Accuracy of Dental Age Estimation Charts: Schour and Massler, Ubelaker, and the London Atlas

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ABSTRACT Dental age estimation charts are frequently used to assess maturity and estimate age. The aim of this study was to assess the accuracy of estimating age of three dental development charts (Schour and Massler, Ubelaker, and the London Atlas). The test sample was skeletal remains and dental radiographs of known-age individuals ($N = 1{,}506$, prenatal to 23.94 years). Dental age was estimated using charts of Schour and Massler, Ubelaker, and The London Atlas. Dental and chronological ages were compared using a paired *t*-test for the three methods. The absolute mean difference between dental and chronological age was calculated. Results show that all three methods under-estimated age but the London Atlas performed better than Schour and Massler and Ubelaker in all measures. The mean difference for Schour and Massler and Ubelaker was -0.76 and -0.80 years (SD 1.27 year, $N = 1{,}227$) respectively and for the London Atlas was -0.10 year (SD 0.97 year, $N = 1{,}429$). Further analysis by age category showed similar accuracy for all three methods for individuals younger than 1 year. For ages 1–18, the mean difference between dental and chronological ages was significant ($P < 0.05$) for Schour and Massler and Ubelaker and not significant ($P > 0.05$) for the London Atlas for most age categories. These findings show that the London Atlas performs better than Schour and Massler and Ubelaker and represents a substantial improvement in accuracy of dental age estimation from developing teeth. Am J Phys Anthropol 154:70–78, 2014. © 2014 Wiley Periodicals, Inc.

Development and eruption of teeth are a useful chronology for life history events and are widely used to assess maturity and infer chronological age in paleoanthropology, bioarcheology, and forensic odontology. Teeth are highly mineralized and minimally affected by environmental an nutritional insult compared with other growth systems (Garn et al., 1965a, 1965b; Elamin and Liversidge, 2013). Teeth develop in a predictable sequence over 20 years and formation and/or eruption of teeth can be used to estimate age up to early adulthood.

Dental age estimation methods include charts of the developing dentition and tooth specific crown/root formation stages. The most well known is the atlas of Schour and Massler (1941a, 1941b) consisting of a series of 21 drawings from in-utero to adulthood. Each drawing shows one side of the jaws with outlines of developing teeth and eruption relative to a line (possibly gingival), and corresponding age. The age categories are consecutive up to age 12 after which the next category is 15 years of age. The last two drawings show fully formed and erupted teeth at 21 and 35 years. This atlas was published as an attachment in the Journal of the American Dental Association. Few details of the sample are known, but it was probably based on anatomical and radiographic sources including Logan and Kronfeld (1933). Smith (1991) points out that 19 of the possible total of 29 were younger than 2 years of age. Several aspects of this atlas have been criticized including no information of the material nor method of analysis, undefined tooth stages and eruption level, and small age ranges (Garn et al., 1959; Smith, 1991). Ubelaker's dental chart (1978) was an attempt to improve on this and was loosely based on Schour and Massler's atlas. He included numerous published sources to correct the age range for each drawing and defined the line as gingival emergence. He including tooth emergence of North American Indians by using "the early end of the published variation" as "some studies suggest that teeth probably form and erupt earlier among Indians" (Ubelaker, 1978). Both Schour and Massler and Ubelaker methods of dental age estimation were innovative and ground-breaking for their time (Messer and Till, 2013). Schour and Massler revised their atlas in 1944 to include a measure of age variation for each age. Ubelaker drew from numerous data sources to update the drawings from this early atlas, although there are differences in some teeth in several age categories (see Smith, 2005). The range for each age category in Ubelaker was described as covering most of the variation seen for each stage. Ubelaker's charts have been modified for modern Australians with separate charts for males and females by adjusting the age of each drawing (Blenkin and Evans, 2012).

A few other dental development charts exist. Nanda and Chawla (1966) drew average root stages for ages 6–12 years as well as the extent of root formation at the

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time of clinical eruption. Gustafson and Koch (1974) used data from 20 sources combining anatomical, radiographic, and gingival eruption data to construct a schematic representation of tooth formation and eruption. This chart is in the form of a grid with lines for tooth types (excluding third molars) and age categories. Brown (1985) illustrated individual permanent tooth stages as line drawings for each year of age from 3 to 12 based on Schour and Massler's atlas. Kahl and Schwarze (1988) updated Schour and Massler's atlas using 993 radiographs of children aged 5–24 and produced anatomical charts of the dentition for ages 5–16 for each sex. Permanent teeth are solid black and differences between the sexes and age categories are not easy to see but mean, median age, and standard deviation for tooth stages for each sex are tabulated.

The London Atlas was developed as a comprehensive, evidence based atlas that attempted to overcome some of the previous limitations and is freely available in numerous languages (www.atlas.dentistry.qmul.ac.uk) and also as a software. This atlas designed for age prediction, is tooth specific and illustrates tooth development and eruption for 31 age categories. The age distribution of the sample is documented and a uniform age distribution was chosen to reduce variation. All age categories are illustrated. Tooth stages and eruption levels are described and illustrate enamel, dentine, and pulp. The position of teeth is spaced so that each tooth is visible. Each drawing is the median tooth and eruption stage for the age category but median, minimum, and maximum tooth stage and eruption level for each age category are tabulated (AlQahtani et al., 2010).

Previous assessment of the accuracy and error of age estimation using dental development charts is sparse. The age range of test samples varies and accuracy is reported in various ways making comparisons difficult, although accuracy is better in younger children compared with older children (Brauer and Bahador, 1942; Miles, 1958; Gustafson and Koch, 1974; Hägg and Matsson, 1985; Liversidge, 1994; Smith, 2005; Blenkin and Taylor, 2012). Recently, new statistical approaches using large samples have greatly improved our understanding of the use of biological age-related changes to estimate age (Braga et al., 2005; Konigsberg et al., 2008; Prince et al., 2008; Prince and Konigsberg, 2008). These studies indicate that appropriate statistical analyses should be used and that sufficient sample size, wide age range and uniform age distribution of both reference and test samples are desirable.

The aim of this study was to assess the accuracy of estimating age from developing teeth using Schour and Massler (1941a, 1941b), Ubelaker (1978), and the London Atlas (AlQahtani et al., 2010).

MATERIAL

The test sample was made up of skeletal remains of individuals from collections of known age-at-death and archived dental radiographs of living patients shown in Table 1 where age categories follow the London Atlas. The skeletal remains were from Luis Lopes collection (Portugal), De Froe and Vrolik collection (The Netherlands), Hamann–Todd collection (The United States), Belleville's collection (Canada), and the Collection d'Anthropologie Biologique (France). This part of the sample is largely under the age of two and comprise of 183 individuals from 31 weeks in utero to 4.27 years. In most cases, developing teeth were assessed from radiographs of skeletal remains. The remainder of the test sample ($N = 1,323$) was panoramic radiographs of dental patients attending the Institute of Dentistry, Bart's and The London School of Medicine and Dentistry, London. This was made up of 649 males and 674 females whose ethnic origin was Bangladeshi and white British aged 2.07–23.86 years. The 933 individuals aged 3–16 are mostly those used by Maber et al. (2006) and Liversidge et al. (2010) to test tooth specific age estimation methods. All the dental radiographs of living patients had previously been taken in the course of diagnosis and treatment.

METHODS

Age was estimated using all developing teeth using the charts of Schour and Massler, Ubelaker, and the London Atlas by the first author. All radiographs were assessed on an x-ray light box. Photographs of radiographs or digital radiographs were assessed on a computer monitor using Microsoft Office Picture Manager. Isolated teeth were examined visually. All cases were numbered and real age was blinded when teeth were assessed. Intra-examiner reliability of dental age assessment for each method was calculated using Cohen's Kappa (Landis and Koch, 1977) by re-assessment of 10% of the test sample selected by random allocation software (Saghaei, 2004). Data were analyzed using SPSS (16.0).

Dental age was compared with chronological age using a paired t-test for each of the three methods with a significant level of $P < 0.05$. The mean difference between dental and chronological ages indicates bias. The absolute mean difference between dental and chronological ages was calculated to express accuracy independent of bias.

Data were analyzed for the whole sample of dentally immature individuals. Data were also grouped for further analysis to compare accuracy for each age category. Age categories were those of the London Atlas. For example, the difference between dental and chronological age from individuals aged 1.00–1.99 years was calculated and results expressed for this age category. The small group of prenatal individuals from the first three age categories were combined in this analysis. Data were also analyzed to excluding third molars for all ages as well as from age 3 to 16 years.

The percentage of individuals estimated to be in the correct age group was calculated for each method for the whole age range and excluding third molars. Correct was defined as dental age being within the age range of the chronological age category. In other words, if a child had a dental age of 3.5 and chronological age was between 3.00 and 3.99 years, the individual was assigned to the correct age category. If dental age of a similarly aged child was 4.5, then age was over estimated by one age category.

RESULTS

Intra-observer error was assessed by the first author after retesting a subsample (160 individuals). Kappa values were 0.838 for Schour and Massler, 0.857 for Ubelaker, and 0.879 for the London Atlas showing excellent reproducibility for all three methods.

Results of age estimation for the three methods are summarized in Tables 2 to 4. All three methods of age

TABLE 1. Number of individuals from known age-at-death skeletal remains and archived radiographs of the test sample

		Collection							
Age category	Midpoint	LL	DeF	HT	B	CAB	Rm	Rf	Total
28 w i.u. < 32 w i.u.	30 w i.u.					2			2
32 w i.u. < 36 w i.u.	34 w i.u.					6			6
36 w i.u. < 39 w i.u.	38 w i.u.					12			12
39 w i.u. < 1 w	Birth	6		4		6			16
1 w < 0.25	0.125	1	2			25			28
0.25 < 0.50	0.375	4	2		2	1			9
0.50 < 0.75	0.625		2		3	2			7
0.75 < 1	0.825	1	1		6	2			10
1	1.5	20	9	9	19	7			64
2	2.5	9		1	1	9	21	20	61
3	3.5	8					30	37	75
4	4.5	1					32	34	67
5	5.5						40	42	82
6	6.5						39	38	77
7	7.5						40	35	75
8	8.5						27	35	62
9	9.5						33	31	64
10	10.5						32	31	63
11	11.5						28	36	64
12	12.5						24	31	55
13	13.5						27	36	63
14	14.5						32	27	59
15	15.5						30	31	61
16	16.5						35	31	66
17	17.5						27	29	56
18	18.5						29	26	55
19	19.5						28	30	58
20	20.5						25	31	56
21	21.5						27	28	55
22	22.5						25	24	49
23	23.5						18	11	29
Total		50	16	14	31	72	649	674	1,506

Age categories correspond to those of the London Atlas. LL, Luis Lopes (Portugal), DeF, De Froe (Amsterdam, The Netherlands); HT, Hamann–Todd (Cleveland); B, Belleville (Montreal, Canada); CAB, Collection d'Anthropologie Biologique (Paris, France); Rm, archived dental radiographs of dental patients male; Rf, archived dental radiographs of dental patients female; i.u., in utero; w, weeks. Other age categories and midpoints in years.

TABLE 2. Results of the mean difference and absolute mean difference between dental and chronological ages in years

Age category	*N*	Method	Mean difference	SD	*P* value	Absolute mean difference
All ages	1,227	Schour + Massler	−0.76	1.27	0.000*	1.01
	1,227	Ubelaker	−0.80	1.27	0.000*	1.03
	1,429	London Atlas	−0.10	0.97	0.000*	0.64
All ages excluding M3	1,034	Schour + Massler	−0.50	0.93	0.000*	0.78
	1,034	Ubelaker	−0.55	0.95	0.000*	0.81
	1,034	London Atlas	0.00	0.72	0.872	0.50
3–16	808	Schour + Massler	−0.58	1.01	0.000*	0.89
	808	Ubelaker	−0.65	1.02	0.001*	0.93
	808	London Atlas	0.01	0.78	0.811	0.55

Negative mean difference indicates that dental age was less than chronological age. Age categories, All ages prenatal to 23.99 years, 3 to 16, 3.00 to 16.99 years; *N*, number of dentally immature individuals; SD, standard deviation; *, mean difference significantly different to zero; M3, third molar.

estimating under-estimated age. Estimated age was closer to chronological age using the London Atlas than Schour and Massler and Ubelaker. In other words, the London Atlas estimated age more accurately and with greater precision than the other two methods. Both Schour and Massler and Ubelaker under-estimated age by around 0.75 year with SD of 1.27 and absolute mean difference just over 1 year. The London Atlas mean value was −0.10 year with smaller SD (0.97) and absolute mean difference (0.64) compared with the older atlases.

A notable feature of the results is the apparent difference in sample sizes between Schour and Massler/Ubelaker and the London Atlas. This is due to the jump in consecutive drawings for age 15–21 years in both Schour and Massler and Ubelaker charts. Age 15 is the oldest age category prior to dental maturity where all teeth are mature and fully erupted except for the third molar

TABLE 3. Results of the mean difference between dental and chronological ages for age categories in years (prenatal age categories grouped)

		Schour + Massler		Ubelaker			London Atlas	
Age category midpoint	*N*	Mean	SD	Mean	SD	*N*	Mean	SD
Prenatal	20	**−0.15**	0.08	**−0.15**	0.08	20	0.00	0.09
Birth	16	0.09	0.34	0.06	0.32	16	0.13	0.32
1.5 m	28	−0.05	0.26	−0.07	0.25	28	0.03	0.17
4.5 m	9	−0.03	0.29	0.00	0.31	9	−0.03	0.18
7.5 m	7	−0.13	0.22	−0.27	0.30	7	−0.07	0.18
10.5 m	10	−0.08	0.14	−0.10	0.16	10	−0.02	0.24
1.5	64	**−0.20**	0.40	**−0.12**	0.46	64	0.08	0.47
2.5	61	**−0.43**	0.57	**−0.35**	0.59	61	−0.10	0.89
3.5	75	**−0.34**	0.62	**−0.33**	0.59	75	**0.12**	0.48
4.5	67	−0.07	0.69	−0.11	0.62	67	**0.24**	0.58
5.5	82	**−0.37**	0.63	**−0.40**	0.61	82	−0.01	0.50
6.5	77	**−0.37**	0.73	**−0.47**	0.74	77	−0.04	0.57
7.5	75	**−0.48**	0.65	**−0.59**	0.67	75	0.06	0.49
8.5	62	**−0.74**	0.64	**−0.79**	0.57	62	0.05	0.52
9.5	64	**−0.81**	0.93	**−1.00**	0.90	64	0.02	0.64
10.5	63	**−0.75**	1.08	**−0.90**	1.09	63	−0.13	0.79
11.5	64	**−0.65**	1.21	**−0.73**	1.30	64	0.00	1.09
12.5	55	**−0.75**	1.00	**−0.81**	1.07	55	0.04	1.20
13.5	63	**−0.64**	1.47	**−0.67**	1.51	63	0.18	1.17
14.5	59	**−0.42**	1.41	**−0.42**	1.41	59	0.05	0.80
15.5	61	**−0.99**	1.15	**−0.99**	1.15	61	−0.13	0.87
16.5	65	**−1.58**	0.60	**−1.58**	0.60	66	**−0.43**	0.78
17.5	28	**−2.51**	0.28	**−2.51**	0.28	52	0.18	1.23
18.5	20	**−3.46**	0.32	**−3.46**	0.32	53	0.11	1.36
19.5	18	**−4.36**	0.26	**−4.36**	0.26	57	**−0.54**	1.44
20.5	6	**−5.49**	0.41	**−5.49**	0.41	42	**−0.76**	1.30
21.5	3	**−6.53**	0.27	**−6.53**	0.27	43	**−0.82**	1.66
22.5	5	**−7.29**	0.22	**−7.29**	0.22	26	**−1.59**	1.90
23.5	0					8	**−1.83**	1.12

N, number of dentally immature individuals; SD, standard deviation; m, months. Bold indicates mean difference significantly different to zero $P < 0.05$.

(root one quarter formed). The next age category is 21 years where all teeth are fully mature and erupted. This presents a problem to estimate age when the third molar is more than root one quarter but not yet mature. The option we chose was to classify these individuals as dentally mature and they drop out of the test sample. The other option is to classify them as dental age 15.

Age estimation using developing teeth omitting the third molars showed that both Schour and Massler and Ubelaker under-estimated age by around 0.5 year while the mean difference using London Atlas was zero. Both SD and absolute mean difference were smaller using the London Atlas than the two older charts.

Figure 1 shows the difference between chronological and dental ages plotted against chronological age for the three methods. Individuals above zero have dental age greater than chronological age and those below have dental age less than chronological age. The results for Schour and Massler and Ubelaker are almost identical in performance. The data group into parallel rows of data points represent dental age categories. The data points at the top left of each row are children with reach dental age a younger chronological age than average (dentally advanced individuals) and lower right data points are those with older chronological age (dentally delayed individuals). In both the Schour and Massler and Ubelaker, the last age category is dental age 15. The gap prior to this, is due to the gap in consecutive age categories with the previous age being 12. Individuals with chronological age of 13 and 14 are assigned to either dental age 12 or 15. The London Atlas has no gaps in consecutive age categories and includes late roots stage of third molars resulting an even scatter in this figure.

Results of more detailed analysis by age category (prenatal categories combined) are summarized in Tables 3 and 4 and illustrated in Figure 2. The principle finding is that Schour and Massler and Ubelaker were similar with mean differences significant for most age categories ($P < 0.05$). Exceptions were birth, the four age categories up to the first birthday, and 4 year olds. In contrast, the mean difference using the London Atlas for age categories were for the most part not significant ($P > 0.05$). Exceptions are 3 and 4 year olds, 16 year olds, and 19 and older. None of the three methods estimated age accurately for ages 19 and older, reflecting the large age variation in third molar tooth stages.

The percentage of individuals assigned to the correct age category was similar for Schour and Massler and Ubelaker (39% and 40%, respectively, $N = 1{,}227$) but considerably better using the London Atlas (53%, $N = 1{,}429$). This was evident across the age range (Fig. 3). If third molars were excluded these percentages were 42%, 43%, and 59% ($N = 1{,}034$) for Schour and Massler, Ubelaker, and the London Atlas, respectively. This probably reflects the fact that each age category is represented in London Atlas and the ages 13, 14, and 17–22 years are unrepresented in the older charts.

DISCUSSION

Age estimation performance can be measured in various ways. Some early studies describe the difference

TABLE 4. Results of the absolute mean difference between dental and chronological ages for age categories in years (prenatal age categories are grouped as one)

Age category midpoint	*N*	Schour + Massler Mean	Ubelaker Mean	*N*	London Atlas Mean
Prenatal	20	0.16	0.16	20	0.08
Birth	16	0.22	0.19	16	0.21
1.5 m	28	0.21	0.20	28	0.13
4.5 m	9	0.24	0.26	9	0.12
7.5 m	7	0.18	0.32	7	0.17
10.5 m	10	0.13	0.16	10	0.17
1.5	64	0.36	0.36	64	0.37
2.5	61	0.61	0.58	61	0.43
3.5	73	0.50	0.48	73	0.37
4.5	70	0.54	0.52	70	0.46
5.5	82	0.59	0.60	82	0.37
6.5	77	0.67	0.71	77	0.44
7.5	73	0.64	0.70	73	0.38
8.5	63	0.84	0.86	63	0.38
9.5	64	1.03	1.13	64	0.47
10.5	63	1.07	1.14	63	0.60
11.5	61	0.99	1.10	61	0.80
12.5	56	1.03	1.08	56	0.85
13.5	64	1.50	1.53	64	0.79
14.5	59	1.14	1.14	59	0.67
15.5	62	0.99	0.99	62	0.66
16.5	65	1.59	1.59	66	0.67
17.5	28	2.51	2.51	52	0.95
18.5	20	3.46	3.46	53	0.99
19.5	18	4.36	4.36	57	1.18
20.5	6	5.49	5.49	42	1.15
21.5	3	6.53	6.53	43	1.43
22.5	5	7.29	7.29	26	1.74
23.5	0			8	1.83

N, number of dentally immature individuals.

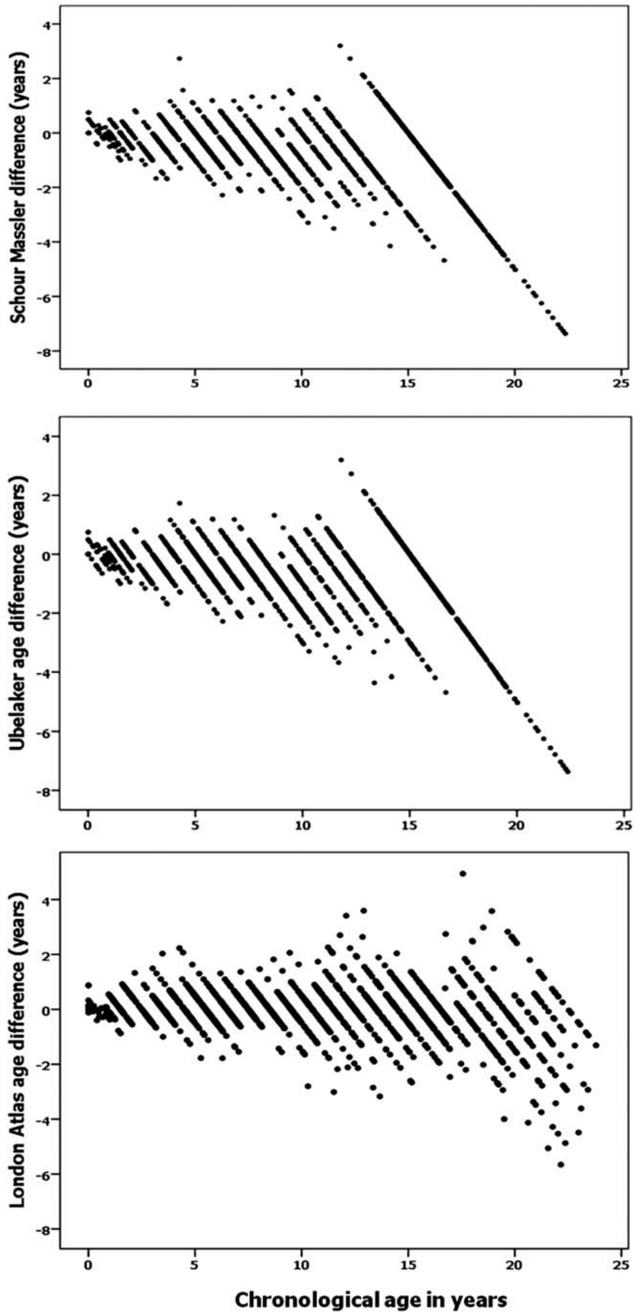

Fig. 1. The difference in dental and chronological ages plotted against chronological age in years for Schour and Massler, Ubelaker, and the London Atlas for dentally immature individuals (up to and including immature third molar teeth). Zero difference indicates identical dental and chronological ages, dots above zero indicate dental age greater than chronological age and dots below zero indicate dental age less than chronological age.

between dental and chronological age in very broad terms. Some report correlation of dental and chronological ages. More recent studies detail the mean and absolute mean difference between dental and chronological ages to report bias as well as accuracy. Other approaches include reporting the coefficient of determination, root mean square error, when regression models predict age, or likelihood ratio of being on one or other side of an age threshold. Results can be influenced by the age distribution and age range of the test sample. A single value of performance for a wide age range is not ideal and analysis by age category or tooth stage can provide additional information. Pictorial methods of age estimation differ in the width of the age categories, the selection of the age midpoint, and measure of dispersion. Estimated age from a chart or atlas is an age category or interval whereas tooth specific reference methods provide a point estimate.

Many studies have tested the accuracy of dental age estimation methods but only a handful evaluate the charts of Schour and Massler and Ubelaker (Brauer and Bahador, 1942; Miles, 1958; Liversidge, 1994; Smith, 2005; Corral et al., 2010; Blenkin and Taylor, 2012). Two early reports remark that dental age can differ to chronological age by about half a year. Brauer and Bahador (1942) commented that age estimated by eruption (movement of the tooth into function and root resorption) did not only always coincide with age using tooth formation stages in their sample of 415 children aged 1–14 years. Miles (1958) illustrates the difference between dental and chronological age plotted against chronological age of 58 individuals aged 3–19 years. He notes that up to the age of about 12 years most estimates fall near the real age, few being more than a year out. Over the age of 12 years, however, there is an increasing amount of scatter and many are 2 years or more above or below the line. Two separate studies show that the accuracy of estimating age using Schour and Massler is better in infants and young children than older children and

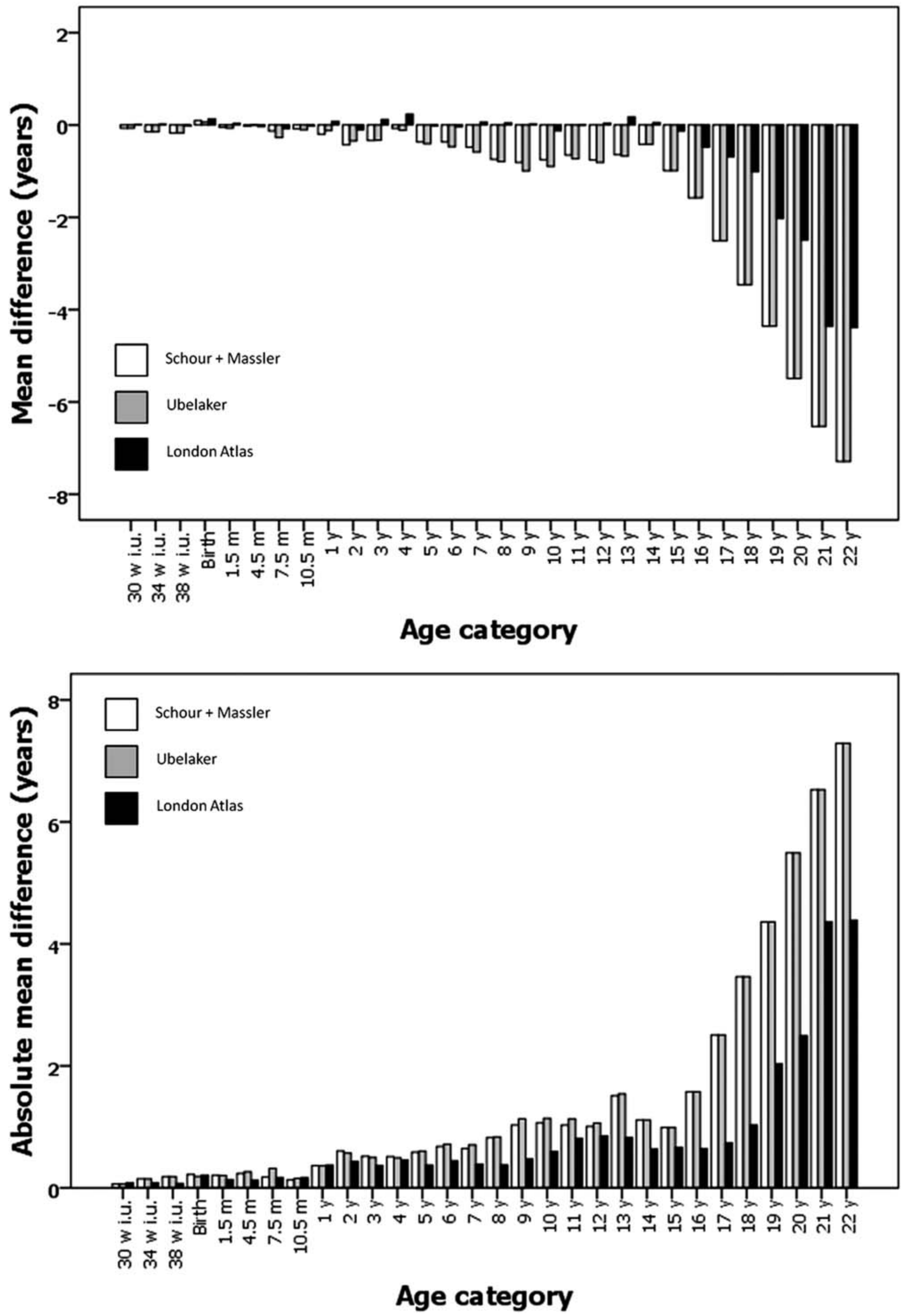

Fig. 2. Bar charts of the mean difference and mean absolute difference in years between dental and chronological ages for each age category. Schour and Massler *open bars*, Ubelaker *gray filled bars*, London Atlas *solid bars*. Age category for age 23 omitted.

teenagers. Schour and Massler estimated age with an average difference of −0.11 year (SD 0.30 year) for 63 individuals from Spitalfields aged 0–5.4 year (Liversidge, 1994). This sample has many very young individuals (29 younger than 1 year, 15 aged 1 year, and 9 two year olds, and a few older children). The second study of modern European American sample reports a mean difference between dental and chronological ages as −0.66 and −0.71 for Schour and Massler and Ubelaker, respectively (Smith, 2005). The absolute mean difference was just over a year for both methods. Sample size of this study was larger ($N = 419$) with a fairly uniform age distribution of 5–15 years. Two recent reports provide summary results on accuracy using dental age estimation charts. An underestimate of 0.43 and 0.25 year for males and females, respectively, was found using Schour and

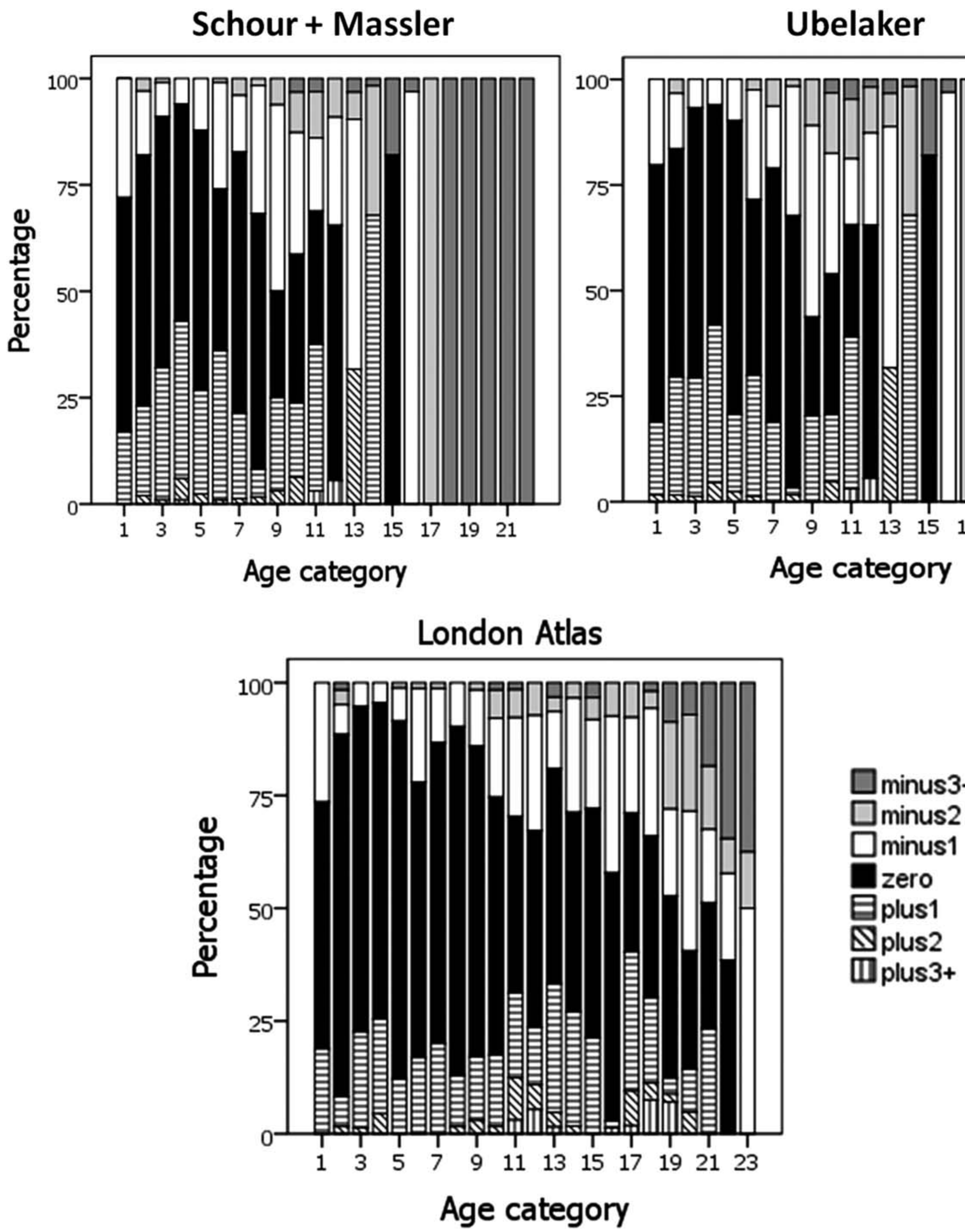

Fig. 3. Percentage of individuals and age category of estimated age by 1 year age categories (from 1 year) for Schour and Massler, Ubelaker, and the London Atlas methods. *Solid bars* indicate the percentage of each age where dental and chronological age categories are identical. The two older methods are similar with several older age categories having no correctly aged individuals. The London Atlas has a greater percentage correctly assigned than Schour and Massler and Ubelaker that is also noted across all age categories with the exception of the last.

Massler (Blenkin and Evans, 2010). Very accurate age estimates were reported using both Schour and Massler and Ubelaker on a test sample of 196 individuals aged 5–19 years (Corral et al., 2010).

The results on the accuracy of both Schour and Massler and Ubelaker in our study are very similar to most findings detailed above. Dental age in very young children slightly under-estimated chronological age. For older children, bias increased and our findings are very similar to those reported by Smith (2005). The trend of increasing scatter with age up to age 12 (Miles, 1958) is also evident in our study.

Comparing results from the older charts with the London Atlas in our study shows that all measures of performance to estimate age were better using the more recent Atlas than the older charts. Age was estimated more accurately, with greater precision and the percentage correctly aged was higher for the London Atlas compared with Schour and Massler and Ubelaker.

Comparing accuracy by very different approaches is problematic. Dental charts and atlases represent a visual assessment of the dentition at given ages. Tooth specific methods tabulate ages for developmental stages of each individual tooth that may be used to predict age. The first approach estimates age as an age category (or the midpoint thereof), the second provides a point estimate and these are not equivalent. Despite this, it is of interest to know how these approaches compare. Three studies report that Schour and Massler estimated age more accurately than tooth specific methods. In two studies (Liversidge, 1994; Corral et al., 2010), this difference was marginal where Schour and Massler was compared with Moorrees et al. (1963a, 1963b). A third study (Blenkin and Evans, 2010) reports considerably better accuracy using Schour and Massler compared with Demirjian et al. (1973).

The results of this study for the ages 3–16 can be directly compared with published results of accuracy of tooth-specific dental age estimation methods (Liversidge et al., 2010) where the same test sample was assessed. Accuracy as the midpoint of an age interval is better using the London Atlas than a point estimate from the most widely used methods including Nolla (1960), Moorrees et al. (1963b), Haavikko (1970), Anderson et al. (1976), Demirjian et al. (1973), and Willems et al. (2001) among others.

The variation in timing of tooth formation between populations is not well understood and the existence of differences and their meaning is contentious. Few studies use statistical approaches appropriate for group comparison, such as probit regression or transitional analysis (conditional on age rather than stage). In our study, both the reference sample of the London Atlas and the test sample were largely drawn from patients attending the Dental Institute (White and Bangladeshi) living in London. These groups are similar in their dental maturity and only small differences in mean age entering permanent tooth stages have been shown (Liversidge, 2011). Another comparative study of mostly White children in various world regions failed to show any meaningful difference or consistent pattern in the timing of tooth formation (Liversidge et al., 2006). This does not hold true for all teeth and there is some evidence of group difference in the timing of the third molars (Liversidge, 2008; Thevissen et al., 2010). However, the impact of group differences on the accuracy and precision of age estimation of an individual is small (Braga et al., 2005; Thevissen et al., 2010; Liversidge and Marsden, 2010). A universal finding is that age variation within groups for each tooth stage is greater than between groups. The undisputed large standard deviation in age for all tooth stages has relevance when estimating age, as it determines the 95% confidence interval of estimated age for an individual.

The strength of our study is the large test sample, uniform age distribution where possible, and wide age range from in-utero to early adulthood. Skeletal material of known age-at-death is rare and our test sample was small and not uniform for age categories on either side of 6 months. In addition, the skeletal sample was not evenly represented by males and females and included a number of individuals of unrecorded sex (detailed in AlQahtani, 2012). A limitation of our study is that Schour and Massler and Ubelaker differ to the London Atlas in several fundamental aspects that could influence the results. Firstly, the midpoint of age intervals differs by 6 months (year start or midyear). Secondly, Schour and Massler and Ubelaker omit several age categories where tooth development is highly variable. Limitations are the gaps in the sequence of age categories and the question of how to assess age once the third molar root is past one quarter but incomplete.

This study validates the London Atlas as an accurate method to estimate age. It is better in all measures of performance than Schour and Massler and Ubelaker. If an age interval is sufficient precision for estimating age, then the London Atlas performs better than most methods based on point estimates from individual teeth including Willems et al. (2001). In spite of these findings, the London Atlas is not without some drawbacks that are unavoidable when maturity is illustrated in age categories. Age is expressed as the midpoint of an age category and not a point estimate. No measure of dispersion of the midpoint age is given, although SD of accuracy from Table 3 can be summarized as <3 months before first birthday, less than a year for ages 1–10, and around a year up to the mid-teens. Although the drawings depict tooth-specific results (median stage of formation and eruption), the high variability in dental development means that it is not unusual to find considerable variation when comparing an individual to the drawings. In addition, a single tooth or several teeth may be advanced or delayed relative to the average. Despite the high age variation in tooth development, this study shows that the London Atlas is a major improvement in estimating age compared with the charts of Schour and Massler and Ubelaker.

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The authors had no conflict of interest to declare when this research was carried out and the manuscript prepared. The software applications for the London Atlas were first available for sale on friday 28th June 2013; the profits of which will be shared by the authors for future research on dental age estimation.

LITERATURE CITED

AlQahtani SJ. 2012. The London Atlas: developing an atlas of tooth development and testing its quality and performance measures. PhD Thesis. Queen Mary College, University of London.

AlQahtani SJ, Hector MP, Liversidge HM. 2010. Brief communication: the London atlas of human tooth development and eruption. Am J Phys Anthropol 142:481–490.

Anderson DL, Thompson GW, Popovich F. 1976. Age attainment of mineralization stages of the dentition. J Forensic Sci 21: 191–200.

Blenkin M, Taylor J. 2012. Age estimation charts for a modern Australian population. Forensic Sci Int 55:1504–1508.

Blenkin MRB, Evans W. 2010. Age estimation from the teeth using a modified Demirjian system. J Forensic Sci 55:1504–1508.

Braga J, Heuze Y, Chabadel, O, Sonan NK, Geuramy A. 2005. Non-adult dental age assessment: correspondence analysis and linear regression versus Bayesian predictions. Int J Legal Med 119:260–274.

Brauer JC, Bahador MA. 1942. Variations in calcification and eruption of the deciduous and the permanent teeth. J Am Dent Assoc 29:1373–1387.

Brown WAB. 1985. Identification of human teeth. Bull Inst Arch 21/22:1–30.

Corral C, García F, García J, León P, Herrera A, Martínez C, Moreno F. 2010. Chronological versus dental age in subjects from 5 to 19 years: a comparative study with forensic implications. Colomb Méd 41:215–253.

Demirjian A, Goldstein H, Tanner JM. 1973. A new system of dental age assessment. Hum Biol 45:211–227.

Elamin F, Liversidge HM. 2013. Malnutrition has no effect on the timing of human tooth formation. PLoS ONE 8:e72274.

Garn SM, Lewis AB, Blizzard RM. 1965a. Endocrine factors in dental development. J Dent Res 44:243–258.

Garn SM, Lewis AB, Kerewsky RS. 1965b. Genetic, nutritional and maturational correlates of dental development. J Dent Res 44:228–243.

Garn SM, Lewis AB, Polacheck DL. 1959. Variability in tooth formation. J Dent Res 38:135–148.

Gustafson G, Koch G. 1974. Age estimation up to 16 years of age based on dental development. Odontol Revy 25:297–306.

Haavikko K. 1970. The formation and the alveolar and clinical eruption of the permanent teeth. An orthopantomographic study. Proc Finn Dent Soc 66:103–170.

Hägg U, Matsson L. 1985. Dental maturity as an indicator of chronological age: the accuracy and precision of three methods. Eur J Orthod 7:25–34.

Kahl B, Schwarze CW. 1988. Updating of the dentition tables of I. Schour and M. Massler of 1941. J Orofac Orthop 49:432–443. In German.

Konigsberg LW, Herrmann NP, Wescott DJ, Kimmerle EH. 2008. Estimation and evidence in forensic anthropology: age-at-death. J Forensic Sci 53:541–557.

Landis JR, Koch GG. 1977. The measurement of observer agreement for categorical data. Biometrics 33:159–174.

Liversidge HM. 1994. Accuracy of age estimation from developing teeth of a population of known age (0–5.4 years). Int J Osteoarch 4:37–45.

Liversidge HM. 2008. Timing of human third molar formation. Ann Hum Biol 35:294–321.

Liversidge HM. 2011. Similarity in dental maturation in two ethnic groups of London children. Ann Hum Biol 38:702–715.

Liversidge HM, Chaillet N, Mörnstad H, Nyström M, Rowlings K, Taylor J, Willems G. 2006. Timing of Demirjian tooth formation stages. Ann Hum Biol 33:454–470.

Liversidge HM, Marsden PH. 2010. Estimating age and the likelihood of having attained 18 years of age using mandibular third molars. Br Dent J 209(8):E13.

Liversidge HM, Smith BH, Maber M. 2010. Bias and accuracy of age estimation using developing teeth in 946 children. Am J Phys Anthropol 143:545–554.

Logan WHG, Kronfeld R. 1933. Development of the human jaws and surrounding structures from birth to age fifteen. J Am Dent Assoc 20:379–427.

Maber M, Liversidge HM, Hector MP. 2006. Accuracy of age estimation of radiographic methods using developing teeth. Forensic Sci Int 159 Suppl 1:S68–S73.

Messer LB, Till MJ. 2013. A landmark report on understanding the human dentition. J Am Dent Assoc 144:357–361.

Miles AEW. 1958. The assessment of age from the dentition. Proc Royal Soc Med 51:1057–1060.

Moorrees CFA, Fanning EA, Hunt EE. 1963a. Formation and resorption of three deciduous teeth in children. Am J Phys Anthropol 19:99–108.

Moorrees CFA, Fanning EA, Hunt EE. 1963b. Age variation of formation stages for ten permanent teeth. J Dent Res 42: 1490–1502.

Nanda RS, Chawla TN. 1966. Growth and development of dentition in Indian children. I. Development of permanent teeth. Am J Orthod 52:837–853.

Nolla CM. 1960. The development of the permanent teeth. J Dent Child 27:254–266.

Prince DA, Kimmerle EH, Konigsberg LW. 2008. A Bayesian approach to estimate skeletal age-at-death utilizing dental wear. J Forensic Sci 53:588–593.

Prince DA, Konigsberg LW. 2008. New formulae for estimating age-at-death in the Balkans utilizing Lamendin's dental technique and Bayesian Analysis. J Forensic Sci 53:578–587.

Saghaei M. 2004. Random allocation software for parallel group randomized trials. BMC Med Res Methodol 4:26.

Schour L, Massler M. 1941a. The development of the human dentition. J Am Dent Assoc 28:1153–1160.

Schour I, Massler M. 1941b. Development of human dentition chart, 2nd ed. Chicago: American Dental Association.

Smith BH. 1991. Standards of human tooth formation and dental age assessment. In: Kelly MA, Larsen CS, editors. Advances in dental anthropology. New York: Wiley-Liss. p 143–168.

Smith EL. 2005. A test of Ubelaker's method of estimating subadult age from the dentition. Master's thesis, University of Indianapolis. http://archlab.uindy.edu/documents/theses/SmithELThesis.pdf.

Thevissen PW, Fieuws S, Willems G. 2010. Human third molars development: Comparison of 9 country specific populations. Forensic Sci Int 201:102–106.

Thevissen PW, Alqerban A, Asaumi J, Kahveci F, Kaur J, Kim YK, Pittayapat P, Van Vlierberghe M, Zhang Y, Fieuws S, Willems G. 2010. Human dental age estimation using third molar developmental stages: Accuracy of age predictions not using country specific information. Forensic Sci Int 201:106–111.

Ubelaker DH. 1978. Human skeletal remains: excavation, analysis, interpretation. Chicago: Aldine Publishing Co. Inc.

Willems G, Van Olmen A, Spiessens B, Carels C. 2001. Dental age estimation in Belgian children: Demirjian's technique revisited. J Forensic Sci 46:893–895.