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PAPER

ODONTOLOGY

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Human Dental Age Estimation by Calculation of Pulp/Tooth Volume Ratios Yielded on Clinically Acquired Cone Beam Computed Tomography (CBCT) Images of MonoRadicular Teeth*

ABSTRACT: Secondary dentine is responsible for a decrease in the volume of the dental pulp cavity with aging. The aim of this study is to evaluate a human dental age estimation method based on the ratio between the volume of the pulp and the volume of its corresponding tooth, calculated on clinically taken cone beam computed tomography (CBCT) images from monoradicular teeth. On the 3D images of 111 clinically obtained CBCT images (Scanora®3D dental cone beam unit) of 57 female and 54 male patients ranging in age between 10 and 65 years, the pulp–tooth volume ratio of 64 incisors, 32 canines, and 15 premolars was calculated with Simplant® Pro software. A linear regression model was fit with age as dependent variable and ratio as predictor, allowing for interactions of specific gender or tooth type. The obtained pulp–tooth volume ratios were the strongest related to age on incisors.

KEYWORDS: forensic science, age determination by teeth, cone beam computed tomography, semi-automated CBCT separation and segmentation, secondary dentine, pulp/tooth volume ratio

Divers age estimation methods (1–7) are developed integrating single or multiple age-related variables. The estimated age prediction outcomes allow to advise legal authorities in their judgment on the chronological age of individuals with a questioned age (8–11) and provide more accurate postmortem profiling of unidentified body remains (12,13). Dental age estimation methods are of particular value because teeth are highly resistant to mechanical, chemical, or physical impacts and time (14–17). Moreover, dental age predictors are minimally influenced by the nutritional, medical, environmental, and living conditions the individual was submitted to (18,19).

The dental age-related parameters are subdivided whether they indicate developmental (20–23), morphological (24–29), or biochemical (30–32) tooth changes. Secondary dentine apposition is a significant morphological dental age predictor (33–37). It is defined as the formation of dentine after the completion of the primary dentine and starts at the moment the related tooth root is completed (38–41). The formation of secondary dentine may be caused by attrition, abrasion, erosion, caries, changes in osmotic pressure throughout the pulp chamber, or aging (37,41–43) and decreases the volume of the dental pulp chamber. Therefore, the volume changes of the pulp chamber in intact teeth are considered as a dental age predictor. Although the apposition of secondary dentine is not homogenously spread over all the walls of the pulp cavity and even differs in relation to the examined tooth type, bucco-ingual and mesio-distal pulp width as well as the pulp cavity height decreases with aging (44–48). These variables can be measured on the involved tooth after extracting and sectioning it (34–37) or on its two dimensional (2D) dental radiographs (49–53). More specifically, the last two variables can be applied for radiological age estimation on living individuals without tooth extraction (49–51). Similarly researchers have tried to relate the ratio of the surface area of the pulp and the surface area of the tooth measured on clinically obtained 2D dental radiographs to chronological age (54). Three dimensional (3D) radiographs of extracted teeth generated by a desktop X-ray micro-computed tomography (CT) scanner (55) or a cone beam computed tomography (CBCT) unit (56) allow for the calculation of the volume of each tooth and corresponding pulp chamber. To reduce the variation in tooth sizes, the ratio of both obtained volumes is related to the chronological age of the subjects. In a pilot setup, the same procedure is applied on CBCT images of unextracted monoradicular teeth (28).

The aim of this study is to generate human dental pulp and corresponding tooth volumes from clinically taken CBCT images

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of monoradicular teeth and to relate their ratio to the chronological age of the subjects.

Materials and Methods

CBCT images from 57 female and 54 male Belgian patients were selected from the database of the University Hospital Sint-Rafaël at the Katholieke Universiteit Leuven and exported in DICOM file format using OnDemand3D software (CyberMed® Inc, Seoul, South Korea). The birth date of all subjects was checked with their identity card during the dental record setup. The subjects were selected upon their chronological age at the moment of radiological exposure for an equal division in 13 age categories of 5 years continuously spread in the range between 10 and 65 years. As second criterion for inclusion, the CBCT image quality allowed for each subject the separation and segmentation of at least one intact and fully developed monoradicular tooth. Of the 111 selected CBCT images, 214 monoradicular pulp and tooth volumes were calculated. As research sample per subject, randomly one related tooth was selected, resulting in a database containing volume information of 64 incisors, 32 canines, and 15 premolars (Table 1).

All CBCT images were generated with a Scanora®3D dental cone beam 3D X-ray unit (Soredex, Tuusula, Finland). Specifications for image rendering were exposures at 85 kV and 8, 10, or 15 mA, field of view selection between 60×60, 75×100, or 75×145 mm, focal dimensions set at 0.15 or 0.20 mm, and scanning time of 10 sec.

The DICOM files were imported in a CT and CBCT diagnostic and treatment planning software (Simplant® Pro Version 11.0 on Windows; Materialise Dental NV, Leuven, Belgium) allowing for the pulp and tooth volume calculations. Separation and segmentation of the involved teeth was automatically performed by setting a grayscale threshold referring to the grayscale of the different tooth and surrounding tissue components and was manually checked and corrected whenever necessary. The program automatically calculated the volume of the obtained 3D images of the tooth and pulp (Fig. 1).

To quantify the proportion of variance explained in age by the pulp–tooth volume ratio on the sample and the subgroups related to sex or tooth type, squared Pearson correlation coefficients were calculated. A linear regression model was used with age as dependant variable and the pulp and tooth ratio as predictor. In the model,

TABLE 1—*Number of examined teeth gender specific classified by tooth type and tooth position: For the tooth position, the FDI (Fédération dentaire internationale) World Dental Federation tooth numbering system was used.*

	Tooth Type																			
	Incisor								Canine				Premolar							
Female	32								13				12							
Male	32								19				3							
Total	64								32				15							
	Tooth Position								Tooth Position				Tooth Position							
	11	21	31	41	12	22	32	42	13	23	33	43	14	24	34	44	15	25	35	45
Female	12	12	3	3	1	0	1	0	5	2	3	3	1	0	1	2	3	2	2	1
Male	14	12	1	3	1	0	1	0	5	2	6	6	0	0	0	0	0	0	0	3
Total	26	24	4	6	2	0	2	0	10	4	9	9	1	0	1	2	3	2	2	4

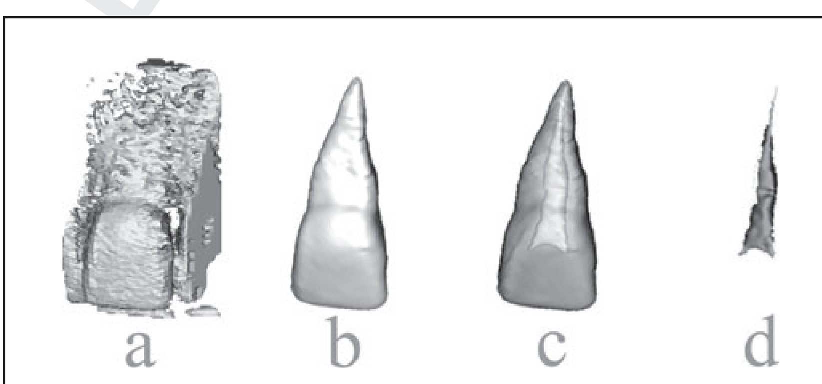

FIG. 1—*Different separation and segmentation steps of an upper central incisor on cone beam computed tomography DICOM data imported in Simplant® Pro software. To segment the selected tooth, a mask is created and an optimal separating grayscale threshold is chosen on axial images showing the tooth root in bone. The mask is cropped in three axis to limit it to the closest region of the chosen tooth, and a 3 dimensional (3D) image is calculated (a). On this 3D calculation, regions not belonging to the tooth are selected and roughly removed. Next slice by slice in each reproduction orientation manual erases and correcting draws are performed to remove the cortical bone parts at root level and parts of the neighboring teeth at crown level. This separation cannot be established by adapting the threshold because there is a too small or no gray value difference between the involved structures. A 3D calculation of the mask assembling all adapted slices generates an image on which the program can calculate the tooth volume (b). At the inner side of the calculated image, a free space is available corresponding with the pulp chamber (c). After adapting the segmentation by drawing a stop in the most apical axial slice of the tooth, a new mask is created filling the internal tooth hole. A 3D calculation of the pulp chamber mask allows for a calculation of the pulp volume (d).*

interactions were included to verify if the relation between age and the ratio differs between women and men or between incisors, canines, and premolars.

To quantify the accuracy of the volume calculations performed with the Simplant® pro software, the real pulp and tooth volumes of three extracted monoradicular teeth with reamed pulp canal were measured, based on the volume displacement law of Archimedes and according to the protocol described in the study of Yang et al. (28). The obtained results were compared with the pulp and tooth volumes calculated on the CBCT images of the same endodontic prepared teeth.

All statistics were performed using SAS software, version 9.2 of the SAS® System for Windows (SAS® Institute Inc., Cary, NC).

Results

The calculated pulp–tooth ratios ranged between 0.002 and 0.091 with a mean value of 0.027 (SD 0.020) and a median of 0.022. The relation between age and pulp–tooth volume ratio was plotted for the research sample (Fig. 2) and separately specified for each gender (Fig. 3) and for each of the three investigated tooth types (Fig. 4). For the sample and the 11 related subgroups, the calculated Pearson correlation coefficient was listed (Table 2).

The regression analysis with age as dependant variable and the pulp–tooth volume ratio as independent variable shows a weak squared Pearson correlation (0.34) for the whole research sample (Fig. 2). The variability in age based on the squared Pearson correlations is for 40.9%, 7.3%, and 22.8% explained for the pulp–tooth volume ratio measured, respectively, on incisors, canines, and premolars. Although there was no statistical evidence that the relation between the pulp–tooth volume ratio and age differs between the types of tooth ($p = 0.15$), regression formulas should be calculated separately for each tooth type. The standard deviation (mean squared error from the regression model) for incisors, canines, and premolars were, respectively, 12.86, 13.10, and 8.44 year. However, the standard deviation was not significantly different between the three tooth types. If a choice of tooth type is conceivable, an incisor should be selected (Fig. 4). The observed relation between the pulp–tooth volume ratio and age was stronger for women than for

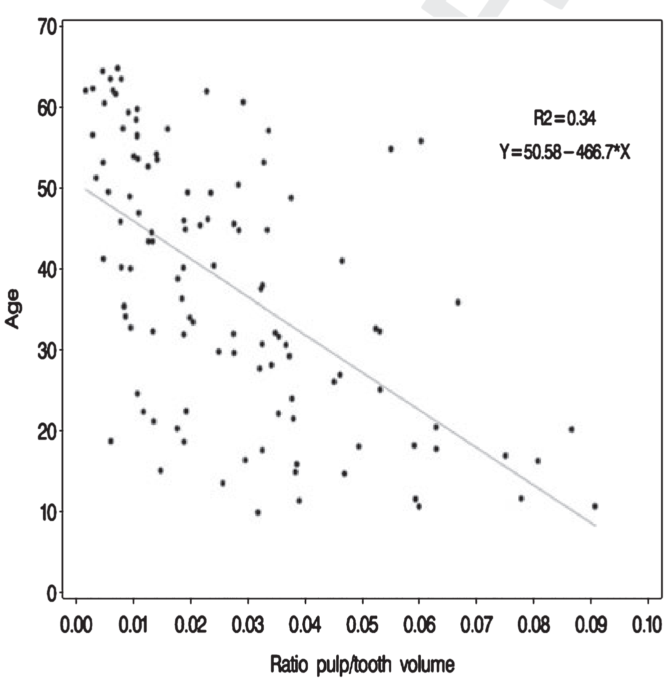

FIG. 2—*The relation between age and pulp–tooth volume ratio for all included teeth.*

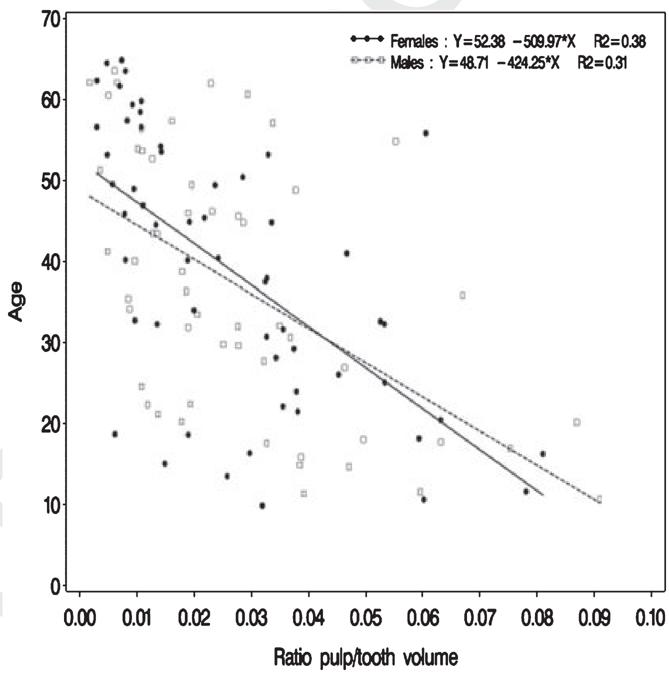

FIG. 3—*The relation between age and pulp–tooth volume ratio sorted on gender. A stronger but not significant Pearson correlation is detected between age and pulp–tooth volume for women.*

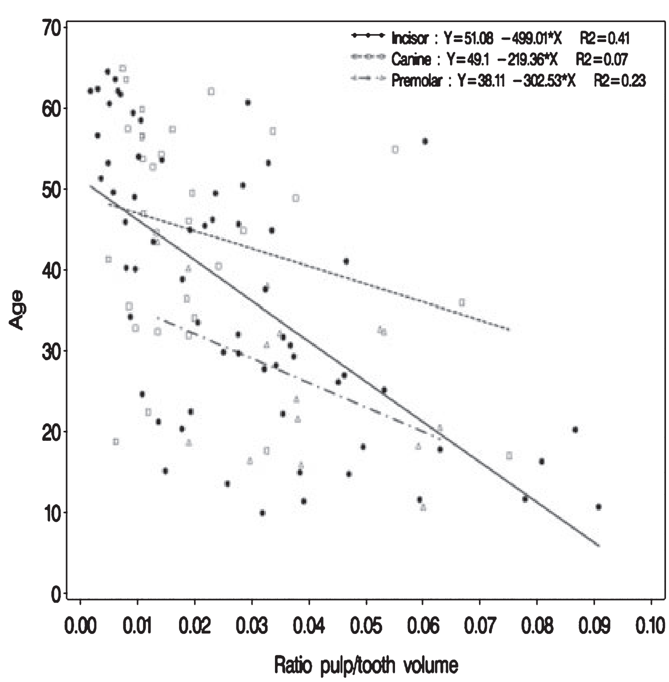

FIG. 4—*The relation between age and pulp–tooth volume ratio sorted on tooth type. Pearson correlation between age and pulp–tooth volume is strongest for the incisors followed by the premolars and the least for the canines.*

TABLE 2—*Pearson correlations between age and ratio pulp volume/tooth volume for the whole sample and the different subgroups: The weakest Pearson correlation was detected for the canines in total as well as for its gender-specific relations.*

	Female	Male	Total
Incisor	−0.61	−0.68	−0.64
Canine	−0.24	−0.28	−0.27
Premolar	−0.35	−0.88	−0.48
Total	−0.61	−0.55	−0.59

men but the difference in relation was not significant ($p = 0.86$); moreover, there was no significant interaction between tooth types and gender ($p = 0.50$). For these reasons, there is no evidence that gender should be considered when using the ratio and type of tooth as a predictor for age (Fig. 3).

The differences between the real volumes and the volumes measured with the Simplant® software on the 3D images of the same teeth differed, respectively, for pulp and tooth maximally 21% and 16%.

The procedure for separation, segmentation, and volume calculation took on the average 3 h per tooth.

Discussion

Opposite to the studies of Vandevoort et al. (55) and Yang et al. (28) in this study, out of the originally 214 separated and segmented single-rooted teeth, for each subject, randomly one tooth was selected. Taking into account multiple tooth samples per subject is not possible within a regression model for age. In fact, each repeated pulp–tooth volume ratio measurement would function as another predictor which was not feasible because the number of repeated measurements differed between the subjects. Even an equal number of included teeth might induce multicollinearity problems owing to the correlation between the repeated pulp–tooth volume ratio measurements.

The strongest Pearson correlation coefficient between the pulp–tooth volume ratio and age was measured on incisors. This was expected because all the correlation coefficients between the variable ratios related to secondary dentine formation and age used in the Kvaal et al. study (49), equally, provided the highest correlation outcomes in the incisor group. Moreover, this tooth type includes lower incisors that have the lowest morphological diversity among human teeth (57). The last argument is of minor value in this study because in the randomly selected incisor group ($n = 64$), only 11 lower incisors were included (Table 1).

The reason why there was no statistical evidence that the relation between the pulp–tooth volume ratio and age differs between the types of teeth can possibly be explained by the relatively low number of included canines ($n = 32$) and premolars ($n = 15$). This likely lack of power could be ameliorated in further research by guiding the selection of one tooth type per subject to a more equal inclusion of different tooth types in the test sample.

The ratio between pulp volume and tooth volume was chosen as age predictor to reduce the variation in tooth sizes and to neutralize possible dimensional changes because of the CBCT recording, the 3D calculations, and the separation and segmentation procedures. More specific, the ratio with tooth volume as numerator was preferred for the same reason as earlier discussed by Kvaal et al. (49). Namely to avoid in the denominator a zero value which is measured in obliterated pulp chambers.

The observed relation between the pulp–tooth volume ratio and age was stronger for women than for men but was not found statistically different. This finding corresponds with the slightly higher age correlation for women. Someda et al. (56) calculated on pulp–tooth volume ratio of the whole extracted lower incisors.

The ratio of the variables indicating secondary dentine formation observed on the studied 3D radiological images is inferior related to age than the variable ratios indicating secondary dentine formation measured by Kvaal et al. (49) on 2D radiological images. Several adaptations of current research setup could ameliorate future results. The need for manual correction of the automatic separation and segmentation process was most extensive at the apical quarter of the tooth root. On these smallest tooth and pulp contours, the computerized distinction of the tooth parts based on the established grayscale threshold became less reliable. This controlling and correcting procedure consumed the majority of the time needed for the segmentation. Moreover, these manual interventions had an negative influence on the precision of the volume registration. To quantify the accuracy of the volume calculations performed with the Simplant® pro software, the real pulp and tooth volumes of three extracted monoradicular teeth with reamed pulp canal were measured and the obtained results were compared with the pulp and tooth volumes calculated on the CBCT images of the same endodontic prepared teeth. Higher differences were found between the corresponding pulp volumes (maximally 21%) than between the related tooth volumes (maximally 16%). A consequence of the inequality of both differences is that the use of the ratio between pulp and tooth volume does not neutralize the made measuring inaccuracies. A part of these inconveniences are inherent on contemporary CBCT technology because relatively small structures such as periodontal ligament space (58) and voids in root canal fillings (59) are less visible on the provided images. Furthermore, the segmentation accuracy is still smaller for CBCT than CT scans owing to lower image contrast (60,61). Taking into account that secondary dentine formation occurs first at the most coronal aspects of the pulp chamber (48), and thus at these locations, secondary dentine responsible for the decreasing pulp volume is deposited to a major extent (52); in a further research, the most apical quarter of the root will be cut automatically with the Simplant® pro software followed by a calculation of the pulp–tooth volume ratios of the remaining tooth parts. These new results will be related to age and compared with the results of current study providing accessory information about the effect of secondary dentine formed in the apical root canal quarter on the pulp–tooth volume ratio.

Dental CBCT is getting commonly used in dental practice (62) because it provides presently high diagnostic images with low radiation doses (63). Furthermore, CBCT technology is constantly evolving. Different CBCT unit manufacturers already provide each on a specific domain: better contrast resolutions, smaller voxel sizes, and higher grayscale bit amounts. Together with adapted separating and segmenting software, these evolutions will allow in the near future for less time consuming and more precise pulp–tooth volume ratio measurement of entire (monoradicular) teeth.

Conclusions

A dental age estimation methodology using 3D calculations on CBCT scans of fully developed monoradicular teeth from living individuals is presented. The variability in age explained by the pulp–tooth volume ratio is gender independent and highest for incisors, respectively, followed by premolars and canines. Future research modifying the presented technique together with awaited ameliorations in CBCT technology may provide an optimized dental age estimation technique.

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Many thanks for your assistance.

Query reference	Query	Remarks
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Q4	**AUTHOR: Please check the correspondence details.**	
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Instruction to typesetter	*Textual mark*	*Marginal mark*
Leave unchanged	· · · under matter to remain	(stet)
Insert in text the matter indicated in the margin	∧	∧ followed by new matter
Delete	∤ through single character, rule or underline or ∤ through all characters to be deleted	∂
Substitute character or substitute part of one or more word(s)	/ through letter or ⊢——⊣ through characters	new character / or new characters /
Change to italics	— under matter to be changed	(ital)
Change to capitals	≡ under matter to be changed	(caps)
Change to small capitals	= under matter to be changed	(sc)
Change to bold type	~ under matter to be changed	(bf)
Change to bold italic	≂ under matter to be changed	(bf+ital)
Change to lower case	B̸	(lc)
Insert superscript	∨	∨ under character e.g. ∨
Insert subscript	∧	∧ over character e.g. ∧
Insert full stop	⊙	⊙
Insert comma	∧	∧
Insert single quotation marks	∨ ∨	∨ ∨
Insert double quotation marks	∨ ∨	∨ ∨
Insert hyphen	=	=
Start new paragraph	¶	¶
Transpose	⊔⊓	⊔⊓
Close up	linking ⁀‿ characters	⁀‿
Insert or substitute space between characters or words	#	#
Reduce space between characters or words	⁀‿	⁀‿