of both linear and nonlinear models was achieved on an AT microcomputer by the nonlinear regression program 3R of the Biomedical Data Analysis Package (BMDP, 1985), which gives least-squares estimates of the parameters using an iterative Gauss–Newton algorithm. Initial parameter estimates were provided, together with the growth model and its derivatives with respect to the parameters. For each child, the program provided extensive output in addition to the parameter estimates, such as residual variance measuring overall goodness of fit, and residuals which are recorded weights minus estimated weights and which assess age-specific goodness of fit. The within-individual parameter error correlation matrix was also given.

Individual velocity curves were computed for all children, using the estimated parameters, by derivation of the growth models:

Kouchi: $dy/dt = BC(t^{(C-1)})$

Karlberg: $dy/dt = BC\exp(-Ct)$

Count: $dy/dt = B + C/(t + 1)$

Reed 1: $dy/dt = B + C/(t + 1) - D/(t + 1)^2$

Reed 2: $dy/dt = B + C/(t + 1) - D/(t + 1)^2 - 2E/(t + 1)^3$

Birth velocities were estimated only for the 75 children for whom birth weight was known.

Statistical analysis

Residual variances were compared between models two by two using the Wilcoxon paired-sample rank test. The first- and second-order Reed models were compared, the first-order Reed model was compared to the Karlberg model, the Karlberg model was compared to the Count and Kouchi models, and the Count and Kouchi models were compared. Using five comparisons, a significance level at 0.01 was needed (Bonferroni's Inequality). Mean residuals were computed for every month of age from birth to 13 months. No distinction was made between sexes, because differences were minor when compared to differences in nutritional status.

RESULTS

Successful fitting was obtained for all linear models and for the nonlinear Karlberg

TABLE 1. Pairwise comparison of residual variances (in kg²)

Model[1]	Mean	SD	Minimum	Median	Maximum	P^2
Count	0.1382	0.1298	0.0013	0.0902	0.6800	
Kouchi	0.1323	0.1300	0.0006	0.0879	0.6829	0.015[3]
Karlberg	0.0971	0.1101	0.0020	0.0745	0.5826	<0.0001
Reed 1	0.0714	0.0805	0.0005	0.0393	0.4610	<0.0001
Reed 2	0.0688	0.0841	0.0006	0.0405	0.4815	0.108

[1]Models are ranked according to increasing goodness of fit.
[2]Wilcoxon's paired-sample rank test.
[3]The two models compared are the one on the line above the *P* value (here the Count model) and the one on the line (here the Kouchi model).

model. The data of 5 children could not be fitted by the nonlinear Kouchi model because extremely high within-individual parameter error correlations aborted the fitting procedure. Results are given for the remaining 90 children.

Goodness of fit

Residual variances were compared pairwise (Table 1). Only paired comparisons were carried out because the aim was to rank the models according to their goodness of fit. The closest fit was provided by the Reed models, but the second-order version did not perform significantly better than the first-order version. The first-order Reed model fitted 62 children better than the Karlberg model ($P < 0.0001$). The Karlberg model fitted 68 children better than the Kouchi model ($P < 0.0001$) and 70 children better than the Count model ($P < 0.0001$). The Kouchi model did not fit the data significantly better than the Count model ($P = 0.015$ compared to a significance level at 0.01, Bonferroni's Inequality). The mean residual variance of the Count model (0.138 kg^2) was twice as high as the mean residual variance of the second order Reed model (0.0688 kg^2).

Mean residuals by age (in g) and 95% confidence intervals of means are given in Figure 2. The fewest significant deviations from zero were obtained using the Reed models. The Karlberg model performed almost as well, while the Count and Kouchi models exhibited strong patterns of systematic under- and over-estimation. In addition, the Kouchi model suffered from extremely large confidence intervals.

A similar cyclical tendency was obvious for all models: underestimation of weight at birth and at age 5–6 months alternated with overestimation at 2–3 months and 11–12 months. Maximum bias was observed at 1 month for the models of Karlberg (−138 g or 3.5% of recorded weight), Count (−281 g or 7.2%), and Kouchi (−264 g or 6.6%). The flexibility of the Reed models ensured good fit in the neonatal period (bias at age one month: −42 g or 1.0% and −15 g or 0.3%, respectively). Using these models maximum bias was at 10 months of age (−93 g or 1.1% and −78 g or 0.9%, respectively).

Velocity estimation

Velocities were estimated between birth and 13 months for all children. Mean velocity curves are given in Figure 3 together with mean monthly increments which were computed from the raw data. The velocity curves also illustrate age-specific goodness of fit. Both Reed velocity curves fitted the increment curve very well, while the Karlberg curve was less satisfactory during the first months. The Count and Kouchi curves exhibited rather poor fit over the whole age span.

The three-parameter models (Count, Kouchi, and Karlberg) had decreasing velocities throughout infancy, because no inflexion point is allowed by these models. The mean age at inflexion of the Reed curves was at 0.7 months of age. Velocity increases before this age and decreases thereafter. The second-order Reed model allowed negative velocities in the neonatal period. Birth velocity estimation was imprecise, as birth is at an end point of the growth curve.

Parameter distribution

Means, medians, and standard deviations of parameter estimates are given in Table 2 (weight units are kg and age units are months). The Kouchi A and B parameters exhibited extreme skewness as illustrated by the gap between means and medians (−45.4 against −8.8 and 48.3 against 11.2, respectively). The skewness was due to 5–10 outliners with extremely high values. Standard deviations were especially high for the

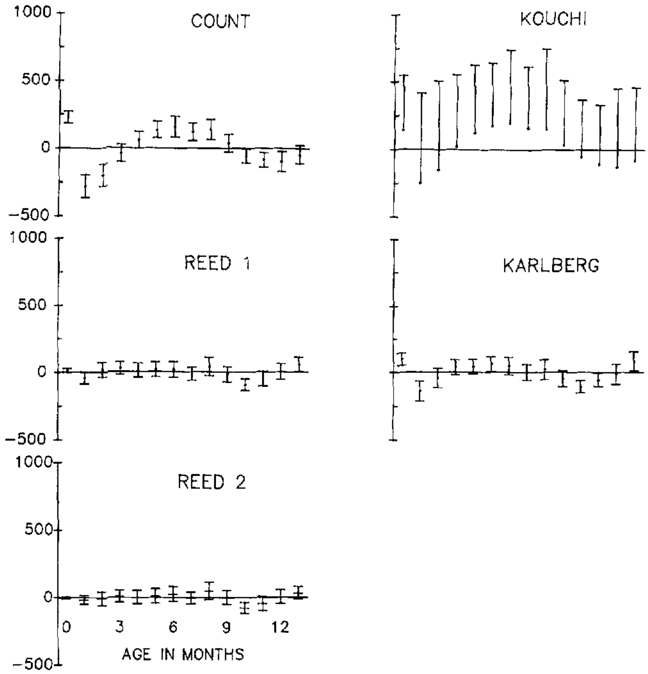

Fig. 2. Mean weight residuals (in g) and 95% confidence intervals of means by age.

Kouchi A and B parameters and for the second-order Reed A, D, and E parameters. Only the Count and Karlberg models had all mean parameter estimates higher than their standard deviations. However, the univariate distributions of the parameter estimates give a very incomplete description of the distributions because of high collinearity among parameter estimates.

Between-individual correlation matrices are given in Table 3. The Count and Karlberg parameters had rather low correlations (no coefficient exceeded .80 or .60, respectively), while those of the Reed models were high. Maximal correlations were found for the Kouchi model as the A and B estimates were linearly related ($r = -1.0$).

Precision

The high between-individual parameter correlations were partly due to high within-individual parameter error correlations (Table 4). When they are very high, the parameter estimates are poor. The Karlberg model had all mean correlations less than .65, while those of the Reed models were all greater than .90. The Kouchi model also had unacceptably high within-individual parameter error correlations, while those of the Count model were rather low. As noted earlier the choice of age scale in these models may affect parameter correlations.

Mean within-individual standard deviations and coefficients of variation of parameter estimates are given in Table 5. The within-individual standard deviations accounted for a very important part of the high between-individual standard deviations of the Kouchi model and the second-order Reed model. The mean within-individual coefficients of variation for the Kouchi model all exceeded 1 in absolute values and those of the second-order Reed model were extremely high (−6.6 for the D parameter estimate and −58.6 for the E parameter estimate).

DISCUSSION

The present study did not consider all models available for the study of weight in preschool children. The Jenss model (Jenss and Bayley, 1937) was not used since it was constructed to approach a linear asymptote, which is characteristic of late preschool growth, but not of infancy growth. No poly-

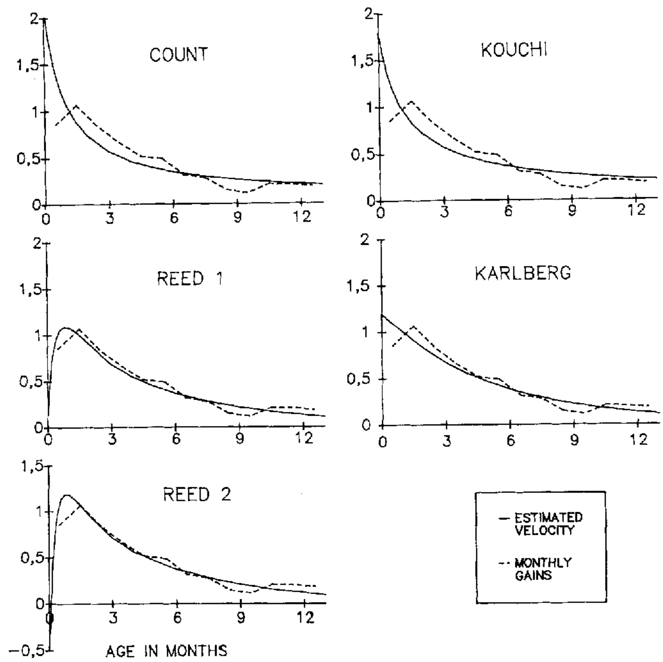

Fig. 3. Estimated weight velocity curves compared to mean monthly weight increments (in kg²/month).

TABLE 2. Means, medians, and standard deviations (SD) of parameter estimates (weight and age units are kg and months)

Model		Mean	Median	SD
Count	A	2.071	2.731	0.659
	B	0.052	0.057	0.121
	C	2.052	2.024	0.658
Kouchi	A	−45.437	−8.781	66.122
	B	48.279	11.207	66.115
	C	0.190	0.169	0.167
Karlberg	A	2.942	2.986	0.580
	B	6.533	6.366	1.493
	C	0.190	0.186	0.066
Reed 1	A	−0.883	−1.325	5.981
	B	−0.192	−0.209	0.352
	C	4.434	4.658	3.787
	D	3.801	3.981	7.369
Reed 2	A	−0.926	1.000	18.408
	B	−0.117	−0.150	0.561
	C	4.363	3.598	8.629
	D	4.661	−0.002	39.404
	E	−1.563	1.703	28.300

TABLE 3. Between-individual correlation matrices of parameter estimates

Count	.214			
	−.387	−.760		
Kouchi	−1.000			
	.678	−.678		
Karlberg	.020			
	−.157	−.571		
Reed 1	.919			
	−.980	−.966		
	−.982	−.874	.945	
Reed 2	.911			
	−.987	−.961		
	−.980	−.825	.941	
	.887	.659	−.816	−.958

nomial models were included because too many parameters would have been needed; only high order polynomials provide satisfactory goodness of fit in preschool growth (Berkey and Kent, 1983) and in pubertal growth (Marubini, 1978; Hauspie, 1989).

Modelling weight is more difficult than modelling height, because weight might decrease with age for shorter periods. In the Congolese infants temporary weight losses during infancy were common. The quality of data collection will also influence the models' goodness of fit, since severe measurement errors increase residuals. The data used in this study were routine weight measurements taken by health workers and they were, therefore, likely to be less accurate than measurements from prospective studies. No reliability data were available. However, mean residual variances were

TABLE 4. Mean within-individual error correlation matrices of parameter estimates

Count	.576			
	−.775	−.946		
Kouchi	−.854			
	.806	−.939		
Karlberg	−.138			
	−.584	−.607		
Reed 1	.943			
	−.990	−.979		
	−.995	−.927	.980	
Reed 2	.976			
	−.997	−.989		
	−.996	−.958	.988	
	.980	.922	−.965	−.993

TABLE 5. Mean within-individual standard deviations (SD) and coefficients of variation (CV) of parameter estimates

Model		SD	CV
Count	A	0.323	0.10
	B	0.082	0.40
	C	0.425	0.23
Kouchi	A	59.099	−1.25
	B	58.929	1.37
	C	0.134	1.47
Karlberg	A	0.254	0.11
	B	0.945	0.11
	C	0.037	0.24
Reed 1	A	2.727	−0.45
	B	0.169	−0.19
	C	1.707	0.40
	D	3.236	0.26
Reed 2	A	17.379	−0.60
	B	0.510	−1.31
	C	8.079	−6.59
	D	36.425	−58.58
	E	23.813	1.49

lower than those of a prospective study on healthy American children between birth and 2 years (0.216 kg^2 for boys and 0.152 kg^2 for girls, Kouchi et al., 1983a). Furthermore, data quality is only a minor issue for the comparison of models.

The Kouchi model failed to fit 5 curves. This is a problem specific to nonlinear models, because adjustment of nonlinear models must use iterative procedures. Computional problems arise if the shape of a growth curve differs from the one imposed by the model (e.g., when fitting a straight line to a model including a curvature) and parameter estimates cannot be provided. Furthermore, the goodness of fit of the Kouchi model was unsatisfactory and the high degree of collinearity was unacceptable.

The I-component of the Karlberg model provided good fit from 2 to 12 months of age. Successful adjustment was obtained for all children and between-individual parameter correlations were low. It was the best three-parameter model among those considered. Still, as this model is nonlinear, adjustment might not succeed for all growth curves in other studies including abnormal growth patterns. When successful adjustment was achieved for most children, as in the case of the Kouchi model in the present study, the remaining curves can simply be excluded from analysis. However, exclusion of even a few curves is not satisfactory, because the growth patterns of these children are obviously different and their exclusion would introduce a bias in the sample.

Linear models are simpler to use than nonlinear models. Fitting can be performed using multiple linear regression programs like BMDP1R. In the present study, the nonlinear regression program BMDP3R was used also for linear models because it provided the within-individual parameter error correlation matrix and because results do not depend on the program used.

The goodness of fit of the linear Count model was not satisfactory. The same observation was made by Berkey (1982) on height data between 3 months and 6 years of age in American children. This model has previously been applied to infancy weight growth in developing countries (Kim and Pollitt, 1987; Wohlleb et al., 1983), but the 0–6 months and the 6–12 months intervals were fitted separately in an effort to improve goodness of fit. No elements of the resulting goodness of fit were given. Berkey and Reed (1987) improved the Count model by adding one, respectively two parameters. These linear Reed models provided the closest fit to the data in the present study. However, the second-order model was overparameterized for this data set. It did not fit the data significantly better than the first-order version, and the within-individual standard deviations were very high. It is a general feature of models that goodness of fit increases together with collinearity, when a parameter is added.

Collinearity is dependent on the age scale. Berkey and Reed (1987) suggested an age scale transformation, where t = (age in months + 9)/9. Using this age scale, t = 0 at conception and t = 1 at birth. The resulting between-individual parameter correlations were not given. Preliminary investigations were carried out with this alternative age scale in the present study, but correlations were not significantly changed. In a study on adolescent height growth, Berkey et al. (1989) were concerned about collinearity using the Reed model because it remained high despite the use of an age scale especially chosen in an effort to reduce it. Kouchi et al. (1983a,b) corrected the between-individual correlations for within-individual error correlations, using a procedure developed by Bock et al. (1973) and mentioned by Berkey (1982). The resulting correlations were low, but the procedure is rather complex.

High parameter correlations are a matter of concern for the comparison between families of curves. If the parameter estimates were independent, families of growth curves could be compared through *t* tests on mean parameter estimates. This method is commonly used (Kim and Pollitt, 1987; Simondon et al., 1991; Byard et al., 1991). However, some degree of collinearity is present in all models, so the modelling of individual curves is not the most efficient approach. Statistically correct methods fit the growth model to the sample of curves in each group to be compared and the estimated parameters are then compared between groups. Methods available for the estimation of parameters are those of Goldstein (1986) and Laird and Ware (1982) for linear models and that of Berkey and Laird (1986) for nonlinear models. These methods take within- and between-individual parameter correlations into account, but still numerical difficulties might arise when parameter correlations are too high (Berkey et al., 1989). These methods have seldom been used for the study of growth, probably because they are rather complex.

The estimation of weights and velocities using the three-parameter models were biased between birth and 1 month, as already noted by Kouchi et al. (1983a). The explanation might lie in the weight loss experienced by most newborns during the first week of life. The three-parameter models will not be able to fit a weight loss because they only allow positive, decreasing velocities, while the first-order Reed model allows one inflexion point. The second inflexion point allowed by the second-order Reed model was not useful on these data.

In conclusion, the present research compared five growth models developed for infancy or early childhood growth. The four-parameter Reed model was the best among the models for the modelling of weight growth between birth and 13 months of age. This result cannot be generalized to other types of growth or other age spans without caution. In Western countries the pattern of infancy growth is somewhat different from that in poorly nourished populations. Growth velocities are higher in developed countries after 3 months of age (Waterlow et al., 1980). However, the postnatal weight loss described here, which required the inflexion point of the Reed model, also occurs in Western countries. Therefore, the fourth parameter of the Reed model is probably necessary also for "normal" infancy weight growth when birth weight is included in the analysis.

In many growth studies only a few measurements are taken per child, so parameter parsimony is crucial. In this case the neonatal period should be excluded from modelling because a three-parameter model might be satisfactory between 2–3 and 12 months of age. The Karlberg model would probably provide the closest fit among three-parameter models. If second-year measurements are included, the I-component of the ICP model is no longer satisfactory alone (Karlberg, 1987; Karlberg et al., 1987). Instead, the Kouchi and Jenss models might be interesting. The Kouchi model fitted well longitudinal weight data for American children between birth and 2 years (Kouchi et al., 1983a), while the Jenss model fitted well semilongitudinal weight data for children in Zaire between birth and 2 years (Pagezy and Hauspie, 1985).

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