Abstract

Implant placement requires precise planning and execution to avoid collision with critical anatomical structures. Technology advances may improve placement outcomes. The purpose of this study was to trial and measure in an in vitro environment the accuracy of placing a single dental implant in the planned position using a specific guided surgery technique compared with a freehand surgery technique. The dental model of a patient missing tooth 16 was printed 30 times (EnvisionTEC 3Dent). Each print was scanned (TRIOS color scanner) to create a 3D surface model, and radiographed (Gendex CB-500) to create cone beam computed tomography (CBCT) data. The surface data and CBCT data were merged (Implant Studio software), and a Straumann RC bone level Ø 4.1 × 8 mm implant placement was planned. A surgical guide was printed (Stratasys OrthoDesk) for each case (n = 30). Simulated cases were assigned to Group A (guided) or Group B (freehand, where the fabricated guide was discarded). Implants were placed, and the models rescanned (TRIOS). The new data was superimposed on the original data, and the surgical implant location compared with the planned position for each model (Convince software) by a researcher blinded to group allocation. Differences in angulation (degrees); shoulder, apex, and depth displacements (mm); and direction of displacement were assessed with Mann-Whitney U and Fisher exact tests. Data was expressed as medians bounded by interquartile ranges (IQRs). Implant angulation and apical displacement were significantly closer to the planned position in the guided group compared with the freehand group (3.91 degrees: IQR 2.45 to 5.38 degrees vs 8.82 degrees: IQR 4.84 to 9.84 degrees, P = 0.005; and 0.87 mm: IQR 0.53 to 1.11 mm vs 1.48 mm: IQR 1.14 to 1.72 mm, P < 0.001, respectively). Implant shoulder displacement, depth displacements, and direction of displacement did not differ between the groups. Within the in vitro environment, merged 3D surface scan data and 3D CBCT scan data can be used to plan and guide implant placement with greater accuracy than with the freehand technique.

Keywords: cone beam computed tomography, computer-aided design (CAD), dental implants, three-dimensional imaging, three-dimensional surface scanning, patient care planning
Introduction

The surgical placement of dental implants has historically been performed with reference to 2D imaging techniques such as periapical radiographs and panoramic images, which only provided basic information about the bony anatomy and were subject to significant limitations such as distortion and magnification. The advent of 3D imaging in the form of computed topography (CT) and then cone beam computed topography (CBCT) has improved the imaging of anatomical structures. However, while identification of anatomical structures has become easier, there are still challenges in applying that information to the patient. For example, there are situations where the patient’s anatomy dictates a limited area for implant placement. Deviation from this position could result in the implant colliding with structures such as the inferior alveolar nerve or adjacent roots. These vital structures buried within the jaw are not readily visible; the operator therefore has to estimate the surgical approach. The accuracy of such estimations is influenced by the number and proximity of reference points to the surgical site. If there are many fixed reference points available in close proximity to the surgical site, the estimation is likely to be more accurate (eg, a one-tooth edentulous site with adjacent teeth on the mesial and distal surfaces). In situations where there are fewer references (sites with multiple missing teeth), the estimation is more challenging and is prone to error. In theory, the construction of a surgical guide will improve the accuracy of the implant placement by eliminating the intraoperative decisions.

With contemporary implant planning techniques, CBCT data and digital data are combined using computer software to plan implant locations in specific patient cases. The software is then used to design a surgical guide that takes into account the desired implant position relative to external patient structures such as the teeth. A typical guide would rest on the adjacent teeth in a definite position and utilize a sleeve through which drills would be inserted for osteotomy preparation. With ‘fully guided’ techniques, the drill position, angle, and depth are precisely controlled. The implant insertion is also performed through the channel to more precisely control the surgical process. Once the guide design is complete, it is manufactured using a 3D printing technique.1

Previous research has shown that drilling with surgical guides can significantly improve the accuracy of the osteotomy compared with freehand drilling for both experienced and inexperienced clinicians in in vitro models2,3 and in patients.4 There are also fewer deviations from the planned implant position using stereolithographic surgical guides compared with conventional ones.5 Another benefit is improved accuracy in implant placement through a guide compared with freehand placement.6

However, surgical guides do not perfectly translate the virtual implant position into reality. Deviations from the planned implant position still occur when stereolithographic guides are used for osteotomy procedures.2,7-9 In a study of 40 implants in six edentulous jaws, 85% of the implants were within 1 mm of the intended position.10 The mean coronal deviation has been shown to vary from 0.22 mm8 to 1.52 mm.11 This is more accurate than the mean apical position, which varies from 0.24 mm8 to 1.97 mm.11 There can also be inaccuracies in the implant angle, varying from 1.5 degrees8 to 7.9 degrees.12 Implant depths, both coronally and apically,9 have been found to be up to 0.38 mm from the planned implant height.9 Errors can be minimized by using shorter drills, reducing the diameter of the drill sleeves,13,14 and ensuring the guide is properly positioned.15

To date, a single one-patient case report16 has been published that describes the accuracy of surgical implant placement employing a surgical guide that used the combined data from digital surface scans and CBCT images.

The purpose of this study was to trial and measure in an in vitro environment the accuracy of placing a single dental implant in the planned position using a specific guided surgery technique and comparing this with a freehand surgery technique. The hypothesis of this study was that the use of a guided surgery technique enables more accurate implant placement than the freehand technique.

Materials and methods

A maxillary dental model with an unrestored dentition and single missing tooth 16 was chosen to represent a patient for this in vitro study. A total of 30 digital dental models of this case were manufactured using an EnvisionTEC 3Dent printer (EnvisionTEC, Dearborn, USA) and numbered sequentially from 1 to 30. A Consolidated Standards Of Reporting Trials (CONSORT) flow diagram representing the study design is outlined in Figure 1.17

Each printed model was scanned using a TRIOS color scanner (3Shape, Copenhagen, Denmark) to create a 3D surface model, simulating 30 patient cases. The model was scanned again using a Gendex CB-500 scanner (Hatfield, USA) to create a 3D CBCT scan.
Identification of an appropriate clinical case
Missing tooth 16, unrestored arch

Individual resin models printed as simulated patients (n = 30)
EnvisionTEC 3Dent printer
Resin models numbered 1 to 30

Resin models surface scanned as simulated patients (n = 30)
3Shape TRIOS color scanner
Virtual 3D surface model created (n = 30)

Resin models CBCT scanned as simulated patients (n = 30)
Gendex CB-500 scanner
Radiographic DICOM data (n = 30)

Virtual 3D surface model (n = 30) combined with the corresponding radiographic DICOM data (n = 30)
3Shape Implant Studio planning software
Virtual planning and surgical guide to place Straumann RC bone level, Ø 4.1 x 8 mm length (n = 30)

Individual stereolithographic surgical guide printing (n = 30)
Stratasys OrthoDesk

Group assignment (n = 30)
Allocation by one researcher. Other researchers were blinded.
30 case numbers were placed in a box and sequentially drawn out; the first 15 drawn were allocated to Group A (guided), and the remainder were allocated to Group B (freehand)

Group A: guided implant placement
Straumann protocol for fully guided surgery using the stereolithographic surgical guide (n = 13)
Two models fractured during implant placement (n = 2)

Group B: freehand implant placement
Visual reference to the planned implant position represented on the computer for each case. The stereolithographic guide was discarded (n = 13)
Two models fractured during implant placement (n = 2)

Blinded: simulated patient resin models (n = 26) surface scanned with an implant scan body attached
3Shape TRIOS color scanner
New virtual 3D surface model created (n = 26)

Blinded: new virtual 3D surface model (n = 26) combined via the reference number with the corresponding planned implant surface model (n = 26)
3Shape Implant Studio planning software
Final implant position compared with the planned implant position for the corresponding model, via the reference number
3Shape Convince comparison software

Blinded: analysis of angle difference, shoulder displacement, apex displacement, depth displacement, and direction of displacement between the final and planned implant positions

Revelation: of the data group allocation (guided n = 13, freehand n = 13) following analysis

Fig 1  CONSORT flow diagram of the study design.
The surface scan data and CBCT scan data for each individual model were entered into the Implant Studio planning software (3Shape). The data were processed according to the manufacturer’s instructions. This included an overlay of the CBCT and surface scan data and the positioning of a virtual dental implant. A Straumann RC bone level Ø 4.1 × 8 mm guided implant (Straumann AG, Basel, Switzerland) was used, and positioned within each of the 30 cases by two collaborating experienced clinicians. A specific prosthetic design was not used in this study. Instead, the clinicians aimed to center the implant in the edentulous space (mesiodistally and buccopalatally). The implant angle was planned to be parallel to the long axis of tooth 15. This location represents a normal clinical position for the implant. Measurements were made from this implant position to the adjacent teeth that could later be used in the freehand technique as reference points for placement.

A surgical guide was also designed to facilitate implant placement with the fully guided technique for Straumann implants for each planned case. The surgical guides were printed using a Stratasys OrthoDesk (Stratasys, Rehovot, Israel) and marked so that they could be matched to the correct model. A Straumann Ø 5-mm fully guided implant sleeve was placed in each surgical guide.

Following fabrication of the 30 surgical guides, all simulated cases were assigned to one of the two groups, Group A (guided) and Group B (freehand), by the researcher undertaking the surgery. This meant that only half of the fabricated guides were used. All 30 case numbers were placed in a box and sequentially drawn out. The first 15 drawn were allocated to Group A (guided), and the remainder to Group B (freehand). Other members of the research team were blinded with respect to the method used to place the dental implant in each of the 30 cases.

The implants in Group A were placed according to the Straumann protocol for fully guided surgery using the constructed surgical guide. The implants in Group B were placed without the use of the guide; the reference measurements from the planning process were used to locate the planned implant position and ‘guide’ the freehand drilling and implant insertion.

Following implant placement, differences between the planned and surgical implant positions were measured by a researcher who was blinded to the group allocation. A copy of the original intraoral scan was made to ensure that the new intraoral scan could be accurately superimposed on the original scan. The implant in each model had an Elos scan body (Elos Medtech, Gothenburg, Sweden) placed, and only the area of the implant/scan body was rescanned with the TRIOS color scanner to record the surgical implant position. Convince comparison software (3Shape) was then used to compare the final implant position to the planned implant position. This was accomplished by first aligning the new intraoral scan with the scan body and the planned implant position scan. As the vast majority of the intraoral scans were identical, the alignment was simple and accurate. The scan body was then identified and used to extrapolate the actual surgical implant position. Finally, the planned and actual implant positions were compared.

The location of both the planned and the final implant positions were computed by measuring the position of the implant shoulder, the position of the implant apex, and the angle of the implant body in three dimensions (X, Y, and Z planes) (Fig 2). Differences between the planned and final implant positions were quantified by calculating:

- Angle difference: the difference in angle between the planned and final implant positions.
- Shoulder displacement (mm): the absolute difference in location of the implant shoulder between the planned and final implant positions.
- Apex displacement (mm): the absolute difference in the location of the implant apex between the planned and final implant positions.
- Depth displacement (mm): the difference in the vertical depth of the implant shoulder between the planned and final implant positions.
- Direction of displacement (nil, occlusal, apical): whether the implant was displaced, and, if so, whether it was occlusal or apical to the planned final position in relation to the long axis of the planned implant position.

Following measurement, the group allocation was unsealed, and the data was collated into those where implants were placed with the surgical guide (Group A), and those where implants were placed freehand (Group B).

**Statistical analysis**

Data was expressed as medians bounded by an interquartile range (IQR). Differences in the planned and final implant positions between the guided and the freehand surgery groups were assessed. Analyses relating to angle differences, shoulder displacements, apex displacements, and depth displacements were undertaken with the Mann-Whitney U test.
Analyses relating to the direction of displacement were undertaken with the Fisher exact test. Significance was set at $P = 0.05$.

Results

Four 3D-printed models, two from each group, fractured during implant placement. These models were therefore excluded from the study. Differences between parameters are shown in Figure 3.

The difference in the angulation of the implants in Group A (guided) (median = 3.91 degrees, IQR 2.45 to 5.38 degrees) was significantly closer to the planned position than in Group B (freehand) (median = 8.82 degrees, IQR 4.84 to 9.84 degrees) ($P = 0.005$).

The difference in apical displacement of the implants in Group A (median = 0.87 mm, IQR 0.53 to 1.11 mm) was significantly closer to the planned position than in Group B (median = 1.48 mm, IQR 1.14 to 1.72 mm) ($P < 0.001$).

The difference in the shoulder displacement of the implants in Group A (median = 0.42 mm, IQR 0.33 to 0.48 mm) did not differ from the planned position significantly more than those in Group B (median = 0.57 mm, IQR 0.36 to 0.87 mm) ($P = 0.17$).

The difference in the depth displacement of the implants in Group A (median = 0.32 mm, IQR 0.13 to 0.41 mm) did not differ from the planned position significantly more than those in Group B (median = 0.17 mm, IQR 0.06 to 0.35 mm) ($P = 0.26$).

Three implants were displaced apically to the planned position in Group A compared with five in Group B. Ten implants were displaced occlusally to the planned position in Group A compared with eight in Group B. No implants had zero displacement. There was no difference between groups ($P = 0.673$) (Fig 4).

Discussion

This in vitro study has shown that a workflow is feasible where surface scans are combined with CBCT scans to produce a virtual implant planning environment and stereolithographic surgical guide. In this instance, the uptake of new technologies provided new opportunities to combine clinical and radiographic data, alter planning protocols, and communicate with team members in a virtual environment. The new workflow had the capacity to support implant placements that were as close or closer to the planned position as a freehand technique.

The guided and freehand techniques resulted in implant placements where the implant shoulder and vertical depth were statistically similar to each other. When considering the spread of the data (the IQR, which represents 25% to 75% of the data), error in placement across both groups ranged from as little as 0.06 mm, but could be up to 0.87 mm. As for the implant shoulder and vertical depth, neither group was consistently more accurate regarding placement in relation to the planned position; both groups achieved an excellent degree of precision. This is not surprising, as this portion of the osteotomy procedure is directly visible to the surgeon during both the guided and freehand techniques, especially in the in vitro environment. However, this is a pilot study and by definition could not be designed with the aid of a power analysis. This means that it is possible that the placement of implants did differ, but the difference was not detectable due to the pilot sample size.

The average difference in accuracy between the techniques of 0.15 mm in shoulder displacement (0.42 mm vs 0.57 mm) and 0.15 mm in depth displacement (0.32 mm vs 0.17 mm) is small. These potential differences in placement are arguably not clinically relevant. Therefore, it has to be questioned whether it would be worthwhile to allocate additional resources to determining whether these small differences are, indeed, mathematically different.
Fig 3  Differences in parameters between the planned and final implant positions when implants were placed with guided surgery or freehand surgery.

Fig 4  Presence and direction of displacement of implants placed during guided (n = 13) or freehand (n = 13) surgery, compared with the planned position.
The angle of the implant and the location of the apex were significantly closer to the planned implant position with the guided rather than the freehand technique. The difference between the average apical displacement of the implant from the planned position for the guided technique was 0.87 mm, compared with 1.48 mm for the freehand technique. Equally, the implant angle more closely represented the planned position when the implant was placed with the guided technique (which had an average displacement of 3.91 degrees) compared with the freehand technique (which had an average displacement of 8.82 degrees).

Both of these dimensions relate to the displacement of the 8-mm implant at its apical location. The presence of this difference is not surprising as it is the nonvisible position of the surgery, which is not directly visible to the implant surgeon using either technique. In these dimensions, the guided technique rather than the freehand one facilitates placement of the implant more closely to the planned position. This is consistent with other published data in both in vitro and in vivo environments. Additionally, it is likely that the difference in displacement would be magnified if longer implants were placed, and reduced if shorter ones were placed. The improvement in accuracy by using a surgical guide is clinically relevant; the implant surgeon can be confident that implants may be positioned satisfactorily where bone volume is limited and critical structures such as adjacent root surfaces need to be avoided.

When using the guided technique, the surgical position of the implant is not identical to the planned position. This is to be expected, as each step involved in producing the guide has an inherent tolerance and risk of error. These may relate to the TRIOS scanning, CBCT scanning, data correlation, and/or guide manufacture. Errors in each successive step would compound. However, despite these possible inaccuracies, this research has shown that this specific guided surgery technique facilitates implant placement closer to the planned position when compared with the non-guided freehand technique. This is an important result as it provides proof-of-concept evidence for this new surgical technique within the in vitro environment.

In this study, in data spread showed that the actual apex location of the guided implant could be as much as 1.11 mm away from the planned position. It is important to allow for appropriate leeway and safety margins when planning implant placement. This safety margin is a combination of bone volume required to maintain blood supply and the potential error of the technique. This study indicates that in cases where 1 mm of bone is needed around the implant, the amount of safety margin allowed should be 2.1 mm (1 mm for bone, and 1.1 mm for potential technique error). The Implant Studio software displays a zone around the planned implant position that replicates a ‘safety margin.’ This zone can be modified to suit user preferences, and to incorporate a margin of error appropriate to each clinical situation. For example, as further research is undertaken it may become apparent that the variance for the guided surgical technique differs between areas of the mouth, between implant lengths, or with operator experience; therefore, increased or reduced safety zones may become necessary.

There is greater potential for the implant apex to vary from the planned position when the freehand technique is used. In this study, in data spread showed that the actual apex location of the freehand implant could be as much as 1.72 mm away from the planned position. This means that the safety margin with the freehand technique has to be greater than with the guided one. Freehand implant placement is an appropriate clinical technique for a range of cases. However, when space is limited and greater certainty is needed, a guided technique offers increased confidence that the final implant location will more closely approximate the planned position. This then increases the number of clinical situations where implant therapy may be considered.

Overall, the average difference in accuracy between the techniques was 0.61 mm in apex displacement and 4.91 degrees in angle. Clearly, an unexpected displacement of 0.5 mm or 5 degrees could be critical in complex planning and placement. The displacement errors in this study, however, probably underestimate actual clinical situations. Access for implant components were unrestricted by patient opening, saliva, and soft tissue, maximizing the potential to place implants as close to the planned position as possible. Although this is beneficial for both techniques, it arguably especially benefits the freehand technique.

The use of a resin model to represent the patient is a limitation of this study. The structure of the model is not the same as a patient. Specifically, it is a homogenous block of resin rather than bone with cortical and trabecular structures. This creates both a different radiographic and drilling experience. It was more challenging to drill through the resin, as it required a slower technique to ensure that it did not chip or melt and adhere to the drill. During implant placement, two models from each group fractured. This was likely due to the brittle nature of the resin material. The fractures occurred at different stages of the experiment and were not clustered in a group.

The resin model was also less radiodense when viewed in the CBCT scan. While there was no movement of the model during scanning, the threshold for viewing the scan had to be lowered significantly when compared to viewing bone. The
smaller difference between the radiodensity of the resin and air made it more difficult to detect the exact position of the outer surface of the model, potentially causing a greater inaccuracy when aligning the CBCT scan to the surface scan data.

One of the limitations of the Straumann guided system is the need for longer drill bits. This, in turn, requires additional vertical space when performing an osteotomy. Not every patient would have sufficient mouth opening, especially in the second molar sites, to allow for the use of this system.

There are additional costs incurred when using this virtually planned and guided technique compared with the free-hand method, these being the software license to plan the implant position and the 3D surface scan, and the cost of fabrication of the surgical guide. The precise costs would vary between regions, but as history has shown they are certain to decrease with time. Despite these additional costs, the guided technique does provide for greater certainty in the final outcome, which can be invaluable in particular cases.

All new techniques are experimental by definition. This original study has provided baseline data that can be used for power analyses in future research, allowing the risk of type II errors to be minimized. This is essential for ethical study design in clinical settings. This study has also provided essential data for clinicians, confirming that the technique is feasible and is at least as good as freehand implant placement within the in vivo environment. Future research is required to confirm whether the techniques are equally satisfactory in the in vivo environment when multiple implants are required, when implants of different lengths are used, or when critical structures need to be avoided. Such research could include a clinical replication of the study. An in vivo study would address most of the limitations of this study with regard to anatomy structures, radiodensity of objects, and surgical access. However, there would be new, potentially confounding factors such as patient movement during CBCT scanning, which would complicate data assimilation and risk of error during implant planning. In addition, future research could involve an extension of the in vitro study to place two parallel implants to facilitate an implant-supported three-unit fixed dental prosthesis.

**Conclusion**

Within the in vitro environment of this study, implants might be placed in proximity to the planned position with both guided and freehand techniques. However, merged 3D surface scan data and 3D CBCT scan data can be used to plan and guide implant placement with greater accuracy than with the freehand technique.

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**References**


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In-vitro-Vergleich zwischen geführter und freihändiger Implantation: Verwendung einer aus Oberflächenscan, Implantatplanungssoftware, DVT und Stereolithografie kombinierten virtuellen Planungs- und Führungstechnik

Schlüsselwörter: digitale Volumentomografie, CAD, Dentalimplantate, 3-D-Bildgebung, 3-D-Oberflächenscan, Behandlungsplanung

Zusammenfassung

Hintergrund: Die Implantatsetzung erfordert eine exakte Planung und Durchführung, um Konflikte mit kritischen anatomischen Strukturen zu vermeiden. Technologische Fortschritte können die Implantationsergebnisse verbessern.


Material und Methode: Das Modell eines Kiefers mit fehlendem Zahn 16 wurde 30-mal 3-D gedruckt (Envisiontec 3Dent). Jede Kopie wurde gescannt (TRIOS Farbscanner), um ein dreidimensionales Oberflächensmodell zu generieren, und geröntgt (Gendex CB-500), um DVT-Daten zu erhalten. Für jede Probe (n = 30) wurden die Oberflächenscan- und DVT-Daten gemerkt (Implant Studio) und auf dieser Grundlage die Insertion eines Bone-level-Implantats (Straumann RC, 4,1 x 8 mm) geplant und eine Implantatschablone gedruckt (Stratasys Orthodesk). Die simulierten Fälle wurde auf die Gruppen A (geführ) und B (freihändig; die Schablonen wurden hier verworfen) aufgeteilt. Nach Insertion der Implantate erfolgte ein erneuter Oberflächenscan (TRIOS) der Modelle. Mittels Überlagerung der neuen und der ursprünglichen Daten wurde von einem für die Gruppenzuordnung verblindeten Untersucher für jedes Modell die tatsächlich erreichte Genauigkeit bei der Platzierung der Implantateposition verglichen. Unterschiede der Winkel-, Schulter-, Apex- und Tiefenabweichung (mm) sowie die Richtung der Abweichungen wurden mittels Wilcoxon-Mann-Whitney- und Exaktem Fisher-Test analysiert. Die Daten wurden als Medianwerte, beschränkt von Interquartilsabständen (IQA), aufbereitet.

Ergebnisse: Implantatneigung und Apexposition waren in der chirurgisch geführten Gruppe (A) signifikant näher an der geplanten Position als in der freihändig Gruppe (B) (3,91°, IQA 2,45°–5,38°, gegenüber 8,82°, IQA 4,84°–9,84°, p = 0,005, sowie 0,87 mm, IQA 0,53 mm – 1,11 mm, gegenüber 1,48 mm, IQA 1,14 mm – 1,72 mm, p < 0,001). Bezuglich der Implantatschulterabweichung, Tiefenabweichung und Abweichungsrichtung unterschieden sich die Gruppen nicht.

Schlussfolgerung: In der In-vitro-Situation lässt sich mit gemergten 3-D-Oberflächenscan- und DVT-Daten die Implantatsetzung mit größerer Genauigkeit planen und führen als mit einer freihändig Technik.