연세대학교
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Morphological analysis of pulp/tooth ratio for age estimation using panoramic radiography

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Morphological analysis of pulp/tooth ratio for age estimation using panoramic radiography

Directed by Professor Sang-Sun Han, D.D.S., Ph.D.

The Doctoral Dissertation
submitted to the Department of Dentistry,
and the Graduate School of Yonsei University
in partial fulfillment of the requirements for the
degree of Doctor of Philosophy

Bulgan Battulga

February 2017

연세대학교
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February 2017

Acknowledgement

First and foremost, I would like to express my special appreciation to my advisor Professor Sang-Sun Han for the continuous support of my study and related research. Your patience, motivation, immense knowledge and guidance helped me in all the time of research and writing of this thesis.

Besides my advisor, I would like to thank the rest of my thesis committee. Prof. Seong-Ho Choi, Prof. Kee-Deog Kim, Prof. Hyung-Joon Ahn and Prof. Ho-Gul Jeong for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives.

Also I am really thankful to Dr. Jae Joon Hwang, who helped me kindly to gain necessary data in the research facilities. Without that precious support it would not be possible to conduct this research. My sincere thanks also goes to our research partner Jeong-Hee Lee for the precise vision, stimulating discussions and collaborations.

Last but not the least, I would like to express my sincere gratitude to my family. My beautiful mother who cheers me up when in great need of inspiration and my wise father who always takes care of my safety while studying abroad. In the end, Yonsei University was the exceptional scientific research experience and extraordinary memory of my lifetime.

December, 2016

B.Bulgan

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It is important to produce data on the relationship between age and dental degenerative changes in different populations using dental radiography, because the results of the same method could vary according to the population. This study aimed to examine the applicability of the tooth coronal index (TCI) and the pulp/tooth area ratio of the whole tooth (PTR) to develop a population-specific method to accurately estimate the age of Korean adults using digital panoramic radiography. The upper and lower canines, as well as the lower first and second premolars of 101 digital panoramic images of Korean adults aged between 20 and 75 years were analyzed.

According to the method of Ikeda et al., the height of the crown and the height of the coronal pulp cavity were measured from the cementoenamel junction (CEJ) to the cusp tip and pulp horn; then the TCI was calculated.

According to the method of Cameriere et al., the pulp and tooth areas of the whole tooth were measured and the pulp/tooth area ratio (PTR) was calculated. Aside from this, we modified the method such that the whole tooth was divided into the coronal and root parts at the CEJ, with the pulp and tooth areas from the cusp tip to the CEJ designated as the coronal part (PcCR) and from the CEJ to the root apex designated as the root part (PrRR); these parts were measured and their ratios were each calculated.

Pearson correlation coefficients, analysis of covariance, linear regression models, and the standard error of the estimate (SEE) were computed using statistical software. To justify the use of linear regression models for purposes of prediction, diagnostic tests of 4 principal assumptions were also performed.

The TCI in an individual tooth showed a poor correlation SEE ranging from 14.9 to 15.4 years. The four-tooth combination model slightly improved on these results, with a SEE value of 14.8 years.

In an individual tooth, the PTR and PrRR showed better correlation than TCI, with SEE ranging from 10.7 to 13.9 years and from 10.5 to 13.7 years, respectively. The PTR and PrRR of the lower second premolar were the most accurate of the regression models. The PTR and PrRR in a four-tooth combination model showed the best age correlation, with SEE values of 10.5 and 9.8 years, separately.

In conclusion, TCI is not thought to be an appropriate method to predict the age of Korean adults. However, PTR in the lower second premolar can

be used as an appropriate indicator for age prediction, and PrRR is more accurate than PTR in Korean adults.

Keywords : age determination by teeth; forensic anthropology population data; forensic dentistry; panoramic radiography

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I. INTRODUCTION

In recent years, there has been an increase in the demand for age estimation in living people. This is important in a number of circumstances; for example, there are a great number of individuals without official identification documents cross international borders. In addition, unidentified corpses need verification of age for legal matters.[1] In all these cases, age is an essential factor for determination in the practice of forensic study. Previous researchers have proposed several skeletal and dental methods for estimating age. Skeletal changes such as modification in the symphysis pubis, sternal rib ends, the auricular surface of the ilium, and endo- and ectocranial suture are associated with aging. However, variation in populations as well as genetic, cultural, and environmental factors make it difficult to estimate the age of individuals. Those skeletal structures are often unsatisfactory for a full osteological analysis.[2]

Age estimation methods using teeth have developed into an essential tool for individual identification in forensic science. Teeth are preserved the longest relative to any other tissue of the human body, and thus they have been used as a marker for estimating human age.[3,4] Dental age estimation classifies subjects into young people and adults. Age estimation of a sub-adult is determined by evaluating the individual's dental developmental stage and maturity.[5] In adults, several age estimation methods based on dental degenerative changes have been developed.[3,6,7] However, dental indicators in an adult are less accurate for predicting actual age relative to the methods used for young people.[8]

In 1950, Gustafson[9] provided the first scientific method for determining the age of an individual by means of 6 dental degenerative features from among those changes found in adults: secondary dentin deposition, attrition, periodontosis, cementum apposition, root resorption, and transparency of the root. Thereafter, the most common age estimation indicators employed in medico-legal practice have been secondary dentin deposition, racemization of aspartic acid, cementum annulation, and root dentin translucency. But the procedures for analyzing these indicators require extraction and sectioning of the tooth, which is a time-consuming, costly, invasive approach that may not be acceptable for ethical, religious, or cultural reasons. Therefore, these biochemical methods cannot be used in living people.[10-13]

On the other hand, dental radiological examination is a non-invasive, simple, reproducible method in forensic science.[14] Philippas et al.[15] first used a radiographic method to determine the influence of age on the formation of secondary dentin.

As secondary dentin is laid down on the inner wall of the pulp cavity, the pulp cavity decreases in size with age.[16] Since then, several authors have evaluated secondary dentin deposition in the pulp cavity using dental radiography.[2,3,6,7,14,16-23] They analyzed the correlation of the reduction of the pulp cavity with age by measuring the height, width, and area of the pulp and tooth, and then calculating the ratios of pulp to tooth.

In 1985, Ikeda et al.[6] measured the heights of the coronal pulp cavity and tooth in the crown and calculated the tooth coronal index (TCI). They suggested that the index decreased with aging. In 1995, Kvaal et al.[3] introduced the method of measuring the height and width of the tooth and pulp on a periapical radiograph. They reported that measurement on dental radiograph might be used as a non-invasive age estimation method; however, the method required testing with different samples. The reason we have not applied the method of Kvaal et al. is because some previous articles have shown completely different results. For example, Bosmans et al.[17] found comparable results to those based on the original technique. In contrast, Prapanpoch et al.[23] result showed no correlation between age and the width and height pulp/tooth ratios. Landa et al.[20] concluded that this method cannot be applied to direct digital panoramic radiographs. In 2004, Cameriere et al.[7] analyzed pulp size decrease in relation to age by calculating the ratio of pulp/tooth area of the whole tooth (PTR) and the ratio of pulp/tooth width at the cementoenamel junction (CEJ) level, as well as pulp/tooth height using the monoradicular teeth. They suggested that the ratio of pulp/tooth area showed the best correlation with age.

However, these previous methods using dental radiography showed different degrees of accuracy in age prediction depending on the population sample.[1,16,19,21,24-27] Although the same method was used in different populations, it could produce different results for each, which means that the applicability of each method varies by population. Therefore, it is important to generate data on the correlation between age and widely known methods such as TCI and PTR in individuals as well as across populations using dental radiography. However, a standardized protocol for the dental radiologic method of age estimation focused on Korean adults has not been previously reported. This study aimed to examine the applicability of the TCI and PTR methods and to develop a population-specific method to accurately estimate the age of Korean adults using digital panoramic radiography.

II. MATERIALS AND METHODS

1. Subjects

One hundred one digital panoramic images of Korean adults were randomly selected at Yonsei University Dental Hospital between March and November 2015. The study sample consisted of 49 males and 52 females aged between 20 and 75 years. The gender and age distribution of the patients are shown in (Table 1). All digital panoramic radiographs were taken using a Cranex 3^{+} Ceph machine (Soredex Orion Corp., Helsinki, Finland). Exposure conditions were set to 67-71 kVp, 10 mA at 19.5 seconds following the manufacturer’s instructions. The selected panoramic images did not have overlap with other anatomical structures. The upper and lower canines and the lower first and second premolars were analyzed. The exclusion criteria were: teeth with developmental anomalies, restoration, caries, root-canal treatment, and any other pathological processes.

2. Measurements

The panoramic images were converted as Digital Imaging and Communication in Medicine (DICOM) files from Picture Archive and Communication Systems (PACS) data into the ImageJ v. 1.43 software program (National Institutes of Health, Bethesda, MD, USA).

Two observers were trained in the method for quantifying the measurements under blinded conditions of subject information. In order to obtain accurate measurements, 2 monitors (Totoku Electric Co., Nagano, Japan) were set with the same resolution (1260×1048 pixels), and were adjusted to the same sharpness, brightness, and contrast for analysis. To test intra-observer reproducibility, 20 panoramic images were randomly re-examined after an interval of 2 weeks.

According to the TCI method, the height between the cusp tip and cementoenamel junction (CEJ) as well as the height between the pulp horn and the CEJ were measured, and the measurements were labeled as CH and CPCH, respectively (Figure 1). Descriptions of morphological variables are shown in (Table 2). TCI was calculated as follows: TCI = CPCH × 100/CH.

According to the PTR method, the pulp and tooth areas of the whole tooth were measured. The whole tooth was divided into the coronal and root parts at the CEJ, and the pulp and tooth areas from the cusp tip to the CEJ and from the CEJ to the root apex were also measured individually. The ratios of pulp/tooth area in the 3 parts were calculated, and the ratios of the whole tooth and coronal and root parts were denoted as PTR, PcCR and PrRR, respectively (Table 2). A schematic representation of the measured variables is provided in (Figure 2). At least 20 landmarks were made to create reproducible boundaries of the tooth and pulp areas using the 'polygon selections' tool to minimize the discrepancies between the 2 observers (Figure 3).

Table 1. Age and gender distribution of the population

Age (years)	Male	Female	Total
20-29	10	14	24
30-39	14	8	22
40-49	9	11	20
50-59	8	11	19
>60	8	8	16
Total	49	52	101

Table 2. Descriptions of morphological variables

Notation	Descriptions
TCI	The ratio of pulp and tooth height in the coronal part
PTR	The ratio of maximum pulp area to maximum tooth area in the whole tooth
PcCR	The ratio of pulp area to tooth area in the coronal part
PrRR	The ratio of pulp area to tooth area in the root part

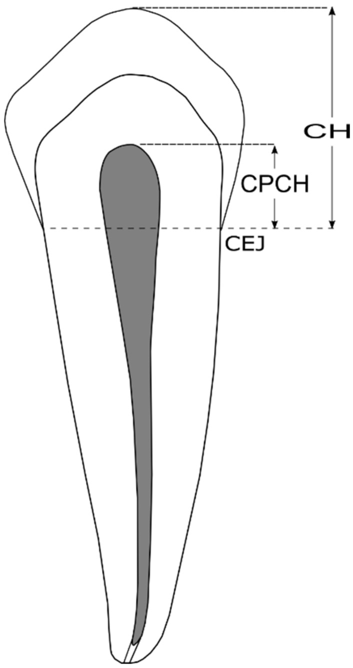


Figure 1. The morphological variables of pulp and tooth height measurements are shown schematically. CH, the height from the CEJ to the cusp tip; CPCH, the height from the CEJ to the pulp horn.

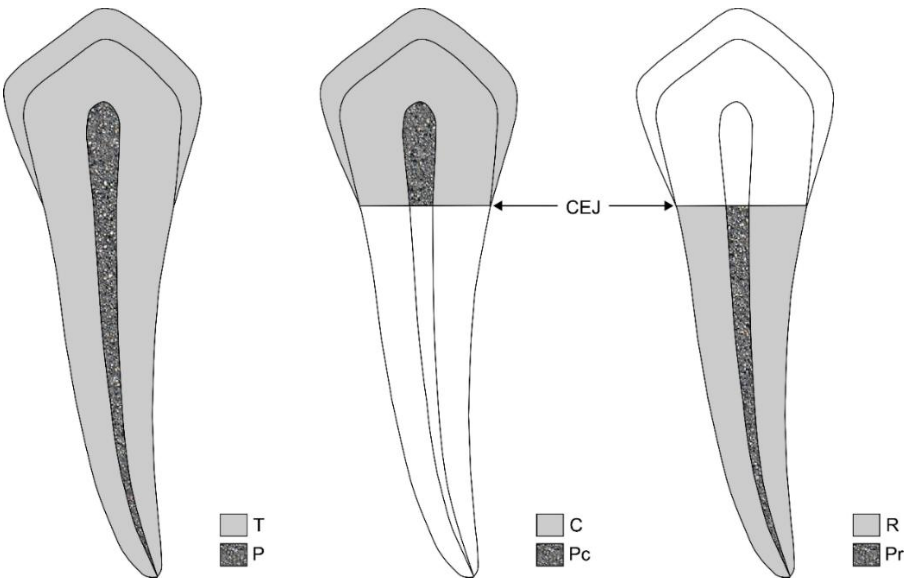


Figure 2. The morphological variables of pulp and tooth area measurements are shown schematically. P, pulp area of the whole tooth; T, tooth area of the whole tooth; Pc, pulp area from the cusp tip to the CEJ; C, tooth area from the cusp tip to the CEJ; Pr, pulp area from the CEJ to the root apex; R, tooth area from the CEJ to the root apex.

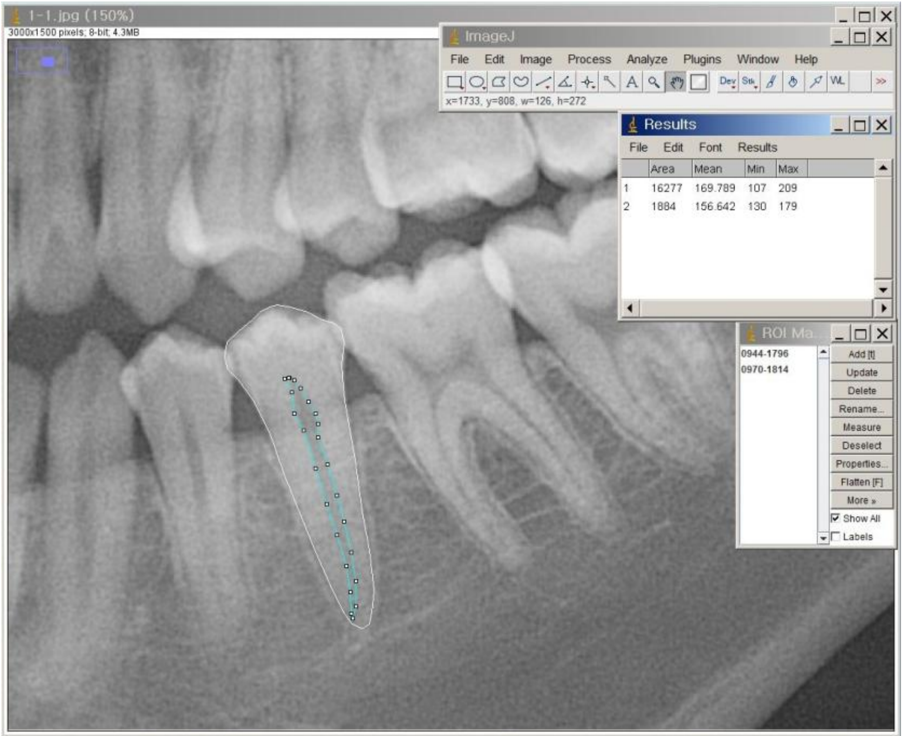


Figure 3. Reproducible boundaries of pulp and tooth areas were created with the 'polygon selections' tool of the image analysis software.

3. Statistical analysis

The intraclass correlation coefficient (ICC) was calculated for inter- and intra-observer reliability with a 95% confidence interval (CI). Analysis of covariance (ANCOVA) was applied to study possible interactions between age, teeth and sex. Pearson correlation coefficients were calculated to find the degree of linear association between the actual age and pulp/tooth ratio in the 4 teeth. Linear regression analyses were performed between the actual age and 4 ratios and to establish equations for age determination. The standard error of the estimate (SEE) was computed to predict the deviation between the actual age and the estimated age. There are 4 principal assumptions that justify the use of linear regression models for purposes of inference or prediction: linearity, the independence of errors, the homoscedasticity of errors and the normality of error distribution. To check these assumptions, we used the Durbin-Watson test, residuals versus fitted-values plot and a probability–probability plot (p-p plot). Statistical analysis was performed using SPSS Statistics for Windows, v. 23.0 (IBM Corp., Armonk, NY, USA).

III. RESULTS

The ICC showed that the intra-observer reproducibility score and the inter-observer accordance score were 0.93 and 0.92, respectively. The ANCOVA analysis showed no significant difference between the sexes ($p>0.05$). Therefore, statistical analyses were not separately performed for male and female subjects.

The Pearson correlation coefficients between actual age and the TCI showed that the correlation coefficients were significant ($p<0.05$) (Table 3). However, the lower first premolar showed a result that was not significant. The simple regression model of the TCI in an individual tooth showed a poor correlation SEE ranging from 14.9 to 15.4 years, and the lower canine showed the best age correlation ($R^2=0.133$) (Table 4). The TCI in the four-tooth combination model slightly improved the results with an SEE value of 14.8 years (Table 4).

The Pearson correlation coefficients between actual age and the PTR, PcCR, and PrRR showed that all of them were significantly correlated with age ($p<0.05$) (Table 3). The simple regression model of the PTR showed better results than that of the TCI method in an individual tooth, with SEE ranging from 10.7 to 13.9 years (Table 4). The PrRR of the lower second premolar was the most accurate regression model, with SEE of 10.5 years (Table 4). In the four-tooth combination model, PrRR showed the best age correlation with an SEE value of 9.8 years, followed by PTR with an SEE of 10.5 years (Table 4). On the other hand, PcCR was found to have the poorest age correlation with R^2 ranging from 0.122 to 0.247 and SEE ranging from 13.8 to 15 years (Table 4).

To validate the model assumptions and check model accuracy, diagnostic tests were conducted as follows. The regression line of showed that the regression model fit the trend of the data reasonably well (Figure 4). The Durbin-Watson test was performed for detecting autocorrelation of errors using the residuals from a regression analysis, resulting in a PTR and PrRR of 1.144 and 1.160, respectively, in the lower second premolars. The residual of the regression models was satisfied with the independence distribution. Standardized residual plots also showed no presence of an outlier; therefore, the assumption that residuals have a mean of zero was most likely satisfied (Figure 5). Figure 6 shows a linear trend on the normal p-p plot, which suggests that the normality assumption of the model was most likely satisfied.

Table 3. Correlation coefficient (r) between morphological variables and actual age

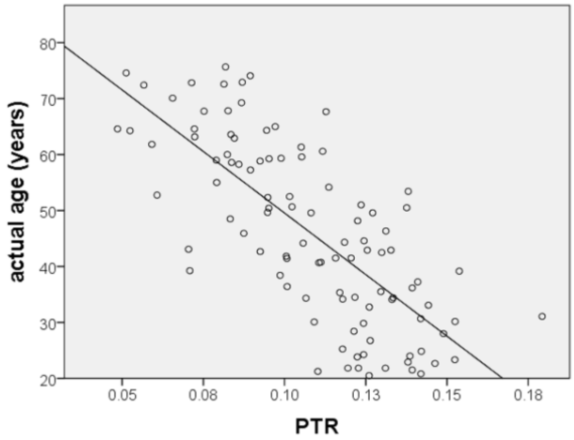
Morphological variables	Upper canine	Lower canine	Lower first premolar	Lower second premolar
TCI	-0.284^{**}	-0.365^{**}	-0.187	-0.306^{**}
PTR	-0.487^{**}	-0.555^{**}	-0.591^{**}	-0.740^{**}
PcCR	-0.350^{**}	-0.461^{**}	-0.380^{*}	-0.497^{**}
PrRR	-0.516^{**}	-0.586^{**}	-0.629^{**}	-0.751^{**}

***p<0.01, *p<0.05*

Table 4. Regression equations derived from morphological variables of an individual tooth and four-tooth combinations

Teeth	Regression equations	R^2	SEE (years)
Upper canine			
TCI	694.893-441.974×TCI	0.081	15.4
PTR	78.964-248.727×PTR	0.237	13.9
PcCR	56.796-166.3×PcCR	0.122	15
PrRR	82.066-201.372×PrRR	0.266	13.7
Lower canine			
TCI	671.547-462.067×TCI	0.133	14.9
PTR	81.116-297.957×PTR	0.308	13.3
PcCR	59.676-261.663×PcCR	0.212	14.2
PrRR	87.199-265.292×PrRR	0.344	12.9
Lower first premolar			
TCI	N/S	N/S	N/S
PTR	83.734-330.991×PTR	0.349	12.9
PcCR	60.093-261.863×PcCR	0.144	14.8
PrRR	84.126-240.664×PrRR	0.396	12.4
Lower second premolar			
TCI	709.339-683.309×TCI	0.094	15.2
PTR	93.552-440.056×PTR	0.548	10.7
PcCR	63.403-402.674×PcCR	0.247	13.8
PrRR	88.829-277.398×PrRR	0.565	10.5
Four-tooth combination			
TCI	757.318-201.170×23TCI-309.130×33TCI+34.405×34TCI-304.303×35TCI	0.164	14.8
PTR	101.264-47.577×23PTR-46.106×33PTR-62.305×34PTR-337.157×35PTR	0.578	10.5
PcCR	68.093-57.19×23PcCR-112.365×33PcCR-31.899×34PcCR-238.017×35PcCR	0.305	13.5
PrRR	102.789-29.261×23PrRR-79.885×33PrRR-62.959×34PrRR-189.017×35PrRR	0.63	9.8

R^2, coefficient of determination. SEE, standard error of the estimate in years.
A value of p<0.05 is considered significant. N/S, not significant.



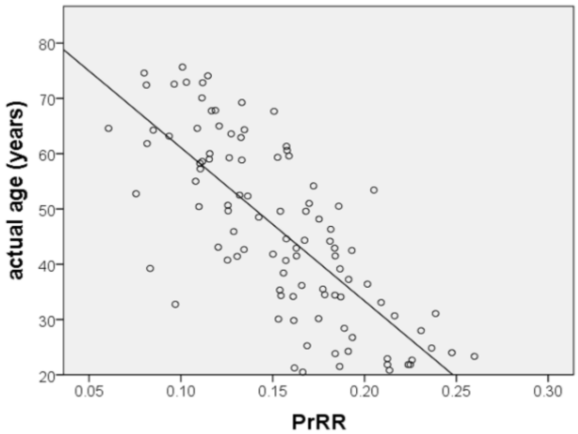


Figure 4. Plots of age against second premolar PTR (upper panel) and PrRR (lower panel).

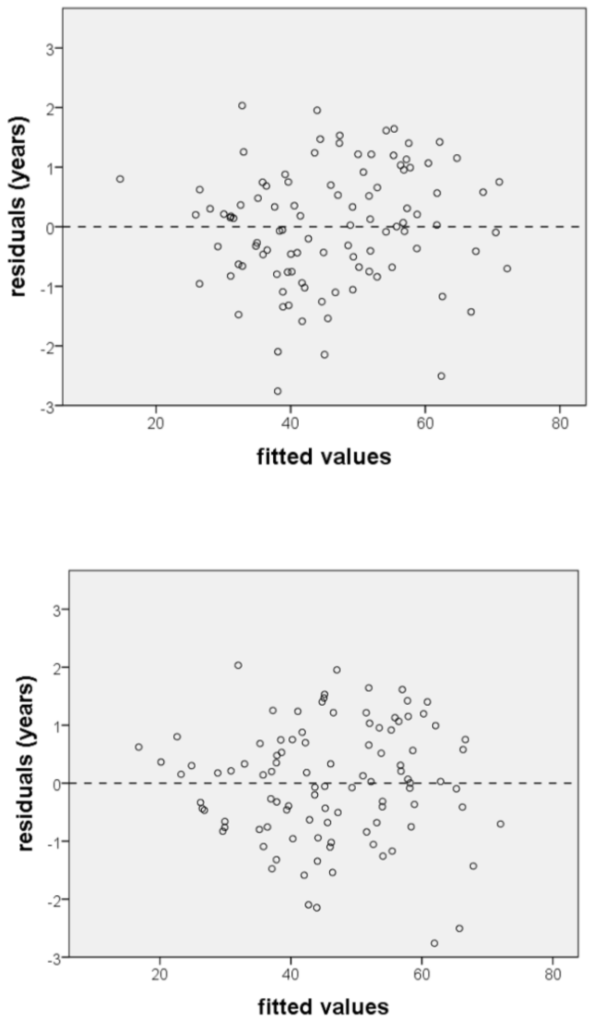


Figure 5. Plots of residuals against fitted values using a simple linear regression model to describe age as a function of PTR (upper panel) and PrRR (lower panel) of the lower second molar.

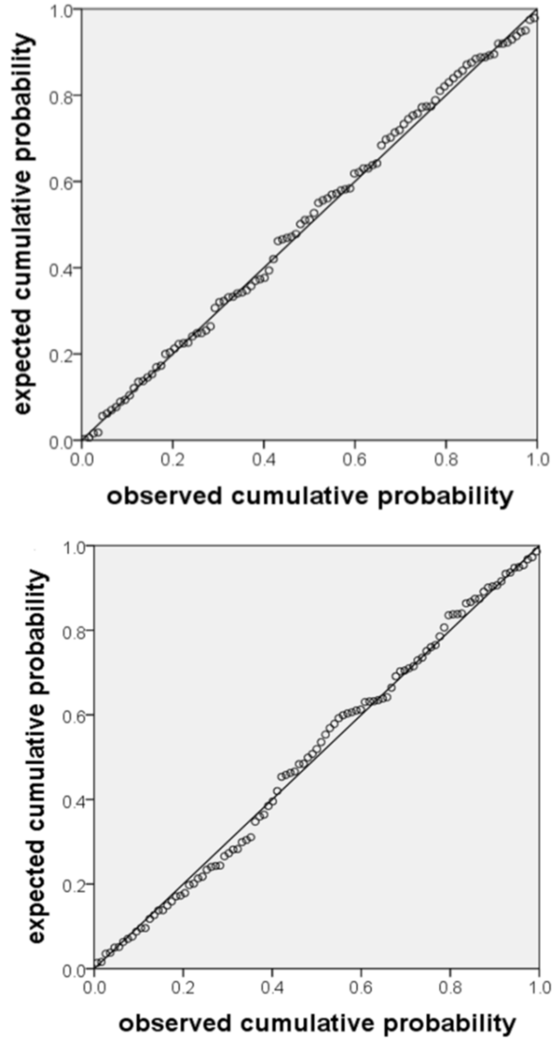


Figure 6. Normal p-p (probability probability) plot of regression standardized residuals in the PTR (upper panel) and PrRR (lower panel) of the lower second premolars.
The normal p-p plot shows a normal distribution of residuals.

IV. DISCUSSION

Dental age estimation is important for the identification of living and dead individuals due to crimes carried out across national borders in the field of forensic science. Thus, there is a global demand for non-invasive, accurate, cost-effective and simple methods of age estimation. The clever use of dental radiologic methods of age determination can meet this demand, especially when extraction or sectioning of the teeth is not possible.[28]

One of the dental age estimation factors is the formation of secondary dentin deposition by reducing the pulp cavity in advancing age.[15] The volume of the pulp cavity gradually decreases with age because of secondary dentin deposition in the pulp cavity wall. Several researchers have applied periapical and panoramic radiography to measuring height, width and area ratios in the pulp cavity and investigated the correlation between age and the reduction of the pulp.[3,6,7]

In the present study, the upper and lower canines and the lower first and second premolars were selected. Because the upper and lower canines, which often remain into old age and the single-rooted teeth with large pulp area are easy to analyze, they are often used in the field of forensic science. Further, the lower premolar has a monoradicular root and is not prone to pathologic changes.[22] Molars have certain limitations, such as multi-rooted teeth that make it difficult to find reference points and that are prone to dental caries. In particular, in East Asians, the second molars often show anatomical variations.[3,29] Pathological stimuli such as caries and trauma affect the formation of irregular secondary dentin (tertiary dentin), and it is impossible to differentiate secondary dentin from tertiary dentin on radiographs. Therefore, teeth with restoration, caries, periodontitis, abrasion, root-canal treatment and any other pathological processes were excluded in this study.

This study used digital panoramic images. In generally, a panoramic radiograph has low resolution. However, it produces more standard images compared to intraoral radiography, which produces discrepancies in magnification due to constantly changing imaging angles. Studies using digital panoramic radiographs have emphasized that the accuracy of this age estimation method mainly depends on the precision of the measurements and the sharpness of the images.[17] Paewinsky et al.[18] suggested that inter-observer differences may be due to interpretation differences because of the need to define the reference points for carrying out the measurements on a monitor screen. Schulze et al.[30] evaluated the precision and accuracy of digital measurements in digital panoramic radiography and concluded that they are adequate for clinical applications. In this study, the intra- and inter-observer reproducibility score was high.

In a literature review of the applicability of the TCI method in different populations, SEE was within 10 years, which is an acceptable range for age estimation in forensic study.[1,16] In 1997, Drusini et al.[16] used panoramic radiographs and found an SEE ranging from 5.88 to 6.66 years. They concluded that TCI is a reliable biomarker for age assessment in living individuals. In 2013 Karkhanis et al.[1] applied panoramic radiographs of both lower premolars and molars and the most accurate age estimation model yielded an SEE of 8.2 years. However, in this study, predictive age based on the TCI was far from actual age, with SEE ranging from 14.9 to 15.4 years. The TCI is not thought to be an appropriate method for predicting the age of Korean adults. This can be attributed to varying rates of attrition on the occlusal surface of the teeth and the pattern of secondary dentin deposition.

In previous studies, the PTR method of age determination has been reported to have a large variation in SEE values between 1.2 and 13.0 according to different populations.[2,7,28,31,32] A study of 100 Italian cases reported that the SEE was within 3.7 years,[7] and the SEE of 606 Spanish Caucasian patients ranged between 4.34 and 6.02 years.[2] In contrast, studies of certain other populations did not show the appropriate accuracy of age prediction.[28,32] A study of 400 members of the Davangere population showed an SEE of 12.0 years,[32] and an Indian sample showed that SEE varied from 12.1 to 13.0,[28] These large variations are thought to be due to ethnic factors like tooth morphology, the secondary dentin deposition pattern and tooth abrasiveness from eating habits.

In addition, the pulp/tooth area ratios in the crown and root part were measured separately. The PrRR in an individual tooth showed a more accurate result than PTR. To justify the use of linear regression models for purposes of prediction, we evaluated the linearity, the independence of errors, the homoscedasticity of errors, and the normality of error distribution of the regression models for the PrRR and PTR of the lower second premolar. The regression model obtained in the present study was satisfactory to the assumptions; thus the model can be used to make predictions. The PrRR of the summed data from four teeth was 9.8 years, making it the smallest deviation from the actual age. The better result from the root area could be explained by considering that the mean rate of increasing dentinal thickness is 6.5 μm per year for the crown and 10 μm per year for the root area.[33] This means that yearly dentin deposition occurred more actively in the root area compared with the coronal area.

Among the 3 variables PcCR was found to have the poorest age correlation, with SEE ranging from 13.8 to 15 years. Based on the TCI and PcCR method, which measured the pulp/tooth ratio in the coronal part, it is thought that estimation based on measurement of the crown part of tooth is less accurate.

V. CONCLUSION

In conclusion, TCI is not thought to be appropriate method to predict the age of Korean adults. However, PTR in the lower second premolar can be used as an appropriate indicator of age prediction and PrRR is more accurate than PTR in Korean adults. In future studies, larger sample sizes would be preferable in order to reduce standard error of age estimation with more advanced dental radiological technologies.

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Abstract (Korean)

파노라마 영상을 이용하여 치수/치아 비율의 형태학적 분석을 통한 연령감정

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동일한 연령감정방법을 적용한 결과는 민족마다 다르게 나타난다. 따라서 치과방사선을 이용한 연령과 치아의 퇴행적 변화의 관계에 관하여 각각의 민족에 따른 데이터의 생산은 중요하다. 본 연구의 목적은 디지털 파노라마 방사선 영상을 이용한 성인 연령감정의 민족 고유의 방법을 개발하기 위해 tooth coronal index(TCI)와 전체 치아의 치수/치아 비율 방법의 적용가능성을 조사하는 것이다. 20세에서 75세 사이의 한국 성인의 디지털 파노라마 영상에서 상하악 견치와 하악 제1, 2 소구치를 분석하였다.

Ikeda의 방법에 따라 백악법랑경계(CEJ)에서 교두와 치수각을 기준으로 하여 치관의 높이와 치수강의 높이를 측정 후 TCI를 계산하였다. Cameriere의 방법에 따라 전체 치아의 치아와 치수강의 면적을 측정하여 치수/치아 비율(PTR)을 계산하였다. 더불어 본 연구는 전체 치아를 백악법랑경계를 기준으로 치관과 치근 부위로 나누어 수정된 방법을 개발하였다. 치관부분(PcCR)은 백악법랑경계에서 교두까지의 치아와 치수

면적을 측정하였고, 치근부분(PrRR)은 백악법랑경계에서 치근단까지의 치아와 치수 면적을 측정하여 각각의 비율을 계산하였다.

SPSS 통계 소프트웨어를 이용하여 피어슨상관계수, 공변량분석, 선형회귀분석, 추정표준오차를 계산하였다. 선형회귀모형의 타당성을 확인하기 위해 4개의 주된 가정의 진단 테스트를 실시하였다. 각각의 치아의 TCI는 14.9년에서 15.4년 범위의 낮은 SEE 값을 보였다. 네 개 치아의 조합 모형은 약간의 개선된 결과로 14.8년의 SEE 값을 나타냈다.

각각의 치아에서 PTR과 PrRR은 TCI보다 더 나은 상관관계를 보였고, SEE는 각각 10.7년에서 13.9년과 10.5년에서 13.7년의 범위로 나타났다. 각각의 치아의 회귀모형에서 하악 제2소구치의 PTR과 PrRR은 연령예측에 가장 정확한 결과를 보였다. 네 개 치아 조합의 PTR과 PrRR 모형은 각각 10.5년과 9.8년의 SEE 값을 보여 연령예측의 정확성이 가장 높은 모형으로 확인되었다.

결론적으로, TCI는 한국 성인의 연령을 예측하기 위한 적절한 방법으로 고려될 수 없다. 그러나, 하악 제2 소구치의 PTR은 연령예측에 적합한 지표로써 사용될 수 있으며, 한국 성인에서 PrRR은 PTR보다 더 정확하였다.

중심단어: 치아 연령감정; 법인류학 인구 데이터; 치과법의학; 파노라마 영상