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8
Standards of Human Tooth Formation and Dental Age Assessment

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INTRODUCTION

Age standards for human growth and development have many uses in human biology. In clinical medicine, a basic chronology of development is needed so that intervention does not harm normal growth. Clinical assessment of child growth also requires normal reference standards so that physiologic age of a tissue system can be compared with chronological age. In some clinical work and in much anthropological work, methods are needed to assess chronological age of human subjects. In forensic osteology, archaeology, paleontology, and demography of some non-Western cultures, the age of the subject is an important unknown variable.

Dental age is one method of physiologic age assessment, comparable to ages based on skeletal development, weight, or height (Demirjian et al., 1973). However, dental development is much less affected than other tissues by endocrinopathies and other developmental insults. This is shown by studies of children with major abnormalities affecting sexual maturation, stature, bone age (and even IQ score) who show comparatively small deviations in timing of dental development (Cattell, 1928; Taft, 1941; Garn et al., 1965a; Niswander and Sujaku, 1965; Kuhns et al., 1972). Dental development has two main aspects: the *formation* of crowns and roots, and the *eruption* of teeth. Of the two, formation of teeth appears to be more robust to environmental influences; it is known that eruption can be affected by caries, tooth loss, and severe malnutrition (Ronnerman, 1977; Alvarez et al., 1988; Alvarez and Navia, 1989). Formation of teeth, like tooth size or morphology, is highly heritable (Garn et al., 1965b; Moorrees and Kent, 1981), and stages of tooth formation have lower coefficients of variation than do stages of skeletal development (Lewis and Garn, 1960). Tooth formation also appears to be comparatively resistant to nutritional effects. This is suggested by the consistently low correlations ($\sim r = 0.1-0.2$) found between tooth formation and relative weight, fatness, stature, or bone age (Lewis and Garn, 1960; Garn et al., 1965b; Prahl-Andersen and Roede, 1979:518) and also by the lack of a clear secular trend in age of tooth emergence in the presence of substantial secular increase in stature (Helm, 1962). This is not to say that the dentition shows no effect attributable to environmental influence but that it tends to be the least affected tissue. Thus, in many cases, the dentition is the single best physiological indicator of chronological age in juveniles.

The purpose of the present work is first, to review available sources for tooth formation chronologies and to explain some aspects of statistical methodology that make critical choice among sources essential; second, to recommend some sources; and finally, to point out some important gaps in our present knowledge. For an introduction to other aspects of tooth formation, Demirjian's (1986) review can be recommended.

OVERVIEW OF THE CHRONOLOGY OF HUMAN DENTAL DEVELOPMENT

Dental age may be based on the formation or eruption of teeth. However, most studies of timing of eruption are actually limited to observing the time of *emergence* of teeth through the gingiva—a single event in time for each tooth. By comparison, formation of teeth offers the advantage of continuous development during the juvenile years. Human teeth have a definitive period of growth, with the last tooth completing development as the skeleton is nearing

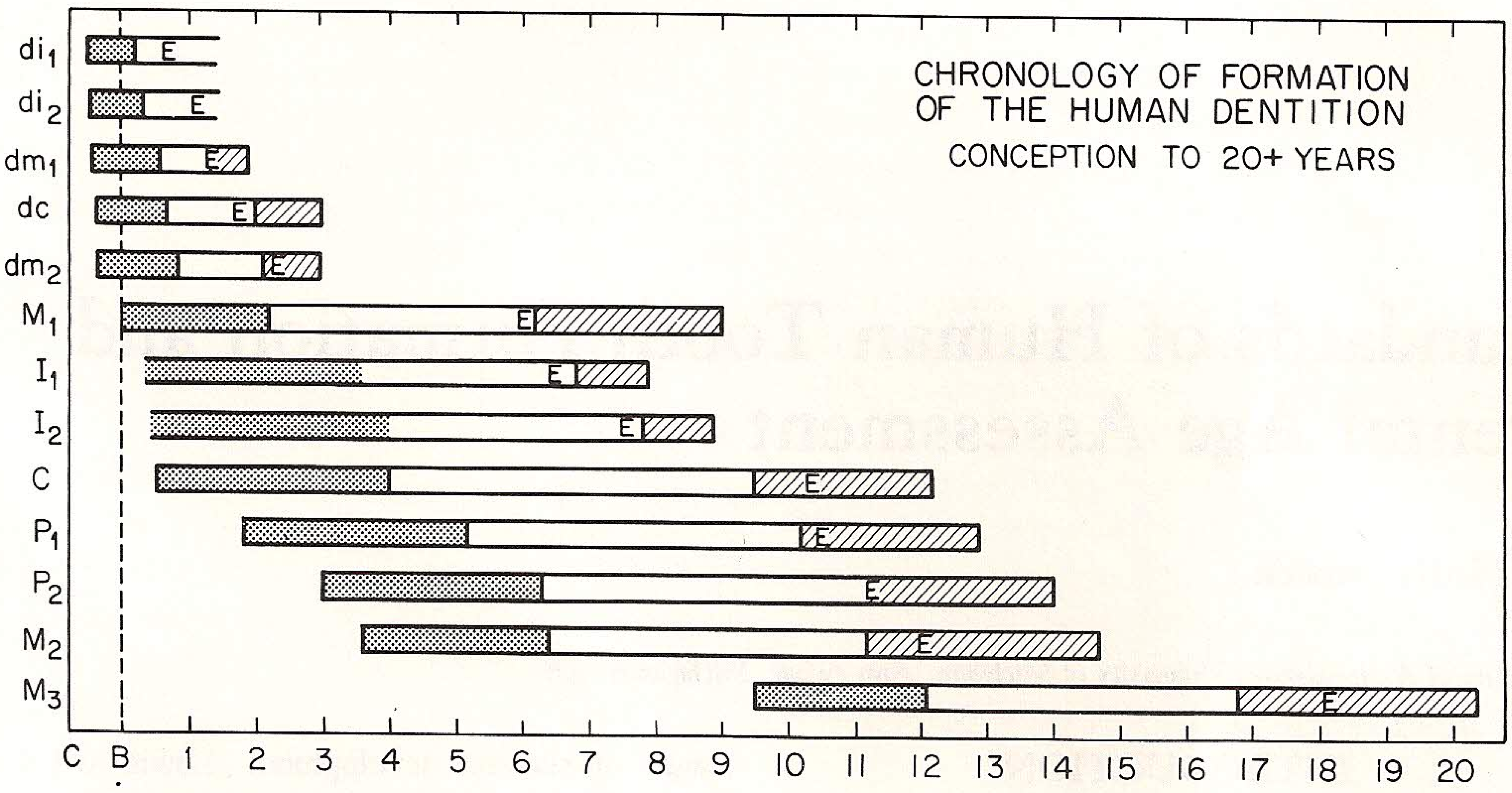

Fig. 1. Overview of events in human mandibular tooth formation showing average age of onset and duration of crown and root formation. Shaded bar, crown formation; unshaded bar, growth in length of the root; hatched bar, closure of root apex. "E" represents age of tooth emergence. Open bars at di1, di2, I1 and I2 indicate uncertainty, as "age of attainment" data (see text) are sparse or unavailable; mid-sex means used throughout. Teeth are listed in order of appearance to emphasize sequential phases of tooth formation, thus placing dc and M1 out of order relative to location. Sources: primarily based on the European-derived subjects of Moorrees et al. (1963a, b), but including data from Sunderland et al., 1987 (prenatal); Anderson et al., 1976 and Kronfeld, 1935a (early stages of incisors); and Lysell et al., 1962 and Hurme, 1949 (tooth emergence). The style of the chart is after Dean and Wood (1981).

complete maturation. During the adult years, teeth undergo attrition and other structural and chemical changes that may provide ways to estimate chronological age (Johanson, 1971; Kay and Cant, 1988; see also Chapter 9, *this volume*). However, at present, accuracy for estimation of adult age is on the order of ±5 years in the best of cases (Hojo, 1954; Miles, 1963; Johanson, 1971; Richards and Brown, 1981). As will be shown below, it appears to be possible to estimate age for juvenile humans far more precisely than for adults.

Development of the dentition, including both formation and eruption of teeth, spans a period of about 20 years in humans. *Tooth formation* includes formation of an organic matrix and its subsequent *calcification* or *mineralization* (for a review of earliest stages of development and matrix formation and calcification, see Kraus and Jordan, 1965, or Bhaskar, 1980). Chronologies of tooth formation considered in this discussion are those of mineralization; most are of mineralization as visualized radiographically. It is of some importance to know the techniques of a study because mineralization is often demonstrable slightly earlier on dissection than on radiography (Logan and Kronfeld, 1933; Nolla, 1952; Garn et al., 1959; Kraus and Jordan, 1965:120). For the most part, prenatal tooth formation is studied by dissection of anatomic material, and postnatal development is studied radiographically (although this is not a universal rule). Because of this, it is not possible to assemble a complete chronology of human tooth formation based on any single technique.

Age of *emergence* of teeth is known for a great variety of human groups and in some cases for socioeconomic levels within groups (Steggerda and Hill, 1942; Hurme, 1949; Adler, 1958; Dahlberg and Menegaz-Bock, 1958; Friedlaender and Bailit, 1969; Garn et al., 1973). Adler (1959) located studies of some 40 ethnic groups in a survey of the literature from the years 1949–1959, and new studies continue to appear (see review in Jaswal, 1983). By contrast, far less is known about chronologies of tooth formation, and there are few major studies. This can be explained because tooth formation requires radiography or dissection, whereas study of emergence requires only looking into a child's mouth. Indeed, several methods have been designed to assign dental age or assess development when a count of teeth present in the mouth is the only available data source (Voors and Metselaar, 1958; Brook and Barker, 1972; Filipsson, 1975; Moorrees and Kent, 1978).

Figure 1 illustrates a basic chronology of human dental development (see legend for sources of data). This chart is based on radiographic studies whenever possible, but beginning formation of deciduous teeth is known only from anatomic material. Although no information concerning variance is given, the chart provides a good overview of the process. First, it should be noted that radiographic tooth formation begins with mineralization visible at cusps of the crown and ends with the closure of the apex of the root. In humans, teeth begin to erupt after root formation has commenced and emerge into the mouth after a substantial amount of root has been formed (Grøn, 1962). In Figure 1, E marks the first appearance of the tooth through the gingiva, the best known marker within the longer process of tooth eruption. Deciduous teeth begin forming prenatally, with mineralization commencing in the second trimester of pregnancy, between 12 and 16 weeks, according to Kraus (1959) (Fig. 1). Crowns are partly completed at birth. Deciduous tooth formation occupies only some 2–3 years from initial mineralization to root completion. By contrast, calcification of the permanent dentition is entirely postnatal, and formation of each tooth occupies some 8–12 years.

Events in formation of the human permanent dentition occur in several phases or clusters (Schour and Massler, 1940). The first molar (M1) and the anterior teeth (I1, I2, C), all begin formation within the first year. A second wave of formation begins for cheek teeth (P1, P2, and M2) between ages 2–4 years. Third molars are substantially delayed in humans, developing some 5–6 years after M2 in European-derived populations, although this may vary widely across human groups (Fanning and Moorrees, 1969). The clustering of human dental development is even more evident in emergence timing, for which four distinct phases of emergence are recognizable: (I) deciduous teeth, most emerging during the second year of life; (II) M1, I1, I2 at 6–8 years; (III) C, P1, P2, M2 at 10–12 years; and (IV) M3 at 18+. This is interesting in a theoretical sense but also has the practical consequence that accuracy of age assessment from tooth emergence is limited for subjects caught during the intervening quiescent periods (e.g., approx ages 3–6, 8–10, and 12–18).

In trying to assemble Figure 1, some surprising gaps in available information were identified. Specifically, no recent (post-1950) study with documented methods could be found giving ages of terminal formation stages for mandibular deciduous incisors or for initiation of permanent incisor crowns; only sparse information is available for completion of permanent incisor crowns. In both cases, bars are left open in Figure 1 to indicate uncertainty. These gaps in information reflect the scarcity of very young children in all studies, the difficulty of taking radiographs of young subjects, and the greater difficulty of visualizing anterior teeth in radiographs (see Nyström et al., 1977).

HISTORY OF CHRONOLOGIES OF TOOTH FORMATION

The first extensive table of events in tooth formation is generally credited to Legros and Magitot (1880, 1881), although dental texts noting some information about timing of tooth formation can be traced back at least an additional 100 years (see review in Kronfeld, 1935b). Legros and Magitot produced tables of the appearance of dental tissues and structures for deciduous and permanent teeth in work that appeared in several separate articles (reprinted together in book form in 1881). The work was largely concerned with prenatal development, and the few values included for postnatal formation of permanent teeth seem to be afterthoughts in comparison with the whole. Legros and Magitot described some characteristics of their prenatal sample (giving ranges for body weight and length), but only briefly referred to the existence of postnatal specimens. Unfortunately, their work reached much of the English-speaking audience through an 1880 translation that did not convey the elegance of the authors' original work and partly misprinted the table of development.

Much early work on formation of the dentition was based on both dissection (surgery or autopsy) and on observation of the location of enamel defects ("hypoplasia") on erupted teeth (Kronfeld, 1935c; Black, 1936:262). Hypoplastic banding on teeth probably inspired the pictorial charts of tooth formation issued by Black (1883) and Peirce (1884) in American dental journals. These charts (Fig. 2) appeared without any description of the basis of the information, either methods or subjects. Indeed, Black's chart simply appeared as the frontispiece of a journal.

In addition to tables and diagrams of dental development, atlases showing either radiographed or dissected specimens, or both, at successive ages have appeared throughout the twentieth century (Symington and Rankin, 1908; Hess et al., 1932; Boller, 1964; van der Linden and Duterloo, 1976). These pictorial atlases serve as guides to both development and anatomy of the dentition. More problematic are stages of development pictured as artists' renderings, because it is far less clear what these are actually based on. Brady (1924) privately printed a pamphlet

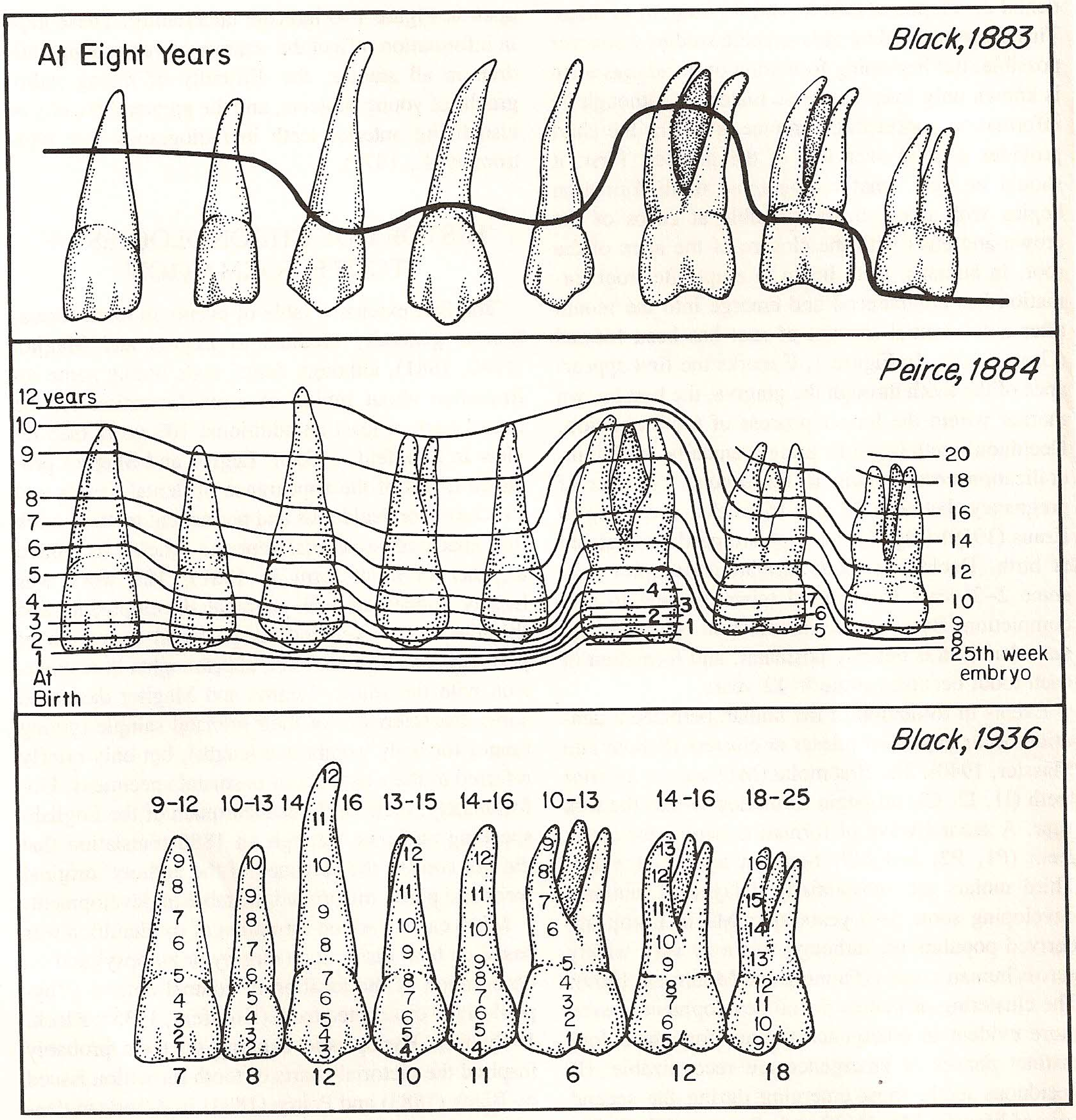

Fig. 2. Three stages in the early evolution of pictorial charts of tooth formation redrawn from original sources. Panel by Black (1883) was one of 12 covering birth to eleven years of age. Peirce (1884) also provided a similar chart for deciduous teeth. Measured against modern studies, all are quite inaccurate.

with 60 such drawings to illustrate developing human teeth from embryos to adults, but the basis of the observations was not described. Schour and Massler (1941) followed this same tradition in presenting their pictorial chart of dental development, a chart that is quite similar to Brady's in style. This chart (''Available in 3 colors; 12 × 18 inches in size. Suitable for framing. 15 cents each. Bureau of Public Relations, American Dental Association'' [Schour and Massler, 1941:1154]) is widespread in dental offices and classrooms even today, although the sources of the information have never been disclosed. This is not to criticize the pictorial ''atlas technique,'' which is well established in growth studies (e.g., Greulich and Pyle, 1950), but rather the lack of documentation in these particular dental charts. Failure to document sources of information also characterizes early tables of dental development. For example, Churchill (1932:170) included a very detailed table for deciduous and permanent teeth in

TABLE 1. Kronfeld's Historic (1935a) Chronology of the Human Dentition (in Part)

Tooth	First evidence of calcification	Crown completed	Root completed
Deciduous dentition			
di1	5 mo in utero	4 mo	1½–2 yr
di2	5 mo in utero	5 mo	1½–2 yr
dc	6 mo in utero	9 mo	2½–3 yr
dm1	5 mo in utero	6 mo	2–2 ½ yr
dm2	6 mo in utero	10–12 mo	3 yr
Permanent dentition			
Upper jaw			
I1	3–4 mo	4–5 yr	10 yr
I2	1 yr	4–5 yr	11 yr
C	4–5 mo	6–7 yr	13–15 yr
P1	1½–1¾ yr	5–6 yr	12–13 yr
P2	2–2¼ yr	6–7 yr	12–14 yr
M1	at birth	2½–3 yr	9–10 yr
M2	2½–3 yr	7–8 yr	14–16 yr
M3	7–9 yr	12–16 yr	18–25 yr
Lower jaw			
Il	3–4 mo	4–5 yr	9 yr
I2	3–4 mo	4–5 yr	10 yr
C	4–5 mo	6–7 yr	12–14 yr
P1	1¾–2 yr	5–6 yr	12–13 yr
P2	2¼–2½ yr	6–7 yr	13–14 yr
M1	at birth	2½–3 yr	9–10 yr
M2	2½–3 yr	7–8 yr	14–15 yr
M3	8–10 yr	12–16 yr	18–25 yr

an appendix to his book, yet the text hardly mentions it.

These many different early charts and tables disagreed on the timing of events. Practical problems demanded better information. William Logan was a surgeon who needed a basic chronology of tooth formation and an anatomic map so that he could avoid damage to developing teeth during surgical repair of cleft palate in young children. Both Logan and Rudolf Kronfeld, a histologist, undertook new work on an autopsy sample, employing both radiographic and histologic techniques (Logan and Kronfeld, 1933). Nineteen infants under 2 years of age and six older subjects (aged 2½, 3, 4½, 8, 11, and 15 years) comprised the sample. By later studies (Kronfeld, 1935a–c; Logan, 1935), some five additional subjects had been added (apparently two were newborn, but ages of the others were not described), and a schedule was assembled of formation of the deciduous and permanent dentitions from birth to 15 years of age (see Table 1).

In making this schedule, Logan and Kronfeld had some 20 subjects covering the first 2 years of life, but only six (perhaps as many as nine) stretched out over the following 13-year period. This part of the chart necessarily included some guesswork. Some values must come from the older literature; for example, Kronfeld's (1935a) table includes prenatal events, although no fetal specimens were ever described in either the 1933 or 1935 studies (as pointed out by Lunt and Law, 1974). Whereas the pool of subjects was appropriate for the immediate purposes, it was far from ideal for standards of normal human growth. Many of the children had died as a result of debilitating illnesses, including tuberculosis, enteritis, and simply "debility"; two newborns had cleft palate (Logan and Kronfeld, 1933:394).

The above work is of historic importance because it forms the basis of a table widely reprinted in textbooks and articles. Schour and Massler (1940) partly reprinted and partly altered the table (Table 2). Subsequent authors reprinted the Schour and Massler table, occasionally with other alterations or without citation (see McCall and Wald, 1940:100; Wheeler, 1940:29; and Arey, 1946:198). Garn et al. (1959) tracked an extraordinary trail of texts that cited sec-

TABLE 2. Part of the Schour and Massler Table From 1940:1920[a]

Tooth	Apposition of enamel and dentin begins	Crown completed	Root completed
Deciduous dentition			
	(months in utero)	(age in months)	(age in years)
di1	4–4½	1½–2½	1½
di2	4½	2½–3	1½–2
dc	5	9	3¼
dm1	5	5½–6	2½
dm2	6	10–11	3
Permanent dentition			
	(age in months)	(age in years)	
I1	3–4	4–5	9–10
I2	10–12 / 3–4[b]	4–5	10–11
C	4–5	6–7	12–15
	(age in years)		
P1	1½–2	5–6	12–13
P2	2–2½	6–7	12–14
M1	Birth	2½–3	9–10
M2	2½–3	7–8	14–16
M3	7–10	12–16	18–25

[a]Originally titled, "Chronology of Growth of Human Teeth." A footnote originally credited the table as "modified from" Logan and Kronfeld (1933); a more precise designation would be modified from Kronfeld (1935a) for the permanent teeth and Kronfeld and Schour (1939) for the deciduous teeth.
[b]Maxillary and mandibular values, respectively.

ondary and tertiary sources for what was largely the Kronfeld (1935a) permanent tooth schedule. Similarly, Lunt and Law (1974) trace the history of the deciduous part of the tooth chronology.

The commonly reprinted version is often called *Chronology of the Human Dentition [Logan and Kronfeld, slightly modified by McCall and Schour]*. As Garn et al. (1959) points out, versions of this *Chronology* have been widely used in anthropology and have appeared in such basic works as *Basic Readings on the Identification of Human Skeletons* (Stewart and Trotter, 1954), and the *Handbook of Biological Data* (Spector, 1956).

A modern period of studies began with the compilation of large numbers of radiographs of children, data collection, and attempts at statistical solutions to the problem of formation schedules. Two of the first efforts were Master's theses in dentistry at the University of Michigan (Pinney, 1939; Nolla, 1952), although Gleiser and Hunt (1955), Demisch and Wartmann (1956), and Fanning (1961) probably provided the first widely available studies. These investigators defined the problem, divided tooth development into stages, and read literally thousands of films of developing teeth of children. Much of the work during the 1950s and 1960s used one of several samples of ongoing child growth studies: the University Elementary and Secondary School Study of Ann Arbor children at the University of Michigan (Nolla, 1952, 1960); the Harvard Longitudinal Studies II of Boston children at the Harvard School of Public Health (Gleiser and Hunt, 1955; Fanning, 1961); the Fels Longitudinal Growth Studies of Ohio children (Garn et al., 1958, 1959); or a combination of both Boston and Ohio samples (Moorrees et al., 1963a,b; Wolanski, 1966). More recently, Canadian growth studies have provided data on French Canadian children from Montreal (Demirjian et al., 1973; Demirjian and Goldstein, 1976; Demirjian and Levesque 1980; Levesque et al., 1981) and on Anglo-Saxon Canadian children from Burlington (Anderson et al., 1976). In Europe, there are semilongitudinal studies of children from the Netherlands and Finland (Prahl-Andersen and Roede, 1979; Nyström et al., 1986), as well as a number of cross-sectional studies of Finnish children (Haataja, 1965; Haavikko, 1970, 1974; Leinonen et al., 1972; Nyström et al., 1977).

Subjects in all the above studies are essentially of European derivation. Surprisingly few studies can be found for other human populations. Nanda and

Chawla (1966) presented data on restricted age groups of children from Lucknow, India; Trodden (1982) surveyed small samples of Inuit and Amerindians from Canada.

Most of the new radiographic studies included at least three stages of tooth formation (beginning calcification, crown completion, and root completion), usually adding several more finely divided stages. Nolla (1952) originally began with eleven stages (including one for no mineralization evident, but crypt visible). Gleiser and Hunt (1955) designed a 13-stage division that has served as a basis for the work of Demisch and Wartmann (1956), Fanning (1961), Haataja (1965), Wolanski (1966), Fanning and Moorrees (1969), Haavikko (1970), Fanning and Brown (1971), Moorrees et al. (1963a, b), Anderson et al. (1976), and Nyström et al. (1977); the version used by Moorrees et al. (1963a) appears in Figure 3. Because stages are based on simple fractions of crown and root completion, the system is easily (and often) modified. Another developmental scale in frequent use consists of an eight-stage system designed by Demirjian et al. (1973) and used in Demirjian and Goldstein (1976), Prahl-Andersen and Roede (1979), Demirjian and Levesque (1980), Levesque et al. (1981), and Nyström et al. (1986). The common basis of three stages permits at least some comparisons across most of these studies. As it turns out, however, comparability of statistical methodology is equal in importance to that of the growth stages recognized. These methods require explanation before proceeding to any recommended chronology.

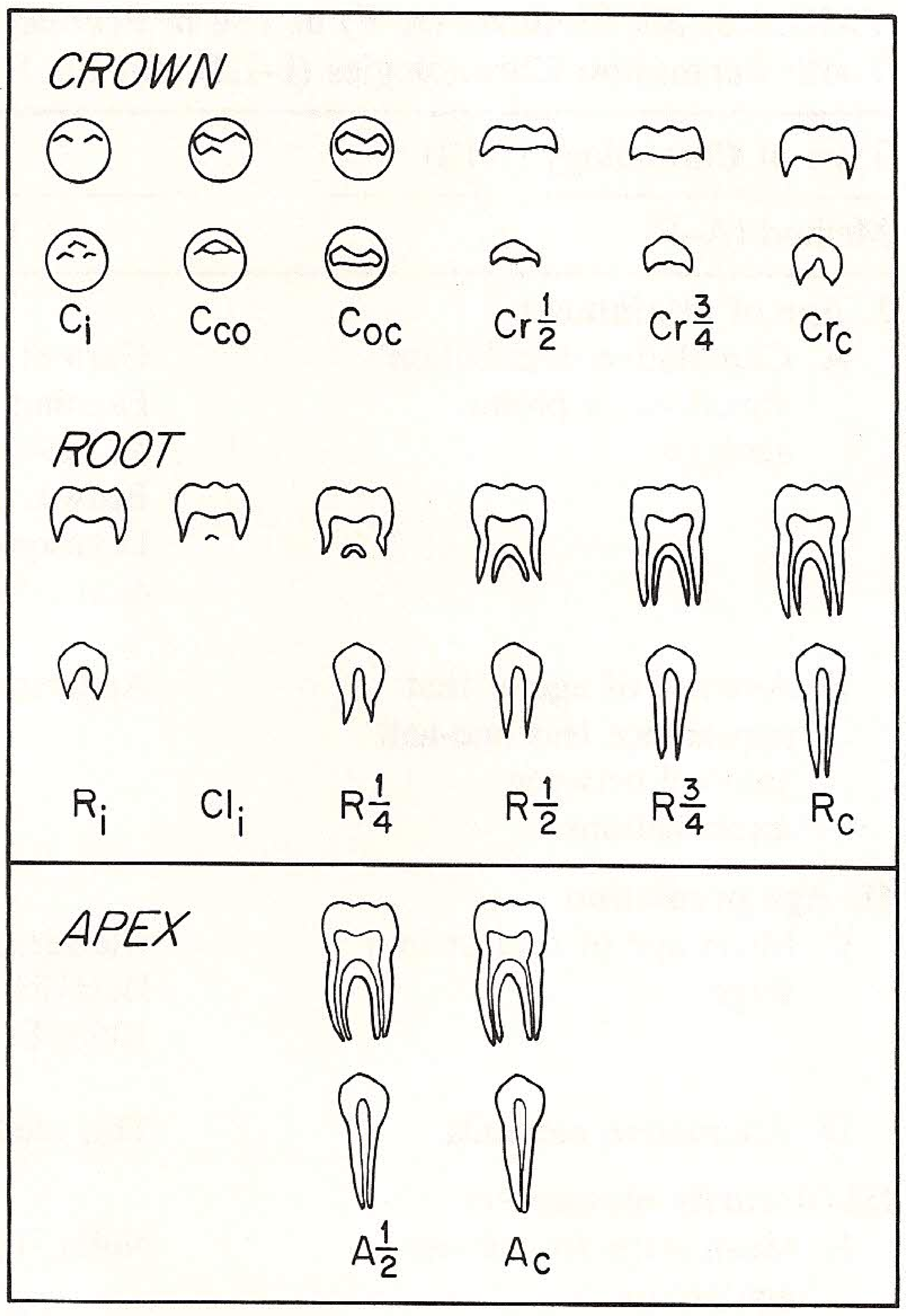

Fig. 3. Stages of permanent tooth formation redrawn from Moorrees et al. (1963a). This scale represents a detailed division of stages and the system has been widely used. The 14 stages are shown here with their standard abbreviations. Capitals: C = cusps; Cr = crown; R = root; Cl = cleft; A = apex; subscripts: i = initiated; co = coalescence; oc = outline complete; c = complete. It is best to designate these stages by abbreviation rather than number because the system is often modified by interpolating in additional stages, or omitting others (e.g., Anderson et al., 1976; Haavikko, 1970; and even Moorrees et al, 1963a).

METHODS IN USE IN CONSTRUCTING CHRONOLOGIES

Determination of a chronology of growth stages is not as easy as one might think. Attainment of a growth stage occurs at a moment in time never observed by an investigator; its attainment may not be closely bounded in time because it is rarely possible to watch a substantial number of human subjects daily, weekly, or even monthly for any length of time. Thus, a procedure is needed to solve for the age of attainment based on more limited observations of subjects at particular points in time. This is true whether the study is longitudinal (the same subjects seen repeatedly over time) or cross-sectional (subjects of different ages each seen once). The result of either type of survey is something like this: in a proportion of cases, the event has not yet happened, and in the remaining, it is over. When did it occur? Several quite different procedures appeared in the literature on tooth formation to answer such questions: some procedures were better than others. Moreover, the various methods produce chronologies that are not comparable; specifically, *underlying variables are fundamentally different*. Thus, it is critical to know which sources use which methods. A review of the literature demonstrates numerous different methodologies in use (Table 3), as described below.

Method A. Cumulative Distribution Functions

There is widespread agreement that cumulative distribution functions provide the best method of determining the age of attainment of a developmental stage (e.g., Tanner, 1986). Some of the best explanations of methodology can be found in the literature

TABLE 3. Six Methods (A–F) in Use in Production of Three Different Types of Statistically Based Tooth Formation Chronologies (I–III) and the Studies That Use Them, Sorted by Type of Data

Type of Chronology (I–III)	Type of data	
Method (A–F)	Longitudinal	Cross-sectional
I. Age of attainment		Haavikko, 1970
A. Cumulative distribution functions or probit analysis	Garn et al., 1958, 1959; Fanning, 1961; Moorrees et al., 1963a,b; Fanning and Brown, 1971; Demirjian and Levesque, 1980[a]; Levesque et al., 1981[a]	
B. Average of age at first appearance less one-half interval between examinations	Anderson et al., 1976	Not applicable
II. Age prediction		
C. Mean age of subject in a stage	Gleiser and Hunt, 1955; Demisch and Wartmann, 1956; Fass, 1969	Haataja, 1965 Trodden, 1982
D. Alternative methods	This study	Leinonen et al., 1972
III. Maturity assessment		
E. Mean stage for subject age group	Nolla, 1952, 1960	Nanda and Chawla, 1966; Lilequist and Lundberg, 1971 (with Crossner and Mansfeld, 1983)
F. Maturity scales	Wolanski, 1966; Demirjian et al., 1973; Demirjian and Goldstein, 1976; Prahl-Andersen and Roede, 1979; Nystrom et al., 1986	None

[a]Large cross-sectional components (>1,000) were added to the longitudinal samples in Demirjian and Levesque (1980) and Levesque et al. (1981).

on tooth *emergence* (Klein et al., 1937; Hurme, 1948; Dahlberg and Menegaz-Bock, 1958; Gates, 1966), an example of which appears in Figure 4. In this graph, the age at which 50% of subjects have reached the stage is taken as the age of attainment of the stage, in this instance, the age of emergence of the tooth. Central tendency and dispersion can be read directly from such a graph, or parametric models may be imposed on the data; after the appearance of probit analysis (Finney, 1939), this method began to be used to estimate parameters (e.g., Clements et al., 1953; Dahlberg and Menegaz-Bock, 1958; Gates, 1966). Cornfield and Mantel (1950), Kihlberg and Koski (1954), Hayes and Mantel (1958), and Gates (1966) discuss assumptions, estimation of mean and variance, and comparisons among samples using tooth emergence data.

Probit analysis takes no special advantage of longitudinal records and treats all data as if they are cross-sectional. There is no reason to prefer longitudinal records for production of a chronology of growth events meant to be used across populations; indeed, this may contribute to underestimation of variance because it is known that tooth development is highly intercorrelated among adjacent teeth (Kent et al., 1978; Moorrees and Kent, 1981; Garn and Smith, 1980). However, most studies of tooth formation have been associated with longitudinal child

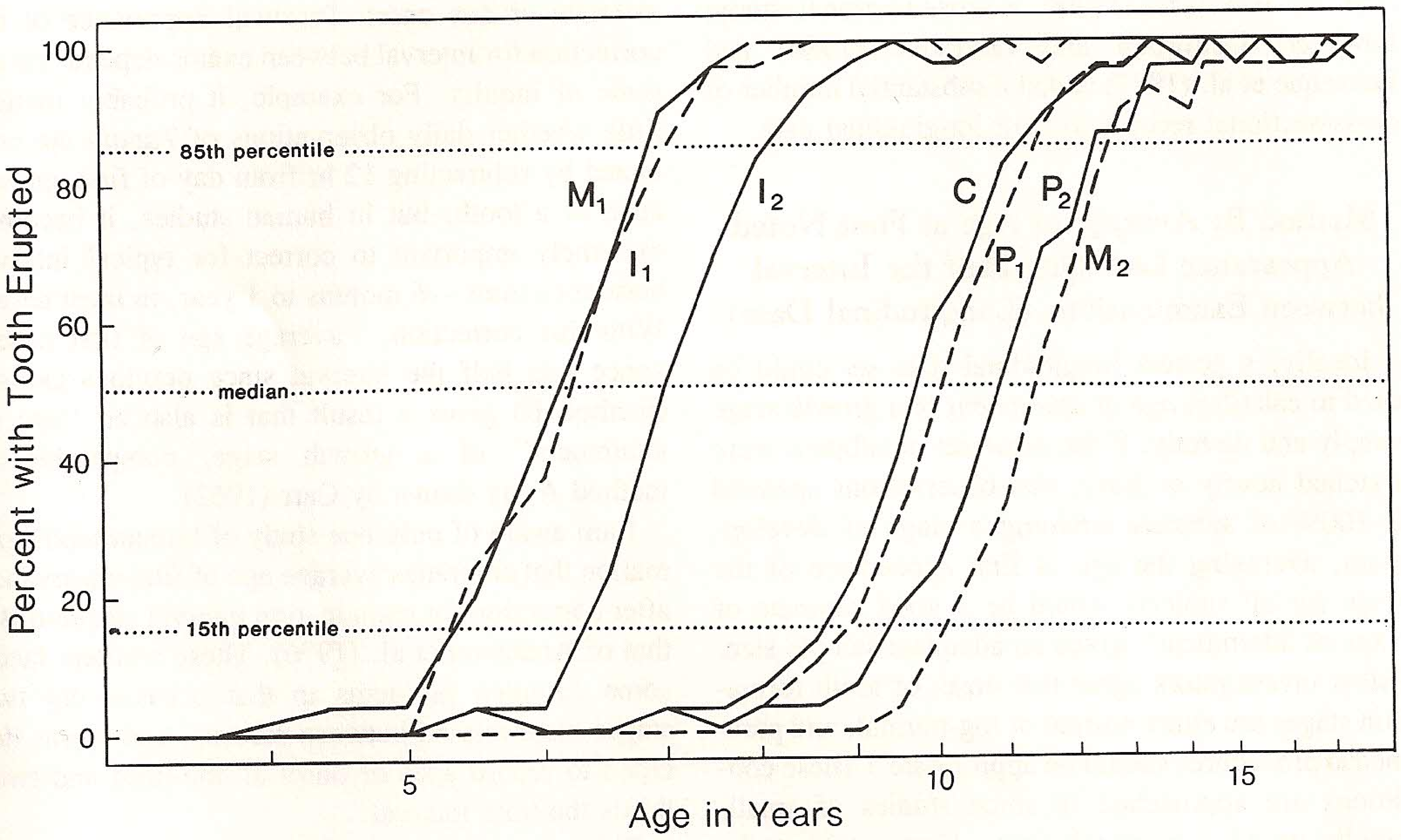

Fig. 4. Example of determining age of attainment of a growth stage using a cumulative distribution function (reprinted from Smith and Garn, 1987:298). Data represent tooth emergence in 2,990 girls from the Ten State Nutritional Survey. The proportion of subjects who have already attained the stage in question is plotted against the midpoint of each age group. Both simple and sophisticated mathematical solutions for the mean or median age of attainment are available. Such methods have been standard practice in studies of tooth emergence for decades, however, they are not universal in tooth formation studies.

growth studies. This historical accident probably accounts for the fact that most chronologies of tooth formation are based on longitudinal data (Table 3).

When observations are very limited (either in cross-sectional or longitudinal data), the age interval in which the growth event occurs may be poorly sampled. If so, resulting data may jump from 0% having attained a stage at one age to 100% at the next available age. In this case, age of attainment of the growth stage may be estimated by the midpoint in time between ages of the oldest subject not having attained the stage and the youngest subject having attained it. More data would be needed to estimate dispersion. These methods are not usually seen in human studies, although limited samples may necessitate this approach in studies of nonhuman primates (e.g., Phillips-Conroy and Jolly, 1988). These several methods (probit analysis, other methods of locating the mean or median in a cumulative distribution function, compromises given small samples) are grouped together here under *cumulative distribution functions* because the basic organization of the data is more important for present purposes than is the sophistication of the solution.

Cumulative distribution functions seem to be the best way of establishing a chronology of tooth formation. First, this method explicitly provides an estimate of *age of attainment* of a growth stage, and I would argue that this is what one expects in a chronology of growth events (see below for chronologies based on other variables). Moreover, most methods of treating cumulative data avoid problems deriving from sample age structure (see Gates, 1966) in contrast to other methods considered below.

The first study to apply these methods to formation data appears to be that of Garn et al. (1958, 1959). Others chronologies obtained from cumulative distribution functions or probit analysis include (Table 3): Fanning (1961); Moorrees et al. (1963a,b); Haavikko (1970); Fanning and Brown (1971); Demirjian and Levesque (1980); and Levesque et al. (1981). Moorrees et al. (1963a) and Fanning and Brown (1971) are based on the same data; the former analyzed by probit analysis using the assumption of log-normality, and the latter analyzed by simple percentiles from cumulative distribution functions. Curves were hand-smoothed in analyses by Demirjian and associates. All these studies are based on longitudinal data, except for Haavikko (1970), a cross-sectional study; however, Demirjian and Levesque (1980) and Levesque et al. (1981) added a substantial number of cross-sectional records to their longitudinal data.

Method B: Average of Age at First Noted Appearance Less One-Half the Interval between Examinations (Longitudinal Data)

Ideally, a perfect longitudinal data set could be used to calculate *age of attainment* of a growth stage simply and directly. If the same set of subjects were watched hourly or daily, and observations spanned 0–100% of subjects attaining a stage of development, averaging the age of first appearance of the stage for all subjects would be a good estimate of ''age of attainment'' given an adequate sample size. (Most investigators agree that onset of tooth formation stages are either normal or log-normal, and parametric procedures should be appropriate.) These conditions are approached in some studies of small, rapidly growing mammals (e.g., Hertenstein et al., 1987), but are not met in human studies. Unfortunately, deviations from this ideal create difficulties. Problems come primarily from three sources: (1) long intervals between examinations, (2) uneven distributions of subject ages, and (3) truncation of studied age groups (i.e., the study sample does not extend from first to 100th percentile of attainment of stages in question).

The length of the interval between examinations creates difficulty because first observance of a growth stage always postdates actual onset. When intervals between exams are long, and when growth stages are few and widely spaced in time, ''postdating'' can amount to months or even years. The simple average of age of first recorded appearance sums over small and large positive errors, as explained by Dahlberg and Menegaz-Bock (1958).

At one time, this method (average age of the first observance) was indeed used to establish chronologies of tooth *emergence* in longitudinal studies. Dahlberg and Menegaz-Bock (1958) demonstrated that such studies gave ages of emergence that were systematically later than those given by cross-sectional studies (which had been analyzed using cumulative distribution functions). These investigators pointed out that the proper correction for the problem of postdated observance was to subtract one-half the length of the interval between examinations from the age at first appearance. This recognizes that actual onset occurred sometime between subject examinations, and the midpoint of the interval is the best estimate of this onset. Practical importance of the correction for interval between exams depends on the scale of inquiry. For example, it probably matters little whether daily observations of *Tupaia* are corrected by subtracting 12 hr from day of first appearance of a tooth, but in human studies, it becomes extremely important to correct for typical interval between exams—6 months to 1 year, in most cases. With this correction, ''average age of first observance less half the interval since previous exam'' (method B) gives a result that is also an ''age of attainment'' of a growth stage, comparable to method A, as shown by Carr (1962).

I am aware of only one study of human tooth formation that computes average age of first observance after correcting for examination interval (method B), that of Anderson et al. (1976). These workers faced some complex problems in that occasionally two stages were missed between records, and it was decided to record ages of onset at one-third and two-thirds the time interval.

This correction solves the problem of ''postdated'' ages, but it cannot correct for problems (2) and (3), those of uneven or truncated sample age distributions. This difficulty also applies to method C, discussed below.

Method C: Mean Age of Subjects in a Stage of Development

Some chronologies of tooth formation are achieved by sorting subjects by stage of development and averaging subject age (Table 3, method C). The resulting statistic, ''age of subjects in a stage,'' is an entirely different variable than ''age of attainment of a stage'' (Goldstein, 1979; Tanner, 1986). Ages associated with being in a stage postdate actual onset of the stage, and this is true whether the study is longitudinal or cross-sectional. Whereas this can be corrected in longitudinal data (method B), no such compensation can be made for cross-sectional data.

''Average age of subjects in a stage'' has some appeal in its appropriateness for demography or forensics, situations in which developmental stage is known and the goal is age prediction. However, results of this method are sensitive to the age structure of the sample (Hayes and Mantel, 1958; Gates, 1966). A good estimate of ''age of subjects in a stage'' depends on presence in the sample of all ages, from the first through the one hundredth percentile of age of attainment of the growth stage, and a relatively flat age distribution (i.e., approximately the same number of subjects in each age interval, see

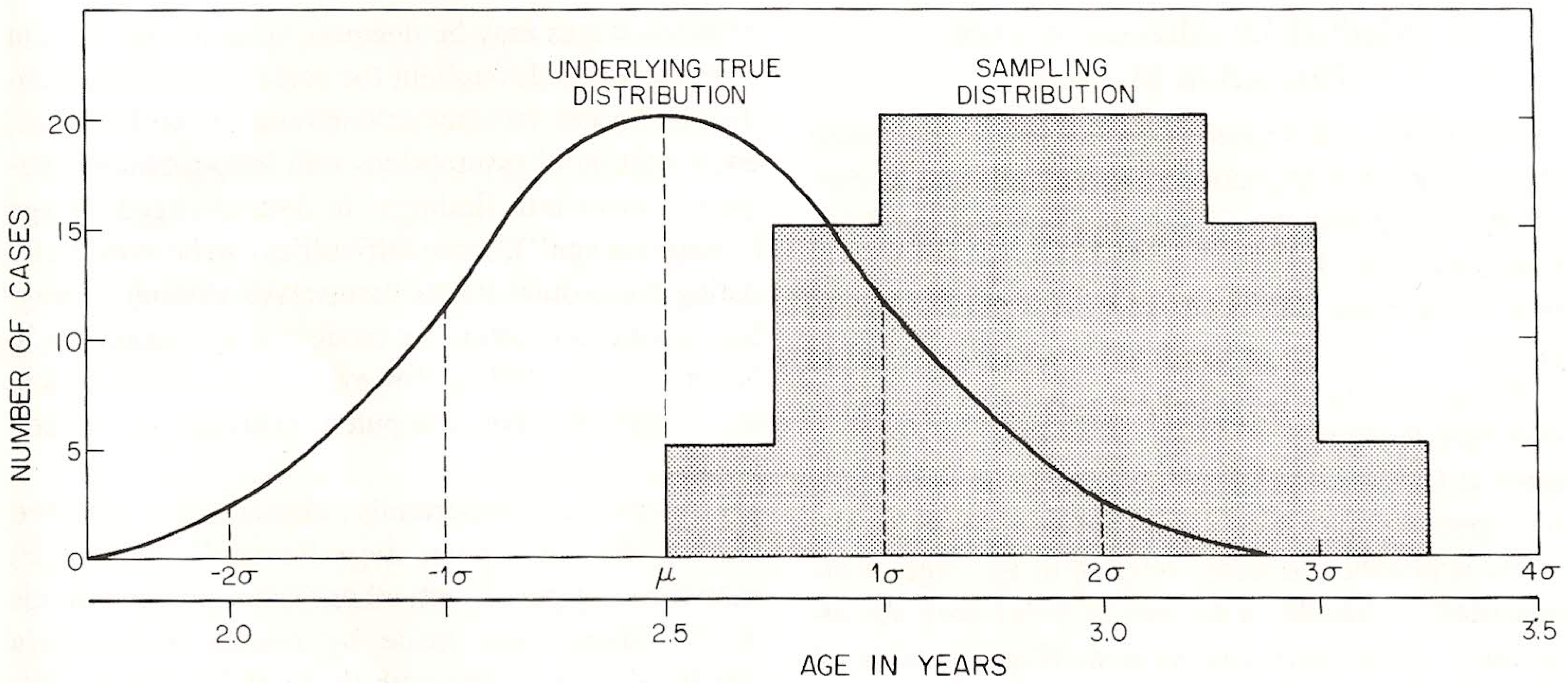

Fig. 5. Hypothetical example to illustrate importance of age structure of a study sample in methods B or C. The smoothed curve models an underlying distribution of true age of attainment of the stage "crown complete" of the first molar (mean of 2.5 years and a standard deviation of 0.25 years). Note that the study sample (shown blocked and shaded) "tails out" at younger ages and is truncated at the true mean. Sample size becomes large only at + 1–2.5σ. At the ages covered by the study sample, only unusually late children have recently completed M1 crowns (most subjects have moved on to subsequent stages); their mean age is much higher than the true age of attainment of the stage.

Goldstein, 1979:68). Unfortunately, neither of these conditions is typical in child growth studies.

Figure 5 attempts to illustrate how the structure of the study sample itself can determine the result when average age of subjects in a stage is computed. In this hypothetical example, as is many actual child growth studies, the study sample is deficient in very young children. Only the tail end of the sampling distribution of the stage of interest has been captured in the sample. In calculating a simple mean age, one can only combine and recombine ages of the children in the sample; thus, answers can never be lower than the minimum age in the sample (2.5 in the case in Fig. 5), no matter what the question. In this case, mean age associated with "crown complete" of M1 describes only subjects at the extreme of the true sampling distribution. This problem occurs in reverse at the high end of the age range when study samples are truncated before the 100th percentile; in this case, the bias is to underestimate age of occurrence. Goldstein (1979:64) points out that even when the complete age range is sampled, the extremes of the maturity scale (complete immaturity and complete maturity) also pose problems in this analysis.

In Figure 5, the children are too old for the study, but the method does not indicate this to the investigator. A cumulative distribution function (method A) would at least indicate that the children were too old for the problem of interest.

To summarize, "average age of subjects in a growth stage" is a different variable than "age of attainment of a growth stage." The former postdates the latter. "Average age of subjects in a stage" is more suited to age prediction. However, its accuracy as a predictor can be compromised by sample design. Truncated and/or highly uneven distributions of subject ages are potential sources of serious bias.

Tooth formation studies that calculated mean age of subjects in a stage were primarily early ones: Gleiser and Hunt (1955), Demisch and Wartmann (1956), Haataja (1965), and Fass (1969), with Trodden (1982) the only recent example. Actually, Fass (1969) describes neither the statistical method nor the number of subjects, their race or sex, or type of sample design (giving only the number of films), but careful reading suggests that this was a semilongitudinal study of patients in the author's pedodontic practice and that the chronology is based on mean and median ages of subjects in developmental stages. The work of Gleiser and Hunt (1955) is based on longitudinal data and covers the first molar only. Demisch and Wartmann (1956) studied the third molar in a cross-sectional sample. Haataja (1965) and Trodden (1982) worked with cross-sectional material. However, Trodden's work is problematic because the author quotes extensively from other investigators (Miles, 1963; Haavikko, 1970; and Demirjian et al., 1973) without attribution.

Method D: Alternative Age Prediction Methods

Age prediction seems to be the least represented purpose in tooth formation studies, and there is currently no chronology or statistical method available that is ideal for this purpose. I include two "alternative" strategies that were suggested by Goldstein (1979).

The problem of *age prediction* has some complexities (see Goldstein, 1979:62–69). One approach is method C, although its results can be compromised by aspects of sampling design. Method A is not directly applicable because, relative to an "age of attainment" schedule, a subject is *in-between the attainment of one stage and the next.* Thus, to assign an age to a subject showing a particular stage, Goldstein (1979:64) points out that it would be appropriate to assign an age that is the midpoint between mean age of attainment of the subject's current stage and the subsequent one (given equal variances). Age prediction tables calculated in this way appear here (below) for the first time, to my knowledge.

Goldstein's (1979) second suggestion for age prediction is to calculate regressions of age on linearized summary scores of tooth formation. Something similar to this appears to have been tried only by Leinonen et al. (1972). In this first attempt, however, it was not clear that the nonlinear model chosen had a sufficient fit to the data, and the model had difficulty as subjects approached complete maturity. Further work might be able to improve on this method.

Method E: Mean Formation Stage for Subject Age Group

Methods B and C encounter problems stemming from averaging of subject ages, so why not avoid this by averaging stages instead? Several studies computed the mean *stage* for age groups of children: Nolla (1952, 1960), Nanda and Chawla (1966), and Liliequist and Lundberg (1971; note that the table of values needed to apply the Liliequist and Lundberg system actually appears in Crossner and Mansfeld, 1983).

In most of these cases, the authors meant to construct a "maturity scale" (see method F), a device for estimating whether a child is advanced or delayed compared to normal development. However, some technical problems are associated with averaging tooth formation stages as done in the above studies. These stages are ordinal measures usually designated by whole integers. They are thus, by definition, not normally distributed. Furthermore, the time lapses between stages may be unequal, so that units are not of equal value throughout the scale. Therefore, standard mean and variance calculations are problematic, and violation of assumptions will introduce some degree of error into findings. In data arranged by age ("stage for age"), some difficulties can be avoided by listing the ordinal stages themselves without averaging, giving percentiles or mode per age group (as in Nyström et al., 1977). However, most such studies in the literature have computed averages of ranked stages.

Perhaps more importantly, chronologies obtained from studies of "mean stage for age" (method E) cannot be compared with other studies using methods A–D. Comparisons made by Nanda and Chawla (1966) of their results with those of Moorrees et al. (1963a) are certainly erroneous. Comparisons even with other studies of mean stage per age depend on comparable division of age intervals and definition of stages. Both Nanda and Chawla (1966) and Liliequist and Lundberg (1971) grouped ages to 1-year intervals from half-year points (e.g., 2.5–3.5), but their stages are differently defined. Nolla (1952, 1960) interpolated readings of stages from interpolated year points on each child's graph, and it is difficult to imagine what effects on the data were produced by this double interpolation.

Difficulties are compounded if such scales are used for age prediction rather than maturity assessment. Thus, Nolla (1960) had computed *mean stage for age,* which is appropriate for assessing maturity. However, she was also interested in the converse, at what *age* is a stage seen—mean age for stage. Apparently, ages given for "completion of calcification" by Nolla (1960:265, Table VI) were obtained by secondarily solving curves of *mean stage for age* for *age given stage,* a procedure analogous to solving a regression equation "backwards" for the independent variable. This appears to be the case also in the study of Crossner and Mansfeld (1983). These investigators used tabular values calculated as mean stage per age to predict age for a group of adopted children of unknown age, thereby, reversing dependent and independent variables.

Method F: Maturity Scales

Maturity scales are designed to circumvent the problems associated with calculation of mean age or mean stage (methods B, C, and E). As in method E, maturity scales are computed as central tendency in stage for age; however, the ordinal scale of growth stages may be first transformed to scores that are linearized with respect to chronological time (Wolanski, 1966; Healy and Goldstein, 1976; Goldstein, 1979), and the use of summary scores over a number of teeth results in a measure that more closely approximates a continuous variable. Tooth formation maturity scales parallel those used to estimate maturity in wrist ossification (Tanner et al., 1962); the latter are sometimes weighted because some bones give more information than others, but this has not proved to be necessary in the case of teeth. Maturity scales for tooth formation have been published by Wolanski (1966), on the same data used by both Moorrees et al. (1963a) and Fanning and Brown (1971) and by Demirjian et al. (1973) and Demirjian and Goldstein (1976). The system of Demirjian and associates has been applied to other European populations by Prahl-Andersen and Roede (1979) and by Nyström et al. (1986).

Maturity scales are designed for a clinical situation in which maturity is assessed for subjects of *known age* and, for this purpose, they seem ideal. However, they are not designed for anthropological or forensic contexts for two reasons. First, these methods are designed for use with summed scores for a particular set of teeth, and no allowance is made for missing data. Rather, the system must be separately calibrated for each set of teeth (systems have been published using four, five, seven, and ten teeth, respectively). Second, as in the case of Nolla (1960), in calculating the relation of scores to age, deviation has been minimized in the direction of *scores,* not age. Thus, solving these relationships secondarily for unknown age may not give the best possible age prediction.

Method G: Pictorial Charts and Atlases

Although it is not possible to categorize pictorial or descriptive chronologies in a strict sense, they are most unlikely to be ''age of attainment'' chronologies, because a transition itself is fleeting and is never observed (Tanner, 1986). Pictorial charts and atlases should be most comparable to statistical studies using method C (mean age for stage) or E (mean stage for age), depending on whether illustrations are chosen to represent an age or a stage of development. They might be used for either age prediction or maturity assessment. However, some atlases are primarily intended as anatomical guides rather than systems of age assessment (e.g., van der Linden and Duterloo, 1976).

The best known of the pictorial charts, that of Schour and Massler (1941; see also Ubelaker, 1978) gives 18 developmental stages for the first 15 years of life. Only one test of this chart seems to be available, by Brauer and Bahador (1942), on 315 Iowa dental and hospital patients. Using the chart, cases could be associated with the picture given for the appropriate year 67% of the time. Errors were not symmetrical (more children were judged ''advanced'' than ''retarded''), and investigators reported difficulties reconciling anterior versus posterior tooth development using the chart. In a test on American Indian material of unknown age, Merchant and Ubelaker (1977) point out systematic differences between ages obtained using the Schour and Massler chart versus standards in Moorrees et al. (1963a,b).

Method H: Miscellaneous

Under the heading Miscellaneous are noted studies of unknown or mixed methodologies. Methods underlying the chart of mandibular tooth formation of Prahl-Anderson and van der Linden (1972) were not described. In addition, even recent textbooks may contain charts of times of tooth formation with no description of sources of data or methods of analysis (e.g., Garino, 1956; van der Linden, 1983). In a historical sense, these are ''orphan'' chronologies.

Gustafson and Koch (1974) took a unique approach. These workers collected all available studies, making no distinctions between those employing histology or radiology, or between methods of measurement or computation, and computed grand means of all values. The resulting chart is meant to be used to assign dental age to subjects. Because this does average over the most extreme values, it would be expected that this method would perform better than the worst of studies, but not as well as the best. I will return to the matter of performance below.

DECIDUOUS TOOTH FORMATION

The studies discussed above primarily concern the permanent teeth, but the discussion applies in principle to deciduous teeth as well. However, deciduous tooth chronologies have additional historical complexities and a more extensive literature. An excellent review of this subject by Lunt and Law (1974) takes the reader step by step through the maze of studies; only a few turnings are mentioned here. Part of the problem is that deciduous tooth formation requires study of both prenatal and postnatal subjects. I have attempted to summarize what seem to be the best available data for several developmental parameters of interest in Tables 4 and 5.

The embryology of tooth development has a long history of descriptive studies. It is clear that absolute variation in prenatal tooth formation is so small that even descriptive works of the nineteenth century

TABLE 4. Available Values for Prenatal Formation of Deciduous Teeth

Tooth	Age of attainment schedule: Beginning calcification (weeks postfertilization) Sunderland et al., 1987		Stage for age schedule: Amount of crown formed at birth	
	50th %ile	Range[a]	Kronfeld and Schour, 1939[b]	Kraus and Jordan, 1963
di1	15	13–17	3/5	—
di2	17	14–19	3/5	—
dc	19	17–20	1/3	—
dm1	16	14–17	Cusps united	Occlusal united
dm2	19	18–20	Cusp tips isolated	Cusps united

[a]Earliest age at which mineralization is seen through age at which 100% of the sample shows initial mineralization.
[b]These values are based on "tooth ring analysis"; they remain almost the only non-pictorial data available for deciduous incisors.

managed to estimate events to within 3 weeks of modern values when data are recalibrated by modern crown-rump to age conversions (Lunt and Law, 1974: 604).

It is difficult to reconstruct the sources of data presented in the early work of Kronfeld, Schour, and Massler. Times of beginning calcification for deciduous teeth given in Kronfeld (1935a), as in Table 1, are of obscure origin. Ages given for beginning of mineralization and for amount of crown formed at birth, in Kronfeld and Schour (1939) and Schour and Massler (1940), were based on the so-called "tooth ring analysis" of Schour (1936), Schour and Poncher (1937), and Schour and Kronfeld (1938), although these sources are rarely credited. As Lunt and Law (1974) reconstruct the history of events, these data apparently come from very few subjects.

A modern period of study began with the work of Bertram Kraus (1959). Kraus collected hundreds of fetal specimens, estimating age of the material by a conversion from crown–rump length (as is standard practice in embryology). Although the largest sample came from American whites, Kraus also obtained some material on Japanese, American Indians, and American blacks. Kraus studied both morphology and chronology of crown formation; and detailed discussion of findings appears in Kraus and Jordan (1963), *The Human Dentition Before Birth*.

A recent study by Sunderland et al. (1987) has the advantage of material of known maternal history and gestation age, although it must be realized that maternal histories are not invariably reliable (see Kuhns et al., 1972). Sample size is substantial (N = 137), although more limited than in Kraus's work. Sunderland et al. (1987) provide a range of values for initiation of deciduous tooth mineralization, including youngest ages at which mineralization is seen and ages at which 50% and 100% of the subjects show mineralization for each tooth, the best form in which such data can be presented (method A). Table 4 compares values for prenatal tooth formation between Sunderland et al. (1987) and older studies.

As is the case for permanent tooth formation, some pieces of the puzzle are surprisingly difficult to come by. No numerical assessment of the state of formation of the human dentition at birth could be located. Kraus and Jordan (1963) mentioned typical values for deciduous molars only. Boller (1964) provided a condensed photographic atlas showing dissections and radiographs for each month gestation. Kuhns et al. (1972) discussed some radiologic findings in newborns. However, in terms of values to print in a table, one is left with those of Kronfeld and Schour (1939), values based on tooth ring analysis, or texts containing orphan chronologies that disagree (cf. Churchill, 1932; Garino, 1956).

For postnatal formation of deciduous teeth, it is still necessary to use the descriptive studies of the 1930s in several instances despite the difficulties with these sources (Table 5). Age of completion of crowns and roots of deciduous incisors is problematic. Values given by Kronfeld and Schour (1939) for crown completion differ from those of Kronfeld (1935a), and it is not clear whether they are based on observations of the autopsied infant sample or on tooth ring analysis. Those given for "root completed" are similar to those of Kronfeld (1935a) and presumably stem from the original infant sample.

The situation is far better for deciduous canines and molars because Fanning (1961) and Moorrees et

TABLE 5. Ages for Postnatal Development of Mandibular Deciduous Teeth Expressed in Decimal Years

Mandibular tooth	Age crown completed (yr): Moorrees et al., 1963b[a] Mean	Age crown completed (yr): Moorrees et al., 1963b[a] −2s.d.–+2s.d.	Age crown completed (yr): Kronfeld and Schour, 1939[b]	Age root completed (yr): Moorrees et al., 1963b[a] Mean	Age root completed (yr): Moorrees et al., 1963b[a] −2s.d.–+2s.d.	Age root completed (yr): Kronfeld and Schour, 1939[b]
di1	—	—	0.1–0.2	—	—	1.5
di2	—	—	0.2	—	—	1.5–2.0
dc	—	—	0.7	—	—	3.25
Males	0.7	0.4–1.0	—	3.1	2.4–3.8	—
Females	0.7	0.4–1.0	—	3.0	2.3–3.8	—
dm1	—	—	0.5	—	—	2.25
Males	0.4	0.2–0.7	—	2.0	1.5–2.5	—
Females	0.3	0.1–0.5	—	1.8	1.3–2.3	—
dm2	—	—	0.8–0.9	—	—	3.0
Males	0.7	0.4–1.0	—	3.1	2.4–3.9	—
Females	0.7	0.4–1.0	—	2.8	2.2–3.6	—

[a]These data comprise an age of attainment schedule.
[b]The basis of these values may be some combination of "tooth ring analysis" and observation of an infant sample; no other values could be located for deciduous incisors in studies with documented methods.

al. (1963b) studied age of attainment of radiographic formation stages for these teeth. In the latter, data for 246 normal children were analyzed using probit analysis. Table 5 includes values from both Moorrees et al. (1963b) and Kronfeld and Schour (1939). In each case for which one can make the comparison, the Kronfeld and Schour values are relatively late, although within 95% confidence limits provided by Moorrees et al. (1963b). In addition to schedules of tooth formation, it should be mentioned that schedules are also available for resorption stages and exfoliation of deciduous teeth (Fanning, 1961; Moorrees et al., 1963b).

COMPARISON OF STUDIES

There have been many attempts to define a chronology of human dental development based on different variables. Patterns in the published data suggest that methodological sources of variation have indeed had a substantial effect. Results can be shown to vary systematically (1) with age structure of the study sample, and (2) by method of analysis.

Age Structure of the Study Sample

Table 6 shows age of completion of mandibular M1 crown given in a range of all avilable studies. If indeed Moorrees et al. (1963a) are correct that crown completion occurs at ~2 years, this finding was out of reach for the other studies because their youngest sampled age groups were above 2 years of age. Reported age of crown completion of M1 is highly correlated ($r = 0.89$) with the age of the youngest child in the study. This correlation suggests that "tailing off" and truncation of samples at young ages has indeed affected results (as illustrated in Fig. 5). Such poor sampling at younger ages must also increase error of estimates for all studies, regardless of method of computation.

Published values for M1 for American Indian and Inuit subjects in Table 6 (Trodden, 1982) appear to be quite late in comparison with Europeans, and this is true for other stages of other teeth as well. This is puzzling, given that in these populations teeth erupt earlier than in whites (Dahlberg and Menegaz-Bock, 1957; Mayhall et al., 1978) but is understandable, given that in Trodden's (1982) study, values are simple averages, ages given are "postdated," and sample size is small and sharply varied over age groups.

Method of Analysis

Figure 6 illustrates the distribution of ages given for completion of crowns of mandibular teeth. Females from European-derived samples are used to minimize effects attributable to race or sex. It can be seen in Figure 6 that the absolute range of ages across studies *decreases* with the later forming teeth, de-

TABLE 6. Evidence of Sampling Effects: Correlation of r = 0.89 between Age of Youngest Child in the Sample and Age Reported for Completion of M_1 Crown

Study	Age of youngest child in study sample (yr)	Age given for completion of M_1 crown (yr)
Moorrees et al., 1963a		
Boys	0.1 (birth)	2.2
Girls	0.1 (birth)	2.15
Fass, 1969		
Combined sample	2.0	2.9
Trodden, 1982		
Inuit boys	2.25[a]	3.2
Inuit girls	2.25[a]	3.2
Indian boys	2.43	3.1
Indian girls	2.75[a]	3.1
Haavikko, 1970		
Boys	2.5	3.5
Girls	2.5	3.5
Anderson et al., 1976		
Boys	3.0	3.7
Nolla 1952, 1960		
Boys	3.4	4.0
Girls	2.1	3.8

[a]Midpoint of youngest age interval used if minimum age is not given.

spite the general fact that variation within and between populations should increase with age for any developmental parameter. This finding is so contrary to expectations grounded in biology that it in itself suggests the operation of methodological artifacts.

When studies are divided into those that use cumulative functions (Fig. 6, white) versus those that compute means of some sort (black), it is evident that the latter give systematically later ages than the former. In a study with numerous methodological problems, Nolla (1960) gives the most extreme ages throughout. The placement of Anderson et al. (1976) with *white block* studies at older ages suggests that their unique method has corrected for "postdating." However, the similarity of their results to *black block* studies at early ages should warn that sample diminution and truncation may have affected results. It should be noted that no studies that use distribution functions are available for completion of I1 and I2 crowns; trends across the data suggest that the few ages available are late.

In Figure 6 most studies using similar methods give similar results. Some exceptions, H at the first molar and D at the canine, may also represent sampling effects. In both cases, a lack of sufficient numbers of young children resulted in partial, truncated distribution functions. In addition, there is also the problem that several different scoring systems for stage of development are represented in Figure 6; furthermore, even studies within Method A actually differ somewhat in treatment of data (including hand-smoothed curves verus raw percentiles or probit analysis with log-transformations). All these sources of variation must be controlled before discrepancies between studies can be attributed to population differences. Population differences can only be established by studies that share methodologies, but to date, few studies have used the same method.

RECOMMENDED CHRONOLOGIES

Recommended sources for deciduous tooth development are presented in Tables 4 and 5. It should be clear from the review above that method A is preferred for generating statistical solutions for schedules of age of attainment of growth stages. Thus, any of the studies in Table 3 (subheading A) can be recommended for this purpose. The studies conducted by Moorrees et al. (1963a) as well by Fanning and Brown (1971) have several advantages. The study is based on semilongitudinal records of 345 normal

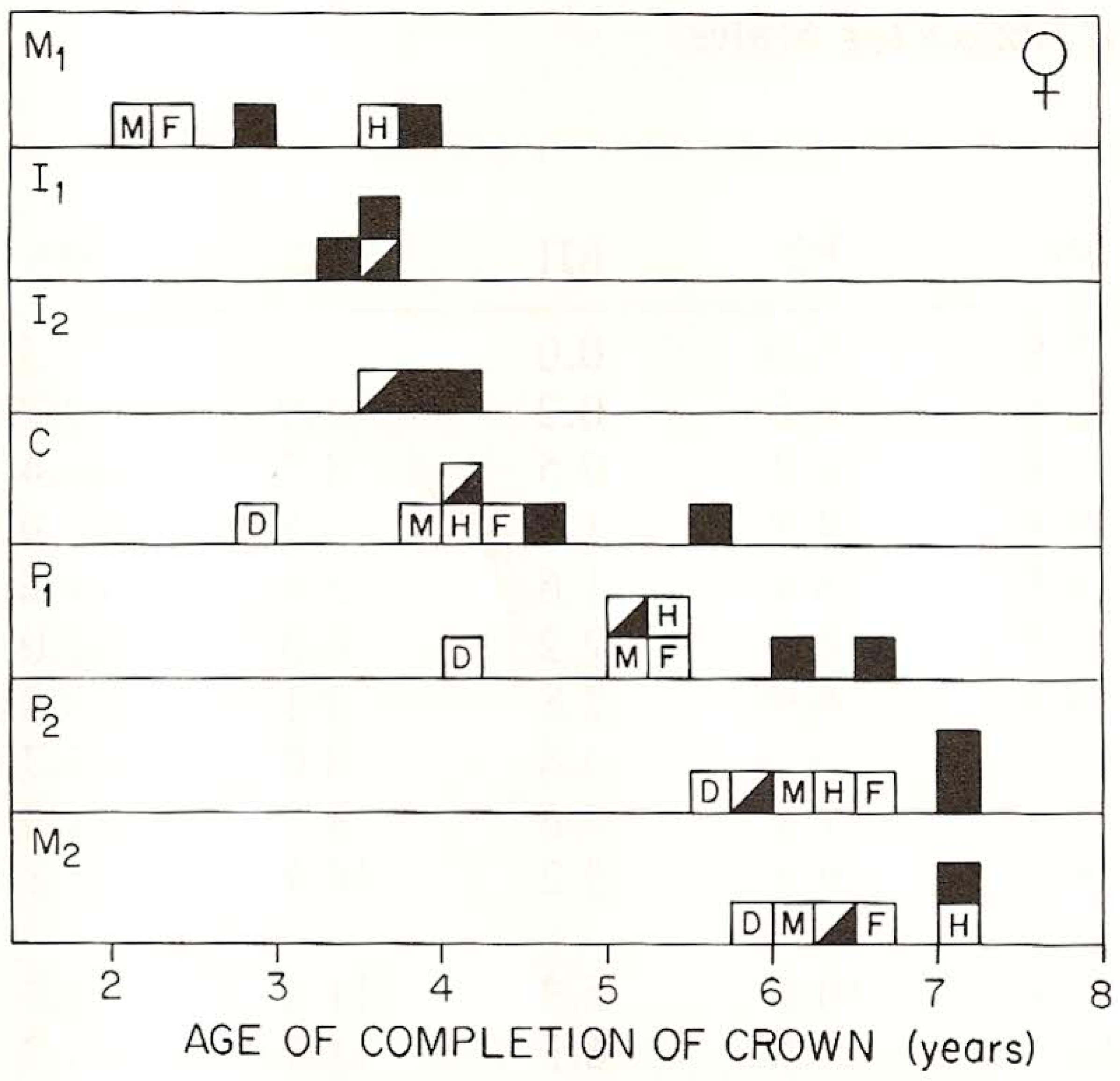

Fig. 6. Distribution of ages of completion of crown given in studies of European-derived samples. White blocks represent studies that use method A (cumulated data): M = Moorrees et al. (1963a); F = Fanning and Brown (1971); H = Haavikko (1970); D = Demirjian and Levesque (1980). Black blocks representing methods C (mean age) and E (mean stage) include Fass (1969) and Nolla (1960); Nolla is consistently the most extreme. Values from Anderson et al. (1976) appear half black and half white because they are partially corrected by a unique method (B, see text). Only Fass (1969) gave mixed sex data; all other values are for females only. Note that studies that compute means (black) give consistently later ages that those using distribution functions (white).

children from Massachusetts and Ohio. Of studies reviewed here, it appears to be the only one with a sample that extends to birth. It also appears that the sample is relatively even over age groups, judging from Fanning and Brown (1971). Moreover, both analyses of these data have taken into account deviations from normality common in growth data. Thus, data from Moorrees et al. (1963a) have been used here to construct to different types of tooth formation chronologies appearing in Tables 7–10; in these tables, stages of tooth formation referred to are those shown in Figure 3. In all cases, separate schedules are needed for males and females; it is well established that female dental development is ahead of males in the permanent dentition, although results have been less clear for the deciduous dentition (see Adler, 1959; see also review in Demirjian, 1986).

Age of Attainment of Developmental Stages

Tables 7 and 8 present *age of attainment* chronologies for stages of tooth development for males and females, respectively. In each case, mean age of attainment has been interpolated from the graphic chart of Moorrees et al. (1963a), and this work should be consulted for accompanying variances. It is emphasized that these tables are in answer to the question: At what age does the event usually happen?—that is, At what age does the transition into the stage occur? Such "attainment" schedules give ages associated with developmental stages that are earlier than ages produced by other schedules such as stage for age or age for stage schedules.

Age Prediction

By contrast, Tables 9 and 10 are designed for age prediction based on stage of development. Thus, these tables are appropriate when the question is: What dental age should be assigned to this child's development? or How old is this individual? These tables employ the same basic data as Tables 7 and 8 above, but data have been reworked with an important difference: the age opposite a stage represents the midpoint between age of appearance of that stage and the next. This type of schedule was suggested in Goldstein (1979), but it appears here for the first time. To assign a dental age, each tooth is assessed independently, and the mean of all available ages is assigned as the dental age. Such a flexible system is needed for age prediction because material is often fragmentary in forensic and archaeological contexts.

One key difference between the two types of tables can be noted in the last lines, in the treatment of the stage "Ac," apex complete. An age can be given for this terminal stage in the attainment scales of Tables 7 and 8. However, note that in Tables 9 and 10, this line contains only missing data. This reflects the fact that no age can be assigned in age prediction when complete maturity is reached, because the subject has past this transition by an unknown amount of time.

The system has some limitations; namely, it lacks data for early stages of incisors, and it is limited to mandibular teeth. Moorrees et al. (1963a) give some data for maxillary incisors, but data for maxillary teeth are rare in all studies. Anderson et al. (1976) is probably the most complete in this regard; however, this is an "age of attainment" schedule.

Maturity Assessment

In a clinical situation in which the goal is to assess the child's overall maturity and his difference from a normal reference group, maturity scales (Table 3, method F) are appropriate. Those of Demirjian and associates are well known. Conceivably, age prediction (Tables 7 and 8) could also provide a general

TABLE 7. Mean Age of Attainment of Developmental Stages for Males (Permanent Mandibular Teeth)[a,b]

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.5	1.8	3.0	0.0	3.7	9.3
Cco	—	—	0.7	2.4	3.5	0.2	3.9	9.7
Coc	—	—	1.4	2.9	4.2	0.5	4.7	10.4
Cr½	—	—	2.1	3.7	4.7	1.1	5.1	10.9
Cr¾	—	—	2.9	4.5	5.4	1.6	5.6	11.6
Crc	—	—	4.0	5.2	6.3	2.2	6.5	12.0
Ri	—	—	4.8	5.9	6.9	2.8	7.1	12.8
Rcl	—	—	—	—	—	3.6	8.0	13.7
R¼	—	5.4	5.7	6.9	7.7	4.6	9.4	14.5
R½	5.3	6.3	8.0	8.6	9.5	5.2	10.1	15.1
R⅔	5.9	6.9	—	—	—	—	—	—
R¾	6.5	7.4	9.6	9.9	10.8	5.9	11.1	16.3
Rc	7.0	8.0	10.2	10.5	11.6	6.3	11.7	16.7
A½	7.7	8.6	11.8	11.9	12.7	7.6	12.9	18.2
Ac	8.1	9.3	13.0	13.4	14.3	9.4	14.9	20.0

[a]Values interpolated from Moorrees et al. (1963a); all ages in years.
[b]Values for molar roots are interpolated from charts for the distal root in this and following tables (Tables 7–10).

TABLE 8. Mean Age of Attainment of Developmental Stages for Females (Permanent Mandibular Teeth)[a]

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.5	1.8	3.0	0.0	3.5	9.6
Cco	—	—	0.8	2.2	3.6	0.3	3.7	10.1
Coc	—	—	1.2	2.9	4.2	0.8	4.2	10.7
Cr½	—	—	2.0	3.6	4.8	1.0	4.8	11.3
Cr¾	—	—	3.0	4.3	5.4	1.5	5.4	11.7
Crc	—	—	4.0	5.1	6.2	2.2	6.2	12.3
Ri	—	—	4.7	5.8	6.8	2.7	7.0	12.9
Rcl	—	—	—	—	—	3.5	7.7	13.5
R¼	4.5	4.7	5.3	6.5	7.5	4.5	9.2	14.8
R½	5.1	5.2	7.1	8.2	8.8	5.1	9.8	15.7
R⅔	5.6	5.9	—	—	—	—	—	—
R¾	6.1	6.4	8.3	9.2	10.0	5.7	10.7	16.6
Rc	6.6	7.6	8.9	9.9	10.6	6.0	11.2	17.2
A½	7.4	8.1	9.9	11.1	12.0	7.0	12.5	18.3
Ac	7.7	8.5	11.3	12.2	13.7	8.7	14.6	20.7

[a]Values interpolated from Moorrees et al. (1963a); all ages in years.

assessment by comparing predicted age with the child's chronological age.

Dental Age

Dental age is meant to convey the age best associated with a developmental stage in a normal reference population. The term is not specific to method, and dental ages can be assigned either in age prediction or in maturity assessment. Age prediction and maturity assessment have similar purposes, although they differ in terms of the definition of dependent and independent variables. The former is straightforward in that the dental age is the predicted age. (The problem of variability and confidence estimates for age predictions is considered below.) Using a maturity scale, it is possible to take a subject's summary score

TABLE 9. Values for Predicting Age from Stages of Permanent Mandibular Tooth Formation—Males[a]

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.6	2.1	3.2	0.1	3.8	9.5
Cco	—	—	1.0	2.6	3.9	0.4	4.3	10.0
Coc	—	—	1.7	3.3	4.5	0.8	4.9	10.6
Cr½	—	—	2.5	4.1	5.0	1.3	5.4	11.3
Cr¾	—	—	3.4	4.9	5.8	1.9	6.1	11.8
Crc	—	—	4.4	5.6	6.6	2.5	6.8	12.4
Ri	—	—	5.2	6.4	7.3	3.2	7.6	13.2
Rcl	—	—	—	—	—	4.1	8.7	14.1
R¼	—	5.8	6.9	7.8	8.6	4.9	9.8	14.8
R½	5.6	6.6	8.8	9.3	10.1	5.5	10.6	15.6
R⅔	6.2	7.2	—	—	—	—	—	—
R¾	6.7	7.7	9.9	10.2	11.2	6.1	11.4	16.4
Rc	7.3	8.3	11.0	11.2	12.2	7.0	12.3	17.5
A½	7.9	8.9	12.4	12.7	13.5	8.5	13.9	19.1
Ac	—	—	—	—	—	—	—	—

[a]Values calculated from data of Moorrees et al. (1963a); all ages in years.

TABLE 10. Values for Predicting Age from Stages of Permanent Mandibular Tooth Formation—Females[a]

Developmental stage	I1	I2	C	P1	P2	M1	M2	M3
Ci	—	—	0.6	2.0	3.3	0.2	3.6	9.9
Cco	—	—	1.0	2.5	3.9	0.5	4.0	10.4
Coc	—	—	1.6	3.2	4.5	0.9	4.5	11.0
Cr½	—	—	2.5	4.0	5.1	1.3	5.1	11.5
Cr¾	—	—	3.5	4.7	5.8	1.8	5.8	12.0
Crc	—	—	4.3	5.4	6.5	2.4	6.6	12.6
Ri	—	—	5.0	6.1	7.2	3.1	7.3	13.2
Rcl	—	—	—	—	—	4.0	8.4	14.1
R¼	4.8	5.0	6.2	7.4	8.2	4.8	9.5	15.2
R½	5.4	5.6	7.7	8.7	9.4	5.4	10.3	16.2
R⅔	5.9	6.2	—	—	—	—	—	—
R¾	6.4	7.0	8.6	9.6	10.3	5.8	11.0	16.9
Rc	7.0	7.9	9.4	10.5	11.3	6.5	11.8	17.7
A½	7.5	8.3	10.6	11.6	12.8	7.9	13.5	19.5
Ac	—	—	—	—	—	—	—	—

[a]Values calculated from data of Moorrees et al. (1963a); all ages in years.

and quote the chronological age at which this would be the 50th percentile as the dental age (as recommended in Demirjian et al., 1973). Variances are not directly available however, because the system is calculated with age as the independent variable. If age prediction is the goal, Goldstein (1979) suggests it would be better to use a system designed specifically for that purpose.

TESTS OF AGE PREDICTION

Several studies have made partial trials of systems of dental age assignment using children of known age, although some do not report actual differences in predicted versus actual ages (e.g., Haavikko, 1974). Anderson et al. (1976) and Gustafson and Koch (1974) provide information on some test subjects aged by their systems; both studies obtain dental ages within a few months of actual ages. Crossner and Mansfeld (1983) compare age predictions using the system of Liliequist and Lundberg (1971) with that of Gustafson and Koch (1974) for 44 children adopted into Sweden from countries in Asia and South America. They find that ages from the two systems agree within two months in 40% of cases and disagree by 3–6 months in 60% of cases. Oddly, no comments are made as to which system performed better, and it seems likely that accuracy was judged after averaging results from both systems. In any case, they report that 70% of the estimates of dental age fall within ±3 months of the true age, and discrepancies are no more than 6 months in the subset of 23 children with known age (age ranged from 2.5 to 11 years).

This degree of accuracy seems remarkable given the extreme heterogeneity of the sample in addition to statistical problems with these systems of assessment. Crossner and Mansfeld note that the system based on Swedish children (Liliequist and Lundberg, 1971) seemed to work as well on children from South America or Asia as on Swedish children. This even more remarkable statement may attest to a lack of population differences between children, but more likely it indicates a lack of precision in the system itself.

A more rigorous test appears in Hagg and Matsson (1985). These workers compared methods of Liliequist and Lundberg (1971), Gustafson and Koch (1974), and Demirjian et al. (1973) for accuracy in age prediction for 150 Swedish children aged 3.5–12.5 years, with each case assessed independently by two examiners. The method of Liliequist and Lundberg (1971) systematically underestimated age and had the lowest overall accuracy, despite the fact that it represents standards from Swedish children. That of Gustafson and Koch (1974) was most difficult to replicate between examiners; its age estimates were poor for females, although acceptable for males. Of the three, the maturity scale of Demirjian et al. (1973) based on French Canadian subjects gave the most accurate age predictions. As should be expected, absolute error varied with the age of the subject. Standard deviations of the difference between dental and chronological age were ~10% of age: 0.65 years for the youngest age group (mean age 6.5), 0.93 years for the middle group (mean age 8.7), and 1.02 for the older group (mean age 1.07). Thus, subject age could be estimated to within 15–25 months with 95% confidence.

It is interesting to note that none of the above systems is ideally suited to age prediction, although all can be forced to this purpose. It appears that several systems based on averages over a number of teeth can estimate age to within 1 year for young children, and this may include children of varying populations. Development of the dentition may be such a good estimator of age that a variety of methods work to some extent. However, it would be valuable to know the limits of accuracy based on the best possible system. In the literature, "misses" are ascribed to dental variation or population differences (see Brauer and Bahador, 1942), although some portion of these "misses" might as well be due to methodological difficulties.

Tables 11 and 12 present results for a preliminary trial of the system of age prediction presented above in Tables 9 and 10. The four Anglo-Saxon Canadian children in the test were chosen because they were not a part of the sample used to construct the chronology itself (which is based on American children from Massachusetts and Ohio); moreover, their stages of tooth formation were rated and published independently by Anderson et al. (1976), in a test of their own system.

As is evident in Table 12, dental age can give remarkably accurate assessments of chronological age. When schedules for the correct sex are applied, dental ages differ from chronological age by 0.0, 0.1, 0.2, and 0.1 years for four children, who range in age from 4.0 to 10.0 years. The Moorrees et al. (1963a) standards (modified as in Tables 9 and 10) age these children more accurately than does the system developed on their own sample in Anderson et al. (1976). This tendency for the Anderson et al. (1976) system to underestimate age should be attributable to the fact that it is an age of attainment schedule (method B).

In juvenile skeletal material, age prediction is often complicated by unknown sex. In this case, it would be appropriate to average dental age estimates based on males and females (Tables 9 and 10). In this case, dental ages differ from chronological ages by 0.1, 0.2, 0.1, and 0.2 years. Even in the worst case, that in which the wrong-sex schedule is used, misses were only ~0.1–0.5 year. Discrepancies due to sex should be small to moderate at young ages, but larger at older ages, with most of the differences appearing in ages assigned to root formation stages of the canine and second incisor. One clue to sex of child may appear in values of CV of dental age, these may tend to be increased when wrong-sex schedules are used, although clearly this is not always the case.

The overall success of age prediction is certainly

TABLE 11. Dental Ages Assigned to Four Canadian Children of Known Age, Using Age Prediction Tables 9 and 10[a]

Subject:true age schedule	I1	I2	C	P1	P2	M1	M2	M3
	Stage of mandibular tooth formation and dental age							
A. Male: 5.0	R¼	Ri	Crc	Crc	Cr½	R¼	Coc	—
Correct sex	—	—	4.4	5.6	5.0	4.9	4.9	—
Incorrect sex	—	—	4.3	5.4	5.1	4.8	4.5	—
B. Male: 10.0	Ac	A½	R¾	R¾	R¾	Ac	R½	Ci
Correct sex	—	8.9	9.9	10.2	11.2	—	10.6	9.5
Incorrect sex	—	8.3	8.6	9.6	10.3	—	10.3	9.9
C. Female: 4.3	Ri	Crc	Crc	Cr½	Cco	R¼	Ci	—
Correct sex	—	—	4.3	4.0	3.9	4.8	3.6	—
Incorrect sex	—	—	4.4	4.1	3.9	4.9	3.8	—
D. Female: 7.0	A½	R¾	R½	Ri	Ri	Rc	Crc	—
Correct sex	7.5	7.0	7.7	6.1	7.2	6.5	6.6	—
Incorrect sex	7.9	7.7	8.8	6.4	7.3	7.0	6.8	—

[a]Cases were scored independently by Anderson et al. (1976); all ages in years.

TABLE 12. Summary Statistics for Test of Recommended System of Age Prediction for Cases A–D of Anderson et al. (1976)[a]

Subject: true age	Schedule	Dental age: Mean	Dental age: Std. Dev.	Dental age: CV	Dental age minus true age
A. Male: 5.0	Correct sex	4.96	0.43	8.6	−0.04[b]
	Sex unknown	4.89	0.43	8.7	−0.11
	Incorrect sex	4.82	0.44	9.2	−0.18
B. Male: 10.0	Correct sex	10.05	0.81	8.1	0.05[b]
	Sex unknown	9.78	0.79	8.0	−0.23
	Incorrect sex	9.50	0.86	9.1	−0.50
C. Female: 4.3	Correct sex	4.12	0.46	11.0	−0.18[b]
	Sex unknown	4.17	0.45	10.7	−0.13
	Incorrect sex	4.22	0.44	10.5	−0.08
D. Female: 7.0	Correct sex	6.94	0.57	8.3	−0.06[b]
	Sex unknown	7.18	0.67	9.4	0.18
	Incorrect sex	7.41	0.80	10.8	0.41

[a]All ages in years.
[b]By comparison, the system of Anderson et al. (1976) misses subject age by −0.02, −0.20, −0.32, and −0.30 years, respectively, using correct sex tables and computing ages over the same teeth as used here.

partly due to the advantage gained by averaging over several teeth; ages estimated for single teeth vary more widely. Coefficients of variation for dental ages of teeth within an individual appear to center around 10 in these children and in others (see Smith, 1989). For the 23 teeth in these four trial cases, accuracy of a dental age based on a single tooth has a standard deviation of ±0.56 years. However, using mean values over five or more teeth, the standard deviation of error decreases markedly (to ±0.09 years), suggesting that dental age can be estimated to within 2 months for young children. This seems overly optimistic but, even if this estimate is too small by a factor of five, dental age prediction would still be quite good.

Low error figures above and in the literature are promising. However, it is not currently possible to assign confidence intervals to age predictions. Standard deviations for age of attainment of developmental stages for single teeth do not reflect variation in a mean age taken over several teeth. Further, the degree of error introduced by applying standards from one population to another is known only within a few European-derived samples (Nyström et al., 1986). Only more large scale empiric tests in the manner of Hagg and Matsson (1985) can begin to establish valid confidence limits. However, it can be said that *the few empiric tests published show good success despite a long list of projected theoretical difficulties.*

SUMMARY

Chronologies of human tooth formation can be divided into two major categories: (1) the older, descriptive literature based on dissection (possibly with some radiologic observations), sometimes with no description of the sample; and (2) those based on investigation of substantial samples, usually radiological, with statistical solutions to the problem of when growth events occur. Just as descriptive studies are not necessarily poor, statistical studies are not necessarily good. The state of the art is summarized below.

Different Types of Chronologies

A substantial number of different statistical methods have been used to produce chronologies of human dental development. *The single most important point of this review is that methods A–B, C–D, and E–F produce three fundamentally different variables* (see Table 3). Comparisons in the literature are often made between chronologies of tooth formation based on these different variables, attributing discrepancies to population differences rather than methodological or sampling effects (Nanda and Chawla, 1966; Haavikko, 1970; Gustafson and Koch, 1974; Mann et al., 1987; Trodden, 1982). The difference between dependent and independent variables has often been ignored in uses of chronologies of tooth maturation. In a number of cases, functions computed to minimize the deviation in y have been secondarily solved for x (Nolla, 1960; Gustafson and Koch, 1974; Crossner and Mansfeld, 1983).

The three major types of methods produce chronologies that should be used for three different purposes. Methods A and B produce chronologies of *age of attainment of growth stages;* an example of this type of chronology is any standard schedule of age of tooth emergence. Age of attainment of a stage is always earlier than age associated with being *in* a stage. The latter is useful for *age prediction,* and methods C and D produce chronologies for this purpose. Methods E and F produce *maturity scales,* used to assess whether a subject of known age is advanced or retarded compared to a reference population. Within these three types of chronologies, methods A, D, and F can be used to avoid technical difficulties present in methods B, C, and E, respectively.

Gaps in Present Knowledge

Missing Methodology. A number of studies are available that are well documented and explained, with investigation of substantial samples and careful attention to methods (e.g., see Table 3, studies listed under methods A, B, and F, in particular). But in other cases, assessment of a study is hampered by a lack of documentation. It is often difficult to decipher statistical methods of studies; pages may be expended on methods of constructing and reading tooth formation stages with only a sentence or two on statistical methods. This review describes *apparent* methodology in a number of cases. However, given the demonstrated importance of methodology, it is hoped that new chronologies will document samples and methods fully.

Missing Teeth. The chronology of human dental development is still not complete even for any single human group. Specifically, data on mean age of termination of deciduous incisor crowns and roots could not be found in modern studies. Only sparse data exist for initiation and termination of permanent incisor crowns. Radiographic studies are needed of the anterior teeth of the mandible of very young children.

Missing Variances. It is not currently possible to assign valid statistical confidence intervals for ages predicted from tooth formation, although undoubtedly, experienced workers are often called on to make estimates. Blind, empiric tests of systems are needed, especially tests comparing results for various human populations. The very few previously published tests report dental ages within ca. ± 0.25 years of chronological age, but one recent extensive test maintains that this is too optimistic, and that accuracy may be ± 1–2 years in most children (Hagg and Matsson, 1985). More straightforward empirical studies could make a significant contribution; studies are especially needed of a system designed specifically for age prediction.

Missing Differences. Very little information is available on tooth formation in nonwhite/non-European-derived human populations. The two studies of other groups (Nanda and Chawla, 1966; Trodden, 1982) are accomplished using methods that limit or preclude comparison to other studies. Clearly, there is a need to analyze data with methods comparable to those used on the most extensive samples of white children (e.g., Moorrees et al., 1963a, b; Haavikko, 1970; Demirjian and Levesque, 1980). What we do know about worldwide population differences in tooth formation amounts to guesses based on tooth emergence studies (e.g., Steggerda and Hill, 1942; Dahlberg and Menegaz-Bock, 1958; Friedlaender and Bailit, 1969; Brown, 1978; Mayhall et al., 1978), studies of patterns in data when European standards are applied to non-European subjects of unknown age (Owsley and Jantz, 1983; Fanning and Moorrees, 1969; Merchant and Ubelaker, 1977; Ubelaker, 1978), and one trial of age prediction using Asian and South American samples (Crossner and Mansfeld, 1983). These lines of evidence suggest that there are patterned differences, but that they *may not* be large.

New radiographic studies are needed to describe more of the world's major human groups. Although it is unlikely that new longitudinal studies will be undertaken anywhere that would require repeated serial radiography of subjects, it would be quite appropriate to assemble chronologies of tooth formation from cross-sectional data, and new studies of this type are not out of the realm of possibility.

CONCLUSION

There are important practical reasons to collect comparative data on human populations and to make information available in the form of all three types of chronologies. All three types are needed for use in clinical medicine because clinicians must assess growth (maturity scales), avoid treatments that may damage developing teeth during critical periods (attainment schedules), and more rarely, assess unknown age of patients (age prediction). Non-European subjects are short-changed to some degree when their development is assessed by European standards. Further, age prediction is needed in demography, skeletal biology, and forensics, including age assessment for abandoned children, orphans, or murder victims. At the very minimum, any human biologist would ask for a standard from each of the world's continents; we have a long way to go before this goal is realized.

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