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Dental age estimation through volume matching of teeth imaged by cone-beam CT

Fan Yang [a,b], Reinhilde Jacobs [a], Guy Willems [b,*]

[a] Oral Imaging Center, School of Dentistry, Oral Pathology and Maxillo-Facial Surgery, Katholieke Universiteit Leuven, Leuven, Belgium
[b] Department of Forensic Odontology, School of Dentistry, Oral Pathology and Maxillo-Facial Surgery, Katholieke Universiteit Leuven, Leuven, Belgium

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Abstract

A custom-made voxel counting software for calculating the ratio between pulp canal versus tooth volume based on cone-beam CT tooth images was developed and evaluated. The aim of this study was to attempt establishing a correlation between the chronological age of a certain individual and the pulp/tooth volume ratio of one of the teeth. Twenty-eight single rooted teeth of 19 individuals with well-known chronological age were scanned by the cone-beam CT (3D Accuitomo, J. Morita, Kyoto, Japan). Next the images were analyzed using the custom-made software. Linear regression analysis was performed. The results of the analysis showed a moderate correlation between the pulp/tooth volume ratio and biological age with a coefficient of determination (R^2) of 0.29. Although the present work was limited to a pilot study, the developed technique showed promising results for dental age estimation in a non-invasive manner using cone-beam CT images in living individuals.

Keywords: Age estimation; Forensic odontology; Cone-beam CT

1. Introduction

Age estimation of living or deceased individuals is an important aspect of forensic sciences. Lots of dental age estimation methods were reported in forensic science literature [1]. Every year thousands of unaccompanied minors with no official identification documents trespass the borders of all European countries hoping to find shelter and protection in the country of destination. On top of that, a lot of criminal acts are committed by individuals pretending to be beneath the age of majority. In all these cases, verification of chronological age is required i.e. in order to be entitled to a guardian and social benefits as is the case in Belgium for unaccompanied minors.

Most of the techniques reported in literature for age estimation in adults are based on age-related changes of teeth [1–3]. The tooth is the hardest structure in the human body, and contains enamel and dentin. Tooth enamel is harder than bone and consists of more or less dead material. It functions as a protective layer around the tooth. Not too many changes take place in enamel, except at the outer border. Dentin on the other hand, lies inside of the enamel surface and constitutes the entire tooth root. It is similar to the bone in composition and has a consistency similar to cartilage, which is softer. Enamel does not show age-related changes except for a loss in permeability, an increase in brittleness and a small amount of wear. Also pathological conditions and behavioral habits such as caries, erosion, attrition and abrasion, may lead to loss of enamel. However, the remaining structures, the pulpodentinal complex (PDC), which includes dentin, cementum and the dental pulp, do show age-related physiological and pathological changes [2]. Quantification of these morphological changes nearly always requires extraction and sectioning of teeth, which is unethical and impossible in living individuals. Therefore techniques that have been or are being developed for age estimation in living individuals mostly rely on radiological imaging of teeth.

A previously reported pilot study on dental age estimation based on extracted teeth focused on tooth images obtained by a microfocus CT (μCT) [4]. From these 3D digital images tooth and pulp were segmented using a custom-made software. The

* Corresponding author at: Katholieke Universiteit Leuven, School of Dentistry, Oral Pathology and Maxillo-Facial Surgery, Department of Forensic Odontology, Kapucijnenvoer 7, B-3000 Leuven, Belgium. Tel.: + 32 16 332459; fax: +32 16 337578.
E-mail address: guy.willems@med.kuleuven.be (G. Willems).

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ratio of pulp and tooth volume, which was calculated by voxel counting, was eventually correlated with age. Nowadays, similar 3D digital tooth images may be acquired from living individuals using a cone-beam CT. The clinical introduction of cone-beam CT creates new opportunities to get three-dimensional tooth radiographs, resulting in a reasonable image quality at a low radiation dose (skin dose 1.19 mSv [5], total dose 20 microSv per examination).

Our present study combines both aspects and aims at developing a voxel counting software to calculate the pulp/tooth volume ratio based on the cone-beam CT tooth images.

2. Materials and methods

2.1. Materials selection

A selection of 28 sets of 3D cone-beam CT tooth images (15 incisors, 12 canines, 1 premolar) was made from the cone-beam CT database in the University Hospitals (UZ Sint-Rafaël, Katholieke Universiteit Leuven). Those teeth were from 19 different individuals, ranging in age from 23 to 70 years of age (Fig. 1). The age and gender distribution of the material is shown in Table 1. The selection was restricted to upper and lower single rooted teeth that revealed neither profound caries nor restorations and showed normal dental anatomy.

2.2. Modality and cone-beam CT technology

The modality was 3D Accuitomo, 'the Dento-Maxillofacial Limited Cone-beam Super High Resolution CT' (J. Morita corporation, Kyoto, Japan) [5–6]. The size of imaging volume was a cylinder with diameter 40 × height 30 mm at the X-ray rotational center. Images were taken under the exposure condition of 80 kV (X-ray tube voltage) and 4 mA (X-ray tube electric current), which were the standard parameters and can be changed for different subjects. A small cone-shaped X-ray beam irradiated the image intensifier with a CCD camera for approximately 17 s while the C-arm made one 360° rotation around the region of interest and a total of 512 frames of two-dimensional images were recorded as an '.avi' format file. The 3D images of *X*, *Y* and *Z* directions were reconstructed with a personal computer. It took about 4 min to carry out arithmetic calculation for the image reconstruction with filtered back-projection method.

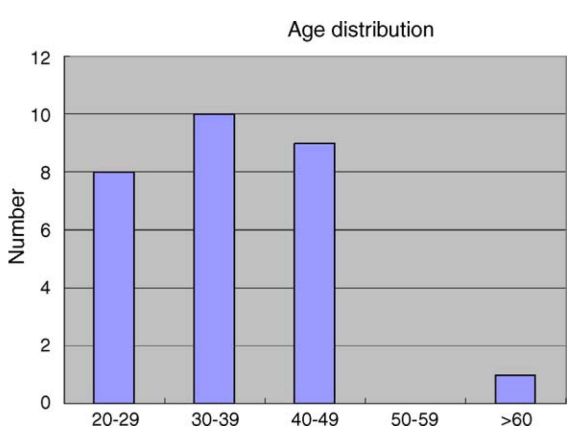


Fig. 1. The age distribution of the selected samples: 19 different individuals, ranging in age from 23 to 70 years of age, were selected in this research. Lack of 50–59 years old group and the limitation of the dataset were based on the fact that most investigations of the frontal region were related to either pedodontic or oral implant indications.

Table 1
Tooth number according to the FDI numbering system, age and gender of the individuals the teeth belonged to

No.	Patient	Tooth number	Age (yrs)	Gender
1	1	23	44	f
2	2	21	42	f
3	2	23	42	f
4	3	22	35	m
5	3	23	35	m
6	4	13	35	m
7	5	21	29	f
8	6	11	28	f
9	6	12	28	f
10	6	13	28	f
11	7	21	49	f
12	8	13	43	f
13	9	31	40	f
14	9	32	40	f
15	9	33	40	f
16	10	23	39	m
17	11	44	38	f
18	12	11	33	f
19	12	22	33	f
20	12	23	33	f
21	13	42	31	m
22	14	13	29	m
23	15	31	23	f
24	15	32	23	f
25	16	12	23	m
26	17	32	70	f
27	18	23	44	f
28	19	13	31	m

f = female; m = male.

2.3. The custom-made software

A semi-automatic software was designed and implemented to work together with the cone-beam CT dedicated software 'iDixel' (J. Morita corporation, Kyoto, Japan) to calculate the volumes and ratios from the cone-beam CT slices. The development tool was MATLAB® (The MathWorks, Inc., Natick, MA, USA).

The balance between the workload of the computer and the speed of the processing was considered, thus the segmentation processing was done by assessing a threshold visually. The objective operation was made as much as possible during processing. However the periodontal ligament space was not clear in most of the images, which was important to segment the tooth thereby separating it from the jaw bones. The complete tooth cannot be segmented perfectly only depending on the threshold setting (Fig. 2). Finally a manual pre-processing step, zoom in and drawing the contour of the tooth using 'Microsoft Paint' (Fig. 3) of Microsoft Windows® (Microsoft, Seattle, USA), was operated before the segmentation process. Fig. 4

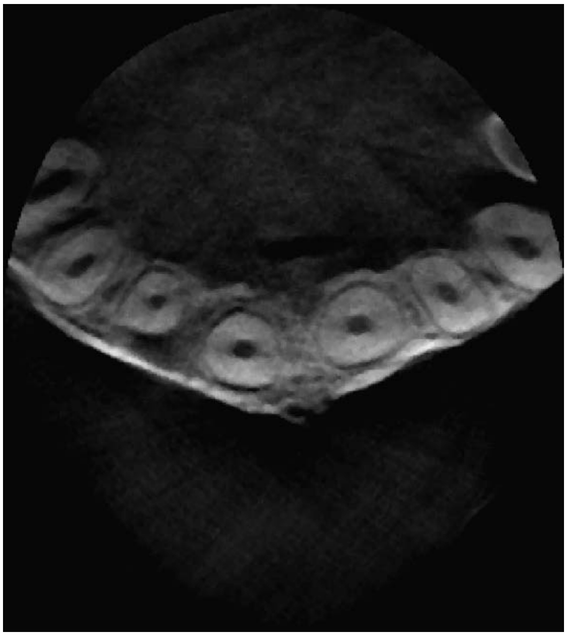


Fig. 2. An original cone-beam CT image slice: which was exported as tiff 8 bits image format by the dedicated software 'iDixel' after adjusting the window/level and reslicing.

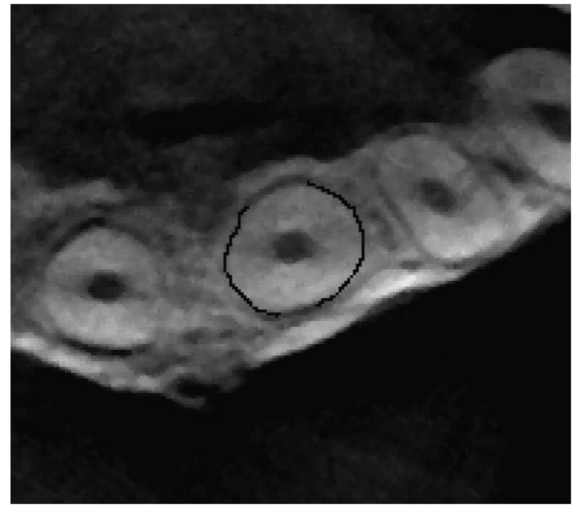


Fig. 3. Based on the fact that the periodontal ligament space was not clear in most of the images, a manual pre-processing step was operated before segmentation. After image magnification in 'paint' of Microsoft Windows® (Microsoft, Seattle, USA), the black curves were drawn along the contour of the tooth in certain blurry areas.

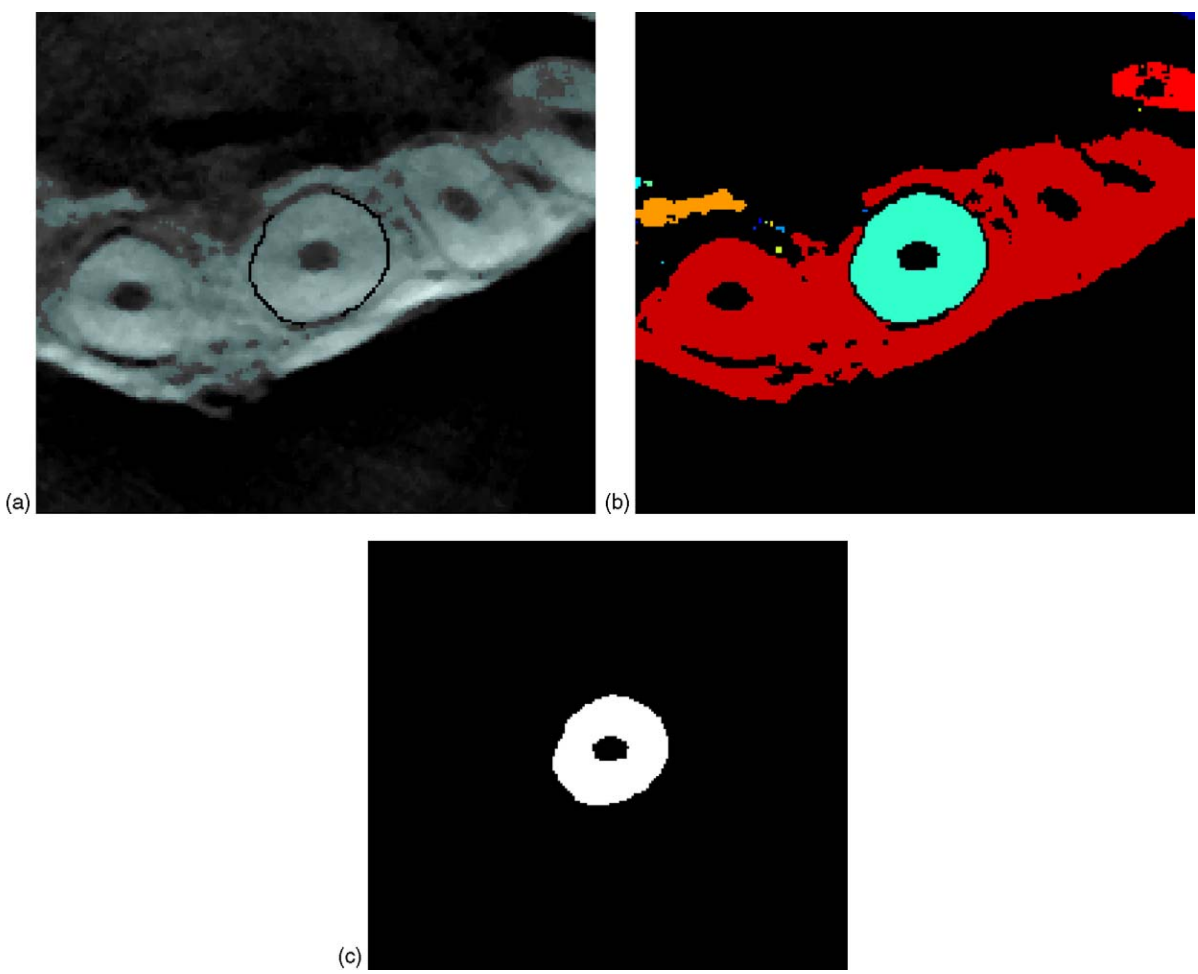
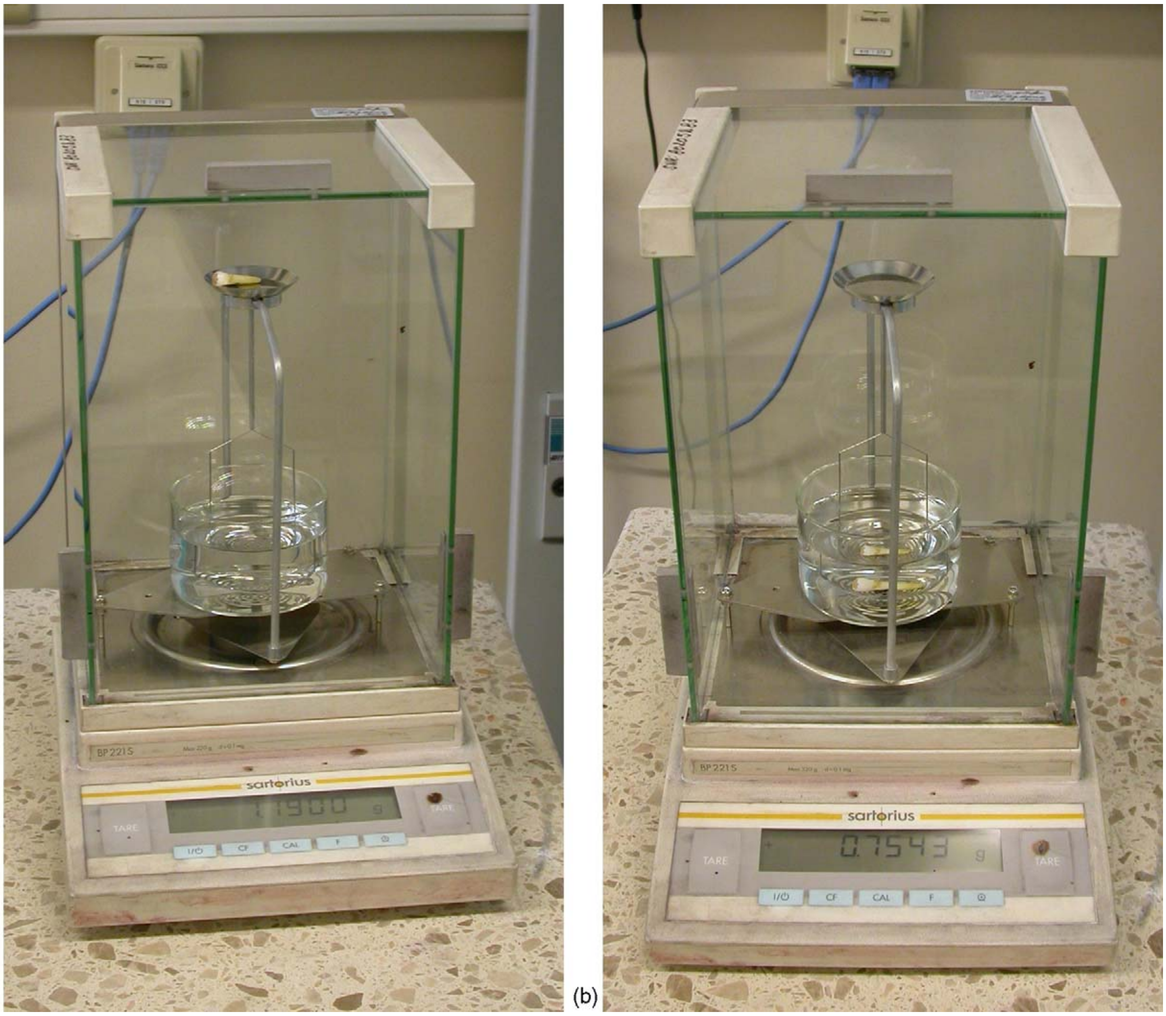


Fig. 4. (a) The transparent view was used to adjust the threshold of segmentation. The observers can set different parameters to change the segmented area. (b) The program labeled different segmented regions, the figure shows the regions marked by different colors. (c) The figure shows the final segmentation result.



(a) (b)

Fig. 5. A beaker of alcohol (0.78 g/cm^3) was put on the stand, prior to further measurements. A set of brackets were fixed on the electro-balance, whose lower tray was submerged in the alcohol. (a) Shows the measurement of the mass of a tooth, m_1 in which the tooth was put on the upper tray. (b) Shows the measurement of apparent mass when submerged, m_2 in which the tooth was put on the lower tray in the alcohol.

shows the optimized final segmentation result. The reproducibility and accuracy of the developed method have been evaluated in a pilot study.

Two extracted teeth were selected and the pulp canal was prepared endodontically. The cone-beam CT images were taken at 70 KV and 1 mA and the ratios of pulp/tooth volume were calculated using the voxel counting software based on the images with different slice thickness and interval settings (ranging from 0.125 to 1.00 mm). Next the teeth were filled with impression material (hydrophilic vinylpolysiloxane impression material), Virtual® (Ivoclar Vivadent AG, Schaan, Liechtenstein).

The volume of the whole tooth was measured by the method based on volume displacement by Archimedes' principle, which was generally used in materials density determination. The buoyant force on a submerged object is equal to the weight of the liquid displaced by the object. The volume can be calculated by, $V = (m_1 g - m_2 g)/\rho_1 g = (m_1 - m_2)/\rho_1$, where ρ_1 is the density of the liquid, V the submerged volume of the object, g the constant 9.8 N/kg, m_1 the mass of the object and m_2 is the apparent mass when submerged. Both m_1 and m_2 of all the teeth were measured in the Department of Metallurgy and Materials Engineering (MTM) of the Katholieke Universiteit Leuven. A set of brackets with double trays was setup on the electro-balance (Sartorius BP 221s, Sartorius, Goettingen, Germany) with a beaker of alcohol with the density of 0.78 g/cm^3 (Fig. 5). Each tooth was measured two times (Fig. 5). When the tooth was put on the upper tray, m_1 was determined; when it was put on the lower tray submerged in the alcohol, m_2 was determined. Then the volume was calculated.

Next the dental substrate was dissolved by immersing samples in successively 30% HCl for 36 h and 2.5% NaOCl for 10 min [7]. The same volume measurement steps were operated to determine the volume of remaining silicon core, which is the pulp volume. Finally the pulp/tooth volume ratios were calculated. This allowed to compare the outcome of the software with the gold standard measures of the pulp. Analysis proofed to show an acceptable reproducibility and accuracy (error: ±7.6%).

2.4. Data processing and statistical analysis

The cone-beam CT images of teeth selected for investigation were all scanned using a standard exposure (80 KV and 4 mA) and positioning protocol by the same operator. The *Z*-axis images were exported by iDixel after adjusting the window/level and reslicing. The contour of the teeth were drawn using 'Paint'. Then the ratios of pulp/tooth volumes were calculated with the voxel counting software. One observer performed the ratio calculation twice to collect a second ratio dataset for intra-observer variation testing. All the measurements and additional information (type of tooth, individual's age and gender, and ratio of pulp/tooth volume) were entered in a spreadsheet (Microsoft Excel®, Microsoft, Seattle, USA).

Statistical analysis was carried out using NCSS (Utah, USA http://www.ncss.com/). Linear regression analyses were performed to the dataset in order to establish a correlation between the chronological age and the pulp/tooth volume ratio. A paired *t*-test was applied using SAS statistical program (SAS Institute, Cary, NC, USA) to calculate and evaluate the intra-observer variations.

3. Results

The pulp/tooth volume ratios varied from 0.0152 to 0.0497. The equation of the straight line relating age and ratio of pulp/tooth volume is estimated as: Age = 54.32 − (554.21 × Ratio) using the 28 observations in this dataset (Fig. 6). The *Y*-intercept, the estimated value of age when ratio is 0, is 54.32 with a standard error of 5.85. The slope, the estimated change in Age per unit change in Ratio, is −554.21 with a standard error of 170.45. The linear regression analysis, where age was the dependent variable and the pulp/tooth volume ratio was the independent variable, showed a coefficient of determination: $R^2 = 29\%$, which is the proportion of the variation in age that can be accounted for by variation in ratio. The square root of mean square error is 8.3 years. The correlation between age and ratio is −0.54.

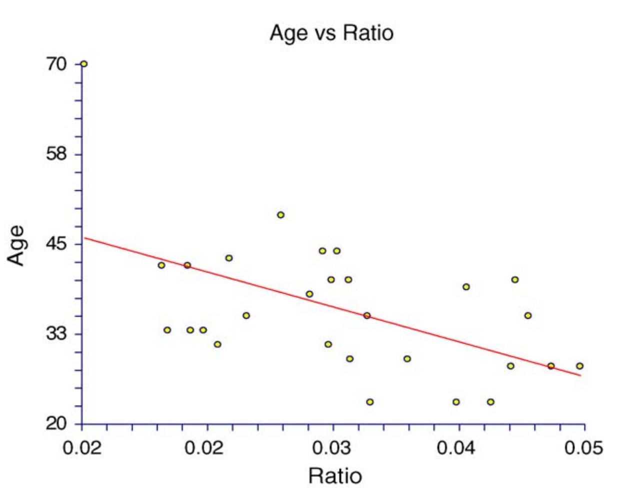


Fig. 6. The linear regression analysis was performed using NCSS (Utah, USA http://www.ncss.com/). It shows the analysis result, which is Age = 54.32 − (554.21 × Ratio of pulp/tooth volume).

The intra-observer *t*-test resulted in a *p*-value of 0.63 which signifies that the intra-observer results do not show significant differences.

4. Discussion

The present software development illustrates an innovative application of cone-beam CT image data to determine chronological age. The fact that this imaging modality can be applied to subjects, without demanding high radiation dose levels may favor its use.

The image data set used for testing the present software development was somewhat limited based on the fact that most investigations of the frontal region were related to either pedodontic or oral implant indications. To verify the usefulness and validity of the present software development, an analysis of a larger data set is definitely required. The total procedure including clinic scanning, image reconstruction, pre-processing (drawing the boundary manually) and post-measurement took less than 1 h per patient. It is much faster than the 5 h per tooth processing time in the previously reported study on μCT [4]. Besides, the present technique allows age determination in living individuals.

In the present study, a linear regression with the biological age was demonstrated. Moreover, the intercept and slope approximated the results from the previous study on μCT [4]. Compared to μCT, cone-beam CT in dental use provides plenty of 3D volume information of the teeth on living individuals in the target area by a single scan. The measurement of the volumes of both pulp and tooth in order to calculate the ratio for the living individuals can be operated non-destructively. Later on, after the appropriate intercept and slope determined based on sufficient datasets, the method can be applied to age estimation.

In addition, further advancements in hard- and software could help optimizing the accuracy and precision of the technique. Recent generations in cone-beam CT have become available, demonstrating better contrast resolution (12 bits 4096 gray levels instead of 8 bits 256 gray levels). The latter may bring more detail in the interesting gray level range and enable improved visualization of the tooth segmentations. Secondly, a large data sample with homogeneous (or equal) age distribution should allow for even more finesse and optimization of the elaborated method. Finally, the technique could be adapted and transformed to the multi-root teeth. That would allow forensic odontologist to use the present method for age estimation using a very objective technique.

5. Conclusion

Cone-beam CT scanning provides us a new method to acquire the 3D images of teeth in living individuals. Using their 3D images the ratio of pulp/tooth volume can be calculated. The presented research shows promising results for age estimation based on the pulp/tooth volume ratio. The newest cone-beam CT modalities and optimization of the ratio measurement software as well as increased numbers of samples can therefore make the technique mature in forensic odontology research.

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