Assessment of Accuracy of Navigated Implant Placement in the Maxilla

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Purpose: *The use of computed tomography (CT) based intraoperative navigation has greatly improved surgery in many specialties. In this study, the precision of the SMN system (Zeiss, Oberkochen, Germany) for navigated drilling and following implant placement in the maxilla was evaluated. This study should demonstrate the suitability of navigation systems for computer-assisted implantation in the maxilla to avoid perforation of the maxillary sinus.* ***Materials and Methods:*** *Sixty target drillings were carried out on 10 standardized polyurethane milling models after CT scanning. The models were produced with cranial open maxillary sinuses. The CT scans were performed with a slice distance of 1 mm. Then the CT data were transferred to the workstation of the SMN system and registration of the reference markers (fiducials) for superposition of the native and CT model was done. Referencing of the model was performed with the aid of a drilling tool. This drilling tool was used for later navigation-assisted drilling into the maxilla. The target of drilling was the maxillary sinus floor. The aim was to come as near as possible without perforation. The distance from the bottom of the drilling holes to the maxillary sinus floor was measured after sectioning of the model. In another 10 models, implants were placed after performing 60 navigated drilling holes.* ***Results:*** *In the first part of the study, an average drilling depth of 6.97 mm and a mean distance to the sinus floor of 0.11 mm (standard deviation = 0.2) was found. In 13 specimens, the inferior border of the sinus was perforated. In the second part of the study, a perforation of the sinus floor by the implants was seen in 47 cases. The mean distance to the maxillary sinus was 0.25 mm (standard deviation = 0.2).* ***Discussion and Conclusions:*** *High precision of CT-based navigation for controlled preimplant drilling was seen, but a high incidence of penetrations into the maxillary sinus was caused by the subsequent implant placement.* (INT J ORAL MAXILLOFAC IMPLANTS 2002;17:263–270)

Key words: *computer-assisted implantation, dental implants, maxillary sinus, navigation*

The use of dental computed tomography (CT) scans for the planning of implant placement has been of great advantage in implant dentistry.[1,2] CT images have been used for presurgical examination of alveolar ridge morphology and to verify the position and extent of critical anatomic structures that should be preserved during implantation.[3] The essential anatomic structures to be preserved are the neurovascular bundle of the mandible and the nasal and maxillary sinus cavities of the maxilla. The main question to be answered by CT data is whether implantation is possible without injuring these anatomic structures and what length of implants can be used. The longest possible implants should be selected. Furthermore, the indications for and kinds of augmentation techniques that are possible can be examined if necessary.[4] The development of new implants with reduced length and increased diameter has circumvented the possible need for augmentation.[5] In many situations, sinus lift operations can be avoided by using this kind of implant, if implantation in the lateral maxilla is necessary. In these cases, optimized planning is necessary to avoid perforation of the sinus floor and to exploit the whole height of the jawbone for maximal stability of the implant.

When CT scans are used for preimplant planning, intraoperative control is more difficult. Even when 3-dimensional CT-based models are used for preoperative planning, transfer of the model surgery into the surgical environment can only be done by mechanical devices.[6,7] These devices can be fixed to the bone or teeth, providing more precision for implant placement. When these drilling devices are used in edentulous patients, poor precision results. Thus, precise

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intraoperative verification of operation planning is more feasible by using CT data for the intraoperative navigation of implantation tools. By using this technique, transduction of the patient and related CT data can be done, and intraoperative control of manipulation in the deep bone without surgical exploration is possible. A drilling tool can be controlled 3-dimensionally by watching the manipulation of this drilling tool on a screen that shows 3-dimensional reconstructions of the CT scan.[8–10]

With this technique, precise placement of implants without injury to critical anatomic structures should be possible. While promising, the main disadvantage in using navigation techniques has been their high median error of transduction of CT data to the patient and low precision of the navigation tools.[11] With a new kind of system, optimized referencing techniques, and better tool systems, errors should be minimized.

The feasibility of utilization of a new CT-based navigation system with an optimized working tool for implantation in the severely atrophic maxilla was the subject of this investigation.

MATERIALS AND METHODS

In the first part of the study, 60 target drillings in 10 polyurethane models of the maxilla were carried out. The polyurethane models were produced on a CNC milling machine (MDC, Kiel, Germany) on the basis of a patient's CT scan. The CT was selected from CT scans that had been performed presurgically prior to sinus lift operations in the lateral maxilla. A patient was selected who had a remaining height of the lateral maxillary alveolar ridge between 6 and 8 mm and was edentulous in this region. The height of the alveolar ridge was measured from the inferior border of the maxillary sinus to the inferior border of the alveolar crest of the maxilla.

The polyurethane models were then milled in a way that provided open sinuses in the cranial region, to make later control of perforation of drilling possible (Fig 1).

These models were then marked with 8 reference points (fiducials). From these models, CT scans, using an electron beam tomograph (Evolution/UltraFast CT, Siemens, Erlangen, Germany), were made. The thickness of the layers was 1.5 mm (slice); the distance of the layers was 1 mm (feed). The CT data were transferred to the workstation of the navigation system (SMN, Zeiss, Oberkochen, Germany). It is a CT-based infrared guided navigation system with different possible working tools.

To determine transfer errors, the diameter of 2 drilled holes into the pterygoid process of the maxilla was measured at the smallest distance measured on CT scan and native model. The native models were measured with the aid of electronic calipers and the CT model was checked by computer-aided measurement on the computer screen. The corresponding values were recorded and the differences and standard deviations calculated.

A 3-dimensional infrared sensor was attached to the model by fixation screws in direct optical contact to 3 distant infrared cameras, which, in turn, had contact with the workstation. Therefore, every 3-dimensional movement of the models' sensors was registered by the cameras and transposed to the CT data on the screen. Following model referencing according to the 6 fiducials with the drilling tool, a calibrated norm-drill was attached. Three infrared sensors were fixed to the polyurethane model (Fig 2). These were in constant optical contact with the 3 infrared cameras.

Motion of the drill tip in relation to the jaw model and the clearly visible maxillary sinus was visualized at the workstation via transposition of the references between the native and CT models and calibration of the tool. Entrance and target of the drilling were planned (Fig 3). The aim for target was the inferior border of the sinus floor. For later measurement of the perforation length, the maxillary sinus was filled with an acrylate. By directing the tool, the relative motion of the drill tip was controlled with a delay of 50 ms. After determining the point of entrance on the model and the target, a CT-directed target drilling was carried out. The drilling was stopped when the drill tip was just short of the caudal border of the sinus as seen on the screen of the navigation workstation. This was carried out 6 times on each of the 10 maxillary models (3 times left and 3 right). Thus, 60 directed target drillings were made.

Following drilling, the results were checked by measuring the distance between the planned and actual target drill distance. The model was opened at each drilled hole with a milling machine (Fig 4). The distance from the sinus floor to the deepest point of the target drill was measured with a dental probing compass (Fig 5). Where sinus perforations occurred, the depth was measured with the inserted acrylic device. Thus, planning errors of up to 0.01 mm were detected. The measurements were carried out 5 times at each drilled hole. The greatest and smallest measurements were discarded and the average of the remaining measurements was determined. The total drilling length was determined in the same manner. The average of the individual averages and the corresponding standard deviation were calculated.

Fig 1 Polyurethane model of the midface and maxilla. The maxillary sinus is opened to the orbit.

Fig 2 A 3-dimensional infrared sensor is fixed to the polyurethane model so movements of the drilling tool in comparison to the infrared sensor can be registered.

Fig 3 Drilling with the drilling tool. The tool is standardized and another 3-dimensional sensor is also fixed to the handpiece.

Fig 4 Cross section of the alveolar ridge and sinus after drilling.

Fig 5 Measurement of the distance between the bottom of the drilling hole and the sinus floor by a probing compass.

Fig 6 Cross section of the model with 3 implants perforating the sinus floor.

In the second part of the study, another 10 models were used for CT scans and navigation drillings as described above. The models were then used for simulation of dental implantation. Thus, the length of the navigated drilling was marked at the drill after navigated drilling and transferred to the implant pilot bore and core bore of a conventional self-cutting screw implant system (SIS Trade, Klagenfurt, Austria). The marked pilot and core drill were used for individual preparation of the implant bed with the depth registered by the navigated drilling. The drilling length was then transferred to the implant and the implant was screwed into the implant bed. The same procedure was performed with an additional 59 drillings in 10 milling models. After implantation, the lateral wall of the maxillary sinus was cut off and the distance from the implant apex to the maxillary sinus floor or the length of perforation was measured as described for the drilling depths in the first part of the study (Fig 6).

Maximal and minimal values were registered for both parts of the study. The significance of the averages was checked by the unilateral *t* test. The optimum of 0 mm difference between planned drilling and achieved distance to the surface was defined as a normal value.

RESULTS

The following results were seen for the first part of the study. Measurement of the distance of the reference drill on the native model and CT scan showed an average deviation of 0.2 mm. An average drilling depth of 6.97 mm (SD = 0.46) and a mean distance to the sinus floor of 0.11 mm (SD = 0.22) was found. In 13 cases, the inferior border of the sinus was perforated. The average depth of penetration into the maxillary sinus measured 0.24 mm. Forty-seven cases of drilling were accomplished without perforation. The average distance to the sinus measured 0.23 mm. The individual results of the drillings are shown in Table 1.

The second part of the study showed the following results. Measurement of the distance of the reference drill on the native model and CT scan showed the same average deviation of 0.2 mm as in the first part of the study.

The mean length of implantation was 7.28 mm (SD = 0.43), and a mean distance to the sinus floor of 0.25 mm (SD = 0.26) was found. In 47 cases, the implants penetrated into the maxillary sinus. The average penetrating length into the maxillary sinus measured 0.38 mm. Thirteen implants were placed without sinus perforation. The average distance of the implant apex to the sinus was 0.16 mm. The individual results of implantation are shown in Table 2.

DISCUSSION

Use of the CT scan has greatly improved preoperative diagnosis for difficult implant cases.[1,2,12] Alveolar ridge CT scans enable precise analysis of potential implant sites.[13] In recent years, the possibility of using 3-dimensional visualization of CT scans has been available, therefore enabling verification of the position of at-risk anatomic structures such as the neurovascular bundle of the mandible and the maxillary sinus.[14]

Thus, 3-dimensional preoperative planning provides the opportunity to avoid injury of critical anatomic structures by better assessing the anatomy of the individual patient. Furthermore, the question of augmentation necessity and technique can be answered. Before the use of navigation techniques, transfer of the planning into the actual surgery could only have been done by mechanical devices with minimal intraoperative control.

Since a new generation of implants with an enlarged diameter and short length has been used to avoid augmentation in borderline cases,[5] precise drilling and implantation by using the maximum bone height for enhanced osseointegration has gained importance. If implants are to be used in the lateral maxillary region, sinus lift operations can be avoided in some cases. When the entire available residual bone height is used, the possibility of injuring the maxillary sinus increases. Consequently, control mechanisms of implant drilling should probably be used. Perforation control is possible using the sinuscope, but it is not possible to avoid damage of the sinus floor by this technique. Apparently, only the navigation technique allows control of the tip of the bore in the bone without a surgical approach.[9,15,16]

Navigation techniques were first used in neurosurgery to localize and resect pathologic structures without destruction of the neighboring brain.[10,17,18] Because of the attractive results, this technique has also been used in other specialties.[18,19] In maxillofacial surgery, osseous segments have been positioned under navigation control to achieve symmetry in an asymmetric face.[20,21] Corrections of facial deformities have been controlled intraoperatively by CT-based navigation.[22] In this field, a mean intraoperative error of 2.4 mm has been seen and seemed to be tolerable.[23] Nevertheless, this mean error can be high for other surgical procedures. Therefore, the precision of navigation systems has been improved with better programs and reference tools.[24,25] Mean deviations of less than 1 mm have resulted. Furthermore, minor transfer errors of the CT scan should be expected. In comparison to the real situation, a mean error of 0.25 mm is caused by an electron beam tomograph, when a slice of 1.5 mm and feed 1 mm is used.[26] This advantage has made endosseous navigation possible to circumvent destruction of endosseous nerves and vessels. The 3-dimensional controlled placement of implants in appropriate prosthetic position has become possible.[8,9,15] For all surgical indications, optical navigation systems have been better than magnetic ones, because many metal instruments are used in the operating room and can cause disturbances during navigation by magnetic guidance.[10,20] With laser sensors, a precision of 0.3 mm has been possible.[24] In systems using infrared sensors, as in this study, a high degree of precision is possible. A mean error of less than 0.3 mm was seen during drilling under navigation control in this study. Thus, perforation of the maxillary

Table 1 Drilling Results

Model no.	Drilling no.	Drilling depth (mm)	Distance to the sinus floor (mm)	Perforation
1	1	6.8	0.2	No
	2	6.2	0.1	No
	3	6.9	0.3	No
	4	7.3	0.3	No
	5	6.8	0.1	No
	6	6.9	–0.1	Yes
2	1	7.1	–0.1	Yes
	2	6.3	0.1	No
	3	6.9	0.2	No
	4	7.2	0.4	No
	5	7.0	–0.1	Yes
	6	7.0	0.1	No
3	1	6.8	0.2	No
	2	6.1	0.2	No
	3	6.8	0.3	No
	4	7.4	0.2	No
	5	6.8	0.2	No
	6	6.7	0.1	No
4	1	7.2	0.1	No
	2	6.3	–0.1	Yes
	3	7.0	0.2	No
	4	7.6	–0.1	Yes
	5	6.9	0.1	No
	6	7.3	0.1	No
5	1	7.2	–0.3	Yes
	2	6.4	–0.2	Yes
	3	7.0	0.1	No
	4	7.6	0.1	No
	5	7.0	0.1	No
	6	6.6	0.3	No
6	1	7.3	0.1	No
	2	6.1	0.2	No
	3	6.8	0.4	No
	4	7.2	0.5	No
	5	6.9	0.1	No
	6	7.1	0.3	No
7	1	7.4	–0.6	Yes
	2	6.2	0.1	No
	3	7.2	0.1	No
	4	7.8	0.2	Yes
	5	6.7	0.5	No
	6	6.7	0.1	No
8	1	7.5	0.1	No
	2	6.0	0.5	No
	3	6.9	0.2	No
	4	7.8	–0.2	Yes
	5	6.8	0.2	No
	6	7.6	0.1	No
9	1	7.3	–0.5	Yes
	2	6.2	0.1	No
	3	7.2	–0.3	Yes
	4	7.7	0.1	No
	5	7.1	–0.3	Yes
	6	6.8	0.1	No
10	1	7.4	0.2	No
	2	6.2	0.3	No
	3	6.9	0.4	No
	4	7.6	0.2	No
	5	6.8	0.2	No
	6	7.6	0.1	No

Table 2 Implantation Results

Model no.	Implant no.	Implant length (mm)	Distance to the sinus floor (mm)	Perforation
1	1	7.2	–0.4	Yes
	2	6.4	0.1	No
	3	7.3	–0.5	Yes
	4	7.7	–0.3	Yes
	5	7.7	–0.3	Yes
	6	7.4	–0.3	Yes
2	1	7.6	–0.3	Yes
	2	7.2	–0.5	Yes
	3	7.3	0.1	No
	4	7.6	0.1	No
	5	7.0	–0.2	Yes
	6	7.8	–0.6	Yes
3	1	7.8	–0.6	Yes
	2	6.9	–0.4	Yes
	3	7.0	0.1	No
	4	7.7	0.1	No
	5	6.7	0.4	No
	6	7.0	–0.3	Yes
4	1	7.7	–0.4	Yes
	2	6.6	–0.3	Yes
	3	7.4	–0.5	Yes
	4	7.8	–0.1	Yes
	5	7.2	–0.3	Yes
	6	7.3	0.1	No
5	1	7.4	–0.6	Yes
	2	6.5	–0.3	Yes
	3	7.8	–0.7	Yes
	4	7.9	–0.4	Yes
	5	6.9	–0.3	Yes
	6	7.2	–0.4	Yes
6	1	7.6	–0.2	Yes
	2	6.8	–0.3	Yes
	3	7.4	–0.2	Yes
	4	7.8	–0.2	Yes
	5	6.9	0.1	No
	6	7.9	–0.4	Yes
7	1	7.0	–0.1	Yes
	2	6.8	–0.5	Yes
	3	7.4	–0.5	Yes
	4	7.7	0.1	No
	5	7.1	–0.3	Yes
	6	7.3	–0.4	Yes
8	1	7.7	–0.4	Yes
	2	7.0	–0.7	Yes
	3	7.0	0.2	No
	4	7.9	–0.3	Yes
	5	7.3	–0.2	Yes
	6	8.3	–0.9	Yes
9	1	7.3	–0.5	Yes
	2	6.2	0.1	No
	3	6.8	0.3	No
	4	7.8	–0.3	Yes
	5	7.3	–0.2	Yes
	6	7.3	–0.3	Yes
10	1	7.1	–0.1	Yes
	2	6.4	–0.3	Yes
	3	6.9	0.2	No
	4	7.6	–0.3	Yes
	5	7.3	–0.4	Yes
	6	7.4	–0.3	Yes

sinus by navigated drilling can be avoided and nearly all the residual bone height can be used for implant placement. The drilling tool is advantageous, because it can be used for referencing prior to surgery and for drilling during surgery. No other tools are necessary, which makes the whole procedure easier for the surgeon.

While there is an easy procedure for preparation of the operation and for intraoperative management, there may be a much higher incidence of errors that are not caused by the navigation system but by the surgeon himself or herself. Optimal drilling does not necessarily mean optimal implantation as shown in this study. Because of the necessity of further steps of preparation of the implant bed, there are other possibilities for perforation of the sinus floor. Therefore, a higher incidence of perforation has been seen after completed implantation in comparison to isolated navigated drilling. Transfer of the drilling depth to implant length is of great importance, because most penetrations into the maxillary sinus are caused by the implant placement and not by the navigated drilling. Navigated drilling up to a distance of 1 mm to the sinus floor may avoid destruction of the sinus floor during the later implantation. If this security distance is recognized, damage of the sinus floor can be avoided.

Precision of navigation can only be achieved by using bone-fixed fiducials, which makes placement of screws or other fiducials to the bone in the patients necessary.[10] This was no problem with the models, but can cause patient concern because another surgical intervention for screw fixation is necessary.

By knowing about the precision of a navigation system in models, clinical studies in humans should be forthcoming.

CONCLUSIONS

A high degree of precision was achieved in computer-assisted surgery by the development of new programs and working tools. The entire residual bone height can be used for implantation in the maxilla without perforation of the maxillary sinus, if a controlled drilling procedure is carried out. A more severe problem with a higher likelihood of errors and perforation of the sinus floor bone may be caused by subsequent implantation.

REFERENCES

1. Solar P, Gahleitner A. Dental CT in the planning of surgical procedures. Its significance in the oro-maxillofacial region from the view point of the dentist. Radiologie 1999;39:1051–1063.
2. Wicht L, Moegelin A, Schedel H, et al. A dental CT study for preoperative assesment of maxillary atrophy. Aktuelle Radiol 1994;4:64–69.
3. Schom C, Engelke W, Kopka L, Fischer U, Grabbe E. Indications for dental CT. Case reports. Aktuelle Radiol 1996;6:317–324.
4. Peleg M, Chaushu G, Mazor Z, Ardekian L, Bakoon M. Radiological findings of the post-sinus lift maxillary sinus: A computerized tomography follow-up. J Periodontol 1999;70:1564–1573.
5. Stellingsma C, Meijer HJ, Raghoebar GM. Use of short endosseous implants and an overdenture in the extremely resorbed mandible: A five-year retrospective study. J Oral Maxillofac Surg 2000;58:382–387, discussion 387–388.
6. Gaggl A, Schultes G, Santler G, Kärcher H. Three-dimensional planning of alveolar ridge distraction by means of distraction implants. Comput Aided Surg 2000;5:35–41.
7. Gaggl A, Schultes G, Santler G, Kärcher H. Treatment planning of sinus lift augmentations through use of 3-dimensional milled models derived from computed tomography scans: A report of 3 cases. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998;86:388–392.
8. Watzinger F, Birkfellner W, Wanschitz F, et al. Positioning of dental implants using computer-aided navigation and an optical tracking system: Case report and presentation of a new method. J Craniomaxillofac Surg 1999;27:77–81.
9. Wanschitz F, Birkfellner W, Watzinger F, et al. Evaluation of the accuracy of computer-aided intra-operative positioning of endosteal dental implants in the edentulous mandible: An in vitro study. J Craniomaxillofac Surg 2000;28(suppl 3):200.
10. Watzinger F, Wanschitz F, Wagner A, et al. Computer-aided navigation in secondary reconstruction of post-traumatic deformities of the zygoma. J Craniomaxillofac Surg 1997;25:198–202.
11. Hassfeld S, Zoller J, Albert FK, Wirtz CR, Knauth M, Mühling J. Preoperative planning and intraoperative navigation in skull base surgery. J Craniomaxillofac Surg 1998;26:220–225.
12. Laney WR, Tolman DE. The Mayo Clinic experience with tissue-integrated prostheses. In: Albrektsson T, Zarb GA (eds). The Brånemark Osseointegrated Implant. Chicago: Quintessence, 1989:165–195.
13. Roy JN, Steiger P, Ling CC. Overlap detection and contour-tracking algorithms for critical organs: Application to kidney. Comput Med Imaging Graph 1990;14:153–161.
14. Kraut RA. Use of 3D dental imaging for treatment planning of implant receptor sites. In: Laney WR, Tolman DE (eds). Tissue Integration in Oral, Orthopedic and Maxillofacial Reconstruction. Chicago: Quintessence, 1990.
15. Schneider M, Eckelt U, Hietschold V. Accuracy tests for the computer assisted insertion of dental implants in a phantom model of the lower jaw. J Craniomaxillofac Surg 2000;28 (suppl 3):200.

16. Schultes G, Gaggl A, Santler G, Feichtinger M, Kärcher H. Measurement of the drilling accuracy of implants with the help of the SMN-Zeiss-Navigation-System. J Craniomaxillofac Surg 2000;28(suppl 3):200.
17. Vrionis FD, Foley KD, Robertson JH, et al. Use of cranial surface anatomic fiducials for interactive image-guided navigation in the temporal bone: A cadaveric study. Neurosurgery 1997;40:755–763, discussion:763–764.
18. Caversaccio M, Ladrach K, Hausler R, Stucki M, Bachler R, Nolte LP, Schroth G. Concept of a frameless computer-assisted navigation system at the skull base, the nose and the paranasal sinuses. Otorhinolaryngol Nova 1979;7:121–126.
19. Wen QH, Arai H, Shimomura T, et al. Advantage of a computer-assisted navigation system in endoscopic sinus surgery. Rhinology 1999;37:98–99.
20. Marmulla R, Wagener H, Hilbert M, Niederdellmann H. Precision of computer-assisted systems in profile reconstructive interventions on the face. Mund Kiefer Gesichtschir 1997;1(suppl 1):65–67.
21. Marmulla R, Niederdellmann H. Computer-assisted bone segment navigation. J Craniomaxillofac Surg 1998;26: 347–359.
22. Zeilhofer HF, Kliegis U, Sader R, Horch HH. Video matching as intraoperative navigation aid in operations to improve the facial profile. Mund Kiefer Gesichtschir 1997;1(suppl 1):68–70.
23. Gunkel AR, Thumfart WF, Freysinger W. Computer-aided 3D-navigation systems. Survey and location determination. HNO 2000;48:75–90.
24. Marmulla R, Hilbert M, Niederdellmann H. Inherent precision of mechanical, infrared and laser-guided navigation systems for computer-assisted surgery. J Craniomaxillofac Surg 1997;25:192–197.
25. Husstedt H, Heermann R, Becker H. Contribution of low dose CT-scan protocols to the total posistioning error in computer-assisted surgery. Comput Aided Surg 1999;4: 275–280.
26. Santler G, Kärcher H, Ruda CH. Indications and limitations of three-dimensional models in cranio-maxillofacial surgery. J Craniomaxillofac Surg 1998;26:11–16.