Digital tooth reconstruction: An innovative approach in forensic odontology

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ABSTRACT

In mass disasters, accidents and crime investigations, where human remains are decomposed, charred or skeletonized, teeth may dislodge due to post-mortem loss or due to mishandling of evidence during the manipulation of skeletal and dental remains. Thus, the identification process is hampered due to the loss of dental evidence. In these situations, forensic tooth reconstruction may aid in the identification process. Forensic tooth reconstruction (FTR) refers to the process that aims to reconstruct the morphology of the missing tooth from the skeletal remains from the intra-alveolar morphology of the dental socket. The study is an innovative attempt to develop a digital approach to reconstruct three-dimensional (3D) printed tooth models through recording intra-alveolar morphology of empty dental sockets which simulate the teeth which are missing post-mortem. An experimental study was conducted on the human mandible, where using volumetric scanning, 3D scanning and printing techniques the tooth was reconstructed from the intra-alveolar morphology of the socket. Through metric analysis and qualitative congruency testing it was established that there was minimal discrepancy between natural tooth and 3D printed tooth. It was determined that teeth missing post-mortem do not necessarily invalidate the identification process. Digital FTR gives accurate results with minimum error.

INTRODUCTION

Digital dentistry has taken over conventional dentistry in recent times through three dimensional (3D) scanning, computer aided design or computer aided manufacturing (CAD/CAM), and rapid prototyping.[1] In prosthetic treatments, computerized scanning and 3D printing systems have come to largely replace traditional techniques for producing various prostheses.[2] 3D printed models and surgical guides help the dentists plan complicated non-surgical and surgical endodontic treatments, by using cone beam computed tomography (CBCT). CBCT has an added advantage as it provides undistorted three-dimensional, volumetric information of the maxillofacial skeleton[1] thus providing enhanced results.

As forensic odontology often deals with the "who" part of an investigation i.e. establishing the identity of an individual, it demands the highest possible degree of accuracy to give a positive identification.[3] Teeth, especially the enamel, being the most calcified structures in the human body, are found to be common remains in mass disaster events.[4] However, in some unusual instances, teeth may be dislodged due to post-mortem loss or due to mishandling of evidence during the search and recovery process. Moreover, careless handling in collection, transportation, packaging and dispatch for examination of human remains from crime scenes or in exhumations may further contribute to tooth loss.[5] In such extreme situations, the retrieval of the information may become difficult and challenging for forensic odontologists as teeth are unavailable for examination. Here, reconstruction of tooth morphology may aid in the identification process.

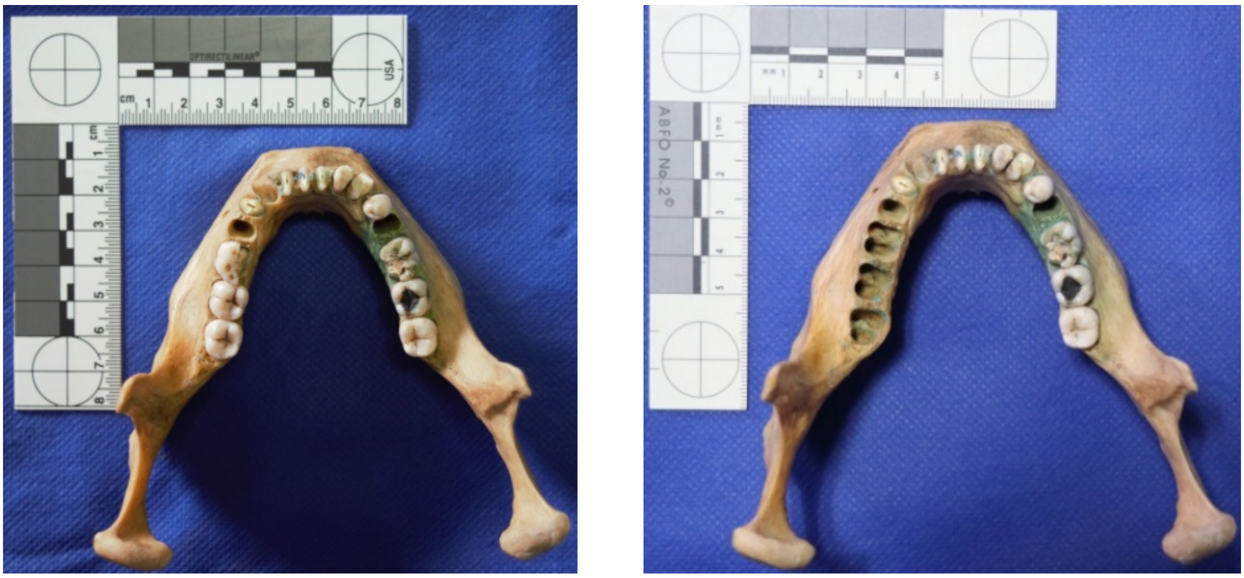
Forensic tooth reconstruction (FTR) refers to the process that aims to reconstruct the morphology of the missing tooth from the skeletal remains from the intra-alveolar morphology of the dental socket.[6] Amalgamation of digital dentistry with tooth reconstruction techniques, can simplify the identification process with minimized manual errors for reconstruction of a tooth. The study is an innovative attempt to develop a digital approach to reconstruct three-dimensional (3D) printed tooth models through recording intra-alveolar morphology of empty dental sockets which simulate the teeth missing post-mortem.

MATERIALS AND METHODS

Data Acquisition

In this in-vitro experimental study, a human mandible with known age, sex and race was obtained from the skeletal archives of Laboratory of Forensic Odontology, Gujarat Forensic Sciences University, Gujarat, India. The mandible possessed the following teeth: left third molar (38), left second molar (37), left first molar (36), left first premolar (34), left lateral incisor (32), left central incisor (31), right central incisor (41), right lateral incisor (42), right canine (43), right first premolar (44), right first molar (46), right second molar (47), right third molar (48), and the teeth present were noted and recorded by the Fédération Dentaire Internationale (FDI) notation (Figure 1a). Later on, the following teeth were removed manually from the sockets, without damaging the socket's structural integrity, simulating teeth missing post-mortem: left third molar (38), left second molar (37), and left first molar (36) (Figure 1b). Intra-alveolar inspection was performed by two examiners, independently, to verify morphological integrity of the socket and the lack of foreign bodies. The entire study was conducted in two phases, phase 1, which comprised 3D scanning and printing the skeletal remains (mandible), and phase 2, which comprised 3D modelling and printing the teeth.

Figure 1. Occlusal view of human mandible; before removal of teeth (a) and after removal of teeth (b)



Phase 1: 3D scanning and printing the mandible

The bone was scanned at Scanmax Dental Imaging Centre (Ahmedabad, Gujarat) by an on-site dental radiographer using a Care stream 9300 premium cone beam computed tomography scanner (Figure 2a). Scanning parameters were – field of view (FOV) 5*5inch, exposure 10 seconds, at 88 kVp, 10 mA). The CBCT images were saved as Digital Imaging and Communications in Medicine (DICOM) data and were transferred to a compact disk (CD). Later, the DICOM data was reconstructed using CS 3D imaging software version 3.8.7. A surface model of the mandible was generated by using (DDS-Pro) and then exported as an STL (stereolithography or standard tessellation file). Then, the STL files were prepared for printing using a 3D printer (da Vinci Jr. 1.0 by XYZ Printing) using poly lactic acid (PLA) material by fused deposition modelling (FDM) technology (Figure 2b).

Figure 2a. Phase 1- Acquisition of data by volumetric scanning (CBCT)

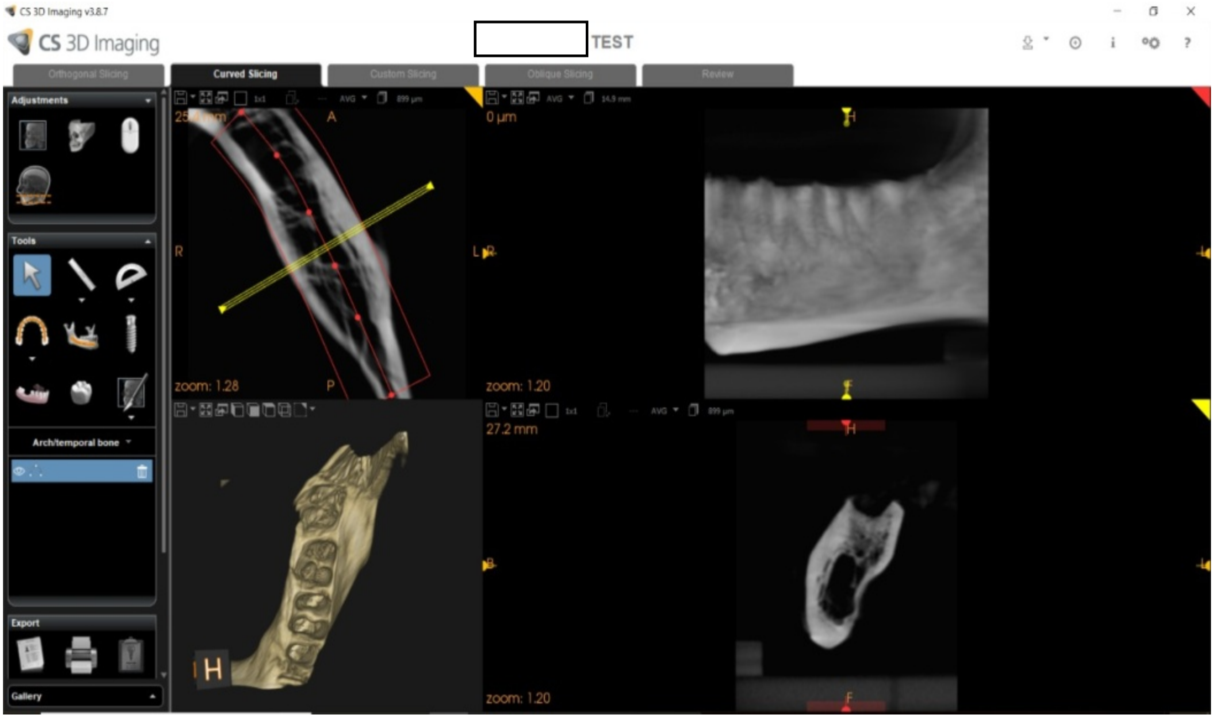
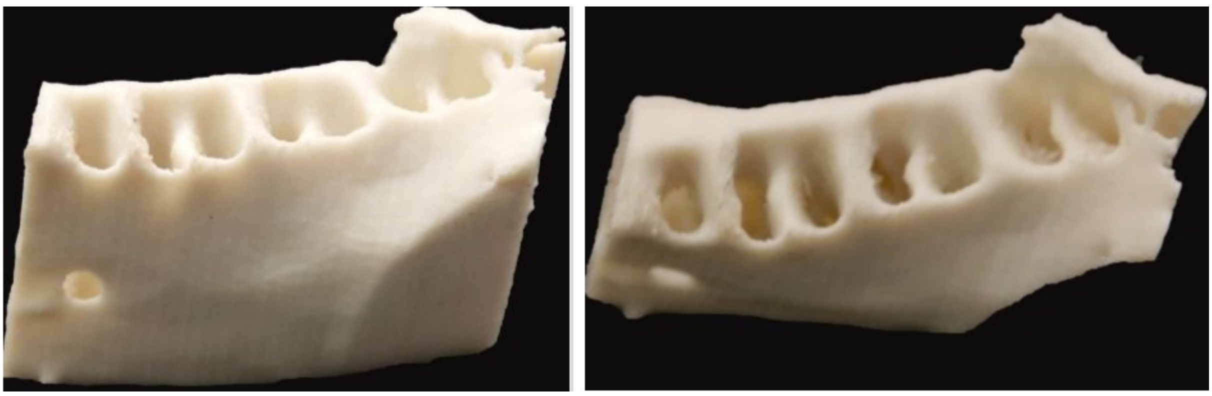


Figure 2b. Phase 1- Three dimensional (3D) printed mandible model



Phase 2: 3D reconstruction and printing of the teeth

Firstly, the intra-alveolar impression of the 3D printed mandible was taken using a combination of very heavy body (putty) addition silicone (Adsil Acura Soft Putty - ADA Sp.no 19) and light body addition silicone (Aquasil Ultra LV/ XLV Smart Wetting® Regular Set, Densply -ADA Sp.no 19) (Figure 3a). Thereafter, the impression was scanned using a structured-light 3D scanner (Neway, Open technology) with an accuracy of 0.02 mm (Figure 3b) and consequently, using Exocad dental software, root digital models were prepared and the crown was constructed digitally using ideal measurements used for a prosthetic cad-cam crowns (Figure 4a).

The STL files were prepared for printing using stereolithography (SLA) 3D printer Nobel 1.0 by XYZ printing. Here, the tooth was printed using clear photopolymerizing resin by a Nobel 1.0 SLA printer by XYZ printing (Figure 4b).

Figure 3a. Phase 2- Intra-alveolar impression of printed mandible

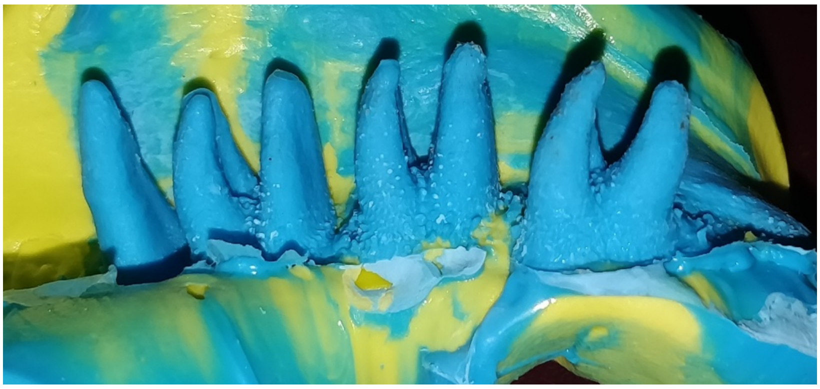


Figure 3b. Phase 2, Surface scanned impression

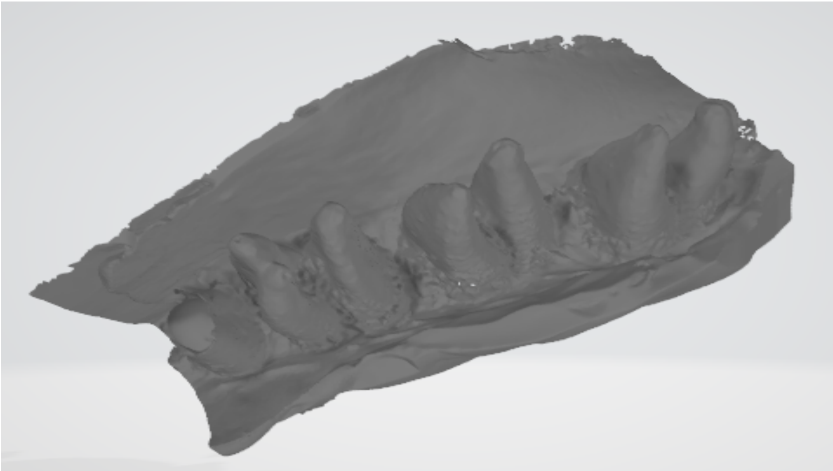


Figure 4a. Phase 2- Tooth reconstructed digitally using CAD software

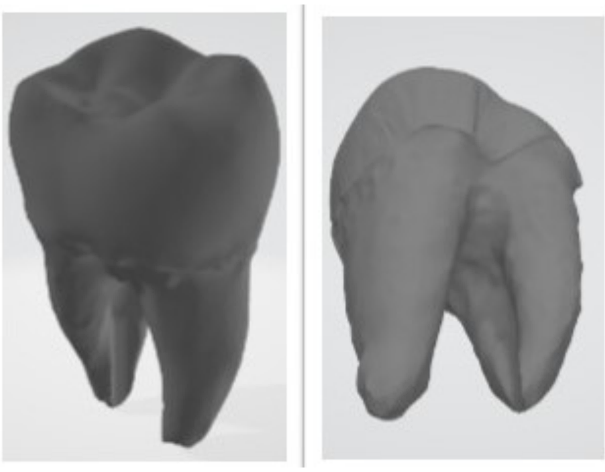


Figure 4b. Phase 2- 3D printed Tooth

RESULTS

Morphological Analysis

The reconstructed teeth were compared with the reference teeth for morphological analysis. It was observed that the anatomy of the reconstructed root resembled the anatomy of the natural tooth root (Figure 5).

The radiographic assessment was done with digital radiovisuography (RVG) (Vatech, at 60kvp/2.5ma,0.12 sec) to assess the adaptability of the teeth in the socket. The material used for printing the teeth was radiolucent and hence the radiograph showed the shadow of the tooth, which showed appropriate adaptability (can be seen by arrows) (Figure 6).

3D Digital Analysis

The utilization of different coloured images allowed a qualitative congruency analysis between reference teeth and reconstructed teeth as show in (Figure 7). The maximum error range was set between -0.5mm and +0.5mm. The areas of positive error are represented by the yellow and red regions, and the areas of negative error are represented by the blue regions. Areas where the error is near zero are represented by the green regions. The mean ± standard deviation (SD) of the RMS values is 0.44 ± 0.5 mm, representing the overall level of 3D morphological error. The average value and variance are represented as 0.24 mm and 0.19 mm respectively.

3D odontometric measurement error

Odontometric measurements

Various linear odontometric measurements of the teeth were obtained from the reference teeth and 3D printed replicas to evaluate the accuracy of the reconstruction approach (Table 1). Also, the following measurements were taken using a digital sliding calliper:

1. Root length error (RLM Error) on mesial aspect = Root length of reconstructed tooth - Root length of reference tooth.
2. Root length error (RLD Error) on distal aspect = Root length of reconstructed tooth - Root length of reference tooth
3. Crown length error (CL Error) = Crown length of reconstructed tooth - Crown length of reference tooth
4. Crown to furcation length error (CFL Error) = Crown to furcation length of reconstructed tooth - Crown to furcation length of reference tooth
5. Mesio-distal dimension error (MD Error) = Mesio-distal dimension of reconstructed tooth - Mesio-distal dimension of reference tooth.

On the basis of the odontometric measurements, the minimum RLM error obtained was 0.28mm whereas the maximum was 0.74mm. The minimum and maximum RLD error was 0.26 mm and 0.68mm respectively. For CL the minimum error was 0.38mm and maximum error 0. 46mm.The minimum and maximum CFL error recorded was 0.38mm and 1. 21mm.The MD error was 0.49mm and 0.58mm

Figure 5. Comparison with Natural Tooth

Figure 6. Radiographic assessment

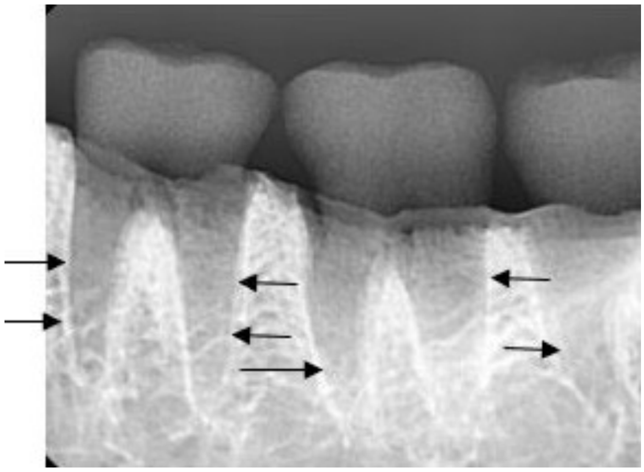


Figure 7. Digital analysis of reconstructed tooth

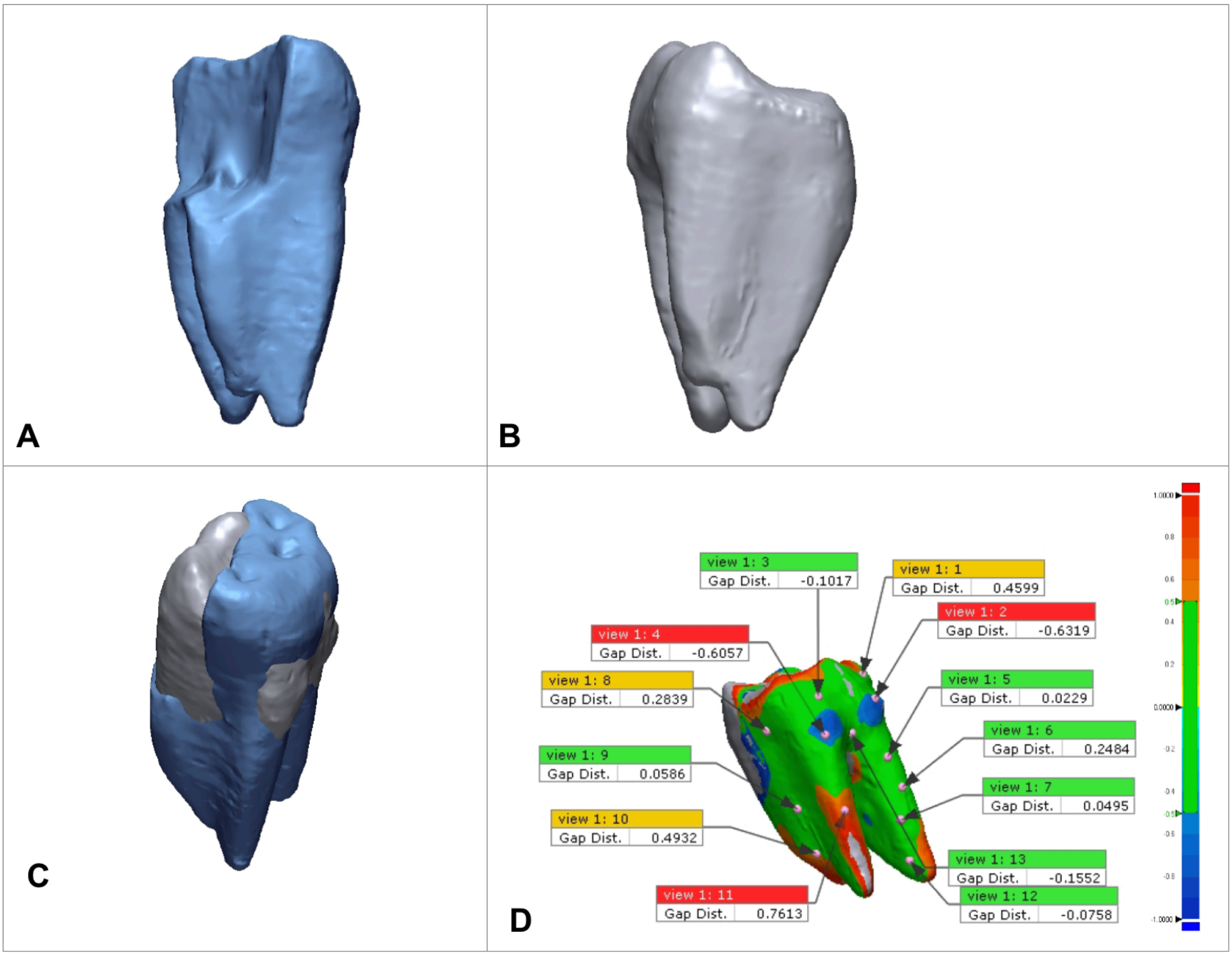


Table 1. Odontometric analysis of natural tooth and digital tooth with their error rate

Crown-Root Dimensions	Dimensions of 36		Dimensions of 37		Dimensions of 38	
	Natural Tooth (in mm)	Digitally reconstructed tooth (in mm)	Natural Tooth (in mm)	Digitally reconstructed tooth (in mm)	Natural Tooth (in mm)	Digitally reconstructed tooth (in mm)
Root Length (Mesial)	9.81	9.53	11.37	10.63	10.71	10.34
Root Length (Distal)	9.90	9.22	12.13	11.58	9.27	9.01
Crown –Length	5.38	5.00	6.56	7.02	6.51	6.11
Mesio-Distal Width	10.60	10.02	10.15	10.81	10.67	10.12
Crown Length to furcation	9.05	7.84	10.09	10.58	10.48	10.10
RLM Error	-0.28		-0.74		-0.37	
RLD Error	-0.68		-0.55		-0.26	
CL Error	-0.38		0.46		-0.40	
CFL Error	-1.21		0.49		-0.38	
MD Error	-0.58		0.49		-0.55	

DISCUSSION

Dental identification assumes a key role in the identification of remains when post-mortem changes, traumatic tissue injury or lack of a fingerprint record invalidate the use of visual or fingerprint methods.[7] Identification through dental remains is of primary importance when the deceased person is skeletonized, decomposed, burned or dismembered.[7] Teeth can provide decisive information for human identification even when they are missing by examining the alveolar bone[8] and intra-alveolar morphology.[9] Post-mortem tooth loss is common in cases of skeletonized or incinerated remains due to loss of periodontal tissue or due to improper handling of the evidence. This dislodgement and loss of teeth may cause complexity in case solving processes[10] and hence hamper the process of identification. Thus, to overcome the hurdles in post-mortem examination in 2018, the authors[6] made an attempt to reconstruct the teeth with dental materials by recording the intra-alveolar morphology of the dental root socket. The reconstructed tooth root showed a discrepancy of 0.5-1mm and thus validated that the dental information can be retrieved even if the teeth are missing post-mortem[6]. With advances in technology and the introduction of computer assisted system for dental identification,[11] the present study was designed to reconstruct the tooth using, volumetric data acquisition, 3-dimensional (3D) scanning and 3D printing techniques.

3D printed replicas of bones have been used as supporting evidence in courts of law in several countries.[12-14] The use of a 3D printed tooth to study the anatomy in complicated endodontic cases has been widely documented,[15] however their use in forensic is yet to be explored. The presently described technique has an added advantage in cases of charred and brittle remains as the model is directly printed using volumetric scanning and 3D printing technique which eliminates the use of alginate or silicone base for replicating the evidence. The use of these materials on brittle remains may cause damage to the remains,[16] something which the use of this technique eliminates. Generally, trueness is a term used to measure the accuracy. It is defined as the comparison between a reference dataset and a test dataset. A higher trueness value results in close or equal to the real value of the measured object. In this technique, the scanned data presented with trueness of 0.03mm. The final 3D printed models produced were on average accurate to the source teeth, with mean differences of 0.24 mm within the accepted range of ±1.00 mm hence proving digital method delivered a minimal loss of structural integrity when compared with the original tooth structures. Thus, digital tooth reconstruction could be a method of choice for accurate results. Adequate precise results were obtained even in cases of dilacerated roots which was critical in conventional reconstruction. The printed tooth can be used as evidence in a court of law and a model that would aid in various investigative procedures for various metric and non-metric analyses. The reconstructed tooth root would also aid in comparative root identification when ante-mortem records are available as the root traits are potentially distinct; especially in population differentiation, in cases such as mass disasters, where the victims might hail from different countries and continents.[17] This would also assist in swift and accurate morphometric analysis of roots. Recent studies have also stated that root length may help in sex determination,[18] hence a reconstructed root may be an aid in this. The intra-alveolar morphology reproduced enables assessment of the root developmental stage that might also aid in age estimation, [17,19] though further studies are indicated in this field. Apart from comparative identification, it may also help in reconstructive identification. The position and protrusion of the teeth would also play an important role in determining the shape, thickness and position of the lips[16] thus the reconstructed tooth would ultimately be beneficial in forensic reconstruction.

The limitation of the present approach is that it requires expert intervention/multi-disciplinary approach, quite expensive and cannot be used in cases where the socket walls are damaged or fractured. However, with technological and technical advancements, the costs are bound to reduce, and the use of this method might become more feasible.

CONCLUSION

A digital approach was developed using 3D technology viz. surface and volumetric scanning, and also 3D printing which showed appropriate morphology visually, when compared with the original teeth. The reconstructed teeth showed appropriate adaptability in radiographs. The reconstructed teeth were digitally compared with the teeth removed from the socket by qualitative congruency analysis which showed the error range of 0.44 ± 0.5 mm, which was below the maximum allowable range of ±0.5 mm. The odontometric measurements of the teeth obtained from the reference teeth and 3D printed teeth showed the average error of 0.24 mm. Thus, it can be stated that the 3D replicas can serve as useful evidence in case of post-mortem tooth loss, giving accurate results with minimum error. With the introduction of newer technologies in future, studies that address the limitations inherent to the present approach can be considered.

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