Age Estimation by Radiological Measuring Pulp Chamber of Mandibular First Molar in Korean Adults

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Purpose: The purpose of present study was to develop a method for assessing the chronological age of Korean adults based on the relationship between age and size of pulp cavity using dental radiographs of mandibular first molars.

Methods: A total of 325 dental radiographs of Korean adults with known age and gender were selected for the study (199 males and 126 females) which were taken in the period between January 2009 and June 2014 at the Pusan National University Dental Hospital. The measurements were carried out on both orthopantomographs (OPGs) and intraoral periapical radiographs of mandibular first molar and the following ratios were calculated: pulp chamber floor height ratio (F/L), pulp chamber ceiling height ratio (R/L), and pulp chamber depth ratio (D/L).

Results: The ratios of measurements on intraoral periapical images of mandible first molar generally produce more reliable data than the measurements on OPGs. The pulp chamber floor height ratio and pulp chamber thickness ratio showed significant correlation with age, whereas the pulp chamber ceiling height ratios showed weak correlation with age. It was found that the best correlations between the ratios and age were found for pulp chamber thickness ratios (r=−0.731 to −0.751). The multiple regression models were derived using 3 ratios that were significantly correlated with age. The determination coefficients (R^2) of the models ranged from 0.556 to 0.596.

Conclusions: Our results indicate that the pulp chamber thickness and pulp chamber floor height in mandibular first molar are an age-dependent variable in adults which can be used to estimate age with reasonable accuracy. The higher image quality of dental radiographs will probably narrow the age estimation error and improve dental age estimation.

Key Words: Dental age estimation; Dentin, secondary; Radiographs

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INTRODUCTION

Age estimation is great important in the practice of forensic science to establish the identity of human remains, as well as living persons. Particularly in Korea, age estimation in adults has been increase in the demand for incorrect birth records in order to be entitled to civil liability, social benefits, employment and marriage. Among various parts of the body structure used for age estimation, dental structures are becoming more and more useful, since tooth can be preserved longer than other tissues because of their resistance to physical and chemical agents. Therefore tooth are considered a reliable parameter of age in living individuals.[1]

Dental age estimation in adults has to be done by several methods based on dental tissue and tooth morphology, such as morphologic, radiologic, histologic, and biochemical methods. However, most methods require tooth extraction for sectioning and processing of dental tissues, which is not feasible in living person. Radiographic evaluation of

teeth is non-invasive, reproducible and simple method that is suitable for application in living person.[2] Deposition of secondary dentin is an important indicator as age estimation in adults. After root formation is completed, secondary dentin is deposited throughout one's life and laid down on the pulpal surface of the primary dentin.[3] The continuous deposition of secondary dentin depicted by reduction in pulp area can be employed for radiographic age estimation by using tooth in adults. Noninvasive radiological methods for age estimation have been developed for studying the amount of secondary dentin formation by measuring the pulp chamber size on radiographs.[1]

In 1995, Kvaal et al.[4] introduced a method for estimating the chronological age of adults based on the relationship between age and the pulp size using intraoral periapical radiographs (IOPRs) taken in situ. The ratios between pulp cavity and tooth measurements were correlated with age and regression models were derived to estimate the age. Bosmans et al.[5] tested the original techniques of Kvaal et al.[4] on digital orthopantomographs (OPGs) instead of IOPRs. They concluded that age estimations were comparable to those based on the original techniques. Paewinsky et al.[6] modified the method of kvaal et al.[4] on digital OPGs and developed new regression models. Drusini et al.[7] applied the method developed by Ikeda et al.[8] and confirmed the negative correlation between the tooth-coronal index (TCI) and age. Since 2004, Cameriere et al.[9-14] have published several articles on a new method of age estimation using the pulp/tooth area ratio (PTR) to quantify the apposition of secondary dentin on intraoral pericapical radiographs. Subsequently, age estimation based on one- or two-dimensional radiographic measurements of the dental pulp cavity size associated with aging has been reported in many studies. However, they showed various accuracy, precision and reliability depending on tooth type, sample size and ethnic groups.[15-28]

The purpose of the present study was to develop new regression models estimating chronological age of Korean adults using mandibular first molars by examining the relationship between age and the pulp size on dental radiographs.

MATERIALS AND METHODS

1. Subjects

The radiographs were collected from patients visiting the Pusan National University Dental Hospital from January 2009 till June 2014. Dental radiograph images from 325 individuals with an age ranging from 20 to 69 years old who were taken both OPGs and IOPRs of mandibular first molars on the same day were selected for the study. The problems associated with OPGs are the overlapping of premolars and the presence of superimposition structures, such as the cervical spine especially in the incisor region. Also, the assessment of the pulp cavity of the maxillary tooth may generally be difficult since maxillary posterior tooth are often overshadowed by bone structure.[20] Besides, the mandibular second molars frequently showed anatomical variation, particularly in Asians.[29] In fact, we found that many radiographic images of mandibular second molars exhibited radicular fusion or proximity and indistinct pulp chamber. For these reasons, in this study, we decided to included only mandibular first molars. The OPGs and IOPRs were obtained from the Picture Archive and Communication Systems database (PACS).

The subjects were grouped according to their ages; 20s, 30s, 40s, 50s, 60s and divided into the two subsets. The study subset (n=275) was used to investigate regression equation to estimate the age from tooth measurements and the test subset (n=50) was employed to assess the accuracy of equation which was derived for age estimation. In the test subset, each age group had 10 subjects that were selected by using random number generating system. When a preliminary study employed 100 subjects was performed, we did not find significant differences between tooth from the left and right side of the jaws. Consequently, in this study, first molar from either side of mandible was chosen best suitable for measurement.

Root canal treatment teeth, teeth with visible periapical pathological process, caries, radiopaque filling and crown were excluded. Tilted teeth, teeth with enamel overlap between neighboring teeth and developmental anomalies were also excluded. Ethical approval was granted by the Institutional Review Board of the Pusan National University Dental Hospital (PNUDH-2014-037).

2. Measurements

The radiographic images, originally obtained in Digital Imaging and Communication in Medicine (DICOM) format, were saved as DICOM files on a computer and were analysed by using the Adobe Photoshop CS5 image editing program (Adobe Systems, San Jose, CA, USA). With the aid of Photoshop tool, the images were enlarged and adjusted with the brightness/contrast, if needed. Four distances were measured on the radiographs by using certain reference points and measurements were recorded (mm). The reference points were: roof of pulp chamber, floor of pulp chamber, the highest point on the root furcation, start point of the lingual groove. The distance between the floor of the pulp chamber and the highest point on the root furcation was recorded as "F", the distance between the roof of the pulp chamber and the highest point on the root furcation was recorded as "R", the distance from the start point of lingual groove to the highest point on the root furcation was recorded as "L" and depth of the pulp chamber was recorded as "D (R minus F)" (Fig. 1). In order to minimize the effect of a possible variation in magnification and angulation of the dental radiographs, the following ratios were calculated: pulp chamber floor height ratio (F/L), pulp chamber roof height ratio (R/L), and pulp chamber depth ratio (D/L). All measurements were carried out by a same observer and re-examined under blinded conditions after 2 weeks to access intra-observer reliability. To evaluate inter-observer agreement, 100 individuals were randomly selected and the second observer recorded the measurements.

3. Statistical Analysis

All statistical analysis were performed by using IBM SPSS Statistics version 21.0 (IBM Co., Armonk, NY, USA). A paired-sample t-test was adopted to evaluate the significance of the differences between the obtained measurements on OPGs and IOPRs. The intra-observer and inter-observer reliability was assessed by interclass correlation coefficient (ICC). In the study subset Pearson correlation coefficients were calculated to explore the linear association between chronological age and the ratios. Regression analysis was performed on the three ratios data and equations were formulated for age estimation. Mean absolute error (MAE) was derived by calculating the mean of absolute value of the errors. Chi-square test was performed to compare the percentage of subjects with the absolute error $<\pm$MAE and those falling within $<\pm$10 years which is acceptable error margins for forensic age prediction. p-value less than 0.05 was considered as statistically significant.

RESULTS

Total of 325 mandibular first molars from 325 individuals were analyzed. The gender and age distribution of subjects are presented in (Table 1). Intraclass correlation coefficients
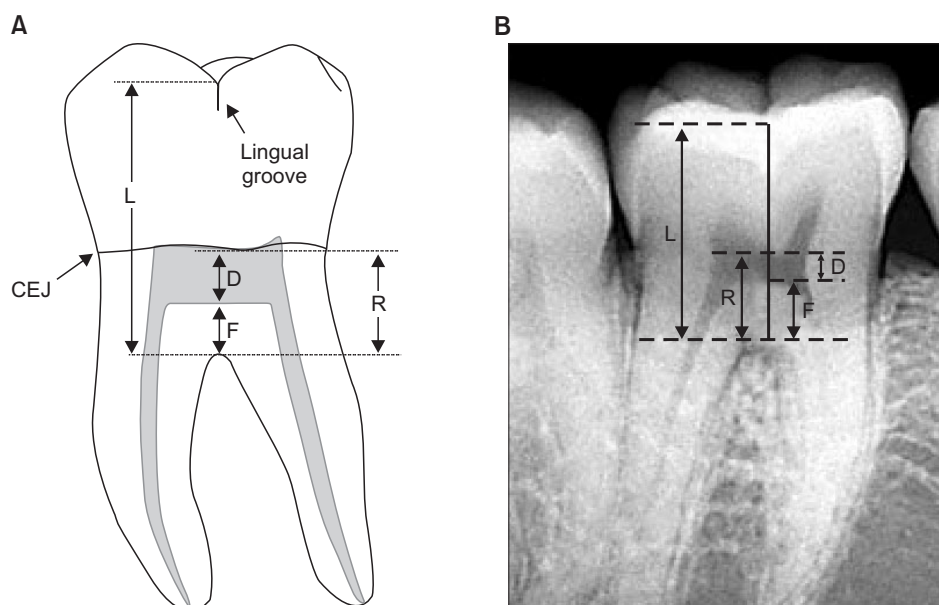
Fig. 1. (A) Schematic representation of tooth measurements (lingual aspect of mandibular first molar). (B) Measurements performed on radiograph of a mandibular first molar by using Adobe Photoshop CS5 program. CEJ, cemento-enamel junction; L, distance from the start point of lingual groove to the highest point on the root furcation; D, depth of the pulp chamber; F, distance between the floor of the pulp chamber and the highest point on the root furcation; R, distance between the roof of the pulp chamber and the highest point on the root furcation.

(ICC) were calculated for the intra-observer and inter-observer variation. The lowest acceptable ICC was set at ≥0.7 for reliability. Although intra-observer and inter-observer agreement showed an excellent ICC (>0.7) in the 3 ratios carried out on the both IOPRs and OPGs, the relatively low ICC was estimated in measuring on OPGs. The comparison of the ratios from measurements on OPGs and IOPRs was performed by using paired t-test. There was significant difference in observation in ratios across two methods, and therefore statistical analysis was performed separately. Independent samples t-test was performed, the sex appears to have significant influence on age determination. Therefore statistical analyses were also performed for male and female sample separately.

Table 1. Distribution of subjects in study

Age group (y)	Male (n)	Female (n)	Total (n)
Study subset			
20–29	31	22	53
30–39	42	23	65
40–49	46	35	81
50–59	33	23	56
60–69	47	23	70
Total	168	107	275
Test subset			
20–29	7	3	10
30–39	5	5	10
40–49	7	3	10
50–59	6	4	10
60–69	6	4	10
Total	31	19	50
Total	199	126	325

1. Linear Correlation (Pearson's Correlation Coefficient)

Pearson's correlation coefficients were estimated to investigate the association between age and the calculated ratios from both OPGs and IOPRs (Table 2). There was a statistically significant positive correlation between F/L and the chronological age in all patients. In R/L variable, it was found to be negatively correlated with the chronological age in all subjects; however, there was no significant correlation between R/L and the chronological age in male and female subjects. The negative correlations were especially significant in pulp chamber depth ratios (D/L) from both OPGs and IOPRs. Correlations were consistently higher in females than males and the best correlation was observed for ratio D/L from IOPRs in female samples (r=−0.751).

2. Simple Linear Regression

The effect of independent variables on the chronological age was analyzed by using the univariate linear regression, the simple linear regression results are presented in (Tables 3, 4). The most accurate models for the pooled sample were for the from both OPGs and IOPRs (R^2=0.537 and 0.553, respectively).

3. Multiple Regression

Multiple regression equations were formulated by using a stepwise manner with 0.05 alpha level in multivariate analysis to select the statistically significant variables. To check the multi-colinearity problem, the variance inflation factor was also estimated whereby F/L, D/L variables were

Table 2. Pearson's correlation coefficients (r) between chronological age and the ratios of measurements from OPGs and IOPRs for the pooled sample, and each sex

Ratio	Pooled sample (n=275)	Male (n=168)	Female (n=107)
OPGs			
F/L	0.540**	0.514**	0.578**
R/L	−0.138*	−0.127[a]	−0.150[a]
D/L	−0.733**	−0.732**	−0.744**
IOPRs			
F/L	0.406**	0.352**	0.496**
R/L	−0.135*	−0.143[a]	−0.145[a]
D/L	−0.744**	−0.742**	−0.751**

OPGs, orthopantomographs; IOPRs, intraoral periapical radiographs; F/L, pulp chamber floor height ratio; R/L, pulp chamber roof height ratio; D/L, pulp chamber depth ratio.
*p<0.05. **p<0.01.
[a]Not significant.

Table 3. Linear regression equations for estimating age (in years) from independent ratios of measurements on orthopantomographs

Ratio	Equation	R^2	SEE (±years)
Pooled sample (n=275)			
F/L	Age=−4.124+151.424×(F/L)	0.292	11.498
R/L	Age=63.133−44.326×(R/L)	0.019	13.530
D/L	Age=61.061−228.330×(D/L)	0.537	9.291
Male (n=168)			
F/L	Age=−4.471+153.473×(F/L)	0.264	11.887
R/L	Age=62.685−41.694×(R/L)	0.016	13.746
D/L	Age=62.597−254.679×(D/L)	0.536	9.436
Female (n=107)			
F/L	Age=−3.474+147.827×(F/L)	0.334	10.946
R/L	Age=63.041−46.422×(R/L)	0.022	13.258
D/L	Age=59.387−202.147×(D/L)	0.554	8.954

F/L, pulp chamber floor height ratio; R/L, pulp chamber roof height ratio; D/L, pulp chamber depth ratio; SEE, standard error of the estimates.

Table 4. Linear regression equations for estimating age (in years) from independent ratios of measurements on intraoral periapical radiographs

Ratio	Equation	R^2	SEE (±years)
Pooled sample (n=275)			
F/L	Age=8.943+102.644×(F/L)	0.165	12.482
R/L	Age=60.277−34.738×(R/L)	0.015	13.535
D/L	Age=62.738−259.102×(D/L)	0.553	9.132
Male (n=168)			
F/L	Age=13.870+88.531×(F/L)	0.124	12.969
R/L	Age=61.512−35.692×(R/L)	0.015	13.715
D/L	Age=63.661−278.443×(D/L)	0.550	9.295
Female (n=107)			
F/L	Age=−1.208+133.271×(F/L)	0.246	11.647
R/L	Age=61.135−39.929×(R/L)	0.021	13.268
D/L	Age=61.686−238.211×(D/L)	0.565	8.849

F/L, pulp chamber floor height ratio; R/L, pulp chamber roof height ratio; D/L, pulp chamber depth ratio; SEE, standard error of the estimates.

included in the multiple regression models. Multiple regression models of the ratios from OPGs and IOPRs improved the accuracy of predicting chronological age (Table 5). Regression analysis produced the following linear regression equations in the pooled sample;

Estimated age (OPGs)=43.311+47.692×(F/L)−197.419×(D/L)

Estimated age (IOPRs)=48.804+35.536×(F/L)−240.222×(D/L)

The coefficient of determination (R^2) of the age estimation was the strongest when the ratios of pulp chamber depth (F/L) and pulp chamber floor height (D/L) from IOPRs were included for the female samples (R^2=0.596).

4. Mean Absolute Error

To validate the accuracy of the estimation, the regression equations were applied on the test subset and estimated age was calculated. Paired t-test was used to compare between the chronological age and estimated age in the test subset. No significant difference was found between the chronological age and estimated age (p>0.05). MAE was derived and found to be 6.07 to 6.85 years. The results showed that the percentage of estimated ages in test subset <±MAE was 47.4% to 52.0% and those falling within <±10 years was 76.0% to 78.9% for the OPGs. For the IOPRs, the percentage of estimated ages in test subset <±MAE was 51.6% to 52% and those falling within <±10 years was 68.4% to 80.0% (Table 6).

Table 5. Multiple regression equations for estimating age (in years) from independent ratios of measurements on both OPGs and IOPRs

Group	n	R	Equation	R^2	SEE (±years)
OPGs					
Pooled sample	275	0.746	Age=43.311+47.692×(F/L)−197.419×(D/L)	0.556	9.115
Male	168	0.747	Age=43.469+51.667×(F/L)−222.636×(D/L)	0.558	9.243
Female	107	0.756	Age=42.870+44.089×(F/L)−172.259×(D/L)	0.572	8.818
IOPRs					
Pooled sample	275	0.755	Age=48.804+35.536×(F/L)−240.222×(D/L)	0.570	8.974
Male	168	0.751	Age=51.264+31.312×(F/L)−263.244×(D/L)	0.564	9.178
Female	107	0.772	Age=41.449+53.043×(F/L)−210.062×(D/L)	0.596	8.569

OPGs, orthopantomographs; IOPRs, intraoral periapical radiographs; F/L, pulp chamber floor height ratio; D/L, pulp chamber depth ratio; SEE, standard error of the estimates.

Table 6. MAE and percentage of estimated ages <±MAE and <±10 years in test subset

Group	MAE (y)	Error <±MAE y	Error <±10 y
OPGs			
Male (n=31)	6.85	19 (61.3)	24 (77.4)
Female (n=19)	6.08	9 (47.4)	15 (78.9)
Total (n=50)	6.59	26 (52.0)	38 (76.0)
IOPRs			
Male (n=31)	6.61	16 (51.6)	24 (77.4)
Female (n=19)	6.07	10 (52.6)	13 (68.4)
Total (n=50)	6.49	26 (52.0)	40 (80.0)

MAE, mean absolute error; OPGs, orthopantomographs; IOPRs, intra-oral periapical radiographs.

Values are presented as number only or number (%).

Chi-square test was performed to compare the percentage of patients with the absolute error <±MAE and <±10 years.

DISCUSSION

The teeth are the hardest structures in the human body resistant to different external influences, such as mechanical, chemical and thermal stimulus. Thus, chronological age estimation based on dental factors is generally accepted as a reliable and feasible method to evaluate an individual's age.[1,2] There are various characteristics of distinct age stages regarding to tooth development, mineralization and eruption, the attrition of crown, formation of secondary dentin, translucency of the root and cementum formation. Tooth development and the sequence of eruption have been used extensively as a method of age estimation in children and adolescents.[30] In adults, following completion of the growth period, dental age estimation becomes difficult. Particularly when nondestructive methods are used, it is not sufficiently accurate. Only aging process and regressive

changes of tooth are helpful for age estimation in adults. One of the best-known features of aging is a reduction in size of the pulp chamber. In 1925, Bodecker[31] pointed out that the apposition of secondary dentin was age-related. The apposition of secondary dentin is a continuing, regular process, which is least influenced by other environmental factors. Thus, the reduction of pulp cavity size as a result of secondary dentin deposit with increasing age could be used as an indicator of age. This regression change can be analyzed by radiological techniques, thus a variety methods for dental age estimation were proposed.

Several studies in Korea have indicated that the amount of secondary dentin is correlated with chronological age and can be measured indirectly by dental radiographs. In 1981, Chung and Kim[32] addressed the age estimation method by using the area ratio between pulp cavity and external feature of tooth. They classified ages from 21 to 70 by 5 years and reported that it was practically applicable to upper and lower incisor tooth. Hong and Ko[33] analyzed intraoral pericapical radiographs from 838 individual ranged from early twenties and early sixties. They divided the subjects into four groups depending on calcification level of pulp cavity. Then they assessed the correlation between the morphological change of pulp cavity and age. Later, Jeon et al.[34] applied the method developed by Ikeda et al.[8] and derived equations of age estimation by measuring the lower canines, premloars from IOPRs of 276 Korean samples. They obtained the results that the correlation coefficient was the strongest in canines of females (r^2=0.247). These methods above mentioned, however, have certain limitations that must be properly considered before application in practical

age estimation such as large error range. Also, there is a need to additional experimental data.

In our study, therefore, we have developed a new procedure by using the pulp chamber floor height ratio (F/L), pulp chamber roof height ratio (R/L) and pulp chamber depth ratio (D/L) of mandibular first molars from radiographs to estimate age of Korean adults. We verified that correlation coefficient between age and pulp chamber depth ratios was statiscally highly significant and correlated inversely (r=−0.732 to −0.751, p<0.01). An interesting observation in the present study was that pulp chamber floor height ratio was significantly positive correlated with age (r=0.352-0.578), whereas pulp chamber roof height ratio showed weakly negative correlated with age (r=−0.150 to −0.127) (Table 2). The pattern for the secondary dentin deposition varied among the different groups of tooth and the secondary dentin tends to be deposited in greater amounts on certain location. In molars, secondary dentin deposition happens preferentially on the floor of the pulp chamber, lesser amounts are deposited on the occlusal and lateral walls reducing the height rather than width of the pulp chamber.[3] Several studies demonstrated that secondary dentin apposition occurs primarily on the pulp chamber floor instead of the roof. One study evaluated ancient and recent populations and observed no significant changes in the dentin depth at the roof of the pulp chamber with increasing age, whereas the dentin at the floor of the pulp chamber showed a definite increase in depth with increasing age.[35] Another study reported a reduction in the height of the pulp chamber in mandibular first molars by 15% that was caused mainly by an increase in depth of the pulpal floor.[36] The results of this study, it showed that both pulp chamber floor height ratio (F/L) have significant influence on age estimation as well as pulp chamber depth ratio (D/L), since the coefficient of determination (R^2) increased when the pulp chamber floor height ratio (F/L) was included (Table 5). When the regression equations were used to estimate the age in test subset, we did not found any significant difference between the chronological age and estimated age in test subset. The MAE in our study was found to be 6.07 to 6.85 years (Table 6) which was within acceptable error limits in forensic age estimation.

Similar age estimation study used mandibular first molar

was done on OPGs by Mathew et al.[37] OPGs of 88 Indian subjects were used for study, a pulp chamber crown root trunk height ratio (PCTHR) was derived between pulp chamber height (PCH) and crown root trunk height (CRTH). A significant negative correlation between PCTHR and actual age was shown (r=−0.56) and linear regression formula was derived (r^2=0.313). In our study, we analyzed 325 Korean individuals by using IOPRs as well as OPGs in order to compare the precision of age prediction. Our study has obtained the results that the coefficients of determination (R^2) were higher than those reported previously from Indian individuals and determined the multiple regression equations estimated age better for IOPRs (R^2=0.564-0.596) than OPGs (R^2=0.556-0.572) in general (Table 5). In addition, the results of our study have shown relatively low inter-observer reliability measured on OPGs, even though high degree of intra-observer and inter-observer agreement was obtained. These results suggested that ratios of measurements on intra-oral periapical images of mandible first molars generally produce more reliable data than the measurements on OPGs. Undoubtedly, compared to IOPRs, OPG shows a lack of detail and OPG projection can be taken at only one angle. This in turn may affect the quality of the measurements performed and thus the accuracy of the calculated age.

Since this is a radiologic study, it is possible that variation in radiographic measurement could be responsible for errors. The main source of errors on measurement seemed to be difficulties in recognition of the reference points on the radiographs when viewed on the monitor, and therefore in defining the line to be measured. In addition, this study population may not fully represent the general Korean population because the small sample size and the availability of clinically sound molars in the adult population may restrict the applicability of those models. Future studies with larger sample groups and tooth other than mandibular first molars are therefore recommended, in order to improve dental age estimation.

In conclusion, the present study investigated measurements of mandibular first molars from both IOPRs and OPGs to examine the relationship between age and age-related changes in the pulp cavity. The results demonstrates that the use of pulp chamber floor height and pulp

chamber depth in mandibular first molars is a practical, simple, reliable and accurate method of age estimation in adults. Therefore it is deemed to be suitable for application in Korean population older than 20 years old if good quality of dental radiographs with clear radiological image are used. An approach to enhance age prediction should, however, be explored by using multiple tooth and develop multiple regression models with larger sample groups.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

REFERENCES

1. Stavrianos C, Mastagas D, Stavrianou I, Karaiskou O. Dental age estimation of adults: a review of methods and principals. Res J Med Sci 2008;2:258-268.

2. Willems G. A review of the most commonly used dental age estimation techniques. J Forensic Odontostomatol 2001;19:9-17.

3. Morse DR. Age-related changes of the dental pulp complex and their relationship to systemic aging. Oral Surg Oral Med Oral Pathol 1991;72:721-745.

4. Kvaal SI, Kolltveit KM, Thomsen IO, Solheim T. Age estimation of adults from dental radiographs. Forensic Sci Int 1995;74:175-185.

5. Bosmans N, Ann P, Aly M, Willems G. The application of Kvaal's dental age calculation technique on panoramic dental radiographs. Forensic Sci Int 2005;153:208-212.

6. Paewinsky E, Pfeiffer H, Brinkmann B. Quantification of secondary dentine formation from orthopantomograms--a contribution to forensic age estimation methods in adults. Int J Legal Med 2005;119:27-30.

7. Drusini AG, Toso O, Ranzato C. The coronal pulp cavity index: a biomarker for age determination in human adults. Am J Phys Anthropol 1997;103:353-363.

8. Ikeda N, Umetsu K, Kashimura S, Suzuki T, Oumi M. Estimation of age from teeth with their soft X-ray findings. Nihon Hoigaku Zasshi 1985;39:244-250.

9. Cameriere R, Ferrante L, Cingolani M. Variations in pulp/tooth area ratio as an indicator of age: a preliminary study. J Forensic Sci 2004;49:317-319.

10. Cameriere R, Brogi G, Ferrante L, et al. Reliability in age determination by pulp/tooth ratio in upper canines in skeletal remains. J Forensic Sci 2006;51:861-864.

11. Cameriere R, Ferrante L, Belcastro MG, Bonfiglioli B, Rastelli E, Cingolani M. Age estimation by pulp/tooth ratio in canines by peri-apical X-rays. J Forensic Sci 2007;52:166-170.

12. Cameriere R, Cunha E, Sassaroli E, Nuzzolese E, Ferrante L. Age estimation by pulp/tooth area ratio in canines: study of a Portuguese sample to test Cameriere's method. Forensic Sci Int 2009; 193:128.e1-e6.

13. Cameriere R, De Luca S, Alemán I, Ferrante L, Cingolani M. Age estimation by pulp/tooth ratio in lower premolars by orthopantomography. Forensic Sci Int 2012;214:105-112.

14. Cameriere R, Cunha E, Wasterlain SN, et al. Age estimation by pulp/tooth ratio in lateral and central incisors by peri-apical X-ray. J Forensic Leg Med 2013;20:530-536.

15. Meinl A, Tangl S, Pernicka E, Fenes C, Watzek G. On the applicability of secondary dentin formation to radiological age estimation in young adults. J Forensic Sci 2007;52:438-441.

16. Landa MI, Garamendi PM, Botella MC, Alemán I. Application of the method of Kvaal et al. to digital orthopantomograms. Int J Legal Med 2009;123:123-128.

17. Saxena S. Age estimation of indian adults from orthopantomographs. Braz Oral Res 2011;25:225-229.

18. Kanchan-Talreja P, Acharya AB, Naikmasur VG. An assessment of the versatility of Kvaal's method of adult dental age estimation in Indians. Arch Oral Biol 2012;57:277-284.

19. Agarwal N, Ahuja P, Sinha A, Singh A. Age estimation using maxillary central incisors: a radiographic study. J Forensic Dent Sci 2012;4:97-100.

20. Erbudak HÖ, Ozbek M, Uysal S, Karabulut E. Application of Kvaal et al.'s age estimation method to panoramic radiographs from Turkish individuals. Forensic Sci Int 2012;219:141-146.

21. Limdiwala PG, Shah JS. Age estimation by using dental radiographs. J Forensic Dent Sci 2013;5:118-122.

22. Karkhanis S, Mack P, Franklin D. Age estimation standards for a Western Australian population using the dental age estimation technique developed by Kvaal et al. Forensic Sci Int 2014;235: 104.e1-e6.

23. Igbigbi PS, Nyirenda SK. Age estimation of Malawian adults from dental radiographs. West Afr J Med 2005;24:329-333.

24. Karkhanis S, Mack P, Franklin D. Age estimation standards for a Western Australian population using the coronal pulp cavity index. Forensic Sci Int 2013;231:412.e1-e6.

25. Babshet M, Acharya AB, Naikmasur VG. Age estimation from pulp/tooth area ratio (PTR) in an Indian sample: a preliminary comparison of three mandibular teeth used alone and in combination. J Forensic Leg Med 2011;18:350-354.

26. Jeevan MB, Kale AD, Angadi PV, Hallikerimath S. Age estimation by pulp/tooth area ratio in canines: Cameriere's method assessed in an Indian sample using radiovisiography. Forensic Sci Int 2011;204:209.e1-e5.

27. Zaher JF, Fawzy IA, Habib SR, Ali MM. Age estimation from pulp/tooth area ratio in maxillary incisors among Egyptians using dental radiographic images. J Forensic Leg Med 2011;18:62-65.

28. Babshet M, Acharya AB, Naikmasur VG. Age estimation in Indians from pulp/tooth area ratio of mandibular canines. Forensic Sci Int 2010;197:125.e1-e4.

29. Jafarzadeh H, Wu YN. The C-shaped root canal configuration: a review. J Endod 2007;33:517-523.

30. Willems G, Moulin-Romsee C, Solheim T. Non-destructive dental-

age calculation methods in adults: intra- and inter-observer effects. Forensic Sci Int 2002;126:221-226.

31. Bodecker CF. A consideration of some of the changes in the teeth from young to old age. Dent Cosmos 1925;67:543-549.

32. Chung ET, Kim CY. An estimation of age based on the changes in the human dental cavity caused by increase in age (by surface index of pulp cavity). Korean J Oral Med 1981;6:101-110.

33. Hong HC, Ko MY. A study of the change of pulp cavity of the adult posterior teeth in ageing. Korean J Oral Med 1993;18:107-117.

34. Jeon HS, Tae IH, Ko MY, Ahn YW. Age estimation by dental radiographs in Korean adults. Korean J Oral Med 2009;34:179-188.

35. Philippas GG. Influence of occlusal wear and age on formation of dentin and size of pulp chamber. J Dent Res 1961;40:1186-1198.

36. Shaw L, Jones AD. Morphological considerations of the dental pulp chamber from radiographs of molar and premolar teeth. J Dent 1984;12:139-145.

37. Mathew DG, Rajesh S, Koshi E, Priya LE, Nair AS, Mohan A. Adult forensic age estimation using mandibular first molar radiographs: a novel technique. J Forensic Dent Sci 2013;5:56-59.