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Review Article

Sex estimation from human dentition: forensic odontology techniques and applications

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ABSTRACT

Sex determination is an intrinsic part of forensic identification since it eliminates half of the potential matches, thus increasing accuracy in situations such as mass disasters, criminal investigations and analysis of shattered or decomposed remains. Forensic odontology has been a very strong branch in this sense, attributable mainly to the outstanding resistance of dental tissues to post-mortem insults like trauma, fire and extended submersion. A range of methodological approaches has been employed for sex estimation from dental evidence, encompassing morphological, odontometric, molecular and technologically advanced modalities. Odontometric measurements, notably the mandibular canine index, crown and root dimensions and dental arch characteristics, demonstrate consistent dimorphic trends. Morphological indicators such as shovel-shaped incisors, Carabelli's cusp and palatal rugae further contribute to biological profiling. The use of radiographic methods, such as orthopantomograms (OPGs), cone-beam computed tomography (CBCT) and micro-computed tomography, enables accurate visualization of sexually dimorphic dental and craniofacial morphology. Molecular markers, such as Amelogenin, SRY and DYS14, offer genetic pathways for sexing, especially in highly degraded remains. Newly developing artificial intelligence and machine learning techniques offer the potential for increased efficiency and predictive precision. Future progress requires standardized guidelines, population-based data sets and cross-disciplinary coordination to maintain forensic odontology as a scientifically sound instrument in personal identification.

Keywords: Dental dimorphism, Forensic odontology, Molecular markers, Odontometric analysis, Radiographic techniques

INTRODUCTION

In forensic science, human identification is essential, especially when dealing with mass disasters, criminal investigations or unidentified human remains. Forensic anthropological practice is based on the creation of a biological profile, which comprises ancestry, age, sex and stature. One of the most important of these is sex determination, which significantly narrows the pool of potential identities by 50% and makes subsequent identification procedures easier.[1-4] Since teeth are the most mineralized and chemically durable parts of the human body, they frequently withstand postmortem insults such trauma, submersion, putrefaction and burning. Because of this, dental evidence is crucial for identifying people. Even in cases when only fragmented remains are available, forensic odontology the field that combines dental science and legal investigation uses these long-lasting structures to help determine a person's sex and identity.[4,5] Sex determination's function in identity narrowing when reconstructing a person's biological profile, sex determination is fundamental. In addition to

reducing the number of potential identities by half, it also helps determine age and height. Traditional osteological sex estimate techniques depend on sexually dimorphic characteristics of the skull and pelvis, which aren't usually maintained. Dental evidence, especially odontometric and molecular characteristics, offers a good substitute in these situations.[6]

For sex estimate, forensic odontology has several benefits: Extreme circumstances are tolerated by teeth, which frequently hold up well after other tissues have deteriorated. Certain dental characteristics show quantifiable sexual dimorphism, including root length, canine index and mesiodistal and buccolingual crown dimensions. The teeth that exhibit the greatest sexual dimorphism are always found to be mandibular canines.[7,8] Morphological sexing is improved by non-metric features such the distal accessory ridge on canines, which is more noticeable in men.

Odontometric indices, such as the Mandibular Canine Index and imaging methods offer reliable, objective metrics.[9]

DNA is abundant in dental tissues, especially pulp. Accurate sex determination is possible even from severely damaged or burned remains because to PCR-based amplification of sex-specific markers such DYS14, SRY and Amelogenin (AMELX/AMELY). Artificial Intelligence: Machine learning models developed on dental datasets have shown excellent sex classification accuracy and can be used as quick, automated tools in forensic investigations.

The purpose and extent of the review with an emphasis on both conventional and modern diagnostic modalities, the main goal of this study is to methodically compile and evaluate the body of research on sex determination techniques in forensic odontology. The methods used to infer sex from dental and craniofacial features include morphological, metric, molecular and artificial intelligence (AI)-driven methods.

The following goals are included in the review's scope: to emphasize the scientific underpinnings and diagnostic utility of dental sexual dimorphism, crown and root morphometry and odontometric indices (such as the mandibular canine index). to assess, particularly in postmortem and environmentally stressful situations, the accuracy of molecular methods, such as PCR-based amplification of sex-specific markers (Amelogenin, SRY, DYS14) from tooth pulp and hard tissues.

To investigate how machine learning algorithms and AI are emerging in forensic odontology as automated sex prediction tools. to evaluate how methodological constraints, environmental factors and population-specific variances impact the precision and repeatability of sex determination methods. to suggest standardized, evidence-based procedures and future initiatives that improve the forensic validity and medico-legal relevance of odontological sex determination. In situations involving fragmented, degraded or skeletonized remains where conventional osteological approaches would not be practical, this review attempts to offer forensic odontologists, forensic scientists and legal authorities a comprehensive resource for human identification.

SEXUAL DIMORPHISM'S BIOLOGICAL FOUNDATION[10]

The Biology of Sexual Dimorphism in Dentition Development Differential growth patterns formed during embryonic and postnatal development are the root cause of sexual dimorphism in the human dentition. Complex connections between ectodermal and mesenchymal tissues control tooth development and these interactions are influenced by homeobox genes, signaling pathways (such as BMP, FGF and WNT) and epigenetic factors. Due to the influence of pubertal hormone surges, sex-based disparities become increasingly noticeable throughout the late mixed dentition and permanent dentition stages.

The mesiodistal and buccolingual dimensions of teeth are usually where dimorphism is seen, with male teeth being larger and having more robust morphological characteristics. Because of their early calcification, extended eruption schedule and significant genetic effect, mandibular canines exhibit the highest degree of sexual dimorphism.

GENETIC AND HORMONAL FACTORS[11]

There are considerable genetic and hormonal influences on the appearance of sexual dimorphism in dentition. Sex-linked genes that affect enamel thickness, dentin deposition and total tooth size are genetically responsible for dimorphism. In addition to being markers for molecular sex identification, the Amelogenin (AMELX and AMELY) genes on the X and Y chromosomes, respectively, also influence the production of enamel proteins during development. Hormonally, androgens like estrogen and testosterone affect the maturation of dental tissue, root elongation and craniofacial growth. The timing and severity of dental calcification and craniofacial ossification are influenced differently by these hormones.

For instance, estrogens are linked to a more delicate and rounded facial morphology in females, whereas androgens are known to promote bigger tooth size and more pronounced mandibular and zygomatic growth in males.

Disparities in the patterns of craniofacial growth in men and women another important factor in determining sex is craniofacial dimorphism, which is represented in the morphology of the jaws and skull. Males tend to have squarer chins, larger mastoid processes, more noticeable

supraorbital ridges and more distinct glabellae. Males typically have larger mandibles, thicker bodies and less obtuse gonial angles (~125°), whereas females have smaller mandibular dimensions and more obtuse gonial angles. Males typically exhibit greater intercanine distances and wider dental arches in the dentofacial region, which contributes to the detectable dimorphism shown in odontometric indices like the Mandibular Canine Index (MCI). These physical differences are caused by sex-specific bone remodeling patterns that are regulated by hormones and genes, as well as differences in the timing of growth spurts.

PARAMETERS OF ODONTOMETRY[12]

Because dental measures are measurable and repeatable, odontometric analysis is essential for determining sex. Sexual dimorphism in teeth, particularly canines and molars, is regulated by both hormonal and genetic factors. Forensic applications have extensively researched and validated the following parameters.

Dimension-based techniques for teeth

Odontometric techniques include sex-to-sex comparisons and accurate measurements of individual teeth. When only dental arches are accessible or the skeletal remains are fragmented, these techniques are recommended.

Buccolingual and mesiodistal diameters[13]

The distance between a tooth's mesial and distal contact points is known as the mesiodistal (MD) diameter. The distance between the buccal and lingual surfaces at the widest point of the crown is known as the buccolingual (BL) diameter. Sexual dimorphism can be accurately detected by these two dimensions. Males often have bigger MD and BL measures than females, according to numerous studies. The greatest degree of dimorphism is always shown in the mandibular canines, which are followed by maxillary central incisors and first molars.

Dimensions of the crown and roots sex

It has been determined using crown height, crown width, root length and total tooth height. These parameters can be accurately assessed using radiography techniques and optical scanners. Because of the impact of androgens during odontogenesis and growth spurts, males typically have greater crown diameters and longer roots.

Canine index (canines maxillary and mandibular)[14]

One of the most reliable odontometric instruments for determining sex is the Mandibular Canine Index (MCI): The formula is MCI= (intercanine distance)/ (mandibular canine mesiodistal width). Both tooth size and arch shape are reflected in this index. Both tooth size and arch shape are reflected in this index. Because of their bigger canine dimensions and wider intercanine intervals, males exhibit higher values. While the mandibular counterpart is more dimorphic, the Maxillary Canine Index (MxCI) can also be utilized. According to reports, up to 89% of Indian populace have successfully completed MCI.

Measurements of mandibular ramus and gonial angle

These factors are tightly related to dental morphology and arch development, while being largely skeletal. Important findings: Males have larger mandibular ramus width and height. The gonial angle is more pronounced and inverted in men (usually less than 125°) and more obtuse in females. In addition to dental indices used in sex assessment, these measurements can be obtained using lateral cephalograms and orthopantomographs (OPGs).

Dimorphism of sexuality in dental arch shapes

The structure and size of the dental arch also exhibit sexual dimorphism: The arches of males are wider, more U-shaped and have wider intercanine/intertermolar and arch perimeters. The arches of females are often thinner and more parabolic. When complete dentition is maintained, arch form analysis can greatly improve the accuracy of sex determination, particularly when paired with intercanine and intermolar distances.

NON-METRIC AND MORPHOLOGICAL FEATURES[15]

Qualitative features that exhibit discernible variation across people and sexes but do not necessitate exact measurements are known as non-metric traits. In forensic odontology, these characteristics are useful for estimating sex and ancestry, especially in cases when dentition is fractured or metrically unclear.

Shovel-shaped incisors and cusp patterns[16,15]

Men and women have different cusp patterns, particularly on molars and premolars. Males typically have larger, more noticeable cusps with more intricate cusp patterns. Deep lingual fossae and prominent marginal ridges characterize shovel-shaped incisors, which are mostly prevalent in East Asian, Native American and some Indian groups. Despite being more prevalent as an ancestral characteristic, they are more likely to manifest and occur in males. Autosomal and X-linked loci determine and regulate these features genetically.

Relevance to forensics

Shovel-shaped incisors can be used to measure population affiliation and may exhibit moderate sexual dimorphism in certain populations.

Protostylid and carabelli trait[16]

A supplemental cusp on the mesiopalatal facet of the maxillary first molars is known as the Carabelli characteristic. It manifests as a pit, groove or cusp and is

more commonly seen and exhibited in males. On the buccal surface of mandibular molars, the term "protostylid" describes an additional cusp or groove that is usually located close to the mesiobuccal cusp. It exhibits a slight male inclination and varies in expression, much like the Carabelli cusp. Both characteristics vary among ethnic groups and are heritable.

Forensic relevance

When present, these non-metric characteristics support biological profiling and can be used in conjunction with odontometric tests to estimate ancestry and sex.

Dimensions and pattern of palatal rugae

The anterior portion of the hard palate has transverse mucosal ridges called palatal rugae. They are constant throughout life and develop early in intrauterine life. Straight, wavy, round, curved and branching forms are among the patterns. Length, form, unification and direction are characteristics of dimensions. Curved and wavy patterns are more common in males and their rugae are typically longer and more noticeable. In general, females exhibit more linear and circular patterns. Male rugae may also exhibit higher complexity and asymmetry, maybe as a result of wider palatal vaults.

Relevance to forensics

When teeth are lost or damaged, palatal rugae provide a solid anatomical landmark for sex estimation and personal identification since they are resistant to trauma and decomposition.

IMAGING AND RADIOGRAPHY METHODS FOR DETERMINING SEX[17,18]

In forensic odontology, radiographic and imaging modalities are essential for the non-invasive evaluation of dental and craniofacial structures. Particularly when traditional metric or morphological analysis is constrained by decomposition, trauma or fragmentation of remains, these methods make it easier to identify sexually dimorphic characteristics.

Radiography in panorama

An extensive two-dimensional image of the complete maxillofacial skeleton, including the teeth, alveolar bone and mandible, is provided by panoramic radiographs, sometimes referred to as orthopantomograms or OPGs. Mandibular ramus height, condylar length, gonial angle and mandibular body height were the parameters evaluated.

Sexual dimorphism

Compared to females, men regularly exhibit higher values for ramus height, condylar length and more acute gonial angles.

Forensic utility

When paired with odontometric information, these measurements have been utilized to determine sex with an accuracy of up to 80–85%.

Cone-beam computed tomography

Compared to traditional CT, CBCT offers three-dimensional, high-resolution imaging of the skeletal and dental structures with less radiation exposure. Benefits include the ability to analyze dental pulp volumetrically, root canal morphology, tooth volume and maxillofacial bone spatial orientation.

Applications

Helpful in identifying mandibular morphology, pulp chamber dimensions and root length—all of which exhibit sexual dimorphism. More recently, CBCT has been used to more accurately evaluate dental volume asymmetry, intercanine breadth and palatal arch form than conventional radiography.

Scientific basis

In forensic situations, particularly when dental features are partially intact, CBCT's multiplanar analysis allows for exact odontometric assessment, which improves sex estimate.

Analysis of orthopantomograms[18]

Odontometric sexing makes considerable use of metrics based on OPG: Variables Measured were corpus length, bicondylar breadth, bigonial breadth and mandibular ramus height and breadth.

Sexual differences

There is evidence of notable dimorphism in the length of the mandibular corpus and the width of the ramus.

Reliability

OPGs provide great sensitivity and specificity in sex estimation when analyzed methodically, particularly when paired with linear odontometric indices like the Mandibular Canine Index (MCI).

Validation

These criteria have been thoroughly tested for forensic profiling in both Indian and international populations.

Digital radiography techniques and micro-CT[18]

Ultra-high-resolution imaging at the microscopic level is made possible by Micro-Computerized Tomography (Micro-CT).

Use in forensics

Used in the in-depth examination of tooth internal structure, pulp chamber morphology and enamel-dentin junctions.

Sexual Dimorphism

The overall volume and enamel thickness of male teeth are typically higher.

Digital radiography

Provides quick, repeatable measurements and tools for image augmentation to examine cranial characteristics and dental morphometry.

Utility

Particularly helpful when traditional techniques don't work on severely fragmented specimens or pediatric remains.

Future recommendations

Future studies in forensic dental identification need to include standardizing the protocols prior to consistent and accurate sex identification occurring during forensic investigations. This necessitates establishing standards for odontometric and radiographic protocols and cut-off values for sex estimation for different populations and races. Because of the large variation that exists between ethnicities and geographical location, there is an urgent need to establish large and full-type databases on the population-based, sex-dimensional characteristics of human dentition and maxilla/facial patterning, as this would increase the accuracy in estimating sex. The deployment of new technologies, including artificial intelligence (AI) and new machine learning technology would be advantageous as they are fast and waning (loss of sample) and lack of completely based ratified dental metrics and radiographs.

The same is likely to hold for methods that use and/or involve 3D sampling error and computerized assessments of 3D expressiveness, including CBCT and Micro-CT; these would represent major advancements in the study of the dentition and maxilla and skull radiographical based assessments. Another area requiring substantial expansion is molecular processes for sex identification. We need to move beyond the conventional sex identification standards of Amelogenin, SRY and DYS14 genes especially in cases where the remains have no preservation.

It is also advisable to mention that an integrative approach involving and partnering forensic odontologists with forensic anthropologists, genomicists, radiologists and AI specialists for the establishment of holistic and robust methods for death registration methods for human identification is ideal. There is also a need for large sample observations and publications on the validity (right decision) of sex identification methods in different populations, across various ages. When dealing with mass casualty incidents and criminal investigations, it is important to develop fast, reliable protocols for the use of dental evidence. Furthermore, there is a need to enhance training and capacity development for forensic professionals in new technologies and methodologies. Lastly, we must develop clear legal and ethical guidelines related to the use of dental evidence in forensic contexts that include data privacy, consent and ethical considerations.

CONCLUSION

Odontological sex determination has significance in forensic identification, especially when the skeleton is in fragments or suffers decomposition and hence is of little use in the case. Teeth undergoing post mortem changes rarely provide opportunities for sex estimation of an individual. This review posits that sex estimation is more precise and reliable if odontometric, morphological, molecular and radiographic techniques are used in combination. Amongst the odontometric parameters, mandibular canine indices and measurements of crowns and roots reflect the greatest sexual dimorphism exhibited in populations.

Non-metric traits such as cusp patterns, palatal rugae and accessory dental traits serve as supportive evidence when sex determination from quantitative data is difficult. Forensic dental identification has witnessed enhanced accuracy through the symbiosis between panoramic and CBCT, digital radiography, molecular biology and AI-based models. Nevertheless, proper standards specific to populations and methodological protocols are indispensable for their efficacy.

To summarize, forensic odontology provides a solid, trustworthy and frequently essential method for estimating sex within the larger framework of human identification. To further improve these methods and guarantee their suitability and dependability in a variety of forensic situations, more research, technical development and international cooperation are crucial.

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