Three-Dimensional Radiological Methods for Age Estimation in Adults by Using the Pulp/Tooth Relation: an Integrative Review

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Abstract. Assessment of secondary dentin apposition is an observable phenomenon widely used to estimate age. An integrative review was performed by searching the keywords "computed tomography AND age estimation AND pulp tooth volume ratio" and "microfocus x-ray AND age estimation AND pulp tooth volume ratio" in the electronic platforms Embase, PubMed, Scopus and Web of Science, in July 2020. Studies included: complete articles with age estimation from human teeth by use of computed tomography or micro-computed tomography, written in English, without time restriction. Excluded studies: not written in English or not in form of an article, clinical cases, literature reviews, if did not realize age estimations or if age estimation is done in animals teeth. The search resulted in 32 different articles. With application of the above criteria only 26 were reviewed. Data collected included: reference, year, country, tooth type, number of subjects, number of teeth, age group, image type, measuring instrument/software, type of analysis, coefficient of determination, correlation coefficient with age and accuracy. These data provided a quick global comparison of various methodologies that use the pulp/tooth relation, being practical

for researchers and forensic team to which method they can use accordingly to a specific case and its expected accuracy.

Keywords: Forensic dentistry; Radiology; Age determination by teeth; Dental pulp; Tooth.

1. Introduction

Age estimation in forensic and anthropological research has been extensively studied in recent years and it contributes to the creation of the individual's biological profile, whether alive or dead. Various parts of the body can be used to estimate age, but it is remarkable the strong resistance of teeth against mechanical, chemical and physical effects of time, and their ability to preserve their morphology for a longer period of time[1,2].

In adults, the dental maturation process is already completed, and their corresponding age estimation techniques are based on degenerative processes, most of them complex and invasive, requiring the extraction or destruction of the tooth by sectioning, which is unfeasible in living individuals[3].

The evaluation of deposition of secondary dentine is an observable phenomenon that it does not need the destruction of the tooth. This deposition begins after tooth eruption, resulting in the gradual decrease in the size of the pulp cavity with age[4], being a significant morphological criterion for age estimation in adults[5].

This phenomenon can be evaluated using the methods of pulp/tooth area ratio or pulp/tooth volume ratio, through imaging scans[6]. According to Zhang et al.[7] one or two-dimensional measuremants cannot reflect real three-dimensional morphological changes because secondary dentin deposition occurs on all surfaces of the pulp cavities. So, this study will perform an integrative review with the aim to provide to researchers and forensic team a quick and global comparison of studies that used three-dimensional radiological methods to analyze this deposition with the purpose of age estimation.

2. Materials and methods

2.1 Sources of information

An integrative method of literature searching and selection was employed in the preparation of this review. The international electronic platforms Embase, PubMed, Scopus and Web of Science were used for searching, using the following keywords:

"computed tomography AND age estimation AND pulp tooth volume ratio" and "micro focus x-ray AND age estimation AND pulp tooth volume ratio". Research on these platforms was performed on 07/09/2020. There was no restriction as to the date of publication of the studies.

2.2 Inclusion and exclusion criteria

The studies were included if they are complete research articles reporting age estimation research in human teeth, using computed tomography or computed micro tomography, were written in English, and had no time restriction. The studies would be excluded if they were not written in English, were not in the form of an article, reported clinical cases, were literature reviews, did not realize age estimations or the age estimation is done in animals' teeth.

2.3 Selection of studies

An initial selection was based on the title and the abstract, applying the inclusion and exclusion criteria. Afterward, the remaining articles had their full text printed and the eligibility criteria were once more applied.

2.4 Data collection process

Two authors performed the search on the platforms and applied inclusion and exclusion criteria. The data from each study were collected by one reviewer and then checked independently by the second reviewer.

2.5 Data collected

The data collected were organized in a Microsoft Excel spreadsheet and they included: reference, year, country, tooth type, number of subjects, number of teeth, age group (years), image type, measuring instrument/software, type of analysis, coefficient of determination, correlation coefficient with age and accuracy.

3. Results

Search in the platforms resulted in a total of 32 different articles. The amount of articles found per platform is observed in Table 1. By applying the inclusion and exclusion criteria, 6 articles were excluded, and 26 were reviewed. The reasons for exclusion were: two of them did not realize age estimation[8,9], two were not in the form

of an article[10,11], one was not a research article[12] and another one used digital panoramic radiographs[13].

Table 1. Articles per platform.

Keywords	Embase	Pubmed	Scopus	Web of Science
Computed tomography AND age estimation AND pulp tooth volume ratio	17	15	21	19
micro focus x-ray AND age estimation AND pulp tooth volume ratio	2	2	2	2

Age estimation through analysis of the pulp/tooth relation can be performed using any type of tooth and, in order to be applicable in a population level, it is interesting that the study uses a significant sample. Such information of each study is presented in Table 2.

Table 2. Sample information of each study.

Reference	Year	Country	Tooth type [FDI]	N Individuals	N teeth	Age range
Aboshi et al.[14]	2010	Japan	34/44, 35/45	-	100	20 to 78
Adisen et al.[15]	2020	Turkey	13/23	131	131	17 to 75
Akay et al.[1]	2019	Turkey	11/21, 12/22, 13/23, 15/25, 31/41, 32/42, 33/43, 34/44, 35/45	134	211	16 to 71
Alsoleihat et al.[16]	2017	Jordan	38/48	155	-	18 to 58
Asami et al.[17]	2019	Japan	14/24, 15/25	111	111	20 to 79
Asif et al.[18]	2018	Malaysia	11/21	110	110	16 to 65
Asif et al.[19]	2019	Malaysia	11/13/23	300	300	16 to 65
Fukui et al.[20]	2017	Japan	11/21, 31/41	60	-	20 to 80
Gulsahi et al.[5]	2018	Turkey	11/21, 12/22, 13/23, 33/43, 34/44, 35/45	204	655	15 to 70
Jagannathan et al.[6]	2011	India	33/43	188	188	10 to 70
Kazmi et al.[4]	2019	Pakistan	23/33	717	1202	15 to 65
Marroquin et al.[21]	2020	Malaysia and Colombia	13/23	81	81	15 to 71
Nemsi et al.[3]	2017	Tunisia	13/23, 35/45	120	-	22 to 67
Pinchi et al.[22]	2015	Italy	21	148	148	10 to 80
Porto et al.[23]	2015	Brazil	11/21	-	118	22 to 70

Sakuma et al.[24]	2013	Japan	34/44	-	136	14 to 79
Sasaki and Kondo[25]	2014	Japan	33/43	363	363	≥ 15
Sironi et al.[26]	2018	Italy	21	286	286	8 to 80
Someda et al.[27]	2009	Japan	31/41	-	155	12 to 79
Star et al.[2]	2011	Belgium	11/21, 31/41, 12/22, 32/42, 13/23, 33/43, 14/24, 34/44, 15/25, 35/45	111	214	10 to 65
Tardivo et al.[28]	2011	France	13/23, 33/43	58	133	14 to 74
Vandevoort et al.[29]	2004	Belgium	11/21, 31/41, 22, 32/42, 13/23, 43, 14/24, 34	25	43	24 to 66
Vane Swetah[30]	2017	Indian	34/44	-	23	10 to 45
Yang et al.[31]	2006	Belgium	11/21, 31, 12/22, 32/42, 13/23, 33, 44	19	28	23 to 70
Zhan et al.[32]	2020	China	21, 22, 23	392	1176	16 to 76
Zhang et al.[7]	2019	China	38/48	414	614	20 to 65

Various software can be applied when analyzing three-dimensional radiographic images, allowing linear as well as area and volume measurements. These data are listed in Table 3.

Table 3. Software and analysis type in each study.

Reference	Image type	Measuring instrument	Analysis type
Aboshi et al.[14]	Micro-CT	TRI/3D-BON	Pulp/tooth volume ratio at 4 levels
Adisen et al.[15]	CBCT	3D DOCTOR	Tooth/root length ratio, pulp/root length ratio, pulp/tooth length ratio, pulp/root width ratio at 3 levels and pulp/tooth volume ratio
Akay et al.[1]	CBCT	Planmeca Romexis and ITK-SNAP	Tooth/root length ratio, pulp/root length ratio, pulp/tooth length ratio, pulp/root width ratio at 3 levels and pulp/tooth volume ratio
Alsoleihat et al.[16]	CBCT	CBCT program	Pulp/tooth mesiodistal diameter ratio
Asami et al.[17]	Micro-CT	ZedView	Volume ratio of: the enamel to the entire crown, the dentin to the entire crown, the pulp chamber to the entire crown, the pulp chamber to the entire crown excluding the enamel
Asif et al.[18]	CBCT	MIMICS	Volume ratios of: pulp/tooth and pulp chamber/crown
Asif et al.[19]	CBCT	MIMICS	Pulp/tooth volume ratio
Fukui et al.[20]	CBCT	-	Pulp/tooth area ratio on mesio-distal, labio-lingual and axial cross-sectional views
Gulsahi et al.[5]	CBCT	3D DOCTOR	Pulp/tooth volume ratio
Jagannathan et al.[6]	CBCT	Advantage Windows workstation	Pulp/tooth volume ratio
Kazmi et al.[4]	CBCT	Planmeca Romexis	Pulp volume

Marroquin et al.[21]	CBCT	ITK-SNAP	Pulp/pulp+tooth volume ratio at the cervical third of the root
Nemsi et al.[3]	CBCT	Adobe Photoshop	Pulp/dentin area ratio
Pinchi et al.[22]	CBCT	Osirix	Pulp/dental hard tissues volume ratio
Porto et al.[23]	CBCT	DentalSlice	Volume of pulp cavity, hard tissue, tooth and ratio pulp cavity/tooth
Sakuma et al.[24]	MDCT	Synapse Vincent workstation	Pulp/tooth volume ratio
Sasaki and Kondo[25]	Micro-CT	Amira	Pulp in the root portion/root portion volume ratio
Sironi et al.[26]	CBCT	Osirix	Pulp/tooth volume ratio and pulp chamber volume
Someda et al.[27]	Micro-CT	TRI 3D-BON	Pulp/tooth volume ratio
Star et al.[2]	CBCT	Simplant Pro Version	Pulp/tooth volume ratio
Tardivo et al.[28]	CBCT	MIMICS	Pulp/tooth volume ratio
Vandevoort et al.[29]	Micro-CT	Visualization TollKit package	Pulp/tooth volume ratio
Vane Swetah[30]	CBCT	N.M.	Pulp/tooth volume ratio
Yang et al.[31]	CBCT	iDixel	Pulp/tooth volume ratio
Zhan et al.[2]	CBCT	MIMICS	Pulp/tooth volume ratio
Zhang et al.[7]	CBCT	3D Slicer and GrowCut effect image segmentation	Pulp/enamel volume ratio

N.M. = Not mentioned; Micro-CT = Micro-computed tomography; CBCT = Cone beam computed tomography; MDCT = Multidetector computed tomography.

Table 4 presents the coefficient of determination and the correlation coefficient achieved by each study, and Table 5 shows the accuracy found. In the tables, the tooth number will be listed according to the dental numbering system of the FDI (Federation Dentaire International).

4. Discussion

The majority of studies assessed the maxillary canine and maxillary central incisor. The chosen of the former is due to being the tooth with the greatest longevity in the dental arch[3,21,28], suffering the effects of diet less than the posterior teeth, suffering less attrition and abrasion than the anterior teeth and being the single-rooted tooth with the widest pulp area and, therefore, easier to analyze[3,28]. And the chosen of the maxillary central incisor can be explained for having a shorter length than the canines, larger pulp cavities than the lower incisors and a simpler root morphology than premolars and molars[23], also allowing a simple morphometric analysis.

Table 4. Coefficient of determination and the correlation of each study.

Reference	Coe	Tooth or group of teeth [FDI]											
		11/21	12/22	13/23	14/24	15/25	31/41	32/42	33/43	34/44	35/45	Canines	All sample
Aboshi et al.[14]	R²									0.625	0.698		
Adisen et al.[15]	R² *1 r *1			0.236 -0.486									
Akay et al.[1]	R² *1 r *2	0.246	0.197			0.521	0.294	0.256	0.349	0.326	0.491		0.390 -0.627
Alsoleihat et al.[16]	R² r												0.13 -0.361
Asami et al.[17]	R² *3				0.45	0.65							
Asif et al.[18]	R² *1 r *1	0.639 0.799											
Asif et al.[19]	R² r	0.70 0.83		0.53 0.73									
Gulsahi et al.[5]	R²	0.532	0.252	0.153					0.210	0.207	0.217		
Jagannathan et al.[6]	r *4								-0.63				
Kazmi et al.[4]	R² *5			0.31					0.33			0.29	
Marroquin et al.[21]	R²			0.42									
Nemsi et al.[3]	r			-0.838							-0.837		
Pinchi et al.[22]	R²	0.58											
Porto et al.[23]	R² r	0.212 -0.467											
Sakuma et al.[24]	R² r									0.571 0.756			
Someda et al.[27]	R² *6						0.71						
Star et al.[2]	R² r											0.07 -0.27	0.34 -0.59
Tardivo et al.[28]	R² r											0.38 -0.591	
Vandevoort et al.[29]	R²												0.31
Yang et al.[31]	R² r												0.29 -0.54
Zhan et al.[32]	R² *7	0.667	0.726	0.674									
Zhang et al.[7]	R² *8 r *8												0.419 -0.647

Coe = Coefficients; FDI = Federation Dentaire International; All = All Sample; R² = Determination Coefficient; r = Correlation Coefficient with age; *1 = For pulp/tooth volume ratio; *2 = For pulp volume; *3 = For the volume ratio of the pulp chamber to the entire crown excluding the enamel; *4 = For Belgian's formula in the study group; *5 = With sex information; *6 = For volume ratio of the pulp cavity to the whole tooth; *7 = In males; *8 = For global sample (teeth 38/48).

Table 5. Accuracy of each study.

Reference	Accuracy per tooth or group of teeth [FDI]										
	11/21	12/22	13/23	15/25	31/41	32/42	33/43	34/44	35/45	Canines	All sample
Aboshi et al.[14] (a)								7.29	6.32		
Adisen et al.[15] (b) [*1]			2 to 12								
Akay et al.[1] (c) [*1]	8.10	6.72		11.38	10.18	8.03	7.67	15.93	14.09		11.09
Asif et al.[18] (d) [*1]	8.646										
Asif et al.[19] (d)	7.603		9.672								
Jagannathan et al.[6] (e) [*2]							8.54				
Marroquin et al.[21] (d)			11.4								
Nemsi et al.[3] (f)			8.27						8.29		7.06
Pinchi et al.[22] (g)	11.45										
Porto et al.[23] (h) [*1]	0.93										
Sironi et al.[26] (i)	3.15 to 13.99										
Someda et al.[27] (j) [*3]					9.19						
Star et al.[2] (c)										13.10	
Tardivo et al.[28] (h) [*1]										1.668	
Vane Swetah[30] (e) [*4]								7.24			
Yang et al.[31] (c)											8.3
Zhan et al.[32] (e) [*5]	8.949	6.804	9.389								
Zhang et al.[7] (e) [*6]											8.410

FDI = Federation Dentaire International; a = Reported as Mean Error (ME) in years; b = Reported as prediction interval for age estimated in years with 60% and 95% confidence, respectively; *1 = Using pulp/tooth volume ratio; c = Reported as Mean Square Error (MSE) in years; d = Reported as Standard Error of Estimation (SEE) in years; e = Reported as Mean Absolute Error (MAE) in years; *2 = Using Belgian's formula in the control group; f = Reported as Residual Standard Error (RSE); g = Reported as Root Mean Square Error (RMSE) in years; h = Reported as Standard Deviation (SD); i = Reported as Interquartile Range (IQR); j = Reported as Standard Error (SE); *3 = For volume ratio of the pulp cavity to the whole tooth; *4 = Using the developed formula; *5 = In males; *6 = For global sample (teeth 38/48).

With the exception of few studies[7,16,21,25], the majority used completely erupted teeth, with fully formed root, without disease, caries, fracture, restorations nor root canal treatment, because pathological reasons and dental interventions can form a type of dentin[23] that is indistinguishable from secondary dentine in imaging scans.

About the sample, when one proposes to determine a method in a population level, a considerable sample amount is expected, and the more expressive number were in the studies of Kazmi et al.[4], Zhan et al.[32] and Gulsahi et al.[5].

The images analyzed in most of the studies were from university/hospital archives or private dental clinics, the tooth being evaluated *in situ*, in other words, still present in living patients[2-7,15,16,18-23,26,28,31,32]. A smaller number of studies used extracted teeth[1,14,17,25,27,29,30], managing to achieve individual tooth image, and the study of Sakuma et al.[24] stands out to use computed tomography took before forensic autopsy.

The choice of analyze studies which used three-dimensional (3D) radiographic images derive from the evidence that is not appropriate to measure the volume of a three-dimensional object, like the pulp cavity, with 2D radiographs[18,19,32].

The cone-beam computed tomography (CBCT) was the 3D image most used[1-7,15,16,18-23,26,28,30-32], followed by micro-computed tomography (Micro-CT)[14,17,25,27,29] and multidetector computed tomography (MDCT)[24].

The Micro-CT although provides better resolutions than CBCT and MDCT, increasing accuracy in detection of the boundaries between pulp and hard tissue[14,17,27], is unpractical in examining living individuals because the tooth extraction or jaw dissection is often required because of the limited scanning area[17,24,32].

About the analysis type, age estimation occurred in most studies through the analysis of the pulp/tooth volume ratio[2,5,6,14,18,19,21-24,26-32]. But although using 3D radiological image, some studies used linear and area ratios for age assessment[1,3,15,16,20].

The pulp/tooth volume ratio can be considered more reliable than calculating the pulp/tooth area ratio, because secondary dentin formation may not be uniform throughout the surface of pulp[15] and, consequently, measures of projected areas can give incorrect impressions of the extent of this process[5,6,23].

Some authors made analysis of the pulp/tooth relation excluding the enamel[3,17] because of some reasons as the risk that the volume of the pulp cavity has decreased due to attrition of the enamel or the crown wears out due to attrition.

Others authors recommended only the use of pulp volume as an indicator for age estimation, without measuring any dental hard tissue[4,27]. In the study of Akay et al.[1], the authors found a better correlation between variability of pulp volume and age

than to use the tooth volume. However, Zhang et al.[7] reported that the use of pulp volume as the independent variable could be problematic because it varies from person to person and even people of the same age do not always have the same pulp volume.

For three-dimensional exams where there is volumetric calculation, various existing software allow a three-dimensional reconstruction based on segmentation of the different structures, which is achieved through established thresholds of different image densities. A manual segmentation allows a more controlled process on images segmentation than the automatic method[15]. And when segmentation of small structure details like the apical portion of the tooth is needed, a manual intervention can be necessary[15,18,19].

About the influence of sex on age estimation, most studies found no significant influence[2,3,5-7,15,18,19,22,24,28,29]. However, Porto et al.[23] and Someda et al.[27] found the greater accuracy of results for women, while Akay et al.[1] and Asif et al.[18] found a higher correlation between pulp/tooth volume or area and age for men.

Even without having found statistically significant differences on the influence of sex, there were authors who developed separate formulas for men and for women[15,32] and others that used a factor specific to sex in their equation improving the predicative power of the model[4,24]. For more reliable results when sex is known, Porto et al.[23] and Someda et al.[27] encourage the selection of an age estimation equation for one sex in particular.

Dental development shows variation between individuals of the same population and between individuals of different regional population groups, so Asif et al.[18] recommended that each population have their own regression equation for dental age estimation of their adult persons, and was observed that most of the studies did this[1-5,7,14,16-19,21-24,27-29,31,32].

The studies that compared the results obtained through equations developed by other authors and the results obtained with specific equations developed for their populations, achieved better results using the specific formula developed[6,30].

About the coefficient of determination, the studies that had better coefficients were Zhan et al.[32] (0.726 for upper left lateral incisor), Someda et al.[27] (0.71 for lower central incisor) and Asif et al.[19] (0.70 for upper right central incisor). And the better correlation coefficients were those reported by Nemsi et al.[3] (-0.838 for maxillary canines and -0.837 for second mandibular premolars).

The term accuracy of an age estimation method represents the level of proximity between estimated and real or chronological age. The studies that had better accuracy were Aboshi et al.[14] (Mean Error = 6.32 years for second mandibular premolars), Akay et al.[1] (Mean Square Error = 6.72 years for upper lateral incisors) and Zhan et al.[32] (Mean Absolute Error = 6.804 years for left upper lateral incisors). The worst accuracies were those from Akay et al.[1] (Mean Squared Error = 15.93 and 14.09 years for first and second mandibular premolars, respectively) and Star et al.[2] (Mean Squared Error = 13.10 for canines).

Three-dimensional radiological exams in which the deposition of secondary dentine and the pulp/tooth relation can be evaluated have an auxiliary role in age estimation, achieving in some studies great accuracies. So, the use of methods considering the pulp/tooth relation can be applied in conjunction with other validated technique of age estimation using tooth or other body parts in order to reduce the fluctuation age range.

5. Conclusion

According to the literature, it can be concluded that assessment of the pulp/tooth relation, is a significant and often used method for age estimation in adults. Although this method can be applied to all kinds of tooth, through several types of imaging exams, maxillary canine and maxillary central incisor were the most widely used, as well as cone-beam computed tomography, which was the most observed exam. In addition, it was a consensus among the evaluated studies that specific formulas must be developed for the specific population of the sample. This integrative review is limited in regards to the quantity and quality of studies selected. However, a review of the subject is important for updating researchers on the existing, most used and most accurate methods. Likewise, this review is also addressed to the forensic team, guiding them as to which method may be used and what its expected accuracy, in accordance with the tooth and the resources available for each case.

Conflict of interest

No potential conflict of interest was reported by the authors.

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