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Dental Radiography for Age Estimation: A Scoping Review

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Purpose: This study was to investigate the types of imaging modalities, analytical methods for age estimation, and the age of the subjects in research on age estimation using dental radiography through a scoping review, and to investigate the overall trends in age estimation studies.

Materials and Methods: A scoping review was designed according to the Arksey and O'Malley guidelines and the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) statement. Three electronic databases were used as search sources (Medline, Embase, and Cochrane Library). Studies were classified according to the three main components of the research question. "What are the imaging modalities, analytical methods, and target age in dental imaging-based age estimation studies?"

Result: The final 198 studies were selected by two reviewers. The most common imaging modality used in studies was panoramic radiography (69.7%), and studies using cone-beam computed tomography have increased over time. Analytical methods for age estimation were 62.6% in studies based on tooth development and 26.3% in studies using pulp/tooth ratio. The subject age was 27.8% for children and 27.3% for adults. Studies conducted in all age groups comprised the smallest category (5.2%).

Conclusion: Panoramic radiography has been the most used types of imaging modalities for age estimation, and the most common analytical method was analysis of tooth development. Most studies targeted specific ages, and very few involved all age groups. Dental age estimation studies should be carried out with appropriate consideration of the imaging modality that is analyzed, the methods that are used, and the age that is targeted.

Key Words: Age estimation; Forensic sciences; Radiography, Dental

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Introduction

Forensic science is becoming increasingly important with the growing frequency of crime rates and catastrophic accidents. Forensic investigations use various methods and data sources, such as fingerprints, footprints, blood, hair, and dental structures that are not damaged in the event of a disaster. In addition to personal identification, forensic science encompasses the tasks of age estimation, sex determination, and classification of specific populations, all of which are difficult to accomplish in a non-invasive manner. Age estimation is one of the most important aspects of personal identification and plays an important role in determining legal age. Radiography is often used for non-invasive age estimation. The types of dental imaging used for age estimation extend from plain radiography, such as periapical radiography and panoramic radiography, to specialized radiographic modalities such as cone-beam computed tomography (CBCT), multidetector computed tomography (MDCT), magnetic resonance imaging (MRI), and combinations thereof in some cases.

Depending on the age group, the analysis of certain body parts using specific methods may be particularly useful. Osseous analysis such as skeletal maturation of the hand wrist and cervical spine is suitable for young individuals[1], and the method based on tooth development is very reliable in individuals under the age of 21[2]. The third molars are mineralized in healthy adults at 14~23 years[3]. The development of the third molars is divided into 8 stages from A to H according to the Demirjian system[4], and Cameriere et al.[5] proposed a cut-off for identifying people above or below 18 years of age using the third molar maturity index (I_{3M}) according to the completion of root development. In the absence of the third molar, the threshold is lowered to 12~14 years, when the second molar is mineralized[6-10]. Another technique for dental age estimation was first described in 1950 in research evaluating the narrowing of pulp cavities based on secondary dentin formation by radiography[11]. Studies based on the pulp/tooth ratio have been conducted among people of all ages, ranging from a study in which Kvaal et al.[12] measured length and width in 1995 to a study in which Cameriere et al.[13,14] measured the area in 2004, and with the development of CBCT, this area of research has expanded to include volumetric measurements[15]. A systematic review of dental age estimation using the pulp/tooth ratio method was conducted in 2017[16]. Dental age estimation studies continue to be actively conducted, as well as studies using other body parts, such as the hand wrist, cervical spine, clavicle, and sinus.

The purpose of this study was to investigate the type of imaging modalities, analytical methods used for age estimation, and the age of the subjects in research on age estimation using dental imaging through a scoping review, and to investigate the overall trends in dental age estimation studies.

Materials and Methods

1. Search Method

We selected a scoping review methodology to analyze general information and trends in various studies for age estimation based on dental imaging. The entire study protocol followed the Arksey and O'Malley guidelines[17] and the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) statement[18]. The research question of this study was: "What are the imaging modalities, analytical methods, and target age in dental imaging-based age estimation studies?"

2. Literature Search and Study Selection

Three electronic databases (Medline, Embase, and Cochrane Library) were searched with no language and publication date restrictions. The literature search was performed on June 29, 2020 included original papers published by June 18, 2020. In order

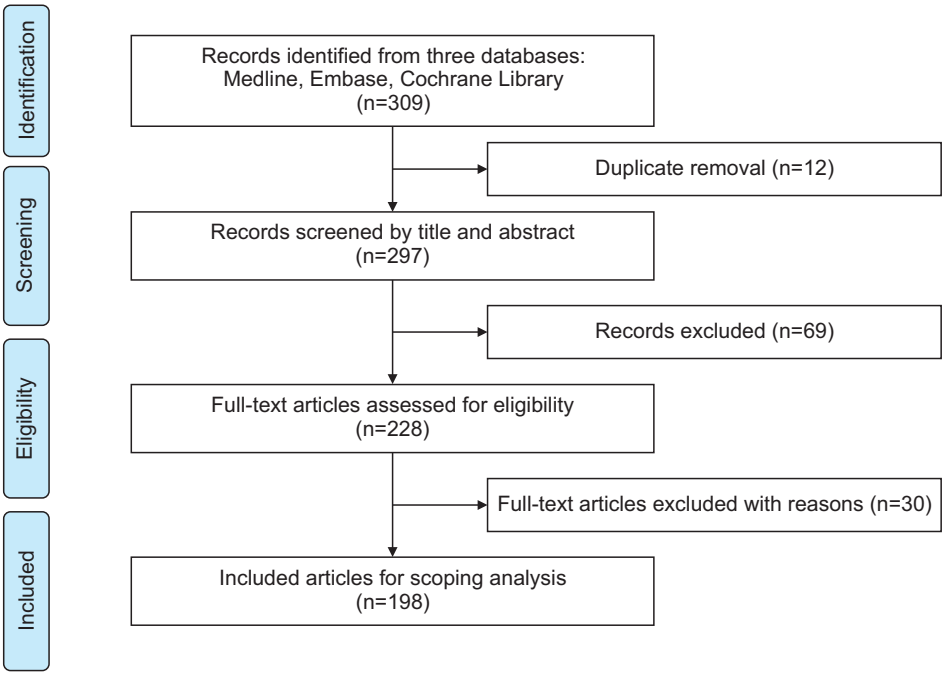

Fig. 1. Flow chart of study selection.

to collect data that fit the purpose, we selected keywords on three topics through expert discussion: research field (forensic odontology and forensic dentistry), image materials (dental imaging and radiography), and the final goals of the study (dental age estimation and age determination by teeth). To avoid missing search results, keywords related to the same concept were combined using the Boolean operator OR; otherwise, the Boolean operator AND was used. Two of the reviewers (KJJ and YHK) independently screened citations (titles/abstracts and full-text) and listed preliminary selections. If there was disagreement between reviewers, the final selection was made through discussion (Fig. 1).

3. Data Extraction and Analysis

Data extraction was conducted by the same two reviewers (KJJ and YHK). Papers were classified according to the three main components of the research question. First, the studies were divided into seven sub-categories depending on the dental imaging modality used: panoramic radiography, periapical radiography, CBCT, MDCT, MRI, micro-CT, and mixed modalities. Second, the studies were divided according to the general method used for age estimation into tooth-based studies, studies using non-tooth structures such as the sinus and hand, and combined studies using tooth and non-tooth structures. Tooth-based studies were additionally classified according to whether they used the tooth development stage or the pulp/tooth ratio. Studies using tooth development were categorized according to whether they used the third molars, teeth other than third molars, or a combination of third molars and other teeth. Finally, studies were categorized according to whether they included all ages, children, adolescents, children and adolescents, and adults, or focused on a legal age threshold or specific age cut-off.

Result

We searched 309 papers from 3 electronic databases and excluded 12 duplicates. Of the 297 papers, 228 papers were reviewed, excluding 69 papers for which full-text could not be found and papers not

written in English. The titles, abstracts, and full-text of 228 papers were reviewed by two reviewers, and the final 198 papers were selected, excluding 30 papers that did not fit the purpose or were ambiguous (Fig. 1).

1. Dental Imaging Modalities

The most common imaging modality used in the studies was panoramic radiography (69.7%)[6,7,19-154], followed by periapical radiography (9.6%)[14,155-172] and CBCT (9.6%)[173-191]. Five studies used MDCT[192-196], four studies used MRI[197-200], four studies used micro-CT[15,201-203], and nine used mixed modalities (Fig. 2)[204-212]. In an analysis of the imaging modality used by year of publication, it was found that studies using panoramic radiography showed a stable increasing trend, and studies using CBCT tended to increase over time (Fig. 3). The papers using CBCT, which showed an increasing trend in recent years, had a total sample of 4,455 individuals from 11 countries (Table 1).

2. Analytical Methods for Age Estimation

Tooth-based studies were 88.9%, studies using non-tooth structure were 6.6%, and combined studies were 4.5%. The most common method was analysis of third molar development (30.3%), and 26.3% of the studies used the pulp/tooth ratio (Fig. 4).

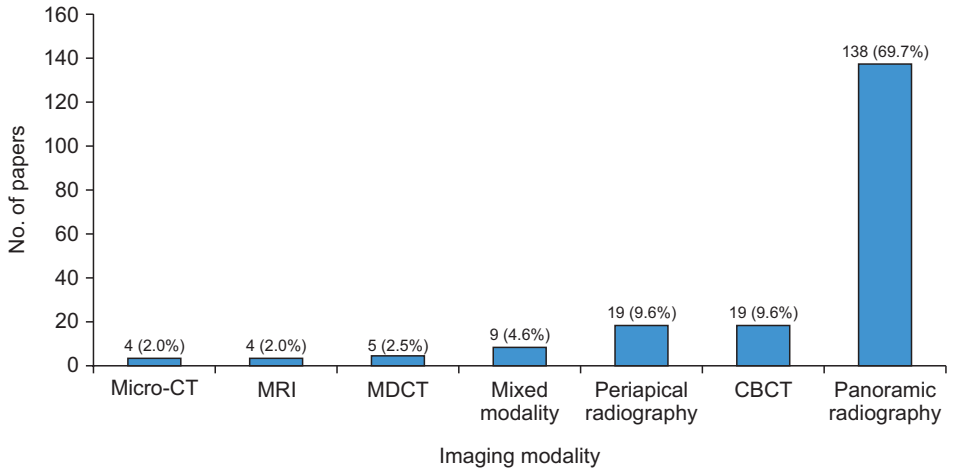

Fig. 2. Distribution according to the imaging modalities. MRI: magnetic resonance imaging, MDCT: multidetector computed tomography, CBCT: cone-beam computed tomography.

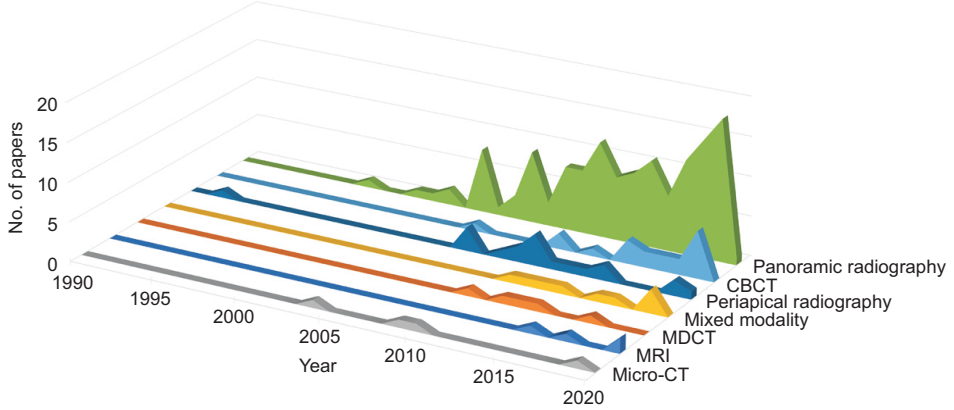

Fig. 3. Distribution of imaging modality by year. MRI: magnetic resonance imaging, MDCT: multidetector computed tomography, CBCT: cone-beam computed tomography.

Table 1. Studies reporting the use of cone-beam computed tomography

Study	Year	Country	Sample size	Age range (yr)	Method	Teeth
Yang et al.[173]	2006	Belgium	19	23~70	Pulp/tooth volume ratio	Single rooted teeth (15 incisors, 12 canines, 1 premolar)
Star et al.[174]	2011	Belgium	111	10~65	Pulp/tooth volume ratio	64 incisors, 32 canines, 15 premolars
Tardivo et al.[175]	2011	France	58	14~74	Pulp/tooth volume ratio	133 canines
Cantekin et al.[176]	2013	Turkey	752	9~25	Tooth development	Mandibular third molar
Ge et al.[177]	2015	China	403	12~69	Pulp chamber volume	Maxillary first molar and mandibular first molar
Pinchi et al.[178]	2015	Italy	148	10~80	Pulp/tooth volume	Upper left central incisor
Porto et al.[179]	2015	Brazil	118	22~70	1. Pulp cavity volume 2. Hard tissue volume 3. Tooth volume 4. Pulp cavity/tooth volume ratio	Maxillary central incisor
Marroquin Penaloza et al.[180]	2016	Malaysia	101	15~75	Kvaal pulp/root width measurements and ratios	Upper central and lateral incisor, and the second premolar Lower lateral incisor, canine and first premolar
Rai et al.[181]	2016	India	60	20~85	Pulp-to-tooth area ratio	Maxillary canine
Koh et al.[182]	2017	Malaysia & China	284	Above 20	Buccal alveolar bone level to the cemento-enamel junction	Lower first premolars of both the left and right side
Nemsi et al.[183]	2017	Tunisia	120	22~67	Pulp/dentin area ratio	Maxillary canine and mandibular second premolar
Asif et al.[184]	2018	Malaysia	110	16~65	Pulp/tooth volume ratio	Maxillary central incisor
Gulsahi et al.[185]	2018	Turkey	204	Above 15	Pulp/tooth volume ratio	Single rooted teeth (maxillary anterior, canine and mandibular canine/premolar)
Andrade et al.[186]	2019	Brazil	116	13~70	Pulp cavity volume	232 teeth (upper central incisors and canines)
Asif et al.[187]	2019	Malaysia & China	300	16~65	Pulp/tooth volume ratio	Maxillary left canines, maxillary right canines and maxillary right central incisors
Farhadian et al.[188]	2019	Iran	300	14~60	Pulp-to-tooth ratio	Maxillary canine (by neural networks)
Kazmi et al.[189]	2019	Pakistan	717	15~65	Pulp cavity volumes	Left maxillary and left mandibular canines
Uğur and Bayrak[190]	2019	Turkey	120	14~75	Pulp tooth area ratio	Maxillary central teeth
Zhang et al.[191]	2019	China	414	20~65	Pulp/enamel volume ratio	Impacted mandibular third molar

3. Subject Age

Of the 198 papers, four papers that did not present the exact subject age range in the abstract or full-text were excluded from the analysis[15,72,112,154]. Of the remaining studies, 54 (27.8%) were conducted among children, followed by 53 (27.3%) that analyzed

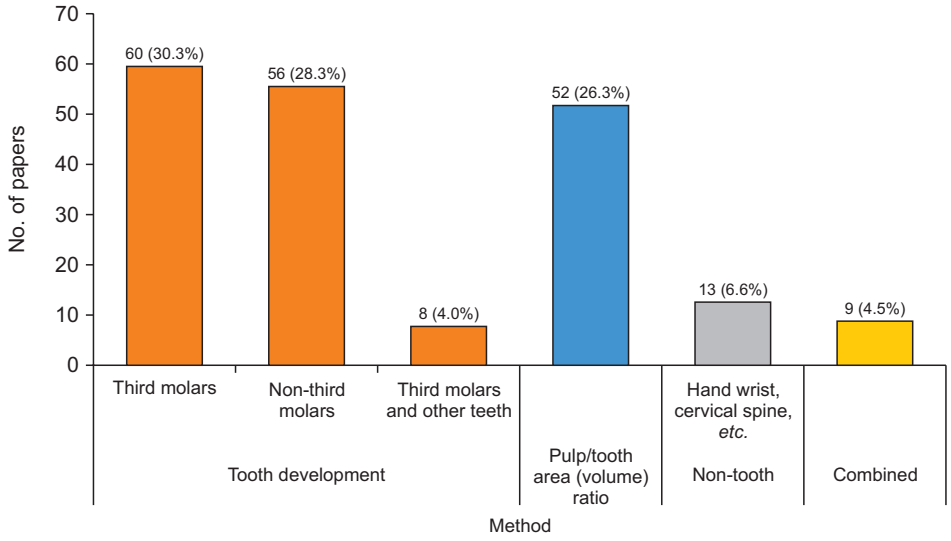

Fig. 4. Distribution according to analytical methods.

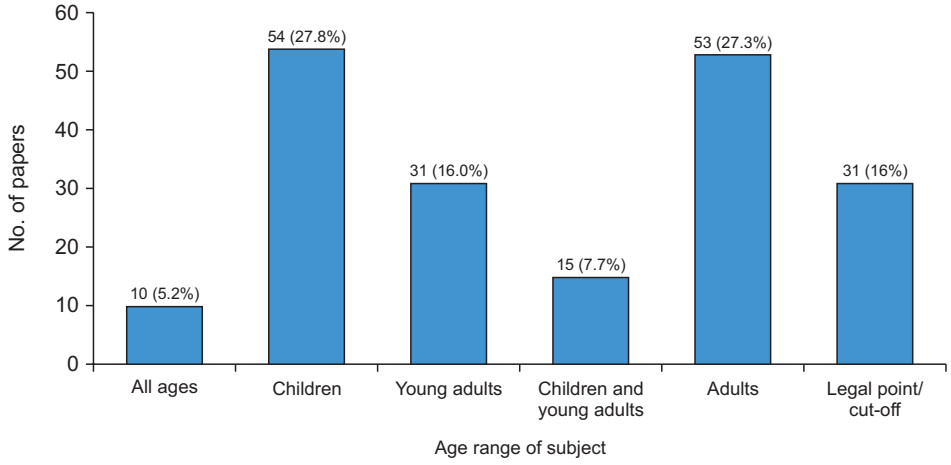

Fig. 5. Distribution according to age of subjects.

adults. Studies involving all age groups comprised the smallest category, with only 10 studies (5.2%) (Fig. 5). It was difficult to make a clear distinction between ages. Children were about 2 to 16 years old, adolescents were about 14 to 24 years old, and adults were over 18 years old.

Discussion

We analyzed studies investigating age estimation based on dental imaging through a scoping review. Approximately 80% of the studies used plain radiography. The most common imaging modality was panoramic radiography, as it is the easiest to perform, and there was a steady increase in the number of these studies over time. Most studies using panoramic radiography analyzed the development stage of the third molars, while some used the development of other teeth or the pulp/tooth ratio. Most studies using periapical radiography analyzed the pulp/tooth ratio. Of the studies using specialized imaging modalities, CBCT-based studies were the most common—as CBCT is widely used in dentistry—and the number of these studies increased over time. A few studies using MRI have been conducted in recent years, and studies using

mixed modalities are also increasing. MDCT has the advantage of being able to reconstruct various cross-sections and obtain three-dimensional (3D) images. Graham et al.[192] used 3D shaded surface displays (SSDs) and reformatted CT images to perform age estimation using the Moorrees, Fanning and Hunt (MFH) method[213], which divides tooth formation into 14 steps. Analyzing the closure of all fontanelles using SSDs can be useful for estimating the age of very young children[192]. Bassed et al.[193] reported that the developmental timing of the third molar tooth and medial clavicular epiphysis may be different on the left and right sides, with a difference in estimated age of up to 3.1 years; thus, the authors suggested that more accurate results can be obtained by considering both sides. Studies using MDCT with high radiation doses are limited. Studies using non-radiative MRI were published in 2015, 2017, and 2020[197-200]. A study analyzed the development of the third molars using the Demirjian method[197], and another estimated age and sex using the dimensions of the maxillary sinus[198]. Two studies published in 2020 conducted multi-factorial age estimation using the third molar, hand wrist, and clavicle[199,200]. De Tobel et al.[199] reported that combining information from different anatomical sites reduced the mean absolute error compared to assessing only one site, and that integrating multi-factorial MRI data for three anatomical sites improved all aspects of age estimation. Neumayer et al.[200] reported that, in light of the concern that scanning multiple sites extends the duration of MRI scans, it was possible to estimate age with high reliability using a method that reduced the existing 20 minutes to 4 minutes. CBCT is used more frequently because it can be used to acquire various cross-sectional images and 3D images with a lower radiation dose than MDCT. This review presented a detailed analysis of the studies that used CBCT, which is an increasing trend. Most of the studies using CBCT analyzed the 3D pulp/tooth volume, while one study analyzed the development of the third molars[176] and another evaluated attrition, secondary dentin formation, and the buccal bone level due to periodontal recession[182].

Many methods have been used for age estimation, and about 90% of studies using radiography targeted teeth. In the studies on teeth, more twice as many studies analyzed tooth development (62.6%) than analyzed the pulp/tooth ratio (26.3%). The most common methods of analyzing tooth development are those developed by Demirjian et al.[4] and Cameriere et al.[5]. Other formulas include the MFH method, the Nolla method, and those developed by Mincer et al.[214] and Köhler et al.[215]. The Demirjian method, which was developed in 1973, uses eight developmental stages from A to H on the seven teeth in the left mandible (central incisor to second molars)[4]. In 2004, Chaillet and Demirjian made this method available for a wider range of age groups through minor modifications (*e.g.*, including the third molar)[216]. As presented in 2006, the Cameriere method measured the height of the calcifying teeth and the width of the open apex in the seven teeth of the left mandible, excluding the third molar, and used the ratios for age estimation. The third molar was later added to this method. The MFH method evaluates the permanent mandibular posterior teeth in 14 stages and the permanent maxillary and mandibular incisors in 13 stages of development. The Nolla method evaluates 10 developmental stages from crypt formation to apex closure for both maxillary and mandibular teeth. This method can be applied with or without the third molar. The Mincer and Kohler methods evaluate the development of the third molar. The method of analyzing the pulp/tooth ratio was proposed by Kvaal et al.[12] in 1995 and extended by Cameriere et al.[13] in 2004. In non-tooth studies, the clavicle[193], hand wrist[169], cervical vertebral development[124], the maxillary sinus[198], frontal sinus[212], and mandibular ramus[100] were analyzed.

It was most common for studies to analyze children and adults, while it was least common for them to

analyze all ages. The majority of studies on children used the Demirjian method, which utilizes the developmental stage of teeth, the Willems method, and the Cameriere method, which utilizes measurements of tooth-size ratios. Studies on adolescents used the development of the third molars. A study of children and adolescents evaluated the development of the third molars and other molars. Most of the studies on adults analyzed the pulp/tooth ratio, and a study estimated age and sex by measuring the maxillary sinus volume on MRI[198]. Studies of all ages most often evaluated the pulp/tooth ratio, while one study evaluated the frontal sinus and reported that there was a meaningful difference according to age and sex[212], and another study studied the mandibular angle and the width and height of the ramus[100]. Most of the studies analyzing legal cut-off points focused on the age of 18 years through the developmental assessment of the third molars, and the apex closure of the mandibular permanent teeth was evaluated for a cut-off of 14 years.

Research on artificial intelligence has recently been emerging in several fields, and artificial intelligence-based research on age estimation is being attempted. In 2017, an attempt was made to automate assessments of the stage of development of the third molar on panoramic radiography[112]. In 2019, Farhadian et al. developed a neural network model using the pulp/tooth ratio method on 300 CBCT scans, and the results showed relatively acceptable performance, with a mean absolute error of 4.12 years[188]. In 2020, Merdietio Boedi et al.[154] reported the automated developmental stage assignment of mandibular third molars on 400 panoramic radiographs using a deep convolutional network.

Conclusion

Panoramic radiography has been the most used types of imaging modalities for age estimation, and in recent years, increasingly many studies are using CBCT and mixed modalities. The most used analytical method was analysis of tooth development, followed by the assessment of pulp/tooth ratio. For subject age, most studies targeted specific ages, and very few involved all age groups. Age estimation is a difficult task; therefore, dental age estimation studies should be carried out with appropriate consideration of the imaging modality that is analyzed, the methods that are used, and the age that is targeted.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

Acknowledgement

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