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Application of CBCT technology in forensic odontology

Moustansir HASSANALY

Dissertação conducente ao Grau de Mestre em Medicina Dentária
(Ciclo Integrado)

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Trabalho realizado sob a Orientação do Professor Doutor Daniel Pérez Mongiovi

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Eu, **Moustansir HASSANALY**, declaro ter atuado com absoluta integridade na elaboração deste trabalho, confirmo que em todo o trabalho conducente à sua elaboração não recorri a qualquer forma de falsificação de resultados ou à prática de plágio (ato pelo qual um indivíduo, mesmo por omissão, assume a autoria do trabalho intelectual pertencente a outrem, na sua totalidade ou em partes dele). Mais declaro que todas as frases que retirei de trabalhos anteriores pertencentes a outros autores foram referenciadas ou redigidas com novas palavras, tendo neste caso colocado a citação da fonte bibliográfica.

ACKNOWLEDGMENTS

In memoriam,
Saifuddin Adamaly
Shireenbay Akbarali Kokar
May the fire of your will always enlighten my path

To God, for everything.

To my family, for their unconditional support. For being the lighthouse in the dark when I was lost and far away from my roots. For always believing in me when I was not able to do it myself.

To my friends, all these noble and valuable souls which entrusted me with their laughs and their light. These years here would have been an empty shell without you. More words are pointless, hearts understand each other. You are a part of me, now and forever.

To my comrade and partner Yassine, half marmiton-half musician, but always with the smile. The moments we shared during our student life and outside are carved in me. For all of that, thank you brother.

To my supervisor, Professor Daniel. For your kindness, your softness, your patience, and your benevolence. Thank you for all your advices and your availability. Working with you this year was my honor.

To this beautiful country, which gave me the privilege to achieve my professional project. Your people and your landscapes will never stop to move me.

RESUMO

Introdução : CBCT é uma técnica não invasiva, rápida, barata e com pouca radiação. Ao ser uma técnica de imagiologia 3D, é mais adequada para a análise de estruturas 3D como dentes, ossos ou seios faciais. Já é amplamente utilizada em odontologia e a sua aplicação em odontologia forense é promissora.

Objetivo : Este trabalho visa fornecer uma visão geral da utilização do CBCT em odontologia forense e apresentar as diferentes aplicações desta tecnologia.

Materiais e Métodos: Para a realização deste estudo, fizemos uma pesquisa bibliográfica na plataforma PUBMED, que após a aplicação de critérios de inclusão e exclusão, resultou num corpus de 41 estudos.

Resultados : Os artigos foram repartidos assim : 1 (2,4%) é sobre identificação das circunstâncias de morte, 3 (7,3%) são sobre identificação por marcas de mordida, 18 (43,9%) são sobre estimativa da idade, 6 (14,6%) são sobre estimativa do sexo, 1 (2,4%) é sobre estimativa da idade e do sexo e 4 (9,8%) são sobre reconstrução facial.

Discussão: As imagens da CBCT permitem processos comparativos e reconstrutivos de identificação, nomeadamente estimativa da idade (em particular, a técnica de estreitamento pulpar), estimativa do sexo, análise de marcas de mordida ou reconstrução facial. As imagens da CBCT mostraram um elevado potencial de comparação com radiografias periapicais e ortopantomografias.

Conclusão: Dada a crescente presença de equipamentos CBCT em clínicas dentárias, os dentistas e odontologistas forenses devem ser treinados sobre como gerir a presença de artefactos nas imagens e sobre como organizar e partilhar estes dados de valor. Deverão ser realizados mais estudos com amostras maiores, nomeadamente para a estimativa da etnia.

Palavras-chave: *cone beam computed tomography; forensic dentistry; legal medicine; forensic radiology; human identification*

ABSTRACT

Background : CBCT is a non-invasive, rapid, cost effective and low irradiative technique. As a 3D imaging process, it is better suited for analysis of 3D structures like teeth, bones or facial sinuses. It is already widely used in dentistry field and its application in forensic odontology is promising.

Aim : This work aims to provide an overview of the use of CBCT in forensic dentistry and to present the different applications of this tool.

Materials and methods: For the realization of this study, we did a bibliographic search on the platform PUBMED, which after application of inclusion and exclusion criteria, resulted in a corpus of 41 studies.

Results : Articles are distributed as follows : 1 (2.4%) is about identification of the circumstances of death, 3 (7,3%) are about identification by bitemarks, 18 (43,9%) are about age determination, 6 (14,6%) are about sex estimation, 1 (2.4%) is about both age and sex determination and 4 (9,8%) are about facial reconstruction.

Discussion: CBCT's images allows comparative and reconstructive processes of identification. It is an accurate tool for age estimation (in particular, pulp narrowing technique), sex estimation, bitemarks analysis or even facial reconstruction. CBCT's images showed a high comparison potential with periapical radiographies and orthopantomographies.

Conclusion: Given the growing presence of CBCT equipment in dental clinics, dentists and forensic odontologists should be trained on how to manage the presence of artefacts in

images and on how to organize and share these valuables data. Further studies should be engaged on larger samples, in particular for ethnicity estimate.

Keywords : *cone beam computed tomography; forensic dentistry; legal medicine; forensic radiology; human identification*

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LIST OF ABREVIATIONS

2D – two-dimensions

3D – three-dimensions

ABL – alveolar bone level

AM – antemortem

CAD/CAM - computer-aided design/computer-aided manufacturing

CEJ - cemento-enamel junction

CBCT – cone beam computed tomography

CT - computed tomography

DCNN - deep convolutional neural network

DEJ – dentino-enamel junction

DPV - direct pulp volumetry

IMTM – impacted mandibular third molar

mAs - milliamperes

MC – mandibular canal

MF - mental foramen

MS – maxillary sinus

PCCR - pulp chamber/crown ratio

PEVR - pulp/enamel volume ratio

PHR - pulp/hard tissue ratio

PTAR - pulp/tooth area ratio

PTVR – pulp/tooth volume ratio

PM - postmortem

PR – panoramic radiography = orthopantomography

RSE - Residual Standard Error

SDD - secondary dentin deposition

STT – soft tissue thickness

1 INTRODUCTION

The American Academy of Forensic Sciences defines forensic dentistry or forensic odontology as "*a vital branch of forensic science that involves the application of dental knowledge, primarily for the identification of human remains*" as well as living persons.[1] Its application can help to victim's identification in case of mass disaster, recognition of injuries or abuse.

Identity can be defined as a set of characteristics that distinguish a person and differentiate them from others. Identification is considered as a comparative process aiming to reveal similar characteristics in missing individuals before and after disappearing.[2,3] In forensic dentistry, antemortem (AM) data is an inestimable value; it allows identification by comparative method with postmortem (PM) data. In absence of antemortem data, forensic odontologists must lead an identification by reconstruction, which is basically establishment of the biological profile (estimation of age, sex, population affinity or even facial reconstruction if needed).

Teeth are widely used in forensic investigation due to their strong potential of preservation over time, regardless of body state.[4] It is the hardest tissue in the human body and can survive to extreme conditions, should it be from natural or manmade disasters or even burials, carbonizations, immersions, trauma, putrefaction, etc.[5–7] They highly resist to physical and chemical stress, nutritional deficiency for a long period of time and are less affected by genetic, hormonal, and external factors compared to rest of the human body.[8,9] Therefore, tooth is a valid and reliable forensic tool.[8] Some of structures around are also

interesting due to their well-preserved potential like alveolar bone, mandible or even sinuses which are protected by dense bones.[10]

Various techniques were developed over time to study these structures. Some of them were highly invasive and destructive, which carried an ethical issue on living people or even on corpses for specific religious, cultural, or scientific motives.[11–13] Therefore, many conservative methods have been introduced and most of them rely on radiological imaging.[13] Periapical radiographs and orthopantomography (PR) are still frequently used, but the development of three-dimensions (3D) imagery brought a new interest in this context. In fact, teeth, bones, facial sinuses among other structures are three-dimensional elements, therefore, 3D imagery is better suited for its study and Cone Beam Computed Tomography (CBCT) is one of the most interesting tools in this regard.

CBCT uses a cone-shaped X-ray beam as a source centred on a two-dimensions (2D) detector system. These both elements rotate around the part of the body examined, producing a three-dimensional image based on a series of 2D frames.[14–16] CBCT is already widely used for head and neck imaging and for diagnosis in almost all fields of dentistry including endodontics, implantology, orthodontics, periodontics and maxillofacial surgery.[15,17,18]

CBCT is a non-invasive and non-destructive method. It offers a good image quality, accurate and detailed anatomical information, rapid scan time and higher voxel resolution.[6,14,19] Compared to multidetector computed tomography it brings lower radiation dose and less artefacts.[4,20] Its radiations can be decreased by using small field of view and large voxel size (X-ray beam limitation). It allows a multiplanar scan (sagittal, axial, and coronal planes) and an accurate reconstruction without magnification from geometric distortion.[4,20,21] It is

currently more cost effective, uses relatively small equipment which permits its mobility and starts to be a routine component in dental clinical practice.[5,14]

The increasing presence of CBCT devices in dental clinics is providing valuable data that may one day prove itself crucial in a forensic context. And another important issue is also how to utilize these data. Therefore, this work proposes to look for CBCT's areas of application related to forensic dentistry.

2 OBJECTIVES

This integrative systematic review aims to provide an overview of the use of CBCT in forensic dentistry and to present the different applications of this tool.

3 MATERIALS AND METHODS

For the realization of this integrative systematic review, we did a bibliographic search on the platform PUBMED using the following combinations of keywords : *((("Cone-Beam Computed Tomography"[MeSH Terms]) OR (cbct)) AND ((forensic dentistry) OR ("Forensic Dentistry"[Mesh]))).*

The criteria of inclusion were: studies belonging to a 10-year time range, studies only made on humans and studies only published in English.

The criteria of exclusion were: studies which area of interest was not primarily forensic (for instance endodontics or implantology), studies which area of interest was not focused on the oral cavity or teeth and studies involving specific pathologies or affections.

The search with the afore mentioned keywords resulted in 115 articles. After applying the inclusion criteria, 84 articles remained. After applying the exclusion criteria, upon reading title, abstract and the article, we decided to select 41 articles.

The flow chart of study selection for our review is indicated in figure 1.

For the introduction and the discussion, we used 10 additional references we judged interesting to complement our study. Among them, 1 was American Academy of Forensic Sciences' website and 4 were systematic reviews.

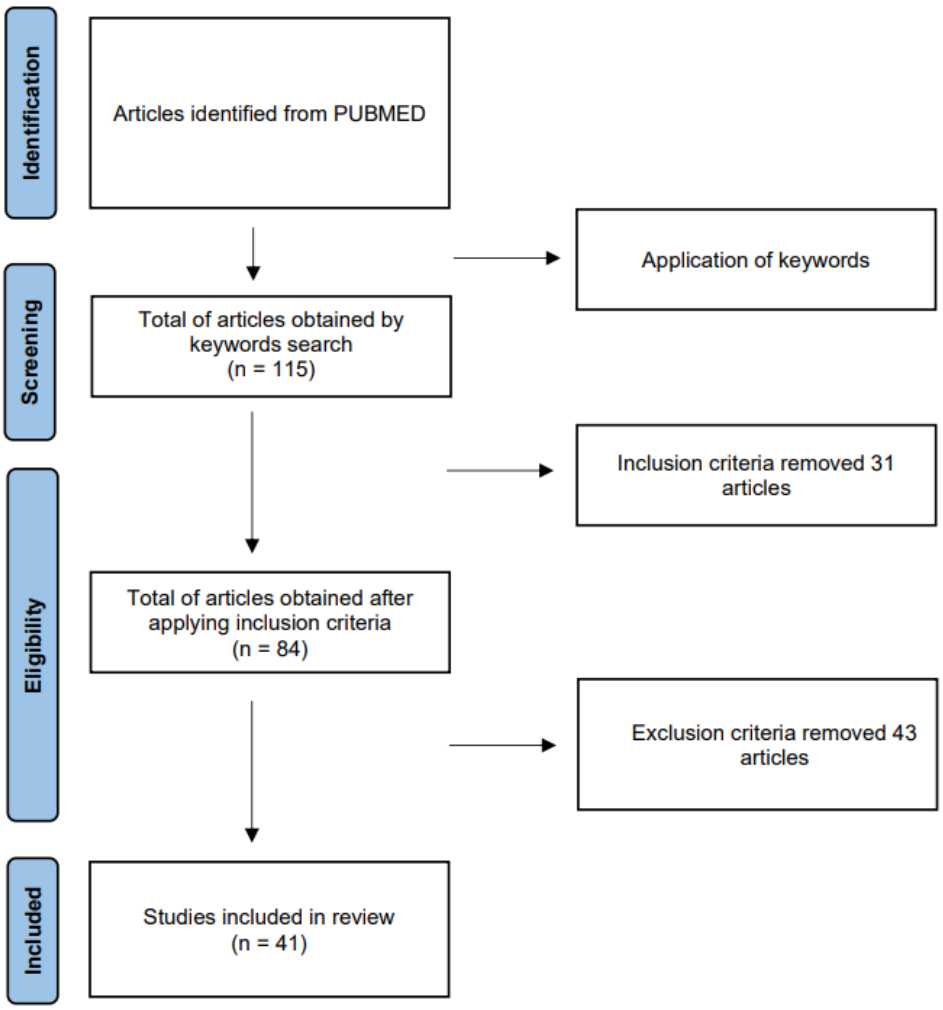

Fig 1: Flow chart of study selection for the review

4 RESULTS

Upon our corpus of 41 studies (also summarized in figure 2) :

- **8 studies (19.5%) were about comparative identification** : 2 were using mandibular midline structures as an identification tool, 4 were comparing CBCT images with classical radiographies, 1 was studying relationship between dental charting and CBCT/PR and 1 was about using a deep convolutional neural network (DCNN) for classifying teeth. They all concluded that CBCT was an accurate tool for the forensic comparative identification.

- **1 study (2.4%) was about identification of the circumstances of death** by studying the dentino-enamel junction (DEJ) migration in function of temperature and concluded on CBCT as a useful tool in this regard.

- **3 studies (7,3%) were about identification by bitemarks**: they all concluded that CBCT is an accurate tool for the bitemarks analysis.

- **18 studies (43,9%) were about age determination:**

13 of them were studying age estimation using the pulp narrowing technique. Among them, 8 were using the ratio method, 3 were using the direct pulp volumetry method (DPV), 1 was comparing these two methods, and the last one was comparing some segmentation methods in volumetric reconstruction.

1 was measuring buccal alveolar bone level (ABL) to the cementoenamel junction (CEJ). 1 was studying mandibular condyle cortication.

3 studies were based on third molar analysis : 1 was about Demirjian's method observation on CBCT images, 1 was about the application of Kohler's method on CBCT by comparison

with extracted teeth and PR and the last one was analysing the surface area of mandibular third molar apices.

Among these 18 studies, all except two, concluded on CBCT's accuracy for age estimation.

- **6 studies (14,6%) were about sex estimation**: 2 were studying the mandibula measurements, 1 was about the maxillary sinus, 1 about the paranasal sinus (in relation with foramen magnum), 1 was studying both maxillary sinus and mandibular canal and the last one was about the volumetric study of dental crown. These studies concluded that these methods based on CBCT are good elements for the sex determination.

- **1 study (2.4%) was about both age and sex estimation**: it was a study about direct pulp volumetry. This method was reported to be accurate for age and sex determination.

- **4 studies (9,8%) were about facial reconstruction:** 3 of them were based upon soft tissue thickness (STT) measures and 1 upon CAD/CAM utilization. They all underlined the value of CBCT in the facial reconstruction process.

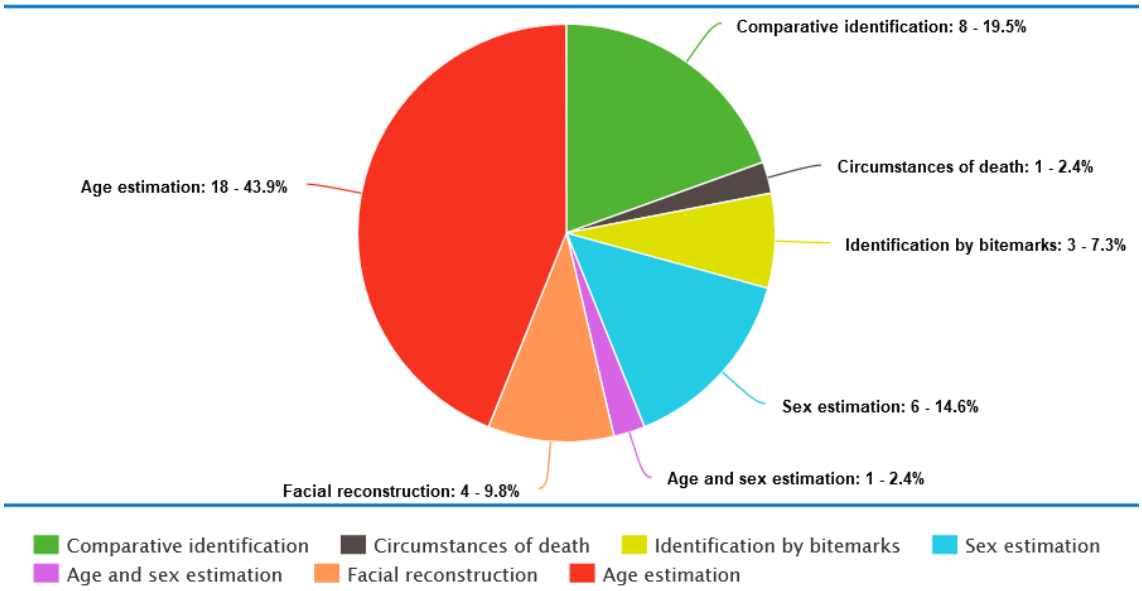

Fig 2: Distribution of the corpus according to the forensic purpose

The relevant data gathered from these included studies are presented in the Table 1.

Table 1. Relevant data gathered from included studies

Study	Forensic purpose	Methods	Origin Population	Results	Conclusion
Murphy et al. (2012)[16]	Comparative identification	Comparison between CBCT images and PR	Not specified (patients from the University Dental Hospital in Cardiff, South Wales)	Information is recorded accurately, the sensitivity being 96.6% (95% CI, 95.1–98.1) and specificity being 98.4% (95% CI, 96.2–100).	This study help validating CBCT as a tool in comparative dental identification of corpses in mass fatalities, chemical, biological, radiological, and nuclear incidents, but further studies are required on this matter.
Trochesset et al. (2014)[18]	Comparative identification	Comparison between CBCT derived images and classic intra-oral radiographies	Not specified	The images generated using this protocol approximate the overall aspect of conventional antemortem images available for forensic comparison.	The images derived from CBCT volumes following this protocol are similar enough to conventional dental radiographs to allow for dental forensic identification.

Eliášová et al. (2017)[14]	Comparative identification	Comparison between CBCT images and classic oral radiographies	Not specified	The advantages of identification by CBCT are a precise single tooth evaluation, detail panoramic image, skull volumes and the disadvantages are the presence of metal alloy artifacts	CBCT imaging addresses some limitations in forensic dental identification as quick routine scan, less image artifact, low image reconstruction times, mobility of the unit and lower equipment cost.
Curi et al. (2017)[22]	Comparative identification	Comparison between AM periapical radiographies and PM CBCT images	Brazilians	60 simulations of identification by superimposition were made, and all (100%) showed sufficient evidence for positive identification results, based on the number of individual traits of the human oral anatomy ($p< 0.01$)	This superimposition protocol is suitable (high level of reproductibility) and is advisable when antemortem records are not available at the moment of the exam.
Mowafey et al. (2015)[15]	Comparative identification	Mandibular lingual canal's analysis (AM/PM comparison)	Not specified (study conducted at University Hospitals Leuven, Belgium)	The observational part of the study showed an average 95% correct identification of the mandibular midline neurovascular structures. Perfect overlap of the same mandible from two different CBCT machine with an error distance equalling zero.	The percentage of fit for the simulated AM and PM data of the same mandible was 100%. This finding together with the significant deviations noted for the non-matching cases, may have a potential role in forensic identification.

Shaheen et al. (2017)[23]	Comparative identification	Mandibular midline lingual structures' analysis (AM/PM comparison)	Not specified (study conducted at University Hospitals Leuven, Belgium)	A significant difference was found between the "Unmatched" and "Matched" classes with means of 0.41 and 0.86 respectively. The testing phase showed an accuracy of 100%.	The mandibular midline canal structures can be used to help victim identification when AM and PM CBCT/computed tomography (CT) mandibular data are present.
Franco et al. (2019)[24]	Comparative identification	Use of INTERPOL dental identifiers and CBCT/PR	Brazilians	Differences were discrete ($p > 0.05$) between PR and CBCT scans ($p = 0.693$). In CBCT scans and PR, dependence between teeth and codes was detected ($p < 0.05$). In the study sample, the strongest associations were found between the codes unerupted (UNE), partially erupted (ERU) and impacted (IMV) and third molars, both in CBCT scans and PR.	In practice, INTERPOL coded dental identifiers registered on CBCT scans and PR can be exchanged during comparison and reconciliation of AM and PM data.
Miki et al. (2017)[25]	Comparative identification	Use of DCNN for classifying teeth	Japanese	Classification into 7 tooth types. The average classification accuracy using the augmented training data by image rotation and intensity transformation was 88.8%. Compared with the result without it, data augmentation resulted in an approximately 5% improvement in classification accuracy	This method gives high classification accuracy without using tooth segmentation and can be useful in automatic filing of dental charts for forensic identification.

Marques et al. (2013)[17]	Identification by bitemarks	Tomographic slices and 3D reconstructions	Brazilians	It was possible to perform the metric analysis and depth of the bitemarks in almost all foodstuffs. These measurements could also be obtained from the dental casts.	CBCT may become an important tool for forensic sciences, in particular, for the registration and analysis of bitemarks in foodstuffs that can be found in a crime scene.
Corte-Real et al. (2018)[26]	Identification by bitemarks	Comparison between 3D reconstruction and actual dentition	Not specified (scans obtained from Coimbra Hospital and Faculty of Medicine of the University of Coimbra, Portugal)	Protocol isn't operator-dependent (Cohen Kappa 0.690-0.910). The researchers arrived at the same observations without statistical difference. This protocol is considered accurate and non-destructive, allowing a correct study of the bitemark pattern by 3D analysis of tomographic volumes.	Bitemarks analysis can be performed with a software searching for the corresponding dentitions in a CBCT database, allowing the identification of the individuals.
Ali et al. (2018)[27]	Identification by bitemarks	Analysis of Intercanine distance and dimensional changes on foodstuffs	Not specified (study conducted on patients coming from Nair Hospital Dental College, Mumbai, India).	Teeth can transfer their characteristics to the bitten foodstuffs. The highest accuracy for comparative bitemark analysis was observed in chocolate (76.6% of excellent matching) followed by cheese (70%), chewing gum (50%), and apple (33.3%).	The CBCT-assisted analysis of bitemarks is a non-destructive, accurate, and efficient method. The CBCT documentation revealed no distortion artifacts, and subsequent analysis in 3D space is possible.

Koh et al. (2017)[28]	Age estimation	Evaluation by measuring buccal ABL to the CEJ of lower first premolars, and structural changes.	Malaysians, Chinese	98% correlation level among both observers. R^2 values for evaluation of ABL were 0.72 and 0.68 for left and right side. R^2 values for structural changes ranged from 0.19 to 0.39.	Measurement of ABL from CBCT highly correlated with chronological age. Therefore, it is suitable for forensic age estimation, not so much the structural changes.
Bayrak et al. (2018)[21]	Age estimation	Mandibular condyle cortication analysis	Turkish	The type of the condyle cortication in the right and left mandible was similar for almost each subject (no statistically significant difference, $p = 0.375$). For male, Type I cortication of the condyle was seen at 14.14 ± 2.3 years, Type II at 16.11 ± 3.18 years and Type III at 19.39 ± 3.96 years. For the female, Type I cortication of the condyle was seen at 13.01 ± 2.16 years, Type II at 15.52 ± 2.71 years and Type III at 17.95 ± 3.13 years	Chronologic age increased as the stages of the cortication process from Type I to Type III in male and female, and all the stages of the cortication in the mandibular condyle of males occur later in time than in females. Further studies should be led on different populations to achieve global results on this method.
Pinchi et al. (2015)[13]	Age estimation	Pulp narrowing : pulp/hard tissue ratio method (PHR) on upper left central incisor	Caucasians	The PHR was statistically significant (p-value < 0.001) as a predictor for age estimation. The gender variable was not significantly correlated with age ($p = 0.7694$). The age cohorts between 30-59 years showed the highest accuracy in age estimation (residual errors -0.71, 2.88, and -5.86 years). Inter-examiner agreement coefficient of 0.99.	The PHR method can be a useful tool for forensic age estimation in adult.

Nemsi et al. (2017)[12]	Age estimation	Pulp narrowing : pulp/dentin area ratio on cervical axial section (maxillary canine and mandibular second premolar)	Tunisians	Dentin deposition on canine and premolar have almost the same correlation with age (r=-0.838 and -0.837 respectively). The Residual Standard Error (RSE) for the entire sample is between 8.27, 8.29 and 7.06 for canine, premolar and for all variables respectively. For younger ages (22-44years) the RSE decreased considerably (4.32, 4.72 and 4.05).	The physiological ratio permit to assess age with a satisfying accuracy, and better in subjects under 44 years. The variability of the ratio with age is gender independent.
Uğur Aydın et al. (2019)[19]	Age estimation	Pulp narrowing : pulp/tooth area ratio (PTAR) on maxillary central teeth	Turkish	There was a significant negative correlation between chronological age and PTAR (R^2 = 0.379). The intra-observer ICC value was 0.869.	PTAR of maxillary central teeth is a reliable method for age estimation.
Marroquin Penaloza et al. (2016)[11]	Age estimation	Pulp narrowing : pulp/tooth width ratio (Kvaal et al method) on upper incisors, canine, and second premolar	Malaysians	The most accurate linear regression models from the individual analysis of the buccolingual measurements were presented for different reference points, between CEJ and root apex, using coronal or sagittal images. Linear regression models ranged between R^2=0.37, SEE=±12.84 and R^2=0.39, SEE=±12.73 years.	This accuracy is outside an acceptable range in for forensic application (SEE ±10.00 years). It is more time consuming than the original method based on dental classical radiographs.

Zhang et al. (2019)[29]	Age estimation	Pulp narrowing : pulp/enamel volume ratio (PEVR) on impacted mandibular third molars (IMTM)	Chinese	Precision and accuracy were given by the mean absolute error in the male, female and pooled sexes samples (9.223, 7.722 and 8.41, respectively) and root mean square error (10.76, 9.58 and 9.986, respectively).	PEVR is a potential index for dental age estimation in forensic context.
Gulsahi et al. (2018)[9]	Age estimation	Pulp narrowing: Pulp/tooth volume ratio (PTVR) method on monoradicular teeth	Not specified (study conducted on Ankara, Turkey)	The PTVR of all teeth ranged between 0.01 and 0.08. A negative correlation was found between the PTVR and age ($p < 0.05$). There was no significant difference in the intercept between both gender ($p > 0.05$).	PTVR was not gender dependent. The strongest correlation between the age and PTVR is measured on maxillary central incisors.
Asif et al. (2019)[8]	Age estimation	Pulp narrowing: PTVR method (maxillary canines, and maxillary right central incisors)	Malaysians	Strongest coefficient of correlation values for maxillary right central incisors (0.83) followed by maxillary right canines (0.74) and maxillary left canines (0.73). Fisher's Z test indicated that dental age estimation is gender independent.	PTVR method is a valuable indicator for dental age estimation, but errors are more frequent in the age range from 46 to 66 years.

Asif et al. (2018)[5]	Age estimation	Pulp narrowing: comparing PTVR and pulp chamber/crown ratio (PCCR)	Malaysians, Chinese	Both methods had strong correlation between chronological age and PTVR. However, PCCR method gave a higher coefficient of determination value (R^2 = 0.78) than first one (R^2 = 0.64). Manipulation using PCCR method was less time consuming and revealed higher inter-examiner reliability (0.982).	PTVR is a valuable gender independent technique and PCCR regression equation should be recommended for dental age estimation.
Porto et al. (2015)[7]	Age estimation	Pulp narrowing : DPV method and PTVR method (maxillary central incisors)	Brazilians	The DPV method and the PTVR showed significant differences between age groups ($p < 0.001$). PTVR technique yielded a negative correlation between pulp/tooth volume and age for males (R^2= 0.152; $p<0.001$) and for females (R^2=0.297; $p<0.001$). Linear regression analysis showed a coefficient of determination of 0.21	There is a weak correlation between the PTVR and age. When gender is known, the estimated age may be more reliable. The study revealed a higher accuracy for females compared to males.
Ge et al. (2015)[30]	Age estimation	Pulp narrowing : DPV method (first molars)	Chinese	The formula proposed is statistically significant ($p=0.000<0.01$). The coefficient of determination R^2 was 0.564. There is a mean absolute error of 8.122 and root mean square error of 5.603 between the actual age and estimated age for all the tested teeth.	DPV method is a useful index for the estimation of human age with reasonable precision and accuracy.

Helmy et al. (2020)[20]	Age estimation	Pulp narrowing : DPV method (second molars)	Egyptians	Significant difference in pulp chamber volume between both sexes (P-value 0.001 in maxillary teeth and 0.004 in mandibular teeth) and between different age groups (p-value 0.001).	The pulp chamber volume of the second molar is a relatively accurate indicator for age estimation and showed significant differences between sexes.
Kazmi et al. (2019)[31]	Age estimation	Pulp narrowing : DPV method (canines)	Pakistani	Mandibular canine pulp volume and sex have the highest predictive power ($R^2 = 0.33$). A statistically significant difference in volumes of pulp was found ($p = 0.000$) between males and females.	Non-linear relationship between mandibular pulp volumes and chronological age is found. The sampling technique and size highly affect the result. Including sex as a predictor improved the age estimation.
Andrade et al. (2019)[4]	Age and sex estimation	Pulp narrowing : DPV method (upper central incisor and upper canine)	Brazilians	Formulas showed good determination coefficients (adjusted $R^2 = 0.7614$ to 0.8367). For sex estimation, when the age was known, the coefficients were also good (adjusted $R^2 = 0.649$ to 0.812). However, when the age was unknown, the coefficients of the sex estimation formulas were low (adjusted $R^2 = 0.649$ to 0.812).	Validation showed high accuracy of age estimation in individuals older than 35 years, as well as high accuracy of sex estimation when the age was known.

Marroquin Penaloza et al. (2016)[32]	Age estimation	Comparison between manual and automatic segmentation (set volume boundaries) methods in volumetric reconstruction (upper canines)	Not specified (data coming from University of Kebangsaan, Malaysia, and National University of Colombia)	There is correlation among the results (r>0.75), but no evidence that these methods are sensitive enough to detect small volume changes such as the dental pulp canal. Automatic segmentation is highly susceptible to be affected by small variations in the setting parameters.	Obtained volume measurements with any segmentation method approximates the measured structure and is not the real volume. But it is worth to persevere with the research in this area for forensic purposes.
Cantekin et al. (2013)[33]	Age estimation	Demirjian's method observation on CBCT images (mandibular third molar)	Turkish	Study conducted on 9 to 25 years old people. Statistical analysis showed a strong correlation between age and third-molar development for the males (R^2 = 0.80) and the females (R^2 = 0.78).	CBCT images are clinically useful for accurate and reliable estimation of dental ages of children and youth.
Franco et al. (2019)[34]	Age estimation	Application of Kohler's method on CBCT by comparison with extracted teeth and PR in estimating third molar root development stage	Brazilians	Between PR and CBCT, the difference in stage allocation was p = 0.81 for stages 5, 7, and 9 and p = 0.80 for stages 6, 8, and 10	Kohler's method can also be applied for third molar staging in CBCT. Care must be taken in stages of late root formation, (stage 9 = apex ½ closed), due to minor discrepancies between PR and CBCT.

Asif et al. (2019)[6]	Age estimation	Analysis of the surface area of mandibular third molar apices	Malaysians, Chinese	Range age from 13 to 24 years. Strong inverse correlation (R^2 = 0.896, SD = 1.144) was observed between chronological age and all the predictor variables: ethnicity, gender, and status of the root development completion (open/closed apices). The results showed that 89.6% of the variation in age can be explained by the predictor variables.	This technique can be used as a reliable method for age estimation in adolescents and young adults.
Farias Gomes et al. (2018)[35]	Sex estimation	Maxillary sinus linear and volumetric measurements	Brazilians	Maxillary sinuses measurements were significantly higher in males, without statistically significant differences between the right and left sides. The most dimorphic measurement was the height, with an accuracy of 77.7% regarding sex estimation. The formula created lead to a sex estimation of 87.8% for females and 80% for males.	The formula developed showed an accuracy of 84% for sex estimation and can be applied as a complementary method for human identification in the Brazilian population.
Gamba et al. (2016)[2]	Sex estimation	Mandibula standard anthropometric measures	Brazilians	The six measurements (ramus length, gonion-gnathion length, minimum ramus breadth, gonial angle, bicondylar breadth, and bigonial breadth) showed an accuracy of 93.33% and 94.74% was found for estimating male and females, respectively.	The formula developed in this study can be used for sex estimation in forensic settings.

Tassoker et al. (2019)[36]	Sex estimation	Mandibular morphometry (comparison PR/CBCT)	Turkish	Two anthropometric landmarks (gonion and condylion) and five measurements (gonial angle, ramus length, maximum and minimum ramus breadth and bigonial width) were taken in account. The study showed good intra-examiner agreement PR (0.82–0.87) and CBCT (0.89–0.95). Males mostly have higher mandibular measurement values. There were statistically significant differences between CBCT and PR measurements ($p < 0.05$), with higher values for PRs.	Forensic doctors and anthropologists should consider this information in their age and gender prediction studies.
Wanzeler et al. (2019)[10]	Sex estimation	Measure of the paranasal sinus in relation with foramen magnum	Brazilians	The volumes of the maxillary, frontal and sphenoidal sinuses of female subjects were smaller than those of male subjects ($p < 0.001$).	Adult paranasal sinus volumes analysed by CBCT may be useful for sex identification when combined and correlated with foramen magnum measurements.
Gamba et al. (2017)[3]	Sex estimation	Analysis of maxillary sinus (MS) and mandibular canal (MC).	Dutch	All measurements showed statistically significant differences between sexes. Sex estimation accuracy values were 75% for MS and 71.9% for MC. When the two methods were combined, the accuracy increased to 78.5%.	The formulas developed in this study can be applied as a complementary method for human identification.

Manhaes-Caldas et al. (2019)[37]	Sex estimation	Volumetric assessment of the dental crown	Brazilians	The volumetric accuracy of the upper central incisor, upper canine and lower canine for sex estimation were 64.1%, 74.4% and 79.5%, respectively. The combined analysis of the upper and lower canines allowed an average accuracy of 83.7%.	This method can be applied for sex estimation in the Brazilian population.
Katsumura et al. (2016)[38]	Facial reconstruction	Cephalometry register and CAD/CAM utilization.	Not specified (skulls provided from Tsurumi University School of Dental Medicine, Kanagawa, Japan)	In the CBCT models: - skull A (no metallic restoration), average errors of 0.116 mm (the values are relative to the original bone size). - skull B, (small number of metallic restorations), average errors of 0.153 mm - skull C, (metallic restorations on multiple teeth including crowns, bridges, etc.), average errors of 0.224 mm	Facial reconstruction by image-reproduction from a CBCT scan is more accurate than from a helical CT scan. The "high-precision reconstructed 3D model" facilitates reliable visualization of full-sized oral and maxillofacial regions in CBCT scans.
Hwang et al. (2015)[39]	Facial reconstruction	Soft tissues thickness (STT) measures	Not specified (study conducted in Chonnam National University Hospital, Gwangju, Korea)	The measurement method of "perpendicular to bone" resulted in high inter- (correlation >0.7) and intra-observer (0.826–0.994 and 0.904–0.996 for Pearson correlation analysis and reliability analysis, respectively) reproducibility at all 32 landmarks	The "perpendicular to bone" method is believed to be a favourable result for forensic facial reconstruction.

Farias Gomes et al. (2020)[40]	Facial reconstruction	STT measures in craniofacial midline	Brazilians	In general: - STT was significantly greater in males than in females ($p < 0.05$). - Class III individuals had significantly thicker soft tissues in the maxilla while class II subjects had thicker soft tissues in mandibular landmark ($p < 0.05$). - Dolichocephalic individuals showed significantly thicker soft tissues in mandibular landmark, whereas brachycephalic subjects had thicker soft tissues in maxillary regions ($p < 0.05$).	Skeletal class and facial type influence STT, showing a soft tissue compensation, with deeper soft tissue in areas with lower skeletal development, and/or where bone is positioned more posteriorly.
Hwang et al. (2012)[41]	Facial reconstruction	STT measures	Koreans	18 of 31 landmarks showed sex differences, the majority showed higher values for male subjects (exception of a few sites corresponding to the zygoma area, which showed smaller values in male than in female). The mandibular area showed greater differences between the right and left sides.	STT measurements can be used as a database for the forensic craniofacial reconstruction
Mejía et al. (2016)[42]	Death circumstances	Relation between DEJ and high temperatures	Not specified (patients from the Universidad del Valle, Cali, Colombia)	Separation of the DEJ on the right is explained by a 40% change in temperature and that of the left side by a 64% change ($P = 0.000$). For each 200°C rise in temperature, DEJ separation widened from 0.72 - 0.76 mm	The DEJ starts to separate from the cervical towards the occlusal as temperature increases. It can be used as a parameter to estimate the temperature to which burnt, carbonized, or incinerated cadavers or human remains had been subjected.

5 DISCUSSION

5.1 Comparative identification

In forensic sciences, identification is validated from positive comparison between antemortem and postmortem data. When an unidentified body needs to be positively identified, classical comparative identification methods such as DNA genotyping, fingerprints and dental analysis are used.[14,35] Facial comparison tools based on landmarks can be used too for identification. Teeth are also relevant elements when soft tissues are damaged or in case of skeletal findings.[14] Every dental characteristic may be useful like caries, crown and root morphology, teeth restauration, presence of implants or prosthesis and abnormalities in oral cavity. Some rare variations like taurodontism are easily detectable by CBCT.[43] In some countries engaged in war, CBCT scans are taken from officers before their departure, as an identification way in case of death.[15,23]

CBCT is considered as an accurate and valuable tool in comparative identification. In 2012, Murphy et al. conducted a study comparing PR and posterior CBCT which results in a 96.6% sensitivity and a specificity being of 98.4%. They noted its strong forensic potential, the rapidity for transferring information to specialists and the fact that CBCT data can be reformatted as conventional radiographic images. It also diminishes the need of body contact (to avoid potential alteration of the rests or to prevent the investigators from possible radiations or toxins) or surgical intervention to facilitate dental examination.[16]

Moreover, it allows a precise single tooth evaluation, detail panoramic image, skull volumes and override some limitations in forensic dental identification by offering routine scanning

times below 30s, less image artifact, low image reconstruction times, mobility of the unit and considerably lower equipment cost.[14]

Trochesset et al. underlined the same advantages. They designed a protocol for comparison between PR and CBCT derived images and concluded that reformatted CBCT volumes contain sufficient anatomic information for conclusive comparison with antemortem intra-oral radiographs. It can also be noted that the 3D structure of CBCT allows, by rotation, to adapt at nonstandard angulation for antemortem radiographies.[18]

The forensic identification also works by comparison/superposition with periapical radiographies. Like with PR comparison, this protocol is accurate and highly reproductible. Curi et al. realized sixty simulations of identification by superimposition, and all (100%) showed positive results.[22]

Periapical radiographies are often taken using Clark's technique which modify the structures in relation with each other if the incidence angle is changed. PR are also subject to distortion. Whereas CBCT is more precise, and images will not appear to be elongated or shortened. Therefore, we should be careful when choosing the study angle, and we should use comparison landmarks like for example root apices, cusps, and other identifiable prominences of different volume depths.[22]

Forensic identification can be based upon a dental charting, for example from INTERPOL. CBCT can be compared to PR on these charts (no statistically significant differences between the prevalence of identifiers in CBCT scans and PR were detected). This underlines the interest and accuracy of CBCT on AM/PM comparison with PR in this case.[24]

One of the issues of this work is that dentists are often inexperienced at recording the dental chart from corpses. Therefore, Miki et al. tried to automate the process using a deep convolutional neural network for classifying tooth in seven types based on CBCT images. After improvement of the images, the protocol reached a 91% of accuracy without the need for precise tooth segmentation. To conclude, this method can be useful in automatic filing of dental charts for forensic identification.[25]

More specific structures can be helpful. It is the case of the mandible. It is the strongest bone of the skeletal face and is frequently well preserved after death. The mandible has various accessory foramina and canals, and those on the lingual side, specifically the medial ones, are called mandibular midline foramina. These structures are varied in number, size, intraosseous canal structures, morphology and moreover bring a significant anatomical variation among people. These distinctions make these midline structures unique for a particular individual.[15,23]

Mowafey et al. observed an average 95% correct identification of the mandibular midline neurovascular structures. Registration of mandibles resulted in perfect overlap (100%) of the same mandible from two different CBCT machines. For different mandibles, they observed average error distance of 0.13-0.18mm. They concluded that every mandible has a specific anatomical structure at the midline, including the lingual foramen and the neurovascular bundles. Its analysis with CBCT can be used as unique identifying feature.[15]

Shaheen et al. presented a semi-automatic CBCT based protocol to identify PM cases by comparing their mandibular midline canal structures (region of interest here) to AM cases. The manual phase is the determination of cephalometric points permitting the

identification of the region of interest. After that, the testing phase showed an accuracy of 100%.[23]

CBCT analysis can also study mental foramen (MF). MF's dimension and relative localization can offer precious information about gender, age, and dental status.[44]

In presence of AM/PM CBCT data, mandible prove itself to be a useful way for identification. Further studies are required on larger samples to develop this technique. This should help to establish a fully automated protocol, or study more unique anatomical landmarks.[15,23]

5.2 Bitemarks analysis

Bitemarks are records of teeth on skin or on deformable substrates.[26] It is a 3D dynamic phenomenon implying the action of teeth, the position of the tongue, the relation between dental arches or the biter's intention.[26] Its forensic value on foodstuffs depends on the nature of bitten surface, the deformation from temperature, and accuracy along with time.[27]

Bitemarks on foodstuff provide a 3D imprint of the suspect's dentition.[27] It can be useful in cases of physical/sexual aggression may it be on human skin or on the food which remains on the crime scene. It can also complement a DNA genotyping procedure.[26]

Basically, it consists in a comparison between the bitemark and existing data to identify the suspect or, at least, to reduce the search. Corte-Real et al. have proposed a protocol based on superimposition based on the correspondence of 4 landmark points (interdental incisors contact points at 2-3mm from the incisal edge). This pilot study opens the door to future investigations.[26]

As a bitemark analysis method, CBCT does not depend on the substrate. It is a non-destructive method as it does not affect the biological material available.[26] We can observe that analysis in inanimate objects and foodstuffs seems to offer more reliability than in the skin.[45]

There are three properties that can be observed

- Transfer of teeth's unique anatomical feature on the bitten zone: CBCT allows to distinguish the two arcades, intercanine distances, the shape of the arch, diastema, or teeth misalignment among other elements.[17,26,27]

- Composition of the food: the more heterogeneous the food (i.e. components are not uniformly distributed or have localized regions with different properties), the more difficult it will be to analyse the bitemark (for exemple, the pizza in Marques et al.'s study).[17,26,27]

- Minor changes on the same bitemarks for different time intervals for all foodstuffs, but it isn't statistically significant (baseline, 3 hours, 6 hours). It may be due to the composition of the food : for instance a poor accuracy of bitemark is registered on apple (firm and porous substrate and its dehydration and decomposition at room temperature) whereas a good accuracy on chocolate, cheese, and chewing gum (due to homogeneity). It is believed that these small differences would not affect the identification of the suspect in a crime scene.[27]

These studies concluded that CBCT-assisted analysis of bitemarks is a non-destructive, accurate, and efficient method. But some issues can be noted: orthodontic treatment can bring matching errors between treated and naturally well-aligned dentitions.[26] The accessibility of CBCT equipment can also be a problem, regarding time alteration of foodstuff and from a logistical point of view.[26]

5.3 Age estimation

Age estimation is an essential part for biological profile determination in a forensic context, or even in civil, law and judicial issues, for instance to determine if one is minor or not, or in illegal immigration.[4,6–8,12,13,21,28,29] Main dental age estimation methods are based on the developmental, morphological, and biochemical tooth changes, but CBCT allows a 3D and non-invasive analysis.[9]

One of the most used method for age estimation is the pulp narrowing, and most of the studies we got from bibliographic search are concerning this technique. After tooth development and eruption, closures of the apices and start of dental function, secondary dentin begins to deposit on the pulp, produced by odontoblasts. This phenomenon act during all the life and results in a progressive decrease of the pulp volume.[12,13,19,20,31] It seems to follow a non-linear relationship with chronological age[31], but several studies approximate it with a linear regression model.

The pulp is a 3D structure and used to be studied by 2D radiographies (in absence of well-developed 3D imaging), bringing distortions issues. Nowadays, CBCT proved to be an accurate way to analyse pulp narrowing for age estimation; volume analysis is preferred

over surface or linear measures because secondary dentin deposition (SDD) is not homogeneous all over the pulp.[6,20]

Two techniques are used for this purpose : the ratio method and the direct pulp volumetry. The ratio method has the advantage to compensate the distortion or magnification errors. Various ratios are used and the most common is the pulp/tooth volume ratio (PTVR), but sections can be studied as did by Nemsi et al., using axial sections of the cervical region.[12] Likewise, Marroquin et al. tried to apply Kvaal's method (originally based on periapical radiographies) on CBCT images. They concluded that this approach was not in an acceptable range for forensic application, did not improve the results and was also more time consuming that the original method.[11] Asif et al. (2018) compared a PTVR with a PCCR and concluded that the second approach is more accurate.[5]

Teeth volume alterations are not only due to age. Enamel decrease can be associated to various exterior factors as attrition, abrasion from chewing, diet, or occlusal stress which can interfere in the age estimation calculation.[7,12,29] Enamel exclusion of the ratio could also be relevant because it doesn't follow pulp morphology as dentin does.[13] One study concluded on a weak correlation of PTVR with chronological age, explaining it by tertiary dentin deposition due to external stimuli, others influences or habits, like bruxism.[7] We can note that these adjustments are not necessary on included teeth analysis as mentioned by Zhang et al.[29]

This is why direct pulp volumetry can be an interesting alternative as it permits to avoid these interferences. SDD is directly related to the pulp and its study might be easier due to a high image contrast between pulp and dentine.[9,13,30] But we should note that people of

the same age do not systematically have the same pulp volume.[29] Dental history should be carefully reviewed as the pulp can variate with orthodontics treatment for instance.[31]

About which tooth is the most interesting for pulp narrowing analysis, some conclusions can be drawn from the analysed works.

Maxillary central incisors are an interesting option for age estimation. They have shorter length than canines, large pulp cavity with unique and straight canal. This permits a simpler and quicker delimitation and radiographical analysis.[7,8,19]

Canines have few internal anatomical variations.[4] Some studies suggested a better SDD in canines than in other teeth with smaller pulps; for instance lateral incisor. Smaller monoradicular teeth may lead to less clear images and, therefore inaccurate pulp analysis.[9] Maxillary canines of both sides are equally effective for age estimation[8], but mandibular canines showed stronger relationship with chronological age in comparison.[31]

For Nemsi et al., left maxillary canine and lower left second premolar have the longest functional survival rate in the mouth and have the largest pulp area among single-rooted teeth.[12]

Molars can also be used. For Ge et al., first molar's analysis provides reasonable precision and accuracy.[30] Second molars can be interesting for its morphological stability and lesser caries and attrition compared to first molars.[20] Moreover, a study from Ge et al. concluded that among the 13 types of teeth, second molars were the best for age estimation.[46] They have a wide pulp chamber which allows a good delimitation of the borders. Their posterior positioning in the oral cavity permits a clear and accurate 3D analysis.[20]

For third molar, CBCT allows the application of Kohler or Demirjian's method, analysing the stages of development of the teeth.[33,34] It is also possible to study the apices.[6] Third molar is the only tooth still in development in young adults, which permits to classify people between adults (more than 18 years old) or minors (less than 18 years old) and be useful for administrative or legal issues.[29,33,34] Third molar variates in function of ethnical groups. IMTM is also an interesting subject because it is free from exterior influence (diet, chewing, abrasion, contact with other teeth and metabolic alterations).[29]

About impact of sex, seven studies concluded on a not statistical significative difference between sexes.[5,8,9,12,13,19,29] On the contrary, five studies revealed a statistical significative difference and recommended to add the sexual factor to the equations, for a higher accuracy in age estimation.[4,7,20,30,31] In fact, size of the teeth may be smaller in females, which could result in a smaller pulp chamber size.[20] For Kazmi et al., sexual dimorphism in the pulp volume is obvious from juvenile age and remains throughout the life, but narrows in old age.[31] Greater samples might be necessary to clarify gender's role on this subject.

In their review of 2017, Marroquin et al. concluded that pulp/tooth area ratio calculation from monoradicular teeth (using a non-linear model for SDD) as a the most reliable, easy, faster, and predictable method for dental age estimation in adults. They suggested a sample size of at least 120 participants to obtain more reliable results. For them, methods based on volume calculation are time consuming and still need improvement.[47]

Age can also be estimated by CBCT using the ABL. Koh et al. studied it by measuring distance from cemento-enamel junction to the highest point of buccal bone on lower first premolars, obtaining R^2 values of 0.72 and 0.68 for left and right side respectively.[28]

Bayrak et al. investigate a relationship between the condyle cortication and chronologic age. They concluded that chronologic age increased as the stages of the cortication progress, both in male and female (with all the stages occurring later in time in males than in females).[21]

5.4 Sex estimation

Sex is an essential part of the biological profile and various methods exist to determine it. Capitaneanu et al. concluded that biochemical analysis was the most accurate odontological sex estimation method but underlined its limitations in forensic practice (availability of the biochemical products, cost, and logistical issues).[48] Thus, radiographical examination like CBCT can play an important role for sex estimation.

Tooth itself is a valuable tool for CBCT analysis. Generally, male teeth have larger diameter.[37] The pulp cavity volume analysis (when the age is known), allows a good sex estimation (which is less precise when age is unknown).[4] The crown itself, with enamel and dentin, has been studied by Manhaes-Caldas et al. and showed that combined analysis of the upper and lower canines allowed an average accuracy of 83.7%.[37] These hard tissues dimorphism in crowns can be explained by the fact that chromosome Y promotes both amelogenesis and dentinogenesis, whereas chromosome X only affect dentinogenesis. This may be why men have bigger crowns than women.[37]

Canines are reported to be teeth with higher sexual dimorphism, in particular mandibular canines due to their stronger resistance to periodontal disease or severe traumas.[37]

Other structures as mandibular canal (MC) and maxillary sinus (MS) can be examined by CBCT.

Sex estimation based on craniofacial features is unreliable until the post-pubertal period due to hormonal influence, thus adults' subjects are preferred in sample constitution.[35]

As mentioned before, mandible's analysis by CBCT is a good way for forensic identification, notably by its sexual dimorphism. The following groups studied this aspect:

- Gamba et al. (2016), studied six measurements (ramus length, gonion-gnathion length, minimum ramus breadth, gonial angle, bicondylar breadth, and bigonial breadth). Four of them (bigonial breadth, ramus length, bicondylar breadth, and gonial angle) showed better results for sex estimation. The measurements for males were higher than those for females. Based on this, they developed a formula for sexual prediction, which reached an accuracy of 85.45% (male estimation) and 92.96% (female estimation).[2]

- Tassoker et al. also observed that males have a larger mandibular morphology. They noted higher values on PR than on CBCT due to distortion which can affect the measures.[36]

- In their 2017 study, Gamba et al. studied more specifically the mandibular canal. They designed a formula for sexual prediction of 75% of accuracy.[3]

Maxillary sinus is a structure that remains intact even after extreme events, and thus is forensically interesting.[35] There is a difference between sexes on MS's size, with male's MS being bigger than women, but without statistically significant differences between the right and left sides.[3,10,35] Various studies under CBCT examination were led:

- Gamba et al. (2017) designed a formula for sexual prediction of 71,9% of accuracy.[3]
- Wanzeler et al. examined 163 subjects and observed a significant difference between men

and women regarding the volume of the MS ($p < 0.001$) on 84.66% of the sample.[10] - Farias Gomes et al. also designed a formula which reached an overall accuracy of 84%.[35]

This sex estimation method seems to show better results when combined with other methods based on other anatomical structures. For instance, when Gamba et al. (2017) combined their MC and MS methods, the accuracy increased to 78.5%.[3] Same goes for Wanzeler et al., using paranasal sinus measurements (and not only MS), they rise the sex estimation up to 96.2% and 92.7% for males and females, respectively. When correlating such values with foramen magnum measurements, sex identification chances increase to 100%.[10]

5.5 Facial reconstruction

Facial reconstruction is a technique that aims to reproduce unidentified or lost facial features of the cranium of an unknown person. The objective is recognition by family/relatives or at least reduce the numbers of candidate subjects.[40] This technique is more a recognition tool than an identification tool and can be useful to complement other primary methods (DNA analysis or dental records, for instance) or as last resort when other methods cannot be used to identify skeletal or human remains.[40]

Usually, soft tissue thickness (STT) is often determined by ultrasound system, which has its advantages in cost and accessibility, but is time-consuming and additional measurements cannot be made later.[39] The recent use of CBCT bring some advantages as the repeatability and confirmation of the measurements.[41]

This forensic tool is based on the study of skull morphology and facial soft tissue and CBCT gives us information about both soft and hard tissues.[39]

Various landmarks are localized in the oral cavity or in nearby structures as mandible.[38–41] Katsumura et al. have studied a comparison between a 3D model of the face reconstructed by CBCT and the actual skull based on the evaluation of 47 landmarks (some of them on the mandible and maxilla). They observed that CBCT is capable of reproducing measurements close to those of real skulls, and therefore prove itself as an excellent tool of reproducibility in the context of dental use or investigation of narrow areas like the oral cavity. The presence of metal artefacts may influence slightly the results ($p=0.005$ versus $p=0.011$).[38]

Hwang et al. (2015) determined that the most effective method for STT determination is the "perpendicular to bone" method : the point of reference is the hard tissue landmark, and the soft tissue corresponding landmark is determined as to meet the line starting perpendicularly from the hard tissue point. This method has also high inter- and intra-observer reproducibility at all 32 landmarks. The reason might be because landmark determination is clearer and more objective on hard tissues than on soft ones. They concluded that CBCT allows the high reproducibility of STT study on living subjects.[39]

Farias Gomes et al. have studied the differences in STT in function of the skeletal and facial type. They concluded that class III or brachycephalic individuals had thicker soft tissues in regions of the maxilla, while class II or dolichocephalic subjects had thicker soft tissues in regions of the mandible.[40]

It can also be noted that facial reconstruction by CBCT evidences sex differences. Farias Gomes et al. demonstrated a STT significantly greater in males than in females for all measured regions, except for the pg-pg' (pogonion-pogonion') landmark.[40]

Hwang et al. (2012), observed that 18 of 31 landmarks showed sex differences with the majority presenting greater values in men, except for a few landmark sites corresponding to the zygoma area (smaller values in male than in female).[41]

About the limitations of these studies, the BMI or body mass of the patients should be included as a factor. Its influence in the STT of the face has been proved in the literature.[40]

5.6 Ancestry estimation

Determination of ethnic group is important for forensic identification. In fact, tooth morphology is affected by genetics (and therefore hormonal and ethnical factors), diet, climate and environmental factors.[19]

Information about CBCT application in ancestry estimation is the most limited part in this work; no study was found using CBCT images of dental traits or cranial features involving jaws for ethnical estimation purposes. Despite all these studies are only representative of the specific ethnic group they are led upon, they are interesting. Ethne can, however, influence other biological parameters, mainly age estimation, and lead to an inaccurate analysis if formulas, specific of a certain population, are applied on other population. The strength of correlation can vary among populations due to different geographical and ethnical origins. Therefore, each population must have their own regression equation for dental age estimation of their adult people.[5] Further research is essential to assess and compare differences between teeth groups, measurement techniques and populations and to confirm the universality of application of these methods.[9]

As demonstrated before, CBCT can bring same information as PR or periapical radiographies. We believed that forensic ancestry markers observable on PR or on periapical radiographies, might be seen and analysed on CBCT images. Further studies are necessary on this subject.

Finally, figure 3 reflects the percentages of the populations where the studies discussed in this work were carried out.

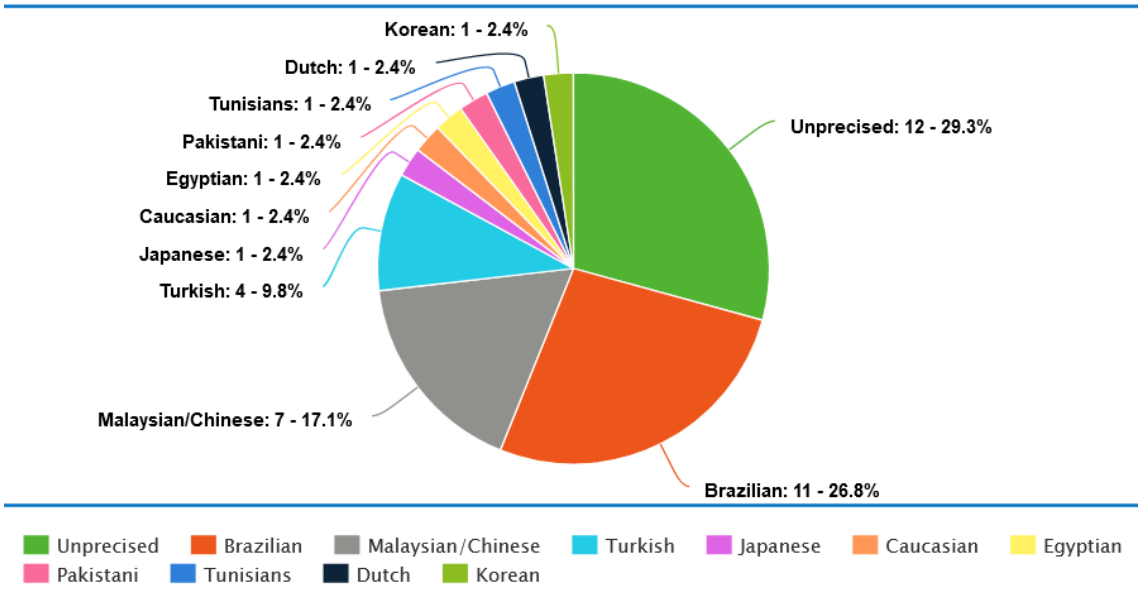

Fig 3: Repartition of population origin in our corpus' studies

5.7 Death circumstances

CBCT also permit to study some death circumstances. For instance, in death from high temperatures, Mejia et al. determined that a gradual separation of the DEJ, moving in a cervical/occlusal direction, was initiated between 200°C and 400°C, and became more obvious as the temperature increased, until total separation was reached at 1000°C.[42]

5.8 Limitations

One of the well-known limitations of CBCT is the appearance of artefacts in the presence of metallic materials, such as those that appear in restorations or crowns when reconstructing 3D images, in the regions above and below the plane of rotation of the source of X-rays.[14] It affects maxillofacial area analysis, limits diagnosis, and can be annoying because all of this information is useful for forensic identification when compared to AM data, even if the comparison process is not based solely on that.[14,38,49] This influence is more important on posterior metallic restorations whose margins become difficult to define in the CBCT scans.[16]

This is a beam-hardening artefact, due to high-density materials (dental implants, restorations, intracanal posts…).[49] Image quality and artefact presence can also be related to patient movement during scan time which can be relatively long (15–20s up to 40s).[50]

This issue caused several studies to exclude cases of metallic alloys in teeth due to the presence of artefacts, which brought them to be less representative of reality.[4,11,19,25,29–31,35,40].

To prevent artefacts influence, Katsumura et al. tried a protocol using 3D dentition data in complement of CBCT data and concluded on its efficiency.[38] Geometric adjustments to the

X-ray tube and detector can limit artefact occurrence. Complement of 2D images reformatted from the original data set can also help.[16]

We could say this problem could be less of an issue in the future, as many people would have mainly composite-type restorations, but the presence of amalgam, other metallic restorations and implants will be enough present for it to continue to be a problem.[18]

When using CBCT, it is necessary to understand its characteristics, its acceptable range of error, and the possibility of artefacts, even if it was not considered to be a major problem.[16,38] It should also be noted that these artefacts are not or hardly affected by the milliamperes (mAs). Regardless, efforts should be taken to minimize mAs instead of relying on a default setting. In fact, clinical image quality often remained acceptable at exposure levels below the manufacturer's recommended setting. Currently, it is not possible to determine minimally acceptable levels for image quality that are applicable to multiple CBCT models.[50]

As mentioned before, more studies should be led on this subject, and not only for the ethnical factor. Samples should be larger, less exclusive, and more representative of the reality. Studies should assess every tooth for comparison purpose and therefore, determine more accurate conclusions, in relationship with global factors as ethne, sex, age and environment.

In their systematic review, Matsuda et al. pointed out a logistical default during mass disasters management because of the requirement for expensive equipment on a large scale, even if CBCT is less expensive than conventional CT.[51]

Forensic sensibility should be included in dentists' formation as they play an essential role in antemortem data collection.[25] They should be trained for data record, organization, and comparative identification. An efficient network should be put on place for a fluid communication between all parts in case of need.

6 CONCLUSION

With the development of 3D imagery, CBCT is gaining more and more interest: it is a non-invasive, rapid, and low irradiative process. It is already widely used in dentistry field, and as can be seen, its application in forensic odontology is promising.

- CBCT's images are accurate for detailed structures analysis. They allowed a comparative identification process, even with periapical and panoramic radiographies. They are also useful for bitemark analysis. They permit to gather information for reconstructive process like age estimation, mainly by using pulp narrowing method. It is also accurate for sex estimation or facial reconstruction.
- CBCT's promising potential should led to further studies upon ethnicity estimate in particular. Larger and less exclusive samples should be used for more representative results.
- Dentists and forensic odontologists should be trained to understand CBCT's technical limits as well as managing artefact presence. In a more logistical way, they should know how to organize and share these valuable antemortem data.

The growing presence of CBCT technology in dental clinics makes available a huge presence of data. To our knowledge, it is the first integrative systematic review led on this precise subject. This review gives a global field of view about CBCT's application in forensic odontology and also points out the need to lead further studies because of its great potential and all the advantages that it provides.

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