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State of the Art of Growth Standards

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Abstract

Growth charts have become widely used, if not universal, tools for the assessment of the growth and health of children. In 2006, the WHO published a set of charts designed to represent standards to which all the world's children should aspire. They were produced in response to the apparent variability in the patterns of child growth documented worldwide, and with the aim of creating a prescriptive standard based on best feeding advice. Our modern understanding and use of growth references arose out of the application of technology, mathematics and charting to the biology of growth in the 19th century. As means of summarizing normal development, modern growth standards have replaced Renaissance conceptions of human form based on idealized proportions in harmony with the cosmos, and the simple reference to key developmental milestones first noted by the ancients. The WHO growth standards are the culmination of a search for a human ideal based on 20th century biology. However, while they may be the 'best' standards based on contemporary feeding advice, they are 'provisional' because all developmental processes in biology, including body growth, are plastic and permit a flexibility of life course trajectories in response to epigenetic, nutritional and other environmental conditions.

Introduction

In 2006, the World Health Organization (WHO) published a set of charts which may be regarded as the current 'state of the art of growth standards' [1]. They are based upon measurements of samples of healthy breastfed infants born of and nursed by healthy non-smoking mothers, from six countries of the world (Brazil, Ghana, India, Norway, Oman and USA) selected to represent a cross-section of

the genetic and cultural diversity of the global population [2]. WHO argued that they are universally applicable and may be considered as not just descriptive, but also prescriptive; in effect standards of growth to which all the world's children should aspire [3].

Growth charts are graphical ways of describing the rates of growth of indices of body size (most commonly mass and length, but also the dimensions of specific organs and parts of the body). The measurement of the rates and patterns of body growth has become a valuable index of child growth and development. Such measurements correlate well with specific and general health indices, and are now widely used to identify not only 'failure to thrive' and obesity, but also to alert pediatricians and public health professionals to the risk of disease and to help them monitor progress and response to treatment.

'Recent Advances in Growth Research: Nutritional, Molecular and Endocrine Perspectives' is the subject of this symposium and the aims of this paper are to take a historical perspective – to trace the origins and development of references and standards for ponderal and linear growth (growth in mass or weight, and length or height) and how they have reached the present 'state of the art'. In doing so, this review focuses largely on the weighing of babies.

Early History of Child Rearing and Anthropometry

The care, growth and rearing of children have been subjects of interest to physicians, philosophers and biologists from antiquity – Hippocrates, Aristotle and Soranus all wrote about child rearing, offering advice about infant care, feeding and diet. They focused on the 'seven ages of man', documenting milestones, such as teething, weaning, menarche and menopause. Anthropometry was born not of medicine or science, but of the arts, inspired by Pythagorean geometry and Platonic philosophy. Artists sought the ideal proportions of man, believing that a scale of proportions, such as governed the positions of heavenly bodies and the harmonics of music, was also to be found in the physique of the human body. Physical measurement of length tended to be expressed as ratios rather than in absolute numbers [4].

The writings of the ancients informed Renaissance physicians and authors, who rediscovered, supplemented and reinterpreted their teachings. An apt example of thinking about child rearing in the 16th century is *Paedotrophia*, a didactic poem on pregnancy, childbirth, infant care and feeding, subtitled 'The Art of Nursing and Rearing Children' [5]. Synthesizing the contributions of classical writers with the new humanistic thinking, this work represents the 'state of the art' of infant care before the 'scientific revolution' that started to inform medical practice and natural philosophy. In the 17th century observation, measurement and experiment sought objective explanations of the structure and workings of living things, and the human body came to be regarded

as a machine, leading to demonstrable theories of the circulation of the blood (William Harvey 1579–1657) and the fate and effects of food in the body (Sanctorio Sanctorio 1561–1636), for instance. The application of technology (including the weighing balance, microscope and thermometer), coupled with quantitation and charting, led to a new (non-humoral) physiology, and with cellular and tissue anatomy and pathology, to the beginning of the end of Galenic medicine [6]. The iatromathematical approach to 'natural philosophy' with the application of measurements of length, weight, temperature etc., to the investigation of living things proved both helpfully descriptive and usefully predictive. The compilation of sequential data on growth invited mathematical analysis and clinical application.

Early History of Weighing and Charting

Infant growth charts have their origin in the weighing of babies, a practice that began sporadically in the 17th and 18th centuries [7]. Undertaken by obstetricians searching for an index of the viability of the fetus, the weight of the newborn became an objective measure useful not just for clinical purposes but also to settle disputes about legitimacy. In the early 19th century, large series of the weights of the newborn were collected and reported, mostly from maternity hospitals in Europe, as obstetricians increasingly applied science to their clinical practice (table 1). Taking into account national differences in weight standards before metrification (adopted officially by Napoleon in 1795), measurements of birthweights show considerable variability within a range either side of the modern mean. Such attempts to define the 'normal' weight of the newborn were examples not just of the descriptive 'anatomo-clinical' method which began to eclipse humoral medicine, but also of the 'méthode numérique', the application of mathematics to medicine to measure and analyze clinical phenomena [8].

Adolphe Quetelet (1796–1874) was a pioneer of the development of statistical methods for the analysis of complex biological and social data. He aimed to define the 'l'homme moyen' ('average man'), based on his belief that the average of all human attributes in a given country serves to define the 'type' of the nation analogous to the 'center of gravity' in physics [9].

'In order to succeed, we must study the masses with a view to separating from our observations all that is fortuitous or individual. Everything being equal, the calculation of probabilities shows that we approach nearer to the truth in direct ratio to the number of individuals' [10].

Observing the 'law of large numbers' proposed by Siméon-Denis Poisson, Quetelet was one of the first to attempt to define the 'normal' growth of infants, collecting the weights of an unknown number of children in the foundling hospital in Brussels [11]. These measurements, which established that girls and

Table 1. Weights of newborn infants in the 18th, 19th and 20th centuries, taken from Tanner [4] and Cone [7]

Date	Author	Place	Boys	Girls
1753	Roederer	Göttingen	3.09	2.93
1786	Clarke	Dublin	3.35	3.09
1804	Friedlander	Paris	2.94	(both)
1830	Quetelet	Brussels	3.20	2.91
1840	Quetelet	Brussels	3.00	3.00
1842	Simpson	Edinburgh	3.47	3.12
1849	Scanzoni	Würzburg	3.53	3.43
1853	Veit	Berlin	3.22	3.13
1855	Hartman	Rostock	3.54	3.44
1860	Hecker	Munich	3.34	3.22
1860	von Siebold	Göttingen		3.25
1860	Duncan	Edinburgh	3.31	3.26
1867	Martin	Berlin	3.25	(both)
1871	Gregory	Munich	3.39	3.33
1875	Roberts	Edinburgh	3.34	3.29
1885	Issmer	Dresden	3.32	3.21
1895	Pearson	London	3.32	3.22
1910	Benestad	Oslo	3.52	3.41
1915	Bruce-Murray	London	3.30	3.16
1925	Low	Aberdeen	3.48	3.43

boys grew at different rates, remained the only source of data on infant growth for several decades.

Physicians, physiologists and obstetricians with an interest in the growth and development of the fetus and child started to include simple growth charts in textbooks of pediatrics in the late 19th century, and with the rise of 'scientific medicine' weighing, measuring and the documentation of growth became prominent subjects in their opening chapters [12]. The distinction between longitudinal and cross-sectional methods of collecting and using growth data was appreciated, but the early growth charts were relatively simple, with a single curve (mean) and no measures of variance (fig. 1).

French Consultations de Nourrissons and Gouttes de Lait

With growing medicalization and scientization of infant and child care and feeding [13], measurements of growth became adopted as useful objective indices to inform diagnosis, treatment and prognosis. Pierre Budin, chief of the 'special care baby unit' (Pavillon des Enfants Débiles) of the Maternity Hospital

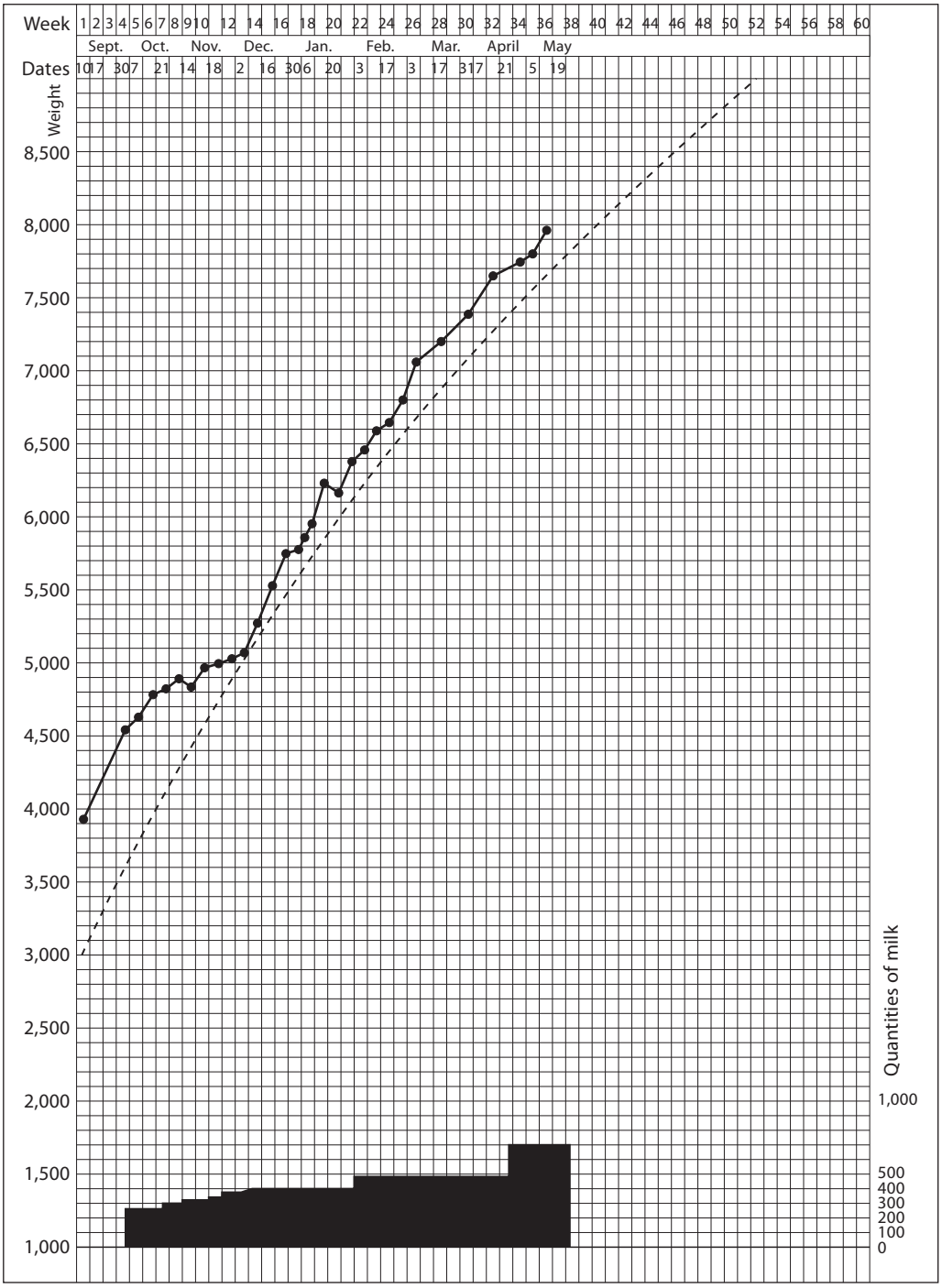

Fig. 1. Growth chart used by Pierre Budin in Paris. The dotted line is the mean body-weight and the histogram is a measure of the volume of feeds taken by infants.

in Paris, pioneered the weighing balance and growth chart as essential clinical tools (along with the thermometer and temperature chart) in the care of infants. Based on his clinical use of growth charts in hospital, he established postnatal maternal and infant welfare clinics to monitor the health of the newborn after discharge from the maternity hospital. These Consultations de Nourrissons and Gouttes de Lait were based on three principles: the support of breastfeeding, the weighing of babies and the provision of clean sterilized milk to infants that were not thriving [14]. The consultations proved very effective and popular, and by 1905 there were more than sixty in and around Paris, and soon they were being adopted and reproduced throughout Europe as well as in Great Britain [15] and North America [16].

'When babies develop normally they put on weight regularly and of a quantity more or less according to their age – this is a general rule. When the curve of weight gain of an infant is good, one can conclude that it is in an excellent state of health, and is in no danger; if it is unwell, one knows that the weight goes down' [17].

The growth chart chosen by Budin (based on data collected in 1864) did not distinguish boys from girls, neither did it take into account mode of feeding (fig. 1). Nevertheless, it became enormously useful as an objective measure of the health of the newborn, and a guide to the use of artificial feeds. The provision of clean, modified, sterilized milk (du lait de vache de bonne qualité et sterilisé) proved effective not only in improving infant growth (in babies whose mothers could not or were not nursed by their mothers) but also in reducing infant mortality [18].

One of Budin's colleagues, Gaston Variot, sought to counter the prevailing opinion that the growth of artificially fed infants was generally inferior to that of the breastfed. He published tables of the weights of around 25–40 boys and girls measured each month [19]. The artificially fed did almost as well as the breastfed, particularly in the second half of the year, but the mixed-fed did the best. '. . .There is only a minimal difference between the weights and lengths of the babies raised on the breast or the bottle, if one applies to the latter modern, improved artificial feeds, as is done in the Gouttes de Lait.' The numbers of infants he weighed may have been small, and Variot's goal was to champion the effectiveness of the Gouttes de Lait, but his study showed the range of normality within which babies thrived. These data represent one of the first systematic attempts to provide growth standards for infants which distinguish between the sexes and take into account the way babies were fed.

The practice of weighing babies was seized upon by public health authorities throughout Europe, North America and elsewhere (Israel, New Zealand, Uruguay), as a means of combating infant mortality [16]. The milk requirements of infants were defined [20] and by the mid-20th century growth monitoring had become a central component of international child health initiatives. Promoted as a 'road to health', the growth chart offered a simple means of charting the trajectory of normal growth and development and identifying deviations from them [21].

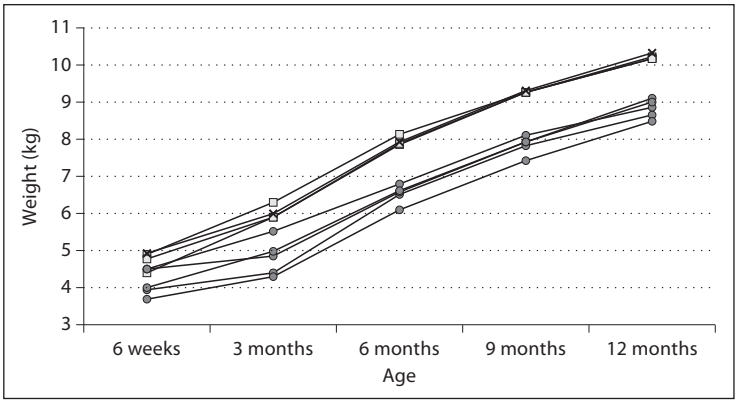

Fig. 2. 'Early' (□; 1892–1914) and 'recent' (●; 1971–2000) infant weight growth data. See Weaver [22] for full details.

Variability of Growth in 20th Century

By the 1970s, a large number of national growth charts was in use, each based on locally compiled data which became used as references against which to compare the growth of children in welfare clinics, school health services and other clinical and public health settings. Analyses and comparisons of the growth curves of these different growth charts show that the rates and patterns of growth in weight of European and North American infants have changed significantly over the last 100 years (fig. 2). Since the development and first use of growth charts for postnatal health surveillance, there appears to have been an increase in the weight of one-year-olds of about 1 kg. Taking into account the higher past rates of infant morbidity and mortality, and poorer quality of artificial feeds, this change is likely to be an expression of the secular increase in physical stature consequent upon improved hygiene and nutrition [22].

Recognition of the variability of the patterns of growth of children worldwide prompted the WHO to set up a working group on infant growth in the early 1990s tasked with compiling new reference data that would be widely applicable. In reviewing the existing references, the working group noted repeated instances of negative deviations in growth rates of healthy breastfed infants compared to the then current WHO references [3]. These were based on growth data collected from predominantly formula-fed infants in the USA in the 1960s and 1970s [23]. The negative deviations in growth (particularly between the 3rd and 6th months) appeared so marked that they encouraged premature introduction of complementary feeding, suggesting that the lactation of women was insufficient to sustain adequate infant growth; or perhaps vice versa [24]. Moreover, the slower weight growth of breastfed babies, both

now and in the past compared with modern formula-fed babies, has implications for our understanding of the risk factors for obesity and cardiovascular disease [22]. The WHO working groups resolved to create a growth reference that also served as a standard – 'a single international reference representing the best standard possible of optimal growth for all children <5 years of age' [2].

Universal but Provisional Growth Standards

Body growth (change in mass and length) is a composite and complex process throughout the life course, and the WHO growth standards represent the 'state of the art' of what we may regard as optimum growth consistent with and defined by our current understanding of human biology (particularly nutrition, genetics and endocrinology). However, the variability of infant growth in time and space, and the plasticity of developmental processes during the life course (fetal life, infancy, puberty, reproduction), mean that the WHO infant growth standards cannot alone be regarded as an ideal growth trajectory for all babies at all times and places. They are *universal*, clinically, in the sense that they represent the best common standard to apply to all the world's children in a public health setting, but they are *provisional*, biologically, in the sense that they are expressions of changing and changeable processes (cultural as well as endocrinological and nutritional) that regulate growth. Maternal height and age of menarche have changed significantly over the last century, for instance, and so too are other major measureable biological factors such as birthweight (table 1) and lactational capacity likely to change, quite apart from cultural processes like the choice and timing of weaning foods.

This plasticity of growth serves a vital function in both the ontogeny of the individual and the evolution of the species. It permits opportunities to pursue alternative developmental courses, in response to adverse events (such as intrauterine growth restriction or undernutrition in childhood, which may be followed by catch-up growth in infancy or puberty), but these can be associated with penalties or costs later on [25]. Mismatches between genetically determined biological processes and new environmental conditions may well be a significant cause of adult disease as the prevalence of infections and other preventable and treatable causes of chronic disease diminish [26].

'Initiatives for the development of a uniform standard for human growth use the assumption that optimum health across the life-course will be achieved through comparable growth in various settings, irrespective of factors such as maternal diet, body composition, or physical activity' [27].

Changes in bodyweight and length are summations of the growth of tissues and organs each of which is subject to its own developmental program, regulated by proximate and remote influences – genetic and environmental factors which determine physiological functions and pathological responses. Different organs

grow at different rates (brain and gut, for instance), and the allometric relations between them, while describable mathematically, are governed by developmental pathways that are part of the life course strategies of different animal species [28]. Developmental plasticity provides individuals with the flexibility to adjust the trajectory of their development to match their environment [26].

Conclusions

One hundred years ago, growth charts were chiefly used to identify children that were failing to thrive; indeed they were vital tools in the battle to combat infant mortality [29]. The current WHO growth charts continue to serve a vital function in monitoring the development and health of the world's children, especially in countries where growth faltering is a precursor and accompaniment of morbidity and a significant risk for premature mortality [30]. In using the WHO growth standards to compare the growth of babies during the last hundred years, the variability and plasticity of infant growth rates are revealed.

The WHO working group acknowledged that the WHO standards 'allow for possible future revision as substantial new biological information on the growth of infants and young children becomes available' [2]. Given the geographical and temporal differences and changes that have been documented around the world in different societies and in different times past, the WHO infant growth standards must be regarded as 'provisional' as are all biological 'indices' that are subject to variation consequent upon genetic, epigenetic and environmental factors.

References

1 www.who.int/childgrowth/standards.
2 Garcia C, de Onis M: A new international growth reference for young children. Am J Clin Nutr 1999;70(suppl):169S–172S.
3 de Onis M, Garcia C, Onyango AW, Borghi E: Comparison of the WHO child growth standards with the CDC 2000 growth charts. J Nutr 2007;137:144–1148.
4 Tanner JM: A History of the Study of Human Growth. Cambridge, Cambridge University Press, 1988.
5 Scevole de St Marthe: Paedotrophia, or the Art of Nursing and Rearing Children (translated by Tytler HW). London, John Nichols, 1797.
6 Singer C: A History of Biology. New York, Henry Schuman, 1951.
7 Cone T: De pondere infantum recens natorum. Pediatrics 1961;28:490–498.
8 Matthews JR: Quantification and the Quest for Medical Certainty. Princeton, Princeton University Press, 1995.
9 Quetelet A: Sur la taille moyenne de l'homme dans les villes et dans les campagnes, et sur l'age ou la croissance est complètement achevée. Ann Hyg Pub 1830;3:24–26.
10 Quetelet A: A Treatise on Man and the Development of his Faculties (translated by Knox R). Edinburgh, Chambers, 1842.
11 Quetelet A: Recherches sur la loi de croissance de l'homme. Ann Hyg Pub 1831;6: 89–113.

12 Weaver LT: In the balance: weighing babies and the birth of the infant welfare clinic. Bull Hist Med 2010;84:30–57.
13 Weaver LT: The emergence of our modern understanding of infant nutrition and feeding 1750–1900. Curr Paediatr 2006;16: 342–347.
14 Budin P: Le Nourrisson (translated by Maloney WJ). London, Caxton, 1907.
15 Ferguson A, Weaver LT, Nicolson M: The Glasgow Corporation Milk Depot 1904–1910 and its role in infant welfare: an end or a means? Soc Hist Med 2006;19:443–460.
16 McCleary GF: The Early History of the Infant Welfare Movement. London, Lewis & Co, 1933.
17 Budin P: Manuel Pratique d'Allaitement. Paris, Doin, 1907.
18 Budin P: Les consultations de nourrissons. Ann Med 1905;1:618–645.
19 Variot G, Fliniaux M: Tables des croissances comparées des nourrissons élevés au sein et au biberon durant la première année de la vie. Com Rend Acad Sci (Paris) 1914;158:1361–1364.
20 Weaver LT: Growing babies – defining the milk requirements of infants 1880–1910. Soc Hist Med 2009;33:320–337.
21 Jelliffe DB, Jelliffe EFP: Human Milk in the Modern World. Oxford, Oxford University Press, 1978.
22 Weaver LT: How did babies grow 100 years ago? Eur J Clin Nutr 2011;65:3–9.
23 www.cdc.gov/growthcharts.
24 Elsom R, Weaver LT: Does breastfeeding beyond one year benefit children? Fet Mat Med Rev 1999;11:163–174.
25 Weaver LT: Rapid growth in infancy: balancing the interest of the child. J Pediatr Gastroenterol Nutr 2006;43:428–432.
26 Gluckman PD, Hanson MA: Developmental Origins of Health and Disease. Cambridge, Cambridge University Press, 2006.
27 Gluckman PD, Hanson MA, Bateson P, et al: Towards a new developmental synthesis: adaptive developmental plasticity and human disease. Lancet 2009;373:1654–1657.
28 Weaver LT, Austin S, Cole TJ: Small intestinal length: a factor essential for gut adaptation. Gut 1991;32:1321–1323.
29 Weaver LT: Feeding babies in the battle to combat infant mortality a century ago. Scot Med J 2009;54:41–46.
30 World Health Organization: WHO Child Growth Standards and the Identification of Severe Acute Malnutrition in Infants and Children. Geneva, WHO and UNICEF, 2009.