Accuracy of chair-side fused-deposition modelling for dental applications

Fusong Yuan
Center of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, China
Yao Sun and Lei Zhang
Department of Prosthodontics, Peking University School and Hospital of Stomatology, Beijing, China, and
Yuchun Sun
Center of Digital Dentistry, Peking University School and Hospital of Stomatology, Beijing, China

Abstract

Purpose – The purpose of this paper is to establish a chair-side design and production method for a tooth-supported fixed implant guide and to evaluate its accuracy.

Design/methodology/approach – Three-dimensional (3D) data of the alveolar ridge, adjacent teeth and antagonistic teeth were acquired from models of the edentulous area of 30 patients. The implant guides were then constructed using self-developed computer-aided design software and chair-side fused deposition modelling 3D-printing and positioned on a dental model. A model scanner was used to acquire 3D data of the positioned implant guides, and the overall error was then evaluated.

Findings – The overall error was 0.599 ± 0.146 mm ($n = 30$). One-way ANOVA revealed no statistical differences among the 30 implant guides. The gap between the occlusal surface of the teeth covering and the tissue surface of the implant guide was measured. The maximum gap after positioning of the implant guide was 0.341 mm (mean, 0.179 ± 0.019 mm). The implanted axes of the printed implant guide and designed guide were compared in terms of overall, lateral and angular error, which were 0.104 ± 0.004 mm, 0.097 ± 0.003 mm, and $2.053° \pm 0.017°$, respectively.

Originality/value – The results of this study demonstrated that the accuracy of a new chair-side tooth-supported fixed implant guide can satisfy clinical requirements.

Keywords Fused deposition modeling, Accuracy evaluation, Chair-side, Implant guide

Paper type Research paper

Introduction

Implant dentures refer to the implantation of an artificial tooth root (i.e. implant) in the alveolar bone of edentulous areas of the oral cavity. After the implant has undergone osseointegration with the alveolar bone, the final prosthesis is then fabricated on the surface of the implant. The implantation process generally does not require preparation of healthy natural teeth and can significantly improve the masticatory function of patients. In addition, the process yields satisfactory aesthetic results, is beneficial for the preservation of local soft and hard tissue and, therefore, has become the best repair and reconstruction treatment for patients with multiple dentition defects (Feng and Xu, 2013).

Under normal circumstances, when the implant is positioned into the alveolar bone in the edentulous area, the long axis of the implant and the direction of functional load of the crown of the missing tooth/teeth should be consistent and have a favourable three-dimensional (3D) position. Furthermore, damage to important anatomical structures (such as the maxillary sinuses, nasal floor, inferior alveolar nerve and adjacent teeth root) should be avoided. These principles need to be followed during implantation surgery and are important prerequisites to ensure success during various stages of implantation and repair.

Conventional unguided implant surgery is highly dependent on the experience and surgical manipulation techniques of the dentist. Subjective factors, such as insufficient experience, poor technique, or adverse emotional state of the attending dentist, small size of the oral cavity of the patient and individual patient-

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related differences, will often adversely affect the site and direction of implantation. If serious, this can result in implant failure, damage to the roots of adjacent teeth, severe damage to the mandibular nerve, damage to arteries at the floor of the mouth or even life-threatening situations.

With advances in oral implant technology, implantation surgeries are improving in terms of accuracy and safety and are increasingly becoming minimally invasive. Intraoperative guidance techniques are being used to increase the accuracy of implantation fossa preparation of various implantation surgeries. The primary method is the use of intraoperative implant guides. According to the design of the model guide, commonly used guides can be classified into three major types: traditional surgical guides, computed tomography (CT) guides and multi-source data fusion guides.

In the older, traditional surgical guide technique, the technician references the final position and shape of the prosthesis based on a pre-implantation research model of the patient for design and production. This only provides the surgeon with an initial location for the implant based on the design of the prosthesis. This is usually combined with "bone mapping" technology (i.e. the use of periodontal probes under local anaesthesia) to obtain the thickness of the soft tissues in the implantation zone. Subsequently, a relatively accurate buccolingual bone border can be obtained, increasing the buccolingual position and torque angle guiding accuracy, without the support of CT data. However, currently, only boundary information, such as alveolar ridge shape, repair space and adjacent and antagonistic teeth, is used when designing traditional surgical guides, and there is no way of achieving a quantitative 3D implant design. The production process is relatively cumbersome and inefficient and requires experienced dental technicians for completion. Additionally, if concurrent "bone mapping" techniques are to be used, an additional step for local anaesthesia is introduced, and the 3D external shape data of the alveolar bone cannot be accurately obtained, thereby restricting its application (Engelman *et al.*, 1998; Brief *et al.*, 2005; Lal *et al.*, 2006).

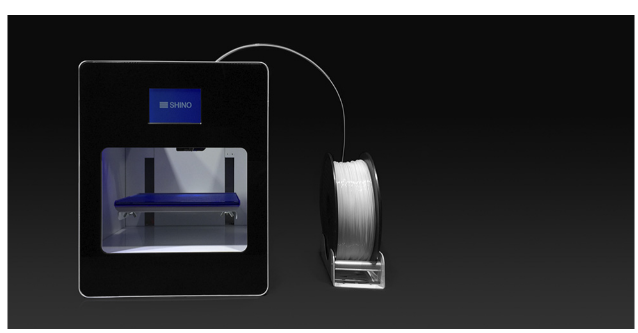
CT guides are produced using CT to acquire 3D data from patients and using computer-aided design (CAD) software to perform 3D reconstruction and preoperative design. As such, the 3D data produced is used to design 3D guides, and 3D printing technology is used to complete production of the guide. The addition of 3D information from the alveolar bone (which is not used for pure model guides) significantly increases the accuracy of the CT guides. However, accuracy of the CT guides depends on the accuracy of the CT scan of dental crowns. Hence, this type of guide usually exhibits large positional errors in adjacent teeth and is mostly used for edentulous supported implant guides (Horwitz *et al.*, 2009; Komiyama *et al.*, 2008).

Multi-source data fusion guides use CT data to obtain 3D information about the alveolar bone in the edentulous area, and 3D scanning data of the dentognathic model to acquire accurate information about the adjacent teeth. This increases the positional accuracy of the mesial and distal adjacent teeth, thereby increasing the accuracy of implant guidance. Currently, the major systems are mostly imported. The most popular systems of this class include the Simplant system (Materialise NV, Belgium), the Nobel Guide system (Nobel Biocare, Sweden), the Image-guided implantology (IGI) system from Israel, the Implant 3D system from Germany, the 3D SENTCAD system from Italy and the Easy Guide system from the USA. In China, products from manufacturers, such as Hangzhou Liuwei and Tianjin Cailifang, are also available; however, their effectiveness remains to be verified. At the same time, existing multi-source data fusion guide systems require CT imaging, fabrication of plaster models, acquiring 3D data from the plaster model, data registration in software, design of implant guides and shipment of the design data back to the company for printing of the finished product. This is not only cumbersome, time-consuming and involves a low level of automation, but the user is required to have expertise with in-depth 3D image manipulation techniques. Due to the high costs involved, and the cumbersome and complex manipulation process, this technique is not widely promoted in China. The current multi-source data fusion guide technology is more commonly limited to a small number of repair needs for missing teeth and cannot satisfy chair-side requirements of high efficiency, high accuracy and low cost. In summary, although the multi-source data integration guide is the most accurate commercial guide amongst the current design and production technology, it has the following limitations:

- The design software and processing equipment are expensive.
- The operation process is cumbersome and time-consuming.
- The degree of automation is low.
- The production process is easy to pollute the environment (Orentlicher and Abboud, 2011; D'Souza and Aras, 2012; Gross *et al.*, 2014; Greenberg, 2015; Edelmann *et al.*, 2016; Dada *et al.*, 2016; Di Giacomo *et al.*, 2016).

With the continuous development of 3D printing technology, the technology is increasingly used in oral clinical. In line with this trend, the research team independently developed a set of small 3D printing equipment that can be used in the clinic (Figure 1). In line with this trend, the research group independently developed a small 3D printing equipment that can be used in the clinic, which controls the production of the 3D body of PLA fine fibre yarn. Polylactic acid (PLA) is a highly versatile, biodegradable, aliphatic polyester derived from 100 per cent renewable resources, such as corn and sugar beets. Because of the degradation mechanism, PLA is ideally suited for many applications in the environment where recovery of the product is not practical, such as agricultural mulch films and bags. Composting of post-consumer PLA items is also a viable solution for many PLA products, and a host of moulded articles. Low-cost PLA products are finding uses in many applications, including packaging, paper coating, fibres, films, The use of PLA in these applications is not based solely on its

Figure 1 The 3D print machine



biodegradability nor because it is made from renewable resources. PLA is being used because it works very well and provides excellent properties at a low price. The use of PLA as a cost-effective alternative to commodity petrochemical-based plastics will increase demand for agricultural products such as corn and sugar beets and will lessen the dependence of plastics on oil. After the PLA fine-fibre filament is melted by the printer, the nozzle is moved by the computer according to the cross-sectional contour information of the printed object, and the ejected material is rapidly cooled to the solid state, and then, the next cross-section is printed, and the layers are superimposed to finally complete the 3D printing of the object (Pang *et al.*, 2010).

Because the current implant guide technology has limitations, such as a low level of automation and non-suitability for chair-side applications, the present study aimed to establish a chair-side design and production method for a tooth-supported fixed implant guide. Additionally, we aimed to perform analysis and evaluation of the accuracy of this implant guide to provide a foundation for accurate guidance during implantation surgery.

Materials and methods

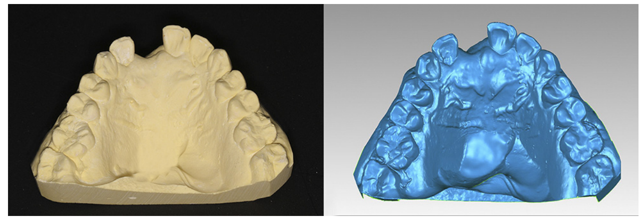
Equipment and materials

A 3D scanner for the dentognathic model (Smartoptics, Germany), CAD software for designing the implant guide (made by ourselves, 3D printing equipment (LingTong, China), silicone rubber impression material (3M, USA) and super-hard gypsum (Heraeus, Germany) were used in this study.

Model preparation and acquisition of 3D data

In total, 30 patients with Kennedy Class III Modification 1 denture defects from the Prosthodontics Department of Peking University Stomatological Hospital (Beijing, China) were recruited for this study. The study was approved by the Bioethics Committee of the Stomatological Hospital of Peking University (No. PKUSSIRB-201628055, 10 August 2016). All of the experimental protocols and procedures were approved by the licensing committee and performed in accordance with approved guidelines and regulations. The patients were informed that their models would be used in the in vitro study, and informed consent was obtained from all subjects. Inclusion criteria were as follows: missing one tooth; otherwise healthy; tooth removed > three months previously; the remaining teeth in the edentulous area had alveolar ridges with bone quality Class I-III; and the remaining teeth were healthy. Patients were also required to have good oral hygiene status, to have good compliance and to provide informed consent. Polyether silicone rubber impression materials were used to obtain upper and lower jaw impressions, which were then infused with super-hard gypsum to fabricate a model. The 3D data of the upper and lower jaws were acquired using a dentognathic model scanner and stored in stereolithography (STL) format for future use (Figure 2).

Figure 2 A gypsum model of a Kennedy Class III Modification I dentition defect and 3D scanning data



Highly automated chair-side virtual implantation and guide CAD

The dentist entered the 3D data of the patient's upper and lower jaw into the implant guide CAD software to design the normal dental crown shape for missing teeth. The occlusal surface of the mesial and distal adjacent tooth near the gap were then extended to the entire occlusal surface, and the occlusal plane was thickened by 2 mm. A Straumman implant was selected and, according to standard implantation criteria, residual alveolar bone conditions of the edentulous area and other anatomical conditions, the best position for the implant guide in the 3D direction was designed. The software then automatically simulated the results of the implantation, and the dentist used the mouse cursor to adjust the spatial location and angle of the implant. Subsequently, the CAD software automatically compiled and synthesized STL data for a tooth-supported implant guide with a guide hole, based on the orientation and location of the implant (Figure 3).

Calibration of printing accuracy of the high-speed 3D printer

The SOLIDWORKS software was used to design three standard blocks. Data were exported in STL format imported into the 3D printer control software to complete the printing and production of the standard block. The 3D data were acquired from the printed standard block using a dentognathic model scanner (Smartoptics). The GEOMAGIC STUDIO software was used to measure the error values in the X-, Y- and Z-axes, which were used for printer accuracy calibration. After calibration, the standard blocks were reprinted with the calibrated higher accuracy settings (Figure 4).

Chair-side high-speed 3D printing of the guide

The guide STL data were inputted into the 3D printer, and the layer thickness was set at 0.2 mm. The printer automatically printed the unsupported PLA implant guide (Figure 5).

Evaluation of positional accuracy of the implant guide

A 3D surface scanner was used to acquire 3D data of the printed implant guide. The registration function of the GEOMAGIC qualify software was used to register the 3D data of the printed implant guide with its CAD data. The software was used to evaluate the overall morphological error rate in the implant guide, and statistical analysis (one-way ANOVA) of the error data was performed. The software was also used to extract and measure data pertaining to internal and external surfaces of the gap produced between the occlusal surface of the natural teeth covering and the tissue surface of the implant. Statistical

Figure 3 The process of designing implant guide

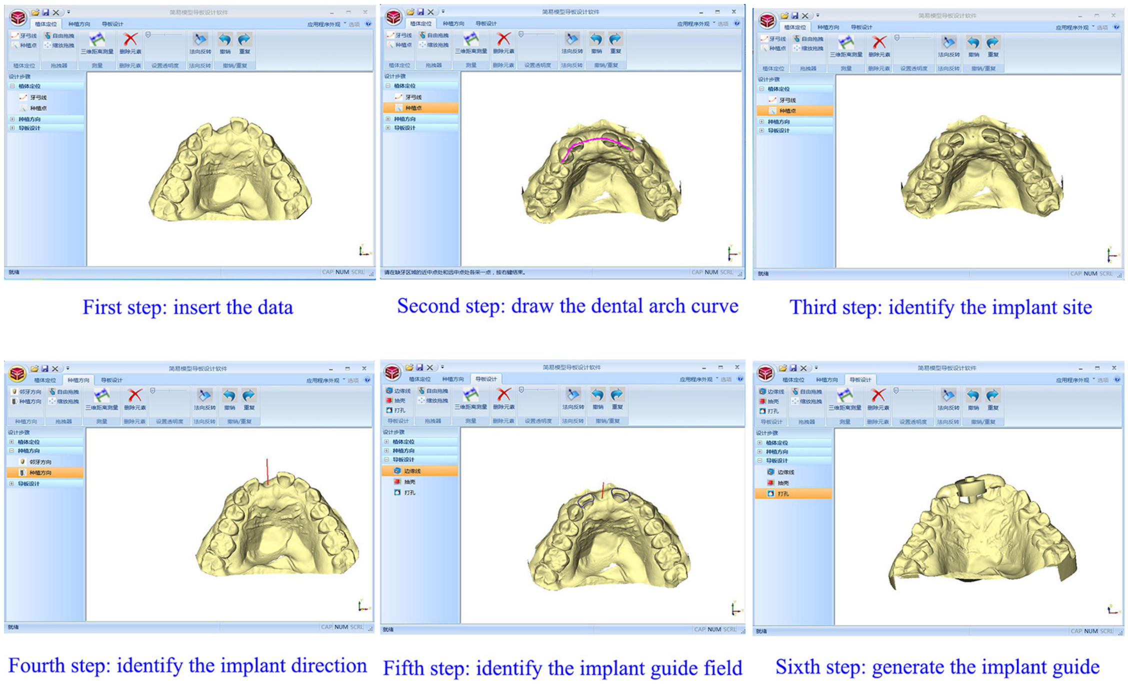


Figure 4 The printed standard block data and the 3D data of its design

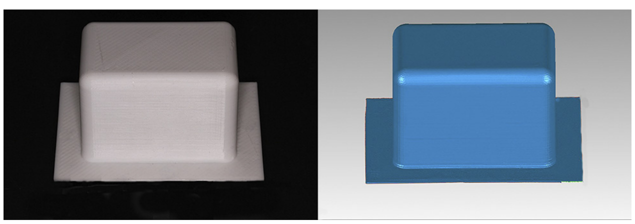
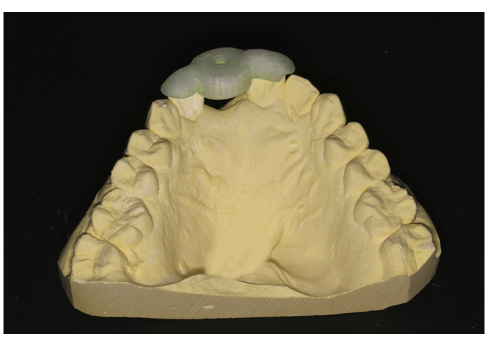


Figure 5 The printed implant guide



analysis of the measurements was subsequently performed (Figure 6).

Comparison and evaluation of the position and angle between the central axis of the printed implant guide and the central axis of the designed guide

The registered scanned guide data and designed guide data were imported into Imageware 13.0, and the upper and lower circles of the guide pore in the scanned guide data were fitted and connected to form a central axis (i.e. the implant axis). A comparison of the location and angle of the implant axis and the designed guide data was performed based on three indicators: overall, lateral and angular error. The overall error is the 3D distance (as shown in the figure) between the vertices of the two central axial lines. When evaluating lateral error, the centre of the crown of the guide pore in the implant guide that is perpendicular to the normal was used as a reference plane. The distance between the intersection of the reference plane and the longitudinal axis of the guide hole in the printed guide and the centre of the crown determines the lateral error. The angular error is determined by the 3D angular error between the two central axial lines (Figure 7).

Results

Implant guide CAD and FDM 3D printing was used to achieve a chair-side, high-efficiency design and production of implant guides. Visual inspection revealed that the positioning of the 30 implant guides was successful, and retention was satisfactory. A comparison of the 3D data of the printed implant guide and the CAD data of the implant guide demonstrated an overall morphological error of 0.599 ± 0.146 mm, and one-way ANOVA results revealed no statistical differences among the 30 implant guides (Table I). The gap between the tissue surface of the implant guide and the occlusal surface of the covering natural teeth did not exceed 0.341 mm, with an average value of 0.179 ± 0.019 mm. One-way ANOVA results did not demonstrate any statistical differences ($p > 0.05$) (Table II). The overall, lateral and angular errors of the central axis of the implant guide and the central axis of the designed guide were 0.104 ± 0.004 mm, 0.097 ± 0.003 mm and $2.053 \pm 0.017°$, respectively. These results suggest that implant-guided CAD

Figure 6 Overall error evaluation of the 3D data and CAD data of the printed implant guide and the gap measurements after positioning of the guide on the model

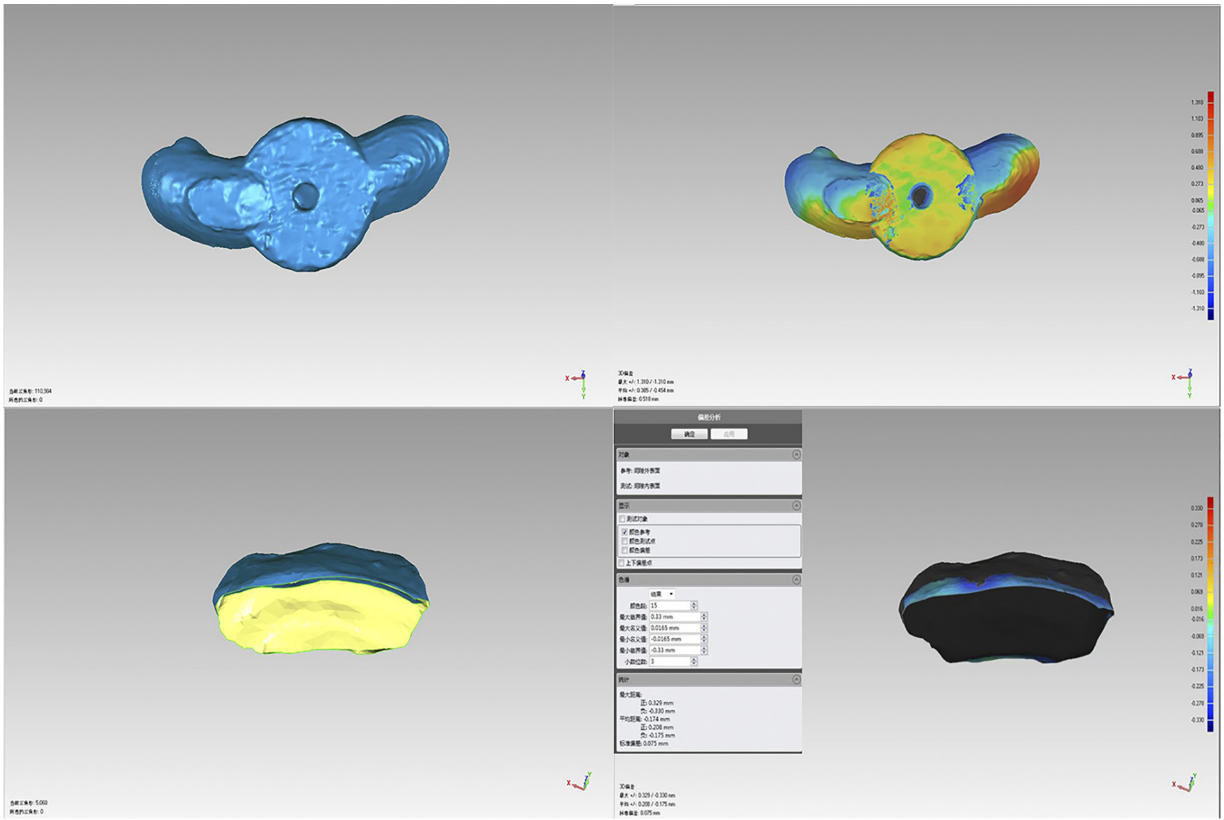


Figure 7 Analysis of positional and angular error between the central axial line of the guide pore of the printed guide and the central axial line of the designed guide

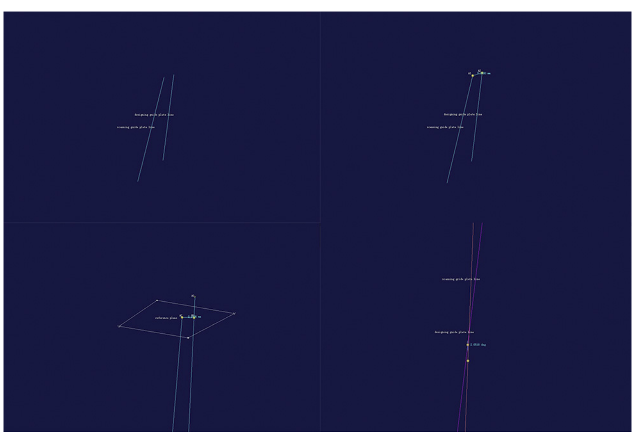


Table I ANOVA of overall error in 30 implant guides

Comparison	Sum of squares	df	Mean square	*F*	*p*
Between groups	0.746	29	0.026	1.517	0.131
Within groups	0.508	30	0.017		
Total	1.254	59			

Table II ANOVA of gap values in 30 implant guides

Comparison	Sum of squares	df	Mean square	*F*	*p*
Between groups	0.008	29	0.000	0.633	0.889
Within groups	0.014	30	0.000		
Total	0.022	59			

and FDM 3D printing can achieve chair-side, highly efficient, accurate and time-saving design and production of implant guides and, moreover, that the finished implant guides satisfy clinical requirements.

Discussion

This study introduced a chair-side solution for the design and production of tooth-supported surgical implant guides and highlighted the implantation concept of "repair" as a guide. Medical digitisation technology and 3D printing techniques are being used in the design and production of guides and help drive the widespread use of digitisation and use of "repair" as a guide for implantation. This study verified the positional accuracy of the implant guide model by introducing gypsum model preparation and by scanning of extra-oral dentognathic models to obtain 3D data. In actual application, an intraoral scanner can be used to acquire 3D data of the alveolar ridge mucosa, mesial and distal adjacent teeth and opposing teeth in the edentulous area. This may reduce the time required for obtaining impressions and model infusions and decrease cumulative errors and also achieve efficient and accurate actual chair-side design and production of implant guides.

The CAD design software used for the implant guides was independently developed by our project group. The overall design concept for this software focuses on "repair" as a guide and the importance of the first drilling for implantation (confirmation of the orientation, position and depth of the implant). The structure reproduces the 3D morphology of the missing teeth based on 3D data from the alveolar ridge mucosa, mesial and distal adjacent teeth and opposing teeth, in the edentulous area of patients. The occlusal surface is extended to the mesial and distal adjacent teeth to obtain a fixed position. According to the individual implantation standard, the position and orientation of the guide pore is then determined (minimum distance between the implant and adjacent teeth of 1.5 mm after implantation; minimum thickness of 1 mm for the buccal and lingual bone wall thickness; coordination of the mesial, distal, buccal and lingual surfaces with the long axis of the adjacent teeth; a distance of 2 mm from the apical portion of the implant to the mandibular nerve; and avoiding damage to important anatomical structures). Currently, the design of this implant guide is only applicable to guiding completion of the first drilling for implantation surgery.

The production of the implant guide was completed using the FDM 3D printing technology (Pennington *et al.*, 2005; Dudek, 2013). In this study, an FDM 3D printer was used to control PLA fine fibres to complete the production of the implant guide. PLA is a renewable, non-polluting biological resin that is extracted from corn and can be used in clinical practice (Athanasiou and Niederauer, 1996; Lunt, 1998; Pang *et al.*, 2010). After the PLA fibres are melted by the printer and, based on the cross-sectional profile information of the object to be printed, the computer controls nozzle movement. The sprayed material cools rapidly and solidifies. The next cross-section is then printed and superimposed, layer-by-layer, until 3D printing of the object is completed.

Factors that affect accuracy in FDM 3D printing primarily involve the following: discretisation during the CAD processing process, characteristics of the print material, the exact diameter of the nozzle, temperature, speed of ejecting and filling of the print material, layer thickness and placement direction of the 3D model. In this study, the diameter of the FDM 3D printer nozzle was 0.4 mm, the movement position of the XY-axis was accurate up to 10 μm, the movement position of the Z-axis was accurate up to 5 μm and the printing thickness could be adjusted from 100 μm (high precision) to 300 μm (low precision). Considering that higher printing precision requires a longer print time, we chose a precision setting of 200 μm. The angle between the guide plane and the horizontal plane was set at 60°, and the time to print one implant guide was approximately 10 min. The experimental results revealed that the printing precision of the implant guide could be controlled in the range of 0.6 mm and was adequate for current clinical requirements. If higher precision is required, the layer thickness can be set up to 100 μm, and the placement direction can be optimized. The design and production protocol for implant guides proposed in this study provides several advantages, including chair-side feasibility, high efficiency and accuracy. To access these features in actual clinical applications, an in-depth investigation of CAD software for implant guide design and 3D printing studies should be undertaken. In addition, the application range of the design software and design accuracy should be expanded, and various parameters for FDM 3D printing technology should be optimised. This will improve the performance of the printed material and help clinicians overcome the current limitations.

Conclusion

The experimental results demonstrated that implant guide CAD and FDM 3D printing can achieve chair-side, highly efficient, accurate and time-saving design and production of implant guides and, moreover, that the finished implant guides match clinical requirements.

References

Athanasiou, K.A., Niederauer, G.G. and Agrawal, C. (1996), "Agrawal, C. Sterilization, toxicity, biocompatibility and clinical applications of polylactic acid/polyglycolic acid copolymers", *Biomaterials*, Vol. 17 No. 2, pp. 93-102.

Brief, J., Edinger, D., Hassfeld, S. and Eggers, G. (2005), "Accuracy of image-guided implantology", *Clinical Oral Implants Research*, Vol. 6 No. 4, pp. 495-501.

Dada, K., Pariente, L. and Daas, M. (2016), "Strategic extraction protocol: use of an image fusion stereolithographic guide for immediate implant placement", *The Journal of Prosthetic Dentistry*, Vol. 116 No. 5, pp. 652-656.

Di Giacomo, G.A., Cury, P.R., da Silva, A.M., da Silva, J.V. and Ajzen, S.A. (2016), "A selective laser sintering prototype guide used to fabricate immediate interim fixed complete arch prostheses in flapless dental implant surgery: technique description and clinical results", *The Journal of Prosthetic Dentistry*, Vol. 116 No. 6, pp. 874-879.

D'Souza, K.M. and Aras, M.A. (2012), "Types of implant surgical guides in dentistry: a review", *The Journal of Oral Implantology*, Vol. 38 No. 5, pp. 643-652.

Dudek, P. (2013), "FDM 3D printing technology in manufacturing composite elements", *Archives of Metallurgy and Materials*, Vol. 58 No. 4, pp. 1415-1418.

Edelmann, A.R., Hosseini, B., Byrd, W.C., Preisser, J.S., Tyndall, D.A., Nguyen, T. and Bencharit, S. (2016), "Exploring effectiveness of computer-aided planning in implant positioning for a single immediate implant placement", *Journal of Oral Implantology*, Vol. 42 No. 3, pp. 233-239.

Engelman, M.J., Sorensen, J.A. and Moy, P. (1998), "Optimum placement of osseointegrated implants", *Journal of Prosthetic Dentistry*, Vol. 59 No. 4, pp. 467-473.

Feng, H.L. and Xu, J. (2013), *Prosthodontics*, 2nd ed., Peking University Medical Press, Beijing.

Greenberg, A.M. (2015), "Digital technologies for dental implant treatment planning and guided surgery", *Oral and Maxillofacial Surgery Clinics of North America*, Vol. 27 No. 2, pp. 319-340.

Gross, B.C., Erkal, J.L., Lockwood, S.Y., Chen, C. and Spence, D.M. (2014), "Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences", *Analytical Chemistry*, Vol. 86 No. 7, pp. 240-253.

Horwitz, J., Zuabi, O. and Machtei, E.E. (2009), "Accuracy of a computerized tomography–guided template–assisted implant placement system: an in vitro study", *Clinical Oral Implants Research*, Vol. 20 No. 10, pp. 1156-1162.

Komiyama, A., Klinge, B. and Hultin, M. (2008), "Treatment outcome of immediately loaded implants installed in edentulous jaws following computer–assisted virtual treatment planning and flapless surgery", *Clinical Oral Implants Research*, Vol. 19 No. 7, pp. 677-685.

Lal, K., White, G.S., Morea, D.N. and Wright, R.F. (2006), "Use of stereolithographic templates for surgical and prosthodontic implant planning and placement: part I: the concept", *Journal of Prosthodontics*, Vol. 15 No. 1, p. 51.

Lunt, J. (1998), "Large-scale production, properties and commercial applications of polylactic acid polymers", *Polymers Degradation and Stability*, Vol. 59 Nos 1/3, pp. 145-152.

Orentlicher, G. and Abboud, M. (2011), "Guided surgery for implant therapy", *Oral and Maxillofacial Surgery Clinics of North America*, Vol. 23 No. 2, pp. 239-256.

Pang, X., Zhuang, X., Tang, Z. and Chen, X. (2010), "Polylactic acid (PLA): research, development and industrialization", *Biotechnology Journal*, Vol. 5 No. 11, pp. 1125-1136.

Pennington, R.C., Hoekstra, N.L. and Newcomer, J.L. (2005), "Significant factors in the dimensional accuracy of fused deposition modelling", *Proceedings of the Institution of Mechanical Engineers, Part E. Journal of Process Mechanical Engineering*, Vol. 219 No. 1, pp. 89-92.

Further reading

Anitha, R., Arunachalam, S. and Radhakrishnan, P. (2001), "Critical parameters influencing the quality of prototypes in fused deposition modelling", *Journal of Materials Process Technology*, Vol. 118 Nos 1/3, pp. 385-388.

Corresponding author

Yuchun Sun can be contacted at: polarshining@163.com