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An advanced navigational surgery system for dental implants completed in a single visit: An in vitro study

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A B S T R A C T

In this study, we have developed an advanced navigational implant surgery system to overcome some disadvantages of the conventional method and have evaluated the accuracy of the system under in vitro environment. The patient splint for registration and tracking was improvised using a bite splint without laboratory work and the offset of an exchanged drill was calibrated directly without pivoting during surgery. The mean target registration errors (TRE) were 0.35 ± 0.11 mm using the registration body, 0.34 ± 0.18 mm for the registration method with prerecorded fiducials, and 0.35 ± 0.16 mm for the direct calibration of a drill offset. The mean positional deviations between the planned and placed implants in 110 implant surgeries were 0.41 ± 0.12 mm at the center point of the platform and 0.56 ± 0.14 mm at the center point of the apex. The mean angular deviation was 2.64°± 1.31 for the long axis of the implant. In conclusion, the developed system exhibited high accuracy, and the improved tools and simplified procedures increased the convenience and availability. With this advanced approach, it will be possible to complete dental implant surgery during a single visit at local clinics using a navigational guidance involving cone-beam computed tomographic images.

1. Introduction

As an increasing number of edentulous patients are treated with implants, the surgical complications are also increasing because of the limitations of the operator's experience and the patient's anatomical variations (Chee and Jivraj, 2007; Zoghbi et al., 2011). Damages to the inferior alveolar nerve or perforation into the maxillary sinus are common complications during implant surgery (Greenstein et al., 2008). An implant has to be precisely placed at locations of the planned position, angle, and depth to reduce complications and to increase the long-term success of an implant-supported prosthesis (Becker and Kaiser, 2000; Buser et al., 2004). Recently, cone-beam computed tomography (CBCT) has been widely used to obtain a 3-dimensional (3D) image of the jaw in local dental clinics because of its lower installation cost, smaller occupied space, and lower radiation dose than general computed tomography (CT) (Benavides et al., 2012; Quereshy et al., 2008). The 3D images can help a surgeon transfer the implant surgical plan to the patient's jaw bone more exactly, with a better understanding of the anatomical structures. Nonetheless, great experience is required to place an implant exactly at the planned location without surgical complications (Van de Velde et al., 2008).

Currently, the most actively studied method for the precise placement of dental implants is the surgical guide template. The implant position is determined preoperatively by planning software using a 3D CT image, and the surgical guide template is generally fabricated by a rapid prototyping machine (Di Giacomo et al., 2012; Nickenig and Eitner, 2010; Nickenig et al., 2010;

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Sarment et al., 2003; Soares et al., 2012). Surgical guide templates provide prosthodontic considerations before surgery and prevent unexpected surgical complications (Lee et al., 2013). However, the method has some disadvantages, including the considerable amount of time and cost required for template fabrication, the impossible intraoperative modification of the preoperative plan, and the possibility of fatal errors occurring if the template is not firmly fixed to the patient's dentition (de Almeida et al., 2010; Di Giacomo et al., 2012). Furthermore, when a patient has limited interocclusal distance, the surgical access with the template is limited because a longer drill has to be used compared to that in a normal case, due to the thickness of the template's drill sleeve (Park et al., 2009). Another method for precise transfer of the planned position is the image-guided navigation method, in which a position tracking camera tracks the position of the drill tip, which is superimposed on the patient's 3D image during surgery (Ewers et al., 2004; Widmann and Bale, 2006). Consequently, a surgeon can place an implant on the planned location precisely by identifying the position, angle, and depth of the drill tip during surgery in real time (Siessegger et al., 2001). However, this method also requires laboratory work for fabricating the registration template before surgery. In addition, the preparation for registration and setting of the tracking devices before surgery is time consuming and somewhat inconvenient. For these reasons, this method is not used as widely as the surgical guide template, despite its high accuracy (Jung et al., 2009; Mischkowski et al., 2006).

In this study, we have developed an advanced navigational implant surgery system using CBCT images for overcoming some disadvantages of previous methods and have evaluated the accuracy of the system in an in vitro environment. The method does not require laboratory work for splint fabrication, and the overall surgery time is shortened as a result of using improved tools and simplified procedures.

2. Materials and methods

2.1. CBCT scanning

A partially edentulous model (Basic-JCP model, Korea Model Technology, Seoul, Korea) was used to evaluate the developed navigation surgery system (Fig. 1). The model had soft tissue and spongeous bone to simulate the real jaw. The 3D image of the model was obtained using CBCT (Implagraphy, VATECH, Seoul, Korea) under the conditions of 85 kVp, 3.3 mA, 24-s scan time, and $1 \times 9\ cm^2$ field of view (FOV) with voxel size of $0.2 \times 0.2 \times 0.2\ mm^3$. The patient-specific splint was improvised using a bite splint shortly before CBCT scanning without any additional laboratory work for fabrication (Fig. 2(a)). Dental occlusion of the patient was recorded on the devised splint using dental impression material (thixotropic vinyl polysiloxane; Parkell Inc., Brentwood, NY, USA). The splint was firmly mounted onto the teeth of the model during CBCT scanning. An image registration body was attached to the splint using a LEGO block to facilitate registration between the patient and image spaces. The registration body could be repeatedly attached to and detached from the splint.

2.2. Registration using a reusable registration body

The registration (M_{reg} in Eq. 2) was performed so as to match the phantom's physical space with the image space using the reusable registration body containing six ceramic spheres 1 mm in diameter before starting the surgery (Fig. 2(b)). The registration based on the reusable registration body was used for mandibular movement tracking and simulation in our previous studies (Kim et al., 2010a,b, 2013). The patient tracking tool was attached to the splint using a

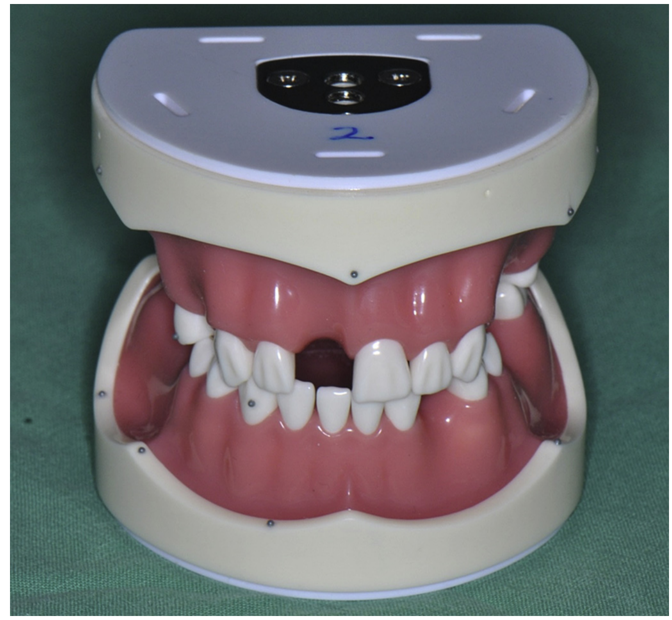

Fig. 1. A partially edentulous model with landmarks for measuring target registration error.

LEGO block (Fig. 2(c and d)). Three-dimensional physical positions of the tracking tools were tracked using an optical camera system (Polaris Vicar; Northern Digital Inc., Waterloo, ON, Canada). The physical positions of the fiducial spheres on the registration body measured by a tracked pointing tool with respect to the patient tracking tool were registered by point-to-point matching in a sequential order with corresponding positions identified on the 3D CT image (Fig. 3). In addition, if the position of the camera with respect to the world coordinate system did not change between registrations for different surgeries, the physical positions of the fiducials previously recorded could be used in another registration without regard to the configuration change of the patient tracking tool. These steps played an important role in reducing the time and work for surgery preparation.

2.3. Intraoperative tracking using universal tracking tools and direct calibration of the drill offset

Before starting the surgery, the splint with the patient tracking was firmly mounted onto the model in the same position as CBCT scanning. The patient tracking tool was adjusted easily to orient in the direction of line-of-sight of the optical camera without obstruction by using a cylindrical joint (Fig. 2(c and d)). The 3D physical positions of the patient and the instrument tracking tools were then tracked by the optical camera system (Polaris Vicar, Northern Digital Inc., Waterloo, ON, Canada). The continuous image position of the drill tip was calculated with respect to the patient by applying Eq. 1 to the measured physical positions from the camera. The location of the drill tip was then tracked on a 3D image regardless of the patient's movement in real time and was visualized on the monitor during the surgery.

The drills were exchanged several times to form an appropriate hole for each implant during the implant surgery procedure. When the drills were exchanged, the offset of the drill tip from the instrument tracking tool was altered, so the new offset vector had to be calibrated and reflected in the instrument tracking equation (Eq. 1) to track the position of a drill tip accurately. Without pivoting the handpiece, the offset vector of a new drill tip could be calculated