

Research dynamics in the applicability of radiological mandibular parameters for forensic sex and age estimation: A systematic review

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Abstract

INTRODUCTION

The mandible is the largest and strongest bone of the human facial skeleton. The absence of any overlying bony structure makes it suitable for radiological imaging in both living as well as deceased or skeletonized individuals. In this systematic review we aim to aid forensic practitioners in making informed decisions about the techniques and parameters involving the human mandible to ensure high quality and credibility of forensic analyses needed for medico-legal as well as humanitarian purposes.

AIM

Our review investigates the research dynamics and utility of radiological mandibular dimensions for forensic sex and age estimation.

METHODOLOGY

Out of 175 articles obtained from scientific databases including PubMed, Google Scholar, Web of Science and Scopus, 55 full-text articles were found eligible for this systematic review. The articles were extracted systematically considering the authorship, year of publication, country, population studied, the mandibular parameters and radiological modality used, sample size, and age thresholds of the subjects.

RESULTS AND DISCUSSION

The maximum number of studies (60%) used radiological mandibular dimensions for sex estimation and 38% researchers estimated both sex and age from these parameters. 69.1% (n=38) articles used panoramic radiographs, 21.8% (n=12) articles utilized cone beam computed tomography/computed tomography scans and only four articles used cephalometric scans for sex and/or age estimations. Orthopantograms (OPGs) were found to be the more commonly used imaging modality in clinical practice. The majority of studies reported mandibular ramus height as the most reliable parameter for sex and age estimation. Fewer than



Original article

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half of the studies reported accuracy percentages of their estimations; around 70% of them reported accuracies below the acceptable forensic thresholds, thus clearly indicating that sex and age estimation should not be performed based on mandibular measurements only.

CONCLUSION

This systematic review is expected to inform future forensic anthropologists that only mandibular morphometry should not be attempted for human identification in medico-legal contexts.

KEYWORDS: Forensic anthropology, identification, mandibular radiological parameters, mandible morphometry

Introduction

Estimating sex and age-at-death, reconstructing stature and deciphering population affinity are the important components of biological profile of an individual's identity in forensic anthropology (Bhatnagar & Pokhrel, 2013). Forensic anthropological analyses provide crucial details about the identity credential of unknown human skeletal remains retrieved from different contexts (Arthanari et al., 2022), and such analyses may help medico-legal experts in their investigations and bringing closure comfort to the families of the deceased. Human remains need to be accurately identified and linked to the missing persons or the victims of crimes or disasters (Huomonen et al., 2010). In different instances of mass disasters, the human bodies or remains are often found unrecognizable, heavily damaged, commingled and fragmented, thus establishing identity of such remains become challenging for the experts (Jambunath et al., 2016).

The mandible is the largest and the most robust bone of the human facial skeleton (Breeland et al., 2025) and is considered as one of the most sexually dimorphic element of the craniofacial skeleton. It is the exploitable shape and size, patterned growth indicators, dense and compact nature of mandible which render it as the commonly preserved and most studied part of human skull for forensic anthropological purposes (Kumar et al., 2016; More et al., 2017). Owing

to the basic structural characteristics associated with mandibles such as dense cortical structure and resistance to post-mortem damage, this facial bone is frequently recovered intact in different situations involving fragmentation, burning, or damage/fracture; mostly encountered in mass disaster incidents. Considering its durable morphology and conveniently measurable morphometry, it qualifies as a valuable skeletal element for forensic identifications, particularly in sex estimation (Abu-Taleb & El Beshlawy, 2015; Behl et al., 2020; Kumar et al., 2016).

Sexual dimorphism of the mandible is reflected in its shape and size with male bones generally being bigger and more robust than the female bones (Raj & Ramesh, 2013); its patterned growth indicators may also provide some valuable clues about age of an individual. Its morphological features may contribute to discern the age, sex and population affinity and, thus identity of an individual, though it may be influenced by the dietary habits and age-group of the individual (Al-Shamout et al., 2012). Forensic anthropologists analyze the well-marked mandibular features such as chin profile, ascending ramus pinching, mental foramen, mandibular torus, gonial eversion, dental structures and pathology, and some other morphological and metrical features. Different mandibular measurements (measured on the bone or its radiological images) have been used for identifying the living as well as the skeletonized individuals. The ease of taking radiographs of mandible is a key

factor for choosing it for radiological examinations in forensic scenarios (Kumar et al., 2016; Shamim et al., 2006), though the shadow from some overlying structures (like zygomatic bone and vertebral bodies) may disrupt correct imaging or its analyses. Various panoramic mandibular parameters have offered multifaceted deep insights into age and sex estimations and the assessment of population affinities (Zangouei-Booshehri et al., 2012), particularly in cases of mass disasters, exhumed remains, mutilations, and missing person scenarios where severely damaged, burnt and fragmented human remains are available for biological profiling purposes.

Different linear and angular parameters/dimensions of the mandible have been recorded by various researchers using different radiological techniques like panoramic radiographs (OPGs), cone beam computed tomographs (CBCT), cephalograms and others. Among these parameters, the mandibular length, ramus height, ramus width, mandibular angle, mental index, coronoid height, mental eminence and symphysis width stand out for its diagnostic potential for different forensic purposes (e.g., Abu-Taleb & El Beshlawy, 2015; Ingaleshwar et al., 2022; Kanya et al., 2017; Karmarkar et al., 2023; Meleveetil et al., 2020). The two-dimensional (2D) modalities like OPGs have been found easy to use, cost effective and more informative to analyze mandibular skeletal features. Also, oral OPGs have been reported as one of the most common imaging methods for routine examination in clinical practice (More et al., 2017). One study reported that orthopantomograms (OPGs) are a useful tool for the measurement of mandible, though there are some magnification and distortion issues with the use of OPGs for forensic purposes (Indira et al., 2012; Kumar et al., 2016; Sambhana et al.,

2016). On the other hand, three-dimensional (3D) modalities such as cone beam computed tomography (CBCT), have been widely used for procedures such as dental implants and orthodontic treatment. Cone beam computed tomography can be considered advantageous due to its high spatial resolution, short scan time and rapid image acquisition. Cone beam computed tomography also provides accurate and reliable linear measurements, making it especially valuable for the evaluation and reconstruction of dental and maxillofacial structures. Furthermore, it enables three-dimensional reconstruction of mandibular features with minimal distortion and negligible magnification, thereby allowing precise and dependable assessment for age and sex estimation (Abd Elsalam et al., 2019; İlgüy et al., 2014). Digital orthopantomograms (OPGs), on the other hand, have been widely utilized in forensic investigations due to their accessibility and routine use in dental practice. Their applicability is attributed to their ability to capture broad maxillofacial structures with relatively low radiation exposure. Several studies have reported that OPGs provide reliable and reasonably accurate linear and angular measurements for mandibular morphometric assessment, owing to their relatively uniform magnification and minimal distortion (Ayesha et al., 2022; Sambhana et al., 2016). The conventional 2D or 3D CT is a valuable imaging technique used for forensic identifications, offering numerous advantages over the traditional radiological projections. These advantages may range from eliminating structural superimposition to visualising subtle density differences, with a strong capacity to generate accurate 3D reconstructions that have the ability to enhance forensic anthropometric measurements and individual identification (Kallalli et al., 2016).

In this study we conduct a systematic literature review to identify the most accurate and reliable mandibular parameters for age and sex estimation, to report the imaging techniques that provide the highest accuracy, and to evaluate and quantify the associated geographic variations in different mandibular parameters. The main aim is to highlight the current research dynamics in the application of mandibular radiological dimensions for forensic anthropological sex and age estimations using different radiological modalities and, to identify any consistent patterns, discrepancies, under-researched areas, prospects and directions in the field.

Material and Methods

Search strategy

A comprehensive search of scientific literature, published from 2010 to 2024, was carried out from databases of scientific search engines of PubMed, Google Scholar, Web of Science and Scopus. A time-frame of 15 years was selected to study methodological consistency and research trends in a specific time duration. As the application of radiological imaging modalities in forensic anthropology increased with the advent of CT and CBCT imaging, as well as with the improvements in voxel resolution and radiological measurement techniques, focus was on radiological mandibular parameters (McCollough & Rajiah, 2023; Patyal & Pandey, 2023; Sehrawat & Ahlawat, 2023). The search strategy included a combination of keywords and Boolean operators like “mandibular parameters”, “sex estimation”, “age estimation”, “radiological method”, “panoramic radiographs (OPGs)” and “cone beam computed tomographs (CBCT)”. The search strings used were “sex” and “age”, and “estimation” and “from” and “mandibular” and “param-

eters” and “using radiological” and “techniques”. To enhance the search strategy, the above said keywords focusing on the anatomical mandibular aspects, forensic purposes, imaging modalities, and variations in radiological methodologies etc., were employed. Furthermore, Boolean operators (such as AND, OR) were applied in combination with the search terms to maximize the sensitivity and specificity of the search; the non-Boolean linking words (such as prepositions) were not treated as part of the Boolean operators, though they might have been included as part of the titles or abstracts of the indexed articles. The extracted references obtained from the literature search were imported into Mendeley Reference Manager v2.115.0 desktop application and any duplicates were removed using the ‘merge’ option under the ‘duplicate items’ section.

Inclusion criteria

Original research articles that used mandibular parameters for sex and/or age estimation based on radiological methods like OPGs, CBCT scans or panoramic radiographs were included in the study. Studies providing detailed methodological descriptions and statistical analyses, conducted with individuals from diverse geographical regions, using varied research designs and published in forensic journals during the considered timeframe (2010–2024) were considered.

Exclusion criteria

Articles describing case reports, reviews, editorials or conference abstracts/proceedings, and pre-prints were excluded from consideration in the present study. Articles not available in full-text, written in language other than English, having insufficient methodological details and reporting high error rates/bias were ignored

for inclusion in this systematic review. Finally, full-text articles/studies not mentioning the sample size and those presenting incomplete data were also excluded.

Study selection and data extraction

Data were collected in three different stages. Firstly, studies were identified from the scientific databases using keywords as outlined above. Studies mentioning mandibular measurements like gonial angle, ramus height, coronoid height, and condylar height in analysis were considered

for further evaluation as these parameters had reported consistent and statistically significant sexual dimorphism in mandible (Abd Elsalam et al., 2019; Esfehiani et al., 2023; Kallalli et al., 2016; Sambhana et al., 2016). Data from the selected articles were extracted in a systematic manner which included: authorship, year of publication, country/geographic region, population studied, mandibular parameters/measurements used, radiological modality utilized, sample size and age ranges of the study subjects (Table S1, Figure 1).

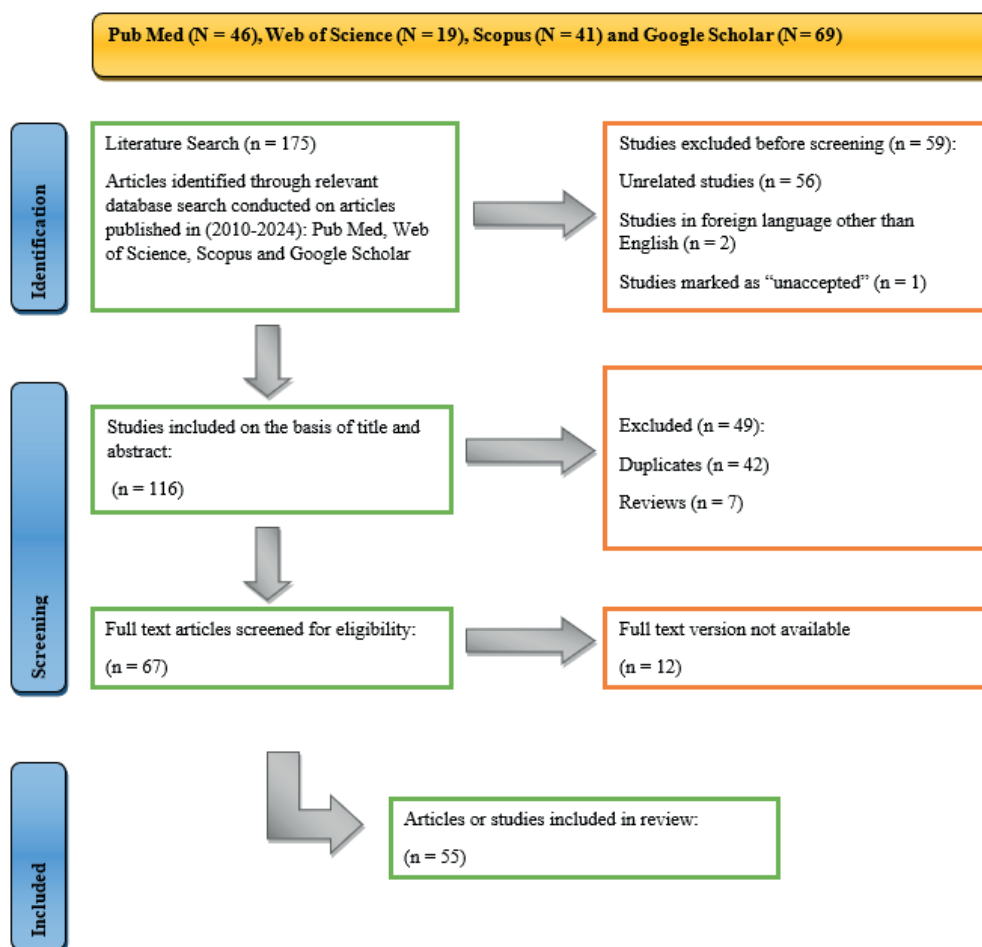


Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA flowchart showing exclusion and inclusion criteria of studies in the present systematic review.

Quality assessment/ Risk of Bias (ROB) Assessment

The methodological rigor of the included studies was assessed using the Joanna Briggs Institute (JBI) Critical Appraisal Checklists, as they are an internationally recognized tool for assessing the methodological quality of systematic reviews (Moola et al., 2020). This tool is structured in such a manner that specific criteria are enhanced through its design which increases transparency, reproducibility, and comparability across studies. Furthermore, this tool evaluates eight domains including clarity of inclusion criteria, description of study setting, validity and reliability of exposure measurements, identification and management of confounding factors, outcome assessment, and appropriateness of the statistical analyses used (Moola et al., 2020). Each study was independently evaluated by two reviewers (JS and ST) and categorized as having low, moderate, or high risk of bias, based on the number of criteria fulfilled. Each item was scored as "Yes" (1), "No" (0), or "Unclear" (0). The study quality assessment level was calculated as the number of "Yes" responses, as studies scoring 7–8 were considered having low risk of bias, 4–6 moderate risk, and ≤ 3 as having high risk. Inter-reviewer agreement was substantial (Cohen's $\kappa = 0.86$). Furthermore, any disagreements or discrepancies were resolved through discussion, with arbitration by a third reviewer (SS or MT) when necessary.

Results

Study selection

The search through four databases and concerned literature identified 175 articles; out of which 59 articles were ex-

cluded being outside the scope of this review, thus a total of 116 articles were selected based on screening of the titles and abstracts. Further, 49 duplicate and review articles were excluded from the sample data, thus 67 eligible articles were zeroed in for full text screening. As full-text versions of 12 articles were unavailable, a total of 55 articles were finally considered for the systematic review in the present study (Figure 1).

Population Characteristics

Sample Size categorization

Varied sample sizes were used by different researchers for their studies and categorized the study population into male and female categories; though some researchers did not mention the sex category in their sample size (see Table S1 for all the articles). Among the 55 studies included in the systematic review, only 12 studies stratified the samples into distinct age-groups to evaluate age-related variations in the mandibular parameters. Further, several other studies stated that mandibular morphology changed with the progression of age and emphasized that age-based categorization has the potential to improve the accuracy and interpretability of the mandibular parameters, even if they did not formally apply the age stratification in their analyses (Arthanari et al., 2024). Out of 55 studies included in this article, 38 authors mentioned the sex and/or age of the individuals of the sample size used by them. The age-group categories used were sub-adults, adults, children and old individuals.

Imaging Modalities Employed

Among the 55 studies, OPGs were used by 38 researchers, 12 studies utilized CBCT/CT scans whereas only 4 authors

reported use of cephalometric scans for recording the mandibular parameters/dimensions in their research work; only a study used both OPG and cephalometric scans for a comparative analysis of two modalities in forensic sex estimation (see Table S1). In Figure 2a, the number of articles/publications using each modality

(CT, MCT: multi-slice computed tomography, CBCT, are shown. Researchers used either 2D or 3D radiological modality for measuring different mandibular parameters; the former includes cephalometric scans, orthopantograms whereas CBCT scans were used as a 3D modality.

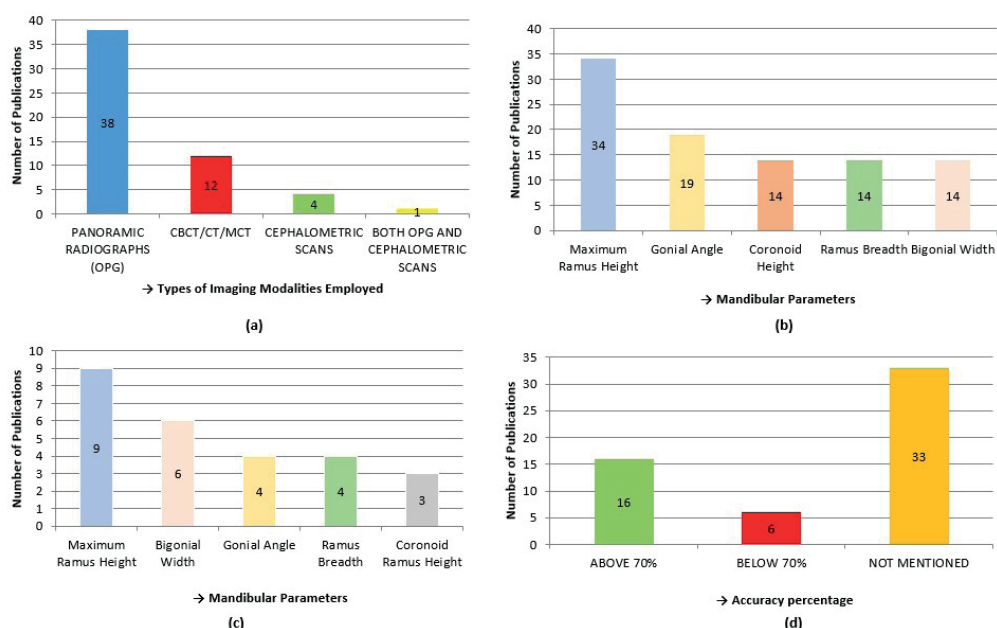


Figure 2. Graphical representation of the number of publications using different types of radiographic modalities (a), the reliability of mandibular parameters for sex (b) and age (c) estimation, and accuracy percentages of sex and/or age estimation, as reported in the different studies considered in our review. CT: Computed Tomography, MCT: Multi-slice Computed Tomography, CBCT: Cone Beam Computed Tomography.

Determination Factor (Estimation of Age, Sex or Both)

The recorded mandibular parameters were used either to estimate sex (n=33) (e.g., Albalawi et al., 2019; Arthanari et al., 2022; Arthanari et al., 2024; Chandrasekhar et al., 2021; Esfehiani et al., 2023; Indira et al., 2012; Kallalli

et al., 2016; Kumar et al., 2016) or age (n=1) (Ayesha et al., 2022) of the studied individuals based on their radiographs or CBCT scans; though some studies estimated both the age and sex (n=21) (e.g., Abd Elsalam et al., 2019; Arthanari et al., 2024; Behl et al., 2020; Chole et al., 2013; Garg et al., 2021;

Ulusoy and Ozkara et al., 2022) of an individual (see Table S1 for all the articles). The most commonly utilized parameters were the ramus height, gonial angle, ramus breadth, bigonial width, coronoid ramus height and condylar ramus height. Sex estimation was attempted by most of the authors. Sex estimation can be considered as the most crucial component of biological profile reconstruction as the other components are generally sex-dependent (Sehrawat, 2018). Though age estimation is most warranted in medico-legal death investigations, it is considered as the most challenging component of biological profile (Bailey & Vidoli, 2023) and our review revealed that age estimation was the least studied component of biological profile based on the mandibular radiographic measurements.

Reliable mandibular parameters for Sex Estimation

Various mandibular parameters considered by different researchers for forensic anthropological purposes are summarized in Table 1. The majority of studies (N=34) found maximum ramus height as the most reliable mandibular parameter for sex estimation (e.g., Chalkoo et al., 2019; Dhaka et al., 2015; İlgüy et al., 2014) followed by the gonial angle as reported in 19 studies (e.g., Leversha et al., 2016; Sairam et al., 2018; Vora & Arthanari, 2022), the coronoid height was reported by 14 studies (e.g., Garg et al., 2021; Kallalli et al., 2016), and ramus breadth and bigonial breadth were also reported as reliable parameters in 14 studies (e.g., Ayesha et al., 2022; Kanya et al., 2017; Ulusoy and Ozkara, 2022) (Figure 2b).

Table 1. Measurements of mandibular parameters mentioned in the studies included in this review

S. No.	Measurement (Abbreviation)	Definition	Alternative name
1.	Gonial angle (GA)	Line is traced tangent to lower mandibular border and distal border line of the ramus on each side. Mandibular angle: intersection of these lines.	Gonion angle, Mandibular angle; Ramal angle, Mandibular Gonial angle
2.	Maximum ramus height / ramus height (MRH/RH)	Ramus height most superiorly (mandibular condyle) to the tubercle, or most inferior ramus border.	Condylar Height, Condylar Ramus Height
3.	Bigonial width (BGW)	Distance between Gonian (Go) points which are inferior, posterior, and lateral points on the external mandibular angle.	Intergonial Width
4.	Antegonial angle (Ant. A)	Two lines parallel to the antegonial region until they converge at the deepest point of the antegonial notch.	Antegonial Notch Angle
5.	Mandibular foramen (MF)	Measurement in three dimensions: superioinferior (X1) (vertical distance from lowest mandibular notch point to foramen), posterioanterior (X2) (distance from foramen to a perpendicular line from mental foramen to posterior ramus border), and anterioposterior (X3) (from foramen to anterior ramus).	Inferior Alveolar Foramen
6.	Mandibular Canal (MdC)	Vertical distance from inferior cortical image of mandibular canal to inferior mandible border.	Inferior Alveolar (nerve) Canal

S. No.	Measurement (Abbreviation)	Definition	Alternative name
7.	Mental foramen (MF)	Tangent along lower mandibular body border and perpendicular line from the lowest mental foramen outline to this tangent. The distance from mental foramen to the point where the perpendicular line intersects the tangent is then measured.	Mental Nerve Foramen
8.	Maximum ramus breadth (MRB)	Distance between mandibular ramus anterior and a line joining posterior condyle and jaw angle.	–
9.	Minimum ramus breadth (mRB)	Smallest ramus diameter in the anterior–posterior plane.	–
10.	Bi-condylar width (BCW)	Distance between lateral condyle points.	Bicondylar Breadth, Intercondylar Distance
11.	Bi-mental width (BiMW)	Distance between both mental foramina.	–
12.	Projective height of ramus (PRH)	Projective ramus height measured as the vertical distance from the highest point of the mandibular condyle to the inferior border of the ramus.	–
13.	Coronoid height (CrH)	Linear distance from the coronion to the inferior border of the mandibular ramus.	Coronoid Process Height
14.	Antegonial depth (Ant. D)	Perpendicular distance from the deepest point of the antegonial notch to a tangent drawn along the inferior border of the mandible.	Gonial Depth
15.	Ramal notch depth (RND)	Linear distance from the ramus tangent line to the deepest point of the ramus notch concavity.	Sigmoid Notch Depth
16.	Cortical bone thickness (CBT)	Thickness of the radiopaque band measured at the point on the inferior border of the mandibular body corresponding to the mesial origin of the antegonial notch.	Cortical Width
17.	Mental index (MI)	Mandibular cortical width at the mental foramen	–
18.	Condylar Width (CW)	Linear distance between the most lateral point of the lateral pole and the most medial point of the medial pole on the axial section.	Glenoid Fossa Width
19.	Condylar length (CL)	Linear distance from the most posterior point of the condyle to the most anterior point of the condylar head on the axial section.	–
20.	Coronoid ramus height (CoRH)	Distance from the coronion to the point of intersection at the gonion.	Coronoid Process Height, Coronoid Height
21.	Mandibular index (MdI)	Mandibular length $\times$ 100/Bi-condylar breadth	–
22.	Mandibular body height (MBH)	Direct vertical distance from the alveolar process to the inferior mandibular border, taken perpendicular to the base at the level of the mental foramen.	–

S. No.	Measurement (Abbreviation)	Definition	Alternative name
23.	Mandibular length (ML)	Distance from the central point of the symphysis region to the most inferior point of the mandibular angle, taken along a projected straight line aligned with the posterior border.	Length of Corpus
24.	Bi-condylar length (BCL)	Straight-line distance between the most lateral points of the two condyles.	–
25.	Bi-mental breadth (BMW)	Distance between inner borders of two mental foramina.	–
26.	Bi-coronoid breadth (BiCRW)	Linear distance between the most lateral points of the right and left coronoid processes. Bigonial width defined as the distance between the most lateral points of both gonion.	–
27.	Gonial height (GH)	Linear distance from the right gonion to the menton.	–
28.	Mental foramina breadth (MFB)	Straight-line distance between mental foramina.	–

Reliable mandibular parameters for Age Estimation

Out of the 55 studies, nine researchers found maximum ramus height as the most reliable mandibular parameter for age estimation (e.g., Arthanari et al., 2024; Ayesha et al., 2022) followed by bigonial width reported in six studies (e.g., Muskaan and Sarkar, 2015; Ulu-soy & Ozkara, 2022). Four studies reported gonial angle and ramus breadth (e.g., Garg et al., 2021; Shah et al., 2020) while three studies mentioned coronoid ramus height as the reliable age estimation parameter (e.g., Behl et al., 2020) (Figure 2c).

Accuracy Percentages

The accuracy percentage of any method or technique reflects its reliability, validity and efficiency, its target users and the readers interested in findings of its application. Among the studies selected for this review, the accuracy percentage was mentioned only in 22 studies out of which only six studies reported accuracy

percentage from radiological mandibular parameters below 70%, and only 16 studies mentioned accuracy percentage of more than 70% (Figure 2d).

Methodological Quality assessment

The majority of studies included in this review showed low to moderate risk of bias, indicating an acceptable methodological quality for conducting a qualitative synthesis (Figure 3, Table S1). Twenty-two studies were found having a low risk of bias, while other 33 studies fell into a moderate risk zone; no study was classified with a high risk of bias. Notably, among the studies classified as having low risk of bias, eight studies demonstrated significantly strong methodological rigor, and no major methodological concerns were identified during the appraisal process. Although the majority of studies demonstrated a moderate methodological quality, several methodological limitations were observed across the included studies.

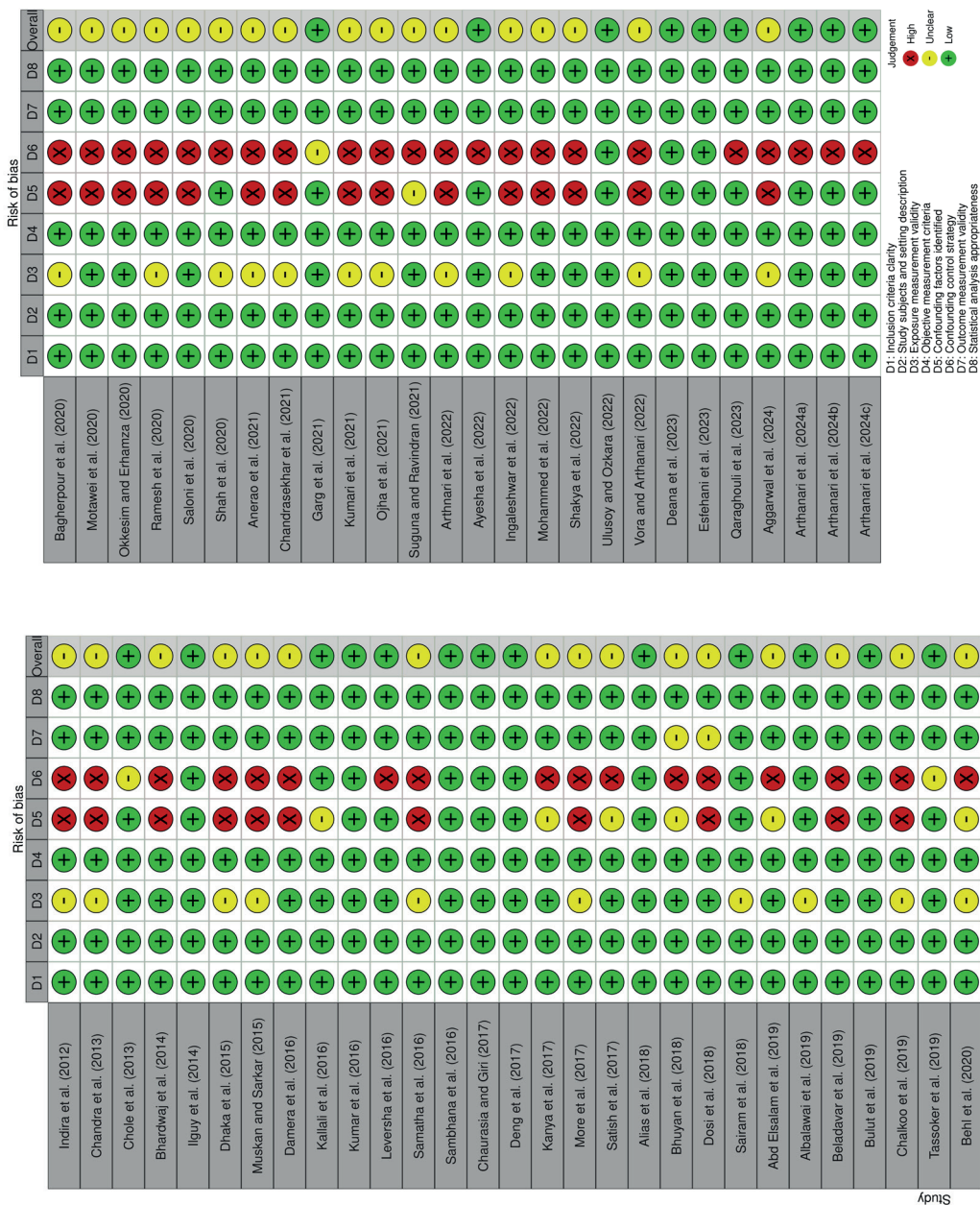


Figure 3. Traffic-light plot summarizing the risk-of-bias assessment of the included studies based on the Joanna Briggs Institute (JBI) Critical Appraisal Checklist. Each domain was evaluated as low risk (green), high risk (red), or unclear risk (yellow). The figure was generated using the ROBVIS visualization tool.

Many studies did not report any intra-observer or inter-observer reliability testing, resulting in unclear ratings for the measurement reliability domain (e.g., Arthanari et al., 2022; Behl et al., 2020; Chandra et al., 2013; Chandrasekhar et al., 2021; Sairam et al., 2018; Samatha et al., 2016). Furthermore, potential confounding factors such as age distribution, skeletal variation, population affinity, nutritional status, and dental status were rarely identified or statistically controlled in most of the studies included in the systematic review (e.g., sArthanari et al., 2024; Ayesha et al., 2022; Dhaka et al., 2015; Kanya et al., 2017; Qaraghoulis et al., 2023; Saloni et al., 2020). Most studies relied primarily on basic statistical comparisons such as t-tests or ANOVA; without giving any due consideration to multivariate regression or adjustments for the confounding factors. The generalization of the results (as extracted from the considered studies) was limited due to small sample sizes, convenience sampling, or the use of limited predictive modeling employed by some studies (e.g., Aggarwal et al., 2024; Alias et al., 2018; Beladavar et al., 2019; Kanya et al., 2017; Leversha et al., 2016; Ojha et al., 2021).

The detailed risk of bias assessment for all considered studies using the JBI Critical Appraisal Checklist is presented in Table S2. Moreover, a domain level risk of bias assessment for the included studies is illustrated in Figure 3, which represents a traffic-light plot generated using the ROBVIS visualization tool (McGuinness & Higgins, 2021).

Discussion

Forensic anthropologists use a multitude of methods and techniques for the most efficient and objective identification

pursuits of unknown human remains retrieved from different forensic contexts (Sehrawat, 2018). The primary responsibility of forensic experts is to estimate sex of the unknowns for establishing a biological profile, particularly during disaster victim identification and in medico-legal contexts. When evaluating other aspects of biological profile, like estimating age, stature and population affinity, sex determination becomes indispensable as it just halves the search process. In instances where skeletal remains are either incomplete, decomposed, or heavily damaged, the mandible proves to be an important craniofacial skeletal element as it is the largest and sturdiest facial bone. The distinctly sexually dimorphic nature of mandible (evident in its growth, size, and masticatory modelling) makes it even more important (Esfehani et al., 2023; Kumar et al., 2016; Qaraghoulis et al., 2023). Thus, mandibular parameters may be useful for biological profiling of heavily damaged, burnt or fragmented human remains (Saini et al., 2011).

Systematic reviews objectively evaluate methodologies, sample sizes, accuracy, reliability and validity of results mentioned by different articles to report the research status and future trends on the topic. Such reviews may help forensic anthropologists to stay updated on the latest developments in the field, evaluate methodological quality and rigor of different studies (Franco et al., 2025). In the present study, the literature search was conducted across four research databases identifying 55 full-text articles for final evaluation and systematic review based on the adopted inclusion and exclusion criteria. The identified studies followed varied methods, primarily involving radiological imaging modalities such as OPGs, CBCT and sometimes magnetic

resonance imaging. Orthopantomograms were used in the majority of studies because of their non-invasive nature, accessibility, comprehensive coverage of the maxillofacial complex, accuracy and reproducibility of linear and angular measurements, highlighting their practical advantages for extracting the mandibular features (Arthanari et al., 2024; Saloni et al., 2020; Sambhana et al., 2016). Additionally, OPGs avoid issues related to overlapping images, and the enhancement of contrast and brightness, along with the enlargement of images, and enable accurate and consistent measurement of selected landmarks. However, OPGs may lack the spatial accuracy needed for detailed analysis of complex anatomical structures. Cone beam computed tomographs/CT scans were used by comparatively fewer number of studies, though such analysis has superior 3D reconstruction capability and detailed multi-planar visualization, which contributes to enhanced measurement precision and overall identification accuracy of this modality (Abd Elsalam et al., 2019; Arthanari et al., 2024; Saloni et al., 2020). Furthermore, discriminant function analysis was found to be the most critical statistical method used for determining sex-based metric factors and establishing sex-specific equations derived from mandibular measurements (Arthanari et al., 2024; Bagherpour et al., 2020; Damera et al., 2016; Qaraghoul et al., 2023; Saloni et al., 2020).

The application of both 2D and 3D imaging modalities demonstrated very distinct and complementary advantages in the measurement of mandibular parameters for forensic and clinical purposes. While 2D modalities, like panoramic radiographs, provide a comprehensive overview of the mandible and facilitate

measurements of linear and angular dimensions, they lack the precision required for detailed analysis of complex anatomical structures (Arthanari et al., 2024). A significant number of studies used 2D panoramic radiographs in their methodology due to their wider availability, cost-effectiveness, and low radiation exposure (Chandra et al., 2013; Indira et al., 2012; Leversha et al., 2016). Panoramic radiography, being a curved-plane tomographic technique, allows for broader anatomical coverage, thus facilitating the measurement of key mandibular landmarks. More advanced 3D imaging modalities such as CBCT, CT, or MCT offer high-resolution volumetric imaging, allowing precise measurement of anatomical landmarks and better visualization of the bone density and its morphology (Anerao et al., 2021; Deng et al., 2017; Jambunath et al., 2016), though very few studies included in our review employed these advanced techniques for measuring mandibular dimensions. Cone beam computed tomography has demonstrated superior accuracy in measuring mandibular length, ramus height, and gonial angle-the critical parameters used for sex and age estimations. While 2D modalities are beneficial for quick assessments and broader accessibility, 3D imaging is essential in cases where higher precision is required. However, the integration of 2D and 3D imaging modalities enhances accuracy, reliability, and scope of mandibular morphometric analysis for forensic anthropological purposes.

The studies presenting higher accuracy ranges between 76% and more than 90% demonstrated substantial variability, reportedly imprinted by the population-specific characteristics, imaging modality used, and the number of variables considered, and these features were part of the

particular studies. While CBCT- and 3D CT-based studies showed higher accuracy levels (ranging above 84%), some authors reported discriminant rates exceeding the 95% mark in males and 100% in females, especially when the primary indicators under consideration were condylar height or combined ramus-based measurements (Abd Elsalam et al., 2019; Alias et al., 2018; Kallali et al., 2016; Shakya et al., 2022). It is pertinent to note that the variations in accuracy rates and the best sexually dimorphic parameter are often found attributed to multiple attributes such as genetics, nutritional status, environmental factors, lifestyle, and indigenous background of an individual (Saloni et al., 2020; Shakya et al., 2022).

Sexual dimorphism has been reflected in some mandibular parameters such as ramus height, gonial height, and muscular attachment sites (Arthanari et al., 2024). Morphological and developmental factors provide necessary explanation for the strong consistency exhibited by the mandibular ramus for having sexual dimorphism when compared to other mandibular regions. For instance, the presence of greater muscle mass and functionality is often associated with males, leading to increased ramus height, broader attachment sites, and more robust morphology, particularly in the coronoid and condylar processes. Additionally, hormonal influences and different rates, durations, and timings of mandibular growth in both sexes further accentuate the structural disparities (Indira et al., 2012; Shakya et al., 2022). However, as sex estimation is a population-specific aspect, existing regional discriminant functions should be regularly revised to address any biological variability across age-groups and populations (Damera et al., 2016; Sambhana et al., 2016).

Our systematic review was formulated to analyse the metrics associated with the mandible that present the greatest sexual dimorphism and help undertake the task of age estimation based on these parameters. Across all studies selected for the systematic review, which represented a variety of populations, approximately 17 articles exhibited an accuracy rate of 70% to 90%. These studies also demonstrated consistent sexual dimorphism, highlighting the medium- to high-grade discriminatory power of various radiological modalities used for mandibular measurements. Furthermore, while most of the studies reported several methodological differences, there was a remarkable consistency in the parameters selected. Among all the parameters evaluated, few of them were found associated with the greatest morphological changes and the most dimorphic portions of the mandible; making the measurements substantially useful for sex determination. The mandibular parameters like ramus height, coronoid height, bigonial breadth, condylar height, inter-condylar distance, maximum and minimum ramus breadth, mandibular body height, and gonial angle were found highly reliable for sex estimation. While ramus height was consistently identified as the best discriminator for sex estimation across multiple populations and radiological modalities (Arthanari et al., 2024; Damera et al., 2016; Qaraghoulis et al., 2023; Saloni et al., 2020; Sambhana et al., 2016), the minimum ramus breadth was reported as the next best complementary variable to ramus height for the purpose (Arthanari et al., 2024; Indira et al., 2012). On the other hand, condylar height was found to be the most consistent parameter for age estimation, followed by the bigonial width as the secondary significant pa-

parameter and the mandibular length-related measurements crucially important for the population-specific assessments of unknown remains (Arthanari et al., 2024). A study presented a contradiction to other studies and reported that minimum ramus breadth had the least sexual dimorphism associated with mandibular ramus (Shakya et al., 2022).

Mandibular ramus was found to exhibit the highest degree of sexual dimorphism, making it a reliable mandibular tool for sex determination in forensic and anthropological scenarios (Kumar et al., 2016; Saloni et al., 2020; Sambhana et al., 2016). Across all radiographic studies reviewed here, consistent evidence of sexual dimorphism was reported in the ramus region, gonial region and the transverse widths of the mandible. Furthermore, the general trend observed across multiple mandibular measurements across different populations indicated that the linear dimensions of the ramus and jaw widths were statistically significantly higher in males than the females (Sambhana et al., 2016; Shakya et al., 2022). The sex estimation accuracy rates associated with mandibular parameters generally range from 71.1% to 84% among most of the studies reviewed in this study (Kumar et al., 2016; Saloni et al., 2020; Shakya et al., 2022). Also, the linear and angular measurements that performed well for discriminating between males and females, were generally found associated with overall size and robustness of the mandible; males having a larger ramus region and wider bigonial/bicondylar dimensions (Abd Elsalam et al., 2019; Alias et al., 2018; Damera et al., 2016;). Similarly, certain mandibular parameters exhibited low sexual dimorphism or negligible or statistically insignificant differences, such as

Sella-Nasion/A-point (SNAr), bi-mental breadth, mental index, etc. (Abd Elsalam et al., 2019; Bagherpour et al., 2020). Conclusively, these observations endorse the fact that the mandible, particularly its ramus and the condylar region, provides a biologically robust and globally consistent framework for sex estimation, and it also highlights the need for continued population-specific validation and methodological standardization studies.

Variability in Study Design and Methodology

The reviewed literature revealed a notable trend in variability of study design, sample size, age-groups selected, and the imaging techniques used. Some studies considered the smaller but demographically diverse populations, while others studied the larger and more heterogeneous group of individuals in their study sample. The funding opportunities, time constraints, logistical challenges, and accessibility of subjects or skeletal remains (as study material) were commonly cited as the most limiting factors for selecting the sample size. Age-group selection was considerably varied as some studies focused specifically on age-related mandibular changes, while others included the broader or undifferentiated age groups; such selections were influenced by the cultural, health, or demographic credentials of the selected population groups. Furthermore, the choice of imaging modality was largely dependent on the researchers' institutional resources, funding, expertise, and the precision required to satisfy the study objectives. Such disparities in choice of radiological modality reflected the adaptive nature of study design in forensic and anthropological research, tailored to available tools, resources, context, and research goals.

Implications for Standardization and Future Research

The diversity in research designs by different researchers underscores the urgent need for standardization of protocols to be used for evaluation of mandibular parameters towards forensic sex and age estimations. Establishing guidelines for imaging techniques, measurement protocols, and sample selection criteria will facilitate more reliable comparisons and meta-analyses in the future. Such insights can direct future research goals and funding priorities, particularly in advancing the use of radiological modalities for forensic anthropological purposes.

The variation in sample size, age-groups and techniques significantly affected the generalizability of the findings across diverse populations. Small or homogeneous samples often limit the applicability of results, making it difficult to draw valid conclusions relevantly applicable to broader demographics. Also, differences in methodologies influence the accuracy and reliability of the measurements which, in turn, impact the robustness of conclusions drawn about age and sex estimations. These variations also highlight the research trends, revealing shifts toward specific methodologies or demographic focuses that reflect changing priorities within forensic anthropology. Furthermore, the lack of uniformity in research design complicated efforts to establish standardized protocols, making it more challenging to compare results across the studies. Ultimately, addressing these variations is crucial for enhancing the credibility of findings and advancing the forensic radiological/anthropological field towards more standardized and effective identification techniques.

Risk of Bias and Quality Assessment

The methodological quality assessment undertaken using JBI Critical Appraisal Checklists indicated that most of the studies included here demonstrated a moderate to low risk of bias. It suggested that qualitative synthesis of the included studies was possible as several studies exhibited clear study designs, well-defined inclusion criteria, and used reliable radio-imaging modalities such as panoramic radiographs or CBCT for recording different mandibular measurements (Deana et al., 2023; Deng et al., 2016; Ilguy et al., 2014). Although certain limitations have been highlighted based on the overall methodological quality of the included studies; their inclusion in the qualitative synthesis remains acceptable based on the continued exploration of mandibular morphometric parameters as a predictor of sexual dimorphism in forensic anthropological identification contexts (Deana et al., 2023; Deng et al., 2016; Esfehiani et al., 2023). Although most of the studies demonstrated acceptable methodological standards; the variability in study designs and analytical approaches employed by different studies was identified across the published literature on the topic. Furthermore, it was observed that several studies relied primarily on simple comparative statistics rather than comprehensive predictive modelling, which may potentially limit the practical forensic applicability of some mandibular parameters (Aggarwal et al., 2024; Alias et al., 2018; Beladavar et al., 2019; Bhardwaj et al., 2014; Chole et al., 2013; Kanya et al., 2017; Ojha et al., 2021).

Some studies even reported inconsistencies in reporting measurement reliability and observer calibration, thereby influencing the reproducibility of mor-

phometric analyses across different populations and the imaging modalities (Aggarwal et al., 2024; Arthanari et al., 2022; Chandrasekhar et al., 2021; Indira et al., 2012; Vora and Arthanari, 2022). All of these methodological differences highlight the need for greater standardization in the protocols associated with mandibular parameters by strengthening the reliability assessment, sampling strategies employed, and the statistical validation of predictive models which, in turn, may improve the robustness of the resultant observations (Damera et al., 2016; Kallali et al., 2016). Nevertheless, the presence of a significant number of methodologically robust studies may strengthen the evidentiary value of the method or technique, required for enhanced credibility of the mandibular measurements as potential forensic indicators of sex, age or both (Aggarwal et al., 2024; Arthanari et al., 2022). Thus, future research endeavors should focus on employing larger, population-specific datasets and validating the multivariate models that may further improve the forensic applicability of these morphometric approaches.

Limitations of this Systematic Review

Though the present review provides a detailed overview of methodologies and techniques used for radiological mandibular parameters for forensic sex and/or age estimation, still there are certain limitations of this study. Firstly, publication bias analysis, such as funnel plot asymmetry and Egger's regression, was not chosen as an analytical tool due to the insufficient number of studies eligible for each comparison in this review, which precluded a meaningful assessment. These publication bias methods necessitate the requirement of minimum 10 studies per quantitative procedure for

accurate statistical power and interpretations (Duval & Tweedi, 2000; Egger et al., 1997; Sterne et al., 2000, 2011). In this study, various outcome types were analysed, including sex estimation parameters, age estimation parameters, and the presence of any modality-specific subgroups; however, none of them met the required threshold values. To prevent the generation of misleading patterns or unreliable estimates, publication bias analysis was excluded from the current review study. Also, non-English studies were not considered in this review, resulting in the exclusion of vast data from around the world for valid generalization and conclusions. The present study does not discuss the current challenges for measuring mandibular parameters through different radiological modalities such as differences in measuring techniques and the results due to advancement and easy accessibility of modalities like CBCT scans. If above limitations or challenges can be overcome, one can suggest a standardized methodology for effective forensic identification strategy to be used in the criminal justice system. Mandibular parameters exhibited notable variations among two sexes and different age-groups of various population groups and it may pose another limitation towards accurate assessments or generalization of mandibular morphology or its dimensions for forensic purpose. Thus, careful considerations and new investigations will address the impact of such variation in the future (Arthanari et al., 2024).

Gonial and antegonial angles have defined limits, though they can serve as useful supplementary indicators for sex estimation of unknown mandibles. While assessing these angles, forensic anthropologists and orthodontists must exercise caution and consider them within

the context of a comprehensive analysis that includes demographic information and various skeletal indicators. To enhance the accuracy and reliability of sex determination using these angles, further research is needed to standardize the measurement techniques and validate them for diverse populations (Arthanari et al., 2024).

Relying solely on mandibular characteristics for age estimation has its limitations; the factors like population variations, sex differences, inter/intra-observer variability, and taphonomic changes may add to these challenges. To enhance the accuracy and reliability of forensic age estimations, forensic anthropologists often recommend utilizing multiple skeletal indicators to mitigate these challenges or limitations (Arthanari et al., 2024). Chandra et al. (2013) reported that larger study samples and a thorough assessment of additional parameters related to the mental foramen are needed to validate the study findings. The high radiation exposure associated with CBCT modality is a serious limitation, though it provides precise results. Most of the mandibular parameter assessment studies are based on the radiological examination of subjects visiting the dental outpatient department of a hospital for different reasons, thus the results obtained cannot be generalized to the entire population group (Ramesh et al., 2020; Shakya et al., 2022).

Conclusions

The present systematic review revealed that the majority of included studies (60%) considered mandibular radiometric dimensions for sex estimation and about 38% estimated both sex and age from these parameters. Fewer than half

of the studies reported accuracy percentages of their findings, and the reported accuracy percentage of most studies was much below the acceptable forensic thresholds. The review also highlighted that by surmounting the reported limitations, there may be a more nuanced understanding of contributions of mandibular shape, size and morphology for forensic anthropological sex and age estimations. Our results clearly reflected that sex and age estimation should not be solely relied upon mandibular measurements only, and these observations are expected to provide directional insights to future forensic anthropologists that mandibular morphometric analyses should be attempted in conjunction with other reliable methods towards human identification for medico-legal purposes.

Additional information

Supplementary materials [online version].

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Author contributions

JSS conceptualized the topic, framed the outline of the manuscript, scrutinized the available literature, wrote the

final manuscript and revised its final version, SS conducted pilot survey of the literature, suggested research trends and preliminary draft of the manuscript, ST helped in literature search and systematic review, drawing figures and revising the manuscript, MT provided valuable clinical inputs, revised and edited the manuscript. All authors read and agreed to the revised version of the manuscript.

Ethics statement

Not applicable.

Data availability statement

The reviewed articles are listed in supplementary materials.

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