Accuracy Assessment of Image-Guided Implant Surgery: An Experimental Study

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Purpose: *To accurately accomplish the drilling of an implant socket, the use of image-guided navigation has become an option. The aim of this study was to evaluate the 3-dimensional (3D) accuracy of navigation-guided drilled holes.* ***Materials and Methods:*** *Laboratory accuracy measurements were obtained on an acrylic resin model with standardized target holes drilled by a computerized numerical control machine. The model was scanned by a multislice computerized tomography scanner and registered with fiducial marker–based algorithms. Navigated drillings were performed using an optical navigation system based on passive marker technology. Coordinates of drilled holes were determined by a 3D-digitizer probe, and accuracy was assessed for all 5 degrees of freedom using a computer-aided design system (Pro/Engineer).* ***Results:*** *A total of 240 drillings were evaluated. Mean registration error was 0.86 mm (SD 0.25 mm). Target point deviation between preplanned and actual drill starting point was 0.95 mm (SD 0.25 mm). The deviation in terms of full length was 0.97 mm (SD 0.34 mm), and mean angular deviation on the coronal and sagittal planes was 1.35 degrees (SD 0.42 degrees).* ***Discussion:*** *The accuracy of image-guided navigation depends on imaging modalities, patient-to-image registration procedures, and instrument tracking. The technical accuracy and the navigation procedure, as evaluated in the study presented, seem to be of minor influence.* ***Conclusion:*** *The data obtained by this in vitro study demonstrate that the accuracy of navigation-based drilling may be sufficient for clinical practice, particularly in terms of the transferability of preplanned trajectories. However, in vivo clinical trials need to be performed to evaluate the clinical accuracy and treatment quality of navigation-guided interventions.* INT J ORAL MAXILLOFAC IMPLANTS 2005;20:382–386

Key words: *computer-assisted surgery, computerized tomography, drill guides, implant surgery, navigation*

Accurate three-dimensional (3D) orientation of surgical instrument trajectories is essential in implant surgery, as the correct placement of endosseous implants represents the determining factor in therapeutic outcome. Any major change of direction and extension of the preplanned implant may result in a substantial loss of biomechanical stability and lead to impaired implant survival. Thorough planning before implant placement, including assessment of both the quality and quantity of bone tissue, is necessary to implement a stable prosthetic restoration and protect vital structures such as nerve tissue and blood vessels from damage. Careful preoperative planning of implant treatment is applicable to many surgical subspecialties, from orthopedic surgery (hip and knee replacements) to oral and maxillofacial surgery (dental implants or implants for craniofacial reconstructions).[1–3] Thus, great effort has been put into improvement of the accuracy of implant positioning.

Navigation systems are mainly used for better 3D orientation in anatomically complex sites, as clinical examination may provide very limited information on bone dimensions. To improve treatment safety, mainly by providing more precise surgical

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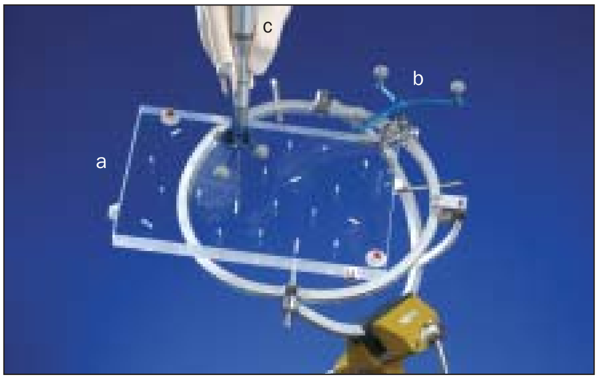

Fig 1 Acrylic resin models *(a)* were equipped with 6 fiducial markers (placed in corners). A reference array *(b)* consisting of 3 reflective marker spheres for object-to-image registration is attached. Navigated drillings were performed using a 1.7-mm surgical trephine *(c)*. A BrainLAB tool adapter for instrument registration was fixed to the surgical drill.

approaches and to reduce operating time, computer-aided navigation can lead to better control of the treatment.[4] The use of navigational guidance for medical implant placement is particularly suitable for patients with limitations of anatomic orientation, eg, as a result of extensive ablative tumor surgery, where correct placement of implants is challenging.[5] Relying on preoperatively acquired computerized tomography (CT) or magnetic resonance imaging (MRI) data, the current position of surgical devices in relation to the patient is displayed on a monitor in near-real time, providing topographic orientation at any time.

Reliability of optical navigation systems has been found to be sufficient for the daily clinical routine.[6,7] The degree of accuracy, depending on image acquisition, CT layer thickness, different methods of patient-to-image registration, and the navigation procedure itself has been assessed by measuring deviations between anatomic landmarks identified in CT images and corresponding positions on object surfaces.[6–8] Yet there are minimal data concerning the precise amount of 3D angular deviation of preplanned trajectories performed by navigational guidance.

An experimental setup was chosen with conventional clinical CT scan protocol and common registration error to assess the mean amount of angular deviation of navigated drills, with regard to the 5 degrees of freedom, to provide data on the accuracy of navigated implant surgery.

MATERIALS AND METHODS

Navigated drilling accuracy was determined using an acrylic resin model of predefined geometry. An acrylic resin reference model was prepared with 24 standardized target holes. Each target hole had a diameter of 1.7 mm and a length of 18 mm; half of the holes were drilled with 0 degrees of angulation and the other half with 30 degrees of angulation. Target holes were drilled by a computerized numerical control (CNC) machine. The reference model was tagged with 6 fiducial markers plugged on predetermined, scattered positions. It was then scanned with high-resolution CT (HRCT) (Somatom Sensation 16; Siemens, Erlangen, Germany) using conventional 0.75-mm-thick axial slices. Images were reconstructed to be 0.39 $\times$ 0.39 mm and as a 512 $\times$ 512-pixel matrix. CT image data were transferred to the navigation system via a hospital network.

Ten blank acrylic resin models were used for accuracy assessment using the frameless optical VectorVision Compact (VVC; BrainLAB, Heimstetten, Germany) navigation system. The VVC works on passive marker technology. Tracking of surgical devices occurs wirelessly using infrared light technology. Position of instruments is calculated via infrared light reflection using reflective marker spheres fixed to the patient or object and instrument.

The laboratory setup is illustrated in Fig 1. A BrainLAB tool adapter consisting of 3 reflective marker spheres was fixed to the surgical drill. Acrylic resin models were equipped with 6 fiducial markers arranged according to the reference model. A reference array was attached to the acrylic resin models in a predetermined position. Three-dimensional object-to-image calibration was performed by a conventional fiducial marker registration. Drilling was performed using a 1.7-mm surgical trephine on the basis of reference model CT data.

The coordinates of the drilled holes were determined by a high resolution 3D-digitizer probe (MicroScribe-3D; Immersion, San Jose, CA) (Figs 2a and 2b) and converted to and analyzed by a CAD system (Pro/Engineer; PTC, Needham, MA).

Fig 2a A high resolution 3D-digitizer probe *(right)* was used to detect the coordinates of the drilled holes. The 3D-digitizer was connected to a computer workstation. The data was converted to and analyzed by a computer-aided design (CAD) system *(left)*.

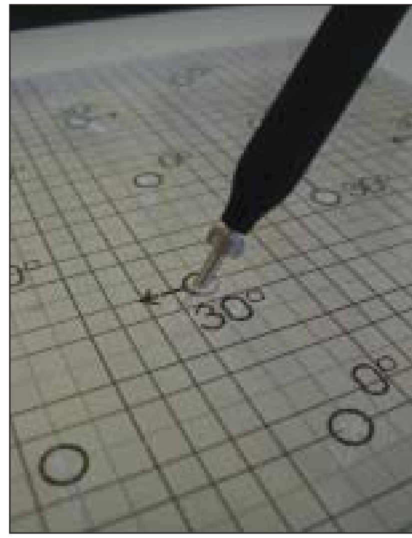

Fig 2b The tip of the 3D-digitizer probe was specifically designed to precisely fit in the 1.7-mm-wide bur holes.

RESULTS

Ten acrylic resin models, each with 24 drilled holes, 12 with 0 and 12 with 30 degrees of angulation, ie, 240 holes, were included in the statistical evaluation. The drilling procedure was performed without major difficulties. Mean registration error was 0.86 mm (SD 0.25 mm). The mean target point deviation, calculated as the difference between the preplanned drill starting point in the reference model and the effective position in the test models determined by the place of penetration, was 0.95 mm (SD 0.25 mm) (Fig 3). Mean accuracy of navigation-guided drilling was 0.97 mm (SD 0.34 mm) regarding full length of the drilled socket (Fig 4). The mean angulation deviation, calculated as the difference in angle between the planned and actual drilled sockets, was 1.35 degrees (SD 0.42 degrees), regarding deviation in frontal and sagittal directions (Fig 5).

DISCUSSION

A number of factors contribute to the accuracy of navigational guidance. In image acquisition, parameters such as CT layer thickness, voxel size, and image data distortion and different methods of patient-to-image registration have a greater impact on navigational precision than technical accuracy and the navigation procedure itself.[9] In this context, imaging modalities have been found to be of more minor influence on localization error than the number and attachment modality of fiducial markers for object-to-image registration.[9] A registration protocol based on external fiducial marker technology in turn results in smaller navigation error than matching with anatomic landmarks.[10] True accuracy can furthermore be improved by surrounding the operative target with a widespread field of fiducial markers.[11] Concerning registration accuracy, stereotactic frame registration outmatches skin or bone marker registration.[12]

The accuracy of navigation systems has been assessed mostly in experimental studies, as clinical evaluation is difficult for various reasons.[5,13–16] In earlier studies on polyurethane milling models to evaluate the accuracy of navigated drilling for implant placement in the maxilla, the mean localization error was found to be smaller than 1 mm.[16] Precision of image-guided implant positioning has been investigated in cadaveric studies[3,13]; these studies have provided important information related to degree of accuracy concerning anatomic structures such as blood vessels or nerve tissue. Angulation of trajectories of drilled holes has been assessed mostly by CT scan data, which in turn has aggravated measurement inaccuracies.[14] Accuracy of image-guided dental implant surgery has been studied in anatomically complex operation sites.[17] In certain cases,

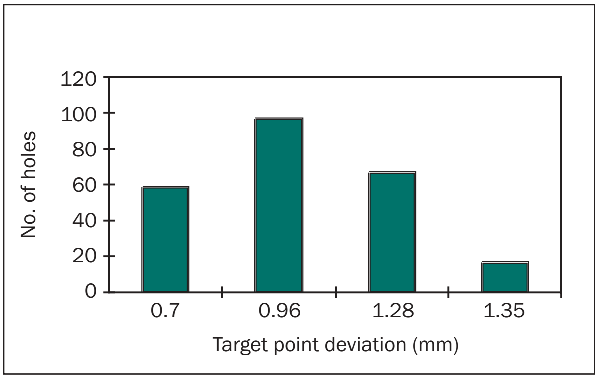

Fig 3 The target point deviation was calculated as the difference between the preplanned drill starting point in the reference model and the actual drill starting point in the test models.

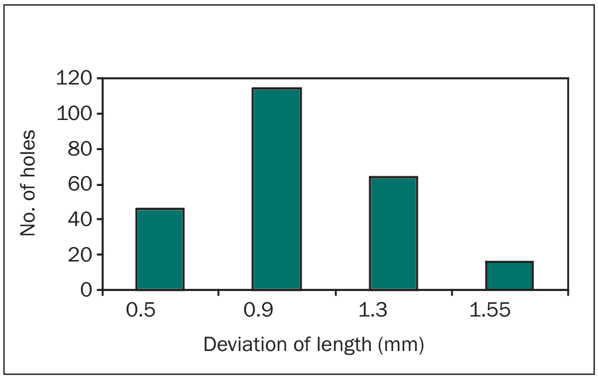

Fig 4 The deviation of length was calculated as the distance between the full length of the drilled sockets and the length of the preplanned sockets.

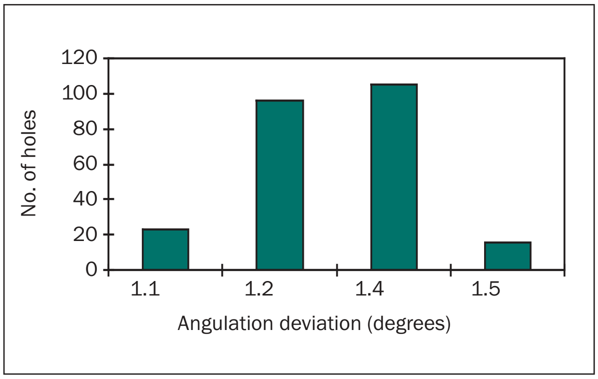

Fig 5 The angulation deviation was calculated as the angle between the preplanned and the actual socket axis in frontal and sagittal directions.

placement of implants longer than those planned prior to operation has been possible.

Compared to these studies, similar results in terms of distances and angulations were found in the present study of navigational accuracy. In the present study, the significance of a 0.95-mm deviation between the preplanned drill starting point in the reference model and the effective position in the test models determined by the place of penetration is questionable, as the drilling was performed using a trephine with a 1.7-mm effective diameter. This setup was necessary for technical reasons regarding the use of a 3D-digitizer probe for coordinate measuring.

New automatic and markerless laser scanning–based techniques using skin surface registration that have become suitable for clinical practice may overcome inaccuracies that emerge mainly from object-to-image registration errors.[18,19] They furthermore may reduce radiation load, as these techniques do not require an additional radiologic scan for fiducial marker detection. Only very few prospective randomized clinical trials comparing accuracy and treatment quality of navigational-guided interventions to conventional ones are available.[4] Further investigations concerning this topic are needed.

CONCLUSION

Craniofacial implant placement is a complex surgical procedure. The clinical benefits emerging from technologic advances in surgical navigation are well known. However, the complexity of the new technical environment needs to be evaluated carefully, taking different types of errors into consideration.

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