Franz-Josef Kramer
Carola Baethge
Gwen Swennen
Steffen Rosahl

Navigated vs. conventional implant insertion for maxillary single tooth replacement

A comparative *in vitro* study

Authors' affiliations:
Franz-Josef Kramer, Gwen Swennen, Department of Oral and Maxillofacial Surgery, Medical University of Hannover, Hannover, Germany
Carola Baethge, Department of Orthodontics, Free University of Berlin, Berlin, Germany
Steffen Rosahl, International Neurosurgical Institute, Hannover, Germany

Correspondence to:
Dr Dr Franz-Josef Kramer
Klinik für Mund-, Kiefer- und Gesichtschirurgie
Medizinische Hochschule Hannover
Carl-Neuberg-Str.1
D-30625 Hannover
Germany
Tel.: +49 511 532 4756
e-mail: Kramer.Franz@MH-Hannover.de

Key words: accuracy, dental implants, image-guided surgery, maxilla, navigation

Abstract

Introduction: Computer-guided navigation has proven a valuable tool in several surgical disciplines. During oral implant placement, its application is intended to accomplish optimal implant localization and to reduce the risk of damage to adjacent structures. The aim of this study was to compare the precision limits of conventional vs. navigated implant insertion in practice.

Materials and methods: In cast models of the maxilla, implants were inserted to replace the left central incisor ($n = 40$) and the right canine ($n = 40$); each of those were inserted either conventionally ($n = 20$) or navigated ($n = 20$). Implant position, angulation and insertion depth were calculated from computer tomography scans of the implants that were connected to an index abutment of 40 cm length.

Results: The variations of implant positions were reduced for implants that were inserted by navigation ($P < 0.05$). In both the axial and the transversal plane, the variations of implant angulations were reduced for implants that were inserted by a navigation protocol ($P < 0.05$). The variations of insertion depth were less ($P < 0.05$) when the implants were placed by navigation in comparison with conventional insertion procedures.

Conclusions: Given the experimental conditions, although they tried to mimic a clinical situation, no final conclusions can be drawn. The *in vitro* application of a navigation system resulted in an improved precision of insertion surgery regarding the position, angulation and depth of an implant. Clinical studies will have to prove if routine image guidance will result in superior surgical outcome.

Date:
Accepted 30 November 2003

To cite this article:
Kramer F-J, Baethge C, Swennen G, Rosahl S. Navigated vs. conventional implant insertion for maxillary single tooth replacement. A comparative *in vitro* study.
Clin. Oral Impl. Res. **16**, 2005; 60–68
doi: 10.1111/j.1600-0501.2004.01058.x

The insertion of implants to replace maxillary incisors or canines requires an accurate position, angulation and insertion depth in order to achieve a functionally and aesthetically satisfying result (Nemcovsky et al. 2000; Andersen et al. 2002). In many clinical studies, conventional implant surgery performed by an experienced surgeon has already been proven to achieve that level in many cases if proper preoperative planning is available (Bouserhal et al. 2002; Lorenzoni et al. 2003). New technologies, however, should be evaluated regarding their potential advantages in practice. During the last decade, image-guidance systems have become a valuable tool in several surgical disciplines (Gunkel et al. 2000) including oral implant surgery (Schramm et al. 2000; Siessegger et al. 2001; Watzinger et al. 2001). Similar to the application of drilling templates (van Steenberghe et al. 2002), image guidance is mainly intended to transfer a preoperatively planned insertion concept into the clinical reality. Both methods are intended to improve the precision of implant placement and thereby to broaden the indications of implant surgery, e.g. into difficult anatomical situations. Additionally, those methods are thought to enhance the safety of patients by reducing the risk of damage to adjacent anatomical structures (Gaggl et al. 2001; Siessegger et al. 2001). In contrast to drilling templates, image guidance provides the surgeon with multidimensional real-time information of the anatomy thus allowing modifications during surgery without loss of guidance (Weinberg 1993). The effectiveness of navigation systems basically depends on their accuracy (Fortin et al. 1995; Chassat & Lavalée 1998). In recent years, navigation systems were developed specifically answering the demands of implant surgery (Watzinger 1999). In several investigations, the metric accuracies of different implant navigation systems were assessed both *in vitro* and *in vivo* (Birkfellner et al. 2001; Brief et al. 2001; Gaggl et al. 2001; Meyer et al. 2003). Due to their particular functional and aesthetic challenges, the insertion of implants to replace maxillary incisors or canines might represent a preferred indication for the application of a navigation system in oral surgery. In order to estimate the potential of image guidance in this field, the aim of this study was to compare the accuracies of position, angulation and insertion depth of implants that were placed conventionally or guided by navigation in an *in vitro* condition that resembles the loss of a central left incisor and a right canine.

Material and methods

In total, 40 identical cast models of the maxilla were created representing loss of the left central incisor and the right canine of the second dentition. All other teeth were intact. Each of the cast models displayed three identical spots of 0.5 mm for referencing, which were located in the alveolar process anterior in the median plane and laterally close to the 6-year-molar at each side. These spots allowed the definition of a triangular reference plane in order to determine the exact implant localization. For surgery, the cast models were fixed opposite to mandibular models into phantom heads and implant surgery was performed either by a conventional ($n = 20$) or a navigated ($n = 20$) insertion procedure (Fig. 1).

Fig. 1. In order to imitate the clinical application, all insertions were performed in a phantom head.

Conventional insertion

All insertions were performed by an experienced implant surgeon following the standard protocol of Branemark et al. (1977). At first, a positioning guide was fixed manually at the residual dentition (Fig. 2a). In the guide, a stick of gutta-percha was integrated indicating the desired position and mesio-distal angulation of the implant (Fig. 2a). In contrast to other concepts of guide construction, which provide a rigid determination of implant position and angulation, it was intended to allow the surgeon widely unrestricted manual modifications of the implant localization and angulation during insertion. For each preparation, a new drill kit was used. The preparation of the insertion socket was started with a guide drill to determine the implant position. In the next step, a twist drill with a diameter of 2 mm was used to generate the preliminary implant socket and to determine the preliminary implant angulation and depth. The depth of the socket was assessed by laser markers at the surface of the twist drill. In order to increase the diameter of the socket, a pilot drill was applied. Finally, minor corrections of implant angulation and insertion depth could be performed applying a definitive twist drill of 3 mm diameter. The definitive insertion depth was controlled with both the laser marker on the twist drill and by insertion of an angulated measurement stick. After completion of the socket preparation, a thread had to be cut into the walls of the socket by a screw tap due to the lack of elasticity of the cast models in order to insert the implants. For replacement of the left central incisor, a screw-shaped implant with a length of 13 mm and diameter of 3.75 mm ($n = 20$) was used. For replacement of the right canine, a screw-shaped implant with a diameter of 3.75 mm and a length of 15 mm ($n = 20$) was used (Fig. 2b).

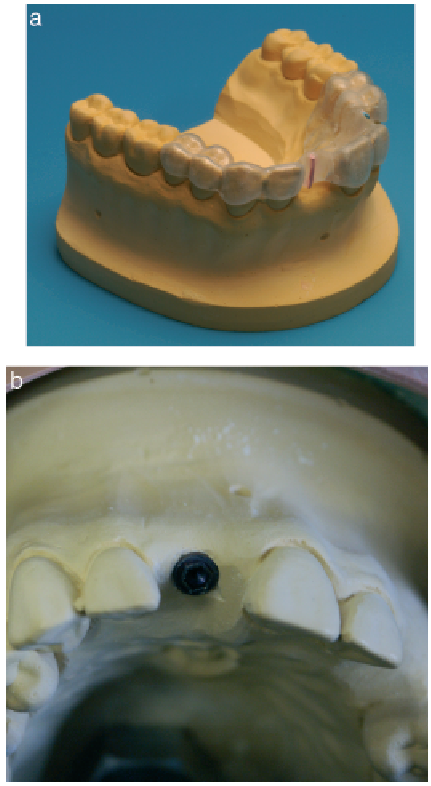


Fig. 2. (a) The positional guide is placed on the remaining dentition. The site of implant surgery is uncovered. (b) Sites after conventional implant insertion.

Navigated insertion

For image-guided implantation, cast models identical to the conventional insertion group were applied. Navigation was performed following the protocol of a commercially available navigation system that was developed specifically for implant surgery (Image-guided Implantology (IGI), DenX, Jerusalem, Israel). On the cast models, an acrylic guide was connected to a horseshoe-shaped computer tomography (CT) guide consisting of 10–12 ceramic spheres of

3 mm diameter required for registration. The alveolar process at the insertion site was left uncovered by the CT-guide (Fig. 3a). A CT-scan (1.25 mm slice thickness, 1 mm table feed, fast incremental scanning, 125 kV, 33 mA, 512 × 512 matrix; General Electric Germany, Munich, Germany) of the cast model with the CT-guide *in situ* was achieved and the data transferred as DICOM-files to a PC-based workstation that was equipped with the related implant planning software (IGI, DenX). Each implant position, angulation and insertion depth was planned according to the software menu. Before the insertion could be started, a reference protocol was applied to unite the cast model situation with both the insertion instruments and the navigation computer. As a component of the tracking system served an extraorally positioned reference body containing seven light-emitting diodes (LEDs) emitting infrared light that was fixed to the patient via the CT-guide, which was fixed intraorally (Fig. 3b). Additionally, 16 LEDs were attached to the surgical instruments (Fig. 3c). An infrared camera connected to the computer workstation received the emitted signals of the LEDs. For each preparation, a new drill kit was used. All steps of socket preparation were performed under the guidance of the navigation system (Fig. 3d). First, the position of the implant was determined exclusively by the navigation system and marked with a guide drill. The preliminary implant angulation and depth were created with a twist drill of 2 mm diameter. After an expansion of the socket diameter with a pilot drill, the definitive socket preparation was completed with a 3 mm twist drill. The surgeon was guided by the navigation system both visually and acoustically; in case of any deviations from the planned procedure, the insertion process was interrupted and the cast model excluded from further analysis.

After completion of drilling, a screw thread was cut into the walls of the socket to place the implants without relevant destructions of the cast models. The type of implants that were inserted was the same as in the group with conventional insertions.

Analysis of implant location

After insertion, each implant was connected to an index abutment. The index abutment was a stick of 40 cm length with a screw for safe reproducible connections to the implant and a defined tip. The cast models with the implants connected to the index abutment were scanned by CT (0.5 mm slice thickness, 0.5 mm table feed, fast incremental scanning, 125 kV, 33 mA, 512 × 512 matrix; Siemens Somatom, Siemens Germany, Munich, Germany) and the data transferred to a computer workstation equipped with an image analysis software (Cbyon Suite 2.6, Cbyon Corp., San Francisco, CA, USA). Multiplanar and three-dimensional reformations of the cast models, the implants and the index abutments were created and the exact locations of the implants analyzed. At first, the three reference spots of each cast model were detected and a reference plane defined

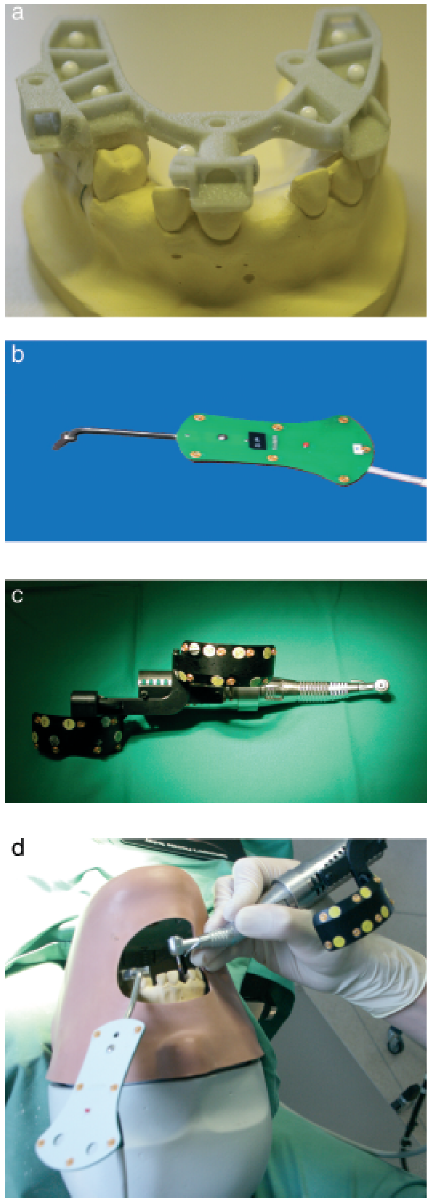


Fig. 3. (a): Cast model with computer tomography guide. (b) Reference body bearing seven active light emitting diodes. (c) The hand piece was connected to a reference device. (d) Implant insertion guided by a navigation system.

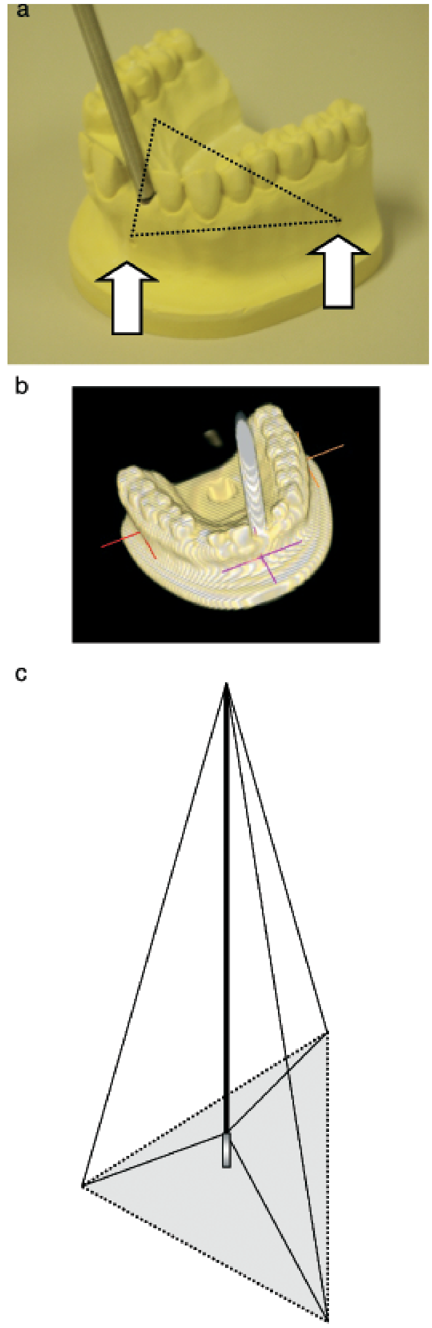


Fig. 4. (a) The reference spots allowed the definition of a reference plane. (b) Geometrical abstraction of the implant location assessment procedure: two pyramids with identical triangular bases were constructed which allowed to calculate each distance and angle. (c) The analysis of the implant localization was performed in a computer workstation with software that allowed precise multidimensional measurements of all relevant distances.

(Fig. 4a, b). The implant–abutment connection and the tip of the index abutment were identified and the distances to the reference spots measured. The situation was geometrically modeled by two overlying pyramids with the same triangular base, in which every angle and length easily could be calculated (Fig. 4c). Now each individual implant position, angulation and depth were evaluated.

The *implant fixed at the index abutment* was defined to be the two-dimensional position at which the implant at the index abutment perforates the surface of the cast model.

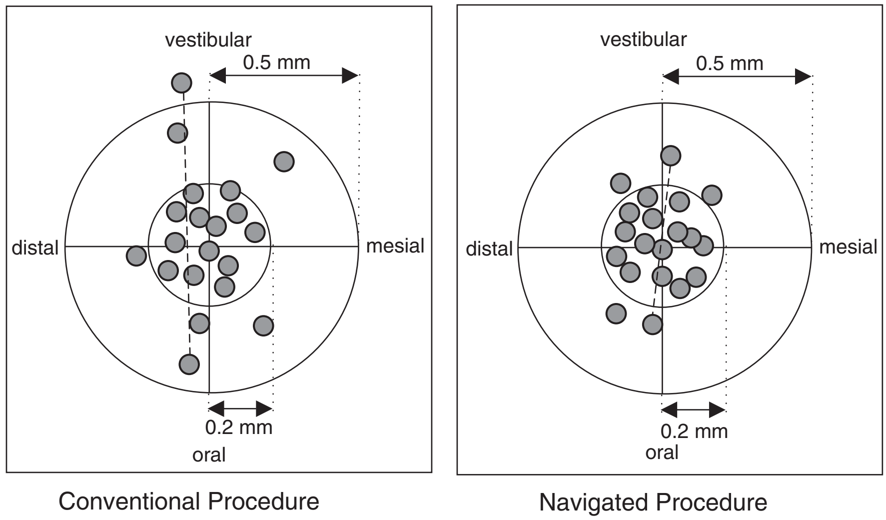
The *implant angulation* was divided into two components: the angulation in vestibulo-oral direction and in mesio-distal direction. For the central incisor, the vestibulo-oral angulation was defined as an angle located in a plane of the central anterior reference spot and a vertical plane of the axis between the lateral spots. The mesio-distal angulation was defined as an angle in a plane parallel to the vertical plane that connects the lateral reference spots. For the right canine, the vestibulo-oral angle was assessed in a plane perpendicular to an upright plane connecting the anterior and right reference spot. The mesio-distal angle was assessed in a plane that is upright to the connection of the central and right reference spots. Implant depth was measured as axial variations at the tip of the index abutment. All results were collected in a database (SPSS, SPSS Corp., Chicago, IL, USA, Version 11.0) and analyzed statistically by Wilcoxon's tests.

Results

Despite some fractures of smaller fragments of the cast models during implant insertion, all steps of socket preparations and implant insertions were uneventful. All implants were inserted successfully and occupied the defined position which was provided by the socket preparations. No significant dislocation of the implants was seen by macroscopic inspection.

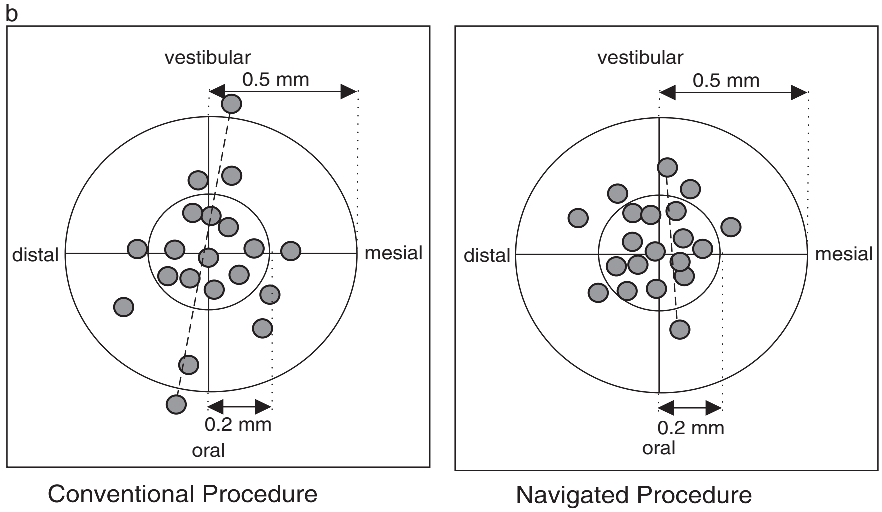
The analysis of the implant positions revealed, for both the incisor and the canine, an increased variation of those implants that were inserted conventionally vs. those that were inserted by navigation ($P<0.05$) (Fig. 5a, b). The maximal

a



	N insertions within a circle of 0.2 mm (%)	N insertions within a circle of 0.5 mm (%)	N Insertions within a circle of 1 mm (%)	N Insertions outside a circle of 1 mm (%)
Conventional procedure	13 (65%)	6 (30%)	1 (5%)	0 (0%)
Navigated procedure	15 (75%)	5 (25%)	0 (0%)	0 (0%)

b



	N insertions within a circle of 0.2 mm (%)	N insertions within a circle of 0.5 mm (%)	N Insertions within a circle of 1 mm (%)	N Insertions outside a circle of 1 mm (%)
Conventional procedure	10 (50%)	8 (40%)	2 (10%)	0 (0%)
Navigated procedure	13 (65%)	7 (35%)	0 (0%)	0 (0%)

Fig. 5. (a) Variations of implant position of the left central incisor. The most distanced implant positions are connected by a broken line. *Left:* conventional insertion. *Right:* navigated insertion. (b) Variations of implant position of the right canine. The most distanced implant positions are connected by the broken line. *Left:* conventional insertion. *Right:* navigated insertion.

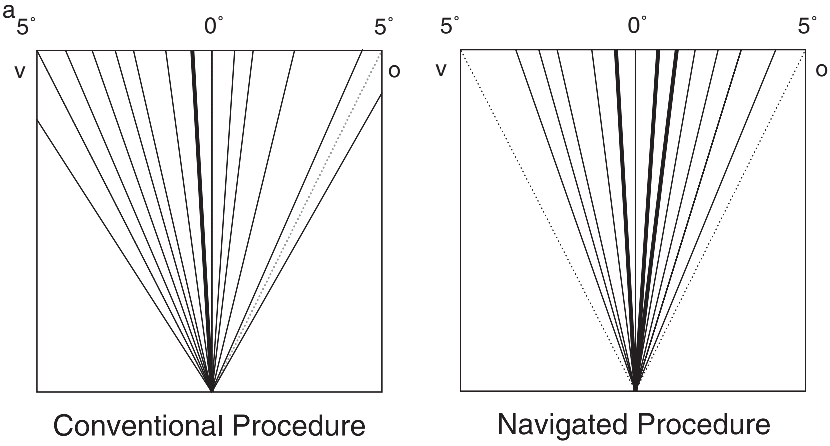
distance between two implant positions at the site of the central incisor was in conventional insertions 0.8 mm and in navigated insertions 0.6 mm (Fig. 5a). The maximal distance between two insertions at the site of the canine was in conventional insertions 1 mm and in navigated insertions 0.6 mm (Fig. 5b).

The analysis of the implant angulation in the vestibulo-oral direction revealed, for both the incisor and the canine, an increased variation of those implants that were inserted conventionally vs. those that were inserted by navigation ($P<0.05$) (Fig. 6a, b). The maximal angle between two vestibulo-oral angulations at the site of the central incisor was in conventional insertions 13° and in navigated insertions 7° (Fig. 6a). The maximal angle between two vestibulo-oral angulations at the site of the canine was in conventional insertions 13° and in navigated insertions 8° (Fig. 6b).

The analysis of the implant angulation in the mesio-distal direction revealed, for both the incisor and the canine, an increased variation of those implants that were inserted conventionally vs. those that were inserted by navigation ($P<0.05$) (Fig. 6c, d). The maximal angle between two mesio-distal angulations at the site of the central incisor was in conventional insertions 13° and in navigated insertions 8° (Fig. 6c). The maximal angle between two mesio-distal angulations at the site of the canine was in conventional insertions 14° and in navigated insertions 8° (Fig. 6d).

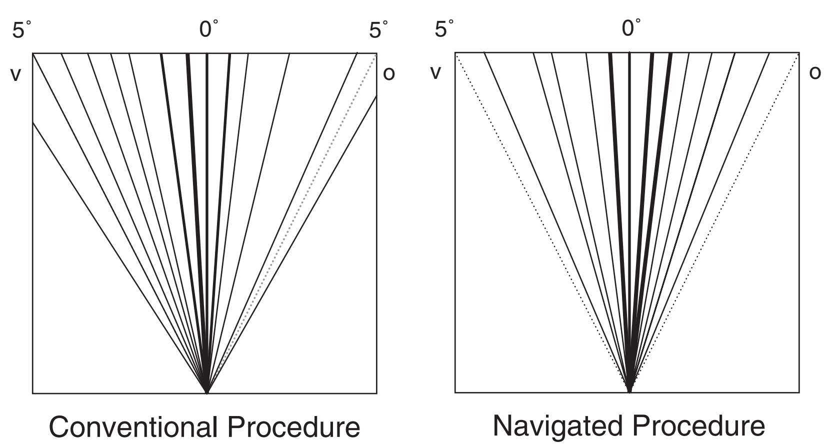
The depth of insertion was less distributed ($P<0.05$) when the implants were placed by navigation when compared with conventional insertion procedures (Fig. 7). The maximal distance between two insertion depths at the site of the central incisor was in the group of conventional insertions 1 mm and in navigated insertions 0.4 mm. The maximal distance between two insertion depths at the site of the canine was in conventional insertions 0.8 mm and in navigated insertions 0.3 mm.

a



	N insertions within an angle ±2° (%)	N insertions within an angle of ±5° (%)	N Insertions within an angle of ±10° (%)	N Insertions outside of an angle of 10° (%)
Conventional procedure	11 (55%)	7 (35%)	2 (10%)	0 (0%)
Navigated procedure	18 (90%)	2 (10%)	0 (0%)	0 (0%)

b

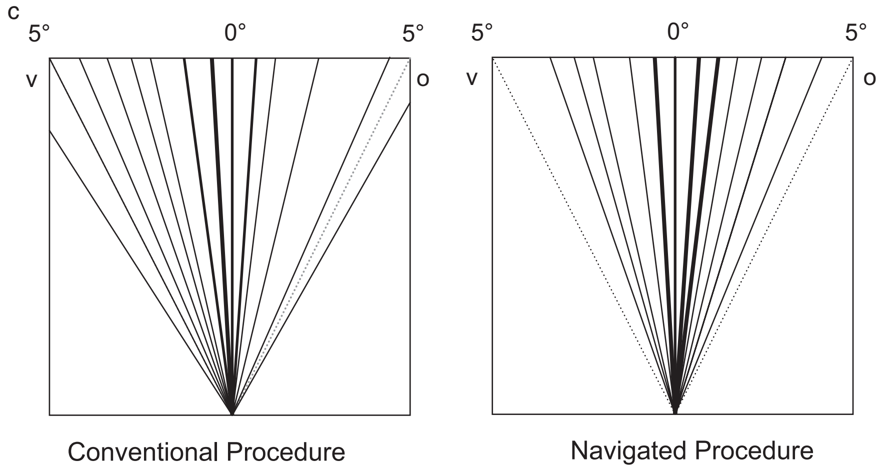


	N insertions within an angle ±2° (%)	N insertions within an angle of ±5° (%)	N Insertions within an angle of ±10° (%)	N Insertions outside of an angle of 10° (%)
Conventional procedure	16 (80%)	4 (20%)	0 (0%)	0 (0%)
Navigated procedure	18 (90%)	2 (10%)	0 (0%)	0 (0%)

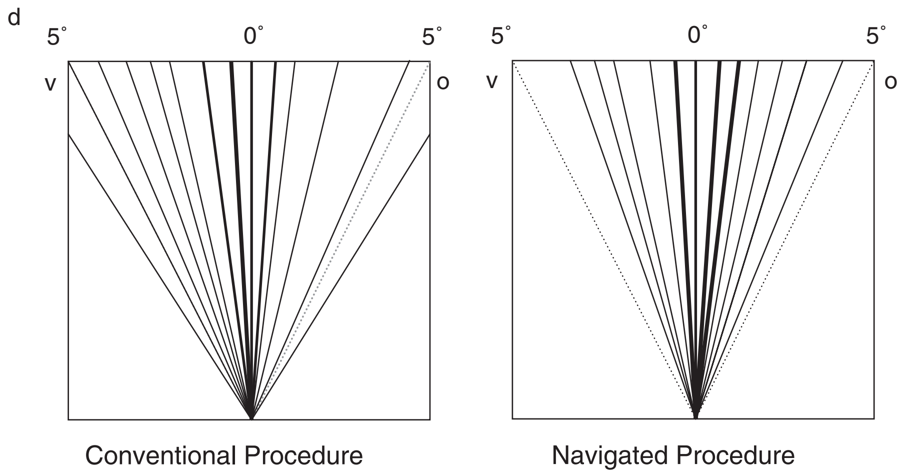
Fig. 6. (a): Variations of implant angulation in vestibulo-oral direction for the left central incisor of the maxilla. *Left:* conventional insertion. *Right:* navigated insertion. (b) Variations of implant angulation in mesio-distal direction for the left central incisor of the maxilla. *Left:* conventional insertion. *Right:* navigated insertion. (c) Variations of implant angulation in vestibulo-oral direction for the right canine of the maxilla. *Left:* conventional insertion. *Right:* navigated insertion. (d) Variations of implant angulation in mesio-distal direction for the right canine of the maxilla. *Left:* conventional insertion. *Right:* navigated insertion.

Discussion

The replacement of teeth in the anterior maxilla is a major challenge when using implants (Andersen et al. 2002; Palmer et al. 2003). Correct implant position,



	N insertions within an angle ±2° (%)	N insertions within an angle of ±5° (%)	N Insertions within an angle of ±10° (%)	N Insertions outside of an angle of 10° (%)
Conventional procedure	12 (60%)	5 (25%)	3 (15%)	0 (0%)
Navigated procedure	18 (90%)	2 (10%)	0 (0%)	0 (0%)



	N insertions within an angle ±2˚ (%)	N insertions within an angle of ±5˚ (%)	N Insertions within an angle of ±10˚ (%)	N Insertions outside of an angle of 10˚ (%)
Conventional procedure	16 (70%)	4 (20%)	0 (0%)	0 (0%)
Navigated procedure	19 (95%)	1 (5%)	0 (0%)	0 (0%)

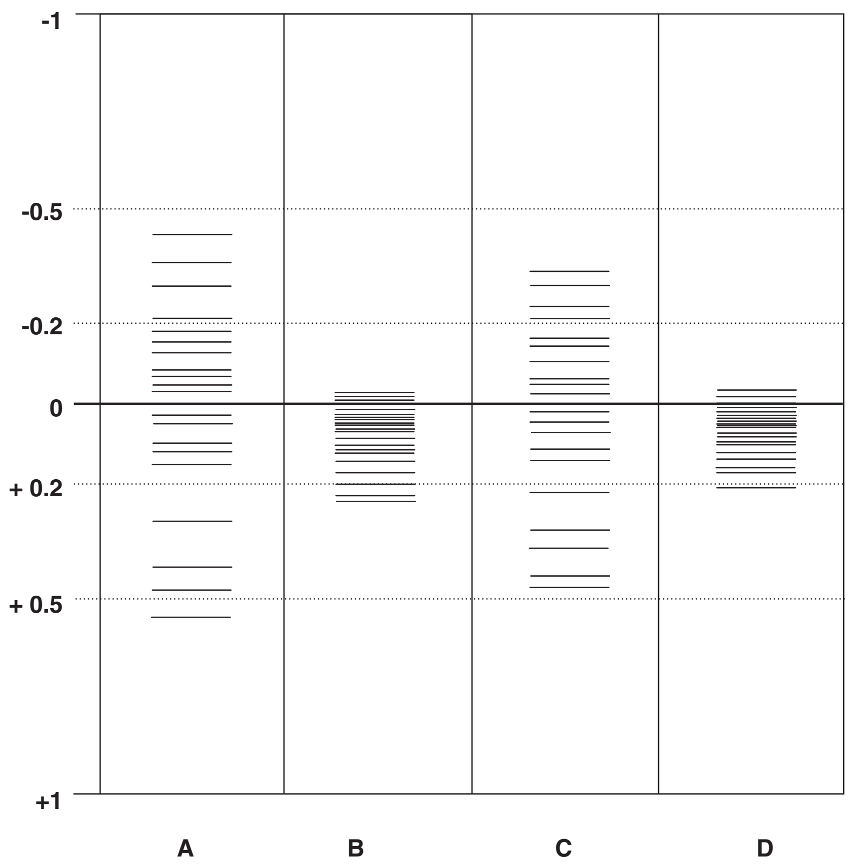
Fig. 6. Continued.

angulation and insertion depth are particularly important in order to gain a maximum of function and aesthetics (Stanford 1999; Lorenzoni et al. 2003). Therefore, the intraoperative guidance provided by application of a surgical navigation system could be valuable to ensure an appropriate preparation of the implant socket and the correct implant insertion. Besides drilling templates, image guidance or navigation is the only method to transfer a virtual three-dimensional planning procedure into reality until now. In contrast to drilling templates, navigation offers an intraoperative real-time multidimensional image of the relevant anatomy enabling spontaneous intraoperative modifications of the procedure with persisting guidance.

Navigation has led to an improvement in the accuracy of implantation compared with a conventional procedure in this study. An index abutment was employed to allow for precise measurements. The use of this method has proven to be reliable and simple. It is of importance that the index abutment is long enough. In this study the extensive length of the index abutment of 400 mm resulted in a 26 fold or 30 fold amplification of any implant angulation, depending on the length of the implant. This allowed the detection of even minimal implant deviations and should also surmount all immanent methodical errors of analysis such as inaccuracies during manual measurements or technical limitations, e.g. the resolution of the CT-scans.

As it is known that a proper implant position is of major importance to soft-tissue aspects, osseointegration (Nemcovsky et al. 2000) and functional loading concepts (Szmukler-Moncler et al. 2000; Lorenzoni et al. 2003), one might assume that navigation could not only affect the accuracy of functional and aesthetic results in individual implant restorations, but also treatment concepts and implant survival rates of implants in general.

Although the given experimental conditions were adopted very close to clinical practice, it has to be considered that the results of this study are based on *in vitro* experiments. Under clinical conditions with their multifactorial environment, the results may be different. The *in vitro* conditions probably allowed for navigation to be applied at best. For example, the fixation of the reference body to the cast model was completely uncomplicated and safely reproducible. It was reported earlier that the accuracy and reproducibility of referencing is fundamental for the accuracy of navigation procedures (Wanschitz et al. 2002). The special situation of loss of only single tooth, which avoided any loading of the reference body to the alveolar



	Left central incisor		Right canine	
	Conventional procedure (A)	Navigated procedure (B)	Conventional procedure (C)	Navigated procedure (D)
< ± 0.2 mm	12 (60%)	17 (85%)	11(55%)	19 (95%)
< ± 0.5 mm	7 (35%)	3 (15%)	9 (45%)	1 (5%)
< ± 1 mm	1 (5%)	0 (0%)	0 (0%)	0 (0%)

Fig. 7. Variations of insertion depths. Lane a: Left central incisor, conventional insertion. Lane b: Left central incisor, navigated insertion. Lane c: Right canine, conventional insertion. Lane d: Right canine, navigated insertion.

process, supported a safe and stable tooth-borne fixation of the reference body.

The prototype of the navigation system that was applied in this investigation was reported to vary with a metric distance of 1.2 mm at worst in a partially edentulous jaw (Brief et al. 2001). This *in vitro* study with image guidance found that the maximal metric variation of implant position was 0.6 mm, which is less than with conventional insertions.

An improvement of orientation in the conventional insertion procedure can be provided by a positional guide. The guide applied in this investigation indicated the desired implant position and mesio-distal angulation, but allowed the surgeon to perform a wide range of individual modifications within the entire insertion site, which might be helpful in some clinical situations. However, in this investigation the application of a different type of positional guide that defines the implant position, angulation and insertion depth more strictly would probably have resulted in a reduced variation of conventionally inserted implants.

Apart from accuracy, several other aspects of practical relevance have to be taken into account in deciding which method of implant insertion technique should be selected for the replacement of single maxillary incisors or canines: The procedure of conventional insertion surgery is well established, in most cases uncomplicated and has resulted in predictable results, while navigation is a relatively new technique (Meyer et al. 2003;Wagner et al. 2003). However, the course of action in image-guided surgery is much more complex than the conventional insertion procedures and incorporates some potentially negative methodical aspects. As discussed earlier, the accuracy achieved depended remarkably on the accuracy of the reference body that has to fit perfectly and has to be safely reproducible during preoperative scanning and surgery (Brief et al. 2001). In any situation this cannot be guaranteed, navigation will not be supportive. Further, a three-dimensional scan of the anatomy by CT or Digital Volume Tomography (DVT) with the CT-guide *in situ* is indispensable for navigation (Gunkel et al. 2000). Although advantageous for three-dimensional treatment planning (Ploder et al. 1995; Verstreken et al. 1996), the exposure of the patient to radiation is increased compared with conventional radiographic diagnostics (Harris et al. 2002). In preoperative planning, the surgeon has to position the implant in virtual reality software applications. This procedure cannot be delegated to medical assistance professionals and may be time-intensive. Finally, during implant surgery, referencing and navigation itself add to the surgical time and may require ergonomic compromises for the surgeon's team. A shortening of the time of surgery can be expected, however, when a minimally invasive strategy can be adopted without the need for mucoperiosteal flaps thanks to image guidance.

Despite the drawbacks, the surgical results in this *in vitro* study were improved in all examined categories (implant positioning, angulation and insertion depth) when implantation was supported by navigation. Therefore, navigation may still be holding some promise for placement of implants, especially when it comes to precision of implant placement, difficult anatomic situations and safety of the patient. Considering the limitations of an *in vitro* environment, the real benefits of image guidance in implant surgery have to be investigated in a clinical, patient-related study.

Résumé

La navigation guidée par ordinateur s'est avérée techniquement valable pour de nombreuses disciplines chirurgicales. Durant le placement d'implants dentaires son application devrait servir à accomplir une localisation implantaire optimale et donc réduire le risque d'endommager les structures adjacentes. Le but de cette étude a été de comparer les limites de précision de l'insertion conventionnelle vs navigation. Dans des modèles du maxillaire, des implants ont été insérés pour remplacer l'incisive centrale gauche ($n=40$) et la canine droite ($n=40$), chacune étant insérée soit conventionnellement ($n=20$) soit par navigation ($n=20$). La position de l'implant, l'angulation, la profondeur d'insertion ont été calculées à partir de scans CT qui étaient en connexion avec un pilier index d'une longueur de 40 cm. Les variations des positions de l'implant étaient réduites pour les implants qui étaient insérés par navigation ($P<0.05$). Tant sur le plan axial que transversal les variations des angulations implantaires étaient réduites pour les implants qui étaient insérés par navigation ($P<0.05$). Les variations de profondeur d'insertion étaient inférieures ($P<0.05$) lorsque les implants étaient placés par navigation comparées à l'insertion conventionnelle. Dans les conditions expérimentales de données, bien qu'elles essayent d'être semblables à la situation clinique, aucune conclusion finale ne peut être tirée. L'application *in vitro* du système de navigation a abouti à une précision améliorée de la chirurgie d'insertion en ce qui concerne la position, l'angulation et la profondeur d'un implant. Des études cliniques devront prouver si ce système résulte en un protocole chirurgical amélioré.

Zusammenfassung

Navigierte und konventionelle Implantatplatzierung für den Einzelzahnersatz im Oberkiefer – eine vergleichende in vitro Studie

Einleitung: Die computergesteuerte Navigation hat sich in verschiedenen chirurgischen Disziplinen als wertvolles Werkzeug erwiesen. In der oralen Implantologie wird sie angewendet, um eine optimale Implantatplatzierung zu erreichen und um das Risiko einer Verletzung von Nachbarstrukturen zu verhindern. Das Ziel dieser Studie war es, die Grenzen der Präzision der konventionellen und der navigierten Implantatplatzierung in der Praxis zu vergleichen.

Material und Methoden: Bei Oberkiefermodellen wurden Implantate eingesetzt, um den linken lateralen Schneidezahn ($n=40$) und den rechten Eckzahn ($n=40$) zu ersetzen. Jedes dieser Implantate wurden entweder konventionell ($n=20$) oder mit Navigation ($n=20$) eingesetzt. Die Implantate wurden mit einem Index-Aufbauteil der Länge 40 cm verbunden. Die Implantatposition, die Angulation und die Einsetztiefe wurden auf CT-Rasteraufnahmen der Implantate berechnet.

Resultate: Die Variationen der Implantatpositionen waren bei mit Navigation gesetzten Implantaten kleiner ($P<0.05$) als bei konventionell gesetzten Implantaten. Sowohl in der axialen als auch transversalen Ebene waren die Unterschiede in der Implantatangulation bei den mit Navigation gesetzten Implantaten kleiner ($P<0.05$). Wenn die Implantate mit Navigation gesetzt wurden, waren die Unterschiede in der Einsetztiefe kleiner ($P<0.05$), als wenn konventionell vorgegangen wurde.

Schlussfolgerungen: Aufgrund der experimentellen Bedingungen kann keine endgültige Schlussfolgerung gezogen werden, obwohl versucht wurde, die klinische Situation zu simulieren. Die *in vitro* Anwendung eines Navigationssystems resultierte in einer höheren Präzision beim Setzen von Implantaten bezüglich Position, Angulation und Einsetztiefe der Implantate. Klinische Studie werden beweisen müssen, ob die routinemässige Führung durch Bilder zu einem besseren chirurgischen Resultat führen wird.

Resumen

Introducción: La navegación guiada por ordenador ha demostrado ser una herramienta valiosa en varias disciplinas quirúrgicas. Su aplicación durante la colocación de implantes orales se realiza con la intención de lograr un localización óptima del implante y reducir el riesgo de daño a las estructuras vecinas. La intención de este estudio fue comparar los límites de precisión de la inserción de implantes de forma convencional frente a la forma por navegación en la práctica.

Material y métodos: Se insertaron implantes en modelos vaciados del maxilar. Para reemplazar el incisivo central izquierdo ($n=40$) y el canino derecho ($n=40$); cada uno se insertó de forma convencional $n=20$ o navegada ($n=20$). La posición, angulación y profundidad de inserción del implante se calcularon a partir de escáneres CT de los implantes que se conectaron con un pilar índice de 40 cm. de longitud.

Resultados: Las variaciones en las posiciones de los implantes se redujeron en los implantes que se insertaron por navegación ($P<0.05$). En ambos planos axial y sagital las variaciones en la angulación de los implantes se redujeron para los implantes que se insertaron por medio de un protocolo de navegación ($P<0.05$). Las variaciones en la profundidad de inserción fueron menores ($P<0.05$) cuando los implantes se insertaron por navegación en comparación con los que se insertaron con procedimientos convencionales.

Conclusiones: Dadas las condiciones experimentales, aunque se intentó imitar una situación clínica, no se pueden sacar conclusiones finales. La aplicación *in vitro* de un sistema de navegación resultó en una mejora de la precisión de la cirugía de inserción respecto a la posición, la angulación y la profundidad de un implante. Estudios clínicos deberán probar si el guiado por imágenes rutinario redundará en unos resultados quirúrgicos superiores.

要約

序：外科手術の幾つかの分野においてコンピュータ支援のナビゲーションは価値あるツールである。口腔インプラント埋入への適用は、最適なインプラントの埋入場所を決め、隣接する構造への損傷のリスクを減らすことを意図している。本研究では、従来のインプラント埋入法とナビゲーションを用いた埋入法の精密度限界を比較した。

材料と方法：上顎の石こう模型において、左側中切歯４０）（ｎ＝４０）と右側犬歯（ｎ＝４０）の部位にインプラントを埋入した；各部位に従来の方法（ｎ＝２０）とナビゲーション法（ｎ＝２０）を用いた。４０ｃｍ長のインデックス・アバットメントに連結したインプラントのＣＴスキャンから、インプラント埋入の位置、角度と深さを計算した。

結果：ナビゲーション法を用いて埋入したインプラントでは、インプラント位置のばらつきは、減少した（ｐ＜０．０５）。軸面および横断面の両方において、インプラントの角度のばらつきは、ナビゲーション・プロトコールに基づいて埋入したインプラントでは減少した（ｐ＜０．０５）。埋入の深さのばらつきは、従来の方法と比べて、ナビゲーション法によるインプラントの方がばらつきの度合いが少なかった（ｐ＜０．０５）。

結論：臨床的状況を模倣しようとはしたものの、実験の諸条件を考慮すると、最終的な結論を導き出すことはできなかった。ナビゲーション・システムのインビトロでの適用は、インプラントの位置、角度、深さに関する埋入手術の精密度を改善した。今後の臨床研究によって、ルーティンの画像ガイダンスが優れた手術の結果をもたらすかどうかを証明しなくてはならないと思われる。

キーワード：歯科用インプラント、ナビゲーション、正確度、上顎、画像支援手術

References

Andersen, E., Haanas, H.R. & Knutsen, B.M. (2002) Immediate loading of single tooth ITI implants in the anterior maxilla: a prospective 5-year pilot study. *Clinical Oral Implants Research* **13**: 281–287.

Birkfellner, W., Solar, P., Gahleitner, A., Huber, K., Kainberger, F., Kettenbach, J., Homolka, P., Diemling, M., Watzek, G. & Bergmann, H. (2001) *In vitro* assessment of a registration protocol for image guided implant dentistry. *Clinical Oral Implants Research* **12**: 69–78.

Bouserhal, C., Jacobs, R., Quirynen, M. & van Steenberghe, D. (2002) Imaging technique selection for the preoperative planning of oral implants: a review of the literature. *Clinical Implant Dentistry & Related Research* **4**: 156–172.

Branemark, P.I., Hansson, B.O., Adell, R., Breine, U., Lindstrom, J. & Ohman, A. (1977) Osseointegrated implants in the treatment of the edentulous jaw. Experiences from a 10-year period. *Scandinavian Journal of Plastic and Reconstructive Surgery* **16** (Suppl.): 1–132.

Brief, J., Hassfeld, S., Sonnenfeld, U., Persky, N., Krempien, R., Treiber, M. & Mühling, J. (2001)

Computer-guided insertion of dental implants – a clinical evaluation. *International Congress Series* **1230**: 739–747.

Chassat, F. & Lavallée, S. (1998) Experimental protocol of accuracy evaluation for computer-integrated surgery: application to four optical localizers. In: Wells, W.M., Colchester, A. & Delps, S., eds. *Medical image computing and computer-assisted intervention – MICCAI'98*, 277–286. Berlin: Springer Publ.

Fortin, T., Coudert, J.T., Champleboux, G., Sautot, P. & Lavallee, S. (1995) Computer-assisted dental implant surgery using computed tomography. *Journal of Image Guided Surgery* **1**: 53–58.

Gaggl, A., Schultes, G. & Kärcher, H. (2001) Navigational precision of drilling tools preventing damage to the mandibular canal. *Journal of Craniomaxillofacial Surgery* **29**: 271–275.

Gunkel, A.R., Thumfart, W.F. & Freysinger, W. (2000) Computer-aided 3D-navigation systems. Surgery and location determination. *HNO* **48**: 75–90.

Harris, D., Buser, D., Dula, K., Grondahl, K., Haris, D., Jacobs, R., Lekholm, U., Nakielny, R., van Steenberghe, D. & van der Stelt, P. (2002) E.A.O. guidelines for the use of diagnostic imaging in implant dentistry. A consensus workshop organized by the European Association for Osseointegration in Trinity College Dublin. *Clinical Oral Implants Research* **13**: 566–570.

Lorenzoni, M., Pertl, C., Zhang, C., Wimmer, G. & Wegscheider, W.A. (2003) Immediate loading of single-tooth implants in the anterior maxilla Preliminary results after one year. *Clinical Oral Implants Research* **14**: 180–187.

Meyer, U., Wiesmann, H.P., Runte, C., Fillies, T., Meier, N., Lueth, T. & Joos, U. (2003) Evaluation of accuracy of insertion of dental implants and prosthetic treatment by computer-aided navigation in minipigs. *British Journal of Oral and Maxillofacial Surgery* **41**: 102–108.

Nemcovsky, C.E., Moses, O. & Artzi, Z. (2000) Interproximal papillae reconstruction in maxillary implants. *Journal of Periodontology* **71**: 308–314.

Palmer, R.M., Palmer, P.J. & Newton, J.T. (2003) Dealing with esthetic demands in the anterior maxilla. *Periodontology 2000* **33**: 105–118.

Ploder, O., Wagner, A., Enislidis, G. & Ewers, R. (1995) Computergestützte intraoperative Visualisierung von dentalen Implantaten (Computer-based intraoperative visualisation of dental implants). *Radiologie* **35**: 569–575.

Schramm, A., Gellrich, N.C., Schimming, R. & Schmelzeisen, R. (2000) Computer-assisted insertion of zygomatic implants (Branemark system) after extensive tumor surgery. *Mund- Kiefer-Gesichtschirurgie* **4**: 292–295.

Siessegger, M., Schneider, B.T., Mischkowski, R.A., Lazar, F., Krug, B., Klesper, B. & Zöller, J.E. (2001) Use of an image-guided navigation system in dental implant surgery in anatomically complex operation sites. *Journal of Craniomaxillofacial Surgery* **29**: 276–281.

Stanford, C.M. (1999) Biomechanical and functional behaviour of implants. *Advances in Dental Research* **13**: 88–92.

van Steenberghe, D., Naert, I., Andersson, M., Brajnovic, I., Van Cleynenbreugel, J. & Suetens, P. (2002) A custom template and definitive prosthesis allowing immediate implant loading in the maxilla: a clinical report. *International Journal of Oral & Maxillofacial Implants* **17**: 663–670.

Szmukler-Moncler, S., Piattelli, A., Bavero, G.A. & Dubruille, J.H. (2000) Considerations preliminary to the application of early and immediate loading protocols in dental implantology. *Clinical Oral Implants Research* **11**: 12–25.

Verstreken, K., Van Cleynenbreugel, J., Marchal, G., Nert, I., Suetens, P. & Van Streenberghe, D. (1996) Computer-assisted planning of oral implant surgery: a three dimensional approach. *International Journal of Oral & Maxillofacial Implants* **11**: 806–810.

Wagner, A., Wanschitz, F., Birkfellner, W., Zauza, K., Klug, C., Schico, K., Kainberger, F., Czerny, C., Bergmann, H. & Ewers, R. (2003) Computer-aided placement of endosseous oral implants in patients after ablative tumour surgery: assessment of accuracy. *Clinical Oral Implants Research* **14**: 340–348.

Wanschitz, F., Watzinger, F., Schopper, C., Ewers, R., Birkfellner, W., Figl, M., Bergmann, H., Patruta, S., Kainberger, F. & Kettebach, J. (2002) Evaluation of accuracy of computer-aided intraoperative positioning of endosseous oral implants in the edentulous mandible. *Clinical Oral Implants Research* **13**: 59–67.

Watzinger, F., Birkenfellner, W., Wanschitz, F., Millesi, W., Schopper, C., Sinko, K., Huber, K., Bergmann, H. & Ewers, R. (1999) Positioning of dental implants using computer-aided navigation and an optical tracking system: case report and presentation of a new method. *Journal of Craniomaxillofacial Surgery* **27**: 77–81.

Watzinger, F., Birkfellner, W., Wanschitz, F., Ziya, F., Wagner, A., Kremser, J., Kainberger, F., Huber, K., Bergmann, H. & Ewers, R. (2001) Placement of endosteal implant in the zygoma after maxillectomy: a cadaver study using surgical navigation. *Plastic and Reconstructive Surgery* **107**: 659–667.

Weinberg, L.A. (1993) CT scan as a radiologic data base for optimal implant orientation. *Journal of Prosthetic Dentistry* **69**: 381–385.