Review Article

Current and Evolving Applications of Three-dimensional Printing in Forensic Odontology: A Review

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Abstract

In these digitized surroundings, we should not overlook the use of three-dimensional (3D) printing in forensic odontology, for investigative or court purposes, which is still comparatively new. We will use the term "3D printing" as it is widely recognized and will perhaps be the simplest phrase for the odontologist for daily use. Alternative terms are additive manufacturing and rapid prototyping. Today, 3D printing is most commonly used in dentistry for the manufacture of drill guides for dental implants, study models for prosthodontics, orthodontics and surgery, the manufacture of dental, craniomaxillofacial and orthopedic implants, and the fabrication of copings and frameworks for implant and dental restorations. However, we are yet to see forensic odontologists, lawyers, and expert witnesses appreciate embrace the advantages of 3D printing for its use in court of law. This may be due to a perception of it being complicated technology, high cost, or simply a lack of understanding of what can be done with 3D printing. 3D image capture devices minimize the amount of angular distortion, therefore such a system has the potential to create more robust forensic evidence for use in courts and medico-legal cases. The major application of 3D printing in forensic odontology includes bite mark analysis, 3D-computed tomography facial reconstruction, dental age estimation, sex determination, and physical models. The aim of this review article is to outline the use and possible benefits of 3D printing in forensic odontology.

Key Words: *Bite mark, digital imaging and communications in medicine, facial reconstruction, stereolithography, three-dimensional, three-dimensional printing*

Introduction

Three-dimensional (3D) printing is a procedure that is used to generate a 3D object during which consecutive layers of material are established under computer control. This object is generated using digital model data from a 3D model. 3D printing involves creating a real-world physical 3D model from a computer model. When printing from computed tomography (CT) data, CT slices can be printed sequentially as two-dimensional (2D) layers, and these can be arranged to create the 3D model. This is termed "additive layer" printing. Similarly, 3D modeling is the procedure of creating a mathematical representation of any 3D surface of an object (either animate or inanimate) through specialized software like computer-aided design (CAD). 3D scanning is the procedure of accumulating digital data on the shape and appearance of a real object, then producing a digital model based on it [Figure 1]. These three terms are in 3D printing. 3D printing is not a particularly new technology. Many of the modalities that are in use today were first developed and used in the late 1980s and 1990s, for example, fabrication of cleft palate devices, and 3D-printed guns.[1,2] Digital imaging and communications in medicine (DICOM) images are used as 3D-printed models which can provide both tactile feedback and tangible depth information of anatomic and pathologic states of an object.[3] It should not be forgotten that 3D printers do not accept DICOM images whereas they take in individual objects (or "parts") defined by surfaces that surround a region of space. A standard file format to define these surfaces is standard tessellation language (STL). The STL format defines surfaces as a collection of triangles (called facets) that fit together like a jigsaw puzzle.[3] Computerized tomography (CT) images are most commonly used for 3D printing because of the wide spectrum of applications and the relative ease of image postprocessing. But theoretically, 3D model can be printed from any volumetric imaging dataset that has sufficient contrast to differentiate tissue, such as cone beam computerized tomography data, intraoral, or laboratory optical surface scan data.[2,3] The article sets out to analyze the importance of 3D printing in forensic odontology and why forensic odontology influences development of 3D printing applications.

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Principles of Three-dimensional Printing

A newer format called additive manufacturing file format (AMF), which was approved by the American Society for Testing and Materials ASTM International in June 2011, has been designed to overcome many of the limitations of the simple STL format, such as enabling the user to incorporate features including surface texture, color, and material properties into each part.[3,4] ASTM International Committee on medical and surgical materials and devices is exploring a standard to assess the cleanliness of medical devices and models made by additive manufacturing (AM) techniques and another standard to guide the design of AM devices for cleanability. They have developed standards that support the application and adoption of AM for diverse materials and processes. These standards are providing a common language, broadly accepted specifications for AM materials, guides for these new technologies, faster production of products and more. To produce a 3D-printed model, DICOM format data are converted into STL-format data or AMF and transfer to AM machine for file manipulation which is a new requirement compared with traditional 3D visualization [Figure 1].[3] Hence, the process of 3D printing can be divided into three parts: image acquisition, image postprocessing, and 3D printing.

Image acquisition

Theoretically, a 3D forensic odontology model can be printed from any volumetric image dataset that has adequate contrast to differentiate tissues. CT images are most commonly used for 3D printing because of the wide spectrum of applications and relative ease of image postprocessing. The high contrast, signal-to-noise ratio, and spatial resolution, enhance structure differentiation and minimize partial volume effects that could limit 3D printing. Image sections should be reconstructed with isotropic voxels of 1.25 mm or less.[5] Thicker sections compromise model accuracy, while very thin sections (e.g., <0.25 mm) require extensive segmentation and STL refinement, particularly in the presence of image artifacts. Cardiac models demonstrate sufficient accuracy with 0.5-mm sections,[6] but thin objects such as the orbital floor may require thinner sections.[7]

Image postprocessing

Postprocessing in radiology evolved to visualize volumetric data in any plane and then to render that volume on 2D display. Manipulating DICOM images for 3D printing involves accurate segmentation of the desired tissues by placing regions of interest (ROIs) around them and then refining the STL representation of the ensemble surface defined by those ROIs.[3] The odontologist should carefully review the final STL model against the source image for accuracy [Figure 1]. After segmentation, most software packages generate a printable 3D STL model of surfaces surrounding segmented tissues on the basis of algorithms that preserve anatomic features, such as interpolation and pattern recognition. Conversion of 3D surfaces to STL can employ any number of triangular facets to fit these surfaces; too few will compromise anatomic features in the 3D printed model, while too many will lead to unnecessary roughness of the object if the segmented surface is not smooth.[3] The recommended number of triangles for 3D printing of anatomic models such as the skull is 600,000, for the face is 450,000, and for the mandible is 200,000.[3] Software for 3D part manipulation, commonly known as CAD or computer-aided manufacturing software, and operator expertise are essential for accurate 3D printing. When the adjustments are complete, the data are transferred to a 3D printing device.[3]

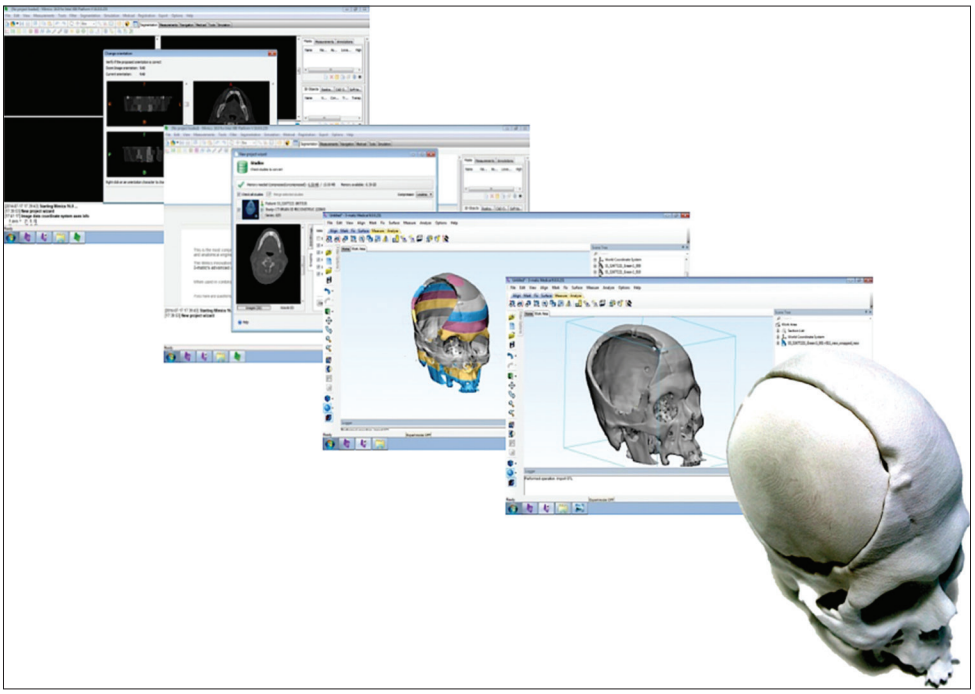

Figure 1: Conversion of computed tomography scan data to three-dimensional model. Translates the digital imaging and communications in medicine file from computed tomography or magnetic resonance imaging scans into computer-aided design file. Three-dimensional Slicing Software Converts computer-aided design file into thin data slices suitable for three-dimensional printing

Figure 2: Projet7000

Figure 3: Frequency-division multiplexing System

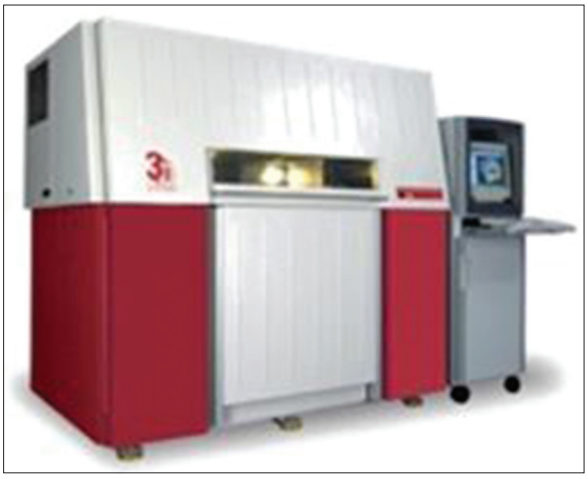

Figure 4: Space Launch System

Figure 5: IPRO SLA System

THREE-DIMENSIONAL PRINTING

All 3D printers use data encoded in the STL file to deposit and then fuse successive 3D layers of material. This is similar to segmenting a tissue volume by successively identifying ROIs on consecutive cross sections that enclose it.[3]

POSTPROCESSING

This is the final preparation of the tangible 3D-printed model. This can include model infiltration, cleaning, finishing, polishing, and sterilization.[2,3]

Three-dimensional printing technologies and materials

There are seven groups of specific 3D printing technologies:

- Vat photopolymerization
  An example of this technology is the ProJet 7000 printer [Figure 2] manufactured by 3D Systems (Rock Hill, SC). The process is more widely known as stereolithography or digital light processing[2,3]
- Material jetting
  An example of this technology is the Objet500 Connex printer (Stratasys, Eden Prairie, Minn). It is also known as photopolymer jetting[2,3]
- Binder jetting
  An example of this technology is the ProJet 660Pro printer. It is most commonly known as powder binder printing
- Material extrusion
  An example of this technology is the Fortus 400 mc printer [Figures 3 and 4]. Material extrusion is previously known as fused deposition modeling[2,3]
- Powder bed fusion
  This category includes selective laser sintering, direct metal laser sintering, selective laser melting, and electron beam melting[2,3]
- Sheet lamination [Figures 2 and 5]
  Sheet lamination is an inexpensive method involving the cutting and bonding of paper, metal, or plastic films one layer at a time[2,3]
- Directed energy deposition
  Directed energy deposition directly deposits material to a location where an energy source is also directed to bond the material.[2,3]

A wide variety of 3D printers and 3D printing materials can be used to print models, but as it is useful to have such models in the court of law, materials that can be sterilized, such as nylon, are particularly interesting.[8] Unfortunately, due to the complex technology and factors such as expense, maintenance

Figure 6: Three-dimensional-printed mandible model made of Selective Laser Sintering on a Sinter Station HiQHS three-dimensional systems machine. Material used is PA 12, biocompatible for *in vivo* applications

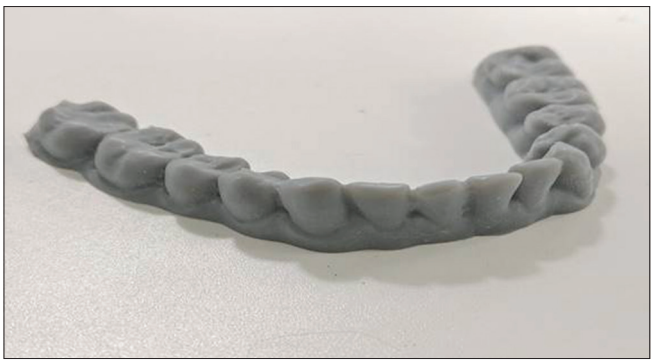

Figure 8: Three-dimensional printed mandible teeth line model along with made by stereolithography. Material used is Photopolymer Resin, biocompatible for *in vivo* applications. Machine used was desktop form laboratories stereolithography

Figure 7: Three-dimensional-printed mandible model along with tumor made of Selective Laser Sintering on a Sinter Station HiQHS three-dimensional Systems machine. Material used is PA 12, biocompatible for *in vivo* applications

Figure 9: Cranioplasty and body of mandible implants in titanium fitted to a three-dimensional printed Selective Laser Sintering model

and repair, cleaning, difficult postprocessing, and also onerous health and safety concerns, to undertake the use of 3D printing is lessen.[2]

Applications of Three-dimensional Printing in Forensic Odontology

Over the past 6 years, 3D printing technology has changed dentistry dramatically due to the progress in intraoral scanning technology. 3D printing has been used to create restorations,[1] physical models, surgical guides,[9] and orthodontic appliances.[10] The aim of this review article is to focus on the applications of 3D printing in forensic odontology, and they are as follows:

1. Bite mark analysis

   The most important application of 3D printing in forensic odontology could be in bite mark analysis where it could help to collect and display valuable evidence. Biting is a dynamic process which relies on multiple factors such as the position of jaws and teeth, number of teeth present, the pressure of biting, and size and shape of the tooth.[11,12] The forensic dentist must first identify the bite mark from any other cutaneous lesion, infection, or injury. This must be followed by verification that the pattern is related to teeth and was not made by a tool or instrument, or any other object. Once we are able to establish that the injury was produced by human teeth, with the help of 3D printing bite marks can then be compared to the suspect's dentition for the purpose of inclusion or exclusion.[13] In bite mark analysis, time is an important factor. In cases where food material is the substrate, evidence must be gathered before the deterioration of the substrate, while in the case of a human bite victim, healing can cause distortion and loss of valuable information. If only imprints of teeth were identified initially, they may diminish in intensity with time.[14] In the conventional method of bite mark analysis, photographs are taken to preserve the marks and stone pour technique are used to fabricate the cast for recording the impression of the bite mark. This can cause distortion of the tooth marks due to external pressure.[15,16] Using digital scanners to document the bite marks eliminates any external pressure and tendency to undergo distortion. This technology may become more useful in cases where taking an impression can be difficult, such as soft tissues, breasts, buttocks, and genital organs.[16] Digital scanning can be carried out to recreate entire bite marks using 3D printing. This information can then be compared with a

suspect's dentition casts and can also be presented in a court of law as evidence. The scans themselves can be used for digital comparison of the suspect's teeth using new software.[17] Thus, 3D scanning can help avoid the rapid loss of information that occurs in some bite marks and helps preserve maximum information in all 3D[18]

2. Analysis of lip print pattern (cheiloscopy), palatal rugae pattern (palatoscopy), tongue print pattern, fingerprint, and footprint
   It can be difficult to take reliable impressions of those areas with traditional impression techniques, and accuracy can also be compromised due to shrinkage. 3D modeling may be useful in these cases. As in the case of bite marks analysis, digital scanning can be used for recording, and may aid the analysis of the above prints[19]
3. 3D facial reconstruction
   Forensic facial reconstruction (or forensic facial approximation) is the process of recreating the face of an individual (whose identity is often not known) from their skeletal remains by using tissue markers and a material such as clay to form an approximate reconstruction. Hence, in forensic odontology, 3D facial reconstruction can play an important role in the identification of a cranium or skull through this technique[20]
4. Dental age estimation
   An accurate 3D model of a dentition could be useful in age estimation, for example in grading the average stage of attrition of molar teeth (Li and Ji method). A 3D-printed model, in this case, may help remove some of the difficulties indirect examination of an individual due to saliva or lack of proper visualization. Similarly, a 3D model of the mandible might also be used for age estimation using the gonial angle
5. Sex determination and population identification
   One of the most important parameters in forensic odontology is the degree of accuracy between the digital model and the printed construct. Clinical studies show that the acceptable degree of accuracy is a relative parameter, and has to be determined for each application.[21-24] The areas where the degree of accuracy of dental models may be important include measurements of intercanine distances, intermolar distances, the overjet, the overbite, tooth sizes, and arch lengths.[24,25] The authors compared tooth sizes and observed no significant difference in the height and width of the crowns of all teeth. They concluded that the 3D-printed dental models should be clinically acceptable[26] It has been demonstrated that there is no dimensional change between the tooth and the 3D scan in of the tooth. An accurate printed construct could help improve the accuracy of sex determination procedures and perhaps also for population identification from the non-metric dental traits such as shoveling, Carabelli formation, 3-cusped upper 2nd molar, and 4-cusped lower 1st and 2nd molar
6. Illustrate the pattern of bone injury
   Printed 3D exhibits may be of special utility where it becomes important to illustrate a pattern of bony injury, for example. The pattern of fracture may provide important information about the process that caused it, and this may be of particular interest to a court[27]
7. Anatomical models [Figures 6-9]
   In the field of forensics, human remains provide definitive evidence; however, the judicial system often relies on photographic prints and scanned copies in the court due to of a number of ethical and legal issues involved with the transfer, transportation, and presentation of human remains to the court and the jury.[18] Presenting human remains can be disturbing to some people, especially to medical laypeople like the jury members. Besides this, handling of human bones and remains by multiple people and in different environments can lead to degradation of evidence.[17] The transportation of human remains is also strictly governed by laws, because of which authorities from different areas may not have access to such evidence. Finally, such presentation of remains may not be acceptable to the family of the victim, and so only photographic representations may be used.[28] Even with all this, it cannot be denied that there is loss of data and information when 3D evidence is represented in a 2D photograph. In such cases, 3D printing can be applied to create accurate three dimensional replicas of the human remains from the evidence, which may help relay relevant information to the court and the jury, without disturbing anyone or creating bias.[29] Below given are some of the objectives of having an anatomical model
   - Analysis of crime
   - Presentation of evidence
   - Study and training aids
   - Ongoing reference
   - Test pieces
   - Investigative tools
8. Analysis phase where religious or cultural beliefs prevent maceration of the skull
   Kettner *et al*. report the usefulness of comparing a printed exhibit of an injured skull with the alleged instrument of causation, a hammer. They point out that such models may be useful in the analysis phase where religious or cultural beliefs prevent maceration of the skull.[30] 3D printing may help further investigation in these cases
9. 3D images in ballistic injury with identification and reconstruction of weapons used.[31]

Examples of Current Application of Three-dimensional Printing in Forensic Odontology

There are many examples of the application of 3D printing in forensics. Some of them are given below:

10. In order to better understand the crime scene and to present cases in court, the Hong Kong Police Briefing Support Unit uses its own 3D printers to recreate crime scenes
11. In 2013, the Japanese police gathered thousands of case-related clues from local citizens, using a 3D printed model of a crime scene
12. In the case of the 2013 death of 6-year-old Ellie Butler in Sutton, England, forensic pathologists supported the homicide prosecution of her parents by presenting detailed replicas of Ellie's severely damaged skull, which were 3D printed from CT scans of her remains. In late

2016, the remains of a woman were found in the woods near Dayton, Ohio, USA, which was decomposed and was unable to be identified. The Greene County Ohio Sheriff's office with help from Ohio State University produced 3D models of the remains to aid in the identification process. After CT scanning and making a 3D printed model of the victim's skull, the model was fleshed out with clay, i.e., facial reconstruction. Finally, photographs of the 3D-printed model were circulated within the public of Ohio State, which quickly led to the identification of the victim

13. New York State Police along with the State University of New York attempted to solve a 47-year-old murder case of an unidentified victim. A forensic artist was engaged to recreate the victim's face using a 3D-printed model of the victim's skull. However, the victim was identified by other means before the completion of the procedure.[32]

Model Accuracy

Discrepancies between segmented anatomy and the 3D-printed model are generally in the order of an imaging voxel size (<1 mm [typically <0.4 mm] and <3% [typically <1%])[33,34] and usually are forensically negligible. They are most prominent along the section axis of image acquisition and the layer (z-) axis of 3D printers. The use of thinner imaging sections and a narrower z-axis printing layer thickness often mitigates discrepancies. However, errors can be generated during any step of the process, including image acquisition and post-processing[35] as well as 3D printing itself.[26,36]

Conclusion

The technology of 3D printing can be boon to forensic odontology, and their implementations have opened numerous directions. The biggest advantage of 3D printing is noninvasive reconstruction of detailed anatomic structures which can be used to solve cases and also to provide quality education and training. 3D printing has made possible to construct complex part with minimal discrepancies that could be accepted in court of law. 3D-printed models of bone and teeth can be useful to forensic odontologists in both analysis and as an exhibit in evidence which can provide the clarity of communications in the courtroom. As increasing resolution and better software become available, and as costs decreases, this technology is taken up by more users in all fields. It is clear that 3D printing will have an increasingly important role to play in forensic odontology.

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Conflicts of interest

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