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ORIGINAL ARTICLE

Radiographic evaluation of Gustafson's criteria for the purpose of forensic age diagnostics

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Abstract The main criteria used in dental age estimation in living young individuals are mineralisation and eruption of the third molars. In order to further diversify the spectrum of characteristics after completion of third molar development, tests were undertaken to determine whether the characteristics studied by Gustafson can be ascertained with the required forensic certainty with the aid of the orthopantomogram and whether the evaluation of these could render forensic odontological age diagnoses possible beyond the 18th year of life. For this purpose, 1,299 conventionally produced orthopantomograms of 650 female and 649 male Germans aged from 15 to 40 years were studied. The characteristics of secondary dentin formation, cementum apposition, periodontal recession and attrition were evaluated in all the mandibular premolars. The correlation of the individual characteristics with chronological age was studied with the aid of a multiple regression analysis in which chronological age formed the dependent variable. Depending on the tooth studied, the *R* values amounted to 0.65 to 0.73; the standard error of estimate was 5.3 to 5.7 years. Basically, the regression equations calculated can be recommended for age estimation in living individuals, although it should be borne in mind that the applicability of the new method presented is limited by the quality of the X-ray images.

Keywords Forensic age estimation · Dental age · Degenerative changes · Gustafson's criteria · Multiple regression

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Introduction

Within the last few years, forensic age estimation of living individuals has established itself as a research priority within the forensic sciences. The relevant age thresholds for criminal liability in many European countries lie between 14 and 21 years [5].

Referring to age estimation in living individuals undergoing criminal proceedings, the Study Group on Forensic Age Diagnostics recommends the combination of a physical examination with an X-ray examination of the left hand, a dental examination including the determination of dentition status and the evaluation of an orthopantomogram. If hand ossification is complete, an additional radiological examination of the clavicles by means of conventional radiography and/or computed tomography should be performed [25]. A multifactorial approach was also proposed by the Forensic Anthropology Society of Europe [4] as well as by the authors of the practitioner's guide to age estimation in the living [2].

Third molar mineralisation and eruption still represent the main criteria in the forensic odontological age estimation of living individuals in the relevant age group. A forensically usable, reliable demarcation of completion of the 18th year of life only seldom succeeds based exclusively on an evaluation of the mineralisation and eruption status of the third molars [16]. For this reason, various authors have investigated the age dependence of degenerative changes to the teeth and the periodontal apparatus [17, 18, 22–24]. However, the frequency with which the described phenomena occur is also limited and a further diversification of the spectrum of forensic odontological methods would be desirable in view of the completion of the developmental biological growth processes around the 20th year of life.

The introduction of the first scientific method for dental age estimation may be attributed to Gustafson [7–9]. According to Gustafson, regressive changes such as secondary dentin formation, periodontal recession, attrition, apical translucency, cementum apposition and external root resorption are typical phenomena related to the chronological age which has been reached.

Matsikidis [19] was able to prove that the regressive changes—attrition, secondary dentin formation, periodontal recession, cementum apposition and external root resorption—which Gustafson originally described in relation to extracted and ground teeth can also be evaluated using dental films. The present study reassessed whether the characteristics investigated by Gustafson can be determined with the required forensic reliability using the orthopantomogram and whether their evaluation can make forensic odontological age diagnoses possible beyond the 18th year of life.

Material and method

The subject of study were 1,299 conventionally created orthopantomograms of 650 female and 649 male Germans aged from 15 to 40 years, made in the period between 1987 and 2008. Table 1 shows the number of cases in the sample per age cohort, divided by sex. Initially, in a pilot study of 100 randomly selected orthopantomograms, the evaluable lower premolars were each assessed with regard to the characteristics of secondary dentin formation, cementum apposition, external root resorption, periodontal recession and attrition. The exclusion criteria in each case were drawn from the recommendations formulated by Matsikidis [19] (Table 2).

It was determined as a result of the pilot study that an assessment of the manifestation of external root resorption with the aid of the orthopantomogram was not possible with sufficient reliability. The main body of the present study, therefore, dispensed with the assessment of this characteristic. Furthermore, it became apparent that the stage classifications developed by Matsikidis for age estimation using the individual X-ray in relation to the remaining characteristics under assessment required modification. The following stage classifications were used for the characteristics of secondary dentin formation, periodontal recession, cementum apposition and attrition:

Table 1 Distribution of the sample by age and sex

Age (in years)	Male	Female	Total
15	25	25	50
16	25	25	50
17	25	25	50
18	24	25	49
19	25	25	50
20	25	25	50
21	25	25	50
22	25	25	50
23	25	25	50
24	25	25	50
25	25	25	50
26	25	25	50
27	25	25	50
28	25	25	50
29	25	25	50
30	25	25	50
31	25	25	50
32	25	25	50
33	25	25	50
34	25	25	50
35	25	25	50
36	25	25	50
37	25	25	50
38	25	25	50
39	25	25	50
40	25	25	50
Total	649	650	1,299

Secondary dentin formation

Stage 0 Pulp horn reaches to above crown equator

Stage 1 Pulp horn reaches at maximum to crown equator

Stage 3 Pulp horn exceeds enamel–cementum boundary and falls short of crown equator

Table 2 Exclusion criteria according to Matsikidis [19]

	CL	F	C	P	RF	IF	R	IM	AE
AT			x				x	x	
SE	x	x	x	x	x		x		x
PE			x				x	x	
CE				x	x	x			x

C crowned tooth or bridge abutment, *F* filling, partial crown or inlay, *P* post and core restoration, *CL* carious lesion, *RF* root filling, *IF* infected tooth, *IM* impacted tooth, *R* retained root, *AE* apicoectomy, *AT* attrition, *SE* secondary dentin formation, *PE* periodontal recession, *CE* cementum apposition

Stage 4 Pulp horn reaches at maximum to enamel–cementum boundary

Periodontal recession

Stage 0 No periodontal recession
Stage 1 Periodontal recession into cervical root third
Stage 2 Periodontal recession into middle root third
Stage 3 Periodontal recession into apical root third

Attrition

Stage 0 No attrition, cusp tips present
Stage 1 Beginning attrition with loss of cusp tips
Stage 2 Attrition reaching into dentin
Stage 3 Attrition reaching into dentin with opening of pulp cavity

Cementum apposition

Stage 0 No visible cementum apposition
Stage 1 Beginning apical cementum apposition
Stage 2 Clearly visible cementum apposition, reaching beyond the apex

Figures 1, 2, 3 and 4 show schematic drawings and pictures of these stage classifications. Stage 3 of secondary dentin formation and stage 3 of attrition were not found in the examined sample. It is therefore not possible to present images for these stages.

In the main study, identification of the characteristics was undertaken on a randomised and blinded basis, i.e. without knowledge of the dates of birth or of X-ray. The identification number, sex and date of birth of each test subject, the date of X-ray examination as well as the stages of the characteristics of the teeth included in the study were recorded.

The correlation between the individual characteristics and chronological age were studied with the aid of a multiple regression analysis. Chronological age formed the dependent variable. The Gustafson characteristics which were determined were reckoned as independent variables. The modelling of the linear regression model was effected in steps with the prognosis-relevant influencing variables attrition, secondary dentin formation, periodontal recession and cementum apposition. At each stage of this process, the significant influencing variable was selected from the remaining influencing variables. Only influencing variables with a significance value of ≤0.05 were included in the model.

To check for potential multicollinearities between the influencing variables, the variance inflation factor (VIF) value was determined in each case. Multicollinearity means that one independent variable can be represented as a linear function of another independent variable. A VIF value of >4 was considered to be a critical multicollinearity.

Results

Table 3 shows the number of teeth which could not be used for purposes of statistical evaluation on the basis of the predefined exclusion criteria or because of the deficient quality of the X-ray image, with reference to the type of tooth and to sex. Depending on the tooth, 45–60 % of cases were evaluable. All the individual parameters studied on relation to the teeth examined were significantly linked to chronological age.

Multicollinearities were not present. All VIF values lay below the critical VIF value of 4 (cf. Table 4). Tables 5 and 6 show the results of the multiple regression analysis. It can be inferred from the tables that in both men and women, tooth number 45 is best correlated with chronological age.

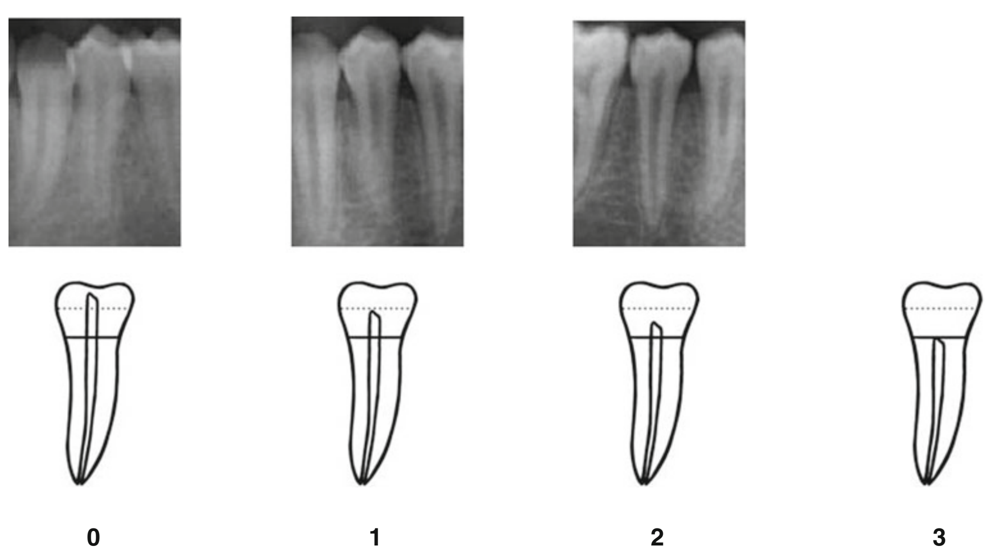

Fig. 1 Stage classification to determine degree of secondary dentin

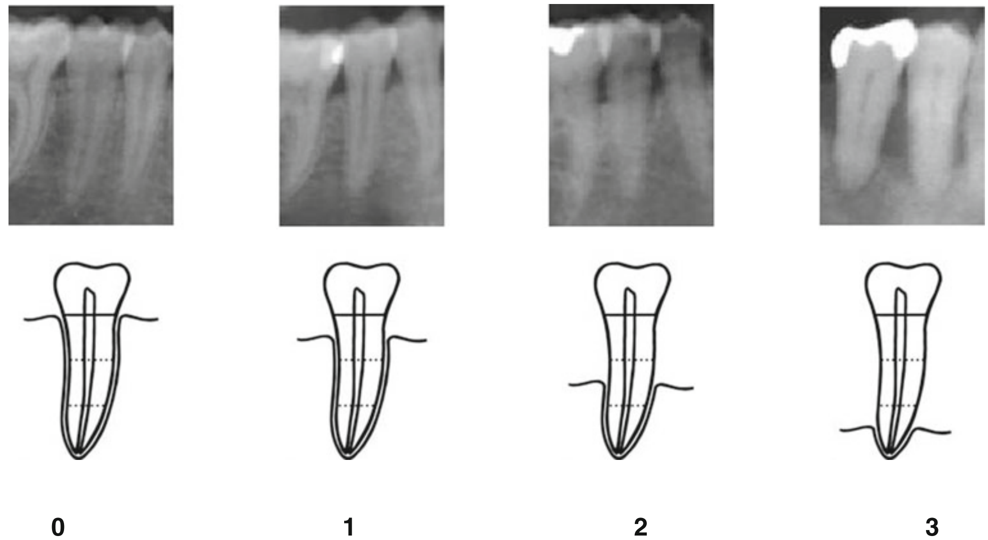

Fig. 2 Stage classification to determine degree of periodontal recession

Discussion

Forensic age estimation of living individuals is a recent focus of scientific interest [11–13, 15, 20, 26, 27, 36]. Third molar mineralisation and eruption still represent the main criteria for forensic odontological age estimation of living individuals in the relevant age group. However, a forensically usable, reliable demarcation of the completion of the 18th year of life based solely on evaluation of the mineralisation and eruption status of the third molars is only successful in exceptional cases, for instance when completely mineralised retained mandibular wisdom teeth are present [16].

Regressive tooth changes are known and attract interest in specialist literature. The degree of severity of these is determined, on the one hand, by the influence of certain environmental factors; on the other hand, these modification processes take place purely in dependence on age and independently of any external influences. Both the hard and the soft tissue of the teeth and the attachment apparatus are subject to constant changes. These commence immediately on eruption and continue throughout life [3, 8, 10, 14, 21, 37].

According to Gustafson [7–9], regressive changes such as secondary dentin formation, periodontal recession, attrition, apical translucency, cementum apposition and external root resorption represent typical age-related phenomena. Gustafson studied a total of 40 teeth; age estimation proceeded on the basis of the combined evaluation of the described parameters. Thin slithers of teeth were examined under the microscope to study and evaluate the progressive change of these parameters. A corresponding score was given depending on the formation of the characteristics. These values yielded a cluster diagram. A regression line was calculated with the aid of which an age estimate became possible in the concrete age estimation case.

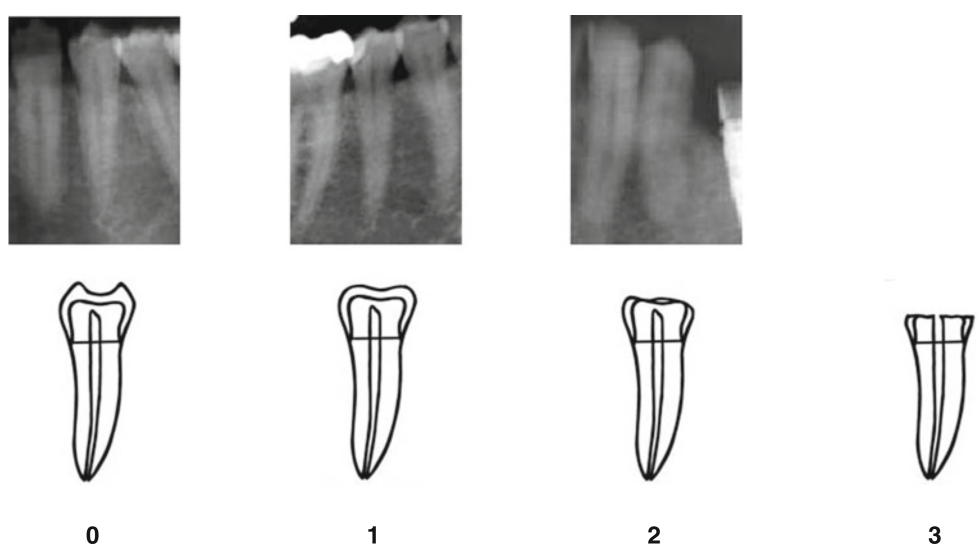

Fig. 3 Stage classification to determine degree of attrition

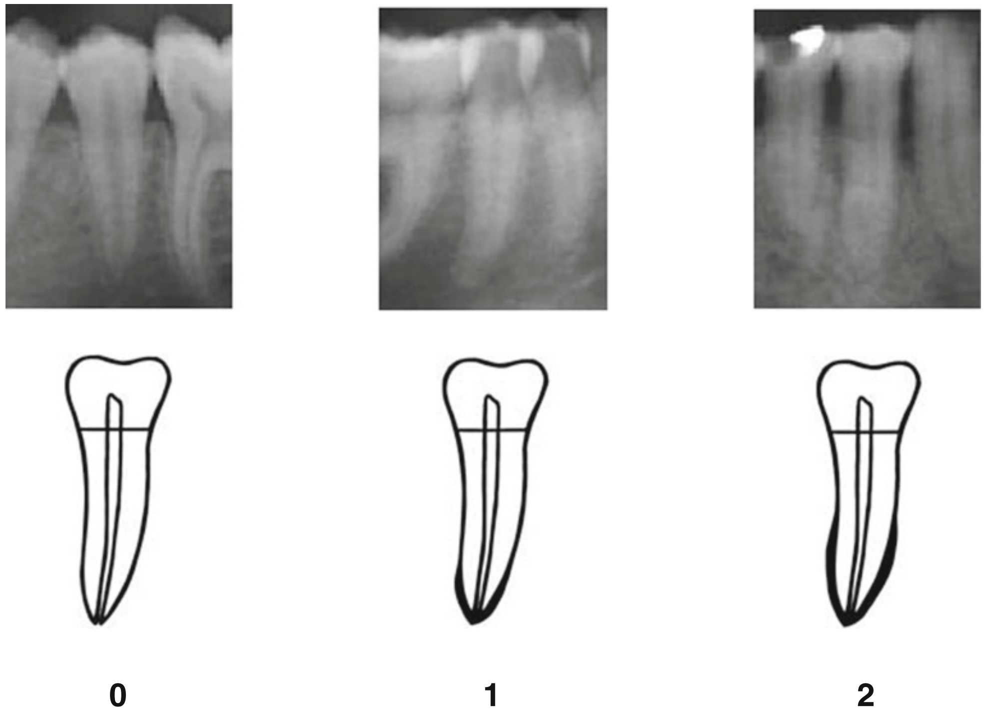

Fig. 4 Stage classification to determine degree of cementum apposition

Solheim [28–35] devoted himself extensively to regressive changes to the teeth and their potential relevance to forensic odontological age estimation. The author's aim was to develop as reliable a method as possible for the dental age estimation of unknown dead individuals and additionally for archaeological cases. As with Bang and Ramm [1], the regressive changes included were to be assessable by examining the extracted, unprepared tooth under the stereoscopic microscope. In principle, Solheim took into consideration some of the age-related characteristics which Gustafson had introduced into the investigation process, such as attrition, root dentin translucency, cementum apposition, secondary dentin formation and recession of the periodontal ligament, and initially tested the suitability of these in isolation [29–33]. Moreover, the author tested other regressive changes to the teeth which were not first described by Gustafson, such as age-related change to the colour of the teeth and the dental root surface structure, in relation to their correlation with the age of an individual [28, 34]. Solheim developed a multiple regression model, created calculation formulae for specific groups of teeth relating to each individual age group and established a new, more accurate, estimation method based on a sufficiently large number of specimens (1,000 teeth) and including as many tooth characteristics with a significant correlation with chronological age as possible. Depending on the group of teeth, correlation coefficients of R=0.76–0.91 were identified [35].

The aim of the present study was to investigate the extent to which this procedure can be applied to the age estimation of living individuals and to what degree certain age-related tooth characteristics displayed in the conventional orthopantomogram are correlated with age. The individuals studied were aged between 15 and 40 years, so the age interval dealt with in forensic age estimation was covered. As an uneven age distribution within the sample can lead to systematic over- or underestimation of age [6], almost without

Table 3 Number of teeth excluded due to pathological changes, teeth which could not be evaluated in relation to all characteristics due to inadequate X-ray image quality and teeth which were included in the statistical evaluation

Tooth	Sex	Number of cases	Excluded teeth	Non-evaluable teeth	Evaluated teeth
34	Female	650	142	125	383
34	Male	649	106	151	392
35	Female	650	284	54	312
35	Male	649	218	80	351
44	Female	650	153	140	357
44	Male	649	98	197	354
45	Female	650	310	49	291
45	Male	649	213	103	333

Table 4 Variance inflation factor values for teeth 34, 35, 44 and 45

Tooth	Males	Females
34	1.31	1.16
35	1.29	1.20
44	1.33	1.31
45	1.42	1.16

exception, 25 male and 25 female individuals per age cohort were included in the study.

The number of regressive changes to the teeth available for selection was naturally limited. In a pilot study, the characteristics of secondary dentin formation, periodontal recession, attrition, cementum apposition and external root resorption were first tested as to their suitability for assessment. It was known from a study by Matsikidis [19] that these characteristics can be determined on conventional dental films at least, and an evaluation of them makes it possible to estimate the chronological age of an individual. With the exclusion criteria formulated by Matsikidis [19] in mind, the assessable inferior premolars of each of the individuals in question were included in our own studies. In the course of the pilot study, it was determined that it was not possible to reproduce the staging proposed by Matsikidis for evaluation of root resorption on the available orthopantomograms. Therefore, this characteristic was excluded from further analysis. For the remaining characteristics, as simple stage classifications as possible with a reduced number of stages and individual stages which are easily distinguishable on orthopantomograms needed to be developed. An attempt was initially made in the pilot study to subdivide each individual characteristic into seven stages, based on Matsikidis [19]. Using the conventional orthopantomogram at least, this procedure was not viable due to limited differentiability. For this reason, the stages used in the present study

Table 5 Regression equations, correlation coefficients (*R*), coefficients of determination (R^2) and standard errors of estimate of multiple regression analyses with age as the dependent variable and dental age changes as independent variables for teeth 34, 35, 44 and 45, males

Tooth	Formula	R	R^2	Standard error of estimate
34	Age=18.43+1.131×CE+4.19×SE+5.202×PE+2.881×AT	0.70	0.48	5.4
35	Age=18.0+1.905×CE+3.662×SE+5.011×PE+3.003×AT	0.70	0.49	5.4
44	Age=18.69+1.292×CE+3.813×SE+5.533×PE+3.14×AT	0.72	0.52	5.5
45	Age=18.28+2.018×CE+3.185×SE+5.433×PE+2.879×AT	0.73	0.53	5.3

CE cementum apposition, *SE* secondary dentin formation, *PE* periodontal recession, *AT* attrition

Table 6 Regression equations, correlation coefficients (*R*), coefficients of determination (R^2) and standard errors of estimate of multiple regression analyses with age as the dependent variable and dental age changes as independent variables for teeth 34, 35, 44 and 45, females

Tooth	Formula	*R*	R^2	Standard error of estimate
34	Age=18.21+3.161×CE+2.4×SE+4.448×PE+4.05×AT	0.67	0.44	5.7
35	Age=17.61+2.596×CE+3.065×SE+5.031×PE+2.687×AT	0.68	0.47	5.5
44	Age=19.11+2.596×CE+2.667×SE+4.3×PE+3.3×AT	0.65	0.43	5.7
45	Age=17.64+3.336×CE+3.161×SE+4.722×PE+2.943×AT	0.69	0.48	5.4

CE cementum apposition, *SE* secondary dentin formation, *PE* periodontal recession, *AT* attrition

are orientated on the smaller number of stages originally used by Matsikidis [19]. Because of the projection of the spinal column on the anterior tooth area which is to be expected for technical reasons associated orthopantomography, the mandibular premolars were included in the study as they are predominantly single rooted and are thus the only suitable group of teeth.

In the present study, stepwise multiple regression analysis was used to develop calculation formulae for the inferior premolars to estimate the age of an individual, taking into account regressive tooth changes with a significant correlation to age, and to determine the corresponding correlation coefficients. The calculated *R* values range from 0.65 to 0.73 and thus turn out to be inferior to the values, for example, which Solheim [35] calculated for the study of ground teeth and which ranged from 0.76 to 0.91. This is not surprising as it may be assumed that a classification of the stage of the influencing variables based directly on the preparation must be more accurate than one based on the conventional orthopantomogram. Moreover, it must be borne in mind that Solheim [35] was able to include a larger number of different regressive tooth changes (a total of seven characteristics) in his study because of the option of extracting the teeth to be studied.

The regression equations calculated in the course of the present study can be recommended in principle for the age estimation of living individuals. However, it should be borne in mind that the applicability of the new method presented is limited by the quality of the X-ray images. After exclusion of pathologically changed teeth and those which could not be assessed due to the quality of the X-ray image, 45–60 % of cases were suitable for evaluation depending on the tooth. If possible, therefore, all inferior premolars which can be evaluated and are not covered by the predefined exclusion criteria should be included in the age diagnosis.

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