Three-Dimensional Accuracy of Implant Placement in A Computer-Assisted Navigation System

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Purpose: *To evaluate the 3-dimensional accuracy of dental implant drilling in a computer-assisted navigation (CAN) system using simulated mandible models.* ***Materials and Methods:*** *Eight acrylic resin models were fabricated to simulate human mandibles containing mandibular canal (MC). Computerized tomography (CT) scans were obtained for each model, and the data were transferred to the system for dental implant planning. The models were mounted on a phantom head to simulate surgical situation. The assessment parameters included entry point localization, drill path angulation, and drilling depth, which were directly measured by sectioning of the models.* ***Results:*** *Eighty drill holes were made on the 8 models. The entry point localization showed a mean deviation of 0.43 mm (range, 0 to 2.23 mm; SD, 0.56 mm) from the plan. The angulation showed a mean deviation of 4.0 degrees (range, 0 to 13.6 degrees; SD, 3.5 degrees). The drill aimed at stopping as close to the upper border of the MC as possible without perforating it, and 65% (52) of the drill holes managed to come within 1 mm. Another 5% of the holes stopped 1 to 2 mm above the MC. None of the drill holes stopped more than 2 mm above the MC. However, 30% (24 of 80) of the drill holes perforated the upper border of MC, and the mean depth of perforation was 0.37 mm (range, 0.01 to 1.04 mm; SD, 0.28 mm).* ***Discussion and Conclusion:*** *The CAN system identified the entry location and angulation with mean deviations of 0.43 mm and 4 degrees, respectively. About two thirds of the drillings achieved accuracy within 1 mm above the MC. Thirty percent perforated into the MC, and the maximal depth was 1.04 mm. In the planning stage, the maximal depth of the implant should be at least 1.1 mm above the superior border of MC as a safety margin.* (Technical Report) INT J ORAL MAXILLOFAC IMPLANTS 2006;21:465–470

Key words: *computer-assisted navigation, dental implants, image-guided navigation*

Surgical navigation was developed initially in the 1980s for stereotactic neurosurgical procedures that involved 3-dimensional localization of intracranial structures or pathologies.[1–3] High accuracy in planning and execution of surgical procedures is important in securing a high success rate without causing iatrogenic damage. Today, this technology is routinely applied in a variety of operations involving, to give a few examples, the anterior skull base,[4–6] paranasal sinuses,[7–10] spine,[11–14] and hip.[15,16] It serves as a powerful tool for diagnostic, treatment-planning, and operational purposes. The most significant advantage of computer-assisted navigation (CAN) is real-time tracking of the actual positions of surgical instruments on anatomic structures.

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Application of this technology in implant dentistry can enhance safe and correct placement of implants. Since the oral cavity is a relatively restricted space, a high degree of accuracy in the surgical navigation system is very important for applications in this region. Gaggl and Schultes[17–19] performed a series of in vitro studies in acrylic resin models of the jaw that showed that CAN systems have very high navigational accuracy, which can prevent damage to the mandibular canal and the sinus floor. However, only the depth drilled was measured, whereas accuracy in entry point localization and drill path angulation were not assessed. Wanschitz and colleagues[20] evaluated the accuracy of a CAN system in intraoperative positioning of dental implants in edentulous dry cadaver mandibles. The positions of the implant tips were measured on pre- and postoperatively using computerized tomographic (CT) scans. The overall accuracy was found to be approximately 1 mm. The shortcoming was that all the measurements were based on CT images rather than actual objects.

The purpose of the current study was to evaluate the 3-dimensional accuracy of localization, angulation, and depth of dental implant drilling in a CAN system using a simulated model of the mandible.

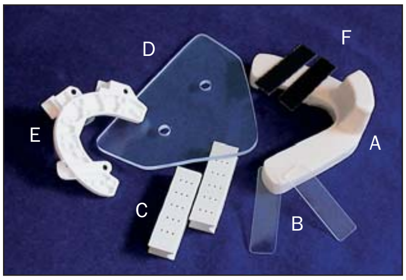

Fig 1a Components of the mandible model before assembly: *(a)* the model base, *(b)* Perspex (1 mm thick), *(c)* the channel blocks, *(d)* the phantom connector, *(e)* the locating horseshoe element, and *(f)* the blind covers.

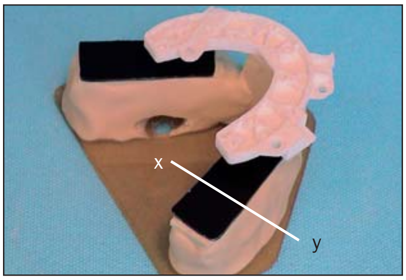

Fig 1b The assembled mandible model with a locating horseshoe element attached. The line x–y indicates where the model was cut to create a transverse section.

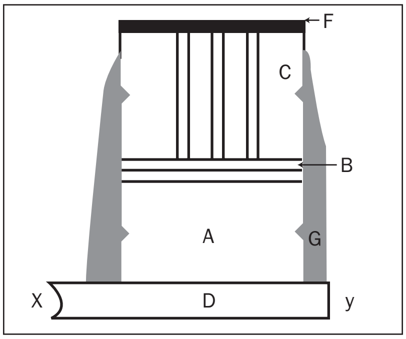

Fig 1c Cross-section of the posterior segment of the mandible model. The 10-mm-tall channel block (C) contained 3 1-mm-diameter holes, which were covered by the blind cover (F). The components were fixed together at the periphery by self-polymerizing acrylic resin (G). The drill was to pass through the two 1-mm-thick sheets of Perspex (B) without perforating the model base (A), which represented the MC. The model base rested on the phantom connector (D).

MATERIALS AND METHODS

A model of the mandible was designed specifically for this study by the Dental Technology Unit of the University of Hong Kong. Each model was composed of the following components: a model base, four 1-mm-thick sheets of Perspex (Lucite International, Southampton, United Kingdom), 2 channel blocks, a phantom connector, a locating horseshoe element, and 2 covers for blinding (Fig 1a).

The model base was designed to simulate the shape of a human mandible and was fabricated from self-polymerizing acrylic resin (Trayplast, Vertex; Dentimex, Zeist, Nederland) with 3 flat areas on its superior surface, 1 at the front to receive the locating horseshoe element and 2 at the posterior segments to receive sheets of Perspex. The height of the posterior segment on each side was 12 mm; the height of the anterior segment was 37 mm. The transverse and the anteroposterior dimensions of the posterior segments were 16 mm and 45 mm, respectively. The model base was cemented to the phantom connector, which was created from a 3-mm-thick clear sheet of Perspex. The assembled mandible model could be subsequently connected to a phantom head by screws in order to simulate the clinical situation. The 1-mm-thick Perspex sheets were rectangular in shape, measuring 13 mm wide and 45 mm long. Two pieces of Perspex, with a total thickness of 2 mm, were placed on each posterior segment of the model base. The junction between the Perspex and the model base represented the superior border of the mandibular canal (MC). The channel blocks placed on top of the Perspex sheets were made of polyurethane (Modralit-3K, Dreve, Germany), which facilitated smooth drilling. The thickness of the channel block was machined to 10 mm, and the width and the length were trimmed to fit on top of the posterior segments of the model base. Five groups of 1-mm-diameter holes were drilled vertically through the channel blocks using a parallelometer (Miko – Parallelometer MP2000E; Metaux Preceus, Metalor, Switzerland). Each group contained 3 holes 3 mm apart aligned in a straight line perpendicular to the long axis of the block. Each group was separated by 7 mm. Figure 1b shows the assembled mandible model, and Fig 1c shows the cross-section assembly of components at the posterior segment.

The Image-guided Implantology system (IGI; DEN X Advanced Dental System, Jerusalem, Israel) was used in this study. It is a system dedicated to the facilitation of dental implant planning and placement. It is composed of software installed in a computer processing unit, a monitor, a tracking camera, and a trackable handpiece. In addition, a locating horseshoe element is required to seat the apparatus stably in the patient's jaw; this element is used for calibration and for attachment to the infrared reference body. In this study, the locating horseshoe was cemented onto the anterior segment of the model base. The top surface of the channel block was covered with a black blind cover on each posterior segment (Figs 1a and 1b) in order to prevent the operator from seeing the entry holes during surgery.

CT scanning was performed (Hispeed FX; General Electric, Fairfield, CT) using a slice thickness of 1 mm in the axial plane. The CT data were saved on a compact disc and transferred to the CAN system. Place-

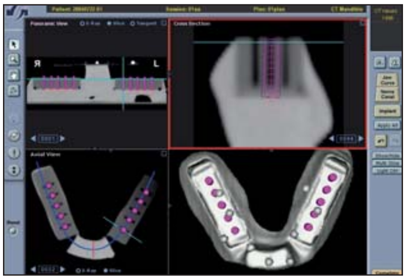

Fig 2 The centers of the implants were positioned to match the centers of the 1-mm predrilled holes during the planning process in the CAN system. The tip of the implant was positioned just above the mandibular base, which represented the top of the MC.

Fig 3 The mandible model was mounted to a phantom head to simulate clinical situation. The locating horseshoe element was cemented onto the anterior segment of the model base and was connected by a metallic pole to a reference body for tracking purposes. The handpiece and the reference body must remain within the area of the tracking camera. They must face the tracking camera to ensure constant tracking for surgical navigation.

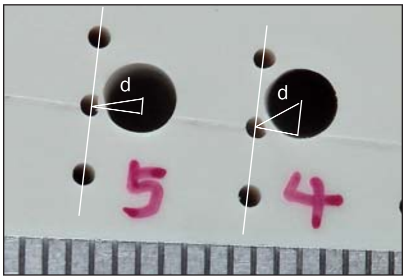

Fig 4 Measurement of the deviation between the center of the predrilled hole (the planned center of the implant) and the actual drill hole. The distance between the centers (d) was calculated by generating a right triangle.

ment of Brånemark Mk III regular-platform dental implants (Nobel Biocare, Göteborg, Sweden) was planned. Five dental implants 4 mm in diameter were selected for placement in the posterior segment on each side of the mandible model. During the planning stage, the centers of the implants were positioned to match the centers of the predetermined 1-mm drill holes. In addition, all the implants were placed with their apices within the model base. The aim was to place the implants just superior to the upper border of the MC (Fig 2).

The drilling sequence of the mandible models was carried out according to the manufacturer's surgical implant protocol.[21] The determined implant sites were drilled carefully under the guidance of the CAN system to ensure minimal deviation from the plan (Fig 3).

When the drilling procedures were completed, the models were sectioned to expose the actual implant positions. Cross-sectional digital photographs were taken of the tested models after removal of the blind covers. The distance between the center of the planned implant position and the center of the actual drill hole was measured at both the top and bottom of each channel block. The difference at the top was the deviation of the entry point of the drill hole from the plan (Fig 4). The deviation in angulation was geometrically calculated by measuring the discrepancies at the top and the bottom of the channel blocks between the planned drill path and the actual drill path (Fig 5). Perforations of the Perspex sheets and the model base were measured with a dial depth gauge with an accuracy of 0.01 mm (Type 185; Mercer, Herts, England) mounted at a right angle on a stand (Eclipse, Sheffield, England) (Fig 6).

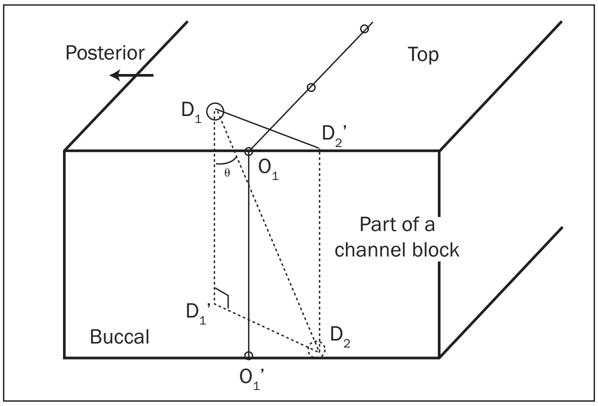

Fig 5 The deviation of the angulation was geometrically calculated after measuring the discrepancies at both the top and the bottom of each channel block. O_1O_1' is the planned path of drilling. D_1 and D_2 are the center of the drilled holes at the top and the bottom surface of the channel block, respectively. D_1D_2 represents the path actually drilled through the channel block. The angle of deviation (θ) is the angle between the path of drilling (D_1D_2) and a line (D_1D_1') that passes through D_1 and touches the bottom surface at D_1' such that D_1D_1' is perpendicular to the top surface of the channel block. The angle of deviation was calculated by the following formula:

$$\tan\theta = D_2D_1'/D_1D_1' = D_1D_2'/D_1D_1'$$

where D_2' is a vertical projection of D_2 to the top surface and D_1D_1' is the thickness of the channel block, which was machined to 10 mm.

Mean deviations in entry point localization and angulation were analyzed by paired *t* tests. Drilling depth was categorized by the distance from the model base, which represented the MC. The mean perforation depth was also calculated.

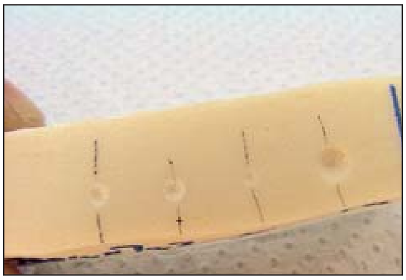

Fig 6a *(Left)* The MC was considered perforated when the drill passed through the Perspex sheets and created depressions on the model base.

Fig 6b *(Right)* The depth of the depressed perforation on the model base was measured by a dial gauge. The depth value represents the depth of penetration through the MC.

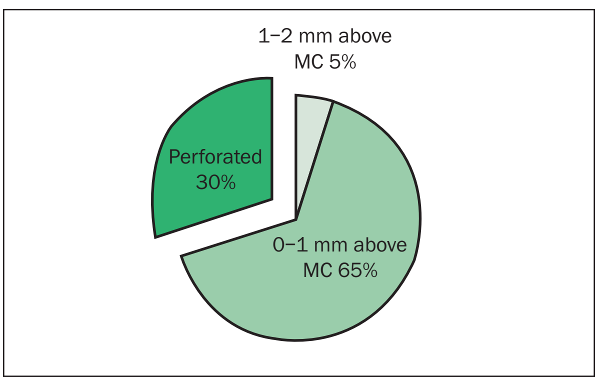

Fig 7 Distribution of drilling depth for the 80 drill holes.

Table 1 Relationship Between Position of Drill Hole in Mandible Model and Deviation in Entry Point and Angulation

Drill hole position	No. of drill holes	Mean deviated distance (mm) in entry point (SD)	Mean deviation (degrees) in angulation (SD)
1	16	0.46 (0.56)	3.2 (2.3)
2	16	0.39 (0.61)	4.1 (3.8)
3	16	0.38 (0.58)	3.8 (3.7)
4	16	0.43 (0.60)	4.3 (3.6)
5	16	0.48 (0.53)	4.7 (4.0)
Total	80	0.43 (0.56)	4.0 (3.5)

Position 1 is the most anterior drill hole; 5 is the most posterior. Position had no significant effect on either entry point deviation (P = .99) or deviation in angulation (P = .83).

RESULTS

Each posterior segment of the mandible models had 5 drill holes on either side, ie, 10 drill holes per model. A total of 80 drill holes were made on the 8 test models used.

The localization of the entry point of the drill deviated from the plan by a mean of 0.43 mm (range, 0 to 2.23 mm; SD, 0.56 mm). The angulation accuracy showed a mean deviation of only 4.0 degrees (range, 0 to 13.6 degrees; SD, 3.5 degrees). There was no predilection of the deviation either mesiodistally or buccolingually.

Concerning the drilling depth, 65% (n = 52) of the drill holes ended 0 to 1 mm above the MC and 5% (n = 4) ended 1 to 2 mm above the MC. None of the drill holes ended more than 2 mm above the MC. The remaining 30% (24 of 80) of the drill holes perforated the upper border of the MC (Fig 7). The mean perforation was 0.37 mm (SD, 0.28 mm), with a range of 0.01 to 1.04 mm.

Whether the drill hole was located on the right side or left side of the model did not affect the accuracy (P = .270). The mean surgical drill entry point deviation was 0.35 mm (SD, 0.46 mm) on the right side and 0.50 mm (SD, 0.66 mm) on the left side. Mean angular deviation was 4.1 degrees on the right side (SD, 3.1 degrees) and 4.0 degrees on the left side (SD, 3.8 degrees), with a P value of .96. The position of the drill holes (anterior versus posterior) did not show any statistical significant effect either (P = .99 for entry point deviation and .83 for angular deviation; Table 1).

DISCUSSION

CT scanning has become a well-established aid in preoperative assessment prior to implant placement.[22,23] It is a valuable tool for 3-dimensional measurement of the bony ridge available and the identification of the neurovascular structures. For routine clinical purposes, panoramic radiography may be sufficiently accurate.[24] However, difficulty in identification of the MC is not uncommon. Todd and associates[25] demonstrated that up to 50% of images could not be identified in tomography due to blurring.

Currently, the transfer of CT information to the operating field is commonly done using a template with drill guides. Naitoh and associates[26] demonstrated good accuracy of the splint in controlling the entry location and angulation in a study involving 6 patients. Nevertheless, the template rests on oral mucosa, which is mobile to some degree; hence, the reproducibility of the splint position is subject to error, particularly in edentulous patients. The lack of real-time control during the surgical procedure is a major drawback. Surgeons can only follow the splint; there is no possibility of adjustment. This is important because occasionally the underlying structures may differ considerably from the images used in planning, and this only becomes obvious during the surgery.

Several in vitro studies have attempted to define the accuracy of the CAN surgical systems. Gaggl and coworkers[18] tested the SMN system (Zeiss, Oberkochen, Germany) in acrylic resin mandible models. One hundred test drills were made to come as near as possible to the upper border of the MC without perforation. The mean distance to the MC was 0.14 mm. The upper border of the canal was perforated in only 11 of 100 cases. Birkfellner and associates[27] studied 30 consecutive edentulous patients who received implants using another optical tracking system and reported a mean error of 1.23 ± 0.28 mm and a maximum error of 1.87 ± 0.47 mm between the planned position and the real position. Wanschitz and colleagues[20] assessed the accuracy of surgical navigation software by placing 4 interforaminal dental implants in 5 dry cadaveric mandibles. The overall accuracy (mean deviation) was found to be 0.96 mm, with a range of 0.0 to 3.5 mm. There was no perforation of the mandibular cortex or damage to the MC.

Few clinical trials have been performed to evaluate the accuracy of CAN systems. Wagner and associates[28] studied the placement of 32 implants in patients after ablative tumor surgery with the CAN system. The mean deviation was 1.1 mm, with a range of 0 to 3.5 mm. The mean angular deviation of the implants was 6.4 degrees, with a range of 0.4 to 17.4 degrees. Based upon the results of this study, it was concluded that the system had adequate accuracy in placing implants in patients with difficult situations.

The CAN system used in the present study is a dedicated dental implant system. The accuracy of its tracking system was studied by Casap and coworkers.[29] An error of less than 0.73 mm was reported; however, only the actual position coordinates of the reference ceramic markers and those identified on the CT image were compared. The actual procedure of using the system in guiding the transfer of the presurgical plan to the patient was not studied. Brief[30] tested the same system with edentulous phantom jaws by comparing the center position of the planned drill hole with that of the end position. Virtual implants 3.75 mm in diameter and 10 mm in length were used. A total of 38 drill holes were prepared in 2 model jaws, 23 in one and 15 in the other. The virtual implant locations were related to spheres previously cemented to the jaw on the CT scan. The top and bottom positions of each drill holes were measured. An accuracy of 0 to 1.2 mm was reported; however, the accuracy in depth was not measured.

In this study, even though the mean deviation in the position of entry point from the plan was only 0.43 mm, the maximum deviation was up to 2.23 mm. There was a wide range of entry-point position deviation, as indicated by a large SD of 0.56 mm. Nevertheless, these figures were comparable to the findings of the in vitro studies of Birkfellner and associates[27] and Wanschitz and colleagues,[20] and slightly better than the results of the in vivo study of Wagner and associates.[28] However, this degree of precision is far from ideal, which leads to uncertainty in the clinical application of CAN systems.

Concerning drilling depth, 65% of the holes drilled using the CAN system were 0 to 1 mm above the MC. However, 30% of the drill holes perforated the MC, and the maximum depth of perforation was 1.04 mm. This degree of error must be noted, because 1 of the most important indications for the use of the CAN system is avoidance of the MC. Therefore, in clinical practice, the maximal depth of the implant should be placed at least 1.1 mm above the superior border of MC as a safety margin.

The steps involved in the CAN system used in this study are rather delicate, and the introduction of errors was possible during any of the preparative or operative procedures. Such error would be in addition to the error directly related to the system hardware. This probably explains the imprecise performance of the system in this study. Further simplification of the CAN system will be important to reduce the chance of introducing errors throughout the tedious steps and to make the system more user-friendly. Currently, the patient has to wear a locating splint while undergoing CT scanning, and even the slightest degree of rocking or incomplete seating of the splint may introduce significant error. This is especially important clinically because the splint may tilt slightly without being noticed by the clinicians when the patient bites down on it. The presence of a radiologist with experience in the CAN system during CT scanning may be ideal to minimize this error. In the planning stage, precise mapping of the MC on the CT scan can sometimes be difficult. Accurate interpretation of the CT scan requires extensive experience. In some patients, the canals may not be able to be visualized clearly even by an experienced radiologist. Aryatawong and colleagues[31] studied the CT scans of 55 patients, and the MC was graded as invisible in as many as 14.3%. During the drilling procedure, the positioning of the drilling burs controlled by the operator is definitely another source of inaccuracy.

CONCLUSIONS

The CAN system identified the entry location and angulation with mean deviations of 0.43 mm and 4 degrees, respectively. About two thirds of the drillings achieved the desired depth (within 1 mm above the MC). Thirty percent of the holes perforated the MC and the maximal depth was 1.04 mm. The maximal depth of the implant should be set to at least 1.1 mm above the superior border of MC as a safety margin.

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