FORENSIC ODONTOLOGY IN THE ERA OF PRECISION FORENSICS: LANDMARK CASES, DISASTER VICTIM IDENTIFICATION, AND EMERGING DIGITAL TECHNOLOGIES

Satwik Chatterjee[1*], Anuj Gaba[2], Oinam Gambhir Singh[3]
[1*]Extern, Department of Forensic Medicine and Toxicology, AIIMS Kalyani, West Bengal, India.
[2]Junior Resident, Department of Forensic Medicine and Toxicology, AIIMS Kalyani, West Bengal, India.
[3]Professor and Head, Department of Forensic Medicine and Toxicology, AIIMS Kalyani, West Bengal, India.
Email: [1*]drsatwikc356@gmail.com, [2]anuj.gaba989@gmail.com, [3]drgambhirsingh@gmail.com
ORCID ID: [1*]0009-0009-8064-6648, [2]0009-0000-6483-9647, [3]0000-0002-3955-3185
Corresponding Author: Dr. Satwik Chatterjee
Extern, Department of Forensic Medicine and Toxicology, AIIMS Kalyani, West Bengal, India.
Email: drsatwikc356@gmail.com

ABSTRACT
What was once considered a subspecialty of dentistry has evolved to become a major arm of forensic science. As dental structures are extremely durable and of extreme individuality, they can provide vital information for the identification of human remains when all other evidence has been exhausted. This article looks back at the history of odontology through key events and case studies that have made an impact in the subject. It then goes on to look at how evidence can be provided for the estimation of age and sex, for the use of bite marks as evidence, for DNA profiling from dental remains, and for post-mortem identification from dental records. It then goes on to highlight the areas where the subject is performing well and those where it is struggling. The article also looks at the current trends that will impact practice in the future, including the use of cone-beam computed tomography (CBCT) and three-dimensional reconstructions. It also goes on to discuss the impact that digital dentistry, artificial intelligence, machine learning, radiomics, and even molecular biomarkers will have on the current practice of odontology for forensic purposes. The article also discusses the current challenges that odontological evidence is facing from an ethical and legal perspective and how these can be addressed by adopting standardized protocols and by adopting an interdisciplinary approach. The history of the subject is discussed and brought up to date on current trends and how the subject is being used in the role of the subject in the pursuit of justice and in humanitarian identification, and how it is at the forefront of the new era of precision forensic science.

Keywords: Forensic Odontology, Human Identification, Disaster Victim Identification (DVI), Dental DNA Analysis, Artificial Intelligence, Cone-Beam Computed Tomography (CBCT), Digital Forensic Dentistry.

INTRODUCTION
What is Forensic Odontology (Forensic Dentistry)? Forensic odontology is the application of dental knowledge. It can be used to solve crimes, to help identify human remains and to provide evidence at trials. Teeth and their surrounding tissues are unique to each individual and, as dental tissues are hard, they can provide evidence of great value when the rest of the body has decayed. They can provide a biological record of a person long after the rest of the body has begun to decay.

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The use of dental evidence for identification in criminal investigations has a long history that dates back to the ancient civilizations. However, the use of dental evidence for the purpose of providing evidence in criminal investigations did not receive any scientific recognition until the 19th century. Since then a large number of cases have been reported in which the identification of human remains using dental evidence played a crucial role in solving of criminal cases. The field of Forensic Odontology has since then developed into an important tool for the investigators and has become an integral part of the work of the forensic expert. In addition to criminal investigations, dental evidence is also used for a number of other purposes including age and sex estimation, bite mark cases, child abuse investigations, mass disaster situations and for the identification of missing persons. Today, Forensic Odontology is practiced all over the world. A number of organizations including the World

Society of Forensic Odontology, Interpol, and the FDI World Dental Federation, play an important role in promoting the use of dental evidence worldwide for identification purposes as well as in the development of dental identification protocols for mass fatalities as well as for humanitarian purposes. The use of dental evidence in identification situations around the world is governed by a number of standardized protocols. There have been several historic events, including major air crashes, earthquakes, tsunamis, and terrorist attacks, where forensic odontology played a role in the identification of human remains and providing evidence for criminal cases. The cases of forensic odontology involvement have contributed to the development of the discipline. Most of these cases have strengths and weaknesses in the dental evidence that was collected, especially bite marks. Most of the cases have been used for critical review and improvement of techniques and applications.

Forensic Odontology has changed significantly in the last few years. From a traditional, two-dimensional discipline with mainly a morphological approach, it has developed to a highly complex, interdisciplinary, modern diagnostic discipline within the Dental Sciences. High-tech terms such as Digital Dentistry, cone-beam CT (CBCT), as well as 3D-imaging techniques, intra-oral scans, and current approaches by Artificial Intelligence (AI), Machine Learning (ML), Radiomics, Molecular Genetics, as well as Digital Record Management have recently entered the field of Forensic Odontology. The sum of all these innovations led to the new development of what is called the “Forensic Odontology 5.0.” The basic idea behind this term is to support the expert as precisely as possible by means of precise diagnostics, especially by means of automatic image analysis as well as by data-driven decision-making.

Historical Evolution of Forensic Odontology

Forensic odontology has evolved considerably since the early days of dentistry. No longer is it an application of dentistry, but rather a major component in the identification of humans and in the administration of justice. Dental evidence has been used for the identification of individuals and for solving crimes for thousands of years. The use of teeth for the identification of human cadavers in various ancient civilizations such as those of Egypt, Rome, and China dates back to around that time. In many cases, teeth were used to identify cadavers that had suffered severe bodily injury to the rest of the body and were therefore unrecognizable.

One of the earliest recorded identifications by dental characteristics was reported in 49 BC, when Agrippina, mistress of the Roman Emperor Claudius, identified the decapitated head of her rival Lollia Paulina by her teeth. It is possible that other similar identifications could have taken place prior to this event but were not recorded. The application of dental identification in cases throughout the Middle Ages and the Renaissance were the exception rather than the rule. With an increasing knowledge of the human body and its individual characteristics, the awareness of individuality in dental characteristics continued to grow.

The scientific discipline of forensic odontology was established in the 18th and 19th centuries. One of the first documented cases of identification by the use of the teeth, was that of Joseph Warren, a physician and leader in the Boston Patriot group, killed on March 5, 1775, during the opening stages of the American Revolutionary War. ***Dr. Warren was identified by a dental bridge, made by silversmith Paul Revere.*** After the tragic Bazar de la Charité fire in Paris in 1897, Oscar Amoedo followed the work on the burnt bodies of the victims. His extensive work on postmortem change in the cadaver was the basis for the principles of identification of human remains by a forensic odontologist. Amoedo’s work culminated in a book, published in 1898, titled L’Art Dentaire en Médecine Légale. This book is a seminal work in the field of forensic odontology and is still considered a key text today. ***Amoedo is commonly referred to as the ‘Father of Forensic Odontology’.***

20th Century: The numerous developments in the dental health sciences have, in a large part, contributed to the vast increase in scope that the dental evidence can undergo. The dental identification of individuals can be greatly enhanced through the more complete and precise documentation of human dental characteristics by the dental chart. In addition, numerous restorative dental procedures such as root fillings, as well as all of the various types of dental appliances, have opened up new areas of application. None, however, have contributed as much as the specialized field of Prosthodontics. It was the use of dental records for the identification of war casualties that marked the beginning of the vast increase in the application of odontology to the many areas of criminal investigation.

In the 21st century, a transformation in the use of dental evidence in forensic investigations has occurred with the advent of the digital age. Not only have three-dimensional facial images and cone-beam computed tomography (CBCT) scans become invaluable in post-mortem identification, but also the use of digital dental records and, intraoral and other scans have enabled a rapid assessment of human remains. The use of micro-CT scans, of artificial intelligence and machine learning, commonly referred to as ‘deep learning’, for example, in the form of radiomics, as well as the potential use of molecular DNA from dental tissues have all increased the accuracy of dental evidence and its use in a variety of other forensic applications.

Period/Year	Historical Milestone	Key Individual(s)/ Organization	Significance to Forensic Odontology
c. 49 BC	Identification of Lollia Paulina through distinctive dental characteristics	Agrippina the Younger	Considered one of the earliest documented instances of dental identification, demonstrating the uniqueness of dentition.
Ancient Egypt (c. 3000–1000 BC)	Recognition of dental morphology and treatment in ancient civilizations	Egyptian physicians	Early understanding of dental anatomy laid the foundation for later forensic applications, although not used systematically for identification.
Ancient China (7th–13th Century AD)	Development of medico-legal practices incorporating physical characteristics	Chinese forensic scholars	Established early principles of forensic examination that later influenced medico-legal sciences.
1775	Identification of Dr. Joseph Warren after the Battle of Bunker Hill using a dental prosthesis	Paul Revere	First scientifically documented forensic dental identification using a prosthetic appliance, marking the birth of modern forensic odontology.
1849	Parkman–Webster murder case	Dr. Nathan Cooley Keep	First criminal conviction in the United States substantially supported by dental identification, establishing the legal value of dental evidence.
1897	Bazar de la Charité fire disaster, Paris	Dr. Oscar Amoedo	Mass fatality incident that demonstrated the effectiveness of dental identification and stimulated the scientific development of forensic odontology.
1898	Publication of *L'Art Dentaire en Médecine Légale*	Dr. Oscar Amoedo	First comprehensive scientific textbook on forensic dentistry; Amoedo became known as the "Father of Forensic Odontology."
Early 1900s	Introduction of systematic dental charting and radiographic documentation	Dental practitioners worldwide	Improved ante-mortem and post-mortem comparison, increasing identification accuracy.
1914–1945	World Wars I and II	Military dental services	Dental records became indispensable for identifying deceased military personnel when visual recognition was impossible.
1950s–1970s	Expansion of forensic dentistry into criminal investigations	International forensic experts	Bite mark analysis, age estimation, and dental profiling became integral components of forensic casework.
1984	Establishment of the American Board of Forensic Odontology (ABFO)	ABFO	Standardized education, certification, and professional guidelines for forensic odontologists.
1984	Introduction of DNA fingerprinting	Sir Alec Jeffreys	Revolutionized forensic identification and enabled the recovery of high-quality DNA from dental pulp and hard tissues.

1990s	Integration of computerized dental databases	National forensic agencies	Enhanced the efficiency of dental record comparison for missing persons and disaster victim identification.
2001	September 11 terrorist attacks	Interdisciplinary DVI teams	Demonstrated the critical role of forensic odontology in one of the largest modern mass fatality identification operations.
2004	Indian Ocean Tsunami	Interpol Disaster Victim Identification (DVI) teams	Large-scale international use of standardized dental identification protocols, highlighting global collaboration in forensic investigations.
2010s	Adoption of Cone-Beam Computed Tomography (CBCT) and three-dimensional imaging	Dental radiologists and forensic researchers	Improved age estimation, craniofacial reconstruction, dental comparison, and virtual forensic examinations.
2020s	Integration of Artificial Intelligence, Machine Learning, Radiomics, and Digital Dentistry	Global forensic research community	Marked the transition toward **Forensic Odontology 5.0**, enabling automated image analysis, predictive modelling, and precision forensic identification.

Table 01: Historical Evolution of Forensic Odontology

Why Teeth Never Lie

Your teeth are your body's most permanent part. As "silent witnesses" to crime, they can serve as powerful evidence to identify human remains. Teeth are the hardest tissues in the human body and as a result of their extremely hard nature (enamel, dentin and cementum), they are a unique and very durable piece of evidence that can provide exceptional resistibility to degradation of the environment. Teeth have withstood great damage in situations where other evidence such as fingerprints, facial skin, and even bone has been severely impaired or destroyed by heat over 1,000°C, long submersion in water, decomposition, chemical exposure, and great physical trauma only to be found, totally undamaged, as powerful evidence of human identity. Each individual has unique dental characteristics, including the morphology of their teeth, their eruption sequence, alignment and spacing, as well as their occlusal relationships. In addition, every individual has natural wear on their teeth, has had dental restorations, prostheses, etc. Many individuals also have dental anomalies that have been present since birth. Even in the case of identical twins, who have nearly identical DNA, there are likely to be differences in the dental characteristics of each individual due to a variety of factors, including environmental, diet, oral hygiene, and dental treatment. As a result, it is highly unlikely that any two individuals will have the exact same set of teeth, and as a result, the comparison of dental evidence is a very reliable form of personal identification.

Dental restorations, whether natural or artificial, can be identified and compared with any available ante-mortem dental records. All modern dental treatment is recorded in some form whether intra-oral and extra-oral photographs, radiographs, or computerized dental charts. Such records can be retrieved and compared with any post-mortem dental evidence found. In many disasters and crimes around the world, dental comparison evidence is the main form of personal identification. It can provide vital information even when much of the rest of the body has been destroyed by fire, water or Animals.

In addition to the identification of human remains, the teeth of a deceased person are a protected reservoirs of genetic information and other evidence from long after the death. The dental pulp, found in the interior of the tooth, is protected from external contamination by the hard dental structures. The high quality of the DNA, both nuclear and mitochondrial, found in the dental pulp even in cases of skeletonized or decomposed human remains makes the teeth an ideal source of biological evidence for a variety of uses. Dental evidence is also used in kinship determinations and to identify missing individuals. Recently, evidence from the oral microbiome, stable isotopes, and a variety of other newly emerging methods of analysis, including proteomics, have found use as evidence of a person's ancestry, geographic origin, dietary habits, age, and environmental exposure, all obtained from a single tooth.

In conclusion, rarely can teeth 'lie' as all dental hard and soft tissues and their associated contents such as enamel, dentin, cementum, and dental soft tissues, even from endodontically treated teeth that have had all dentin and hard and soft tissues removed, will provide permanent bioevidence of every human being. Moreover, each individual's teeth, whether natural or replaced by dental hard and soft tissues, will have provided a unique anatomical feature, or features and/or a wealth of bio information as well as an ever-increasing amount of digital bio information. It therefore follows that the bioevidence of human teeth will no doubt feature large in the ongoing drive for more Precision Medicine, or even for even more Intelligent or 'Smart' Medicine, and that this bioevidence will be utilized in a wide variety of investigations, be they of a criminal or humanitarian nature.

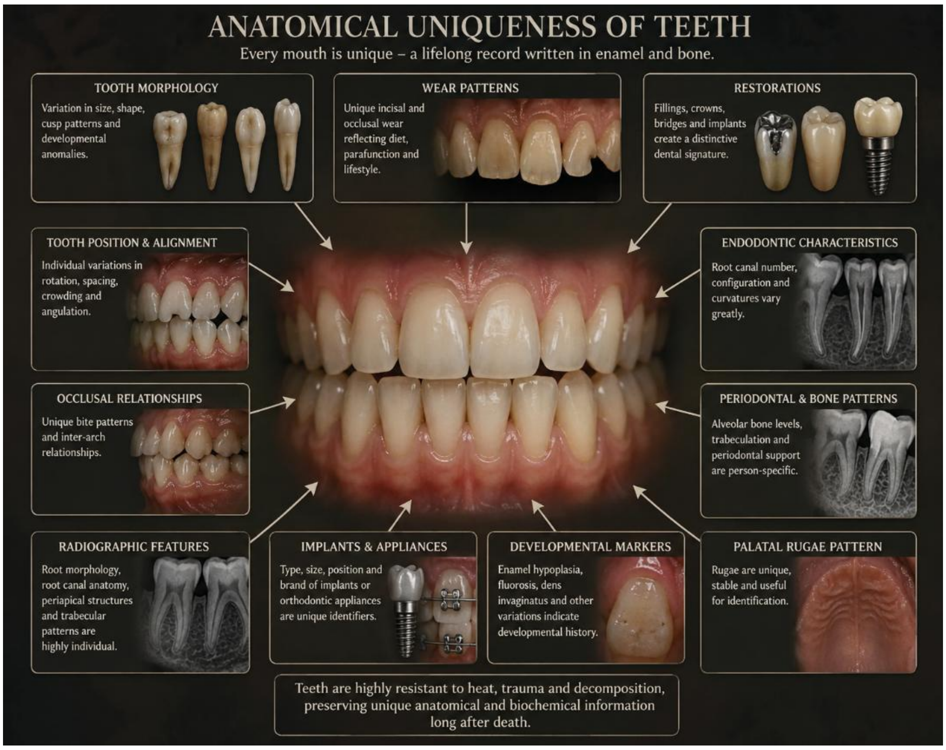

Figure 01: Anatomical Uniqueness of Teeth

Landmark Cases that Changed the Course of Forensic Dentistry

Country/Region	Year	Landmark Case/Event	Role of Forensic Odontology	Scientific Significance
Ancient Rome (Italy)	49 BC	Identification of Lollia Paulina	Recognition through distinctive dentition	Earliest documented example of dental identification.
United States	1775	Identification of Dr. Joseph Warren	Dental prosthesis comparison	First scientifically documented forensic dental identification.
United States	1849	Parkman–Webster Murder Case	Denture identification	Established dental evidence as admissible in criminal courts.
France	1897	Bazar de la Charité Fire	Burned victim identification	Inspired Dr. Oscar Amoedo to establish modern forensic odontology.
Germany	1945	Identification of Adolf Hitler	Dental restorations and radiographs	Demonstrated the reliability of dental evidence in wartime investigations.
United Kingdom	1987	King's Cross Underground Fire	Dental identification of fire victims	Reinforced the importance of dental

				records in fire disasters.
United States	1974–1979	Ted Bundy Serial Murder Case	Bite mark comparison	Popularized bite mark evidence in criminal investigations.
United States	1978	John Wayne Gacy Investigation	Dental chart comparison	Enabled identification of multiple unidentified homicide victims.
Canada–Ireland	1985	Air India Flight 182 Bombing	Dental comparison of fragmented remains	Demonstrated international collaboration in aviation disaster identification.
Bosnia & Herzegovina	1995	Srebrenica Mass Graves	Dental records with DNA	Important humanitarian identification during war-crime investigations.
United States	2001	September 11 Terrorist Attacks	Dental records, radiographs, prostheses	One of the largest forensic identification operations in history.
Indonesia, Thailand, Sri Lanka & India	2004	Indian Ocean Tsunami	Interpol DVI dental identification	Thousands of victims identified using standardized dental protocols.
Pakistan	2005	Kashmir Earthquake	Dental examination in DVI operations	Highlighted forensic odontology in large-scale earthquake response.
China	2008	Sichuan Earthquake	Dental record comparison	Improved national disaster victim identification systems.
Atlantic Ocean (France/Brazil)	2009	Air France Flight AF447	Dental charting and radiographs	Successful identification after prolonged underwater recovery.
Japan	2011	Great East Japan Earthquake and Tsunami	Dental chart comparison and digital databases	Accelerated development of national electronic dental record systems.
Norway	2011	Utøya Terror Attack	Dental identification	Demonstrated rapid forensic response in mass casualty incidents.
Ukraine (International Investigation)	2014	Malaysia Airlines Flight MH17	Digital dental records and DNA	Showcased multinational forensic collaboration.
Nepal	2015	Nepal Earthquake	Dental examination under Interpol DVI	Reinforced the importance of forensic dental teams in humanitarian missions.

South Korea	2022	Itaewon Crowd Crush	Dental records and radiographic comparison	Assisted identification of severely traumatized victims.
Türkiye (Turkey)	2023	Kahramanmaraş Earthquake	Dental identification integrated with DNA	Demonstrated the role of digital forensic dentistry in modern disaster response.

Table 02: Landmark Forensic Odontology Cases Across the World and Their Scientific Contributions in Forensic Dentistry

Year	Case/Event	Role of Forensic Odontology	Impact on the Discipline
1999	Odisha Super Cyclone	Dental examination of decomposed victims	Highlighted the need for organized forensic dental identification in India.
2001	Gujarat (Bhuj) Earthquake	Dental examination during victim identification	Increased awareness of forensic odontology in national disaster response.
2004	Indian Ocean Tsunami (Tamil Nadu, Andaman & Nicobar Islands)	Interpol DVI protocols, dental chart comparison, radiographic matching	India's first large-scale forensic odontology deployment in an international humanitarian disaster.
2006	Mumbai Suburban Train Bombings	Dental comparison of fragmented and burned remains	Demonstrated the usefulness of dental evidence in terrorist incidents.
2008	Mumbai 26/11 Terror Attacks	Dental examination integrated with DNA profiling	Reinforced multidisciplinary forensic identification in mass-casualty events.
2010	Air India Express Flight IX-812 Crash (Mangalore)	Dental identification of severely burned victims	Confirmed the value of dental records when visual identification was impossible.
2013	Uttarakhand Flash Floods	Dental examination alongside skeletal and anthropological analysis	Supported identification of highly decomposed disaster victims.
2020	Air India Express Flight IX-1344 Crash (Kozhikode)	Dental charting, radiographs, and DNA correlation	Highlighted the importance of digital dental records in aviation disaster victim identification.
2023	Balasore Triple Train Collision (Odisha)	Dental records, radiographs, and DNA profiling	Demonstrated the role of forensic odontology in one of India's largest railway disasters.
2025	Air India Flight AI171 Crash (Ahmedabad)	Multidisciplinary DVI involving forensic odontologists, dental charting and radiographic comparison where feasible, integrated with extensive DNA profiling because of severe thermal damage	One of India's most complex aviation DVI operations, emphasizing the importance of coordinated forensic pathology, odontology, anthropology, radiology, and molecular genetics in high-temperature mass-fatality incidents.

Table 03: Notable Forensic Odontology Cases in India

Dentistry in Mass Disaster Identification

Disasters, whatever be the cause, are in most cases very bloody. The identification of the victims in such cases is very often not possible due to severe thermal damage, fragmentation, decomposition or other environmental influences. In most such cases, the only parts of the human body which can be used for identification are the teeth. In case of mass disasters, therefore the role of the dentist, the expert in forensic odontology, becomes extremely important in the process of Disaster Victim Identification (DVI). The dentist has to work fast, to achieve results of scientific value. The use of dental evidence for the identification of human remains in mass disasters is accepted worldwide and is one of the three primary methods of identification together with fingerprints and DNA. According to the International Criminal Police Organization (INTERPOL) Dental evidence is one of the three primary methods of victim identification.

The information that can be used by the forensic odontologist regarding the human dentition in identifying human remains from mass disasters is based on several hard and individual structures of the dental tissues. The hardest structure of the human body, dental enamel, remains capable of identification even after severe thermal changes, mechanical trauma, or advanced decomposition. Each human mouth has a unique set of dental structures that can be used to establish the identity of human remains even after death. Therefore, many characteristics of the human dentition are used by the forensic odontologist in identifying human victims. These dental characteristics include tooth morphology, natural dental structures, restorations, dental prostheses, orthodontic appliances, dental wear, root morphology, and anomalies of dental development that occurred while an individual was still in utero. Any information regarding the human dentition of any individual can be gathered and compared with the information gathered from postmortem dental analysis of human remains for the purpose of human identification. The information can be obtained in the form of clinical dental records, dental radiographs, 3 dimensional computerized tomographic (CAT) scans, intraoral and extraoral photographs, dental casts and models, etc.

The INTERPOL DVI protocol follows four different phases. Firstly there is the scene examination, where the team begins to search for and gather any relevant evidence. Secondly, there is the post-mortem data collection, where the team use forensic odontology to gather as much dental evidence as possible from the victim's remains and record the findings. This information can then be compared with the victim's ante-mortem dental records, which can be obtained from family dentists, hospital records, military records, dental insurance providers and even from national dental registries. The final phase of the protocol is the reconciliation, where the team attempt to match any found fingerprints with the dental and DNA evidence in order to identify the victim.

The application of the maxillofacial expert in disaster situations all over the world has become more evident in recent years, and has provided a valuable aid to the identification of victims in most disasters. The largest Disaster Victim Identification (DVI) operation in history was the one carried out as a consequence of the Indian Ocean tsunami in 2004, where thousands of bodies from all over the world were identified by the maxillofacial expert using the INTERPOL standardized dental identification protocol for DVI. In the same way, the maxillofacial expert was applied in the identification of the victims of the terrorist attack of September 11, 2001 in the United States, the Air France Flight 447 crash in 2009, the Great East Japan Earthquake and Tsunami in 2011, the Nepal earthquake of 2015, the downing of Malaysia Airlines Flight MH17 in 2014, the Gujarat earthquake in 2001, the 26/11 terrorist attacks in Mumbai, the crashes of Mangalore and Kozhikode, the Balasore train collision, and the Air India Flight AI171 crash. In most of these situations, the application of the maxillofacial expert has been carried out as part of a DVI team that has worked in conjunction with other experts in order to provide an accurate identification of the victims through different methods of identification, such as radiological identification, forensic anthropology, and DNA profiling.

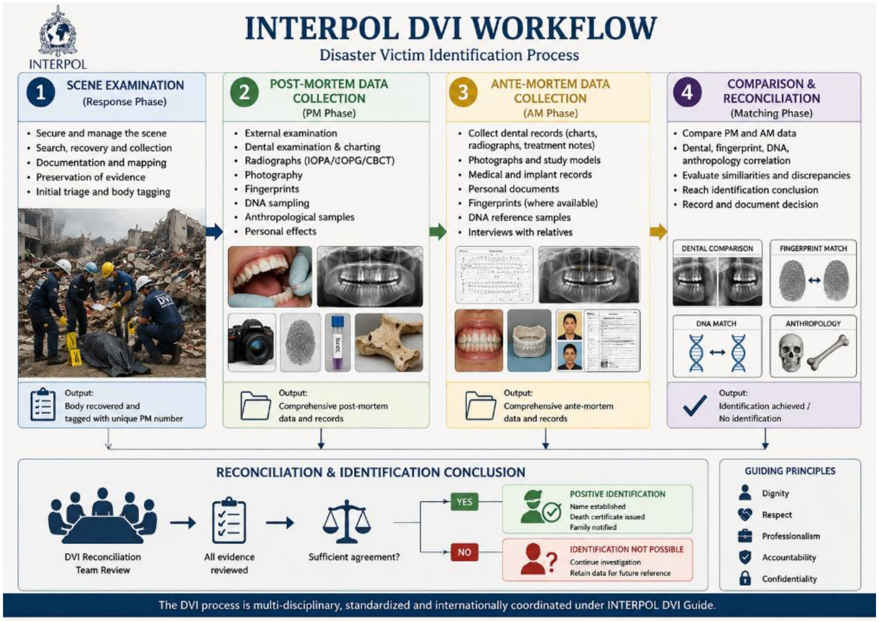

Figure 02: Interpol DVI Workflow associated with Forensic Odontology

Modern Technologies Revolutionizing Forensic Odontology

The use of the latest digital technologies is changing the field of dental identification. For a long time, Forensic Odontology was a purely manual specialty. The expertise of the dental expert was largely based on his or her experience and on the analysis of the available evidence. As a result, accuracy and speed of processing were enhanced. The latest digital technologies are now also speeding up the processing of a case while allowing to deal with a greater number of cases. The greater volume of data also makes it possible to increase the precision and to set up a more structured approach. Hence, the use of the latest digital technologies will enable the setting up of a new approach of dental identification, namely Forensic Odontology 5.0, based on precision diagnostics and on the use of artificial intelligence in a completely digital-based forensic environment.

New technologies are now incorporated into the practice of Forensic Odontology, the most notable being the range of different digital technologies now used by the forensic odontologist. A fundamental change to many of these changes has been the use of Cone-Beam Computed Tomography or CBCT. The use of this technology allows the craniofacial structure to be viewed three-dimensionally in extreme detail with little distortion. Information from three-dimensional images are useful not only for the estimation of the age of a individual as well as for sex determination but also for identification purposes. Postmortem records can be compared with the records of individuals known to have died to confirm or to rule out an identification in individual cases. The three-dimensional images obtained by the use of CBCT allow for accurate facial reconstructions from skeletonised remains by a variety of different techniques. Micro-CT or micro-radiology is another application that allows even greater detail in structures such as individual teeth as well as in dental structures and tissues in general. Three-dimensional images are obtained by using highly focused X-ray beams which allow a specimen to be examined in extreme detail without the danger of any damage being caused.

The dental information of individuals who have died can be readily managed by digital dentistry. The dental information of individuals who have died can be made into digital dental records by intra-oral scanners, and these dental records as well as the digital dental records (EDR) that are stored in the cloud, CAD/CAM dental records, three-dimensional surface images of the human face, and virtually reconstructed human faces can be all retrieved and analyzed in short order. Images of the dental records of individuals who have died can be easily compared with the images of dental records of individuals who are alive in order to identify them. In addition, three-dimensional surface images of the human face can be used for making a facial approximation, for analyzing bite marks that have been made by human bites, and for preserving evidence digitally without actually touching the physical evidence. In the fast process of identification of human remains by means of Forensic Odontology, as it is the case in disaster victim identification (DVI) as well as in missing persons, a number of processes can be supported by so-called Artificial Intelligence (AI) and Machine Learning (ML) to increase efficiency. In order to support the process of age estimation and of sex estimation, for example, by means of radiographs, so-called deep learning algorithms are being used in order to automatically detect single teeth within an image as well as to separate them from the surrounding tissues. The algorithms can be connected to all kinds of scanners, such as CBCT scanners as well as to conventional panoramic units, dental archives and digital dental records, in order to support the odontological identification of humans in a fast and efficient way.

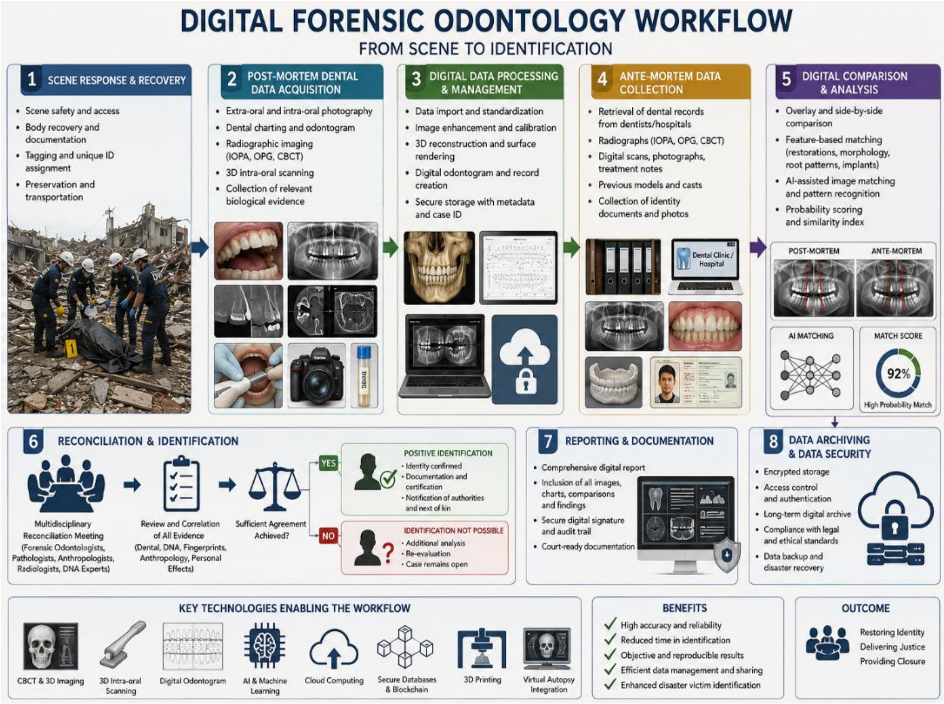

Figure 03: Modern Technologies in Forensic Odontology (Digital Workflow)

Artificial Intelligence in Forensic Odontology

Artificial intelligence (AI) is presently changing the way of practice of the specialized branch of Forensic Science known as Forensic Odontology. ***The application of AI in Human Identification as well as in other medico-legal cases has the potential of speeding up the process of existing methods of analysis of dental evidence by computer-based methods and by comparison of dental records automatically.*** Dental identification evidence at present is time-consuming and is prone to variations between individual examiners. The existing methods of dental identification are based on visual examination of dental information which have been recorded in the form of ***dental radiographs, dental charts, and morphological characteristics of teeth and dental tissues.*** The vast amount of information obtained from the above can be analyzed by the use of ***machine learning (ML), deep learning (DL) and computer vision (CV)*** which are able to process large amount of information automatically and provide quick and accurate results with minimal human error.

Newer approaches to Automatic Dental Analysis have emerged in the past years and are often referred to as "end-to-end" ***Automated Dental Analysis Systems (ADAS).*** Within the scope of this paper, the term AI-based matching systems will be used. So-called algorithms, mainly based on ***Convolutional Neural Networks (CNNs)*** can automatically detect all teeth on one dental image, also dental restorations (e.g., crowns and bridges), dental implants as well as root filled teeth. After segmentation of all structures of interest an automatic generated digital ***odontogram, so-called "OD,"*** is generated. The newly created ***odontogram*** can easily be matched against the dental records of an individual, who is of interest for identification purposes. As already mentioned before, a major advantage of the ***AI-based matching systems is the huge time saving especially in case of a large number of victims in a mass disaster situation (DVI).***

Using AI in forensic odontology allows for a wide range of both estimated and predicted characteristics of both biological and non-biological origin. In terms of age estimation, it has been shown that ML models are able to accurately assess the age of individuals through the use of tooth developmental parameters as well as a wide range of other measurements and/or calculations derived from a variety of different tooth types, via their corresponding radiographic images. ***Using ML models in conjunction with CBCT images of the skull, sex estimation in humans has also been reported with high levels of accuracy through the use of a wide range of both craniofacial and***

odontometric measurements. This allows for AI systems to not only estimate and/or predict characteristics of age in humans, but also to estimate ancestry as well as provide assistance in bite mark cases through comparison to antemortem dental records. ***AI systems can also be used to create facial reconstructions from skull remains as well as perform craniofacial superimposition*** in order to provide investigators with additional lines of evidence in human identification cases. The use of AI in forensic odontology is solely intended to assist the odontologist in his or her work. In addition to the well-known problems such as possible bias in the algorithms, the analysis of images of poor quality, the large number of needed annotated data sets of a forensic nature, the many ethical questions, and the often not yet clarified legal admissibility of the results, a worldwide standardization of the applications of AI in the forensic odontological examination has to be achieved.

As digital dentistry is evolving rapidly, the integration of ***AI with current CBCT*** (cone-beam computed tomography) technology, as well as with ***radiomics, genomic information and even with dental records stored in blockchain, and with virtual forensic systems***, will bring to the area of identification of humans in both a forensic and in a medico-legal setting, the management of massive number of victims in disasters, and the evaluation of dental evidence in criminal investigations, the ***new area of Forensic Odontology 5.0***.

Molecular Forensic Dentistry

Teeth have long been a source of information for the identification of human remains. The morphology of the external form of the teeth has been the main focus of the work of the forensic odontologist, but within the teeth are contained a multitude of complex molecular structures that form the bulk of the evidence that can be found in the hard mineralized structures of the teeth. Described by many in the field as ***'biological time capsules'***, the teeth of the individual act as a vast storage hold of genetic, proteomic and biochemical evidence that can provide robust evidence of the presence of an individual for long periods of time following the decay of soft tissues. As the structures of enamel and dentin are encased within the molecular evidence, they are able to resist the majority of environmental deterioration caused by heat, moisture, biological activity, chemical assault and physical trauma, thus dental structures become one of the most durable sources of molecular evidence to be found in the human body and has become a vital tool for the forensic scientist.

DNA profiling from dental pulp also forms part of the work of molecular forensic dentistry. Dental pulp, dentin and even cementum from extracted teeth, natural shed teeth and even from within the oral cavity all contain high quality nuclear and even mitochondrial DNA. This can be used for individual identification, for kinship determination, for missing person identification and for disaster victim identification (DVI) where other biological evidence has been destroyed. A range of techniques have been developed for the analysis of such evidence and these have increased in recent years with the ***introduction of PCR, of STR (Short Tandem Repeat) analysis, of Next Generation Sequencing (NGS) and of complete mitochondrial genome sequencing.***

In terms of the identification of species, the proteomics of dental tissues can be used for the comparison of stable dental proteins. The use of such evidence can be particularly useful in cases where the remains of a person have been subjected to severe degradation, to the extent that DNA evidence is either lacking or would be of no value. In such cases, it is possible that other forms of biological evidence have been recovered from the scene of a crime, but this would not be of any use for the purposes of identification. As has already been stated, there is an ever-increasing interest in the use of epigenetics within the field of forensic science. ***Epigenetics*** are changes that occur to the DNA of an individual, which can affect gene expression, and are generally considered to be stable and to be passed down from one generation to the next. The majority of studies that have utilized epigenetics for identification purposes have looked at the stable DNA methylation patterns that are present within cells. These patterns can provide estimations of an individual's chronological age, through the identification of various ***'age-dependent' molecular modifications***, which have been shown to accumulate over time. In addition to the use of epigenetics for identification purposes, there is also considerable interest in the oral microbiome, not only for identification purposes, but also for the estimation of the post-mortem interval, as well as giving an indication of an individual's lifestyle and various environmental exposures.

Bite Mark Analysis: Past, Present, and Future

Bite mark comparison, or the comparison of human bites, is one of the most contentious areas of application in forensic odontology today. For decades, evidence of human biting has been used to identify suspects in crimes such as homicide, sexual assault, child abuse, and other violent crimes. Bite mark evidence is used for identification of individuals on the basis of the concept of uniqueness of the human dentition. A human bite is defined by the forensic science literature as a ***"patterned injury produced in skin and other soft tissues by contact with teeth and/or surrounding tissues of the mouth."*** Such injuries are considered to be unique to the individual, and have historically been used as evidence in criminal cases. There are many documented cases of the use of bite marks as evidence in criminal proceedings. For example, the notorious serial killer Ted Bundy was reported to have left human bite marks at the scenes of some of his crimes. Evidence of human biting is still used today as evidence in criminal cases.

More recently, however, the application of bite mark comparison has on several occasions led to the wrongful conviction of a person later exonerated by DNA. The scrutiny brought to bear by these wrongs has spawned a comprehensive review of the subject of bite mark comparison by such organizations as the National Academy of Sciences as well as the ***President's Council of Advisors on Science and Technology (PCAST)*** as to how comparison of bite marks might be elevated to a stronger scientific basis with more objective methods of comparison as well as with more effective methods of comparison and analysis utilizing more objective methodologies.

However, no longer is there reliance on simple comparison of a suspect's teeth and the corresponding mark on a victim. Rather, various technologies are being utilized for documentation and comparison of marks and injuries in an attempt to establish a link between a perpetrator and the mark or injury left on the victim. High quality digital photographs, three-dimensional surface images, Cone-Beam Computed Tomography (CBCT) scans, and even photogrammetric images are being utilized and compared. Also, computer-assisted overlays are able to superimpose images, thus allowing for precise comparison of various marks. As far as emerging technologies are concerned, use of artificial intelligence and machine learning is currently being explored for their utilization in bite mark analysis. These technologies could potentially automate the process of pattern recognition as well as quantify a variety of the morphological characteristics of a given mark or injury, thus having the potential to decrease human error or bias. DNA evidence found in saliva that has been left on a victim during the time of a crime is also becoming one of the most reliable pieces of evidence in the armory of the forensic odontological experts, often even proving to be more solid than the above-mentioned bite mark analysis.

Bite mark analysis in the future will be an entirely integrated forensic discipline where many experts, from various backgrounds (dental, anthropological, pathological, biologist, crime scene investigators, etc.), work together as a team in order to examine all of the available physical evidence found at crime scenes and in the aftermath of human rights violations. Instead of relying on traditional morphological comparison to try to match a single set of human dental records to a human bite mark, bite mark analysis will become yet another form of physical evidence that will be found in association with other types of physical and biological evidence. Together, all of the various forms of physical and biological evidence will provide investigators and prosecutors with enough information to determine the circumstances of a crime or human rights violation. DNA profiling information of saliva at an incident where a human bite mark injury was found will, more often than not, become the best physical evidence found at a crime scene. In such cases, the bite mark itself will likely become extraneous information, although it can serve to support other pieces of physical evidence found at a scene of violence or human rights abuse.

Age, Sex, and Ancestry Estimation

Estimation of age, sex and ancestry by means of dental evidence is a further area of application of dental analysis in individual identification. The evidence provided by the dental morphology of an individual, and in particular by the dental remains in the jawbone, which decay long before the soft tissues, and are resistant to the action of environmental agents, can be used in a large number of situations and by means of a wide range of methods, to establish a biological profile of a person with a satisfactory degree of accuracy. Dental evidence has recently become a relevant element in many situations of forensic investigation, and it is used in the identification of human remains found in all types of circumstances, in missing person cases, in skeletal remains of archaeological sites, as well as in other crimes. Combining dental analysis with information provided by anthropology, dental radiology and molecular biology, a large amount of effective evidence can be produced which can be used for the identification of individuals.

Dental age assessment is one of the most established methods for estimating human age. Since teeth develop in a genetically determined but environmentally affected process from fetal life through adulthood, it is possible to study tooth development in order to date children and adolescents as well as adults. For children and adolescents several parameters have been proposed by several authors, such as ***Demirjian (1989), Moorrees and McClean (1960), Nolla (1960), Cameriere (2001), and the "London Atlas" (2006)***. These parameters can be accurately assessed by means of a panoramic radiograph and, more recently, by three-dimensional imaging such as ***cone-beam computed tomography (CBCT).*** On the other hand, in the adult dentition, dental age is assessed by several parameters that are able to evaluate the degree of aging of dental hard tissues, such as secondary dentin deposition, reduction of the pulp chamber, cementum annulation, root transparency, and several components of wear, including surface wear (attrition and abrasion) and periodontal attachment loss. In the last years, three-dimensional imaging, radiomics, and artificial intelligence for the automatic assessment of dental tissues have introduced new perspectives in the field of dental age assessment, allowing to accurately measure complex morphological features of dental tissues, such as the ***pulp-to-tooth space.***

As in other parts of the skeleton, ***dental sexing is based on sexual dimorphism in physical characteristics of both teeth and their supporting structures***. While some teeth exhibit greater sex differences than others, measurement of dimensions of individual teeth, particularly, provides some of the most consistent results. Dental crown morphology, as well as root length and cross section of individual teeth, also can be used to predict sex of both dentate and edentate remains. In particular, the permanent canine displays greater sex differences than any other dental element, and therefore can be one of the most reliable indicators of sex, particularly when utilized in combination with odontometric measurement, and, especially, with the use of high resolution three dimensional images (CBCT scans). With such images, accurate sex determinations also can be made by measuring tooth volume, assessing characteristics of the tooth pulp and other features of the dentition, as well as by several mandibular measurements. As in other aspects of forensic anthropology, in situations in which identification of the skeleton is particularly difficult (e.g., due to mutilation) analysis of DNA, especially from hard dental tissues and pulp, particularly of the ***Amelogenin gene, provides the most reliable method of determining sex of human remains.***

Estimating the Ancestry of an Individual using Dental Evidence. In many cases, evidence obtained from the dental remains of an individual can be very useful to estimate the ancestry of an individual, especially when identifying human skeletal remains. As there is considerable variation between different populations, evidence from dental remains of an individual should be interpreted with caution; however, variations in dental morphology, non-metric traits, cusp patterns, root morphology, and craniofacial traits can give clues about an individual's ancestry. ***Anterior teeth, for example, have a number of cusp patterns that are found in greater frequency in certain populations, such as shovel-shaped incisors and Carabelli's cusp.*** Also, certain non-metric traits, such as variation in root morphology, are found in greater frequency in some populations than others. In addition, ***stable isotope analysis of dental enamel can be used to determine the geographical origin of an individual as well as their history of migration and change in diet.*** Genome-wide and oral microbiome studies have also emerged as additional tools for estimating an individual's ancestry as well as environmental background.

Ethical and Legal Concerns

Ethical/Legal Issues	Concerns	Recommended Practices
Patient Confidentiality	Unauthorized disclosure of dental records and personal information	Ensure secure storage, restricted access, and compliance with data protection laws.
Informed Consent	Use of dental records or biological samples without appropriate authorization	Obtain informed consent whenever applicable and adhere to ethical guidelines.
Chain of Custody	Tampering, contamination, or loss of forensic evidence	Maintain complete documentation and uninterrupted evidence handling procedures.
AI and Digital Ethics	Algorithmic bias, lack of transparency, and erroneous automated decisions	Use validated AI systems with expert human oversight and explainable AI principles.
Professional Competency	Errors arising from inadequate training or subjective interpretation	Promote continuous education, accreditation, and adherence to standardized forensic protocols.
Human Rights and Dignity	Respect for cultural, religious, and family sensitivities during victim identification	Conduct investigations with dignity, transparency, and compassion while following international DVI guidelines.

Table 04: Ethical & Legal Concerns in Forensic Odontology

Future Roadmap

The future of forensic odontology will be influenced by four main elements: Digital dentistry, Molecular biology, Artificial intelligence (AI) and precise forensic science. These elements of the future of forensic odontology. Digital dentistry, Molecular biology, Artificial intelligence (AI) and precise forensic science will merge together and transform the work flow of the forensic odontologist into an integrated and high-tech, data-driven work flow to identify humans as quickly and accurately as possible and in an objective way. The images can be analyzed automatically by the computer, the process of learning deep can be carried out by AI, the dental records can be matched by AI and therefore the work of the forensic odontologist will be revolutionized in both identification cases and in mass disaster situations (DVI). A number of new methods in forensic odontology will be introduced by CBCT scans, 3D facial reconstruction, virtual autopsy and the digital odontograms. The documentation and comparison of evidence in identification of victims of single and mass disasters will be greatly enhanced by these new methods.

Molecular evidence such as data generated by next-generation sequencing (NGS), epigenetic information of human age, the oral microbiome, proteomics, and stable isotope analysis of evidence, can be utilized by the forensic odontologist. Dental information can be stored utilizing Blockchain technology and be correlated with corresponding dental records and be shared globally via cloud-based databases while protecting individual and other sensitive information.

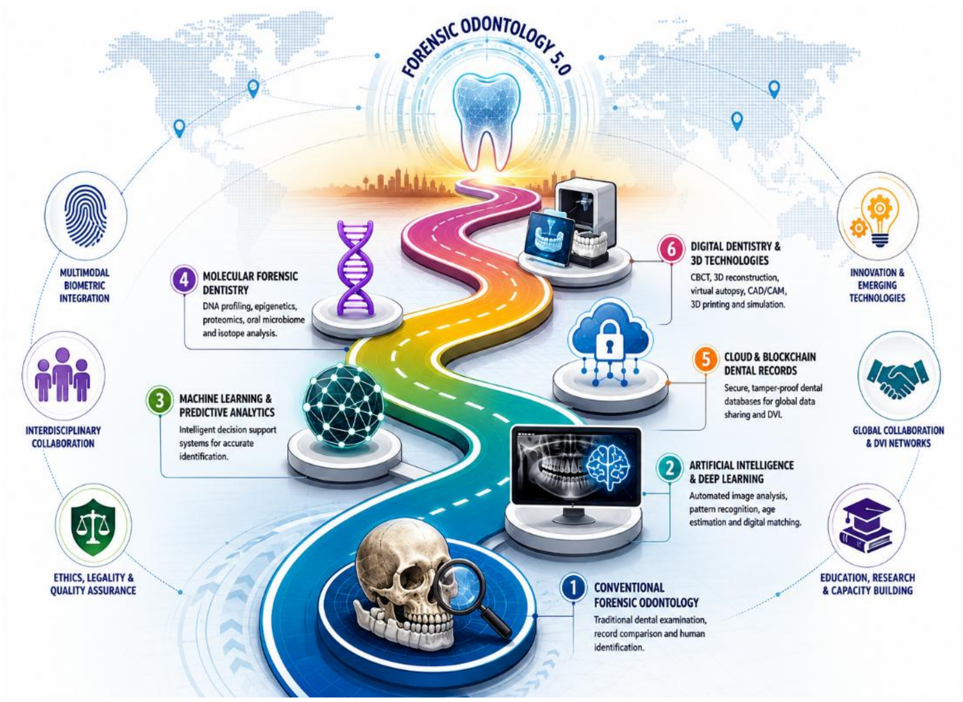

Figure 04: Future Roadmap in Forensic Odontology (2026-2050)

CONCLUSION

Forensic odontology has developed much from the initial simple method of dental comparison by visual inspection. It is now a specialized, multi-faceted, technologically advanced arm of forensic science. Teeth are individual, durable and complex thus forming a unique evidence for identification of humans, assessment of age and sex, racial identification, crime solving, mass disaster management and humanitarian crisis. Dental evidence of origin in landmark cases, mass disasters and various humanitarian missions around the world have significantly influenced the use of dental evidence in legal and medical systems worldwide.

New technology for the assessment of dental evidence is being increasingly incorporated into the work of the odontological expert. By means of digital dentistry and three-dimensional representations (conventional as well as by means of cone-beam CT scans), dental experts are in a position to process and analyze greater amounts of data than previously. Furthermore, molecular forensic methods, radiomics and the use of artificial intelligence, as well as secure databases, are increasingly entering into the analysis of dental evidence. However, despite the incorporation of such novel technology, the dental expert has not become superfluous. On the contrary, his area of work is being expanded. It is up to the individual expert to give a sound, evidence-based scientific judgment on the basis of the data gathered and processed in line with predefined criteria. However, a variety of problems, not least of all of an ethical nature, the expert must solve. He is not only dependent on an up-to-date knowledge of the relevant legislation, but also on the secure storage of digital data and on an internationally coordinated approach in order to be able to provide evidence by means of teeth and to have such evidence admitted as reliable proof in court.

Future perspectives of the discipline of Forensic Odontology will develop towards Forensic Odontology 5.0 and will need support of interdisciplinary research and development and a modernization of current methods with a subsequent worldwide standardization. As an important component of precision of the new forensic medicine, the future Forensic Odontology will be based on an integration of clinical dentistry with the newest computational science achievements as well as with the results of molecular biology and humanitarian-forensic practices.

REFERENCES

1. Pretty IA, Sweet D. A look at forensic dentistry—Part 1: The role of teeth in the determination of human identity. *Br Dent J.* 2001;190(7):359–366.
2. Pretty IA, Sweet D. A look at forensic dentistry—Part 2: Teeth as weapons of violence. *Br Dent J.* 2001;190(8):415–418.
3. Pretty IA. Forensic dentistry: 1. Identification of human remains. *Dent Update.* 2007;34(10):621–622.
4. Pretty IA, Sweet D. The scientific basis for human bitemark analyses—A critical review. *Sci Justice.* 2001;41(2):85–92.
5. Sweet D, Hildebrand D. Recovery of DNA from human teeth by cryogenic grinding. *J Forensic Sci.* 1998;43(6):1199–1202.
6. Avon SL. Forensic odontology: The roles and responsibilities of the dentist. *J Can Dent Assoc.* 2004;70(7):453–458.
7. Stavrianos C, Petalotis N, Metska M, Stavrianou I. Forensic dentistry: Current concepts and applications. *Res J Med Sci.* 2010;4(2):72–79.
8. Senn DR, Weems RA. *Manual of Forensic Odontology.* 5th ed. Boca Raton: CRC Press; 2013.
9. Clement JG, Ranson DL. *Craniofacial Identification in Forensic Medicine.* London: Arnold Publishers; 1998.
10. Acharya AB, Sivapathasundharam B. *Forensic Odontology.* 3rd ed. New Delhi: Jaypee Brothers Medical Publishers; 2020.
11. Hill AJ, Lain R, Hewson I. Preservation of dental tissues under extreme environmental conditions. *Forensic Sci Int.* 2011;205(1–3):40–46.
12. INTERPOL. *Disaster Victim Identification Guide.* Lyon: International Criminal Police Organization; 2023.
13. INTERPOL. *Disaster Victim Identification Forms.* Lyon: International Criminal Police Organization; 2023.
14. Berketa JW. Disaster victim identification. *Forensic Sci Med Pathol.* 2015;11(2):203–207.
15. Sweet D. Why a dentist for identification? *Dent Clin North Am.* 2001;45(2):237–251.
16. Berketa JW, James H, Lake AW. Forensic odontology involvement in mass disaster investigations. *Forensic Sci Int.* 2012;219(1–3):84–89.
17. Pretty IA. The barriers to achieving an evidence base for bitemark analysis. *Forensic Sci Int.* 2006;159:S110–S120.
18. Bush MA, Bush PJ, Sheets HD. Similarity and match rates of the human dentition. *J Forensic Sci.* 2011;56(3):621–628.
19. National Research Council. *Strengthening Forensic Science in the United States: A Path Forward.* Washington, DC: National Academies Press; 2009.
20. President's Council of Advisors on Science and Technology (PCAST). *Forensic Science in Criminal Courts: Ensuring Scientific Validity of Feature-Comparison Methods.* Washington, DC; 2016.
21. Cameriere R, Ferrante L, Cingolani M. Age estimation in children by measurement of open apices. *Int J Legal Med.* 2006;120(1):49–52.
22. Demirjian A, Goldstein H, Tanner JM. A new system of dental age assessment. *Hum Biol.* 1973;45(2):211–227.
23. Moorrees CFA, Fanning EA, Hunt EE. Formation and resorption of teeth. *J Dent Res.* 1963;42:1490–1502.
24. Kvaal SI, Kolltveit KM, Thomsen IO, Solheim T. Age estimation of adults from dental radiographs. *Forensic Sci Int.* 1995;74(3):175–185.
25. Nolla CM. The development of permanent teeth. *J Dent Child.* 1960;27:254–266.
26. Cameriere R, Ferrante L, De Angelis D, Scarpino F, Galli F. The comparison between Demirjian's and Cameriere's methods. *Int J Legal Med.* 2008;122:493–497.
27. Franklin D. Forensic age estimation in human skeletal remains. *Wiley Interdiscip Rev Forensic Sci.* 2019;1:e1321.
28. Ge ZP, Yang P, Li G, et al. Artificial intelligence applications in forensic odontology: A systematic review. *Forensic Sci Int.* 2023.
29. Pinchi V, Pradella F, Buti J, et al. Artificial intelligence in forensic dentistry: Current status and future perspectives. *Int J Legal Med.* 2023.
30. Murphy M, Ge ZP, Kazmi SZ, Hamba TO, Nemsi H. Cone-beam computed tomography in forensic odontology: Applications for

human identification and age estimation. *Forensic Imaging.* 2022.
31. Krishan K, Kanchan T, Garg AK. Dental anthropology in forensic identification. *Forensic Sci Int.* 2015;251:145–152.
32. Blau S, Ubelaker DH. *Handbook of Forensic Anthropology and Archaeology.* 3rd ed. Routledge; 2024.
33. Christensen AM, Passalacqua NV, Bartelink EJ. *Forensic Anthropology: Current Methods and Practice.* 3rd ed. Academic Press; 2020.
34. Pittayapat P, Jacobs R. Digital dental imaging in forensic science. *Dentomaxillofac Radiol.* 2017;46:20160333.
35. Shah P, Velani PR, Lakade L, Dukle S. Teeth in forensic identification. *Indian J Dent Res.* 2019;30(2):291–298.
36. Acharya AB. Role of forensic odontology in disaster victim identification. *J Forensic Dent Sci.* 2011;3(2):68–72.
37. de Boer HH, Blau S, Delabarde T, et al. The role of forensic odontology in humanitarian forensic action. *Forensic Sci Int.* 2019;299:266–273.
38. ISO 21043-1. *Forensic Sciences—Part 1: Terms and Definitions.* International Organization for Standardization; 2018.
39. ISO 21043-2. *Forensic Sciences—Recognition, Recording, Collecting, Transport and Storage of Items.* ISO; 2018.
40. American Board of Forensic Odontology (ABFO). *Standards and Guidelines for Forensic Odontology.* Latest edition.
41. ICRC. *Management of Dead Bodies after Disasters: A Field Manual for First Responders.* Geneva: International Committee of the Red Cross; 2020.
42. WHO. *Management of Dead Bodies after Disasters: A Practical Guide.* World Health Organization; updated edition.
43. Silva RF, Prado MM, Daruge E Jr. Current advances in molecular forensic odontology. *Forensic Sci Int.* 2021.
44. Jain A, Gupta P, Kaur J, et al. Digital transformation and artificial intelligence in forensic odontology: Emerging applications and future perspectives. *Forensic Imaging.* 2024.
45. Acharya AB, Krishan K. Future directions in forensic odontology: From digital dentistry to precision forensic medicine. *J Forensic Dent Sci.* 2024.

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