Accuracy of Implant Placement with a Navigation System, a Laboratory Guide, and Freehand Drilling

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Purpose: Computer-aided surgery under navigation system guidance is widely applied in dental implant procedures. However, the accuracy of drilling with such navigation systems has not been comparatively evaluated alongside those of laboratory guide-based and freehand drilling. Therefore, this study aimed to compare the accuracies of these three drilling systems. Materials and Methods: A navigation system, a laboratory guide, and freehand drilling were used to drill 150 holes on 30 cast models. Two master models—one each for the maxilla and mandible—were prepared with the idea of placing five implants per cast. After drilling five holes on each cast, postoperative cone beam computed tomography images were acquired to measure the magnitude of errors. Results: The navigation system and laboratory guide were more accurate than freehand placement with respect to total errors at the entry and apex, lateral error at the apex, and angular error. The navigation system was more accurate than the laboratory guide with respect to angular error. Laboratory guide-based drilling was more accurate than freehand drilling in terms of lateral error at entry. Conclusion: In comparison with the laboratory guide and freehand placement, the navigation system exhibited lower angular and axial errors. Despite its higher accuracy, the navigation system requires the operator to pay greater attention. INT J ORAL MAXILLOFAC IMPLANTS 2018;33:1213–1218. doi: 10.11607/jomi.6585

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Dental implant placement is a common treatment option for edentulous patients. However, poor implant positioning can cause serious complications, including maxillary sinus perforation and mandibular nerves.¹,² Computer-aided systems (CAS) are commonly employed for improving accuracy in dental implant placement. Several studies to date have compared the accuracies of different assisted surgery systems, including navigation systems, freehand placement, stereolithographic guides, and laboratory guides.³⁻⁷ Furthermore, some studies have also compared the accuracies of implant placement on different supporting structures, including tooth, bone, and mucosa.⁸⁻¹¹ However, to the authors’ knowledge, no study to date has compared the accuracies of implant placement using navigation systems, laboratory guides, and freehand drilling. This study compared the accuracies of the three drilling systems using seven different measurements of error relating to different angles. The findings of this study could serve as an accurate reference for clinicians intending to use these drilling systems.

MATERIALS AND METHODS

Preparation of Master Models

A set of cast models of the mandible and maxilla were used as the master models. To reduce the number of variables, the same targets were set for each system. Thus, 10 holes (3.5-mm diameter; 10-mm
depth) were drilled in the two master models to serve as targets, and each hole was embedded with a titanium pin (3.5-mm diameter; 20-mm length). For measurement of accuracy, two vacuum-formed splints—hereafter referred to as “measurement splints”—were attached to each of the master models, along with four ceramic balls each (3.0-mm diameter; SiN2, Emblem Asia Technology), to serve as measurement markers (Fig 1).

**Preparation of Drill Models**

A total of 30 replica cast models (15 each of the maxilla and mandible) were fabricated from the two master models. Using each system, predefined holes were drilled in five each of the replica maxillary and mandibular models.

For navigation system–guided drilling, two registration splints—different from the measurement splints—were fabricated for the maxillary and mandibular models, using a registration template and fiducial markers (Figs 2a and 2b). These splints were placed on the two master cast models and imaged by cone beam computed tomography (CBCT; AZ3000CT, Asahi Roentgen; voxel size, 0.15 × 0.15 × 0.15 mm). Then, preoperative planning software (Aq Navi, Taiwan Implant Technology Company) was used to plan the placement of five implants (3.5-mm diameter; 10-mm length) in the predrilled holes. For drilling with the laboratory guide, the five titanium pins placed on the master models were used to attach metal rings (6.1-mm diameter) to the targets. The rings were affixed to the vacuum-formed splints with dental resin (Figs 2c and 2d). For freehand drilling, the holes in the master models were replicated (Figs 2e and 2f) without any further modifications.

**Drilling**

**Navigation System.** Before drilling, the optical sensor of the navigation system was set to verify the correct position of the tracking zone (Fig 3a). For registration, the fiducial markers on registration splints were touched with the positioning tool. During drilling, the dentist followed instructions regarding location, angle, and depth displayed on the screen of the navigation system. The
coordinate system was defined along the buccolingual and mesial-distal axes, which allowed for intuitive operation (Fig 3b). The dentist took care to avoid blocking the optical sensor during drilling (Fig 3c).

**Laboratory Guide.** Laboratory guide-based drilling was performed with the aid of three different sizes of sleeves (outer diameter, 6.08 mm; length, 5.0 mm; internal diameters, 2.1, 2.9, and 3.6 mm; Fig 4a). The sleeve was placed on the laboratory guide before drilling (Fig 4b). The laser mark on the drill was used to guide the depth of drilling (Fig 4c).

**Freehand Placement.** The two master models were used as visual references for freehand drilling, with the laser mark on the drill being used to guide the depth of drilling.

**Drilling Protocol**
Drilling was performed according to the same protocol for all three methods: 2.0-mm pilot, 2.8-mm twist drill, and 3.5-mm final drill.

**Accuracy Measurement**
After drilling, CBCT images of the two master and 30 replica cast models were acquired with the measurement splints attached. Each image was analyzed using the preoperative planning software to identify the coordinates of the four measurement markers and five drill holes. Commercial software (SolidWorks 2012, Dassault System) was used to align the measurement markers on images of the master and experimental models (Fig 5) and measure the magnitude of error. Seven types of error, including total errors at entry and apex and angular error, were evaluated to analyze the discrepancies between the master and experimental models (Fig 6). The experimental procedure is summarized in Table 1.

**Statistical Analyses**
Differences in errors among the three systems were determined by one-way analysis of variance using commercial statistics software (IBM SPSS Statistics for Windows, Version 22.0, IBM). Levene’s test was performed to evaluate homogeneity within each type of measurement error for all three systems. Depending on the presence or absence of homogeneity, post hoc analysis was performed with Scheffé’s or the Games-Howell method, respectively.
RESULTS

Mean and Standard Deviation
The total errors at the entry point for drilling with the navigation system, laboratory guide, and freehand placement were 1.07 ± 0.48, 1.02 ± 0.46, and 1.44 ± 0.56 mm, respectively. The values of other measurement errors for drilling with the navigation system, laboratory guide, and freehand, respectively, were as follows: axial errors at entry—0.43 ± 0.31, 0.65 ± 0.46, and 0.69 ± 0.5 mm; lateral errors at entry—0.92 ± 0.51, 0.7 ± 0.38, and 1.14 ± 0.62 mm; total errors at apex—1.35 ± 0.55, 1.50 ± 0.79, and 2.00 ± 0.79 mm; axial errors at apex—0.44 ± 0.31, 0.71 ± 0.46, and 0.69 ± 0.51 mm; lateral errors at apex—1.23 ± 0.57, 1.25 ± 0.84, and 1.77 ± 0.84 mm; angular errors—4.45 ± 1.97, 6.02 ± 3.71, and 9.26 ± 3.62 degrees (Table 2).

Homogeneity
The three systems exhibited homogeneity (P > .05) in total and lateral errors at entry and apex (P = .419, .069, .088, and .058, respectively).

Heterogeneity
The three systems exhibited heterogeneity (P < .05) in axial errors at entry and apex and angular errors (P = .002, .003, and .001, respectively).

Comparison
The navigation system and laboratory guide exhibited lower total errors at entry (P = .001 and P < .001, respectively) and apex (P < .001 and P = .003, respectively) than freehand placement. The navigation system exhibited lower axial errors at entry (P = .017 and P = .006, respectively) and apex (P = .004 and P = .011, respectively) than the laboratory guide and freehand placement (P = .017 and P = .006, respectively). The laboratory guide exhibited lower lateral error at entry than freehand placement (P < .001). With regard to lateral error at the apex, the navigation system and laboratory guide performed better than freehand placement (P = .002 and P = .004, respectively). With regard to angular error, the navigation system performed better than both the laboratory guide and freehand placement (P = .027 and P < .001), while the laboratory guide performed better than freehand placement (P < .001).

DISCUSSION
The accuracy of drilling with the navigation system or laboratory guide was greater compared with that of freehand drilling, with no differences in total error between the former two methods. However, in terms of axial error at entry, the navigation system was more accurate than the laboratory guide and freehand placement. The lack of difference in axial error at entry between the laboratory guide and freehand placement might have been because both systems used a laser mark on the drill as a guide for depth control. Thus, human factors, such as dexterity, vision, and hand tremor, could cause inaccuracies in the depth of drilling. In contrast, the navigation system provided
real-time monitoring of the depth of drilling, based on
which, the dentist could decide the point at which to
stop drilling with more certainty.

Although there was no difference in lateral error at
entry between the navigation system and laboratory
guide, the latter exhibited the highest accuracy among
the three systems, which might be explained by the
difference in guidance method among the three sys-
tems. The laboratory guide holds the drill in place
throughout the drilling process, allowing the dentist
to simply follow the sleeve. In contrast, the navigation
system only provides instructions on the proper loca-
tion, which the dentist then has to manually locate—a
process that requires good hand-eye coordination.
Thus, dentists typically choose to first drill a pilot hole
and later modify the drilling path. As for freehand drill-
ing, dentists rely on a mental picture and preexisting
knowledge of anatomical structures to decide the
correct location. Hence, this method can also be influ-
enced by human factors.

With regard to total error at the apex, the naviga-
tion system and laboratory guide were more accurate
than freehand placement. Brief et al found the
drilling accuracy of the navigation system at the apex
to be greater compared with that of freehand drilling.
Similar to the present findings, Somogyi-Ganss et al
also found that the total and lateral errors at apex and
angular deviation of a dynamic CAS system were lower
compared with those of the laboratory guide.

It is interesting to note the differences in lateral er-
rors at entry and apex between the navigation system
and laboratory guide. With regard to lateral error at en-
try, the laboratory guide was more accurate than the
navigation system, while, with regard to lateral error
at the apex, the latter was almost as accurate as the
former. These differences in lateral errors can be ex-
plained by the difference in angular error between the
two systems. The angular error of the navigation sys-
tem was lower compared with that of the laboratory
guide and freehand placement, with the angular error
of the laboratory guide being lower compared with
that of freehand drilling. When drilling under naviga-
tion system guidance, dentists can modify the drilling
path based on real-time angular information from the
system. In contrast, with the laboratory guide, dentists
can only follow the guide during drilling. Moreover,
the laboratory guide exhibited two types of error: tol-
erance and manufacturing errors (Fig 7). While the ex-
tra tolerance in the sleeve-guide is inevitable, because
the space is necessary for circulation of cooling water
and rotation of the drill bit, the manufacturing error
depends on operator skill. These two factors could
possibly result in angular deviation. Furthermore, the
deeper the drilling, the greater the lateral deviation
caused by any angular error. During freehand drilling,
dentists need to control the drill path with reference to
the surrounding anatomical structures, which requires
experience.

The navigation system has several advantages, in-
cluding the possibility of flapless surgery, CBCT image
guidance, and real-time correction. Navigation
systems in implant treatment typically use CBCT im-
ger than two-dimensional (2D) images as basic
reference. Because they allow visualization of three-
dimensional (3D) space and exhibit greater accuracy
than 2D images, CBCT images are highly applicable
dental implant treatment. Identification of the
mandibular incisive canal (MIC) during pre-procedural
planning is critical in order to avoid injury during sur-
gery. This process can be reliably completed using
CBCT images. These images can help dentists obtain
more anatomical information before surgery, thus pre-
venting anatomical injuries—such as perforation and
nerve injury—by defining a safe range for the surgical
plan. Because CBCT provides information on bone
structure, navigation systems can use these data to
supply dentists with real-time images of the drilling
which allows them to modify the position and angle
of drilling to avoid injuries. Additionally, navigation
systems allow dynamic modification of the surgical
plan, thus providing flexibility for dentists, who would
otherwise have to spend time recreating the surgical
procedure. Possible sources of error in the navigation
system include CBCT images, the tracking system, the
registration process, and human factors.

Image quality plays an important role in the accu-

Fig 7 Tolerance of laboratory guide. (a) Sleeve tolerance error #1: the tolerance between metal ring and the outer diameter of the sleeve. (b) Sleeve tolerance error #2: the tolerance between inner diameter of sleeve and the drill.
of soft tissues.23 Because the surgical plan is based on the use of CBCT images in the navigation system,24,25 any distortion or error in CBCT images could lead to errors in planning. Distortion of CBCT images could also cause errors in registration, because the positioning of fiducial markers relies on CBCT images.

There were some limitations to the present study. This study used cast models to perform the drilling experiments. The cast models were ideal for quantifying accuracy, because there was no saliva, no blood or other clinical interferences when drilling, and the models were stable throughout the drilling. However, this model did not replicate important clinical issues, such as the different densities of bone and existing sockets, which would make stable and precise drilling more difficult. Besides, the process of this experiment could not eliminate the effect of operator experience on the results. Hence, the results of this study may vary in a clinical setting.

CONCLUSIONS

This study compared the accuracies of three drilling systems employed in dental implant placement—a navigation system, a laboratory guide, and freehand drilling. The navigation system and laboratory guide exhibited greater accuracy than freehand drilling. While the navigation system exhibited the best performance of all three systems in terms of minimizing axial and angular errors, the navigation system and laboratory guide exhibited comparable performance in minimizing lateral error at entry. Although the navigation system is more accurate, it requires greater time and attention from both the technician and dentist for appropriate setup.

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