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ORIGINAL ARTICLE

Dental age estimation in the living after completion of third molar mineralization: new data for Gustafson's criteria

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Abstract There is a need for dental age estimation methods after completion of the third molar mineralization. Degenerative dental characteristics appear to be suitable for forensic age diagnostics beyond the 18th year of life. In 2012, Olze et al. investigated the criteria studied by Gustafson using orthopantomograms. The objective of this study was to prove the applicability and reliability of this method with a large cohort and a wide age range, including older individuals. For this purpose, 2346 orthopantomograms of 1167 female and 1179 male Germans aged 15 to 70 years were reviewed. 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 the chronological age was examined by means of a stepwise multiple regression analysis, in which the chronological age formed the dependent variable. Following those results, R^2 values amounted to 0.73 to 0.8; the standard error of estimate was 6.8 to 8.2 years. Fundamentally, the recommendation for conducting age estimations in the living by these methods can be shared. The values for the quality of the regression are, however, not precise enough for a reliable age estimation around regular retirement date ages. More precise regression formulae for the age group of 15 to 40 years of life are separately presented in this study. Further research should investigate the influence of ethnicity, dietary habits and modern health care on the degenerative characteristics in question.

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

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Introduction

Age estimation in the living has been in the focus of forensic research for several years [6, 16, 27, 45–56]. In particular, it includes legal issues, refugee issues, and the field of competitive sports [7, 8, 29, 32, 33, 43, 44]. The validation of the completion of the 18th and 21st year of life is of special importance in all of these. Providing a proof for the completion of the 18th year of life by means of the established dental methods is however not possible with the forensically required certainty, even if all the third molars of a person are completely mineralized, as their mineralization can be completed before the 18th birthday [52, 53]. Therefore, other methods for age estimation after the completion of third molar mineralization are needed.

For age estimation in living individuals undergoing retirement proceedings, the Study Group on Forensic Age Diagnostics recommends the implementation of the well-known morphological methods of dental age estimation based on existing radiographs from childhood or adolescence. If no previous radiographs should exist, aspartic acid racemization

Table 1 Distribution or the sample by age and sex

Age (in years)	Female	Male	Total
15	21	21	42
16	22	27	49
17	41	23	64
18	32	30	62
19	25	25	50
20	25	27	52
21	24	26	50
22	21	23	44
23	17	26	43
24	24	24	48
25	22	24	46
26	28	30	58
27	25	23	48
28	23	23	46
29	25	26	51
30	22	20	42
31	24	28	52
32	21	25	46
33	23	23	46
34	21	28	49
35	24	22	46
36	14	20	34
37	21	26	47
38	22	23	45
39	19	23	42
40	20	23	43
41	21	23	44
42	22	19	41
43	23	20	43
44	21	21	42
45	18	23	41
46	21	19	40
47	20	21	41
48	19	22	41
49	21	19	40
50	21	22	43
51	22	21	43
52	19	21	40
53	18	21	39
54	19	19	38
55	22	21	43
56	19	22	41
57	21	17	38
58	23	18	41
59	16	18	34
60	22	18	40
61	11	18	29
62	21	19	40
63	19	11	30
64	10	15	25
65	17	12	29
66	6	9	15
67	15	11	26
68	15	15	30
69	12	12	24
70	24	10	34
Total	1167	1179	2346

is the recommended method [41]. Further methods with good reliability suitable for older age groups are the analysis of tooth-cementum annulations (TCA) and the Lamendin method with its revisions [1, 4, 5, 19, 34, 58, 59]. Only these methods appear to be sufficiently reliable after the completion of tooth development [4, 5, 10, 20, 24, 26, 30, 36, 37, 39–41, 58, 59]. Since these methods are applicable only to extracted teeth, their use is severely restricted in living individuals for ethical reasons [38, 41]. Furthermore, it has to be mentioned that a comparatively high interobserver-error in TCA-analysis is a cause of concern [35, 42].

Another method for age estimation after the completion of tooth development is the method according to Kvaal et al. [18] using the size of the pulp in full mouth radiographs. However, weaknesses of this method have been described [9, 32]. Therefore, the method according to Kvaal et al. [18] can currently not be seen as a valid alternative for age estimation after third molar mineralization.

Degenerative dental characteristics appear to be suitable for forensic age diagnostics. The first attempts of scientific dental age estimation date back to Gustafson in 1947 [12]. Gustafson presented the characteristics of secondary dentin formation, periodontal recession, attrition, apical translucency, cementum apposition, and external root resorption as phenomena correlating with chronological age [12–14]. In 1981, Matsikidis proved that the characteristics presented by Gustafson for extracted and ground teeth can also be applied to dental films [22]. As not all the characteristics evaluable in an extracted tooth are equally evaluable in radiographies and also since method-related loss in resolution and artificial distortion are to be expected, the accuracy of estimate of the Matsikidis-method was lower than the accuracy of estimate of methods presented for extracted teeth [15, 21, 52].

In 2012, Olze et al. were able to show that the characteristics presented by Gustafson can be determined using orthopantomograms as well. They presented regression formulae for age estimation in the age group of 15 to 40 years, by using these characteristics [29].

The aim of the present study was to validate the method proposed by Olze et al. [29] within a large study population in

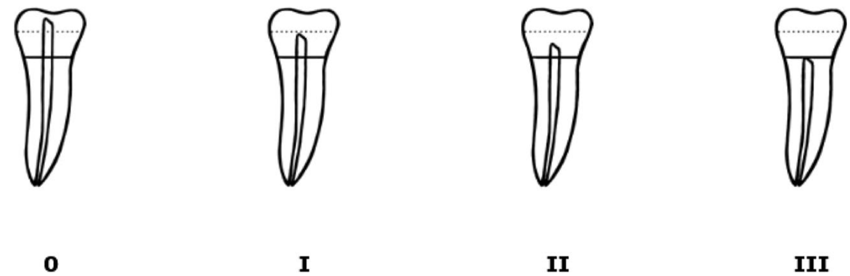

Fig. 1 Stage classification to determine degree of secondary dentin. *Stage 0* Pulp horn (top of the pulp chamber) reaches to above crown equator (largest mesio-distal width). *Stage I* Pulp horn reaches at maximum to crown equator. *Stage II* Pulp horn exceeds enamel-cementum junction and falls short of crown equator. *Stage III* Pulp horn reaches at maximum to enamel-cementum junction

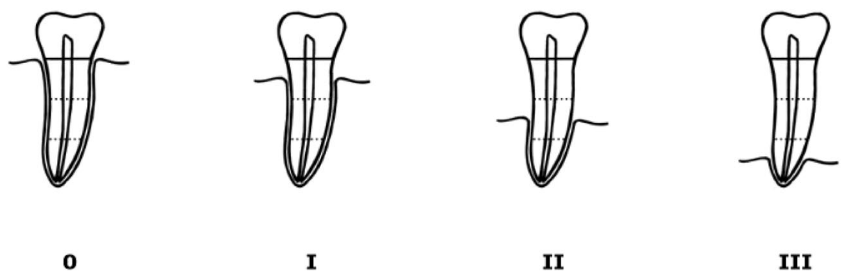

Fig. 2 Stage classification to determine degree of periodontal recession. *Stage 0* No periodontal recession. *Stage I* Periodontal recession into cervical root third. *Stage II* Periodontal recession into middle root third. *Stage III* Periodontal recession into apical root third

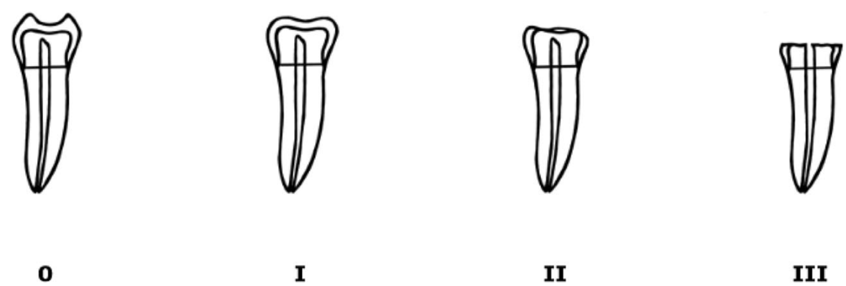

Fig. 3 Stage classification to determine degree of attrition. *Stage 0* No attrition, cusp tips present. *Stage I* Beginning attrition with loss of cusp tips. *Stage II* Attrition reaching into dentin. *Stage III* Attrition reaching into dentin with opening of pulp cavity

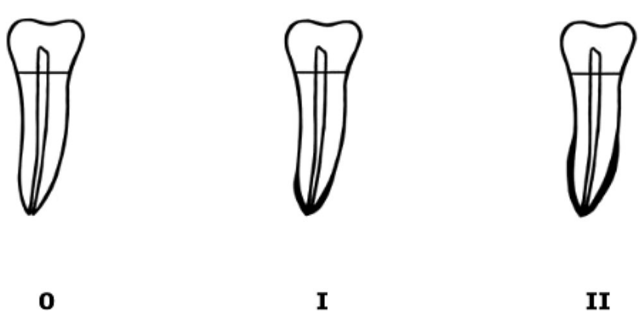

Fig. 4 Stage classification to determine degree of cementum apposition. *Stage 0* No visible cementum apposition. *Stage I* Beginning apical cementum apposition. *Stage II* Clearly visible cementum apposition, reaching beyond the apex

Table 2 Exclusion criteria according to Matsikidis

	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

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

Table 3 Number and percentage of teeth excluded or missing

Tooth	Sex	Number of cases	Missing teeth	Non-evaluable teeth	Evaluated teeth	Percentage evaluated
34	Female	1167	104	480	583	49.96%
34	Male	1179	98	388	693	58.78%
35	Female	1167	191	772	204	17.48%
35	Male	1179	147	730	302	25.61%
44	Female	1167	91	564	512	43.87%
44	Male	1179	101	381	697	59.12%
45	Female	1167	205	786	176	15.08%
45	Male	1179	149	793	237	20.10%

the age group of 15 to 70. In order to compare our results with the findings presented by Olze et al. [29], separate calculations for the age group 15 to 40 years were performed.

Materials and methods

Subject to the study were 2346 orthopantomograms of 1167 female and 1179 male Germans between 15 and 70 years of age, collected from two dental practices and a maxillofacial surgery practice in the Paderborn area in Germany. The orthopantomograms were made in the period between 1985 and 2011. The first examiner was a dentist with profound professional experience including the examination of orthopantomograms. Prior to the study he had intensively become acquainted to the issue and also discussed it with a forensic dentist experienced in dental age assessment by means of Gustafson's criteria. After intensive training, the first examiner was very qualified in this method.

Table 1 shows the number of cases in the sample per age cohort divided by sex. The characteristics of secondary dentin formation, cementum apposition, periodontal recession and attrition were determined in all mandibular premolars using the stage classifications according to Olze et al. [29] (Figs. 1, 2, 3, and 4). The determination of external root resorption was waived, as Olze et al. [29] had found that it cannot be evaluated in orthopantomograms. The exclusion criteria in each case were drawn from the recommendations presented by Matsikidis (Table 2) [18]. Teeth were excluded due to one of Matsikidis' recommended reasons or due to poor quality of the orthopantomogram. Missing teeth could be missing because of agenesis of the tooth, extraction, or trauma.

The evaluation of the orthopantomograms was performed randomized and blinded, i.e., without knowledge of the dates of birth or the date of the radiographical examination. Each

Table 4 Frequencies of the various stages of the examined features for females

Stage	Tooth	Secondary dentin *n*	Periodontal recession	Attrition	Cementum apposition
0	34	10	145	434	499
	35	5	139	347	453
	44	10	154	413	453
	45	6	131	337	408
I	34	278	709	326	367
	35	187	677	193	297
	44	288	753	333	384
	45	181	681	211	312
II	34	391	199	74	159
	35	293	143	61	167
	44	389	148	70	184
	45	291	122	43	185
III	34	170	5	6	0
	35	155	7	8	0
	44	149	7	5	0
	45	147	6	1	0

n number of cases

Table 5 Frequencies of the various stages of the examined features for males

Stage	Tooth	Secondary dentin *n*	Periodontal recession	Attrition	Cementum apposition
0	34	16	14	534	531
	35	2	6	397	509
	44	17	15	496	529
	45	2	9	389	493
I	34	321	864	287	363
	35	192	835	197	311
	44	323	879	292	339
	45	195	840	188	304
II	34	373	186	87	169
	35	310	174	86	186
	44	387	169	98	200
	45	315	163	64	201
III	34	168	9	14	0
	35	180	5	8	0
	44	166	10	11	0
	45	143	9	12	0

n number of cases

orthopantomogram was assigned an identification number. Identification number, date of birth, the subject's sex, date of radiographical examination, and the stages of the teeth included in the study were recorded. In case of non-evaluable teeth, it was distinguished between non-presence and lack of assessability.

The correlation between chronological age and the individual degenerative characteristics was examined by means of a multiple regression analysis, with the chronological age being the dependent variable and the examined degenerative characteristics being the independent variables. The modeling of the linear regression model was developed in single steps with the prognosis-relevant influencing variables of the degenerative characteristics. 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 regression. Finally, regression formulae to fill in the stages of the degenerative characteristic for reliable age estimations were developed. To every single regression formula, the coefficient of determination and the standard error of estimate were calculated as well. The multiple regression analysis was carried out for the whole age range of 15 to 70 years and also separately for the age group of 15 to 40 years. Furthermore, a study on multicollinearities between the influencing variables was performed, for which the variance inflation factor (VIF) value was noted. A VIF value of >4 was considered to be a critical multicollinearity.

For intra-rater agreement, 100 randomized orthopantomograms were reevaluated by the first examiner. For inter-rater agreement evaluation, the same 100 orthopantomograms were also evaluated by a second examiner. The second examiner was a dentist without experiences in dental age assessment. Cohen's kappa coefficients were calculated for intra- and inter-rater agreement.

Results

Table 3 shows the number and percentage of teeth which could not be used for statistical evaluation due to predefined exclusion criteria or because of poor quality of the orthopantomogram. The number of missing teeth is provided as well. Depending on the

Table 6 Regression equations, coefficients of determination (R^2), and standard errors of estimate (SEE) of multiple regression analysis with ages as the dependent variable and dental age changes as the independent variables for teeth 34, 35, 44, 45, of males in the age group of 15 to 70 years

Tooth	Formula	R^2	SEE
34	13,815 + 7,445*SE + 7,501*CE + 4,935*AT + 2,998*PE	0.77	7.11
35	8,250 + 8,165*SE + 6,543*CE + 5,255*AT + 3,725*PE	0.8	6.75
44	13,455 + 6,845*SE + 7,343*CE + 5,027*AT + 4,009*PE	0.76	7.04
45	9,754 + 7,127*CE + 7,086*SE + 5,132*AT + 4,227*PE	0.78	6.99

Table 7 Regression equations, coefficients of determination (R^2), and standard errors of estimate (SEE) of multiple regression analysis with ages as the dependent variable and dental age changes as the independent variables for teeth 34, 35, 44, 45, of females in the age group of 15 to 70 years

Tooth	Formula	R^2	SEE
34	14,583 + 8,270*CE + 5,000*SE + 5,838*AT + 5,379*PE	0.73	8.17
35	13,069 + 7,487*AT + 7,350*CE + 4,662*SE + 4,386*PE	0.79	7.26
44	14,579 + 7,378*CE + 6,236*PE + 6,240*AT + 4,691*SE	0.74	8.18
45	13,256 + 8,695*AT + 5,928*CE + 5,614*PE + 3,995*SE	0.75	7.67

examined tooth, 15–59% of cases were evaluable. Concerning the second premolars, a lower percentage of cases was evaluable. Tables 4 and 5 show the frequencies of the various stages of the examined features. All the examined characteristics were statistically linked to chronological age. The intra-rater agreement was substantial to almost perfect (Kappa 0.78–0.92). The inter-rater agreement was worse than the intra-rater agreement in every case (Kappa 0.38–0.75). Multicollinearities could not be detected. All VIF values were smaller than the critical limit of 4. Tables 6 and 7 show the results of the multiple regression analysis for the age range of 15 to 70 years. Tables 8 and 9 show the results for the multiple regression analysis for the age range of 15 to 40 years. From these tables can be drawn that the values for the standard error of estimate were slightly lower concerning the second premolars when compared to the values for the standard error of estimate concerning the first premolars. Furthermore, the values for the standard error of estimate were lower for the age group of 15 to 40 years compared to the age group 15 to 70 years. Tables 10 and 11 show the values for the quality of the multiple regression for the age group of 15 to 40 years in direct comparison to the results of Olze et al. [29]. These tables show that the quality of the regression could be improved for this age group.

Discussion

In the past, it was shown that regressive dental changes in correlation to chronological age qualify for age estimations after the completion of the third molar mineralization [18, 28]. These changes begin immediately after eruption and continue throughout the whole life [3, 13, 15, 17, 25, 60]. In 2012, Olze et al. published a study of their results on an investigation of Gustafson's criteria in orthopantomograms [29]. In their study, they included 1299 radiographs of 650 female and 649 male Germans between 15 and 40 years of life. The characteristics of secondary dentin formation, cementum apposition, periodontal recession, and attrition were evaluated in all of the mandibular premolars. They developed a staging system with less stages compared to the staging system Matsikidis had presented for regressive dental changes. This was done for a better applicability to orthopantomograms [29]. They studied the correlation between individual characteristics and chronological age by means of a stepwise multiple regression analysis in which chronological age formed the dependent variable. Regression formulae to calculate the estimated age of a person were presented. They recommended their method for age estimation with the restriction that the quality of the radiographs often limits the applicability of the method [29].

The aim of the present study was to investigate the validity of the results of Olze et al. [29]. The individuals studied were 15 to 70 years old, meaning the age interval included all ages of forensic importance. As an uneven age distribution within the sample may lead to systematic over- or underestimation of age [11], the attempt was made to fill every age cohort equally. Especially in the older age cohorts, this objective could not always be achieved, as there were not as many radiographs available for the older age cohorts, even though the radiographs had been collected from three different dental and oral maxillofacial surgery practices. In the age cohort of 15 to 40 years the objective of equal distribution could mainly be achieved. The stage classifications presented by Olze et al. [29] were used. The mandibular premolars were examined since Olze et al. [29] described them to be the only suitable teeth for this purpose.

After exclusion of missing teeth, those that could not be assessed due to the quality of the radiographs and those teeth that had been excluded due to the criteria by Matsikidis [22], 15 to 59% of the cases were suitable for evaluation. The bottom limit is much lower here than the values Olze et al. [29]

Table 8 Regression equations, coefficients of determination (R^2), and standard errors of estimate (SEE) of multiple regression analysis with ages as the dependent variable and dental age changes as independent variables for teeth 34, 35, 44, 45, of males in the age group of 15 to 40 years

Tooth	Formula	R^2	SEE
34	14,706 + 4,069*SE + 4,300*AT + 4,103*CE + 5,137*PE	0.49	5.1
35	11,534 + 5,196*SE + 5,081*CE + 3,190*AT + 4,219*PE	0.59	4.64
44	14,488 + 4,294*SE + 3,716*AT + 5,257*PE + 3,595*CE	0.47	5.17
45	12,984 + 4,617*SE + 4,461*CE + 3,860*AT + 3,827*PE	0.51	4.93

Table 9 Regression equations, coefficients of determination (R^2), and standard errors of estimate (SEE) of multiple regression analysis with ages as the dependent variable and dental age changes as the independent variables for teeth 34, 35, 44, 45, of females in the age group of 15 to 40 years

Tooth	Formula	R^2	SEE
34	18,535 + 5,186*AT + 3,565*PE + 3,452*CE + 1,957*SE	0.49	5.14
35	16,505 + 4,403*AT + 3,193*PE + 4,329*CE + 2,646*SE	0.54	4.71
44	18,330 + 4,581*AT + 4,419*PE + 3,625*CE + 1,777*SE	0.5	5.05
45	16,605 + 4,533*AT + 2,551*SE + 3,270*PE + 3,356*CE	0.55	4.68

presented in their study. They had been able to evaluate 45–60% of cases [29]. The low value of our study can be explained by the older cohort in this study, in that a higher age means an increase in the likelihood of Matsikidis' criteria [22] being met or to having lost a certain tooth during lifetime. The common upper value of about 60% appears to be set due to the quality of the radiographs and therefore appears to be the upper limit of the method.

The intra-rater agreement was substantial to almost perfect. The inter-rater agreement was worse than the intra-rater agreement in every case. This must be seen against the background of the second examiner being a dentist completely inexperienced in age estimation methods. Thus, the low inter-rater agreement shows once again that age estimation is a task for experts only [57].

In the present study, stepwise multiple regression analysis was used to develop calculation formulae regarding the lower premolars in relation to regressive tooth changes with a known significant correlation to age, in order to estimate the age of an individual and to determine the corresponding correlation coefficient according to Olze et al. [29]. Regression analyses should only be used for metrically scaled variables, whereas the age estimation characteristics examined in this study are ordinally scaled variables. As an alternate multivariate analysis method for ordinally scaled variables, the Bayes theorem was proposed [2]. However, a study by Thevissen et al. [54] showed that by applying the Bayes theorem, an improvement in the accuracy of estimation could not be achieved in comparison to when applying linear regression analysis. We therefore deemed it appropriate to use regression analyses for the statistical evaluation of our data.

Regression analyses were performed separately for the age cohorts 15 to 70 years and 15 to 40 years and per sex, for the best possible comparability of this study's results and those presented by Olze et al. [29]. The calculated R^2 values range from 0.69 to 0.77 and thus are similar to or above the values for the age cohort presented by Olze et al. [29]. With the formulae presented in this study, more accurate age estimations are possible in the age group 15 to 40 years. For the age group 15 to 70 years, the values for the standard error of estimate were higher. The range for the R^2 is 0.73 to 0.8 and the range for the standard error of estimate in this age group lies at 6.8 to 8.2 years. The pronounced standard errors of estimate appear too high for reliable age estimations in the elderly. These findings underline the problem of utilizing morphological characteristics for age estimations in the elderly.

In our study, the values for the standard error of estimate were slightly lower concerning the second premolars when compared to the values for the standard error of estimate concerning the first premolars. A possible explanation for this could be that the second premolars take part in the occlusion with five contact points, whereas the first premolars take part in it with only two contact points. Improper burdening of the first premolars could thereby accelerate degenerative changes.

In conclusion, the method presented by Olze et al. [29] could be validated in the present study. The method is applicable and reliable for dental age diagnostics in the age group up to 40 years. For age estimations concerning older age groups, e.g., around retirement date ages, the method appears to be too inaccurate. The values for the standard error of estimate are too high for a precise and reliable age estimation

Table 10 Comparison of the quality values of the regression including correlation coefficients (R), coefficients of determination (R^2), and standard error of estimate (SEE) of multiple regression analysis for teeth 34, 35, 44, 45 of the males in the age group of 15 to 40 years from the results of Olze et al. (2012) [25] and the present study (p.s.)

Tooth	R (Olze)	R (p.s.)	R^2 (Olze)	R^2 (p.s.)	SEE (Olze)	SEE (p.s.)
34	0.7	0.7	0.48	0.49	5.4	5.1
35	0.7	0.77	0.49	0.59	5.4	4.6
44	0.72	0.69	0.52	0.47	5.5	5.2
45	0.73	0.72	0.53	0.52	5.3	4.9

Table 11 Comparison of the quality values of the regression including correlation coefficients (R), coefficients of determination (R^2), and standard error of estimate (SEE) of multiple regression analysis for teeth 34, 35, 44, 45 of the females in the age group of 15 to 40 years from the results of Olze et al. (2012) [25] and the present study (p.s.)

Tooth	R (Olze)	R (p.s.)	R^2 (Olze)	R^2 (p.s.)	SEE (Olze)	SEE (p.s.)
34	0.67	0.7	0.44	0.49	5.7	5.1
35	0.68	0.73	0.47	0.54	5.5	4.7
44	0.65	0.71	0.43	0.5	5.7	5.1
45	0.69	0.74	0.48	0.55	5.4	4.7

around retirement date ages. Furthermore, the method is limited by the number of radiographs suitable for evaluation. Moreover, the examined phenomena must be questioned for whether or not they depend on ethnicity. This has to be considered, especially concerning the age estimations in refugees [23, 31, 44]. Additionally, the influence of dietary habits and modern health care on the degenerative dental characteristics has not been investigated yet. Therefore, despite a long history of studies on these characteristics, more studies are needed to more precisely draw the boundary line between physiological age-related changes and pathological processes. Also, it should be investigated, whether methods free of ionizing radiation like magnetic resonance imaging can be utilized for Gustafson's criteria, as MRI appears to be suitable to detect mineralization stages in the third molars [31].

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