Abstract

Introduction: A major challenge in dentistry is the replacement of teeth lost prematurely due to trauma, caries, or malformations, especially in growing patients. The aim of this study was to assess the accuracy of CAD-CAM surgically guided tooth autotransplantation in cryopreserved cadaver mandibles using guided templates and custom-designed osteotomes.

Methods: Cryopreserved human cadaver heads were digitized and scanned using an intraoral optical scanner and a large-volume cone beam computed tomography (CBCT) device. First, virtual surgical planning was performed to create a 3D tooth replica, two surgical guides, and a custom-made osteotome for each single-rooted tooth autotransplantation procedure/case. Surgical sockets were created in the selected mandibles using guided tooling consisting of an initial guided osteotomy with implant burs and a final guided osteotomy using custom osteotomes. After tooth autotransplantation, second large-volume CBCT images of the five cadaver mandibles were obtained. The discrepancy in mm within the 3D space (apical and mesiodistal deviations) between the final position of the autotransplanted teeth and their digitally planned 3D initial position was calculated and analyzed statistically ($P< .05$).

Results: All donor teeth were placed without incident within their newly created sockets in the real mandibles. The mean difference between the digitally planned root apex position and the final tooth position was 2.46±1.25mm. The mesiodistal deviation of the autotransplanted teeth was 1.63±0.96mm.

Conclusions: The autotransplantation of single-rooted teeth with custom-designed and 3D-printed surgical tooling provided promising results. The technique was able to create surgically prepared sockets that could accommodate transplanted teeth in mandibles.
Key Words: autotransplantation; CBCT; custom-designed osteotomes; human cadaver mandibles

Introduction

Fixed bridges, implants, removable partial dentures, and orthodontic space closure are the most commonly used treatment options for adults who have lost one or more teeth. However, for child and adolescent patients whose alveolar and maxillofacial bones are still developing, tooth autotransplantation may be a preferable option in specific cases (1,2) as, unlike implants, a transplanted tooth behaves in a similar way to a natural tooth by maintaining the alveolar bone and occlusion during growth (3).

In general, autotransplantation is carried out immediately after the extraction of the affected tooth. It has been reported that this type of autotransplantation has high success rates for both immature and mature teeth (4). For example, Chung et al. (5) concluded that the survival rate of autotransplanted teeth with complete root formation at 1-year and 5-year follow-up were 98.0% and 90.5%, respectively. Similarly, Kafourou et al. (6) reported an 87.6% overall success rate of tooth transplantation and a tooth autotransplantation survival rate of 94.4% in children and adolescents. However, there are a variety of situations in which the recipient site in the alveolus must be surgically created (7), for example, when the patient presents with congenitally missing teeth or previous tooth loss. The absence of periodontal ligament (PDL) fibers on the walls of surgically prepared sockets (8) is the most important difference between replantation and transplantation in existing sockets. Patients with surgically created sockets have also been reported to have a high success rate (9). For example, the survival rates of third molars transplanted into fresh extraction sockets and surgically created sockets were reported to be 93.1% and 88.9%, respectively, with no significant difference between the two groups (9).

Regardless of root development, three factors can negatively affect the long-term survival of transplanted teeth: 1) damage to the PDL of the donor tooth caused by repeated attempts to insert and reinsert the tooth into the recipient socket; 2) prolonged extra-oral time, which has a negative impact on viable PDL cells on the surface of the donor tooth; and 3) insufficient gap between the alveolus and the root of the donor tooth. (10-12). At the same time, the experience and skills of the clinician has been reported to play a fundamental role in this highly technique-sensitive surgical procedure (13).

Cone beam computed tomography (CBCT) and digital planning software have substantially reduced the complexity and failure rate of tooth autotransplantation (14,15). Such software allows the design and manufacture of three-dimensional (3D) printed surgical guides, which aim to bring autotransplantation surgery closer to guided surgery. It is reported that digitally planned surgery combined with precise bone removal (osteotomy) decreases trauma to the tooth and alveolar bone (16). A guided osteotomy is a relatively new technique that can be applied when performing these precise surgical procedures (17). A custom-designed osteotome (instrument for cutting bone) with the same dimensions and shape as the donor tooth could theoretically offer a more accurate fit between a freshly or surgically prepared socket and the donor tooth. The benefits of such a customized osteotome include minimally invasive surgery, shorter extraoral time, fewer attempts at insertion, a precisely predefined donor tooth position, an optimum gap between the bone of the socket and the tooth, and an overall more precise and simpler surgical management (18,19).

The ideal method of quantifying the precision of autotransplantation with customized-designed osteotomes is to perform the procedure in surgically prepared sockets instead of existing extraction sockets (20). Anssari et al. (21) performed a computer-assisted template-guided tooth autotransplantation using customized 3D designed/printed surgical tooling in cadaver mandibles. A comparison between the planned position of a transplanted tooth and its actual position revealed a mean apical deviation of 2.61±0.78 mm and a mean angular deviation of 5.6-5.4 degrees (21). Although these values are within the generally accepted ranges for surgical guides in implant treatment, they may be too imprecise for autotransplantation since a deviation of a few millimeters may not allow the correct fit between the replica and donor tooth whilst also having a negative impact on its alignment within the jaw; hence the need for even greater planning precision.

The aim of the present study was to assess the accuracy of surgically guided autotransplantation of single-rooted teeth using guided templates and custom-designed osteotomes in cryopreserved cadaver mandibles. This accuracy was established by comparing the final position of the autotransplanted teeth in the surgically created socket with the ideal 3D position previously planned digitally.

Materials and methods

The current study was reported according to the Preferred Reporting Items for Laboratory studies in Endodontology (PRILE) 2021 guidelines (22). The PRILE flowchart setting out details of the study is illustrated in Supplemental Figure 1. The study design of the current study was approved by the Institutional Ethics in Research Committee (END-ECL-2020-08). Cryopreserved human cadaver heads from the Department of Anatomy were used to assess the deviation between the digitally planned and final position of a surgically guided tooth autotransplantation procedure.

Procedure (Fig.1)

Sample selection

Ten cryopreserved human cadaver heads were initially screened. Cadaver heads with partially edentulous mandibles with missing single-rooted teeth (incisors, canines, and premolars) and edentulous spaces with adequate width, and height for autotransplantation were included. The exclusion criteria were mandibles that were either completely edentulous or had a full complement of teeth, as well as those with excessive bone resorption. A total of five heads met the selection criteria.

3D data acquisition

The selected cadaver heads were scanned with a large-volume CBCT unit (i-Cat 3D, Imaging Sciences International, Hatfield, PA, USA) with an 8x8 cm field of view (FOV), operating at 9 mA, 85kV with a 0.2 mm voxel size. All heads were placed in the CBCT unit with the occlusal plane parallel to the floor and supported in a static position by a headrest, and a strap passed through the upper third of the head, maintaining an adequate height. The CBCT scans were then exported to Digital Imaging and Communications in Medicine (DICOM) files. Subsequently, the teeth and their surrounding soft tissues were digitized by an experienced operator using the intraoral optical scanner device (Primescan, Dentsply Sirona, Bensheim, Germany) to improve the design of the surgical guides. Finally, the scanned files were exported and saved in a standardized triangulation language (STL) file format.

Virtual surgical planning and guided instrument design

The CBCT DICOM files, and the STL files of the intraoral scans, were uploaded and matched using software (Nemoscan™ version 11, Nemotec SL, Madrid, Spain). Single-rooted donor teeth were selected for the surgical procedure. First, a segmentation of virtual donor teeth was made for both the digital planning process and to export them in STL format to later print them and use them as a 3D tooth replica. Then, the height and width of the recipient area for each donor tooth were calculated using the same software. The location of each virtual new socket was preset based on the functional parameters of the relevant edentulous area. The optimal 3D position and inclination for the donor tooth were planned for each case leaving the virtual tooth at least 2 mm from the buccal and lingual cortical plates. In this way, it was possible to simulate an *in vivo* situation and at the same time avoid possible procedural errors such as fenestration or bone dehiscence during the procedure (Fig. 2).

Once the virtual donor teeth had been placed in the new virtually created recipient sockets, individualized guided instruments were designed following the superimposed data and the planned position of the virtual donor teeth. Two guides for each case were designed to aid the autotransplantation procedure: a first guide for initial implant bur guided osteotomy, and a second guide for a guided osteotomy using custom osteotomes for the final adjustment/modification of the new socket. The first surgical template preparation was based on the guided system for Straumann implants (Straumann AG, Basel, Switzerland). A custom implant with an active length and diameter equal to that of the guided surgery bur was virtually oriented to cover as much as possible the external outline of the digitally transplanted tooth. In all cases, the bur size selection was 2.8mm in diameter (Guided Implant Surgery Bone Level; Straumann AG, Basel, Switzerland) since all the selected donor teeth were single-rooted and had similar dimensions. The surgical guide outline was determined, and a minimum guide thickness of 2 mm was chosen to ensure adequate resistance without compromising the comfort of the operator. The design of the surgical template was totally tooth-supported, extending whenever possible 2/3 teeth mesial and/or distal of the area being treated to confirm optimum seating of the template. The cylinder of the drill handle was inserted into the sleeve (Ø 5 mm) fixed to the surgical template. For each Ø 2.8 mm implant bur, an ergonomic drill handle was used.

Then, custom-designed osteotomes were created according to the root dimensions of the virtual donor tooth and virtually placed in the virtual recipient socket (Fig. 3). With this position, a second surgical 3D guiding template was prepared for final socket adjustment/modification with the custom-designed osteotomes, allowing a more accurate positioning of the donor tooth. The surgical templates/guides were designed with an occlusal reference fixed to three adjacent teeth to ensure good stability (Fig. 4).

3D printing of the tooth replica, the guided template, and the surgical tools

The surgical templates for implant burs, the custom osteotome guided templates, the 3D replica of the segmented donor tooth, and the custom-made root-shaped osteotome were all exported as STL files and printed in biocompatible resin (Dental LT clear resin, Somerville, Massachusetts, USA) with a stereolithography 3D printer (Form 3B, Formlabs, Somerville, Massachusetts, USA). The custom-designed osteotomes were printed with castable wax resin (Formlabs, Somerville, Massachusetts, USA) and subsequently converted into a cobalt-chrome alloy tool using a traditional casting method based on the lost wax process (Fig. 5).

Surgical procedure

Following the digital planning, the donor teeth were extracted atraumatically (Fig. 6A). The 3D guided templates were then positioned and checked both optically and by palpation to confirm a good fit. A pilot bur guided the drilling sequence to create the new socket. The initial guided osteotomy was performed with implant burs (Straumann AG, Basel, Switzerland) up to a 2.8 mm diameter at the planned length (Fig. 6B). Then, the final guided osteotomy was performed by gently tapping the custom osteotomes with a hammer through the template in the apical area of the alveolus (Fig. 6C,D). As can be seen in the figures, the osteotomes were designed with a metal stopper that matched the design of the guide to prevent over-insertion during the expansion phase. Likewise, in each metal stopper, orientation marks were made in the part that corresponded to the buccal area to ensure the correct expansion of the socket.

The 3D replicas of the donor teeth were inserted into the surgically created sockets during the transplantation procedure to confirm that the new socket was a suitable shape and size and matched the root anatomy (Fig. 7A, B). The donor teeth were subsequently transplanted into the new socket. A single operator (F.A) with 10 years clinical experience in autotransplantation performed the entire procedure (Fig. 7C).

Evaluation of the pre-operative planning of the donor tooth position and postoperative location of the donor tooth

The accuracy of the position of the donor tooth in the newly created sockets was assessed with a second large-volume CBCT image taken with i-Cat 3D (Imaging Sciences International, Hatfield, PA, USA) at the settings used to make the pre-operative scans and the data saved as DICOM files.

Pre- and postoperative DICOM files were imported to Geomagic software (3D Systems, Rock Hill, South Carolina, USA) to examine the accuracy of the donor tooth position. Overlap between preoperative CBCT (initial ideal 3D digital position of teeth) and postoperative CBCT (final position of donor teeth after autotransplantation surgery) matched in all cases. In order to check this match, dimensional discrepancies between the pre-operative virtual 3D planning and the final position of the donor tooth in both apical and mesiodistal directions were evaluated in hundredths of a mm. A single examiner (G.O) with extensive experience in the use of the software was responsible for making these measurements, which were considered objective and highly accurate. The examiner was blinded as he was not involved in the digital preview plan.

Results

Five cryopreserved human mandible cadavers underwent 10 tooth autotransplantation procedures, that is, eight incisors, one canine, and one premolar were transplanted to a newly created socket in each of the five mandibles. Each donor tooth was successfully transplanted into its respective socket following uneventful guided drilling and osteotomy procedures. All donor teeth adapted adequately to their newly created sockets, with 90% of cases requiring minimal modifications during the osteotomy, for example, by reinserting the osteotome to widen the initial socket. The osteotome was used to make a final adjustment to the diameter of the 3D replica. The replacement of the 3D replica for the donor tooth was carried out without any additional modification, which allowed the accuracy of the 3D impression to be verified. The mean apical and mesiodistal deviations were 2.46 ± 1.2 mm and 1.63 ±1.0 mm, respectively (Table 1).

Discussion

Autotransplantation is a predictable technique for the replacement of missing teeth, premature and/or traumatic tooth loss, and unrestorable teeth (4). The current study used cryopreserved cadaver mandibles to assess the accuracy of surgically guided autotransplantation using custom 3D-designed surgical tooling.

In recent decades, digital technology has improved the diagnosis, planning and development of autologous transplant surgery allowing more complex treatments to be carried out in a more predictable way (23). Lee et al. (23) first described the fabrication of a replica of a donor tooth using preoperative 3D radiographic imaging. These replicas served as guides to simplify the recipient socket preparation process. They also minimize the extra-oral time of the donor tooth and the number of attempts at adjustment, thereby reducing iatrogenic damage to the donor tooth, periodontium, and bone of the recipient socket (4). However, there are challenging scenarios in which a 3D replica is insufficient, and auxiliary elements such as position guides for osteotomy are required.

Surgical planning software is a recent development aimed at digitizing autotransplantation surgery. One of the most innovative aspects of this planning software is the development and manufacture of 3D-printed surgical guides that facilitate the preparation of the new socket to accommodate the donor tooth (14). This technique has revolutionized autotransplantation in fresh extraction sockets, but it is still not completely accurate when autotransplanting teeth into surgically created sockets. This inaccuracy occurs because there is always a discrepancy between the shape of an implant bur and that of a donor tooth. Hence, the creation of custom-designed osteotomes is a concept that has been developed to significantly improve the dimensions of the new socket at the recipient site (17,21). Furthermore, the 3D position of the donor tooth in the socket is key to its survival (4). When donor teeth are placed in recipient sockets with an insufficiently wide buccolingual space, protrusion of the roots through bone dehiscence and subsequent resorption of the alveolar ridge may occur (24). Hence, this scenario must be anticipated through adequate 3D planning and the use of customized instruments that reduce the discrepancy between the planned and final tooth position (21).

In contrast to Anssari et al. (21), who used only the mandible of formalin-fixed human cadavers, the present study used whole heads from cryopreserved human cadavers, allowing the reproducibility of the technique and the result to be extrapolated *in vivo*. Studies undertaken on cadavers offer more similar conditions than other types of laboratory studies (25,26).

The surgical technique for creating the new sockets described in this study differs in various ways from those published by Bauss et al. (7,27) and Yu et al. (9). To perform the mucosal incision, Bauss et al. (7) first removed the mucosa to create a surgical socket corresponding to the diameter of the donor tooth. However, in the present study transmucosal drilling was performed without raising a flap. The soft tissue over the alveolar bone was removed with a tissue punch prior to the guided drill. Previous studies (7,9,27) performed the osteotomy with low-speed implant burs irrigated with copious saline to avoid damaging the bone. In contrast, the current study completed the apical area of the socket using custom 3D-printed surgical tooling. Regarding the new socket, Bauss et al. (7) and Yu et al. (9) widened the cavity more than its radiologically estimated size, as the surgery was not a guided procedure. In addition, a minimal osteotomy helps to stabilize the donor tooth and avoids excessive bone manipulation. Bauss et al. (7) used the donor tooth as a template to prepare the new socket, while the present study prepared the socket using 3D replicas to avoid damaging the donor tooth and its periodontal ligament.

Favorable PDL healing is a critical factor for the survival of all types of autotransplantation, especially in surgically created sockets where the PDL is only present around the donor tooth. Thus, Yu et al. (9) observed a post-extraction socket survival rate of 93.1%, while the rate for surgically created sockets was 88.9%, with no significant differences between the two groups. Those results coincide with the findings by Bauss et al (27), in which a survival rate of 94% for surgically created sockets was reported.

In the present investigation, the guided osteotomy of the new socket, employing surgical 3D-guiding templates and custom osteotomes, was performed with no remarkable problems (donor tooth extractions without fractures, proper guided osteotomies, etc.) and without incident. In all 10 cases (1 tooth per case), a satisfactory match between the new socket and donor tooth was established. When preparing the sockets, the autotransplantation to the five edentulous sites was accomplished without distal support for the template, which did not bend or fracture. Anssari et al. (21) found that a lack of distal support allowed the ends of the template to deviate, however, this was not observed in the current investigation. In the present investigation, the apical deviation did not exceed 2.46±1.2 mm. Anssari et al. (21) reported a mean apical deviation of 2.61±0.78 mm (P >.05), which is comparable to the values in the present study. Errors in translating clinical information to digital data and *vice versa* contribute to the accuracy of any given procedure (21). As stated above, the dimensions of the 3D-printed tooth replicas were the same as those of the donor teeth, so no additional readjustments were needed to the recipient sockets. However, the accuracy of the replica is an issue to consider as it depends on various factors such as the quality of pre-operative 3D data collection (CBCT and intraoral scanning) and the experience of the operator who virtually segments the teeth (8). Future studies should focus on the misalignment between the position of the virtual tooth and the final position of the real tooth in the real mandible to control and reduce these discrepancies. The discrepancies observed may be due to multiple factors such as the type of DICOM files from the CBCT images, inadequate alignment between DICOM and STL files, errors in CAD design, errors in template production, incorrect intraoperative positioning of the template, presence of a gap between the cylinder guide and bur implant location, and operator experience (28-31). There is an evident lack of appropriate surgical instruments for the perfect development of the technique and to be able to use it accurately and safely *in vivo*. In addition, it would be interesting to compare the planned initial and final positions also taking into account the buccolingual direction of the teeth.

The present study was performed with cryopreserved human cadaver heads. The application of this technique has potential during autotransplantation, especially when compared to a freehand technique. However, prospective, and randomized clinical studies are needed to confirm the results of the current study. In addition, another aspect to consider for future research is to evaluate the usefulness of virtual and augmented reality in cases of tooth autotransplantation.

Conclusions

Within the limitations of this study, the digital workflow method of surgically guided autotransplantation using 3D-printed surgical tooling and custom-designed osteotomes was suitable for surgically creating sockets that matched the dimensions of donor single-rooted teeth and facilitated their accurate placement.

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The authors deny any conflicts of interest related to this study.

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Figures and Table Legends

Figure 1. Flowchart summarizing the sequence of the digital design component and the surgical procedure. (* STL - standardized triangulation language)

Figure 2. Pre-operative virtual 3D planning. The red tooth was the selected donor tooth (#25). Once segmented, it was virtually inserted in an edentulous area. The pink tooth is the same donor tooth once it has been positioned in the optimal 3D position within the newly created recipient alveolar socket (tooth position #27).

Figure 3. Design of osteotomes in the planned 3D position. The custom osteotome (purple outline) was designed to replicate the shape of the root of the donor tooth. The yellow outline defines to prepared drill site.

Figure 4. Guided surgical template design combined with custom osteotomes. The red tooth represents the original position of the donor tooth (initial position in transparency) and the pink tooth the final position of the tooth in the new socket that will be created surgically.

Figure 5. Custom osteotome manufacturing process. The custom-designed osteotomes were printed with castable wax resin (Formlabs, Somerville, Massachusetts, USA) and subsequently converted into a cobalt-chrome alloy tool using a traditional casting

method based on the lost wax process. At the end of production, buccal orientation marks were made on each of the metal stoppers of the custom osteotomes.

Figure 6. A) Extraction of the donor tooth. B) Initial guided osteotomy by using implant burs. C-D) Final guided osteotomy with a custom-designed osteotome. Note the use of the hammer to complete the insertion of the osteotome into the desired final position.

Figure 7. A) Surgically created socket. B) 3D replicas of teeth in the surgically created sockets. C) Transplantation of the donor tooth in the surgically created sockets.

Supplementary Figure 1. PRILE 2021 flowchart.

Table 1. Measurements of deviation parameters between each transplanted donor tooth versus its planned position