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ORIGINAL ARTICLE

Validation of reference data on wisdom tooth mineralization and eruption for forensic age estimation in living persons

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Abstract Estimation of dental age is an important part of forensic age estimation in living persons. As the quality of the values given in population-specific reference studies has a great impact on the estimation, the aim of this study was to validate reference data for wisdom teeth mineralization and eruption of a German population concerning the diagnosis of the age limit of 18 years in persons with known age. Mineralization and eruption was evaluated in 307 orthopantomograms of Central European subjects aged 17.5–18.5 years. Dental age was estimated using reference data and compared to chronological age. Statistical methods were used to analyze the differences and to propose adjusted reference values. Estimation of dental age relying on mineralization resulted in overestimations of 2 years on average in 76% of the males and 82% of the females. Using eruption, all men and 75% of the women were overestimated by up to 7 years. The differences between estimated and chronological age in both men and women were associated with the mineralization and eruption stage, respectively. The higher the stage, the higher was the risk of overestimation. The mineralization stages up to stage E were associated with underestimations. Using the proposed adjusted reference values resulted in more accurate estimations of dental age. Validation of reference values for dental age estimation showed great overestimations resulting in high error rates with numerous persons being younger than the estimated dental age. Adjustments are proposed which reduce differences between estimated dental age and chronological age.

Keywords Forensic · Age estimation · Wisdom teeth · Third molar · Mineralization · Eruption

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Introduction

Forensic age estimation in living persons is based on three fundaments, namely an external examination of the body, the analysis of bone age by using radiologic methods, and the estimation of dental age which to date is usually based on the evaluation of an orthopantomogram (OPG). For the evaluation of dental maturity, various morphological criteria of tooth development have been observed, and various parameters and methods to assess distinct developmental stages have been proposed [1–3, and references therein]. One well-established approach is based on the assessment of mineralization of the wisdom teeth according to different stages (A–H) proposed by Demirjian and Mincer et al. [1, 4]. Additionally, third molar eruption which follows a defined sequence of stages (A–D) can be used for the estimation of dental age [5].

The correlation of the specific mineralization or eruption stages of each third molar with age has been evaluated for different populations, and the corresponding values are used as reference data in daily forensic practice for the age estimation in living persons [5–14]. The choice of which study to refer to not only depends on the ethnic origin of the examined person but also on the exact purpose, e.g., criminal or civil proceedings, and on the age limit in question. The reference studies state statistical numbers such as the mean and standard deviation concerning the chronological age of the investigated persons at each stage of wisdom tooth development separately for males and females. In most studies the numbers are given for all wisdom teeth individually, but in some the results are limited to only mandibular third molars [11] or even just a single wisdom tooth [12, 14].

As the choice of the respective reference study is crucial for the outcome of the assessment of dental age, it is important to evaluate the quality and accuracy of such reference data and to determine the distribution of the differences between estimated dental age and chronological age.

Therefore, the aim of this study was (1) to validate the reference values of wisdom tooth mineralization and eruption of a German population [5, 7, 15] in a sample of persons with known chronological age, (2) to analyze the differences between estimated dental age and chronological age, and (3) to propose adjustments to the reference values in view of a possible reduction of estimation errors if needed.

Materials and methods

Study design

The design of the study was a retrospective cross-sectional evaluation of dental panoramic radiographs (orthopantomograms).

Sample

OPGs of a population of 307 Central European individuals living in Switzerland (168 females, 139 males) with a chronological age between 17.5 and 18.5 years (females: age range 17.68–18.37, median 18.01, mean 18.01; males: age range 17.68–18.34, median 18.02, mean 18.01) were reevaluated. The radiographs were originally taken in the course of medical care at different dental departments and dental practices in Switzerland during the years 1979–2005 and collected for a study conducted at the University of Zürich. All OPGs had been performed according to standard dental practice and covered the upper and lower jaw. The overall image quality was good; in a few cases, imaging quality was slightly limited but still diagnostic. A case number was assigned to each radiograph, and sex, date of birth, and data of radiographic examination were recorded. Cases with missing data or unclear ethnic origin according to the names of the patients were excluded.

Dental evaluation

The OPGs were evaluated by two examiners (HM, 1 year of experience in assessing mineralization and eruption stages; MM, 4 years) concerning the presence of the four wisdom teeth and eligibility for assessment regarding image quality and dental position, and the mineralization stage of each wisdom tooth according to Demirjian and Mincer et al. [1, 4]. The examiners were blinded to the date of birth and the date of examination, and to the scores of each other. The results of the two examiners were compared, and Cohen's kappa was calculated for each wisdom tooth as a measure of interobserver agreement. Additionally, mean differences were calculated by subtracting the scores of HM from those of MM, with the stages A–H corresponding to scores from 1 to 8. Estimation of dental age was only performed on the basis of the results of examiner HM. The eruption stage was evaluated by one examiner (HM) only using the stages defined by Olze et al. [5]. Wisdom teeth with obstructed eruption were excluded from the analysis of the eruption stages. In cases where the gingival soft tissue was radiologically not well defined, the auxiliary definition of stage C proposed by Peschke was used [16]. The numbers of wisdom teeth found being in the respective mineralization and eruption stages are shown in Table 1.

Statistical analysis

For statistical analysis the evaluation results for mineralization and eruption stages of one examiner (HM) were used. Analysis was performed using the software R 2.12.0 (the R project, www.r-project.org). Chronological age at the time of the radiographic examination was calculated by subtraction of the examination date from the date of birth and recorded as years with one decimal place. For the estimation of dental age, the reference values for a German population, further named as "standard reference data," were used for mineralization [7, 15] and eruption [5] of each wisdom tooth (maxillary right, 18; maxillary left, 28; mandibular left, 38; mandibular right, 48). The mean value of the corresponding stage in the standard reference data was defined to be the estimated dental age of a person. Age estimation was validated for each sex, scoring method, and wisdom tooth separately.

The estimation error was defined to be the difference between estimated age and chronological age. Thus, a positive difference indicates an overestimation, and a negative result an underestimation. The mean difference was calculated for each mineralization and eruption stage,

Table 1 Number of wisdom teeth (18, 28, 38, and 48) of the investigated sample being in the different mineralization and eruption stages, respectively

Mineralization		Wisdom tooth				Eruption				
	Stage	18	28	38	48	Stage	18	28	38	48
Males	C	0	0	1	0	A	18	14	17	12
	D	4	2	3	4	B	78	83	48	46
	E	9	9	14	12	C	14	12	22	22
	F	23	19	27	28	D	19	21	11	12
	G	39	40	61	61					
	H	29	37	11	10					
Females	B	0	0	1	0	A	41	37	27	36
	C	0	0	0	1	B	84	91	70	59
	D	7	8	14	8	C	16	15	22	17
	E	8	8	13	25	D	13	12	12	14
	F	30	28	51	44					
	G	52	43	62	54					
	H	21	19	8	9					

respectively. Accuracy was defined as the mean of the estimation errors.

Empirical distribution functions of the estimation errors displaying the cumulative relative frequency of the errors in the form of an increasing step function were calculated separately for each wisdom tooth, for mineralization and eruption as well as for females and males. In addition to the estimations using the individual wisdom teeth, the mean of the individual dental age estimations were calculated using all assessable wisdom teeth.

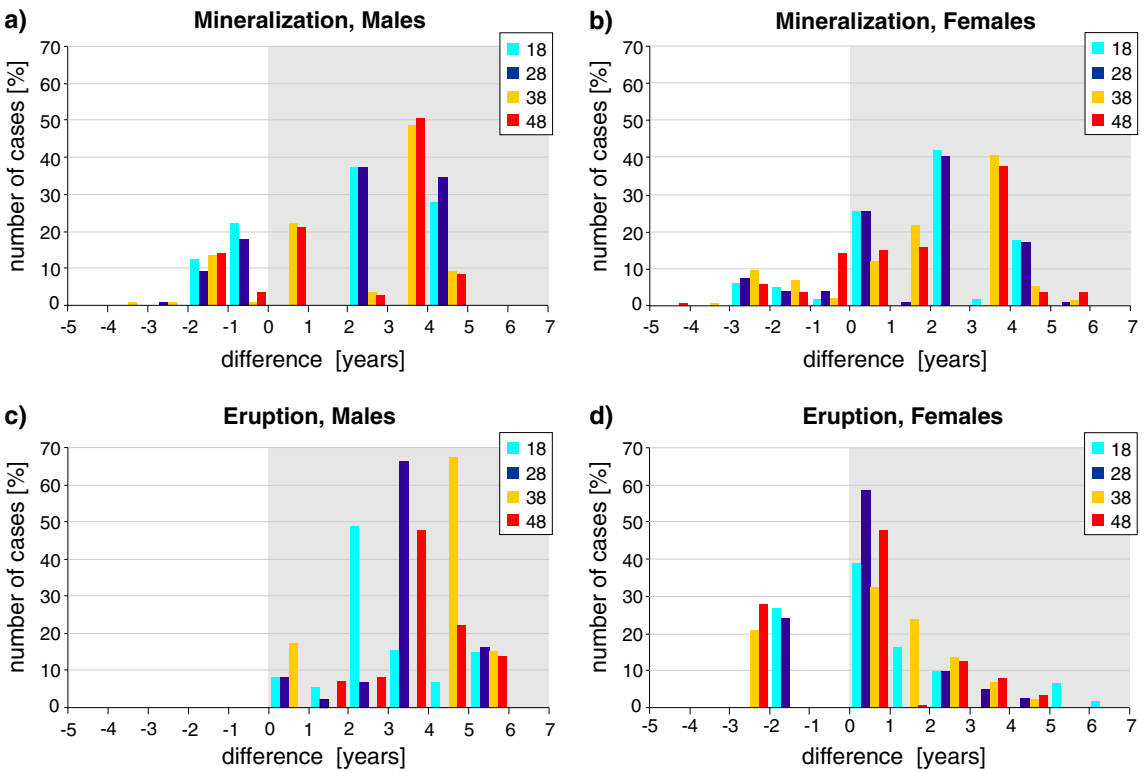

Fig. 1 Distribution of the estimation errors based on standard reference data on mineralization and eruption. The height of the columns represents the relative number of evaluated cases in percent with different colors for the individual wisdom teeth (18, 28, 38, 48); the *x-axis* shows the absolute difference between the estimated dental age and chronological age in years. A positive difference stands for an overestimation (*shaded area*), negative values correspond to underestimations

Proposition of adjusted reference values

Adjusted reference values were obtained by subtracting the median estimation error from the standard reference value of the individual wisdom teeth, thereby forcing the adjusted empirical distribution functions to become 0.5 at a difference between estimated dental age and chronological age of 0 years. This procedure corresponds to a parallel shift of the empirical distribution functions of each individual wisdom tooth and of the mean distribution function of all wisdom teeth. As adjusted standard deviations, the standard deviations of the estimation errors were calculated.

For the use of the mean of all assessable wisdom teeth to estimate dental age, correction factors and corresponding standard deviations were calculated. The respective correction factor is added to the mean estimated dental age of all assessable wisdom teeth, correcting for slight statistical irregularities in the centering of the mean empirical distribution function.

Results

Validation of reference data

Figure 1 shows the distribution of the errors of dental age estimations based on the standard reference data for mineralization and eruption of the individual wisdom teeth in males and females. Age prediction relying on mineralization resulted in overestimations, i.e., positive differences, cumulated up to 5 years in 65–84% of the males, depending on the respective wisdom tooth, and up to 6 years in 75–87% of the females. In males the average overestimation of all wisdom teeth was 2.1 years; the highest rate of overestimations was seen in the mandibular wisdom teeth

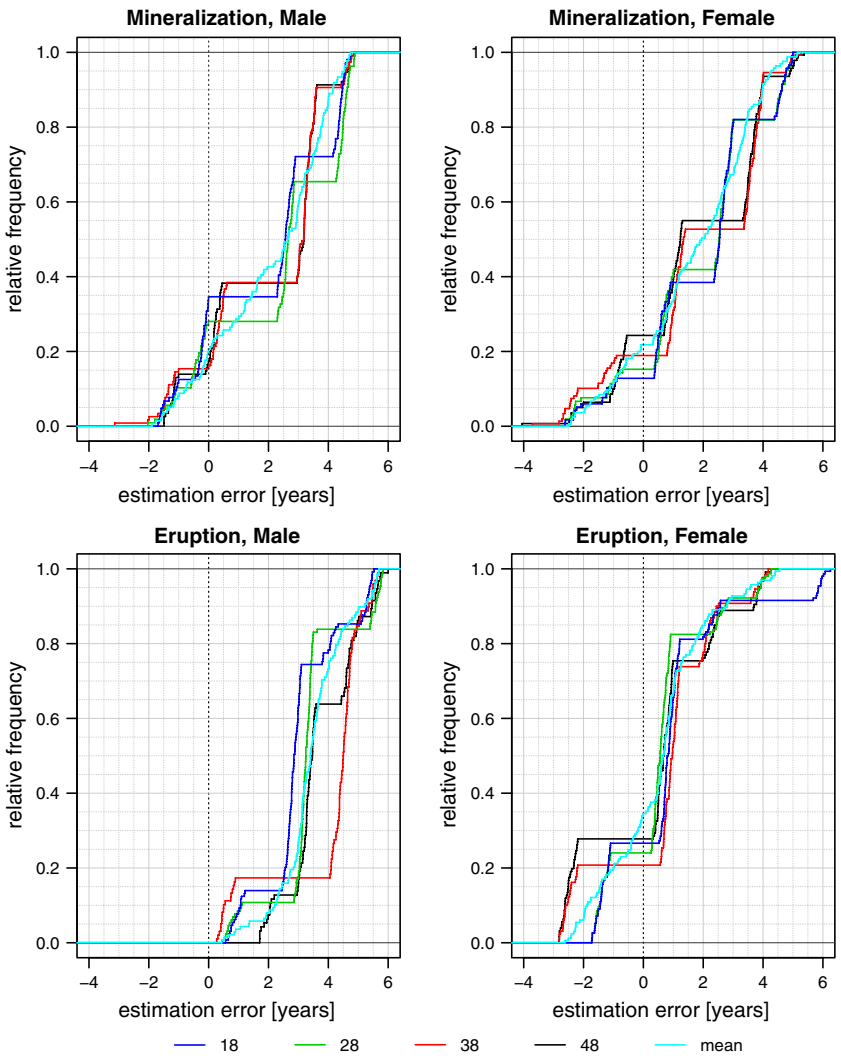

Fig. 2 Empirical distribution functions of the estimation errors concerning mineralization and eruption based on standard reference data. Functions are shown for the individual wisdom teeth and their mean (*different colors*). The *x-axis* shows the absolute difference between estimated dental age and chronological age in years. The *y-axis* represents the relative frequency. Example: the proportion of males being overestimated less than 2 years using the eruption stage of tooth 18 is about 0.1, i.e., 10%

with up to 50%. In most cases of underestimations in men, the error was less than 2 years. These underestimations were almost independent from the specific wisdom tooth and affected between 9% and 14%. In females, the mean overestimation of all wisdom teeth was 1.9 years, while the rate of overestimations was similar for the different wisdom teeth with proportions between 37% and 42%. However, in the mandibular teeth, the overestimations were greater with a mean of slightly more than 3 years. Generally, underestimations in women were broadly distributed up to 3 years irrespective of the concerned wisdom tooth. Based on eruption stages, dental age of both, males and females, was mostly overestimated. In males 100% of the subjects were overestimated by 3.5 years on average and maximal differences of up to 6 years. The highest rates of overestimations with about 67% were found for the teeth 28 and 38. Depending on the specific wisdom tooth, about 75% of the females were overestimated. In most cases and for all wisdom teeth, the overestimation was only 1 year or less (mean, 0.6 years); however, there were 13 women where the error based on tooth 18 was between 5 and 7 years. Underestimations occurred in about 25% of the women and were between 1 and 2 years for the maxillary wisdom teeth and between 2 and 3 years for the mandibular wisdom teeth.

Figure 2 shows the empirical distribution functions of the cumulated relative frequencies of the differences between estimation and chronological age separately for mineralization and eruption. Each curve corresponds to a single wisdom tooth. Ideally, the relative frequency should increase from 0 to 1 corresponding to 0–100% over a range of time as narrow as possible, e.g., from −1 to 1 year, meaning that the maximum error of the estimation would be ±1 year. Additionally, a difference of 0 years should optimally correspond to a relative frequency of 50%. However, the curves showed that an error of 0 years corresponded to frequencies between 0% in the case of eruption in males up to about 30% in the eruption in females. The relative frequency of 100% was reached at an error of up to 6 years.

The mean differences between estimated and chronological age were associated with the respective mineralization and eruption stage. Figure 3 shows that the extent of the estimation error directly depends on the found developmental stage. The higher the stage, the higher was the risk of overestimation. Overestimations in mineralization started at the stage F and reached a maximum of 4.4–4.7 years—depending on the wisdom tooth—for stage H in males and 4.7–5.1 years in females, respectively. The mineralization stages B to E were associated with underestimations from about 4 to 0.8 years. Standard deviations (not shown in the figure) in males were between 0.06 and 0.39 years, in females between 0.16 and 0.67 years. The mean differences between estimated and chronological age using eruption

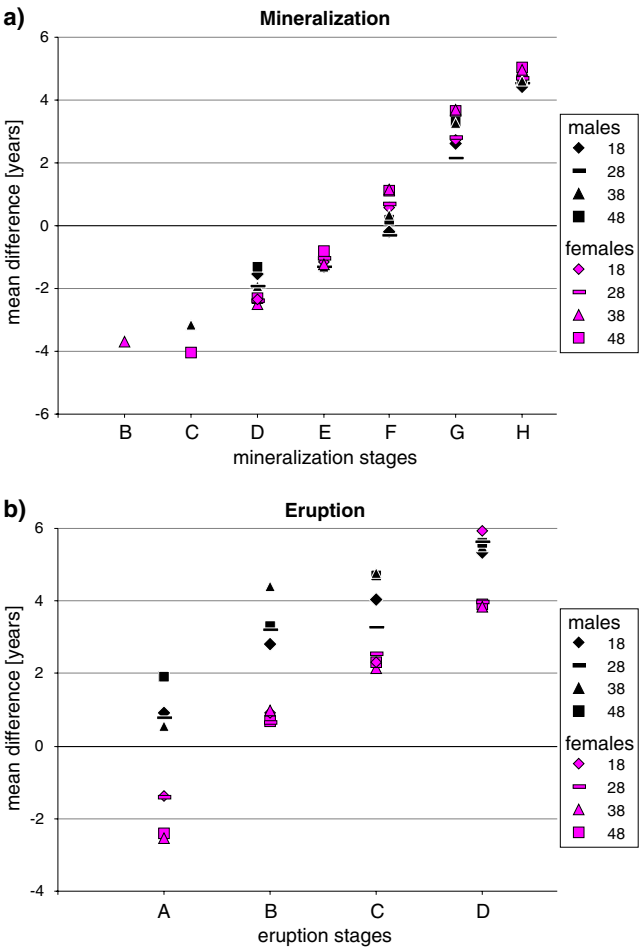

Fig. 3 Mean differences in years between estimated and chronological age corresponding to the different mineralization and eruption stages, respectively. *Pink data points* correspond to the values found for the different wisdom teeth in females, *black data points* stand for the values found in the males. For better visibility standard deviations are not shown

similarly showed to be correlated with the stage. In women stage A was associated with an underestimation of 1.4–2.5 years—depending on the wisdom tooth—while wisdom teeth being in the other stages led to overestimations. In men all stages were associated with overestimations up to 5.6 years. Standard deviations of the mean differences in eruption (not shown in the figure) in males were between 0.12 and 0.21 years, in females between 0.15 and 0.74 years.

Interobserver agreement

Interobserver agreement was moderate for the maxillary wisdom teeth with Cohen's kappa values of 0.39 (tooth 18; N=222) and 0.42 (tooth 28; N=213). For the mandibular wisdom teeth, the agreement was good with a kappa of 0.58 (tooth 48; N=256) and 0.60 (tooth 38; N=266), respectively. The mean differences between the two examiners were 0.11–

Table 2 Adjusted reference values in years [mean and standard deviation (SD)] for the mineralization stages B–H for the individual wisdom teeth

Mineralization		Wisdom tooth							
	Stage	18		28		38		48	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Males	B	11.8	2.1	12.9	2.1	10.1	2.0	n.a.	n.a.
	C	11.0	2.1	11.9	2.1	11.4	2.0	11.3	2.0
	D	13.9	2.1	13.7	2.1	13.1	2.0	13.5	2.0
	E	14.1	2.1	14.0	2.1	13.5	2.0	13.5	2.0
	F	15.2	2.1	15.1	2.1	15.1	2.0	15.0	2.0
	G	18.0	2.1	18.0	2.1	18.1	2.0	18.1	2.0
	H	19.9	2.1	20.0	2.1	19.5	2.0	19.5	2.0
Females	B	12.0	2.0	10.1	2.0	12.7	2.2	12.6	2.2
	C	11.7	2.0	12.6	2.0	13.2	2.2	12.9	2.2
	D	13.2	2.0	13.2	2.0	14.2	2.2	14.5	2.2
	E	14.3	2.0	14.5	2.0	15.5	2.2	16.0	2.2
	F	16.1	2.0	16.2	2.0	17.8	2.2	17.8	2.2
	G	18.2	2.0	18.2	2.0	20.4	2.2	20.5	2.2
	H	20.2	2.0	20.2	2.0	21.7	2.2	21.9	2.2

The SD for each wisdom tooth is identical for all stages

0.17 on average with the scores of examiner MM slightly higher than those of examiner HM.

Proposition of adjusted reference values

The new reference values resulting from the adjustment of the distribution functions of the cumulated relative frequency are listed in Tables 2 and 3. As every point of each curve was shifted by the same amount, the standard deviation is the same for every stage of a certain tooth. Figure 4 shows the effect of the proposed adjustments on the accuracy of the estimations of dental age compared to those based on the standard reference values. The use of the adjusted values for the estimation of dental age resulted in considerably smaller differences from chronological age than the standard reference values. Using the adjustments the estimation errors range from 0 to 1.2 years and mostly correspond to underestimations of up to 1.5 years. Residual small overestimations by up to about half a year occur for the mineralization stages in females in tooth 38 and 48 as well as for the eruption in both, males (teeth 18, 28, and 48) and females (tooth 18).

Correction factors and standard deviations for the estimation of dental age using the mean of all wisdom teeth ($mean_{teeth}$) are given in Table 4. Standard deviations are generally smaller as those when using a single wisdom tooth.

Table 3 Adjusted reference values in years [mean and standard deviation (SD)] for the eruption stages A–D for the individual wisdom teeth

Eruption		Wisdom tooth							
	Stage	18		28		38		48	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Males	A	16.1	1.3	15.6	1.3	14.1	1.6	16.4	1.1
	B	18.0	1.3	18.0	1.3	17.9	1.6	17.8	1.1
	C	19.3	1.3	18.2	1.3	18.3	1.6	19.2	1.1
	D	20.6	1.3	20.5	1.3	19.1	1.6	20.2	1.1
Females	A	15.8	1.9	16.0	1.5	14.5	1.9	14.8	2.1
	B	18.1	1.9	18.0	1.5	17.9	1.9	18.0	2.1
	C	19.5	1.9	20.0	1.5	19.2	1.9	19.6	2.1
	D	23.2	1.9	21.4	1.5	20.9	1.9	21.3	2.1

The SD for each wisdom tooth is identical for all stages

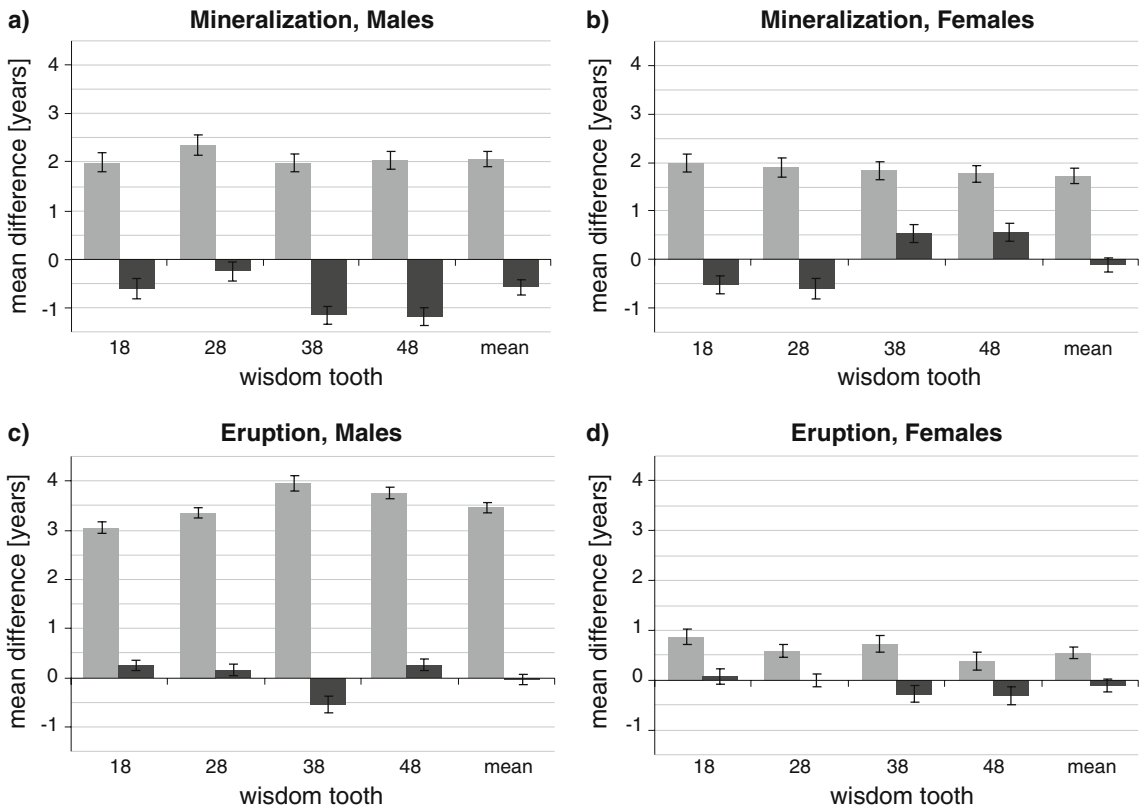

Fig. 4 Accuracy of estimations of dental age using standard reference values (*light gray*) and adjusted reference values (*dark gray*), respectively. The *y-axis* represents the mean difference between estimated dental age and chronological age in years. *Error bars* show the standard error of the mean

Discussion

Standard reference values for the estimation of dental age based on mineralization and eruption stages of the wisdom teeth in a German population were validated using the orthopantomograms of a sample of Central European males and females with known age around their 18th birthday. The aim was to investigate how well the estimated dental age corresponds to chronological age, and to analyze eventual differences between the two. New reference values resulting from a statistical adjustment were proposed in view of a reduction of estimation errors.

The main finding was that the estimations of dental age relying on mineralization resulted in overestimations in 76% of the males and 82% of the females with differences between estimated and chronological age of 2 years on average, and up to 6 years in individual cases. Using eruption stages, all men and 75% of the women were overestimated by up to 7 years. The estimation error was associated with the mineralization and eruption stage, respectively, with greater overestimations with each higher stage starting at stage F for mineralization and stages A–B for eruption. Although the investigated sample of persons was particular with a very narrow age range, the results of estimated dental ages being about 2 years on average too high are impressive.

To check for a potential influence of the examiner evaluating the developmental stages, mineralization was assessed by a second examiner. The systematic slightly higher scoring of the more experienced examiner confirms the reliability of our conclusions which are based on the evaluations of the less experienced and, thus, more cautious examiner.

The main reason for the clear overestimation in most of the cases lies most probably in the age range of the investigated samples used in the corresponding reference studies [5, 7, 15]. As shown in a recently published study,

Table 4 Correction factors and standard deviations (SD) in years for the estimation of dental age using the mean of all assessable wisdom teeth

	Correction factor	SD
Mineralization, males	0.176	1.842
Mineralization, females	−0.064	1.954
Eruption, males	0.008	1.131
Eruption, females	0.109	1.625

the age of the sample used in reference studies should ideally cover the entire range of age during which the investigated feature develops, and, additionally, a uniform age distribution should be provided [17]. The reference values used in this study for both, mineralization and eruption, were based on samples with an age range from 12 to 26 years. While the lower limit of 12 years seems to be reasonable particularly for the diagnosis of an age limit of 18 years, the upper limit of 26 years is rather high compared to other reference studies [4, 17–19]. Additionally, the distribution of the ages in both reference studies used is not uniform with a proportion of persons of 18 years and older of about 60% (eruption in females) to over 90% (eruption in males). The influence of a disproportionate inclusion of persons with a high probability of completed dental development leads to a bias with higher estimations of dental age [17, 20]. This effect can clearly be shown by the results of this study. The most important conclusion of the presented analysis is that reference values to estimate dental age should be used very cautiously, particularly in cases with higher developmental stages.

To overcome the demonstrated problems, several strategies can be discussed. Prospective studies allow investigating samples with a well-balanced age range. However, they require a greater effort in recruiting appropriate volunteers, particularly, as the performance of an orthopantomogram without medical indication will not be legal in most of the countries. For retrospective studies with imbalanced age range of the investigated sample, a weighting of the persons in the sample to balance the configuration of the sample related to chronological age was proposed [17]. At last, to test a method of handling the bias on the level of a user of published reference data, a statistical adjustment of such reference values was proposed here. It could be shown that the differences between estimated dental age and chronological age were generally reduced. As a side effect, the proportion of persons being underestimated increased using the proposed adjusted reference values.

Taking a mean of all present wisdom teeth led to slightly smaller standard deviations. Particularly if some of the third molars are missing, it seems reasonable to use all available data.

Regarding limitations of the study, it has to be considered that the age range of the sample used in this study was very narrow covering an interval of less than 1 year, however, with a symmetrical distribution of the sample around the 18th birthday. Conclusions concerning the applicability of the standard reference values to samples of other ages cannot be drawn, as they have only been tested for the specific age range of the used sample. Regarding the ethnic origin of the examined persons, a certain error rate has to be admitted as the exclusion of persons with an origin different from Central Europe was performed on the basis of the names which, e.g., does not allow for adoptions.

In conclusion, the validation of reference values for the estimation of dental age by assessing mineralization and eruption stages in a German population with a sample of persons living in Switzerland showed that on average, the persons of the sample were clearly overestimated by about 2 years. A statistical adjustment of the reference values was proposed which resulted in more accurate estimations of dental age in persons around the age limit of 18 years. This method could serve as a workaround for reference studies with imbalanced age ranges.

Conflict of interest The authors declare that they have no conflict of interest.

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