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New forensic approach to age determination in children based on tooth eruption

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Abstract

The present study proposes equations for age determination both in living and dead children, obtained with the help of stepwise ascending multiple linear regression. The equations should be applied, based on the number of erupted teeth and tooth germs, which were detected on radiographs, during clinical examination and in infant skeletal remains. The proposed equations proved to be efficient just like Demirjian's method used as a reference today, and permit age estimation till 20 years of age.

Keywords: Age determination; Children; Erupted teeth; Tooth germs; Multiple regression analysis

1. Introduction

In children, the determination of the number of erupted teeth might contribute to the estimation of age at death as well as to the identification procedure of unknown skeletons by trying to find concordance with disappeared children's characteristics, with the help of which personal identity can finally be confirmed or excluded. However, it also allows the age evaluation of living children with unknown identity, suspected of crime or violence with aggravating circumstances by the police. This later case has a great importance, since in French law the penal threshold established at the ages of 13, 16 and 18 years, initiates different penal proceedings [1–3]. Children's age determination can be realized first by matching the dental status with the reference drawings of Ubelaker or with the average age of eruption diagrams [4]. It was Hagg and Taranger [5] who pointed out that the examination of short period phenomenon, such as dental eruption, are preferable to the more arbitrary long-period based studies, which actually use variables like phases of tooth formation in infants of 6–25 months of age. The analyses of Gustafson and Koch [6] resulted in the "tooth development diagram", which gives a correlation between dental development and age, based on the four developmental stages of teeth (initiation of calcification, crown completion, eruption and root completion), with a precision of <2 months. The method is easy to use, by reading the diagram with the help of a ruler, but applicable only in children of 3–13 years of age. This method was slightly altered by Kashyap and Koteswara Rao [7]. Another interesting method was proposed by Liliequist and Lundberg [8], a correlation between the radiological length of 11 ossification centers in the left hand and of the left inferior dental quadrant was set up in a population between 6.5 and 14.5 years of age divided in 1-year age classes.

Concerning the above mentioned methods, we have to keep it in mind that Bernhard and Glocker [9] demonstrated on a female population of 5–13 years of age that there is no acceleration in the development of the permanent dentition during the course of centuries, the results suggest that the human dentition is primarily genetically determined [8]. Triratana et al. [10] pointed out that environmental factors play a lesser role in dental development than general physical development. In concordance with this, the results of Townsend and Hammel [11] showed that the dental eruption

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sequence in children, i.e. the number of teeth present in the mouth, is significantly independent of the environmental influence and can provide a more accurate and unbiased age estimation than height measurement, and as good as the results of Demirjian's method, today's reference work [11–14]. It should be noted that Towlson and Peck [15] as well as Kraul and Pathak [16] unsatisfactorily carried out a correlation analysis in young populations of 2–44, and 4–31 months of age, respectively, concerning height and weight, and the number of erupted teeth. Kumar and Sridhar [4] proposed an average age of eruption for each tooth. In teenagers, near the age of 18 years, which is the majority threshold in France, age determination raises above all the question concerning the eruption of the third molar teeth. However, the different analyses regarding the wisdom teeth do not seem to yield precise conclusions [17–22].

At present, the calculation of age estimates is much more precise. It seems that both the original and simplified formulas of Demirjian et al. [13], Demirjian and Goldstein [14] are easy to use and have practical interests. His method is founded on developmental stage evaluation, i.e. germ formation, development and eruption, of either 7 teeth (I1, I2, C, PM1, PM2, M1, M2) or 4 teeth (I1, PM1, PM2, M2 or PM1, PM2, M1, M2) in the left half of the mandible, transformed into scores, of which sum gives, from tables, the age of the individual. It originally tested on a Canadian child population of 3–16 years of age, and validated on Norwegian children of 5.5–12.5 years of age [23], but did not yield reliable results in Asian people [24] and Indians [25], which was explained by diversity of development stages in children between 5 and 12 years of age [26].

Furthermore, we have to note that age determination encounters a lack of precision not only due to the applied method, but also to the observers [27,28].

To summarize it, we can say that the age of an unknown immature individual can be fairly reliably determined from the dentition and its eruption sequence. Although it seems that none of the techniques is easy to use and practical at the same time for the forensic practitioner, and most of them result in a slight over or underestimation depending on the applied technique [29], but Demirjian's method still yields the best results. New models easier to use yielding more accurate results are required.

The aim of the present study is to provide mathematical models for age calculation based on counting erupted teeth, and, if possible, germs, applicable both in clinical and radiological examinations.

2. Material and methods

2.1. Preliminary data base

A preliminary sample, selected in a university-affiliated Department of Odontology consisted of 810 panoramic radiographs of 397 boys (49.0%) and 413 girls (51.0%) of 6.10–21.08 years of age (average age of 12.63 years). We collected individuals presenting one erupted first permanent molar, with intact healthy arches and no congenitally missing teeth. The number of each type of erupted tooth was simultaneously determined by two observers on the radiographs. To define the criterion of tooth eruption from a radiological point of view, we considered that the line lying over the erupting tooth's cusps had to reach over the line joining the mesial and the distal cemento–enamel junctions of adjacent teeth. The number of germs was also noted. A germ was considered to be present at the stage of crown calcification, corresponding to Demirjian's stage A [13,14].

The studied variables were age (AGE), number of permanent upper and lower incisors (P.U.INC. and P.L.INC.), canines (P.U.CAN. and P.L.INC.), premolars (U.PM. and L.PM.), 1st molars (P.U.1MOL. and P.L.1MOL.), 2nd molars (P.U.2MOL. and P.L.2MOL.) and 3rd molars (U.WISD and L.WISD.), number of deciduous upper and lower incisors (D.U.INC. and D.L.INC.), canines (D.U.CAN. and D.L.CAN.), molars (D.U.MOL. and D.L.MOL.), number of germs, except those of the 3rd molars, and germs of the 3rd molars (GERMS and WISD.GERMS).

This preliminary sample allowed us to set up regressive models for age calculation (Table 1).

To improve the accuracy of predicted age, we set up a mathematical model taking into account several variables in order to calculate the continuous variable, which is real age, i.e. we used a stepwise ascending multiple regression analysis [30–32]. It was the equation of the multiple regression analysis based on the selected relevant variables which enabled us to calculate the estimated age of an individual.

Table 1
Explicative variables correlated to actual age for regressive models 1–4

Variables	Coefficients			
	Model 1	Model 2	Model 3	Model 4
Constant	16.088	13.652	13.704	9.726
D.U.INC.		−0.514	−0.567	
D.U.MOL.		−0.236	−0.367	
D.L.INC.				−0.571
D.L.CAN.				−0.378
P.U.CAN.		0.314	0.530	
P.U.1MOL.	−0.226	−1.748	−1.449	
P.U.2MOL.	1.564	1.012	1.359	
U.WISD.	0.832	0.944	2.041	
L.P.M.		0.252		0.579
P.L.2MOL.		0.285		1.056
L.WISD.	0.912	1.537		2.236
GERMS	−1.699			

As a result, the step by step ascending multiple regression analysis yielded four regressive models:

- Model no. 1, based on the integration of all the variables, permitting to determine the age of a dead or living person from the radiographs showing dental germs. The age is calculated by the following computational formula:

$$\text{Estimated age 1} = 16.088 - (0.226 \times \text{number of erupted permanent upper 1st molars}) + (1.564 \times \text{number of erupted permanent upper 2nd molars}) + (0.832 \times \text{number of erupted upper } 3rd \text{ molars}) + (0.912 \times \text{number of erupted lower } 3rd \text{ molars}) - (1.699 \times \text{number of germs on radiographs except wisdom tooth germs}).$$

- Model no. 2, based on all the variables, except those of the germs; this model is supposed to be used in the absence of radiographs, when only data from the clinical intra-buccal examination are available.

  The age is estimated by the following formula:

$$\text{Estimated age 2} = 13.652 - (0.514 \times \text{number of erupted deciduous upper incisors}) - (0.236 \times \text{number of erupted deciduous upper molars}) + (0.314 \times \text{number of erupted permanent upper canines}) - (1.748 \times \text{number of erupted permanent upper 1st molars}) + (1.012 \times \text{number of erupted permanent upper } 2nd \text{ molars}) + (0.944 \times \text{number of erupted upper wisdom teeth}) + (0.252 \times \text{number of erupted lower premolars}) + (0.285 \times \text{number of erupted permanent lower 2nd molars}) + (1.537 \times \text{number of erupted lower 3rd molars}).$$

- Model no. 3, based on the variables of maxillary teeth except those of the germs; this model can be applied in the case of incomplete skeletal remains, where only the maxillary teeth are available.

  The age is estimated by the following formula:

$$\text{Estimated age 3} = 13.704 - (0.567 \times \text{number of erupted deciduous upper incisors}) - (0.367 \times \text{number of erupted deciduous upper molars}) + (0.530 \times \text{number of erupted permanent upper canines}) - (1.449 \times \text{number of erupted permanent upper 1st molars}) + (1.359 \times \text{number of erupted permanent upper 2nd molars}) + (2.041 \times \text{number of erupted upper 3rd molars}).$$

- Model no. 4, based on the variables of mandibular teeth, except those of the germs, applied to incomplete skeletal remains where only the mandible is available.

  The age is estimated by the following formula:

$$\text{Estimated age 4} = 9.726 - (0.571 \times \text{number of erupted deciduous lower incisors}) - (0.378 \times \text{number of erupted permanent lower canines}) + (0.579 \times \text{number of erupted lower premolars}) + (1.056 \times \text{number of erupted permanent lower 2nd molars}) + (2.236 \times \text{number of erupted lower 3rd molars}).$$

2.2. Modern validation sample

A validation sample of 290 children of known age examined in two university-affiliated Departments of Odontology (190 in Marseilles and 100 in Dijon) consisted of 143 boys (49.3%) and 147 girls (50.7%) between 6.56 and 20.23 years of age (average age of 12.11 years). Their panoramic radiographs permitted to calculate the estimated age with a 95% confidence interval for each child using the four regressive model equations. These radiographs also provided data for the age determination of the 100 children from Dijon (49 boys and 51 girls) between the ages of 7.54 and 19.15 years (average age of 11.64 years). In order to estimate the age of each child, we applied Demirjian's method for seven teeth and the four regressive models obtained from the preliminary data base.

2.3. Osteoarcheological validation sample

A sample of 25 child skeletons was selected from the series of Fédons and Observance, originating from Lambesc and Marseilles, and dating from the 16th and the 18th centuries, respectively [33]. The age at death was determined according to the "dental" method (based on the tables of Ubelaker), according to an "osseous" method (based on the stages of epiphyseal union and the diaphysal length) and, lastly, according to three of the regressive models (Models no. 2–4), since model no. 1 is not applicable in the absence of radiographs.

2.4. Data analysis

The known real ages of the children composing the samples were determined in years and decimals by the software EPI INFO® (CDC/ENSP) and their distribution within the preliminary and validation samples were tested by the Kolmogorov–Smirnoff–Lilliefors test.

The regressive models were applied according to a multiple regression analysis using a stepwise ascending selection, with a 5% level of significance for the selected variables.

The regression analyses between the different variables and real age were carried out by Pearson's test. To compare the means between the age estimates and real ages, we used the parametrical Student's *t*-test, the paired *t*-test or the Anova. All these statistical analyses were carried out with the software SYSTAT 8.0® (SPSS), with a 5% level of significance.

3. Results

3.1. Regressive models

The mean age did not show significant sex differences in the modern validation sample ($P = 0.40$; *t*-test), including the Dijon sample ($P = 0.49$; *t*-test).

The set of explicative variables was correlated with the real age (Table 2).

On the one hand, a positive and quite strong association was found between the real ages and age estimates derived from the models 1, 2 and 4 ($r = 0.786$, 0.782 and 0779, respectively, with $P = 0.00$, by the Pearson's test) (Table 3), revealed as precise estimates, since no significant difference was observed between them and the real ages ($P = 0.08$, 0.07 and 0.10, respectively, by the paired *t*-test) (Table 4).

On the other hand, the model 3 did not yield a precise estimate: the difference observed between the estimate and the real age (0.27) was significant ($P = 0.02$, paired *t*-test). The regressive models showed confidence intervals of ±3.5 years (Models 1 and 2), ±3.7 years (Model 3) and ±3.8 years (Model 4) (Table 4).

With regard to confidence interval, all the formulas yielded high rated age estimates (95.17% for the Models 1 and 2, 95.86% for the Model 3 and 97.24% for the Model 4), and the best rates were obtained for the widest confidence intervals. However, these percentages were not very different compared to each other (by the χ^2-test $P = 0.87$ for the Model 1 or 2 versus the Model 3, $P = 0.85$ for the Model 1 or 2 versus the Model 4, $P = 0.96$ for the Model 3 versus the Model 4).

Table 2
Correlation between variables and chronological age in data base sample

	r	*P*-value
P.U.INC.	0.34	0.00
P.U.CAN.	0.70	0.00
U.P.M.	0.69	0.00
P.U.1MOL.	−0.12	0.02
P.U.2MOL.	0.74	0.00
U.WISD.	0.43	0.00
P.L.INC.	0.18	0.00
P.L.CAN.	0.65	0.00
L.P.M.	0.71	0.00
P.L.1MOL.	−0.12	0.01
P.L.2MOL.	0.70	0.00
L.WISD.	0.50	0.00
D.U.INC.	−0.30	0.00
D.U.CAN.	−0.68	0.00
D.U.MOL.	−0.69	0.00
D.L.INC.	−0.18	0.00
D.L.CAN.	−0.63	0.00
D.L.MOL.	−0.69	0.00
GERMS	−0.77	0.00
WISD.GERMS	0.18	0.00

3.2. Comparison between Demirjian's method and the regressive models concerning age estimation

Regarding the global sample: the age estimates determined by Demirjian's method and our various regressive models (Models 1–4) differed significantly from the real

Table 3
Correlation between chronological age and regressive model estimated ages in validation sample

	r	*P*-value
Regressive age 1, chronological age	0.786	0.000
Regressive age 2, chronological age	0.782	0.000
Regressive age 3, chronological age	0.742	0.000
Regressive age 4, chronological age	0.779	0.000

Table 4
Comparison between chronological and estimated age by regressive models in modern validation sample ($N = 290$)

	Mean error (years)	S.D.	*P*-value (paired *t*-test)
Regressive age 1, chronological age	−0.185	1.838	0.08
Regressive age 2, chronological age	−0.194	1.850	0.07
Regressive age 3, chronological age	−0.274	2.017	0.02
Regressive age 4, chronological age	−0.177	1.845	0.10

Table 5
Comparison between chronological and estimated age by Demirjian's method, models 1–4 in global sample ($N = 100$)

	Mean error (years)	S.D.	*P*-value (paired *t*-test)
Demirjian's method	−0.87	1.42	0.00
Model 1	−0.47	1.80	0.01
Model 2	−0.47	1.85	0.01
Model 3	−0.63	2.15	0.00
Model 4	−0.44	1.67	0.00

ages (paired *t*-test), with an overestimation ranging from 0.44 years (Model 4) to 0.87 years (Demirjian) (Table 5).

According to sex: in boys, a significant difference between age estimates was also observed (ranging from 0.58 to 0.82 years) (Table 6).

In girls, the regressive models yielded a precise estimate, not much different from the real age (paired *t*-test), unlike Demirjian's method, which overestimated it by 0.92 years ($P = 0.00$, paired *t*-test) (Table 6).

According to the quartiles of the sample: the sample analysis by halves showed that all the methods yielded

Table 6
Comparison between chronological and estimated age by Demirjian's method, models 1–4 according to sex

	Boys ($N = 49$)			Girls ($N = 51$)		
	Mean error (years)	S.D.	*P*-value (paired *t*-test)	Mean error (years)	S.D.	*P*-value (paired *t*-test)
Demirjian's method	−0.82	1.63	0.00	−0.92	1.21	0.00
Model 1	−0.61	1.83	0.02	−0.34	1.79	0.17
Model 2	−0.62	1.89	0.02	−0.33	1.82	0.20
Model 3	−0.77	2.17	0.01	−0.50	2.13	0.10
Model 4	−0.58	1.78	0.02	−0.31	1.57	0.18

Table 7
Comparison between chronological and estimated age by Demirjian's method, models 1–4 according to half-sample

	<11.5 years old ($N = 48$)			≥11.5 years old ($N = 52$)		
	Mean error (years)	S.D.	*P*-value (paired *t*-test)	Mean error (years)	S.D.	*P*-value (paired *t*-test)
Demirjian's method	−1.17	1.37	0.00	−0.57	1.40	0.00
Model 1	−0.96	1.75	0.00	0.02	1.72	0.92
Model 2	−1.03	1.79	0.00	0.10	1.73	0.67
Model 3	−1.22	2.06	0.00	−0.02	2.07	0.94
Model 4	−0.94	1.58	0.00	0.06	1.61	0.79

Table 8
Comparison between chronological and estimated age by Demirjian's method, models 1–4 according to quartiles of sample

	<10.5 years old ($N = 25$)			≥10.5 and <11.5 years old ($N = 27$)			≥11.5 and <12.5 years old ($N = 26$)			≥12.5 years old ($N = 22$)		
	Mean error (years)	S.D.	*P*-value (paired *t*-test)	Mean error (years)	S.D.	*P*-value (paired *t*-test)	Mean error (years)	S.D.	*P*-value (paired *t*-test)	Mean error (years)	S.D.	*P*-value (paired *t*-test)
Demirjian's method	−1.24	1.42	0.00	−1.06	1.42	0.00	−0.69	1.16	0.00	−0.44	1.66	0.22
Model 1	−0.95	1.54	0.00	−0.93	2.00	0.02	−0.35	1.67	0.29	0.47	1.70	0.20
Model 2	−1.11	1.73	0.00	−0.91	1.92	0.02	−0.22	1.68	0.50	0.50	1.73	0.19
Model 3	−1.41	2.15	0.00	−1.00	2.04	0.01	−0.40	2.31	0.37	0.43	1.66	0.23
Model 4	−0.79	1.32	0.00	−1.03	1.85	0.00	−0.46	1.67	0.17	0.67	1.33	0.20

Table 9
Comparison between estimated ages calculated on the basis of tooth eruption, long bone diaphyseal length and epiphyseal fusion, and regressive Model 4 in the osteoarcheological validation sample ($N = 25$)

	Mean error (years)	S.D.	*P*-value (Wilcoxon's test)
Estimated age by bone vs. estimated age by teeth	0.24	1.92	0.35
Estimated age by regressive model 4 vs. estimated age by bone	0.93	5.62	0.38
Estimated age by regressive model 4 vs. estimated age by teeth	0.69	4.99	0.44

incorrect estimates under the age of 11.5 years (median), but our method (Models 1, 2, 3, 4) did not show significant difference between the real and estimated age after the age of 11.5 years, unlike Demirjian's method, which overestimated the real age by 0.57 years ($P = 0.00$, paired *t*-test). (Table 7). Moreover, we have to state that significant errors between the age estimates and the various methods were observed in the 1st and in the 2nd quartiles of the sample. Demirjian's method yielded an incorrect estimate for the ages of 11.5 and 12.5 years (3rd quartile of the sample), unlike the regressive models. After the age of 12.5 years, all the methods yielded precise estimates, without significant differences between the averages of true and estimated ages (Table 8).

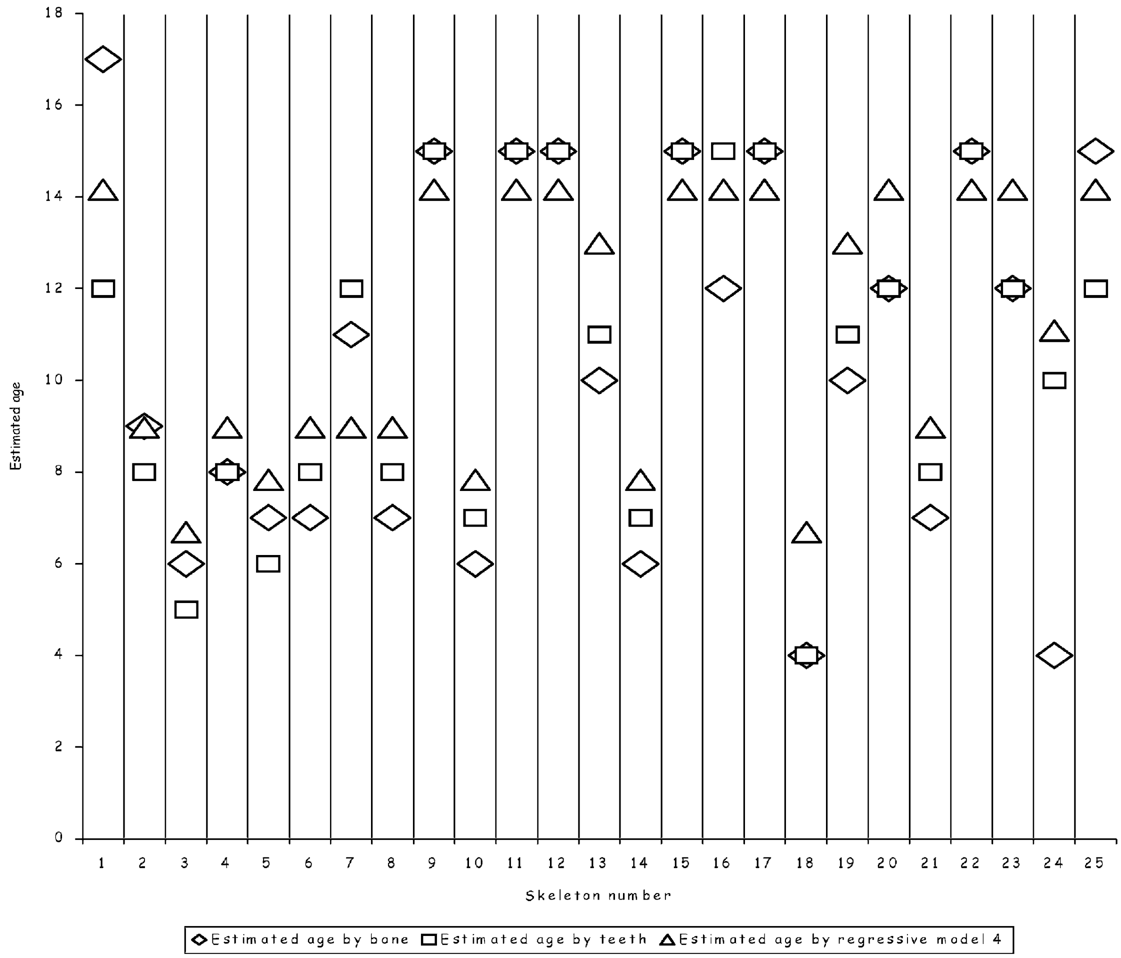

Fig. 1. Comparison between estimated ages calculated on the basis of tooth eruption, long bone diaphyseal length and epiphyseal fusion, and regressive Model 4 in the osteoarcheological validation sample.

3.3. Application of the regressive models of age estimation in past populations

The methods for the determination of "dental" age with the help of Ubelaker's tables, the "osseous" age by the degree of epiphyseal union and diaphyseal length, and the regressive model 4, obtained from the mandibular variables, except those of the germs, do not differ significantly (by the Wilcoxon's test, $P = 0.35$ for "osseous" versus "dental", $P = 0.38$ for "osseous" versus Model 4 and $P = 0.44$ for "dental" versus model 4) (Table 9). The graphical representation shows the superposition of age estimates for different individuals (Fig. 1).

4. Discussion

Age determination is an important problem in forensic anthropology. Odontology might provide solution with the help of specific techniques depending on the fact whether the individual is a child or an adult. In children, the reference method of age determination remains Demirjian's method using four or seven teeth. However, it has several limitations: (1) age cannot be precisely evaluated after 16 years of age; (2) it is based on observations derived from radiographs; (3) the appreciation of developmental stages is difficult because the choice of the tooth developmental stage is quite subjective; and (4) it proved to be applicable in Canadians but not reliable if applied to other populations [34]. The dental development provides a reliable age indicator in children [35,36], although some authors assumed that "skeletal" methods are more accurate [37]. The eruption through the gum, which is an important part of dental development, can be used as an age estimator. There were several studies conducted on the determination of average age based on the number of erupted teeth [4,5,16,38,39]. However, Towlson and Peck questions the reliability of tooth eruption as age indicator [15].

Our work was based on the counting of each type of erupted tooth and the present germs and was carried out on independent samples: a preliminary, and later, on a validation sample. As a result, we propose a 95% confidence interval age estimate, obtained from the models provided by the regression analysis. The calculated ages resulting from the multiple regression analysis (Models 1, 2, 3, 4) were correlated to real age (Pearson's r between 0.786 and 0.742, with $P \leq 0.05$).

The age estimates calculated with the help of the regressive models proved to be reliable estimations of the real age, derived from the formulas using all variables (Model 1), all variables except those of the germs (Model 2), or using all mandibular variables except those of the germs (Model 4). They presented no significant errors in comparison with the real age (paired t-test, $P = 0.08$, 0.07, 0.10, respectively).

The "global" regressive model, based on the utilization of all the variables (Model 1), resulted in the narrowest confidence interval (±3.5 years).

The formula based on the maxillary variables without germs (Model 3) yielded a significant overestimation with 0.27 years (paired t-test, $P = 0.02$).

Demirjian's method was found to globally over-estimate age by almost one year (by the paired t-test, 1.17 years before 11.5 years of age for $P = 0.00$ and 0.69 years between 11.5 and 12.5 years of age for $P = 0.00$). The regressive models used from 11.5 years of age and Demirjian's method from 12.5 years of age appeared to provide reliable estimates, presenting no significant errors in comparison with the real age.

Finally, the age-at-death estimation derived from the regressive models, which uses mandibular variables except those of the germs (Model 4) yielded similar results to those obtained by classical anthropological estimations, resulting from dental data provided by Ubelaker's tables and from osseous data using the degree of epiphyseal union and the diaphyseal length. There was no significant difference found between the means of the "dental", "osseous" and " regressive" age estimates ("osseous" versus "dental": 0.24 years for $P = 0.34$; "osseous" versus regressive model 4: 0.93 years for $P = 0.38$; "dental" versus regressive model 4: 0.69 years for $P = 0.44$, with Wilcoxon's test).

Since three of the regressive models did not yield significant difference between the means of estimated age and real age, we can conclude that they really provide reliable age estimates. These are the Model 1, derived from all the selected variables, the Model 2, derived from all the variables except those of the germs and the Model 4, derived exclusively from mandibular variables except those of germs.

The four formulas provide reliable confidence intervals: indeed, we obtained more than 95% of high rating for the four models applied to the validation sample.

5. Conclusion

Our work proposes a novel method for age determination in children with calculation models, which is as simple and accurate as Demirjian's method. Moreover, it covers the period between 6 and 20 years of age, which suits perfectly the penal requirements. The reliability of formulas was proved to be equal to that of Demirjian's method. This age estimation gave similar results as the other anthropological methods.

All these results allow us to propose four regressive models providing 95% confidence interval age estimates in any situation, i.e. whether there are available panoramic radiographs or not, and even if we have incomplete skeletal remains. Therefore, from a practical point of view, it is possible to quantify age as the central value of the confidence interval. For this reason, we recommend, so far as possible, to use the regressive Model 1, based on reliable variables selected from the whole set.

These new methods of age determination in children provide an original approach for forensic odontologists to answer the questions of the Legal Authorities and the Police concerning the age of a dead or a living child, as well as those of the anthropologists regarding the determination of age-to-death of child skeletons belonging to past populations.

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