Ehrenberg law-like relationship and anthropometry

N. Forcheh

University of Botswana, Gaborone, Botswana

[Received October 2000. Revised May 2001]

Summary. Ehrenberg presented the simple law-like relationship $\log(w) = 0.8h + 0.4 \pm 0.04$ between the weight and height of children aged 5–13 years. Several researchers have confirmed that this relationship holds, irrespective of the child's ethnic, racial, gender and social class. In anthropometry, a weight–height relationship is used to measure the nutritional status of children. For this purpose, the World Health Organization have adopted the National Center for Health Statistics population as the international reference population. The relationship between the World Health Organization–National Center for Health Statistics anthropometric standards and Ehrenberg law-like relationship is examined. Differences between the weight-for-height relationship in anthropometry and the law-like relationship between weight and height for children are small and can be attributable to functional differences. It is found that an Ehrenberg law-like relationship can be extended to include children who are under 5 years old. Criteria for using the law-like relationship to assess the nutritional status of these children are thus suggested. The criteria are evaluated using anthropometric data of a sample of 513 children from a rural district of Botswana. The results indicate that the proposed method of using the law-like relationship to assess nutritional status is much simpler and at least as reliable as the existing methods in anthropometry.

Keywords: Anthropometry; Children under 5 years old; *D*-statistic; Ehrenberg; Law-like relationship; Nutritional status; Reference standard; Wasting

1. Introduction

Government and child welfare officers routinely use anthropometric indices to monitor and to assess the nutritional status of children. In Botswana, for example, each child is expected to attend monthly medical check-ups from birth until they are 5 years old. Apart from occasional vaccinations within the first 18 months, the main purpose of the check-ups is to weigh the child and to record their weight on a growth chart. The chart shows the expected weight of the child at each time point together with the lower and upper limits of this expected value. If the weight of the child falls outside the lower limit, then that child qualifies for the Government-sponsored intervention programme for malnutrition, which has been on going since the mid-1980s.

The most frequently used anthropometric index for child nutrition is weight for age, which gives the expected weight of a child at each given age. Weight for age has been criticized for failing to distinguish tall thin children from children who are short with adequate weight (Gorstein *et al.*, 1994). Its main use is to follow the child's growth over time (as used in obstetrics charts) since any decline in weight for age may indicate acute changes associated with wasting (Gorstein *et al.*, 1994).

Two other important and popular anthropometric indicators are weight for height and height for age. These indicators reflect various physiological and biological processes in the

Address for correspondence: N. Forcheh, Department of Statistics, Faculty of Social Sciences, University of Botswana, Private Bag UB 00705, Gaborone, Botswana.
E-mail: Forchehn@Mopipi.UB.BW

 0964–1998/02/165155

individual (World Health Organization, 1986). Weight for height is particularly useful because it can still be calculated when the age of the child is either not known or is unreliable, a situation which is often faced by aid workers during intervention programmes in rural and war-torn communities. Jamison (1995) and Warner (2000) have questioned the use of age-independent weight for height for the assessment of nutritional status. Jamison proposed new weight-for-height values derived from expected weight-for-age and expected height-for-age tables, whereas Warner recommended that other direct measures of body composition such as skin-fold thickness should be used instead.

Following a review of many studies on weight for age, weight for height and height for age, Gorstein *et al.* (1994) concluded that weight for height outperforms weight for age and height for age in three key areas when used at the individual level:

(a) in populations where ages are unknown or inaccurate,
(b) in the identification of wasted children and
(c) in identifying changes in weight over short time periods.

They also argued that

> 'children of all ages who have low weight-for-height, or have experienced growth faltering in terms of weight-for-height are likely to respond positively towards intervention or treatment of the causes of their condition'.

Although all three measures are not reliable beyond puberty, the popular use of the Quetelet body mass index BMI given by weight/height^2 as an index of nutrition or health of adults indicates the superiority of weight for height over weight for age and height for age.

Waterlow *et al.* (1977) recommended that the anthropometric indices produced by the United States National Center for Health Statistics (NCHS) should be adopted as the international reference standards. The World Health Organization (WHO) (1981) endorsed this recommendation and later adopted the NCHS population as the international reference population (World Health Organization, 1983). Although many other anthropometric indices exist for monitoring nutrition, the focus in this paper is on weight for age, height for age and weight for height of children by age (in months) and sex. Furthermore, most of the discussions and analyses are based on weight for height. This is justified by the advantages of this index over the other two as discussed above and is necessitated by the desire to link the anthropometric results to Ehrenberg's law-like relationships between the weight and height of children. The data which are analysed in this paper can be obtained from

`http://www.blackwellpublishers.co.uk/rss/`

2. Law-like relationships in anthropometry

To use anthropometric standards to determine nutritional status, the Centers for Disease Control, WHO and others have recommended that a standardized Z-score be calculated. To ensure that the Z-score has a standard normal distribution, different means and standard deviations are assumed for male and female children and for children of different age groups (in monthly intervals). The WHO and the Centers for Disease Control recommend that a Z-score less than -2 indicates a low level of anthropometry, whereas a value less than -3 indicates very low anthropometry. Furthermore, weight for height is a measure of wasting, low height for age is a measure of stunting and low weight for age is a measure of underweight. Thus, in terms of nutritional status, a low weight for height signifies moderate wasting (malnourished), whereas a very low weight for height signifies severe wasting. Moderate and severe stunting and underweight are similarly defined.

Because of its normality, the proportion of the reference population whose Z-score falls below -2 is 2.5% (2.3% if μ is replaced by the median). When used at the population level, the proportion of children in a given population whose Z-score falls below -2 can be compared with 2.5 to determine whether there is a nutritional problem.

The adequate use of anthropometry to assess nutritional status depends on the existence of some formal 'law-like' relationships between weight and height, weight and age and height and age of children, with a separate relationship for boys and for girls of the same age. The use of an international reference population implies that the same law-like relationship holds for all children irrespective of their ethnic, social–economic or any other background. A preference of a local or national reference population over an international reference population assumes that the law-like relationship is different for different populations. Whatever reference population is used, the existence of some law-like relationship between weight and height, weight and age, and height and age is implicit when anthropometric indices are used to monitor nutritional status.

3. Ehrenberg's law-like relationship of weight and height

The formal use of a law-like relationship to characterize the relationship between the weight and height of children was first proposed by Ehrenberg (1968). Ehrenberg suggested that the weight and height of children aged 5–13 years are related by the law-like equation $\log(w) = 0.8h + 0.4 \pm 0.04$, where $\log(w)$ is the logarithm (to the base 10) of the weight in kilograms and h denotes the height in metres. This means that the log-weight of a child lies between $0.8h + 0.36$ and $0.8h + 0.44$. For the populations studied (discussed later), Ehrenberg argued that this relationship was true regardless of sex, socioeconomic status and the race of the child. Ehrenberg's law-like relationship was thus even more inclusive than that usually assumed in anthropometry.

The link between Ehrenberg's proposed law-like relationship between weight and height and the corresponding relationship that is implicit in anthropometry does not appear to have been recognized or investigated in the literature. Furthermore, Ehrenberg's law-like relationship does not appear to have been extended to children under 5 years old. This paper examines the fit of Ehrenberg's law-like relationship to the NCHS weight-for-height data of children aged 5–10 years. The adequacy of Ehrenberg's law-like relationship to children under 5 years old is also investigated and the use of the relationship as an index of nutrition established. Using this index, a diagnostic chart for monitoring wasting in children who are under 5 years old is also proposed. Finally, both Ehrenberg relationships and the WHO–NCHS standards are used to examine the nutritional status of children under the age of 5 years in a rural district of Botswana.

4. Review of Ehrenberg's law-like relationship

Ehrenberg's (1968) law-like relationship was derived by using data collected on British (Birmingham) boys in yearly age groups from 5 to 13 years and from one social group. The relationship was then validated by using data from samples of

(a) Birmingham boys classified by yearly age groups from 5 to 13 years from two other social classes,

(b) Canadian (Ottawa) boys classified by yearly age groups from 6 to 11 years and from three time periods (1933–1935, 1938–1940 and 1953–1955) and classified as either above or below average socioeconomic status,
(c) Ottawa girls in 1933–1935, also classified as either above or below average socio-economic status, and
(d) French boys and girls aged $5\frac{1}{2}$, $8\frac{1}{2}$ and $11\frac{1}{2}$ years, classified into seven socio-economic groupings according to the occupation of the head of household.

Ehrenberg concluded that the law-like relationship held to within one decimal place for all these children. The only discrepancies were in the intercept constant (0.4). French children of manual workers (actually Hutu and Tutsi boys living in mining camps in Rwanda in 1957–1958 (Lovell, 1972)) had the same slope constant, but a slightly different intercept constant. Hence the law-like relationship between weight and height, according to Ehrenberg, held irrespective of the sex, age, social class, race and many other potential explanatory variables.

The relationship was fitted to the mean weight and height of children of the same age so that any within-group differences were ignored. Some researchers have thus stated the original law-like relationship in terms of means: $\log(\bar{w}) = 0.8 + \bar{h} + 0.4$ (Kpedekpo, 1970; Lovell, 1972; Uche, 1981).

Kpedekpo (1970) applied the law-like relationship to data on 5000 Ghanaian children aged 5–18 years and classified into four groupings: rural, urban, privileged urban and expatriate (Euro-American). Kpedekpo concluded that Ehrenberg's law-like relationship held for privileged Ghanaian children and for expatriate children, but that a slight modification in the value of the intercept constant (from 0.4 to 0.36) was required for the description of the relationship between the weight and height of other Ghanaian children.

Lovell (1972) applied the law-like relationship to 13 different data sets. The children included prosperous Jamaican children of Chinese, European, Afro-European and African descent and poor Jamaican children mainly of African descent measured in 1963. They also included Jamaican children attending school in different localities and different periods and school-children from other Caribbean islands. In all 212 groups of boys and 179 groups of girls aged 5–18 years were studied, with a total of 280 groups aged 5–13 years.

Lovell concluded that the Ehrenberg law-like relationship could be widened to include West Indian children in general, and children of Chinese origin in particular. He suggested, however, that although the value of the intercept constant is always 0.4 to within one decimal place it was slightly larger for well-nourished than for less-well-nourished communities. Drawing from Kpedekpo's (1970) results, Lovell suggested a modification of the law-like relationship to $\log(\bar{w}) = 0.8\bar{h} + c$ for age-specific groups of children, where c was dependent on the community and possibly related to nutritional standards. In particular, the value of c was 0.39 for the Birmingham children (Ehrenberg, 1968), privileged Ghanaian children and Euro-American children living in Ghana, but only 0.36 for non-privileged and rural Ghanaian children (Kpedekpo, 1970). The only children who did not satisfy the law were Rwandan Tutsi and Hutu children, for which a more appropriate intercept constant would be 0.34. Interestingly, Lovell concluded his paper by suggesting that $c = \Sigma\{\log(\bar{w}_i) - 0.8\bar{h}_i\}/n$ could be used to compare the nutritional well-being of different communities, especially of the same race. Following Lovell's suggestion, Ehrenberg (1975) reanalysed a 1905 data set on the heights and weights of Glaswegian children that was first analysed by Elderton (1915). He concluded that the

> 'height–weight relationship used by Lovell also holds for the Glaswegian boys and girls, but the soci-economic factors appear to differ for black and white children'.

Previous researchers who have examined the Ehrenberg law-like relationship agree that a law-like relationship exists between the weight and height of children aged from 5 to 13 years. These researchers also agree that the same relationship holds approximately for all children, irrespective of their gender, race and social class.

5. The National Center for Health Statistics reference population and standards

A good description of the NCHS data is contained in the *Anthropometric Desk Reference* electronic handbook at the Web site

`http://www.odc.com/anthro/deskref/desktoc.html`

Other useful discussions of the data include World Health Organization (1986), Gorstein *et al.* (1994) and Jamison (1995).

The NCHS reference standards were constructed using data from two population cohorts. The first cohort consisted primarily of middle class white US children aged from birth to 36 months. The data for this survey were obtained from a longitudinal survey conducted between 1960 and 1975 by the Fels Research Institute. The second cohort included children from all ethnic backgrounds and social classes in the USA, aged from 2 to 18 years. The data for this cohort were obtained through three cross-sectional surveys: the Health Examination Survey cycle I (1963–1965) and cycle II (1966–1970), and the first National Health and Nutrition Examination Survey (1971–1974) conducted by the NCHS.

The NCHS reference standards are published as means plus or minus the standard deviation of height and weight for each month of age up to 119 months and of weight for height for each 1 cm interval from 49 to 100 cm (weight for length) and 65 to 137 cm (weight for stature). The standard deviation values range from −3 to 3, with separate upper and lower standard deviations shown. The upper and lower standard deviations for weight for age and weight for height are different. This is because the distributions of these values are asymmetrical, a characteristic which is not shared by the height-for-age data (Gibson, 1990).

Gibson (1990) reviewed the data collection procedures that were used for all these surveys and concluded that the procedures were well standardized and met criteria established by the International Union of Nutritional Sciences for the creation of growth standards. However, Gorstein *et al.* (1994) have pointed out some important operational limitations with the data sets arising from the use of the two different cohorts and survey methods. Firstly, the indices are generally divided into two age categories: from birth to 36 months and from 2 to 18 years. Secondly, the reference populations have different characteristics. The children included in the first (Fels) cohort were in general taller and thinner than those included in the second (NCHS) cohort.

The NCHS use data from the first cohort to construct weight-for-age and height-for-age reference standards for children under 24 months and the data from the second cohort for indices of children aged 2 years or more. This introduces a slight disjuncture at 24 months. As an illustration, the height for age of girls who are aged 21–26 months is shown in Table 1. By these data, at 22 months a girl is 'taller' by 2 mm than she would be when she reaches 24 months! The published weight-for-height data are also split into weight for length for children who are not yet standing and weight for stature for children who are already standing. The lengths (lying height) range from 49 to 100 cm, whereas the statures (standing height) range from 65 to 137 cm. Thus there is a considerable overlap in length and stature (from 65 to 100 cm). Unless otherwise stated, NCHS weight for height will be synonymous

Table 1. Disjuncture in the normalized NCHS–Centers for Disease Control anthropometric reference†

Position	*Age (months)*	*Lower standard deviation*	*Mean height*	*Upper standard deviation*
Length	21	3.2	83.8	3.2
	22	3.2	84.7	3.2
	23	3.2	**85.6**	3.2
Stature	**24**	3.2	**84.5**	3.2
	25	3.3	85.4	3.3
	26	3.3	86.2	3.3

†Compiled from `http://www.odc.com/anthro/deskref/desktoc.html`: height for age, girls (0–119 months). The disjuncture is highlighted in bold.

with weight for stature in this paper. This corresponds to children from about 8 or 9 months to 119 months.

The adoption of the NCHS population as an international reference (World Health Organization, 1983) was justified on the basis that 'the effect of ethnic differences on growth of young children is small compared with the effect of the environment' (Habicht *et al.*, 1974; Graitcer and Gentry, 1981). Greco and Power (1995) analysed data from a 1958 birth cohort of the national child development study of Great Britain and reported that only one in three short and underweight children at age 7 years became short and underweight adults at age 23 years. They also noted that catch-up was evident for most children at age 16 years.

The World Health Organization (1985) contended that ethnic differences are not sufficiently large to invalidate the NCHS population both as the reference and as a standard. This is perhaps supported by Tanner (1989) who insisted that human development is a product of genetic and environmental factors, and that this interaction develops non-linearly through time. Tanner also reviewed case-studies on adult outcomes of child undernutrition and concluded that much depends on the incidence after the episode of malnutrition.

Finally, the use of an international reference has also been justified on the basis that

> 'the development of statistically valid national reference values is costly and often beset with logistic problems'

(World Health Organization, 1986). Goldstein and Tanner (1980), Graitcer and Gentry (1981) and Palti *et al.* (1995) have also investigated the appropriateness of the NCHS reference standards to diverse populations. Although some limitations of the NCHS reference have been noted, these researchers have generally found that the NCHS standards are adequate as an international reference.

6. Fitting the law-like relationship to World Health Organization–National Center for Health Statistics weight for height of children 5–10 years old

The NCHS give different weight-for-height values for male and female children, whereas Ehrenberg gives a single relationship. The weight-for-height data do not contain the age of the children. So the cut-off values for children aged 5–10 years had to be estimated by using information from the weight-for-age and the height-for-age data. Using the tabulated NCHS mean weight-for-height, weight-for-age and height-for-age data, the expected weight and height of a girl who is 60 months (5 years) old are 17.7 kg and 108.4 cm respectively, whereas the corresponding values for a boy are 18.7 kg and 109.9 cm. Comparing these with the mean weight-for-height data, the appropriate cut-off height for children who are 5 years old is 109 cm when gender differences are ignored, and 108 cm for girls and 110 cm for boys when gender differences are taken into account. Since the Ehrenberg relationship ignores gender differences, the cut-off height for children who are 5 years old was taken to be 109 cm.

The plots of mean weight for height for girls and for boys aged from standing age to 10 years are shown in Figs 1(a) and 1(b) respectively. In each plot, the expected weight for height based on Ehrenberg's law-like relationships have been fitted. These expected weights clearly lie very close to the expected weights of both male and female children. In fact, Ehrenberg's curve lies within 1 standard deviation of the expected NCHS weight of both males and females and for all ages. Hence any child whose weight-for-height relationship fits the Ehrenberg equation will be interpreted as 'normal' using the WHO–NCHS standards.

To assess the adequacy of the fit formally, the expected NCHS weights W_N of well-nourished children 5–10 years old were compared with the corresponding expected weights obtained by using the Ehrenberg law-like relationship. For comparison, the deviation scores D_N in log-kilogram units were used, where

$$D_N = \log(W_N) - 0.8h - 0.4. \quad (1)$$

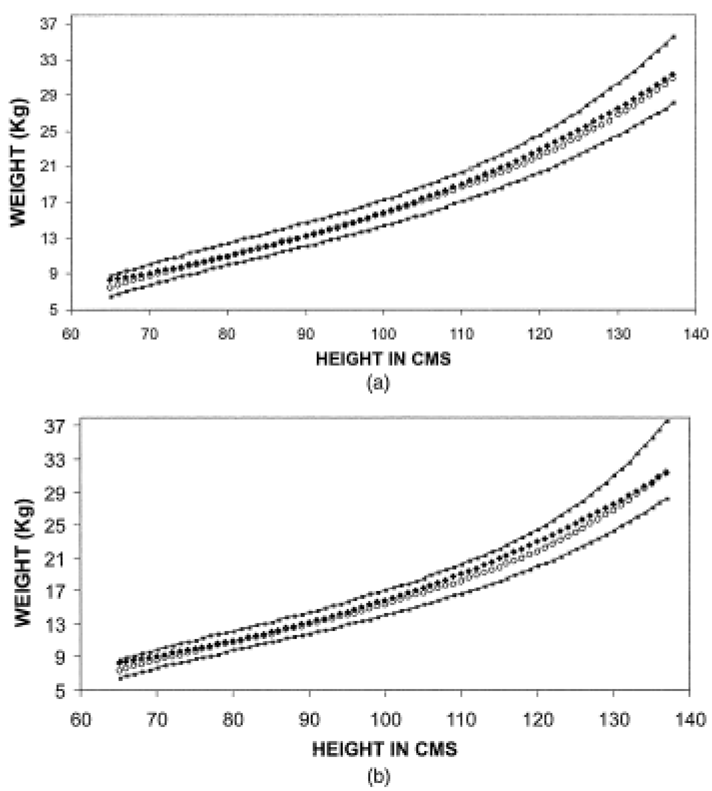

Fig. 1. Variation in NCHS weights with height for (a) boys and (b) girls from standing age to 10 years showing the fitted Ehrenberg law-like relationship: ■, mean NCHS data plus or minus 1 standard deviation; ○, mean NCHS data; ◆, Ehrenberg relationship

Here h denotes the height in metres of a child whereas W_N denotes the expected weight from NCHS tables. For the 5–10 years cohort, these heights ranged from 109 cm to 137 cm as discussed at the beginning of this section.

These deviation scores ranged from −0.015 log-kg to −0.006 log-kg for boys with a mean of −0.012 and a median of −0.012. The corresponding range for girls was from −0.022 to 0.002, with a mean of −0.015 and a median of −0.019. The magnitudes of these deviation scores are thus very small. They are in fact smaller than those reported in various case-studies in the literature (Kpedekpo, 1970; Uche, 1981).

However, despite this apparent good fit, the Ehrenberg expected weights differ from the expected WHO–NCHS weights in a systematic way. Only two of the 29 deviations for the girls and none of the 29 for boys were positive. In addition, the standard errors of the means were 0.0014 for girls and 0.0004 for boys, which suggest a non-zero expected value for both boys and girls. Following the usual tradition (e.g. Ehrenberg (1968) and Kpedekpo (1970)) a simple adjustment to the model was made by subtracting the overall mean deviation (0.014) from the constant. This gives the adjusted relationship

$$\log(W) = 0.8h + 0.386. \tag{2}$$

This is still within the suggested law-like relationship of $\log(W) = 0.8h + 0.4 \pm 0.04$.

Using this adjusted model, the deviation scores ($D_N = \log(W_N) - 0.8h - 0.386$) for boys ranged from −0.001 to 0.008 with a mean of 0.002, a median of 0.002 and a standard deviation of 0.0024, whereas those for girls ranged from −0.008 to 0.016 with a mean of −0.001, a median of −0.005 and a standard deviation of 0.0075.

The Ehrenberg law-like relationship thus adequately describes the mean weight for height for the NCHS tables. The overall fit can be significantly improved by changing the intercept constant from 0.4 to 0.386. If separate relationships were used for boys and girls, then the best fits would be obtained by setting the intercept constant to 0.388 for boys and 0.385 for girls.

7. Extension of the law-like relationship to children under 5 years old

There does not appear to be any published study that has attempted to extend the Ehrenberg law-like relationship to children aged less than 5 years. This group forms the most important group of children in the study of anthropometry. This is because they are the most susceptible to malnutrition. Furthermore, changes in weight and height over short time periods are more noticeable in this cohort, yet the damaging or rewarding effects of environmental factors have not yet become permanent, and if identified can be arrested and growth retardation reversed.

For this extension, the NCHS weight-for-height data were used as the standard since these are the standards adopted by the WHO and remain the most widely used standards for monitoring wasting worldwide. Only weight-for-stature data (children of standing age) were used. The mean heights for this age group range from 65 cm to 109 cm for boys and from 65 cm to 108 cm for girls. However, a common cut-off of 108 cm was used in line with the cut-off used for a child in the previous section who was 5 years old.

When the Ehrenberg original law-like relationship ($\log(w) = 0.8h + 0.4$) was fitted to the weight-for-height data of the boys, the deviation scores ranged from −0.045 to 0.005, with a mean of −0.006, a median of −0.002 and a standard deviation of 0.0115. When the analysis was repeated for the girls, the deviations ranged from −0.051 to −0.006 with a mean of −0.0146, a median of −0.012 and a standard deviation of 0.0099. The model therefore generally overestimated weights, with almost all the residuals being negative.

On the basis of these results, the intercept constant was adjusted from 0.4 to 0.39. This adjustment led to a good overall fit of the model. The residuals for boys ranged from −0.035 to 0.015 with a mean of 0.0045 and a standard deviation of 0.0117, whereas the residuals for girls ranged from −0.041 to 0.004 with a mean of −0.0046 and a standard deviation of 0.0099. Although the model tended to overestimate weights slightly, the residuals were quite small. When expressed in kilogram units, the deviations ranged from 0.91 kg to 1.01 kg, which are small in comparison with the weight range of 7.5 kg or more that was used. The suggested adjusted model in equation (2) did not provide a better fit, although it was slightly better than the original law-like model.

These results indicate that the law-like relationship can be extended to include children who are under 5 years of age. With the intercept constant adjusted from 0.4 to 0.39, the law-like relationship appears to fit children who are less than 5 years old even better than it does children aged 5–10 years. This fact is also evident in Fig. 1 for the original model. The distribution of deviation scores from fitting the adjusted model to children under 5 years old is shown in Fig. 2.

An appropriate law-like equation for normal children from a walking age to 10 years could hence be expressed as $\log(w) = 0.8h + 0.39$. This relationship is independent of the sex of the child, although it provides a better description of the weight for height of boys compared with girls.

8. Using the law-like relationship to assess nutritional status

Let $W_k = \mu + k\sigma$ denote the expected cut-off weight for a child at a certain level of nutritional status, where μ and σ are the expected weight and standard deviation of an adequately nourished child of a given height.

For the NCHS reference population, μ and σ both depend on the gender and height of the child. In addition, there are separate values of the standard deviation σ for upper ($k > 0$) and lower ($k < 0$) intervals. The values of W_k for $k = -3, -2, 2, 3$ denote cut-off weights for severe wasting (malnutrition), moderate wasting, moderate obesity and severe obesity respectively. The weight of an adequately nourished child should therefore fall in the range from $\mu - 2\sigma$ to $\mu + 2\sigma$. Let H denote the height in metres of a child of a given age and gender, and define

$$D_k = \log(W_k) - 0.8H - 0.39, \qquad k = -3, -2, 0, 2, 3. \tag{3}$$

The statistic D_k is shown to be a simple and adequate statistic on which cut-off values for nutritional status (wasting) of children could be based.

To establish cut-offs, the NCHS weight-for-height data for children from standing age (65 cm) to 5 years old (137 cm) were used. Some summary measures for D_k and suggested cut-offs for the five categories of nutritional status are shown in Table 2. More detailed distributions are shown in Fig. 2, and a diagnostic chart is shown in Fig. 3.

9. Cut-off for severe and moderate wasting

From Fig. 2, it is observed that the distribution of D_k is left skewed for the normal, moderate wasting and severe wasting cohorts. The values of D_{-3} (severely malnourished) range from −0.2568 to −0.1188, truncating sharply on the right. The values of D_{-2} (moderately malnourished) range from −0.1696 to −0.0717, again truncating sharply on the right. The gender-disaggregated ranges are shown in Table 2. The overlap between the severe and

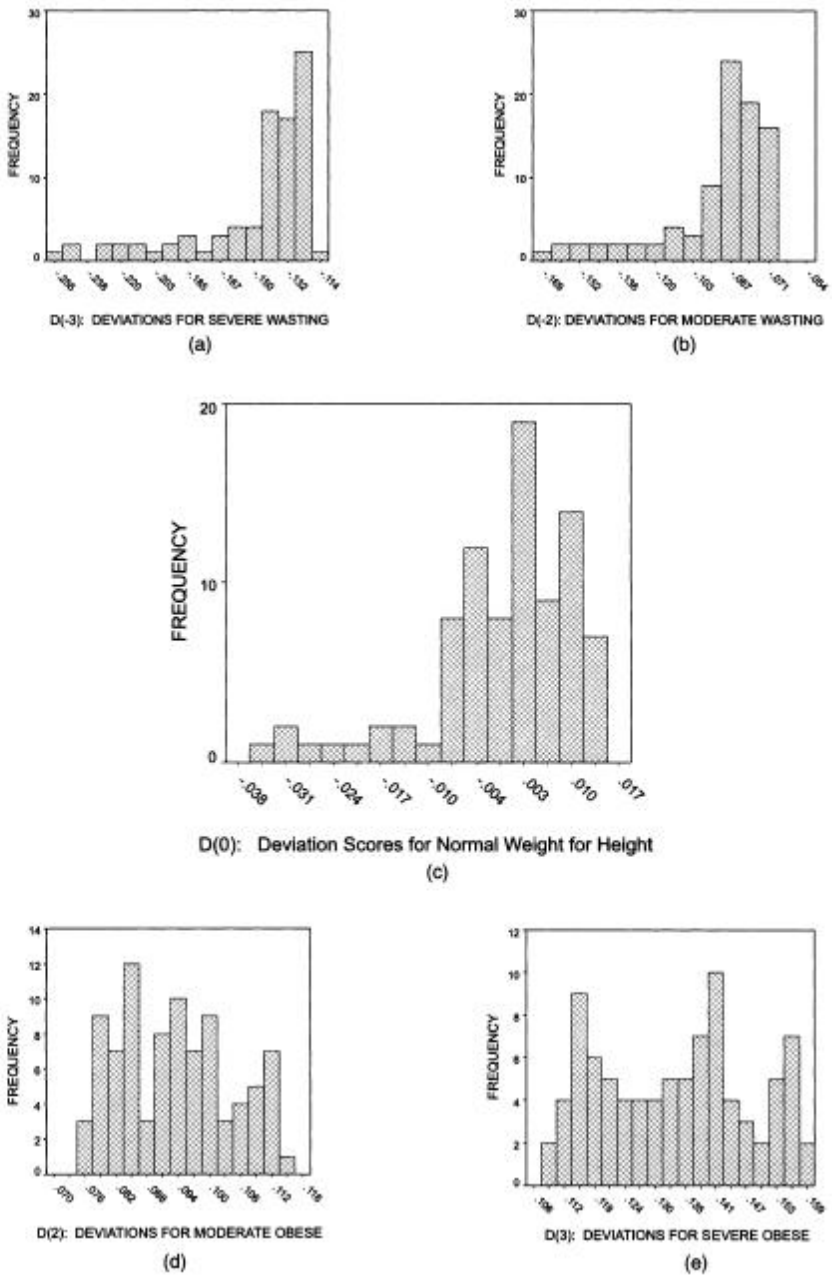

Fig. 2. Distribution of deviation scores from expected cut-off NCHS log-weights for various nutritional statuses: (a) severe wasting (standard deviation, 0.03; mean, −0.149; $N = 88.00$); (b) moderate wasting (standard deviation, 0.02; mean, −0.093; $N = 88.00$); (c) normal weight for height (standard deviation, 0.01; mean, 0.000; $N = 88.00$); (d) moderately obese (standard deviation, 0.01; mean, 0.094; $N = 88.00$); (e) severely obese (standard deviation, 0.01; mean, 0.133; $N = 88.00$)

Table 2. Range of values of $D_k = \log(W_k) - 0.8h - 0.39$

Condition	*Sex*	*Range of D_k (ignoring age)*		*Suggested cut-off for D_k*
		Minimum	*Maximum*	
Severe wasting	Female	−0.257	−0.130	⩽−0.12
	Male	−0.247	−0.119	
Moderate wasting	Female	−0.170	−0.081	From −0.12 to −0.07
	Male	−0.162	−0.072	
Normal weight	Female	−0.032	0.004	From −0.07 to 0.07
	Male	−0.035	0.015	
Moderately overweight	Female	0.076	0.101	From 0.07 to 0.12
	Male	0.076	0.115	
Severely overweight	Female	0.113	0.143	Over 0.12
	Male	0.110	0.158	

moderate categories is due to the inherent dependence of the NCHS weight for height on age, whereas the Ehrenberg relationship ignores age differences.

A close examination of the distributions of D_{-3} and D_{-2} indicates that a suitable cut-off between the severe and moderate wasting cohorts is −0.12. With this cut-off, an *ad hoc* estimate of the proportion of severely wasting children (based on the NCHS reference) who would be 'misclassified' as moderate wasting (based on the *D*-statistics) is 2.27%. The corresponding proportion of moderately wasting children who would be misclassified as severe wasting could be as high as 20%. Other cut-offs such as −0.13 and −0.15 gave results that were worse than with the −0.12 cut-off. When separate cut-offs were used for males and females, the overall degree of agreement increased. In summary, if the log(weight) of a child is less than the expected weight for height obtained by using the law-like equation by between 0.07 and 0.12, then that child is likely to be moderately malnourished (wasting). If the

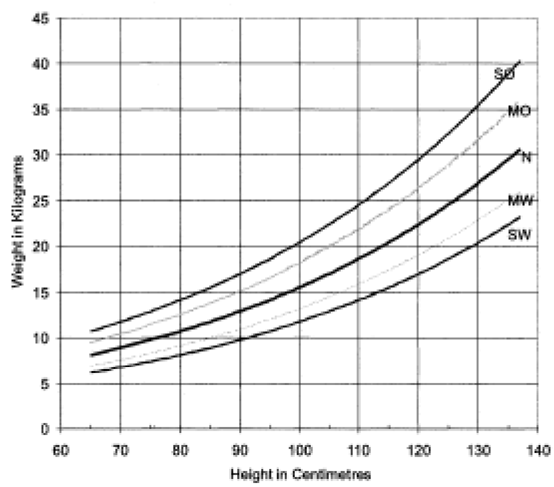

Fig. 3. Diagnostic chart for identifying wasting and obesity in children under 5 years old based on the *D*-statistic: SO, severe obesity; MO, moderate obesity; N, normal; MW, moderate wasting; SW, severe wasting

difference is less than 0.17, then that child is almost certainly severely malnourished, irrespective of their sex and age.

10. Normally nourished and obese children

Interestingly, there is no overlap between the distribution of the *D*-statistic for the normal children ($D_N = D_0$) and for other children (Table 2 and Fig. 2). Thus, if interest was simply to classify children as wasting, normally nourished or overweight, then the *D*-statistic and the standardized *Z*-score based on the WHO–NCHS reference should lead to identical results. As shown in Table 2, the suggested cut-off for normal children is from −0.07 to 0.07.

The analyses were repeated to determine cut-off values for moderately and severely overweight. The values of D_2 ranged from 0.0762 to 0.1008 for girls and from 0.0764 to 0.1146 for boys, whereas the values of D_3 ranged from 0.1134 to 0.1434 for girls and from 0.1096 to 0.1579 for boys. Hence if the log(weight) of a child is greater than the expected weight for height obtained by using the law-like equation by between 0.07 and 0.12 then the child is moderately overweight. If the log(weight) is greater than the expected weight by 0.12, then that child is severely overweight irrespective of their sex.

11. Using the *D*-statistics to monitor wasting in children under 5 years old

The suggested cut-off values for the *D*-statistics are useful during intervention programmes in screening children, or for population studies, when interest is to compare wasting in different populations or in the same population before and after an intervention programme. For example, during an intervention programme, the weight and height of each targeted child would be measured at the beginning of the programme. The severity of wasting in the area could be ascertained by using the percentage of children whose *D*-score falls below −0.07 and those whose *D*-score falls below −0.12. At regular intervals during the intervention, weights and heights of appropriately selected samples of children could be obtained and the various proportions determined again, and the effect of the programme could be ascertained by examining the changes in the proportions.

For following up an individual child, the use of the *D*-statistic on its own would be more limited. Instead, it would be more desirable to note the child's weight against their height on a chart at regular intervals, and to note from the chart whether the individual child is responding to the intervention. If a particular child is failing to respond to the intervention, there may be a need to hospitalize the child for more intensive monitoring. A weight-for-height chart would be useful not only to determine whether an individual child is experiencing wasting at any given time, but it may also give an indication whether the weight, height and weight for height are following the expect growth pattern. Such a chart is presented in Fig. 3.

Fig. 3 has been obtained by converting the cut-off points suggested for the *D*-statistics into weight-for-height values. It shows the expected trend for weight for height for a normally growing child, as well as the regions indicating severe wasting, moderate wasting, moderate obesity and severe obesity. For example, on the basis of the proposed *D*-statistic, the weight of a child who is 100 cm tall and is undergoing normal growth is 15.5 kg (15.7 kg using the NCHS standard). If the weight falls below 13.2 kg (13.0 for the NCHS standard) then the child is at risk of wasting and, if it falls below 11.7 kg, then the child may be experiencing severe wasting. The corresponding values for moderate and severe obesity are 18.2 kg and 20.4 kg respectively. Each of these values differs from those obtained from the NCHS standards by less than 1.0 kg, indicating very good agreement between the standards.

As would be expected, the difference between the expected weight of a child from normal to wasting or obesity increases as the child becomes taller (and hence older). For example the difference between the expected weight and the cut-off for wasting is 5.4 kg for a child who is 120 cm tall but only 2.1 kg for a child who is 70 cm tall. So this measure should be robust to the effect of age on weight and height.

12. Case-study: the Ngamiland data for children under 5 years old

The nutritional data for the children under 5 years old that are used in this paper were collected as part of a large scale study in the district of Ngamiland, to assess the socio-economic effect of the 1995–1996 cattle lung disease contagious bovine pleuropneumonia (CBPP) on households in the district.

Ngamiland is a large, rural northern district of Botswana. Cattle were the major source of livelihood for the majority of households in Ngamiland before the cattle lung disease (Fidzani *et al.*, 1999). However, the Government's programme to eradicate CBPP led to the destruction of all Ngamiland cattle in 1996 and the voluntary restocking in 1997–1998. As a result, only a small proportion of households were relying on cattle as their primary source of livelihood at the time of the survey in August 1997.

Since the 1993 Botswana agricultural census, Ngamiland has been divided into Ngamiland East and Ngamiland West agricultural districts. Each agricultural district is further divided into the village, the land and the cattlepost settlements, and each of these settlements is further divided into blocks of approximately the same number of households in each. During the CBPP study, the number of blocks was estimated to be about 138 in Ngamiland East and 150 in Ngamiland West. Furthermore, the numbers of blocks in the village, land and cattlepost settlements were estimated to be in the ratio of 2:2:1 in Ngamiland West, and 4:3:3 in Ngamiland East (Fidzani *et al.*, 1999). Thus, using a two-stage stratified sampling method with proportional allocation to select blocks, 46 blocks were selected from Ngamiland East of which 18 were from village settlements, 14 were from land settlements and 14 were from cattlepost settlements. Similarly, 50 blocks were selected from Ngamiland West, of which 20 were from the village and land settlements each and 10 were from the cattlepost settlement.

Systematic sampling was used to select 10 households from each selected stratum. This led to a total of 960 households being selected for study. Only households that had children under 5 years of age were included in the nutritional part of the study. If a household had exactly one or two children under 5 years old, then these children were included in the study. If the household had more than two children under 5 years, then two of the children were randomly selected and included in the study. In all, 498 households (51.7%) had no child younger than 5 years of age, 259 (27.1%) had one child and 203 (21.2%) had two or more children under 5 years of age. Thus a total of 667 children from 462 different households were included in the study.

Trained research assistants measured the weight and height of each child. The ages were obtained from birth certificates and/or from the parents. Other nutrition-related information that was collected included the birth weight, sex of the child, current breast-feeding status, number of meals per day, morbidity in the last 2 weeks and background information on the head of the household such as sex, marital status and age.

The quality of the data was quite high, especially considering that the population sampled was rural with low socioeconomic status. The exact dates of birth of 626 (93.9%) of the children were known, whereas the weights of 649 and height or stature of 648 children were also properly determined. As expected, weight for height could be determined for a higher proportion (96.0%) of children than weight for age (91.3%) and height for age (91.6%). The low missing value rates could be attributed largely to the excellent system of birth and death registration in Botswana, and also to the adequacy of the data collection process. The parents of almost all the children whose ages were unknown had either never attended school (65.9%) or had attended only primary school (26.8%).

13. Socioeconomic background of the children

Approximately three in five (62.2%) of the heads of the households had no formal education. A further 28.2% had some primary education, 8.1% had secondary education and only 1.5% attended school beyond the secondary level. Just over half of the children (53.7%) were from male-headed households. Furthermore, only 39.9% of the children were from homes where the head was married. A further 20.9% of the children were from homes in which the head was living together with a partner, whereas 26.1% of the children were from homes in which the head had never married. In almost nine in 10 (87.1%) of the homes headed by a married person, that head was a man. It is likely that husbands of the 12.9% of married women who headed their households lived and worked elsewhere. Women headed a good proportion (41%) of homes where there was cohabitation. The heads of households ranged from 20 years to 87 years, with a mean of 48.3 years. Hence, the parents were generally in their middle ages. The children in this study could therefore be classified as rural children with low socioeconomic status.

Children from homes where the head's level of education was primary recorded the lowest mean birth weight, current weight and current height. In contrast, households where the parent had post-secondary educational qualifications recorded the highest means for these variables. The differences were not statistically significant, however. Similarly, neither the sex of the head of household, nor their marital status nor their level of education significantly affected the key measures of growth and nutrition, namely current weight, current height and birth weight.

These findings can be understood from the fact that Ngamiland is a rural district. Thus, most households led a similar way of life. It was found, for example, that almost all children under 1 year of age were currently breast-feeding and virtually no child over 3 years was still breast-feeding. Perhaps of even greater effect was the Government intervention programme to provide food rations not just to destitute families but to almost the entire district. In a follow-up study in August 2000 by the social welfare division of the Ministry of Local Government, it was found that up to 94% of households in Ngamiland still receive regular 'CBPP rations' as they are called. Some households with children under 5 years old receive 'clinic rations'.

14. Nutritional status of Ngamiland children

For comparative purposes, the nutritional status of Ngamiland children aged 5 years and below was assessed by using the prevalence of wasting. The prevalence of wasting was determined by using both the standardized *Z*-scores and the corresponding cut-off values, based on the WHO–NCHS reference standards and the *D*-statistic based on the modified Ehrenberg law-like relationship. It should be recalled that the *D*-statistic was developed only for children who are walking. However, the information about whether each child in the survey was walking or not was recorded. Hence it was assumed that children who were younger than 9 months or shorter than 65 cm were not walking. These children were excluded from the analysis. This led to 135 (20.8%) of the original 648 children being excluded from the analysis. The summary results are shown in Fig. 4 and in Table 3.

The results in Fig. 4 indicate that the proposed *D*-statistic and associated chart provide a good summary of the Ngamiland children under 5 years old post CBPP. There is no systematic difference between the male and female children in the plot. This indicates that the same law-like relationship holds for male and female children in Ngamiland. There is no justifiable reason from the plot why girls' weight for height should be any different from that for boys.

From Table 3, the results from fitting the NCHS standard to these data are found to be quite comparable with those obtained by using the *D*-statistic. Both methods identify the same children as severely wasting. In all, the incidence of severe wasting was 2.14%. Genderwise, 3.45% of boys suffered from wasting compared with 0.79% among female children. On the basis of the WHO–NCHS standards, 3.51% of the children were classified as moderately wasting. Genderwise, this comprised 4.2% of the boys and 2.8% of the girls. Using the *D*-statistic, the overall estimated proportion of children experiencing moderate wasting was 7.02%. This was made up of 5.7% of boys and 9.2% of female children. The proportion of children who were not suffering from wasting was estimated to be 94.4% and 90.84% by using the WHO–NCHS standard and the *D*-statistic respectively. This is clearly a very impressive agreement rate, especially in view of the simplicity of the *D*-statistic.

The 18 children (3.51%) who were classified as experiencing moderate wasting on the basis of the *D*-statistic but classified as normal by using the reference standards were examined further. It was found that four of the 18 children were boys. All these boys were underweight (i.e. had a low weight for age), whereas three of them were stunted (low height for age). Of the 14 girls, four were both severely underweight and stunted, two were moderately underweight as well as stunted and two were underweight but had normal height for age. Hence only six (33.3%) of these children could be classified as normal by using the other two anthropometric measures of nutritional status, namely weight for age and height for age. Furthermore, the *D*-statistic for five of these six girls ranged from −0.070 to −0.077. This

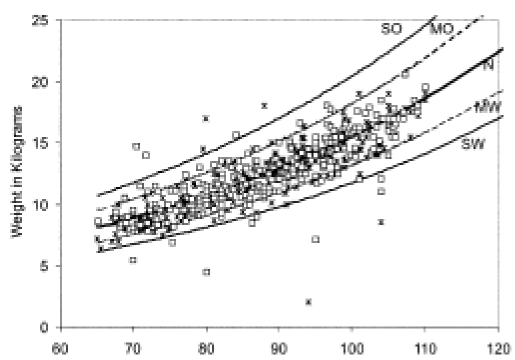

Fig. 4. Weight and height of Ngamiland children under 5 years old (×, girls; □, boys) based on the *D*-statistic: SW, severe wasting; MW, moderate wasting; N, normal weight for height; MO, moderate obesity; SO, severe obesity

Table 3. Incidence of wasting among Ngamiland children under 5 years old

Sex of child	*Wasting based on Ehrenberg relationship*	*Wasting based on WHO–NCHS standard*						*Group total*	
		Severe		*Moderate*		*Normal*		*Count*	*Table (%)*
		Count	*Table (%)*	*Count*	*Table (%)*	*Count*	*Table (%)*		
Male	Severe	9	1.75					9	1.75
	Moderate			11	2.14	4	0.78	15	2.92
	Normal					237	46.20	237	46.20
	Group total	9	1.75	11	2.14	241	46.98	261	50.88
Female	Severe	2	0.39					2	0.39
	Moderate			7	1.36	14	2.73	21	4.09
	Normal					229	44.64	229	44.64
	Group total	2	0.39	7	1.36	243	47.37	252	49.12
Group total	Severe	11	2.14					11	2.14
	Moderate			18	3.51	18	3.51	36	7.02
	Normal					466	90.84	466	90.84
	Group total	11	2.14	18	3.51	484	94.35	513	100.00

indicates that they would have been classified as normal if gender had been taken into consideration when using the D-statistic. This is because, as can be seen from Table 2, the upper limit for moderate wasting for girls on the basis of the D-statistics is −0.08.

15. Discussion

This study has reviewed Ehrenberg's historic law-like relationship between the weight and height of children aged 5–13 years. It has found that the literature that has investigated this law-like relationship overwhelmingly supports Ehrenberg's initial claim of a possible law-like relationship. The paper has argued that law-like relationships between weight, height and age are also implicit in anthropometry, where the weight-for-height, weight-for-age and height-for-age indices are used to determine the nutritional status of children. It has also noted that the relationship does not appear to have been applied previously to children who are under 5 years old, who are the main cohort in anthropometry.

The study therefore extended the law-like relationship to include children under 5 years of age and found that it describes the relationship between WHO–NCHS weights and heights of children from standing age to 10 years very adequately, irrespective of the sex of the child. Building on this good fit, the possible use of the law-like relationship to assess nutritional status has been explored. The D-statistic which gives the deviation of the logarithm of a child's weight from the expected log(weight) based on the law-like relationship ($0.8h + 0.39$ for children under 5 years old) has been proposed as a suitable measure on which nutritional status could be based. Suitable cut-off values for severe and moderate wasting, normal weight and overweight based on the D-statistics are shown in Table 2. A diagnostic chart for monitoring wasting in children under 5 years old has been provided. If used to follow up child growth monthly, then the chart could also provide information about changes in two other important measures of nutritional status, namely height for age and weight for age.

The degree of fit of the *D*-statistics and that of the WHO–NCHS standards to a data set from Ngamiland, a rural district of Botswana, has been compared. Both methods reveal that the incidence of severe wasting among children under 5 years old was very low in Ngamiland (2.14% in each case) a year after the Government eradication of CBPP programme started. The incidence of moderate wasting was also quite low especially when based on the WHO–NCHS reference standards. The overall incidence of wasting was found to be 5.6% and 9.2% by using the WHO–NCHS reference standards and the *D*-statistic respectively.

The low incidence of wasting among these children from low socioeconomic backgrounds perhaps owes much to the Government intervention programme of providing food rations to all needy families and children following the slaughter of all the cattle in the district as a means of stamping out CBPP. Incidentally, all children who were identified as suffering from wasting by using the reference standards were also identified as wasting by using the *D*-statistic. The children who were identified as wasting by using *D*-statistics but not by using the NCHS standards were found to be of low weight for age or low weight for height, which are two other important measures of nutritional status. The *D*-statistic therefore appears to be more sensitive than the WHO–NCHS reference standards.

The *D*-statistic is computationally superior to the competing *Z*-score used in the NCHS standards. To determine the *Z*-score of each child, and hence his or her nutritional status, not only do we need to know the reference weight for height but also the reference standard deviation. As a result, the determination of the nutritional status of children is usually computed by using special purpose packages such as the EPI-Info program (available from the Centers for Disease Control, Atlanta, at `http://www.cdc.gov/epiinfo/`). The advantage of the *D*-statistic over the *Z*-score may be particularly important in rural areas like Ngamiland, where health workers may be armed with just a calculator and would need to make quick decisions about a child's nutritional status.

The Ehrenberg law-like relationship, in contrast, does not require knowledge of any reference. The *D*-statistic can be determined by using any pocket calculator. For survey data, the *D*-score for any number of children can be obtained in a matter of seconds by using any spreadsheet program or data analysis package. This computational advantage is particularly useful in rural communities and in conflict-ravaged areas, where computers and computer experts are unlikely to be available, and immediate decisions whether a particular child should be put under an intervention programme or not are required. Its high association with the tested but cumbersome WHO–NCHS reference standards makes its use even more appealing. The diagnostic statistic proposed may prove to be an important tool for following up child growth. Further research is needed to examine its relationship to weight for age and weight for height.

Acknowledgements

The author would like to thank the reviewers for the generous suggestions on improving the paper, notably on the inclusion of a diagnostic chart. Thanks also go to all the colleagues at the University of Botswana who kindly agreed to act as internal reviewers of the paper.

References

Ehrenberg, A. S. C. (1968) The elements of lawlike relationships. *J. R. Statist. Soc.* A, **131**, 280–302.

——(1975) Children's heights and weights in 1905. *J. R. Statist. Soc.* A, **138**, 239–241.

Elderton, E. M. (1915) Height and weight of school children in Glasgow. *Biometrika*, **10**, 288–339.

Fidzani, B., Mlenga, W. S., Atlhopheng, M. and Shatera, M. M. (1999) Socio-economic effects of CBPP in Ngamiland. *Technical Report*. Division of Agricultural Planning and Statistics, Ministry of Agriculture, Gaborone.

Gibson, R. S. (1990) *Principles of Nutritional Assessment.* Oxford: Oxford University Press.
Goldstein, H. and Tanner, J. M. (1980) Ecological considerations in the creation and the use of child growth standards. *Lancet*, Mar. 15th, 1980.
Gorstein, J., Sullivan, K., Yip, R., de Onis, M., Trowbridge, F., Fajans, P. and Clugston, G. (1994) Issues in the assessment of nutritional status using anthropometry. *Bull. Wrld Hlth Organizn*, **72**, 273–283.
Graitcer, P. L. and Gentry, M. (1981) Measuring children: one reference for all. *Lancet*, ii, 297–299.
Greco, L. and Power, C. (1995) Adult outcome of normal children who are short or underweight at age 7 years. *Br. Med. J.*, **310**, 669–670.
Habicht, J. P., Yarbrough, C., Martorell, R., Malina, R. M. and Klein, R. E. (1974) Height and weight standards for preschool children: how relevant are ethnic differences in growth potential? *Lancet*, i, 611–615.
Jamison, P. L. (1995) Height and weight among Inupiat (Eskimo) and other children: age independent vs. age dependent weight for height. *S. Afr. J. Sci.*, **91**, 469–477.
Kpedekpo, G. M. K. (1970) Heights and weights of children in Ghana. *J. R. Statist. Soc.* A, **133**, 86–93.
Lovell, H. G. (1972) Heights and weights of West Indian children. *J. R. Statist. Soc.* A, **135**, 569–578.
Palti, H., Adler, B. and Bendel, J. (1995) Growth of a national sample of Israeli children: are local standards needed? *Am. J. Biol.*, **7**, 407–414.
Tanner, J. M. (1989) *Foetus into Man: Physical Growth from Conception to Maturity*, 2nd edn. Ware: Castlemead.
Uche, P. I. (1981) Height and weight of Nigerian children; the fit of Ehrenberg's equation. *Biometrics*, **37**, 149–151.
Warner, J. T. (2000) Reliability of indices of weight and height in assessing nutritional state in children. *Lancet*, **356**, 1703–1704.
Waterlow, J. C., Buzina, R., Keller, W., Lane, J. M. and Nichaman, M. Z. (1977) The presentation and use of height and weight data for comparing the nutritional status of groups of children under the age of 10 years. *Bull. Wrld Hlth Organizn*, **55**, 489–498.
World Health Organization (1981) Development of indicators for monitoring progress towards health for all by the year 2000. In *Health for All*, vol. 4. Geneva: World Health Organization.
——(1983) *Measuring Change in Nutritional Status: Guidelines for Assessing the Nutritional Impact of Supplementary Feeding Programs for Vulnerable Groups.* Geneva: World Health Organization.
——(1985) Energy and protein requirements: report of a Joint FAO/WHO/UNU Expert Consultation. *Technical Report 724.* World Health Organization, Geneva.
——(1986) Use and interpretation of anthropometric indicators of nutritional status: report of a WHO Working Group. *Bull. Wrld Hlth Organizn*, **64**, 929–941.