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Accuracy of image-guided implantology

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Abstract

Objectives: The accuracy of two commercially available systems for image-guided dental implant insertion based on infrared tracking cameras was compared with manual implantation.

Material and methods: Phantoms of partially edentulous mandibles were used. In a master phantom, pilot boreholes for dental implants were placed. These boreholes were reproduced in slave phantoms using either of the two image-guided systems and manual implantation. The resulting positions were determined using a coordinate measurement machine and compared with the master model.

Results: In comparison with manual implantation, the difference of borehole positions to the master phantom was significantly lower using either of the systems for image-guided implant insertion.

Conclusion: Image-guided insertion of dental implants is significantly more accurate than manual insertion. However, the accuracy that can be achieved with manual implantation is sufficient for most clinical situations.

Dental implants have become a common means for the replacement of lost teeth. Today, screw-shaped rough implants made of titanium are standard. They have proven to be reliable with good long-term results. However, diligence is mandatory during implant placement. Firstly, the implant must be placed in such a way that the bottom and sides are covered fully by bone or bone-replacement material. Secondly, the implant must not damage neighbouring anatomic structures. These are in particular the mandibular nerve in lower-jaw implantology and the schneiderian membrane of the maxillary sinus in upper-jaw implantology. Thirdly, the position of the implant has to be compatible with the intended prosthodontic rehabilita-

tion. Otherwise, the functional or aesthetic result might be less than optimal.

Proper planning prior to implantation and its exact intraoperative transfer are the keys to address these issues properly. Panoramic radiography is still the standard for planning of implants. It is often sufficient for routine cases (Tal & Moses 1991). However, precise measuring of the bone is impossible, because panoramic radiographs have a magnification factor that is not always uniform. Methods have been developed based on templates with radiographic markers that would allow a better assessment of the bone dimensions in panoramic radiographs by determination of the magnification factor (Mupparapu & Singer 2004). However, there is no information

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about the dimension of the bone in the bucco-lingual direction. This can be obtained using computer tomography (CT) or digital volume tomography (DVT). Templates have also been used to intraoperatively guide the implantologist (Chiche et al. 1989). They can be used for the transfer of a planning that was made on a plaster model (Kopp et al. 2003) or in a computer-based planning-system (Heurich et al. 2002). A recent development is systems for dental implantation, using a navigation system (Brief et al. 2002b; Homolka et al. 2002). They were developed in order to improve the accuracy and safety of dental-implant placement. In addition to this, exact preoperative planning shall improve the aesthetic and functional result of the restoration. In the meantime, these systems are commercially available. The aim of this study was to assess the accuracy of these systems.

Material and methods

Evaluation operations were executed on phantoms of partially edentulous jaws using 'RoboDent' (RoboDent GmbH, Berlin, Germany) and the 'IGI DenX' system (Denx Ltd, Moshav Ora, Jerusalem, Israel).

Both systems follow the same workflow and use the same principles of navigation:

- (1) A template with registration markers, provided by the manufacturer of the respective system, was created.
- (2) With the template in the patient's mouth, volume data of the region of interest were obtained, e.g. by CT or DVT.
- (3) The image data were written on a CD-ROM and were loaded into a computer-based implant planning system.
- (4) On the computer, the bone of the respective jaw was segmented and a 3D model of the bone was created. The mandibular nerve as a structure at risk was identified and would be displayed continuously in the bone model. The registration markers were identified in image data as well.
- (5) The dental surgeon would now place the implants virtually in the bone model and easily check for complete cover by bone and collision with other implants or anatomic structures. If the template was created using radio-opaque teeth for the teeth to be replaced, the later prosthodontic reconstruction could easily be taken into consideration as well.
- (6) After planning had been finished, implantation started. Both systems used stereoscopic camera navigation systems to detect the position of the patient and the position of the handpiece with the drill. Therefore, a reference frame was connected to the patient, using the template. Another reference frame was connected to the handpiece.
- (7) For the calibration of the drills, both systems followed different workflows. In the RoboDent system, the desired drill was attached to the handpiece. Holding the handpiece, the tip of the drill was moved into a prefabricated cavity in the connecting part between the template and its reference frame. The handpiece was now pivoted around the tip of the drill and the positions of the handpiece were measured with the infrared cameras. From these data, the position of the tip and the length of the instrument were calculated. In the DenX system, the type of drill used was selected in a menu in the software. In neither system, the diameters of the drill were calibrated, as the implant positions were defined by the centres of entry and apex. The correct choice of the tool diameter was left to the implantologist.
- (8) In a short registration procedure, the position of the registration marker was identified in reality. Now the systems 'knew' the position and orientation of the patient's jaw and the drill in relation to the respective reference frame. On the computer, the position of the bone of the jaw and the handpiece with the drill were now displayed continuously.
- (9) The systems then guided the dental surgeon to drill the holes for implants that had been planned before. The correct position, orientation and path for the movement of the handpiece were indicated in real time, using specific indicators and pictograms.

Both systems worked according to this principle. However, there are the following

differences between the two systems: the RoboDent system controls the drive of the drill while tracking the position of the handpiece. The drill will be stopped if the dental surgeon tries to drill a hole for the implant at a position that was not planned beforehand. This feature is named 'navigated control' by the manufacturer. The second different feature of the RoboDent system is an additional external small display that gives indications to the dental surgeon to guide the handpiece according to the implant planning. This display can be positioned near the patient's head so that the dental surgeon does not have to turn his head away from the site of surgery in order to see the indications from the system.

The accuracy of the systems was investigated by using phantom jaws made of PolyPlast (Arident, Sinsheim/Eschelbach, Germany). We used partly edentulous lower jaws with missing molars 36, 46 and 47. Sixteen identical models were produced. In one of the models, the master model, three boreholes were placed in the regions of the missing teeth (036, 046, 047). The boreholes had a depth of 13, 12 and 12 mm. They were produced using a pilot drill with 2 mm diameter. A navigation template to fit on the phantom jaws with fiducial markers was produced for each of the implant systems. Now, CT-scans of the master model were performed with either of the navigation templates attached to the teeth of the master model. The CT-scans of the master model with the navigation templates were transferred to the respective implantation planning system. In either of the planning systems, the boreholes were located in CT-image data. Three implants were planned exactly at the positions of the boreholes that had been drilled prior to the CT-scan.

For each implant system, the navigation template was then transferred to five of the copies of the master model (slave models). Guided by the navigation systems, the pilot boreholes for the three implants were made. In this way, five models with a total of 15 boreholes were 'implanted' with either system. For subsequent comparison, in five other slave models the three boreholes were placed manually at the positions of the master model as being displayed on the planning software, without assistance from a navigation system or a boring template. The implantations were

performed by five implantologists, who would implant three models using either of the three methods.

Finally, all boreholes were measured with a coordinate measurement machine (Bronze LSo6-02, FARO Technologies Inc., Lake Mary, FL, USA). This coordinate measurement machine is built of tubes connected with joints and is shaped similar to an arm. Highly precise rotational sensors are integrated and give exact angular information about the flexion of each joint. An integrated circuitry calculates the spatial position of the tip of the arm from the rotational information of the joint sensors and the known length of the arm segments. These are read out by a computer. A template was fixed to the base plate of the measuring machine. All models were then attached to the template in exactly the same position. Now the coordinates of the apical end and the entry of each borehole were measured in the master model and all slave models (Fig. 1). The inaccuracy of the implantation was calculated.

The translational error was defined as the aberration of the borehole entry and apex position in the slave models as compared with the respective positions in the master model. The angular error was defined as the aberration of the borehole

direction in the slave models as compared with the respective positions in the master model.

For each implant borehole in the master model, its direction in space was calculated. Hence, all error measurements could be given in relation to the implant axis rather than in relation to an arbitrary spatial axis. The translational error was divided into a lateral error, a longitudinal error and a total error (Fig. 2). The lateral error was the circular deviation of the slave borehole to the entrance or apex point of the master borehole. It was always measured in the plane rectangular to the master borehole's axis.

The longitudinal error was the distance of a measured apex point of the corresponding borehole in the slave model to the apex point of the master model, along the master model's borehole axis. The total error was the distance of a measured apex point of a borehole in the slave model to the corresponding apex point of the master model. The angular error was the difference between the axis of the boreholes in the master model and the axis of the respective boreholes in the slave models (Fig. 2).

Results

The boreholes created with the RoboDent system showed an average deviation perpendicular to the borehole axis of the master model of 0.35 mm at the entry and 0.47 mm at the apex. The boreholes created with the IGI DenX system showed an average deviation perpendicular to the borehole axis of the master model of 0.65 mm at the entry and 0.68 mm at the apex. Boreholes created without the assistance of a navigation system showed an average deviation perpendicular to the borehole axis of the master model of 1.35 mm at the entry and 1.62 mm at the apex (Table 1, Figs 3 and 4). Both systems had a significantly lower lateral deviation at the entry point and at the apex than manual implantation ($P < 0.0001$ for RoboDent vs. manual implantation at entry and apex, $P = 0.0023$ at entry and $P = 0.0001$ at apex for IGI DenX vs. manual implantation, all values two-tailed, unpaired alternate *t*-test).

The average longitudinal deviation provides information on whether the depth of implantation was accurate. It was 0.32 mm

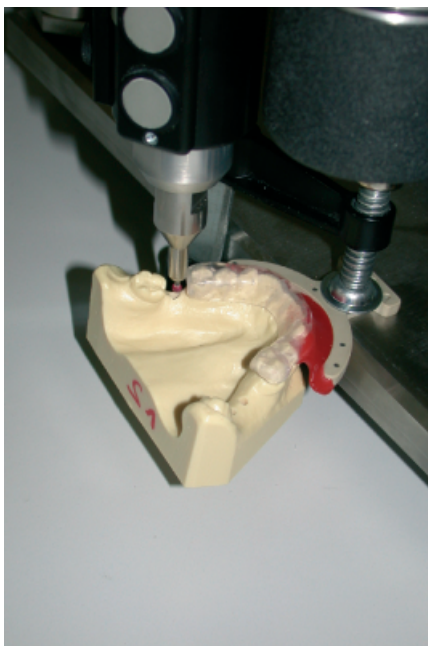


Fig. 1. The model is inserted into a template that is fixed to the baseplate of the coordinate measurement machine (CMM). The tip of the CMM is guided to the desired position for measurement.

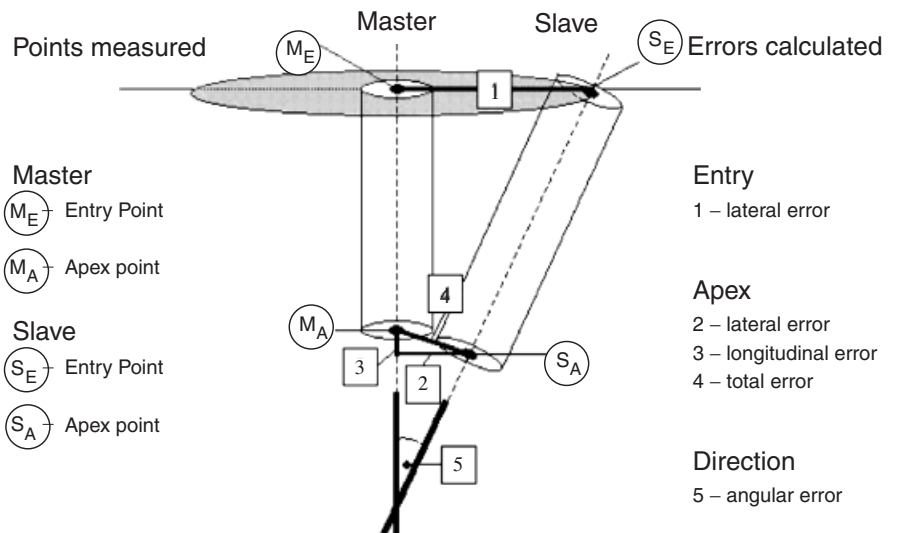


Fig. 2. Methods of determination of implantation error.

Table 1. Lateral deviation of entry and apex

	RoboDent system	DenX IGI system	Manual implantation
Entry	0.35 ± 0.17/0.75	0.65 ± 0.58/2.37	1.35 ± 0.56/2.16
Apex	0.47 ± 0.18/0.72	0.68 ± 0.31/1.22	1.62 ± 0.68/2.68

Lateral deviation of the pilot borehole position in the slave models compared with the master model (all data: mean ± SD/max (mm)).

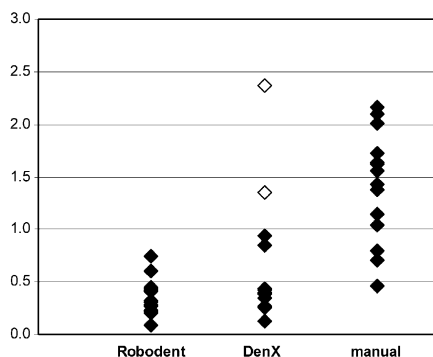


Fig. 3. Lateral error (mm) at entry point.

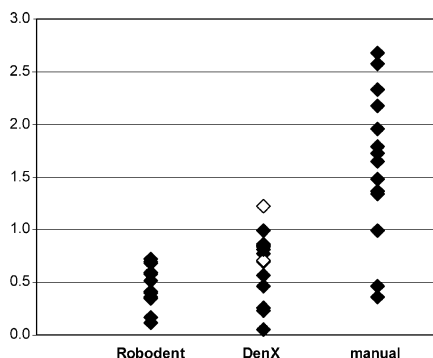


Fig. 4. Lateral error (mm) at apex point.

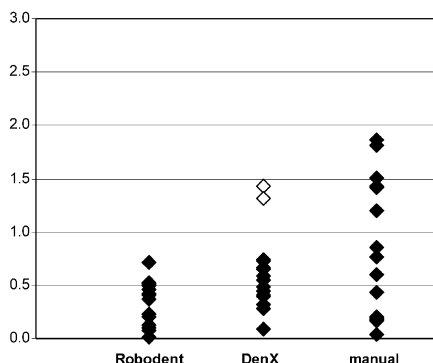


Fig. 5. Longitudinal error (mm) at apex point.

for RoboDent, 0.61 mm for IGI DenX and 0.84 mm for manual implantation (Table 2, Fig. 5). Here only RoboDent was significantly better than manual implantation ($P = 0.0094$ for RoboDent vs. manual implantation and $P = 0.2439$ for IGI DenX vs. manual implantation, all values two-tailed, unpaired alternate t -test).

The total distance of the apex position to the reference was 0.6 mm for RoboDent, 0.94 mm for IGI DenX and 1.89 mm for manual implantation (Table 3, Fig. 6). Both systems were significantly better than manual implantation ($P < 0.0001$ for RoboDent vs. manual implantation and $P = 0.0005$ for IGI DenX vs. manual im-

plantation, all values two-tailed, unpaired alternate t -test).

The average angular deviation provides information on the accuracy of the direction of implantation. It was 2.12° for RoboDent, 4.21° for IGI DenX and 4.59° for manual implantation (Table 4, Fig. 7). Here as well, only RoboDent was significantly better than manual implantation ($P = 0.0005$ for RoboDent vs. manual implantation and $P = 0.7931$ for IGI DenX vs. manual implantation, all values two-tailed, unpaired alternate t -test).

Discussion

Using a navigation system is not the only method to transfer an implant planning into the patient's mouth. The role of surgical robots for this task (Brief et al. 2000) is as yet unclear. However, templates can be used for the transfer of preoperative

planning into intraoperative positioning of the implant (Sicilia et al. 1998). The templates serve as bore-guides using integrated holes or tubes to indicate the planned positions. A variety of methods for the creation of templates are published. On the one hand, there are methods to transfer a planning that was made on a model with a wax-up of the desired restoration (Solow 2001; Tsuchida et al. 2004). On the other hand, there are methods to transfer a virtual planning that was made on the volume image-data of the patient, similar to the planning systems used in this study. In the first step, the template is used as a diagnostic template and is worn by the patient during imaging. By transferring the virtual planning in the image data into tube positions on the template, it is transformed into a surgical template. This transfer can be performed either using a mechanical positioning device (Heurich et al. 2002; Kopp et al. 2003), or numerically controlled

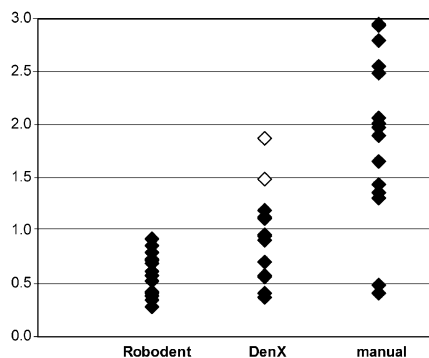


Fig. 6. Total error (mm) at apex point.

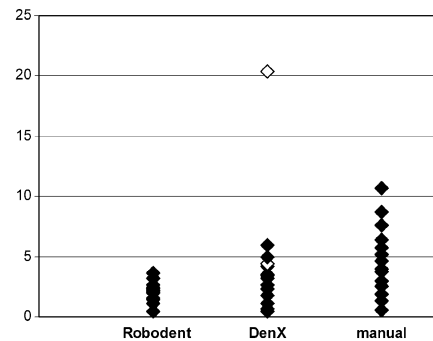


Fig. 7. Angular error (degree) of direction.

Table 2. Longitudinal deviation of apex

	RoboDent system	DenX IGI system	Manual implantation
Apex	$0.32 \pm 0.21/0.71$	$0.61 \pm 0.36/1.43$	$0.84 \pm 0.65/1.87$
Longitudinal deviation of the apex of the pilot borehole in the slave models compared with the master model (all data: mean \pm SD/max (mm)).			

Table 3. Total deviation of apex

	RoboDent system	DenX IGI system	Manual implantation
Apex	$0.60 \pm 0.20/0.92$	$0.94 \pm 0.40/1.88$	$1.89 \pm 0.80/2.95$
Total deviation of the apex of the pilot borehole in the slave models compared with the master model (all data: mean \pm SD/max (mm)).			

Table 4. Angular deviation of axis

	RoboDent system	DenX IGI system	Manual implantation
Axis deviation	$2.12 \pm 0.78/3.64$	$4.21 \pm 4.76/20.43$	$4.59 \pm 2.84/10.66$
Angular deviation of the axis of the pilot borehole in the slave models compared with the axis of the pilot bore hole in the master model (all data: mean \pm SD/max (deg)).			

drilling machines (Fortin et al. 2002). Alternatively, new templates can be created using stereolithography (Tardieu et al. 2003).

Basically, the systems that transfer a planning performed on volume image data to a surgical template perform the same task as the navigation systems in this study. However, the main advantage of the navigation system is that the implantologist has a higher flexibility. If the implant planning is to be changed, this is easily carried out in the planning system and immediately executed with the navigation system. If a template-based system is used, new bore-templates have to be produced. A basic assumption for this study was that a correctly placed pilot borehole would result in an accurate implant placement. We felt that this assumption was valid for two reasons: firstly, because in our clinical experience a pilot drill hole is a reliable guide for the subsequent dilation of the hole. Secondly, because the process of implant insertion is independent of the way the borehole direction was controlled and hence is beyond the scope of the systems used in this study.

Image-guided implant systems are based on a volume image data set, e.g. CT-scan. This is required for planning of the implants in the computer planning systems and also for later registration. The advantages of CT-image data for the proper planning of implants have been discussed in literature. It is superior to panoramic radiography in implant planning and assessment of risk-structures (Reddy et al. 1994; Lindh et al. 1995; Bou Serhal et al. 2001, 2002). The radiation dose could be considerably reduced but it is still higher than that of panoramic radiography (Hassfeld et al. 1998). The CT data can be used to measure distances, positions and bone mineral density (Hassfeld et al. 1998; Homolka et al. 2002). Implant size can be better planned (Schropp et al. 2001). The main advantage for planning is a proper representation of the alveolar ridge width. This is a very important factor for implant planning (Eufinger et al. 1997). Manual ridge mapping has proven to be inaccurate (Allen & Smith 2000). The main disadvantage is the irradiation exposure of the patient. Protocols reducing the dose of a CT-scan to doses comparable to panoramic radiography resulted in a poor image quality (Diederichs et al. 1996). The use of MRI was proposed

as well (Gray et al. 2003), but the imaging of the bone in negative contrast is not yet suitable for implant planning. However, in this study only accuracy was investigated, not the other benefits of 3D imaging and planning.

Recent studies for the assessment of implant position accuracy compared CT-image data (Brief et al. 2002a; Wanschitz et al. 2002b). For the evaluation of the boreholes created with the navigation systems or manually, a coordinate measurement machine was used in this study. The single-point accuracy of this device is 0.168 mm (annual maintenance report). For a reasonable comparison of the holes created with the reference holes in the master model, calculating the spatial difference of the entry and the apex point was not sufficient for two reasons.

Firstly it was not possible to compare the spatial coordinates of the entry point. By placing a borehole it was not possible to bring the tip of the digitizer arm to a definite position at the entry of the borehole, because there was no support by the 'bone' any more. When measuring a position in the entry of the borehole, we could not be sure, that we would always measure at the same height in this channel. However, in this way we could define the direction of the implant borehole from its apical point in the master model. Thus, in the slave models we could measure the lateral displacement of the implant's entry point orthogonally to this path. This is no limitation, because the longitudinal position of the entry point is defined by the alveolar ridge anyway. These restrictions did not apply for the apex of the borehole, because the bone was still underneath the apex to support the tip of the digitizer arm.

Secondly, a closer view of the error components along the axis of the implantation yielded more clinically relevant information. We could now give information about lateral error, depth error and angular deviation of the boreholes created with the systems.

Both systems investigated were based on the same concept of image-guided implantation, and they have a similar workflow. In the situation investigated, both systems proved to have a significantly higher accuracy than manual implantation. The absolute differences between the RoboDent system and the DenX system were not very high, and in our experience both navigation

systems are secure and reliable. The error found was in accordance with the data of non-commercial systems found in the literature (Birkfellner et al. 2000; Watzinger et al. 2001, 2002b; Meyer et al. 2003).

Both systems compared favourably to manual implantation: when we had a closer look at the data, we discovered two outliers with considerably worse accuracy in the results of the DenX system. They are marked as white diamonds (Figs 3–7). These two boreholes had been drilled in two different slave models at two different implant locations. The other boreholes in these models had not been that incorrect.

There are several factors that have an effect on the accuracy of image-guided interventions.

Imaging

Image quality affects the result at two points. Firstly, the surgeon makes the planning using the image data to assess the anatomic situation and to decide about the position of the implants. Secondly, image quality affects the quality of registration. An exact localization of fiducial markers in image data is a prerequisite for an accurate registration of the image data to the patient.

Navigation system

The accuracy of the navigation camera is important as well. During registration, it is used to locate the fiducials, and during surgery to determine the spatial relation between the drill and the patient's jaw. Commonly used infrared camera-based navigation systems have an accuracy of 0.3 mm approximately (Morris 2001).

Registration

For the transfer of preoperatively obtained image and planning data into intraoperative reality, registration accuracy is crucial. It depends on the accuracy of the localization of the fiducials in image data and reality. It also depends on a secure fit of the template in the patient's mouth during registration and surgery. The accuracy of the determination of targets (here: implant positions) depends on the accuracy of registration (Fitzpatrick et al. 1998).

Interaction

The system must guide the dental surgeon in an intuitive way (Wanschitz et al. 2002a). The information must be passed onto the user without delay.

If an error was made during the registration, a difference between the indicated and the real position during implantation would result. This is true for the patient-to-image registration as well as for the registration of the instrument. Furthermore, the systems work under the assumption that there is no change in the spatial relation between the one reference frame and the patient's jaw, or the other reference frame and the drill. If this relation was changed, e.g. by bending of the connectors to the reference frames or shift of the template in the patients' mouth, an error would result, even though all steps of registration had been performed correctly. However, the extent of error is not necessarily uniform. Erroneous registration can result in a still perfect positioning at one spot in the volume and gross misalignment at another point at the same time.

Another possible source of error is that the implantologist did not pay due attention to the otherwise correct indications of the system on the monitor. Technical faults like a bad calibration of the camera or the reference frame could also result in a non-uniform inaccuracy of the tracking. Retrospectively, the reason for the outliers could not be clearly attributed to the design of one system or to a possible mistake by the implantologist. This warrants the permanent verification of all circumstances during operation of these systems. Overreliance in the systems might result in less than optimal results. However, the observed inaccuracies of the two outlier boreholes was still in the same order of magnitude as the inaccuracies observed in manual implantation.

The intraoperative guidance of the implantologist was satisfactory with both systems. The small additional display of the RoboDent system that could be positioned close to the patient's head rendered some convenience to the implantologist. We felt that the intraoperative guidance from the graphical user interface of the IGI DenX system was slightly more intuitive.

The experience shows that in most clinical situations oral implants can be inserted without a guiding system for the transfer of preoperative planning. The accuracy is apparently sufficient for a successful outcome. However, there are situations where highly accurate implantation is mandatory:

when there is relatively little amount of bone available, so that malpositioning of the implant would result in perforation of the cortical bone, the mandibular nerve or the schneiderian membrane, systems for guidance of the implantologist can give additional safety.

However, template-based systems where the planning is merely based on a wax-up can only help to optimize the positioning of the implants for later prosthodontic treatment. Those template systems where the planning is based on volume image data as well can also help to take the hidden part of the anatomy into consideration. However, they still lack the flexibility of image-guided implantology based on a navigation system.

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Résumé

La précision de deux systèmes commerciaux pour l'insertion implantaire dentaire guidée par image basée sur des caméras de traçage infra-rouge a été comparée à l'implantation manuelle. Des fantômes de mandibules partiellement édentées ont été utilisés. Dans le fantôme principal des trous pilotes ont été forés à la fraise. Ces trous ont été reproduits dans les fantômes secondaires utilisant soit l'un des deux systèmes guidés soit le manuel. Les positions qui en résultaient ont été déterminées en utilisant une machine de mesure avec les coordonnées et comparées au modèle principal. En comparaison à l'implantation manuelle la différence dans les positions des trous vis-à-vis du fantôme principal était significativement plus faible en utilisant les deux types d'insertion implantaire guidée. L'insertion guidée par images d'implants dentaires est significativement plus précise que la manuelle. Cependant la précision obtenue avec l'insertion manuelle est suffisante dans la plupart des situations cliniques.

Zusammenfassung

Die Genauigkeit der bildgesteuerten Implantologie

Ziele: Die Genauigkeit von zwei kommerziell erhältlichen Systemen für die bildgesteuerte Implantatplatzierung, welche auf Infrarotleitkameras

basieren, wurde mit der manuellen Implantation verglichen.

Material und Methoden: Es wurden Modelle von teilbezahnten Unterkiefern verwendet. Im Meistermodell wurden Pilotbohrlöcher für dentale Implantate präpariert. Die Bohrlocher wurden in Zweitmodellen mit einem der bildgesteuerten Systeme und mittels manueller Implantation reproduziert. Die erreichten Positionen wurden mit einem Koordinatenmessgerät bestimmt und mit dem Meistermodell verglichen.

Resultate: Im Vergleich zur manuellen Implantation waren die Unterschiede in den Positionen der Bohrlocher, welche mit einem der Systeme zur bildgesteuerten Implantatplatzierung angebracht worden waren, signifikant kleiner.

Schlussfolgerungen: Die bildgesteuerte Platzierung von dentalen Implantaten ist signifikant genauer als die manuelle Implantation. Jedoch ist die Genauigkeit, welche durch manuelle Implantation erreicht werden kann, für die meisten klinischen Situationen ausreichend.

Resumen

Objetivos: Se comparó la precisión de dos sistemas comercialmente disponibles para la inserción de implantes dentales guiados por imagen basados en cámaras infrarrojas de seguimiento a la implantación manual.

Material y Métodos: Se usaron fantasmas de mandíbulas parcialmente edéntulas. En un fantomas maestro, se realizaron agujeros con fresas piloto para implantes dentales. Estos agujeros de fresas se reprodujeron en fantasmas esclavos usando los dos sistemas de imagen guiada y la implantación manual. Las posiciones resultantes se determinaron usando una maquina de medición de coordenadas y se compararon con el modelo maestro.

Resultados: En comparación con la implantación manual, la diferencia de las posiciones del agujero de la fresa respecto al fantomas maestro fue significativamente mas baja usando cualquiera de los sistemas para inserción de implantes guiada por imagen.

Conclusiones: La inserción guiada por imagen de implantes dentales es significativamente mas precisa que la inserción manual. De todos modos, la precisión que se puede lograr con la inserción manual es suficiente para la mayoría de las situaciones clínicas.

要旨

目的：赤外線トラッキング・カメラに基づく市販の画像誘導インプラント埋入システム2つを、手技による埋入と比較した。

材料と方法：下顎部分無歯顎の模型を用いた。主模型にパイロット・ボアホール（探索用穴）を作成した。2つの画像誘導システムと手技による埋入のいずれかを用いて、これらのボア・ホールを従模型に複製した。最終の位置は、座標測定装置を用いて決定し、主模型と比較した。

結果：手技による埋入に比べて、ボアホールの位置の主模型との違いは、いずれかの画像誘導インプラント埋入システムを用いた方が有意に低かった。

結論：画像誘導によるインプラント埋入の正確さは、手技による埋入よりも有意に高かった。しかしほとんどの臨床状況において手技による埋入によって達成できる正確さで十分である。

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