The Influence of the Digitization Method on the Assessment of Accuracy and Reliability of Implant Placements

Ajitesh Singh
Marquette University

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THE INFLUENCE OF THE DIGITIZATION METHOD ON THE ASSESSMENT OF ACCURACY AND RELIABILITY OF IMPLANT PLACEMENTS

by

Ajitesh Singh, DDS

A Thesis submitted to the Faculty of the Graduate School, Marquette University, in Partial Fulfillment of the Requirements for the Degree of Master of Periodontics

Milwaukee, Wisconsin

May 2023
ABSTRACT
THE INFLUENCE OF THE DIGITIZATION METHOD ON THE ASSESSMENT OF ACCURACY AND RELIABILITY OF IMPLANT PLACEMENTS

Ajitesh Singh, DDS
Marquette University, 2023

Purpose: Studies investigating the accuracy of implant placement are utilizing different methods to digitize the post-operative implant position to compare it with the planned reference position. This study aimed to compare the influence on radiographic and digital methods in the accuracy of static computer-assisted and free hand implant placement.

Methods: In total, n=40 implants were placed either fully guided (n=20) or free-handed (n=20) in standardized mandible replicas. A static surgical guide was planned for the fully guided surgery group (FG) for an implant at the lower right first molar site and 3D printed. In the free-hand group (FH) the implant surgery was performed without a surgical guide after the planning was reviewed. Three different methods (CBCT, lab scanner [LS], and intra-oral scanner [IOS]) were used to digitize the actual implant position for both groups. Planned and actual position were compared using a treatment evaluation tool in the planning software. The angle deviation was defined as primary outcome parameter. Accuracy of FG and FH were statistically compared using ANOVA and the digitization methods (CBCT, LS, IOS) were compared with a paired t-test. Reliability of the methods was analyzed using Cronbach’s alpha method.

Results: All three methods (CBCT, LS, and IOS) showed acceptable agreements (Cronbach’s alpha of 0.7 and 0.9, respectively) for both groups. Significant higher accuracy (each p<0.001) in terms of angular deviation was detected for FG in comparison to FH

with a lab scanner (FG 1.76±0.71° vs FH 3.58±1.06°) or an intra-oral scanner (FG 1.58±0.96° vs FH 3.03±1.12°). While the angular deviation obtained with CBCT was also lower in the FG group (2.01±0.86°) than in the FH group (2.31±1.91°), the difference was statistically insignificant (p=0.44). There were no significant differences between radiographic and digital impression methods for FG. However, in FH, the difference between CBCT vs LS was statistically significant (p<0.001).

Conclusion: If studies aim to compare fully guided and freehand procedures, digital impressions appear to be more suitable for detecting differences, e.g., the use of an intra-oral scanner. Using pre- and post-op CBCTs for analyzing the accuracy of implant placement may require higher sample sizes to detect significant differences.
ACKNOWLEDGEMENTS

Ajitesh Singh, DDS

In no particular order I would like to sincerely thank all those who made this research possible. To Dr. Arndt Guentsch as my advisor and mentor on the project. This project could not have been completed with your guidance and insight. To Dr. Moawia Kassab for pushing me to be the best clinician possible and being a pilar of the periodontal program. To Dr. Vrisiis Kofina for helping me write this manuscript and continued guidance through the program over the past three years. To my family and Stephanie for the abundance of support and encouragement throughout the program. Finally, to my co-residents for the comradery and lifetime friendships made.
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Chapter 1
Introduction

The prevalence of tooth loss in the United States is widespread, with roughly 47% of the population missing dentition among adults 30 years old and over. Further analysis showed 2.2% of individuals ages 20 to 64 are fully edentulous (Javed, 2017.) This equates to roughly 180 million people missing teeth in the United States. Dental implant therapy has gained increasing acceptance as a treatment modality for the replacement of missing teeth. The rising popularity of dental implants can be attributed to several factors, which includes advancements in implant design and surgical techniques, allowing for convenience and patient satisfaction. In recent years dental implants procedures have become routine and their prevalence has been increased from 0.7% in 2000 to 5.7% in 2016. It is estimated that the prevalence will hit 17% by 2026 (Elani, 2018).

Although implants are often thought of as modern technology, their use can be traced back to ancient civilizations where various materials were used to replace missing teeth. Around 2500 BC, the ancient Egyptians made the first recorded attempts to repair missing teeth using objects like metal, seashells, and even animal teeth. These early implantation attempts failed to deliver long-term fixes due to unsuccessful integration with native bone. In other attempts to replace missing teeth, the ancient Romans invented the dental bridge in the fourth century AD. A gold band was attached to the remaining natural teeth and used to hold the artificial teeth to the dental prosthesis. Although this was a substantial advancement over earlier techniques, the bridges could still only be used to replace a short span of teeth and did not offer long term solutions. (Ring, 1985)
In the 1900s there were multiple iterations of primitive implant designs that eventually lead to the modern dental implant. In the 1930s orthopedic procedures were using materials such as vitallium alloy, which showed biocompatibility with native bone. This technology was borrowed and used by the Strock brothers who implanted vitallium screws in both humans and dog subjects. The procedures were successful in providing function of the missing dentition and set the path for future innovation. In the 1940s, scientists Formiggini and Zeponni developed a unique spiral stainless-steel design that allowed for the surrounding native bone to grow directly into the structure of the implant, resulting in a stronger and more stable foundation (Linkow, 1991).

In 1952, Dr. Per-Ingvar Brånemark, a Swedish orthopedic surgeon, incidentally discovered that titanium had the ability to integrate with bone tissue, a process later coined as osseointegration. This discovery was fundamental in the development of the modern dental implant allowing for biocompatibility and true integration with native tissue (Brånemark, 1983). In the following decades, Dr. Brånemark and his team developed and refined implant surgery techniques and implant designs. They introduced the concept of a fixture, which is the portion of the implant that is inserted into the bone, and an abutment, which connects the fixture to the replacement tooth. They also developed the two-stage implant surgery procedure, which includes a healing period between the placement of the implant and the attachment of the replacement tooth (Brånemark, 1985).

As implant technology advanced from Brånemark’s discovery in the 1950’s, attempts to define success were investigated. Multidimensional analysis resulted in the definition of implant success to encompass a combination of clinical, functional, and
biological parameters. In the 1980s Albrektsson introduced criteria to standardize the definition of implant success and guide clinical decision making in implant dentistry (Albrektsson, 1986). More recently, the Academy of Periodontology released a modernized criterion for implant success (Papaspyridakos, 2012):

1. Absence of persistent signs/symptoms such as pain, infection, neuropathies, paresthesia, and violation of vital structures
2. Implant immobility
3. No continuous peri-implant radiolucency
4. Negligible progressive bone loss (less than 0.2 mm annually) after physiologic remodeling during the first year of function ~1 mm
5. Patient/dentist satisfaction with the implant supported restoration

This modified Albrektsson criteria was changed to include patient satisfaction as a category for success and has been widely adopted in the field of implant dentistry (Papaspyridakos, 2012).

Multiple systematic reviews have verified the long-term success of dental implants with ranges from 94-97% success. (Jung, 2008; Lekholm, 1999; French, 2021). The success rate of dental implants has positively correlated with advancements in technology and methodology within the field of implantology. There have been significant advancements in optimizing workflow efficiency and ensuring reliable implant placement. Traditionally, radiographs were used to evaluate implant placement. However, radiographs have limitations, including a two-dimensional view resulting in a lack of depth perception. This makes it difficult to accurately assess the three-
dimensional position of the implant in relation to critical structures such as the sinuses, neurovasculature, and adjacent teeth (Greenstein, 2008).

In the late 1990s, cone beam computed tomography (CBCT) for dental implants became available. The technology made it possible to plan and place dental implants using precise three-dimensional imaging of the patient's dental anatomy and surrounding tissues. Computer-aided design/computer-assisted manufacturing (CAD/CAM) was developed to streamline the fully guided implant process. Implants could be virtually designed for the optimal prosthetic restoration, and overlayed with the CBCT to plan for the ideal surgical positioning. One of the key areas of development has been the use of optical imaging for the evaluation of dental implant accuracy after placement (Jacobs, 2011).

Radiographic and digital analysis includes verification through post-operative CBCT, laboratory scanner, and intraoral scanner. The lab scanner uses digital technology to produce an accurate and detailed three-dimensional image of the implant and surrounding anatomy. This image can then be compared to the original treatment plan to determine if the implant has been placed accurately. Comparatively, intraoral scanners employ optical technology to generate a three-dimensional image of the surgical site, which can then be compared to pre-operative ideal positioning. This technology offers the advantage of being performed chairside, eliminating the need for additional impressions for the lab scanner. Both lab scanners and intraoral scanners are non-invasive and produce results rapidly, making them highly convenient tools for evaluating dental implant accuracy (Schou, 2009; Karoussis, 2001).
Chapter 2
Review of Literature

Malpositioned implants have negative clinical implications, including poor esthetics and lack of functionality (Chen, 2007). These undesired outcomes can be limited by the use of computer-assisted implant surgery to achieve the prosthetically ideal position (Gargallo-Albiol, 2020). The introduction of CBCT has allowed practitioners greater insight into the anatomy and dimensions of the surgical space to ensure more accurate outcomes (Marlière, 2018). The CBCT can be paired with an intraoral scan to produce CAD/CAM 3D printed static guides for surgical placement. In fully-guided cases, the osteotomy is completely prepared with the static guide, and the implant is also placed through the guide. In freehand placement, there is no use of a static guide. The osteotomy and implant placement are dependent on the practitioner’s perceptual ability and understanding of the edentulous space. Implant placement requires a specific location in three-dimensional space for long term success. In a tooth bound space, the adjacent teeth are used as landmarks for implant placement ensuring at least 1.5mm of space from the implant and natural tooth and 2-3mm below the adjacent cemento-enamel junctions. (Vela, 2018)

Improper treatment planning of implant placement can result in surgical complications, such as incorrect angulation and placement. This can cause negative outcome by compromising anatomy and leading to perforation of cortical plates, impingement of nerves, damage to adjacent roots, or perforation to the sinus (Tatakis, 2019). Additionally, the improper placement can compromise the prosthetic outcome, leading to unfavorable esthetics or loading (Chen, 2007). Uneven forces on the implant
can result in premature bone loss and compromise the longevity of the implant. (Esposito, 1998)

Whether the implant is placed fully-guided or freehand, there are several different methods to measure the accuracy of the implant after it has been placed. Accuracy is defined as the combination of trueness and precision. The international organization for standardization (ISO) defines “trueness” as the closeness of agreement between the arithmetic mean of a large number of test results and the true or accepted reference value. "Precision" refers to the closeness of agreement between test results (ISO 5725-1:1994).

The accuracy and clinical performance of static computer assisted implant systems was investigated by Tahmaseb et al. in 2014. Twenty-four studies were included in a meta-analysis which revealed statistical significance between fully-guided and freehand implant placement at the entry point of implant insertion. The fully-guided group showed superior accuracy with a mean deviation of 0.78 mm in 1011 implants and the freehand group showed mean deviation of 1.38 mm in 868 implants. (Tahmaseb, 2014).

Along with bodily deviation, angular deviation is also a critical parameter of concern with implant placement. Younes et al. published a randomized controlled trial in 2018 that compared groups of fully guided, pilot-guided, and freehand implant placement in partially edentulous patients. A total of 71 implants were placed, and the results showed that fully-guided implants had the highest accuracy. Fully-guided implant placement had a mean angular deviation of 2.30°, while freehand placement resulted in a mean angular deviation of 6.99° (Younes, 2018). Recently, Varga et al. reported a randomized controlled trial evaluating the mean accuracy of free-hand vs guided
protocols including pilot, partial, and fully guided implant placement. Two-hundred and seven implants were placed and assessed for actual position vs planned position. Angular deviation showed the largest mean deviation in the free hand group (7.03°). Angular deviation gradually decreased with an increasing amount of guidance. The smallest deviation was seen in the fully guided group (3.04°). Coronal and apical deviation were also evaluated and followed the same pattern of decreasing deviation with increased guidance (Varga, 2020).

For accuracy assessment after implant placement, radiographic techniques are frequently utilized to assess the clinical accuracy. In this method, two CBCT scans are performed on each patient, one prior to implant surgery and one after implant surgery. A reconstruction software program is employed to analyze deviations between the ideal and postoperative implant positions. The validity of the implant position evaluation is significantly influenced by the quality of CBCT images, which may be degraded by factors such as image artifacts, patient movement, and scan parameter settings (Schriber, 2020). Additionally, the use of post-operative CBCT creates excess radiation exposure for patients. Without a direct patient benefit, postoperative imaging of dental implants by CBCT cannot be justified, apart from ethically permitted clinical research (Hämmerle, 2015).

To circumvent the drawbacks of radiographic methods, non-radiographic techniques have been introduced, including digital methods using optical scanners. Digital dental models can overcome certain drawbacks associated with plaster models and additional CBCTs, such as patient discomfort and vulnerability. Being also advantageous in terms of cost, time, and space required, digital models are quickly
becoming the new standard in clinical practice. Currently there are two ways to generate a digital 3D model: direct intraoral digital impression with an intraoral scanner and extraoral scanning of conventional plaster casts or impressions (Shely, 2021). In an in vitro experimental study, the accuracy of seven common extraoral scanners (Sirona ineos inLab, Sirona X5, Dentium, Imes Icore 350I, Amann Girrbach, 3shape D700, and 3Shape E3) were evaluated. Statistical analysis showed the best trueness was for 3Shape E3 scanner with the average of 35.37µm (Vafaee, 2021). In another study, impressions were obtained via two conventional and seven digital impression systems. Digital quadrant impression methods achieved a level of precision, comparable to conventional impression techniques. Time efficient capturing of impressions was possible with all tested digital impression systems. The clinical precision of digital quadrant impression models was sufficient to cover a broad variety of restorative indications (Ender, 2016).

Optical scanning enables the evaluation of implant positioning by using a scanbody, creating a digital impression which can then be compared to the pre-surgical implant planning (Marques, 2021). Jan van Hooft et al. conducted an evaluation on the accuracy of 23 fully-guided implants immediately post-placement. The evaluation was completed utilizing a CBCT, an intraoral scan (IOS), and scan abutments. The achieved implant positions were compared to the planned implant positions using both postoperative CBCT and intraoral scans. On the mesiodistal plane, the mean differences between the CBCT and IOS methods were 0.09 mm (p = 0.419) at the tip, 0.01 mm (p = 0.910) at the shoulder, -0.55° (p = 0.273) in angulation, and 0.2 mm (p = 0.280) in implant depth. Meanwhile, on the buccolingual/buccopalatal plane, the mean differences were 0.25 mm (p = 0.000) at the tip, 0.12 mm (p = 0.011) at the shoulder, -0.81° (p =
0.002) in angulation, and 0.17 mm (p = 0.372) in implant depth. Significant differences were noted at the tip, shoulder, and angulation on the buccolingual/buccopalatal plane (p < 0.05); however, no significant difference was found in implant depth deviation. Though these results showed statistical significance in several categories, they indicate minimal clinical significance. However, this does support the hypothesis that a postoperative IOS is a valid alternative for determining implant placement accuracy (van Hooft, 2022).

Cristache et al. inserted 65 dental implants in the mandible and maxilla and a digital impression was taken postoperatively. An inspection tool software was utilized to measure the 3D inaccuracies of the implant position at the entry point, apex, and angle deviation.

The mean and standard deviation of the 3D error at the entry point was 0.798 mm (±0.52), and at the implant apex was 1.17 mm (±0.63). The majority of the superimposed surfaces suggested a high level of accuracy between the treatment plan model and the actual placement of the implants. However, to date there has not been a study to compare the influence of radiographic (CBCT) and the digitization methods (laboratory scanner vs. intraoral scanner) on the assessment of the accuracy of implant placement when comparing fully-guided and freehand implant placement. We hypothesize that the registration method has no influence on the assessment of implant placement accuracy.
Chapter 3
Materials and Methods

The study conducted an in-vitro protocol using a clinical case of a patient with a toothless space in the #30 site. The study followed proper ethical guidelines by obtaining Institutional Review Board (IRB) approval for the use of CBCT data from a patient for research purposes. The study obtained data from CBCT of a partially edentulous patient for the purpose of fabricating replica models of the mandible. The CBCT data was converted to a Standard Tessellation Language (STL) file format and prepared for three-dimensional printing using PreForm 3D Printing Software and a Form 3B Printer. Researchers printed 40 identical mandibles using Formlabs Grey Resin v4 (Formlabs Inc., Somerville, MA, USA). Digital implant planning was completed using coDiagnostix software (Dentalwings, Chemnitz, Germany) and a prosthetically-driven implant position was planned for a single unit implant supported crown. A single operator placed n=40 implants using either a fully-guided or freehand approach without a static surgical guide. For the fully guided group, a surgical guide was designed and printed using Formlabs Surgical Guide v1 Resin. The guide was then placed in Form Wash for cleaning and light-cured with Form Cure.

<table>
<thead>
<tr>
<th>Straumann® GuidedSurgery sleeve</th>
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<tbody>
<tr>
<td>Position</td>
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Figure 1: Straumann Guided Surgery Protocol produced from the implant planning software coDiagnostix
Osteotomy preparations were performed using a W&H Dental Implant Motor SI-915 (W&H Group, Burmoos, Austria) and handpiece, following manufacturer recommendations for the standard fully guided system (Straumann BLT; Straumann AG, Basel, Switzerland) using a sequential drilling approach (Figure 1). Each osteotomy was prepared fully guided using the corresponding drill handles inserted completely into the guide. Any debris were removed from the osteotomy site using compressed air. The same protocol was repeated for each implant placed.

To start, the coronal Ø 2 mm of the osteotomy site was flattened with the Ø 3.5 mm milling cutter and Ø 3.5 drill handle. The initial osteotomy was started with a Ø 2.2
mm extra-long twist drill and Ø 2.2 drill handle, which would allow the implant to fully seat in the dense resin model. The Ø 2.8 mm long twist drill with a 2.8 drill handle was used to widen the osteotomy followed by a Ø 3.5 mm long twist drill and a Ø 3.5 drill handle (Straumann AG, Basel, Switzerland). The osteotomy was completed with the 3.5 mm profile drill and C-Handle followed by a Ø 3.5 mm guided bone tap for final preparation. With the osteotomy completed a Straumann BLT 4.1 x 10 mm implant was placed through the guide, using the guided implant transfers until the planned the H4 position was reached. A total of n = 20 4.1 x 10 mm implants were placed.

In freehand placement the operator had access to the virtual planning for orientation. The implant osteotomy is performed without a surgical guide following the same drilling sequence as the fully-guided group per Straumann BLT protocol. A total of n = 20 4.1x10mm implants were placed freehand. Upon completion of implant placement, a Straumann Cares RC MONO Scanbody 4.1 x 10 mm (Straumann AG, Basel, Switzerland) was hand torqued into position on all implant fixtures for both fully-guided and freehand groups for analysis with the digitization methods.

*Figure 3. (Left) Full-guided protocol with 3.5mm twist drill, (Right) Freehand protocol with 3.5mm twist drill*
The following two groups represent the fully digital registration method:

- **Group A:** A laboratory scanner was used to digitize all n=40 implants (fully-guided and freehand)
- **Group B:** An intraoral scan of all n=40 implants (fully-guided and freehand)

The 3Shape E3 laboratory scanner (3Shape, Copenhagen, Denmark) was employed to digitize all 40 mandibles. The scanner outputted an STL file for each mandible. In addition to the lab scanner the same steps were taken using the Planmeca Emerald S intraoral scanner (Planmeca, Helsinki, Finland). The mandibles were scanned and processed through Romexis to generate the STL files which were also used to compare to the ideal virtual planning.

For both the lab scanner and intraoral scanner, the imported STL file was subjected to analysis in coDiagnostiX software. The planned implant position was superimposed onto the actual position using a best-fit algorithm. The best-fit algorithm chose identical, unaltered fixed points on each mandible replica for its analysis. The standardization of these points ensured consistency across all trials. This process allowed for the identification of the three-dimensional positioning of the placed implant in the mandible.

Using the coDiagnostiX treatment evaluation tool, the angular and 3D deviations at the implant crest and apex, as well mesio-distal, bucco-lingual, and apical deviation. All n=40 mandibles were subject to a post-operative CBCT. The next group represents the radiographic assessment method:
• Group C: Investigator (AS) aligned the post-operative CBCTs with the planned implant position in the pre-operative CBCT.

The Viso G-7 CBCT (Planmeca, Helsinki, Finland) was used with the following parameters: XS patient size, teeth field of visualization, 90 kV, 71 mAs, 150 µm, and artifact reduction algorithm.

The DICOM files were then imported to the coDiagnostiX software where the scans were used to manually superimpose the actual placement over the ideal to investigate angular deviation as the main variable being investigated. An example of the implant position relative to the planned implant position, as well as the measurements for each placed implant, can be seen in Figure 5.
Figure 5. A) Shows an example of a merged CBCT with a placed implant with the virtually planned implant position. A virtual implant template (red outlined) has to be manually superimposed over the implant fixture. The evaluation software will compare the actual implant position with the virtually planned position (blue outline) and will deliver the respective 3D-deviations. (B) This is a representative example of a lab scan of a mandible with a scan abutment that is then merged with the virtual planning.
Statistical Analysis:

A previous study (Guentsch, 2020) showed that a sample size of each n=20 achieves a statistical power from 91% when fully-guided vs. freehand single implant placement were compared. This suggests that the same sample size should be used for the proposed study with the p-value ≤ 0.05 and an effect size being 0.42, provided 80% power using ANOVA.28. Means, standard deviations, and 95% confidence intervals were calculated for trueness and precision using IBM SPSS Statistics 27 (IBM, Armonk, USA). The primary outcome was the difference in angular deviation between where the implants were physically placed versus where they were virtually planned, called the three-dimensional trueness. Secondary outcomes included three-dimensional deviation in the bucco-lingual, mesio-distal, and corono-apical directions at the crest and at the apex. These values were compared between the groups, which represents the three-dimensional precision. Tertiary outcomes included the reliability of the intragroup values.

Figure 6. Planned versus placed implant position and corresponding measurements
The means, standard deviation, and 95%-confidence intervals were analyzed statistically with 1-way ANOVA and the Scheffe procedure. The ANOVA-1 represents the trueness, and the Scheffe procedure represents the precision. The intra-operator reliability was calculated using Cronbach’s alpha.
Chapter 4
Results

This study examined the accuracy of implant placement with fully-guided (FG) and freehand (FH) placement using three different methods: lab scanner (LS), intraoral scanner (IOS) and cone-beam computed tomography (CBCT) for post-operative analysis. The results showed significant differences among the three groups for angular deviation from ideal implant placement.

Fully-guided implant placement showed significantly higher accuracy than freehand placement for both lab scanner (FG 1.76±0.71° vs FH 3.58±1.06°) and intraoral scanner (FG 1.58±0.96° vs FH 3.03±1.12°) post-operative analysis. The CBCT comparison showed lower deviation in the FG group (2.01±0.86°) than in the FH group (2.31±1.91°), but the difference was not statistically significant. There were no significant differences between radiographic and digital impression methods for full-guided groups. However, in freehand placement, the difference between CBCT vs lab scanner was statistically significant (Figure 7).

![Figure 7. The intergroup comparison all three methods of testing accuracy showed no statistical significance the fully-guided placement. In the freehand group significance was found between the CBCT group and the lab scanner](image-url)
For 3D deviation of the implants, the crestal measurements of 3D offset showed statistical significance for FG (0.25±0.09 mm) vs FH (0.55±0.19 mm) among the lab scanner groups. Crestal mesio-distal measurements showed statistical significance for the FG (0.19±0.17 mm) vs FH (0.55±0.27 mm) for the CBCT groups. Crestal bucco-lingual and corona-apical measurements showed no significance among the groups.

For Apex 3D measurements, statistical significance was observed for the FG (0.48±0.18 mm) vs FH (1.05±0.33 mm) among the lab scanner groups. Apex measurements in the mesio-distal, bucco-lingual, and corono-apical direction showed statistical significance for the FG (0.28±0.22 mm, 0.24±0.24 mm, 0.13±0.09 mm) vs FH (0.68±0.28 mm, 0.63±0.35 mm, 0.35±0.14 mm) lab scanner groups, respectively. Apex measurements in the mesio-distal direction also showed significance for the FG (0.26±0.20 mm) vs FH (0.70±0.29 mm) CBCT groups.

Regarding the precision the highest mean angular deviation was seen in the freehand CBCT group while the lowest deviation was found in the fully-guided lab scanner groups.

Fully-guided implant placement showed significantly higher accuracy than freehand placement for both LS (FG 0.81±0.62° vs FH 1.25±0.95°) and CBCT (FG 0.99±0.75° vs FH 1.42±0.97°) groups during post-operative analysis. Crestal three-dimensional offset was statistically significant for FG (0.10±0.07 mm) vs FH (0.23±0.17 mm) in the lab scanner groups. Crestal measurements in the mesio-distal direction showed statistical significance in FG (0.11±0.07 mm, 0.17±0.12 mm, 0.25±0.20 mm) vs FH (0.28±0.20 mm, 0.40±0.28 mm, 0.32±0.22 mm) for lab scanner, intraoral scanner, and CBCT groups. Crestal bucco-lingual measurements showed statistical significance in FG
(0.13±0.10 mm) vs FH (0.27±0.19 mm) lab scanner groups. Crestal corono-apical measurements showed statistical significance in FG (0.35±0.40 mm) vs FH (0.15±0.11 mm) intraoral scanner groups. Apex three-dimensional offset was statistically significant for FG (0.20±0.15°) vs FH (0.39±0.31°) lab scanner groups. Apex measurements in the mesio-distal direction showed statistical significance in FG (0.35±0.25 mm) vs FH (0.0.46±0.33 mm), for intraoral scanner groups. Apex bucco-lingual measurements showed statistical significance in FG (0.28±0.22 mm) vs FH (0.43±0.31 mm) lab scanner groups. Apex corono-apical measurements showed statistical significance in FG (0.34±0.40 mm, 0.34±0.36 mm) vs FH (0.16±0.12 mm, 0.23±0.19 mm) intraoral scanner and CBCT groups.

Investigation into the reliability of the two digital methods with each other but also to compare the digital methods with the radiographic methods was analyzed by Cronbachs alpha. All three methods (CBCT, LS, and IOS) showed acceptable agreements (Cronbach’s alpha of 0.7 and 0.9, respectively) for the fully-guided and freehand group.
Figure 8. Angular deviation for the fully-guided protocol analyzed by three verification methods: lab scanner, intraoral scanner, CBCT.

Figure 9. Angular deviation for the freehand protocol analyzed by three verification methods: lab scanner, intraoral scanner, CBCT.
Table 1. Trueness as deviation from the original planned implant position of fully-guided and freehand implant placement each assessed by lab scanner, intraoral scanner, and CBCT.

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<tr>
<th>Trueness</th>
<th>FH_LS</th>
<th>FH_IOS</th>
<th>FH_CBCT</th>
<th>FG_LS</th>
<th>FG_IOS</th>
<th>FG_CBCT</th>
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<td>As difference to the reference value (Comparing actual vs. planned implant position, n=20 implants each group)</td>
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<tr>
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<td>3.03*</td>
<td>2.31</td>
<td>1.76*</td>
<td>1.57*</td>
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<tr>
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<td>0.21</td>
<td>0.09</td>
<td>0.16</td>
<td>0.27</td>
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<td>0.39</td>
<td>0.70*</td>
<td>0.28*</td>
<td>0.37</td>
<td>0.26*</td>
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<td>&lt;.001</td>
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<td>(0.23-0.53)</td>
<td>(0.56-0.83)</td>
<td>(0.17-0.38)</td>
<td>(0.22-0.5)</td>
<td>(0.17-0.36)</td>
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<td></td>
<td></td>
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<tr>
<td>Mesio-distal</td>
<td>0.63*</td>
<td>0.49</td>
<td>0.34</td>
<td>0.24*</td>
<td>0.28</td>
<td>0.38</td>
<td>4.92</td>
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<tr>
<td>Bucuo-lingual</td>
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<td>0.3</td>
<td>0.19</td>
<td>0.13*</td>
<td>0.22</td>
<td>0.31</td>
<td>3.69</td>
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<tr>
<td></td>
<td>(0.28-0.41)</td>
<td>(0.23-0.35)</td>
<td>(0.11-0.26)</td>
<td>(0.09-0.17)</td>
<td>(0.08-0.36)</td>
<td>(0.19-0.43)</td>
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</table>

*statistically significant difference between corresponding fully-guided and freehand group
Table 2. Precision as distances between datapoints of the actual delivered implant position as found by the lab scanner, intraoral scanner, and CBCT

<table>
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<tr>
<th>Precision</th>
<th>FH_LS</th>
<th>FH_IOS</th>
<th>FH_CBCT</th>
<th>FG_LS</th>
<th>FG_IOS</th>
<th>FG_CBCT</th>
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<tr>
<td></td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
<td>Mean</td>
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<tr>
<td>(SD)</td>
<td>[1.11-1.38]</td>
<td>[1.17-1.45]</td>
<td>[1.26-1.54]</td>
<td>[0.72-0.90]</td>
<td>[1.02-1.25]</td>
<td>[0.88-1.09]</td>
</tr>
<tr>
<td>[95%-CI]</td>
<td>[0.24-0.3]</td>
<td>[0.25-0.31]</td>
<td>[0.09-0.11]</td>
<td>[0.21-0.29]</td>
<td>[0.24-0.32]</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Sleeve-Bone Distance</th>
<th>4 mm</th>
<th>F-value</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle (degree)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( \Delta 3D )</td>
<td>0.23*</td>
<td>0.28*</td>
<td>0.10*</td>
</tr>
<tr>
<td>Mesio-distal</td>
<td>0.81*</td>
<td>0.32*</td>
<td>0.25</td>
</tr>
<tr>
<td>Bucco-lingual</td>
<td>0.27*</td>
<td>0.29</td>
<td>0.13</td>
</tr>
<tr>
<td>Corono-apical</td>
<td>0.16</td>
<td>0.23</td>
<td>0.19</td>
</tr>
<tr>
<td>Apex (mm)</td>
<td>0.39*</td>
<td>0.36</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*statistically significant difference between corresponding fully-guided and freehand group
Chapter 5
Discussion

This study aimed to assess the accuracy of implant placement in vitro. Angular deviation was used as the primary outcome parameter. Computer assisted implant placement with the use of a static guide was compared to freehand implant placement. The goal was to determine if there are differences in evaluating implant angular deviations by using traditional radiographic (CBCT) and digital registration methods (lab scanner, intraoral scanner).

When assessed using both the lab scanner and the intraoral scanner, our findings revealed that the fully-guided group exhibited significantly higher accuracy than the freehand group. Although the fully guided CBCT group demonstrated less angular deviation than the freehand group, this difference was not statistically significant. Intergroup comparisons for the fully guided group showed no significance, indicating that all three methods tested are viable options to check for accuracy. In the freehand group, the lab scanner demonstrated greater detail and variation in angular deviation within the same model when compared to CBCT (3.58° vs 2.31°, p < 0.05). This highlights the superior capability of the lab scanner method to capture more detail when measuring the angular deviation. When comparing the intraoral scanner to the CBCT, there was no statistical significance seen in angular deviation measurements. Based on these results, our study supports the use of digital registration models, either lab scanner or intraoral scanner, for both freehand and fully-guided implant placement, and the null hypothesis was rejected.
Traditionally the method of choice for comparing post-surgical placement of the implant in three-dimensional space was a CBCT. In modern times, the disadvantages of CBCT have become more apparent and include unnecessary radiation exposure, higher patient cost, and image distortion due to artifacts (Hämmerle, 2015). Validating the accuracy of digital methods can allow clinicians to overcome the need for a post-surgical CBCT, saving the patient increased radiation exposure and costs.

In traditional CBCT scans, it has been shown that an accuracy for voxel superimposition greater than 0.2 mm is difficult to achieve (Fokas, 2018; Schnutenhaus, 2018). This is often due to the quality of the image obtained, due to the metallic nature of the dental implants, artifacts such as beam hardening are unavoidable, and reduce the image exactness (Naitoh, 2013). Beam hardening occurs due to high-density of the dental implants. Only the most intense x-rays can penetrate the material, which creates the appearance of shiny bands. Additionally, if two implants are placed next to each other, the area between them can appear with dark bands (Schulze, 2011). These artifacts cause difficulty with finding the exact outline of the implant (Terrabuio, 2021). The ambiguity of the outline then creates a situation where the confirmation of the implant position is subjective. In order to compare the direct implant position pre and post operatively, at least three or more identical reference points are needed (Maes, 1997). Since the references are subjectively selected, an inherent error is introduced.

The lab scanner used in this study has an accuracy rating of 4 μm according to the manufacture (3Shape), which is more accurate than the CBCT. In an in vitro setting, digital lab scanners have been shown to be more accurate than intraoral scanners.
However, other studies have shown no significant difference between implant positions when comparing the two digital methods to one another (Zhou, 2020).

The overall angular deviation in all three of the fully-guided groups is lower than that of the freehand groups, this was statistically significant in the intraoral and lab scanner groups, but not in the CBCT group. The static guide limited the amount of deviation and allowed more accurate placement of the implant in the desired position.

When looking at the freehand implant placement, the lab scanner was able to show higher detail than the CBCT method in verifying post-operative implant position. The intraoral scanner was able to show a similar level of detail than the CBCT. This demonstrates that digital methods can produce the same or higher level of detail than the traditionally used CBCT method.

With fully-guided implant placement, there were no differences in angular deviation for all three methods. This indicates that the digital methods are as useful as the traditional CBCT for post-operative analysis when using a static guide. We can conclude that the digital methods of post-surgical implant placement are viable options to check the accuracy of single site implant placement, regardless of placement with a guide or freehand.

As discussed, the use of pre-operative and post-operative CBCT has been well documented but a shift in digital verification has become more widespread.

Our results are in agreement with a previous study done by Derksen et al. who evaluated the accuracy of computer-guided implant surgery using tooth-supported templates. The study chose to evaluate the accuracy of their implant placement using an intraoral scan. The implant scanbodies were seated and the digital scans were loaded into
coDiagnostiX software for analysis. The results of the study showed angular deviation values of 2.7°. This is in correlation with our findings. For a subgroup in the same Derksen study, a subset of patients underwent a post-operative CBCT allowing for comparison with the intraoral scans. The results showed that the maximum reported deviation was 0.2mm, which coincides with the previous data for the threshold of verification with a CBCT (Derksen, 2019).

Skjerven et al. studied the postoperative intraoral scan vs CBCT to measure guided implant surgery. Twenty-eight implants were placed in 13 patients with the use of a tooth-supported surgical guide protocol. After submersion of 12-15 weeks post-operative CBCT’s were taken for implant position verification. After the uncovering of the implants, scan bodies were mounted, and digital scans were completed using an intraoral scanner. The intraoral digital scans were then compared to the post-operative CBCT imaging of the implants using specific identified positions on the implant body. The results of the study showed the angular difference between CBCT and intraoral scanning at the coronal point was −0.011 (±0.6)°, whereas the three-dimensional deviation was 0.03(±0.17) mm indicating the accuracy measurements using the intraoral scanner are comparable to that of the CBCT (Skjerven, 2019). Similarly, in our study, the angular difference between the CBCT and intraoral scanning was 0.48°; the crestal three-dimensional deviation was 0.1 mm.

Yi et al. also compared digital and radiographic methods in an in vitro model. Forty single unit implants were placed in resin models using a fully guided system after the ideal position had been virtually planned. After the surgery CBCT, scans were taken and overlayed onto the virtual planning. Digital scans were then taken with the use of a
scanbody and Interclass correlation coefficients (ICCs) analysis was completed. The ICCs are a tool for assessing the consistency between results obtained through various methods or by different observers. Higher ICCs correspond to reduced variation resulting from random and systematic errors. ICC values can range from 0 to 1, with ICCs > 0.75, 0.40-0.75, and < 0.4 indicating good, moderate, and poor agreement, respectively. The study results indicated that the entry point, apex point, and angle measured 0.986, 0.993, and 0.968, concluding that conventional CBCT and digital registration showed good agreement in terms of evaluating the accuracy of implant positioning using tooth-supported surgical template (Yi, 2022). This agrees with the results of our study, that digital methods are as reliable as CBCT in determining post-operative implant positioning.

Tang et al. had an analysis of digital and radiographic methods to evaluate accuracy after implant placement in a freehand method. Virtual planning was completed, and 32 implants were placed freehand in 19 patients. No significant difference was found between the accuracy evaluated by the digital registration method and the radiographic method (Tang, 2019). In our study with the freehand group, no significance was found between the intraoral scanner method and CBCT, however a significant difference was found between the lab scanner method and CBCT.

Within the methodology of the present study, different technologies were utilized. The accuracy of these technologies has been previously investigated and verified. The accuracy of lab scanners versus intraoral scanners has been investigated. In our study, the 3Shape E3 lab scanner was used to create a digital impression. An in vitro
study by Vafaee et al. compared seven different digital scanners and concluded that the 3Shape E3 had the best trueness and precision (Vafaee, 2021).

A Form 3 SLA three-dimensional printer was used to print the static surgical guides for our study. Other three-dimensional printers on the market can be used to produce surgical guides, and research by Wegmüller et al. assessed the precision of several consumer-level three-dimensional printers, including the Form 3 SLA printer. The professional Material Jetting 3D printer (Object30Prime, Stratsys Ltd., Minneapolis, MN, USA) showed the greatest trueness (RMS 0.09 + 0.01 mm), followed by the SLA-printed guides. The deviations found were deemed acceptable and the researchers concluded that the accuracy differences between the printed guides were negligible (Wegmüller, 2021).

The same Form 3B three-dimensional printer was also used in our trial to make the replica mandibular models. A study by Msallem et al. used an earlier version of the printer used in this study, the Form 2 (Formlabs Inc., Somerville, MA, USA). The study assessed the accuracy of five different three-dimensional printers by replicating human mandibles. The printed mandibles were compared with the original reference mandibles and with each other. The study found statistically significant differences in the accuracy of the printers when the printed models were compared to each other. However, the authors concluded that the differences were minor and would not have any clinically significant differences (Msallem, 2020).

The scanbodies used in our experiment were the Straumann Cares RC MONO. Tan et al. investigated the three-dimensional positional accuracy of different implant scanbodies through intraoral and lab scanners. The CARES Mono Scan body had a mean
vertical linear distortion of 3.9 + 10.5 µm, a mean two-dimensional tolerance
displacement of 11.6 + 10.7 µm, and a mean global linear distortion of 13.8 + 5.3 µm. Of
all the implant scanbodies investigated, the Straumann Cares RC MONO scanbody
system was found to be the least accurate. The scan body system and torque magnitude
were shown to have significant effect on the distortion variables. The measurements
taken on the implant positions could have been influenced by the type of implant, the
scanbody system, and the amount of torque applied to the scanbody (Tan, 2020).
The findings of this investigation demonstrated that digital registration can be used to
evaluate the accuracy of single-tooth implant surgery using tooth-supported surgical
templates and acrylic resin models. It is important to note that our model analyses were
conducted in vitro and under ideal conditions. Further clinical research is needed to
validate the efficacy of this novel method and the clinical applications. It is important to
note that the digital registration method was only tested on tooth bound sites and further
research is needed for bone or tissue supported guides.
In this in vitro study, implants were placed in replica mandibles either using a static guide for fully-guided placement or without a guide for freehand placement. Digital (lab scanner, intraoral scanner) and radiographic (CBCT) methods were used to analyze the accuracy of implant placement in comparison to the virtually planned ideal position. Intergroup comparisons showed no significance between the three methods for the fully-guided group. In the freehand group significance was seen between the lab scanner and CBCT groups. Thus, if studies aim to compare fully-guided vs freehand procedures, digital impressions, such as an intraoral scanner, appear to be suitable for detecting differences. Future studies will be needed to validate these methods in vivo.


Vela X, Méndez V, Rodríguez X, Segalá M, Tarnow DP. Crestal bone changes on platform-switched implants and adjacent teeth when the tooth-implant distance is less than 1.5 mm. Int J Periodontics Restorative Dent 2012;32:149–155.


