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Article *in* Forensic science international · March 2017
DOI: 10.1016/j.forsciint.2017.03.007

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Forensic Science International 275 (2017) 203–211

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Age estimation in adults by dental imaging assessment systematic review

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ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form 28 January 2017
Accepted 17 March 2017
Available online 27 March 2017

Keywords:
Forensic dentistry
Adults
Age estimation
Dental imaging
Systematic review

ABSTRACT

Importance: The need to rely on proper, simple, and accurate methods for age estimation in adults is still a world-wide issue. It has been well documented that teeth are more resistant than bones to the taphonomic processes, and that the use of methods for age estimation based on dental imaging assessment are not only less invasive than those based on osseous analysis, but also have shown similar or superior accuracy in adults.
Objectives: To summarise the results of some of the recently most recently cited methods for dental age estimation in adults, based on odontometric dental imaging analysis, to establish which is more accurate, accessible, and simple.
Evidence review: A literature search from several databases was conducted from January 1995 to July 2016 with previously defined inclusion criteria.
Conclusion: Based on the findings of this review, it could be possible to suggest pulp/tooth area ratio calculation from first, upper canines and other single rooted teeth (lower premolars, upper central incisors), and a specific statistical analysis that considers the non-linear production of secondary dentine with age, as a reliable, easy, faster, and predictable method for dental age estimation in adults. The second recommended method is the pulp/tooth width–length ratio calculation. The use of specific population formulae is recommended, but to include data of individuals from different groups of population in the same analysis is not discouraged. A minimum sample size of at least 120 participants is recommended to obtain more reliable results. Methods based on volume calculation are time consuming and still need improvement.

1. Introduction

Age estimation is one of the most important characteristics used to establish the identity of any individual in different legal, forensic, or anthropological research context [1]. To this end, forensic teams depend on osseous analysis based methods, which have acceptable results for young individuals or in their early adulthood [2], and dental development based methods, which are highly reliable in individuals under 21 years of age [3]. However, these methods have some disadvantages: the poor resistance of bones to the taphonomic process [4], and once the individual reaches the threshold of 21 years of age, and the third molars development concludes [3], the currently available dental development based methods are no applicable. In individuals with the congenital absence of third molar teeth, this threshold falls down up to 14–15 years of age.

To respond to the need of an ageing population, and with the evident resistance of teeth to the taphonomic process, alternative methods for dental age estimation in adults have been proposed. Primarily, these are based on the formation of secondary dentine, studied since 1950 [5] and the subsequent narrowing of the pulp cavity, which can be observed in dental radiographs, leading to the proposal of minimally invasive methods. This systematic review focuses on three methods based on odontometric analysis of the pulp cavity, performing length and with measurements [6], area measurements [7] and lastly volume calculation [8]. The objective of this review is to summarise the results of these recently most cited methods for dental age estimation in adults, to establish which method is more accurate, accessible, and simple.

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http://dx.doi.org/10.1016/j.forsciint.2017.03.007
0379-0738/

1.1. Description of the problem or issue

Different methods have been published for dental age estimation in adults, based on the pulp/tooth dimensions' ratios. Nevertheless, the obtained results of the application of some of these methods for dental age estimation, in adults from different population groups, surpass the accepted threshold in forensic sciences which says that the standard deviation of a method for adult's age estimation should preferable be below a standard deviation (SD) of years ±10 years [9].

1.2. Description of the methods being investigated

The methods for dental age estimation in adults analysed in this paper were selected based on their minimally invasive nature, not requirement for the extraction of teeth to be performed, and pulp/tooth ratio calculation which have been applied in individuals from different populations. Kvaal et al. [6] method is based on the analysis of linear measurements of the pulp, tooth, and root length as well as root and pulp width measurements at three different root levels, initially applied on periapical radiographs and later on panoramic radiographs and tomographs. Cameriere et al. [7,10] method is based on the analysis of pulp and tooth area measurements on periapical and panoramic radiographs. Finally, the different methods for dental age estimation in adults based on pulp/tooth volume ratio from cone beam computer tomography [8,11–14] were also included in this systematic review.

1.3. How these methods might work

The included methods in this study are based on a negative correlation between age and the pulp chamber size, as well as on the tooth/pulp ratio calculation, regardless the nature of the used measurements: length/width, area, or volume. In other words, all of them look at the association of one age related phenomenon, as it is the formation of secondary dentine and the decrease of pulp chamber size with age, which has been accepted as an age indicator, observable and measurable with different dental imaging techniques. As an ideal, the accuracy of the studied methods should not exceed the threshold of a SD ±10 years [4,1].

1.4. Why it is important to do this review

The relevance of this review is grounded on the need to recommend a method for dental age estimation with the follow characteristics: simple, fast, non-invasive, non-expensive, reproducible and over all, accurate, that can be systematically used in different academic and forensic scenarios. Helping the reconstruction of identity profiles of unidentified deceased individuals or alive individuals with doubtful identity documents.

2. Methods

2.1. Criteria for considering studies for this review

Qualitative analysis of the information: original studies, in humans, reporting the use of any of the listed methods for dental age estimation, based on pulp/tooth ratio calculation (length/width, area, volume) that preferably reported intra-inter observer calibration, generating population specific formulae or in case that did not, that reported if the obtained results were obtained by using the method's author's original formulae. English or Spanish language that expressed the results in terms of accuracy for dental age estimation.

Quantitative analysis of the information: same criteria than qualitative analysis plus the exclusion of studies which sample included individuals younger than 14 years of age, studies with small samples ($n < 50$), studies using extracted teeth, and studies that did not report the use of specific population formulae.

2.2. Search methods for identification of studies

The information was searched though the data-base available at the University of Western Australia which included the collections of:

Directory of open access journals (DOAJ), Medline/Pubmed (NLM), OneFile (GALE), ProQuest, collection, (Web of Science), Science Direct Journals (Elsevier), Social Sciences Citation Index (Web of Science, Scopus (Elsevier)), SocialSciences Citation Index (Web of Science), Wiley (CrossRef), Wiley Online Library. Also, google scholar, by looking at the papers that reference the original study performed by Kvaal et al. Cameriere et al., and those methods for age estimation that referred in their methodology the use of CBCT and volume reconstruction of pulp chamber and tooth.

The search key words were as follow: Kvaal and dental age estimation; Cameriere and dental age estimation; age; and tooth volume.

The literature search included papers published after the publication of the original papers of the authors to July 2016, the search was conducted during the years 2014 to 2016. In the lack of a manual for systematic review in forensic dentistry, this systematic review follows the Cochrane handbook for systematic reviews-methodology review, and when possible the RevMan software recommended by the Cochrane handbook (Figs. 1–3).

2.3. Data collection and analysis

2.3.1. Selection of studies

The initial selection was based on the title and then abstract. Papers with titles that referred the inclusion of only minors were excluded (children). Studies reporting also the use of third molars or developing teeth, were excluded. Studies that included in the tittle also the use of other methods for dental age estimation in children were excluded (Demirjian) or any other invasive method for dental age estimation were excluded (Diagrams 1–3, Tables 1–3).

2.3.2. Data extraction and management

The collected information was organized in an excel spreadsheet as follow: Author, year, country, number of participants (male and female), age, intra and inter-observer agreement assessment, imaging technique to obtain the images, measuring instrument, best correlation coefficient between age and the different age predictors, best result in terms of accuracy per individual tooth or per set of teeth, when possible, as well as the highest error recorded by set of teeth or individual tooth (Tables 4–6).

2.3.3. Assessment of risk of bias in included studies

To avoid bias in this systematic review, and to avoid false positive (declare that a method is more accurate than other when it is not) or false negative conclusions (declare that a method is less accurate than other when it is not), it was necessary to analyse the possibility of author bias. This owed to the participation of the same authors in repeated publications. To this end, the results were analysed comparing individual papers, and then grouping them per author. Additionally, in certain cases were there were doubts in regards to the origin of the sample, which means the likelihood to find studies that had used the same sample, the authors were contacted to confirm the origin of the sample, and in case that two studies had the same sample, the authors were asked to suggest which study should be included in

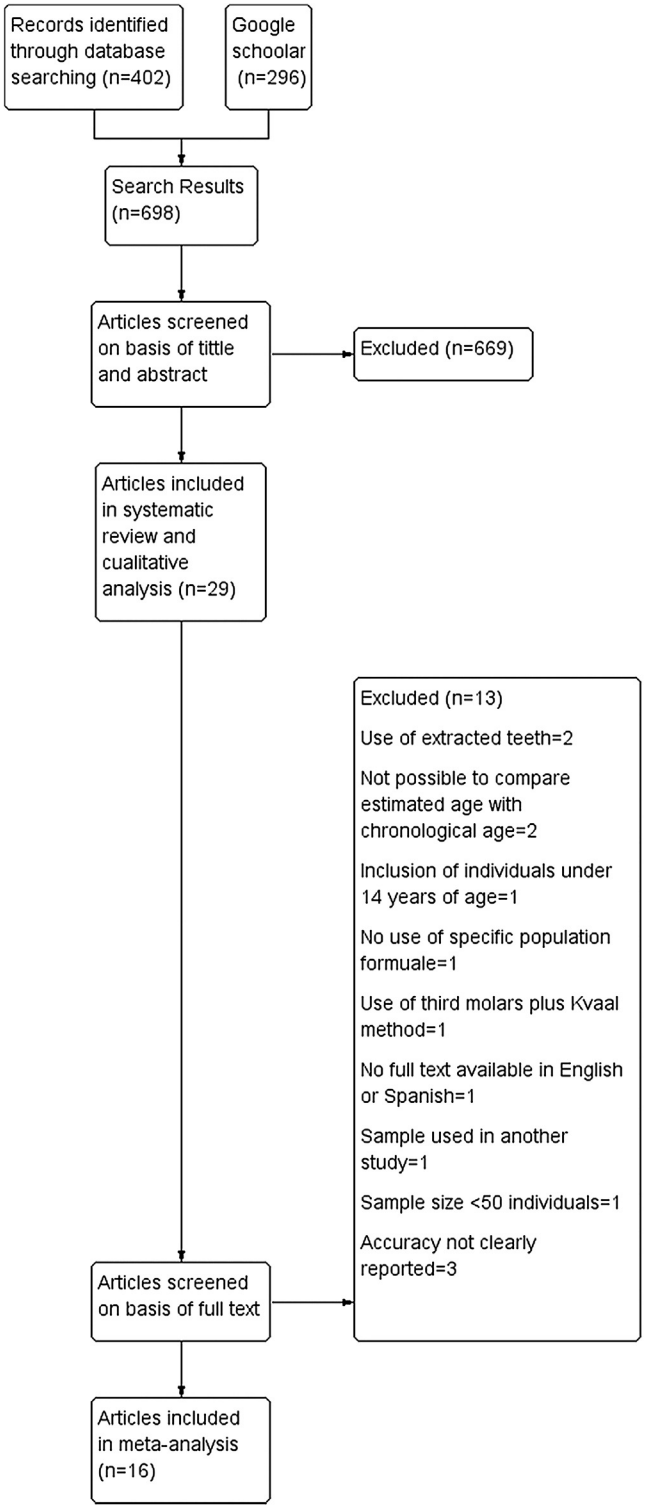

Fig. 1. Flow chart of the study selection for Kvaal et al. method.

the meta-analysis, in case that the study met the criteria for the quantitative analysis. In the same way, to deal with missing data, the authors were contacted via e-mail.

There was another possible source of bias observed in this study: the use of non-specific population regression models and equations, which could cause the judgement of a method as no or less accurate. To overcome this issue, only studies using specific population formulae were used in the quantitative analysis.

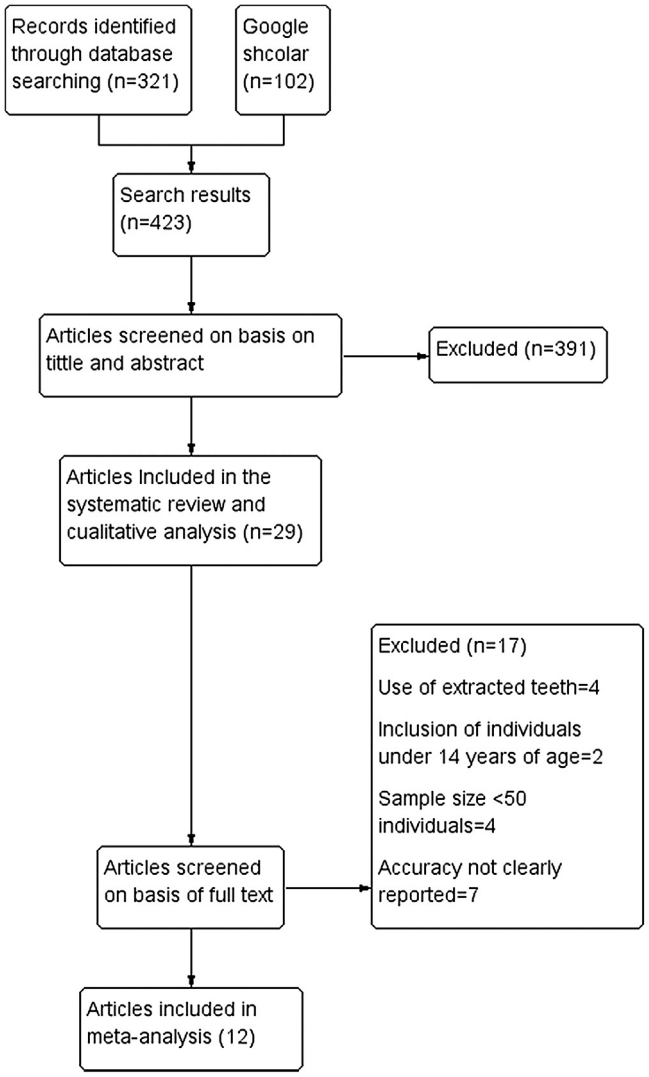

Fig. 2. Flow chart of the study selection for Cameriere et al. method.

3. Results

3.1. Kvaal et al. [6] (29 Papers, n = 3254)

3.1.1. Qualitative analysis

The original paper about Kvaal et al. [6] method was published in 1995. Since then, this method has been applied to a global sample of 3254 individuals from 12 different countries (Graph 1, Table 1). The initial methodology suggested the use of periapical radiographs from six different teeth, using vernier callipers to measure the maximum tooth length, the pulp length and root length, and a stereomicroscope with a measuring eyepiece to the nearest 0.1 mm to measure pulp and root width at three different levels previously described by the author of this method [6]. Just few studies have followed the original methodology with slight adaptations [1,6,9,16–19]. In 2005, this method is applied on panoramic radiographs (20), which became popular [21–35]. The use of digital imaging in dentistry also introduced the use of different software to perform the odontometric measurements. The most commonly used software are: Adobe Photoshop (different versions n = 5), Image J (n = 4) and Kodak dental imaging software (n = 2). From those studies that tested the effect of sex on the accuracy of the age estimated, 3 found that sex does not affect the models [16,20,31] and 2 that it does [19,24]. In the original

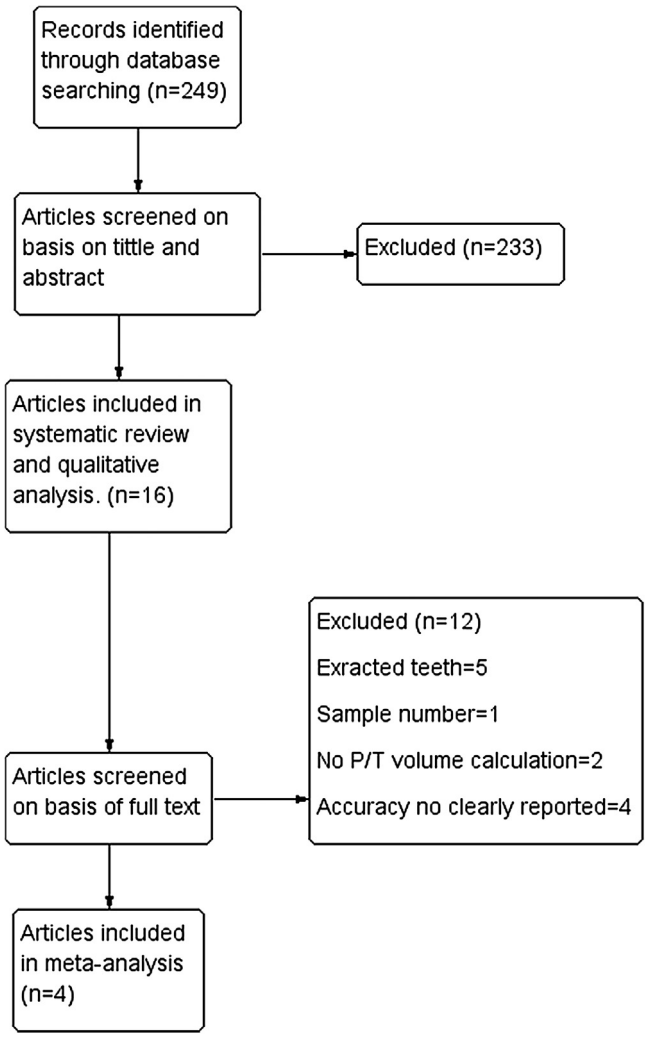

Fig. 3. Flow chart of the study selection for methods based on volume calculation.

study, sex was included as a factor for the mandibular lateral incisor, indicating that pulp cavity size changes occurred faster in males, as females need another 6 years to get the same age as females for this tooth [6].

3.1.2. Quantitative analysis

From the total sample, only 16 papers met the inclusion criteria for the quantitative analysis (Table 4). The most accurate result (SD = 5.6, r = −0.95) was obtained from panoramic radiographs using Hipax program (version 3.01) software, 168 participants (95 female and 102 male) in a Caucasian group [20] The larges error reported error was SEE > 13 years $r^2 = 0.1$ [16,36] obtained from the lower canine, following original Kvaal methodology on periapical radiographs [36] and the Adobe Photoshop 6.0 software in panoramic radiographs [16].

Kvaal et al. measurements have been reported to have a high degree of intra and inter-observer agreement indicating the reproducibility of the measurements, even in those studies that did not follow the original methodology. Only one study reported significant differences in regards to the root length and pulp width at the level B and root width at the level A measurement, although this study reported a SEE = ±13.8 ($r^2 = 0.38$), the average error of age estimation was ±18–21 years using periapical radiographs [36].

Note: the studies that did not meet the inclusion criteria for the quantitative analysis also reported high intra and inter-observer agreement [32–34], One study reported that the lower lateral incisor produced lower intra-observer correlation [33], and one of them affirmed that the use of stereomicroscope improve the accuracy of the age estimates [9].

Table 1
Total studies reporting the use of Kvaal et al. method.

Author	Year	Country	Total[a]	Age
Kvaal et al. [6]	1995	Norway	100	20–87
Kvaal et al. [17]	1999	Sweden	21	20–60
Willems et al. [9]	2002	Belgic	29	26–85
Soomer et al. [1]	2003	Caucasian	20	14–95
Bosmans et al. [21]	2005	Belgic	197	19–75
Paewinsky et al. [20]	2005	Germany	168	18–81
Meinl A. [32]	2007	Austria	44	13–24
Avendaño et al. [19]	2009	Colombia	107	21–50
Landa M. [33]	2009	Portugal	100	14–60
Shetty et al. [16]	2010	India	100	20–70
Sharma et al. [72]	2010	India	50	15–60
Saxena. [31]	2011	India	120	21–60
Saxena et al. [41]	2011	India	160	21–60
Chandramala et al. [22]	2012	India	100	20–70
Kanchan et al. [36]	2012	India	100	25–77
Agarwal. [18]	2012	India	50	20–70
Erbudak et al. [30]	2012	Turkey	123	15–57
Thevissen et al. [34]	2012	Belgic	450	15–23
Limdiwala et al. [23]	2013	India	150	20–55
Parkin et al. [29]	2013	India	30	15–60
Kostenko. [73]	2013	Ukraine	64	–
Karkhanis et al. [25]	2014	Australia	279	20–62
Misrlioglu et al. [26]	2014	Turkey	114	17–72
Patil et al. [70]	2014	India	200	20–50
Ayad et al. [24]	2014	Sudan	99	15–30
Muszynska et al. [35]	2015	Poland	3	–
Marroquin et al. [27]	2016	Australia	74	12–28
Mittal et al. [28]	2016	India	152	14–56
Rajpal et al. [71]	2016	India	50	15–57
29 papers		12 countries	3254	12–95

[a] Number of individuals reported in each study. Sample size.

Table 2
Total studies reporting the use of Cameriere et al. method.

Author	Year	Country	Total[a]	Age
Cameriere et al. [7]	2004	Italy	100	18–72
Cameriere et al. [53]	2006	Italy	33	–
Cameriere et al. [10]	2007	Italy	100	20–79
Cameriere et al. [37]	2007	Italy	100	20–79
Cattaneo et al. [65]	2008	Ethiopia	1	52
Cameriere et al. [38]	2009	Portugal and Italy	229	20–84
Singaraju et al. [39]	2009	India	200	18–72
Babshed. [4]	2010	India	178	20–70
De luca et al. [2]	2010	Spain–Italy	73	–
Babshed et al. [51]	2011	India	61	21–71
Cameriere et al. [74]	2011	Italy	90	50–79
Jeevan et al. [40]	2011	India	228	16–72
Saxena [31]	2011	India	120	21–60
Vodanovic et al. [66]	2011	Croatia	192	–
Zaher et al. [42]	2011	Egypt	144	12–60
De luca et al. [52]	2011	Mexico	85	18–60
Cameriere et al. [43]	2012	Spain	606	18–75
Cameriere et al. [47]	2013	Portugal	116	18–74
Charis et al. [44]	2013	India	120	20–70
Cameriere et al. [47]	2013	Portugal	116	18–74
Azevedo et al. [45]	2014	Italy	81	19–74
Misirlioglu et al. [26]	2014	Turkey	114	17–72
Azevedo et al. [45]	2015	Brazil	443	20–78
Ravindra et al. [48]	2015	India	308	9–68
Cameriere et al. [75]	2015	Italy	70	20–70
De Angelis et al. [68]	2015	–	1	–
Fabbri et al. [67]	2015	Italy	18	–
Sakhdari et al. [49]	2015	Iran	120	>12
Torkian [76]	2015	Iran	120	>12
29 papers		11 countries	4167	12–79

[a] Number of individuals reported in each study. Sample size.

Table 3
Total studies reporting the use of volume calculation.

Author	Year	Country	Total[a]	Age
Vandervoort et al. [8]	2004	Belgic	52	24–66
Yang et al. [11]	2006	Belgic	19	23–70
Someda et al. [12]	2009	Japan	155	12–79
Agematsu et al. [62]	2010	japan	258 teeth	20–79
Aboshi et al. [13]	2010	Japan	50	20–78
Star et al. [56]	2011	Belgic	111	10–65
Tardivo et al. [57]	2011	France	58	14–74
Jagannathan et al. [14]	2011	India	188	10–70
Sakuma et al. [54]	2013	Japan	136	14–79
Tardivo et al. [58]	2014	France	210	15–85
Sasaki et al. [55]	2014	Japan	363	15–70
Mendonca et al. [61]	2015	Brazil	72	22–70
Ge et al. [63]	2015	China	403	12–69
De Angelis et al. [59]	2015	Italy	91	17–80
Pinchi et al. [60]	2015	Italy	148	10–80
Ge et al. [64]	2016	China	240	16–63
16 papers		7 countries	2296	10–85

[a] Number of individuals reported in each study. Sample size.

3.2. Cameriere et al. [7] (29 papers n = 4167)

3.2.1. Qualitative analysis

The original paper documenting Cameriere et al. method [7] was published in 2004. In this systematic review, 29 papers using this method were found, having a global sample of 4167 individuals from 11 countries (Graph 2, Table 2). This method was initially applied to digital panoramic radiographs, using (AutoCAD2000, Install Shield3.0, 1997) and different versions of this software have been used in 11 studies. The most used software to perform the pulp/tooth area measurements is Adobe Photoshop (13 studies). This method was designed to be applied in single rooted teeth, especially canines, but it has also been tested in premolars and central and lateral incisors. From those studies that assessed the effect of sex on the regression models, the vast majority reported that sex does not affect the regression model [4,7,26,31,37–46]. Only 4 studies reported that sex affect the regression model [47–50].

3.2.2. Quantitative analysis

Twelve studies met the inclusion criteria for the quantitative analysis (Table 5). The use of this method has shown a standard error of estimation (SEE) from ±1.2 [42] to ±12–13 years (r = 0.2–0.4) [51] From these studies, 2 reported a median error < ± 5 years [7,38], 6 studies reported an error from ±5 to ±8.5 years [26,40,42–44,46], and three studies reported an error from ±10 to ±13 years [4,47,51]. From the included studies in the qualitative analysis, only one reported significant intra-observer differences in lateral incisors and first premolars ($p < 0.05$) [51].

Note: all the studies that did not meet the inclusion criteria for the qualitative analysis and that did intra and inter-observer calibration, reported high intra inter-observer agreement [37,49,52,53].

3.3. Volume (16 papers n = 2444)

3.3.1. Qualitative analysis

Owed to the low number of studies doing pulp/tooth volume reconstruction, in the qualitative analysis those studies using extracted teeth were included. The first study doing pulp/tooth volume reconstruction reported the use of micro-focus X-ray in 2004 [8]. In this systematic review, 16 studies were found using the pulp/toot volume reconstruction, by means of micro-focus computer tomography, CT scan or CBCT, and the use of different software to do manual or semiautomatic volume reconstruction, such as Tri 3D Bon, Mimics®, ITK-SNAP 2.4, Osirix, Amira among others, in a global sample of 2444 individuals from 7 countries (Graph 3, Table 3). However, the methodology of some of them require the use of extracted teeth [8,12,13,54,55]. In regards to the effect of sex on the regression models, 9 studies reported that sex has no effect [8,14,26,54,56–60]. 3 studies reported that the models are more accurate in female than in male, having a higher determination coefficient for women than form men [12,61,62], as follow: R2 0.6 for males and R2 0.7 for females [12], or R2 = 0.29 for males and R2 = 0.15 for men [61] and R2 = 0.67 for male and R2 = 0.75 for female when the mandibular central incisor is used or R2 = 0.56 for male and R2 = 0.58 for female when the second premolar is used. Two studies, which only reconstructed the pulp cavity volume, also reported significant difference between tooth type and sex [63,64], One of them found a significant difference in the volume between the volume of both genders ($p = 0.028 < 0.05$) and a stronger relation between pulp chamber and age for female (R^2 0.6) than for male (R^2 0.5) [63]. The other one reported a signifficant difference in volumebetween genders for 12 types of teeth ($p = 0.000$) [64].

3.3.2. Quantitative analysis

Four studies meet the inclusion criteria for the qualitative analysis. The error of these studies variates between ±3.47 years [58] to ±28 years [59]. It was reported high intra-inter-observer agreement [60]. Among those studies that did not meet the inclusion criteria for the quantitative analysis, seven studies also reported high intra-inter-observer agreement [8,11–14,57,63,64].

4. Discussion

Age estimation in adults is a challenge in all forensic contexts, especially in cases that require the use of non-invasive methods. The formation of secondary dentine and the non-linear narrowing of the root canal with age [11], is one age predictor measurable in dental radiographs and tomographs, leading to the proposal of different methods for age estimation in adults as an alternative to more invasive methods and as a complement to osseous analysis [2,17,35,65–68].

In the same way, many methods have been suggested for dental age estimation in adults. Nevertheless, there are few available studies that compare their accuracy [69]. In the lack of a consensus to uniformly apply a method for age estimation in adults, the need to perform a systematic review seemed to be evident. This systematic review summarises and compares the results of some of the most used methods for dental age estimation in adults, performing a qualitative and quantitative analysis.

In terms of the qualitative analysis, it has been reported that there are no significant differences between right or left teeth [14,57]. Another aspect to test among the different papers was the effect of sex of the different methods. Although not all the included studies assessed the effect of sex on age estimation, those that did (n = 38), 71% (n = 27) affirm that sex has not statistically significant effect on age estimation, when pulp/tooth ratio is calculated. However, if only pulp volume is measured and used as age indicator, there is a significant difference between the accuracy for males and females [63,64].

In the light of the evidence one could suggest that ratio calculation not only diminishes the effects of tooth magnification in dental radiographs, as reported by Kvaal et al. [6], but also reduces the effect of sexual dimorphism related to tooth size. The age of the participants is also another relevant aspect to include, in this systematic review those studies including participants under 14 years of age where excluded for two main reasons. First, there are other methods more reliable for aging teenagers and infants, and second, before 14 years of age, not all the teeth have completed

Table 4
Kvaal et al. method. Studies included in the quantitative analysis.

Study	Sample	Measuring instrument	SEE ± years per tooth or group of teeth (FDI)									
			6_teeth	upper	lower	11/21	12/22	15/25	32/42	33/43	34/44	11/21_32/42	13/23
Kvaal et al. [6] 1995, Norway	100 PER 20–87 years	Stereomicroscope and Vernier callipers	8.6	8.9	9.4	9.5	10	11	10.5	11.5	11.5		
Bosman et al. [21] 2005, Belgic	197 OPG 19–75 years	Adobe Photoshop software	9.5	9.2	9.9	9.7	9.8	9.3	11.6	8.2	8.1		
Paewinsky et al. [20][a] 2005, Germany	168 OPG 14–81 years	Hipax program	5.6				6.4						
García et al. [19] 2009 Colombia	107 PER 21–50 years	Scion Image software				7.1							
Ranjani et al. [16] 2010, India	100 PER 20–70 years	SV- 4 mini slide viewer, digital Vernier callipers, Stereomicroscope	10.5	10.2	11.8	11.5	12.4	11.8	12.7	13.3	11.8		
Erbudak et al. [30] 2012, Turkey	123 OPG 14–57 years	Image J software				10.01		10.12	8.73			8.82	
Saxena et al.[b] [41] 2011, India	120 OPG 21–60 years	AutoCAD2005 software											3.63
Kanchan-Talreja et al. [36] 2012, India	Group A 47 PER 25–75 years	Adobe Photoshop software	12.08	12.08	12.4	12.79	13.25	11.87	13.3		13.28		
	Group B 43 PER 25–77 years		11.9	11.27	12.46	11.17	13.4	12.62	13.43	13.89	12.75		
Limdawala and Shah [23] 2013, India	Group A 100 PER 25–50 years	Kodak Dental Imaging Software	8.3	8.21	9.09								
	Group B 50 PER 25-50 years		9.45	9.5	9.88								
Misirlioglu et al. [26] 2014 Turkey	144 OPG 17–72 years	Easy-Dent PC software			5.88				7.36	7.52	6.94		
Patil et al. [70] 2014, India	200 PER 20–50 years	Image-Pro Plus II software				6.5							
Karkhanis et al. [25] 2015, Australia	200 OPG 20–62 years	Image J software	8.99	9.6	8.36	9.36	9.64	9.52	10.22	10.9	10.53		
Mittal et al. [28] 2016, India	152 OPG 14–60 years	VistaScan DBSWIN software	7.97	8.59	7.51	8.15	8.53	7.89	8.85	7.95	7.58		
Rajpal et al. [71] 2016, India	50 PER 15–57 years	Kodak Dental Imaging Software	6.42	7.3	7.84								

PER = periapical radiographs. OPG = panoramic radiographs. Tooth numeration FDI (Federation Dentaire International).
[a] Error reported as standard deviation.
[b] Error reported as the difference between the chronological age and the estimated.

the apex closure, which by definition, is a requirement for the formation of the secondary dentine [77].

For the qualitative analysis, characteristics related with sample size and inclusion criteria stablished in different studies were compared. As compared to previous efforts, we did not find a significant correlation between sample size and the accuracy of the method, when all the data were analysed together ($r^2 = 0.1$, p-value <0.05, sample size of the analysed studies n = 50–604) or when the data were analysed individually for each method. It is necessary to highlight that from the studies included to perform this analysis (n = 30) only 4 (13.3%) had a sample smaller than 100 individuals (n = 50–91 individuals), which may suggest that in any study for age estimation the minimum sample should include data from at least 100 participants, or over 100 teeth from different individuals in those studies using only one tooth type. Some of the excluded studies for the quantitative analysis, fail in this aspect [56,57,61,62], including data from several teeth of the same individual and counting them as different samples, which may affect the reported results.

A previous study recommended a minimum of 120 participants to achieve 80% of power and 5% of significance [31]. One almost universal inclusion criteria, among the papers, was the use of only totally sound teeth. Only two studies did not follow this parameter, using teeth with cervical lessons to do volume calculation [55]. or using panoramic radiographs that did not meet the inclusion criteria suggested by Limdiwala et al. [23]. Both of them found not significant effect of these situations on the accuracy of the results.

Another aspect to consider, is the description of the different methods, in terms of the procedure to measure the different pulp/tooth dimensions, as well as the statistical processing of the data. In certain cases, it was necessary to re-read the papers several times to understand the proposed methodology and how the accuracy was reported.

In the quantitative analysis two main characteristics were compared among the studies: repeatability of the measurements, in terms of intra and inter-observer agreement and their accuracy, reported as standard error of estimation (SEE), mean absolute error (MAE) or standard deviation (SD). It is necessary to mention that owed to this variety in the approach to evaluate and to report the obtained accuracy, it was not possible to perform a deeper statistical analysis, a meta-analysis, to confirm that one method was superior to another, however in this review we found that in average, the studies using pulp/tooth area ratio reported a lower error (Tables 4–6).

All the studies reported significant intra- and inter-observer agreement, regardless the used method and the measuring instrument, which suggests that after adequate training any of these methods is reproducible. However, in regards of the

Table 5
Cameriere et al. method. Studies included in the quantitative analysis.

Study	Sample	Measuring instrumet	SEE ± years per tooth (FDI)								
			32/42	11/21	12/22	31/41	32/42	33/43	34/44	35/45	13/23
Cameriere et al. [7][a] Italy, 2004	100 OPG 18–72 years	AutoCAD2000									3.27
Cameriere et al. [38] Portugal and Italy, 2009	229 PER 20–84 years	Adobe Photoshop						4.33			4.24
Babshet et al. [4] India, 2010	178 PER 20–70 years	Adobe Photoshop AutoCAD 2004						10			10
Babshet et al. [51] India, 2011	61 PER 21–71 years	Adobe Photoshop AutoCAD 2004	12.22				12.28	13.08	12.45		
Jeevan et al. [40][a] India, 2011	228 PER 16–72 years	Adobe Photoshop						6.39			4.28
Zaher et al. [42] Egypt, 2011	144 PER 12–60 years	AutoCAD2008		2.63	1.94						
Cameriere et al. [43] Spain, 2012	606 OPG 18–75 years	Adobe Photoshop							6.38	5.75	
Cameriere et al. [47] Portugal, 2013	116 PER 18–74 years	Adobe Photoshop		7.03	6.64	10.8	10.9				
Charis et al. [44][a] India, 2013	120 PER 20–70 years	Jenoptic ProgRess Version ss2.7							5.4		
Azevedo et al. [45][b] Italy, 2014	81 PER 19–74 years	Jenoptic ProgRess Version ss2.7									3.05
Misirlioglu et al. [26] Turkey, 2014	114 PER 17–72 years	Adobe Photoshop									6.75
Azevedo et al. [45] Brazil, 2015	443 PER 20–78 years	Adobe Photoshop						6.41			5.79

PER = periapical radiographs. OPG = panoramic radiographs. Tooth numeration FDI (Federation Dentaire International).
*** Error reported as mean error.
[a] Error reported as mean absolute error (MAE).
[b] Error reported as the module of the differences between the chronological and estimated age.

simplicity of the technique, and the access to the required tool to measure and to calculate the respective pulp/tooth ratio dimensions, Kvaal et al. and Cameriere et al. are more convenient, using periapical radiographs or panoramic radiographs, as the radiological technique does not affect the accuracy of the measurements, as long as the quality of the image allows the observer to clearly observe the boundaries on the root canal and tooth surface [23]. The volumetric reconstruction of anatomic structures involves a more technical and time consuming training as well as the use of more complex software, that are not always free access. This could be considered as an obstacle for the big scale application of some of these methods. Likewise, the user spends more time doing the volumetric reconstruction per tooth, which variates from 4 h [8] to 15 min [61], when reported.

Another important aspect in regards of accuracy, is the use of the specific population formulae, which also improves the results of the age estimates, independently of the used method [14,30,42,46,64,70]. In those studies, using non-specific population formulae the reported error was notably larger (error > ±20 years) [32,33]. However, the use of data from different population in the same statistical analysis, to generate a unique age estimation equation, is not discouraged [2,21,47]. Furthermore, it has been reported that the pulp chamber size variation can be detected only each 10 years, which opens a question mark about the reliability of those methods reporting a lower error.

In the specific analysis of Kvaal et al. method, although this method required the inclusion of six different single rooted teeth per idividual, the use of only one tooth [19], only upper central incisor [70], canines [26], mandibular teeth [33], or different combination of teeth to apply the odontometric analysis described by Kvaal and co-workers [25,27], has also been reported, with acceptable results (SEE < ±10 years). It has also been reported that its accuracy depends on the quality of the image and on the precision of the measurements [23]. Several studies reported that tooth length is not strongly correlated with age [16,18,20,23] as tooth length would depend on tooth wear, bruxism, and food habits, rather than a physiological aging related process [16].

In regards to Cameriere et al. method, it only requires the use of one teeth, and the majority of the studies report the use of canines. However, one study using three different lower teeth (Lateral incisor, canines, first premolars) found that lower canine had the poorest correlation coefficient with age (r = −0.2) (51). Another study found more accurate estimations from upper lateral incisors, claiming that the narrowing velocity in the pulp chamber of this tooth is twice faster than in the lower incisors [47].

Table 6
Volume calculation based methods.

Author	Sample	Image segmentation method	Measuring instrument	Accuracy
Star et al. [56] 2011, Belgic	111 CBCT 10–65 years	Automatic segmentation (threshold), and manual correction	Simplant®	11/21 SD = 12.8 13/23 SD = 13.1 15/25 SD = 8.4
Tardivo et al. [58] 2014, France	210 CT 15–85 years	Semiautomatic	Mimics®	13/23 MAE = 3.4 33/43 MAE = 4.6
De Angelis et al. [59] 2015, Italy	91 CBCT 17–80 years	Manual	Osirix software	prediction interval = ±28 years
Pinchi et al. [60] 2015, Italy	148 CBCT 10–80 years	Cone shape approximation	Osirix® software	SEE = ±11.45

CBCT: cone beam computed tomography; SD: standard deviation; MAE: mean absolute error; SEE: standard error of estimation.

Although, the majority of the studies reporting the use of this method also mention its creator as part of the authors, which could generate certain bias in the results. It was observed that in those studies that did not count with his participation, the results in terms of the repeatability of the method and accuracy were similar [26]. In average, Cameriere et al. method reported the lowest error (total average ±5.6 years), and a sample of at least 120 individuals was observed as adequate to obtain more accurate age estimates [31].

The combined use of Kvaal et al. width ratios and Cameriere area ratios has been reported on canines from digital panoramic radiographs, finding more accurate age estimates when the pulp/tooth width ratio at level C and pulp/tooth area ratio were using together [31] or when area ratio calculation from canines is used individually [26].

In this systematic review we found the following advantages about the use of pulpt/tooth area calculation over other methods: area measurement on digital radiographs with different software is faster, and the most recent study using this method proposes a software to do and automatic selection of the borders of the pulp and tooth, which minimizes the required time to obtain the area of tooth and pulp chamber, and reduces the error associated with the observer, when performing the area selection [75]. Linear measurements can also be performed on digital radiographs, but, the observer needs to take nine measurements per tooth, in six teeth, and calculate several ratios. In the method using pulp/tooth area measurements, only one ratio needs to be calculated and allows the researcher to develop the respective statistical regression model. In the same way, the use of canines, especially upper canines to calculate pulp/tooth area ratio has certain advantages, as their longer survival, in comparison with other teeth, less wear, and the big size of the pulp chamber [59]. Also, as observed in Table 5, there are not only more studies reporting the use of upper canines to do pulp/tooth area calculation but also, these studies present an acceptable accuracy, in contrast to what was reported by Kvaal and Solheim, when doing pulp/tooth length/with ratio calculation who observed that upper canines had the lowest correlation with age, when using dental radiographs of extracted teeth [77], which was an exclusion criteria in this systematic review.

Finally, although the use of pulp/tooth volume ratio calculation from non-extracted teeth still requires more research. The initial results of the analysis of pulp volume among individuals of different age groups, bring important and detailed information to understand of the formation of secondary dentine. It has been reported that the pulp/tooth volume ratios in the cervical area were more correlated with age, and that this correlation decrease towards the apex [13]. Also, that the most marked reduction in volume ratio was observed between the second and the fifth decades of life in lower first and second premolars, and between the second and the third decades of life in lower first premolars. [13] This clear findings may enlighten the proposal of future and more accurate methods for age estimation in adults.

5. Conclusion

The narrowing of root canal caused by the formation of secondary dentine is a well-accepted age indicator in adults. This systematic review observed that age estimation methods based on pulp/tooth area ratio calculation reported more accurate results, even when one tooth is analysed per individual. However certain conditions need to be fulfilled: a sample of minimum 120 individuals, older than 14 years of age, assessment of the accuracy of the observer, and generation of specific population equation. The inclusion of data of individuals from different population group in the same analysis is not discouraged. These studies must consider in their statistical analysis the non-linear deposition of secondary dentine through life. This systematic review also recommends the use of dental age estimation methods, firstly pulp/tooth area ratio calculation of single first, upper canines and other single rooted teeth (lower premolars, upper central incisors) and secondly pulp/tooth length/with ratio calculation, as reported by Kvaal et al., in combination with other methods that include diverse age indicators to produce a more reliable age estimates. The authors of this systematic review also recommend future studies to report their results in terms of standard deviation, mean absolute error and standard error of estimation simultaneously, with this, there will be more be more homogeneity. Thereby, to perform a proper meta-analysis will be more likely.

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