1. INTRODUCTION

The WHO Multicentre Growth Reference Study (MGRS) was implemented between 1997 and 2003 to develop growth standards for children below 5 years of age. The MGRS collected primary growth data and related information from 8440 healthy breastfed infants and young children from diverse ethnic backgrounds and cultural settings (de Onis et al., 2004a). The first set of the WHO Child Growth Standards based on length/height, weight and age that describe the attained growth of healthy children was released in April 2006. The second complementary set, based on head and arm circumference and subscapular and triceps skinfolds, followed a year later (WHO Multicentre Growth Reference Study Group, 2006a; 2007). The standards are based on a prescriptive approach using well-defined criteria, rigorous data-collection methods, sound data-management procedures, and state-of-the art statistical methods (de Onis et al., 2004b; Borghi et al., 2006).

A key component in the MGRS design was a longitudinal cohort of children who were examined in a sequence of 21 visits starting at birth and ending at 24 months of age. Such frequently collected and well-controlled data are highly unusual, especially given the study’s rigorous inclusion criteria (de Onis et al., 2004b). A principal rationale for the MGRS longitudinal component was to allow for development of velocity growth standards.

Proponents of the use of growth velocity consider it a superior quantitative measure of growth compared to attained size for age (Tanner, 1952; Roche and Himes, 1980; Baumgartner et al., 1986; Guo et al., 1991). They point out that, whereas pathogenic factors affect growth velocity directly, their impact on attained size becomes evident only after the altered rate of growth has had time to produce its result (Tanner, 1952). In other words, examining velocity should lead to earlier identification of growth problems than would the examination of attained growth only. Despite their hypothesized advantage, there are far fewer velocity references than there are for attained growth, in part due to scarcity of appropriate longitudinal datasets.

This report presents the WHO growth velocity standards and describes the methods used to construct the standards for weight conditional on age, weight conditional on age and birth weight, length conditional on age, and head circumference conditional on age. Strictly speaking, velocity is a change in value expressed in units per time period (e.g. g/time), while an increment is a change in value expressed in units (e.g. grams). Nevertheless, since the increments presented in this report refer to specific time periods (i.e. 1- to 6-month intervals), the terms velocity and increment will be used interchangeably.

As part of the preparatory work for the construction of the standards presented in this report, an advisory group met in March 2007 to review uses of growth velocity standards in clinical practice, public health programmes, and research settings and to discuss available strategies and related methods for the construction of the velocity standards. Two background documents were prepared to guide the advisory group’s discussions, one on technical and statistical issues (Himes and Frongillo, 2007) and another on the presentation and application of such standards (Wright, 2007).

Among technical issues discussed, the first was whether to model increments (i.e. using measurements) or changes in z-scores. The complexity in applying growth velocity using available presentation formats associated with the z-score scale was recognized.

The second technical issue concerned which approach to statistical modelling to use for the increments, i.e. GAMLSS (Rigby and Stasinopoulos, 2005) or multi-level (ML) (Goldstein, 1986) modelling. The consensus was in favour of GAMLSS over ML modelling because it had been used more extensively in growth curve construction and its capabilities and associated diagnostic tests were better understood. Multi-level modelling was believed to be potentially extremely complex given the large number of growth intervals in the WHO standards data that would have to be modelled. In addition, use of the GAMLSS method as recommended by the background document on statistical issues (Himes and Frongillo, 2007) provided consistency with the methodology used to construct the WHO attained growth standards. Technical aspects regarding presentation and application included the choice of
variables and intervals, and whether data should be displayed as tables or curves. The need for
guidance on the use and interpretation of velocity standards was also recognized. It was decided to
develop velocity standards for the following anthropometric variables: weight (the most commonly
used measurement and the most responsive to short-term influences); head circumference (the next
most-used measurement in clinical settings, mainly by neonatologists and others caring for infants);
and length (potentially useful since stunting originates in the first two years of life, and detecting
changes in velocity during this period may be beneficial in terms of prevention). It was hypothesized
that BMI velocity might be useful in predicting changes leading to extremes of adiposity. However,
unreliability in BMI increments is a composite of measurement error from various sources. Moreover,
BMI peaks during infancy and then drops through the second year. These characteristics make BMI
velocity difficult to interpret, and there is little knowledge of its prognostic utility. Therefore, BMI
velocity standards were not developed. The final choice of variables (weight, length and head
circumference) is similar to other published velocity references (Falkner, 1958; Tanner et al., 1966a,
1966b; Roche and Himes, 1980; Tanner and Davies, 1985; Baumgartner et al., 1986; Roche et al.,
1989; Guo et al., 1991; van't Hof et al., 2000).

When selecting measurement intervals, account should be taken of the fact that the calculation of
increments involves two measurement errors; hence data are usable only if the measurements are taken
with reasonable care and accuracy. Measurement intervals should be wide enough that expected
growth exceeds measurement error (Tanner, 1952; Cole, 1995; Himes, 1999). In some cases, velocity
reference data (conditional on age) have been presented in yearly intervals (Tanner et al., 1966a;
1966b; Prader et al., 1989), usually from early childhood to early adulthood. However, such intervals
cannot be used to detect nascent growth problems with a view to initiating timely corrective action.
Falkner (1958) presented reference data for length, weight and head circumference in intervals ranging
from three months in the first year to six months in the second year, and one interval from age 2 to
3 years. Baumgartner et al. (1986) published data for 6-month increments from birth to 18 years.
Roche et al. (1989) presented centiles of monthly weight and length increments from the Fels
Longitudinal sample (birth to 12 months). Two years later, Guo et al. (1991) published reference
values of g/d or mm/d in variable (1- to 3-month) intervals. Following wide consultation with potential
users of these standards (e.g. paediatric endocrinologists, neonatologists, lactation counsellors,
managers of child health programmes, and researchers), the increments presented in this report are
those considered to be the most useful clinically.

The WHO velocity standards for weight are presented in two output types. The main output concerns
increments conditional on age, presented as 1-month intervals from birth to 12 months, and in 2- to 6-
month intervals from birth to 24 months. The second output presents empirical centiles of increments
from birth to 60 days in 1-week and 2-week intervals that coincide with the measurement schedule in
the MGRS: birth to 7 days, and 7-14, 14-28, 28-42 and 42-60 days. These data are presented both as
net increments in grams and as g/day velocities over each index period. It is expected that they will be
especially useful for lactation management purposes during this critical period for establishing
breastfeeding.

The velocity standards for length are presented in 2- to 6-month increments from birth to 24 months.
For head circumference, 2- and 3-month increments are presented from birth to 12 months, and 4- and
6-month increments from birth to 24 months. We did not consider 1-month increments for length and
head circumference to be clinically useful as the measurement error over such a short period exceeds
the 5th centile as early as 6 months of age. For similar reasons, the 2- and 3-month increments for head
circumference go up to 12 months of age only. The Technical Error of Measurement (TEM) in the
longitudinal study of the MGRS was 0.38 cm for length and 0.24 cm for head circumference (WHO
Multicentre Growth Reference Study Group, 2006b). Growth standards should allow for low velocities
(e.g. 5th centile) to be detected with some certainty if they are to be clinically useful in detecting
growth problems. The overall choice of intervals is supported by approaches suggested by other
authors (Himes, 1999).
An important consideration regarding the presentation of standards relates to whether centiles are presented as curves or tabulated values. Curves for attained growth are commonly used to track individual growth patterns, but they cannot serve an equivalent purpose for growth velocity. High levels of intra-individual variation in velocity are normal, and it is not unusual for an infant whose increment at one interval was on the 5th centile to gain at the 75th centile during the next interval. Correlations between subsequent increments are typically low, reflecting a natural pattern of saltatory growth (Lampl et al., 1992) as well as possible catch-up or catch-down growth that contribute to overall narrowly canalized patterns in attained growth trajectories of individual children. For users habituated to attained growth curves, the interpretation of velocity curves presents a counter-intuitive logic: children are not expected to track on a fixed velocity curve (Healy et al., 1988) except perhaps in the median range (Tanner et al., 1966b). For example, a child whose weight velocity tracks on the 3rd centile from 5 to 16 years of age would be lighter at 16 years than a 5 year-old (Baumgartner et al., 1986). On the other hand, a child following the 97th centile from pre-school age would, by maturity, be pathologically enormous (Tanner et al., 1966b).

The lack of correlation between increments makes it difficult to define what constitutes a normal or abnormal sequence of increments, leading to the recommendation that velocity be examined always in conjunction with related measures of attained growth (Tanner, 1952). Different variants of charts combining the concepts of attained size and velocity have been developed and proposed for clinical use, particularly in the United Kingdom (Wright et al., 1994; Cole, 1997; Cole, 1998; Wright et al., 1998). However, those tools do not appear to have gained currency even when incorporated into computerized applications.

The models used in developing the WHO growth velocity standards produce centiles on a continuous scale, but the final centile values are presented in tabular format only for the specific age intervals described earlier. Graphic diagnostic outputs with point estimates linked as curves (not model-based curves) are presented throughout the report to facilitate comparisons between fitted and empirical centiles. Electronic copies of the full set of velocity standards are available on the Web: www.who.int/childgrowth/en. These standards provide a set of tools for monitoring the rapid and changing rate of growth in early childhood.