Original Articles

# Implant Stability in the Era of Digital Dentistry: Comparing Traditional and Technology-Enhanced Surgical Methods

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## Abstract

Implant success is strongly influenced by surgical technique and implant stability throughout the osseointegration process. This retrospective study aimed to compare implant stability in the posterior maxilla using three surgical approaches: freehand, static-guided, and dynamic navigation techniques. Patients who underwent delayed placement of a single Straumann implant between 2015 and 2022 were included. Insertion torque and primary implant stability were recorded at the time of surgery, and secondary stability was assessed approximately three months postoperatively. Additional variables—such as age, sex, healing duration, systemic conditions, implant site, dimensions, type, surface treatment, and adjunctive procedures—were also collected. A paired *t*-test was used to compare primary and secondary stability within each group, while a linear mixed-effects model identified factors associated with changes in implant stability. A total of 49 patients (57 implants) were analyzed. No significant differences were found among groups in terms of baseline characteristics, insertion torque, or primary stability. All groups showed an increase in secondary stability over time. However, the improvement was statistically significant only in the dynamic navigation group (9.32 ± 9.42 ISQ, $p < 0.01$) and the static-guided group (6.26 ± 8.01 ISQ, $p = 0.003$). Among the assessed variables, only the primary implant stability was significantly associated with the change in stability. Within the limitations of this study, both dynamic navigation and static-guided surgery demonstrated superior outcomes compared to the conventional freehand technique. These results underscore the clinical value of digital technologies in enhancing surgical accuracy and optimizing implant stability during osseointegration.



**Keywords:** Digital dentistry, Implant stability, Insertion torque, Resonance frequency analysis

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## Introduction

Dental implants have become a fundamental component in modern oral rehabilitation, providing long-term functional and aesthetic outcomes for edentulous and partially edentulous patients.[1] Implant stability is a critical factor that directly impacts the long-term survival and osseointegration of the prosthesis, thereby influencing the efficacy of implant therapy.[2] It is usually divided into two phases: primary stability, which is derived from the initial mechanical anchorage in the bone, and secondary stability which is achieved through bone healing and osseointegration.[3,4]

Placing implants in the posterior maxilla is a particularly complex procedure due to a variety of anatomical and technical limitations. These include restricted access and visibility, frequently reduced inter-arch space, and progressive bone loss following tooth extraction, which is routinely worsened by sinus expansion. Additionally, this region is typically characterized by low-density (type IV) bone, which is composed of a thin cortical shell surrounding porous trabecular bones. This bone is associated with reduced implant success rates.[5] Failure to achieve adequate implant stability, particularly in the posterior, may result in early implant failure, marginal bone loss and prosthetic complications.[6] Although our clinical focus is the posterior maxilla—where Types III–IV bone predominate—the freehand, static-guided, and dynamic navigation approaches are routinely applied across bone Types I–IV, with osteotomy adjustments tailored to local bone quality (e.g., under-preparation in low-density bone; countersinking and avoidance of over-compression in dense cortical bone).

Free-hand implant placement remains one of the most widely practiced surgical procedures due to its clinical adaptability and cost-effectiveness. However, its success is considerably dependent upon the operator's proficiency and comprehension of anatomical structures. This inherent variability has the potential to compromise the precision of implant positioning and impact long-term stability, particularly in anatomically challenging regions.[7] To address these challenges, digital dentistry has implemented a variety of tools to improve precision and outcomes in implant surgery. These consist of static guided surgery and dynamic navigation system. These innovations aim to improve the accuracy of implant positioning, reduce human error and potentially improve both primary and secondary stability outcomes. In particular, these technologies mitigate operator-dependent errors—includingentry-point deviation, angulation and depth control issues, and cumulative drill drift—by constraining the drill path (static guides) or providing real-time feedback (dynamic navigation).[8]

In this context, "human error" refers to entry-point, angulation, depth, and drill-diameter deviations; by constraining the drill path (static guides) or providing real-time feedback (dynamic navigation), these systems reduce over-/under-preparation, cortical over-compression, and thermal insult.[9] Several studies have compared the clinical effectiveness of digital instruments to the conventional freehand technique; however, the majority have prioritized surgical accuracy while minimizing operator variability.[7] Nevertheless, there is a lack of comparative data regarding the impact of these procedures on the increase in implant stability during the critical osseointegration period, which is the first three months.

This study aimed to compare the ability of freehand, static-guided, and dynamic navigation techniques in improving implant stability during osseointegration in the posterior maxilla by measuring insertion torque, primary stability, and secondary stability.

## Materials and Methods

This retrospective cohort study was conducted at the Department of Oral and Maxillofacial Surgery, Chulalongkorn University, Bangkok, Thailand. Patient records from January 2014 to December 2023 were reviewed, focusing solely on implant placements in the posterior maxilla. This study was approved by the Human Research Ethics Committee of the Faculty of Dentistry, Chulalongkorn University (HREC-DCU 2022 – 016)

***Subjects***

Initially, 62 implant cases were identified. To maintain consistency, one immediate and one early implant placement were excluded. Additionally, cases with abnormal or excessive changes in ISQ values were also excluded as outliers to ensure data reliability. The final analysis included 57 cases of delayed implant placements (Fig. 1). All eligible cases during the study period were included; no a-priori sample-size calculation was performed due to the retrospective design.

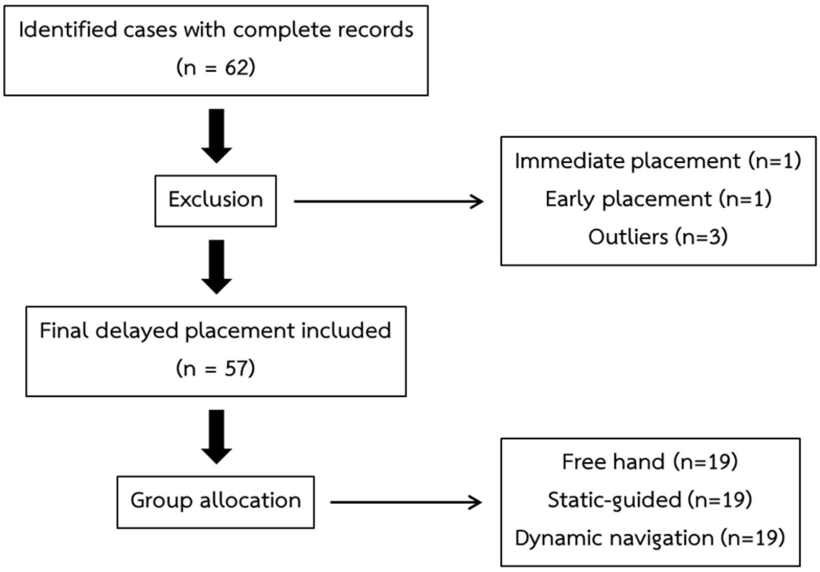


*Figure 1* *Flowchart of the group allocation*

The inclusion criteria and exclusion criteria were as follows:

**Inclusion criteria:**

- Patients aged over 18 to 85 years
- Placement of at least one Straumann dental implant system in the posterior maxilla
- Complete documentation including participant and implant characteristics, surgical techniques, insertion torques, and primary and secondary stability at immediate placement and at follow-up 2-5 months after implant placement

**Exclusion criteria:**

- Implant failure due to trauma or unrelated surgical complications
- Use of medications affecting bone metabolism (e.g. bisphosphonates, etc.)
- History of head and neck radiation therapy
- History of grafting at the intended implant site before the index surgery (e.g., staged GBR or staged sinus floor augmentation)

**Data collection**

Data were extracted from institutional records and categorized as follows:

**1. Patient-related variables:** age, gender, systemic conditions, implant placement location

**2. Implant-related variables:** diameter, length, type (bone level and tissue level), surface treatment (SLA or SLActive), and adjunctive procedures (guided bone regeneration; GBR, osteotomes, simultaneous sinus lift, or none)

**3. Surgical variables:** placement technique (free-hand, static-guided surgery, or dynamic navigation), insertion torque (Ncm). primary and secondary implant stability

**Outcome measurement**

**1. Primary outcomes**

To compare the increase in implant stability (ISQ values) during the osseointegration period among three surgical techniques (freehand, static-guided, and dynamic navigation) in the posterior maxilla.

ISQ was recorded immediately after implant placement (primary stability) and again during the osseointegration period at approximately 8–20 weeks post-operatively (±2 weeks). The exact follow-up interval (in days) was recorded for each case. ISQ gain was defined as follow-up ISQ minus baseline ISQ.

**2. Secondary outcomes:**

To evaluate factors associated with changes in implant stability, including:

- Patient-related factors (age, gender, systemic conditions, implant placement location)
- Insertion torque
- Implant dimensions (diameter, length)
- Implant type and surface treatment
- Adjunctive procedures (GBR, osteotomes, simultaneous sinus lift)

**Insertion torque measurements**

Insertion torque was recorded at the time of implant placement using either a calibrated torque wrench or a motor-based system, depending on the surgical protocol and clinical accessibility, and was measured in Newton centimeters (Ncm).

**Resonance frequency analysis**

Primary and secondary implant stability were assessed using resonance frequency analysis (RFA) and expressed as implant stability quotient (ISQ) values, measured with the Osstell Mentor™ device (Integration Diagnostics Ltd., Sweden) immediately after implant placement and at follow-up.

**Surgical protocols**

All patients rinsed with 0.2% chlorhexidine for 30 s, followed by local anesthesia using 2% mepivacaine or 4% articaine with 1:100,000 epinephrine. A crestal incision was made and full-thickness mucoperiosteal flaps were elevated. Osteotomies were prepared under copious irrigation with sequential drills per manufacturer specifications, and implants were placed according to the planned positions, and IT and ISQ were recorded.

In the free-hand group, osteotomy positioning was guided by the surgeon's interpretation of anatomic landmarks and intraoperative measurements referenced to the virtual plan, after which sequential drilling and implant placement were performed to the planned depth and angulation

In the static-guided group, preoperative CBCT DICOM data were imported into coDiagnostiX v9.7 (Dental Wings), STL files from extraoral scans of stone casts (D900L, 3Shape) were merged for prosthetically driven planning, and a 3D-printed soft-tissue–supported surgical guide was fabricated. Prior to surgery, three mini-implants (S-mini ball, Neobiotech) were placed on each edentulous arch as reference/fixation points; the guide was seated and verified with a bite index, three pin holes were drilled, the flap was raised, and the guide was fixed to bone with pins. Osteotomy and implant insertion were then completed using the Straumann Guided Surgery system in a fully guided manner, and IT and ISQ were recorded.

In the dynamic navigation group, CBCT DICOM data were imported into IRIS 100 (EPED Inc.) for planning and real-time navigation. An infrared tracking camera monitored the handpiece and stent; fiducial markers registered patient position to the CBCT. After calibration and accuracy verification, osteotomy preparation and implant placement were performed under real-time navigation with on-screen guidance of drill position and angulation relative to the plan, after which IT and ISQ were recorded.

Implant placement, IT and ISQ measurements were performed by multiple surgeons as part of routine clinical care. Due to the retrospective design, no assessment of intra- or inter-rater reliability (ICC) was conducted.

**Statistical analysis**

All statistical analyses were performed using SPSS software (SPSS Statistics for Windows, version 28; IBM). Descriptive statistics were reported as means and standard deviations for continuous variables and as frequencies for categorical variables. Normality of continuous variables was assessed using the Shapiro–Wilk test. Within each technique, change in implant stability was tested with a paired *t*-test (primary vs secondary ISQ). Between-technique inference was based on ISQ gain (ΔISQ = secondary – primary ISQ) using one-way ANOVA.

A linear mixed-effects model was applied to identify factors associated with implant stability change during osseointegration, according to multiple implants placed in individual patients. Fixed effects included patient demographics (age, gender, systemic disease, implant placement location), implant characteristics (diameter, length, implant type, surface treatment), and surgical variables (adjunctive treatment, insertion torque, primary stability). A random intercept was included to control for clustering by patient. Post hoc power for the primary paired ISQ change was estimated (two-sided $\alpha$=0.05) using G*Power 3.1, and a sensitivity analysis was conducted to determine the minimal detectable effect (MDE). Statistical significance was set at $P < 0.05$.

## Results

After excluding outliers, a total of 57 implants in 49 patients (20 males, 29 females; age range 21–85 years, mean 60.84 ± 10.49 years) were analyzed. The study population was equally distributed across the three groups: free-hand (n = 19), static-guided (n = 19), and dynamic-guided (n = 19). All implants were placed using a delayed protocol, with healing periods ranging from 51-161 days. Table 1 presented the baseline characteristics across the three groups, showing no significant differences in patient demographics, implant characteristics, or surgical variables among the groups.

*Table 1* *Baseline data*

| Variables | | | Surgical technique | | |
|---|---|---|---|---|---|
| | | | Free-hand | Static-guided | Navigation |
| Patient factors | Age (years) | mean±SD | 60.84±5.94 | 61.05±9.26 | 60.63±14.87 |
| | | *P*-value | | 0.99[a] | |
| | Gender (n) | Male/ Female | 10/7 | 6/10 | 4/12 |
| | | *P*-value | | 0.14[b] | |
| | Systemic conditions (n) | Yes/ No | 6/13 | 7/12 | 7/12 |
| | | *P*-value | | 0.91[b] | |
| | Implant placement location (n) | Premolar/ Molar | 5/14 | 11/8 | 8/11 |
| | | *P*-value | | 0.14[b] | |
| | Healing time (day) | mean±SD | 97.11±22.77 | 99.68±32.80 | 100.37±31.87 |
| | | *P*-value | | 0.94[a] | |
| Implant factors | Implant diameter (mm) | mean±SD | 4.50±0.44 | 4.27±0.48 | 4.35±0.63 |
| | | *P*-value | | 0.40[a] | |
| | Implant length (mm) | mean±SD | 9.37±1.17 | 9.47±1.31 | 9.47±1.31 |
| | | *P*-value | | 0.96[a] | |
| | Implant system (n) | BL/ BLT/ BLX/ SP/ TE | 7/8/0/2/2 | 14/4/0/1/0 | 10/8/1/0/0 |
| | | *P*-value | | 0.15[b] | |
| | Surface treatment (n) | SLA/ SLA active | 18/1 | 15/4 | 18/1 |
| | | *P*-value | | 0.19[b] | |
| | Adjunctive procedure (n) | No/ GBR/ OS/ SS | 13/1/2/3 | 12/3/4/0 | 14/2/0/3 |
| | | *P*-value | | 0.23[b] | |
| Surgical factors | Insertion torque (Ncm) | mean±SD | 26.32±9.11 | 27.11±9.02 | 24.74±9.93 |
| | | *P*-value | | 0.73[a] | |
| | Primary stability (ISQ) | mean±SD | 71.03±7.90 | 68.03±7.72 | 65.61±11.21 |
| | | *P*-value | | 0.19[a] | |

*SD=Standard Deviation, BL=bone level implant, BLT=bone level tapered implant, BLX=bone level with aggressive thread design implant, SP=standard plus, TE=Tapered effect, GBR=guided bone regeneration, OS=osteotome, SS=simultaneous sinus lift, ISQ=Implant stability quotient; a One-way ANOVA, b Chi-square test, * Significant at P-value <0.05, ** Significant at P-value <0.01, *** Significant at P-value <0.001*

Figure 2 showed the primary and secondary ISQ values across surgical techniques. All groups exhibited an increase in ISQ during the osseointegration period; however, statistically significant increases were observed only in the dynamic navigation ($P < 0.001$) and static-guided groups ($P < 0.01$), while the free-hand group did not reach significance. These findings indicated that navigation-assisted and static-guided surgery may enhance implant stability in the posterior maxilla during early healing compared to the conventional free-hand technique. Across techniques, ΔISQ did not differ significantly—free-hand 4.32 ± 8.84, static-guided 6.26 ± 8.01, dynamic navigation 9.32 ± 9.42 ($P = 0.22$).

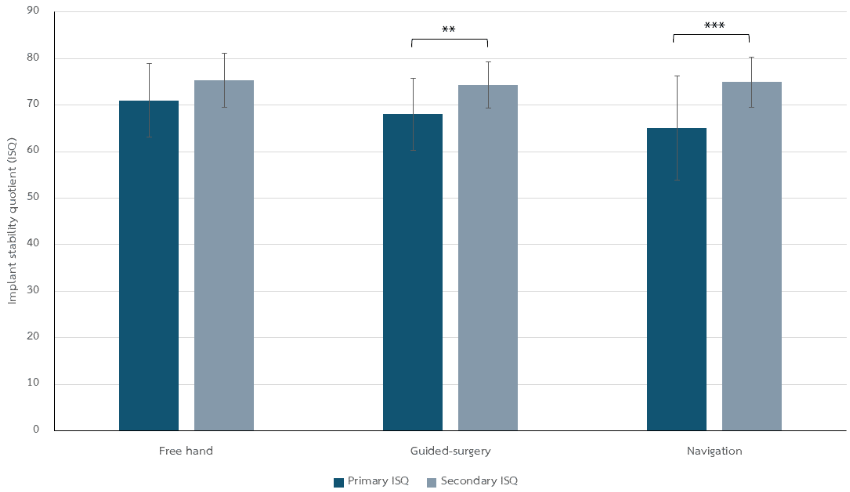


*Figure 2* *Primary and secondary implant stability quotient (ISQ) values for free-hand, static-guided, and dynamic navigation techniques*

Among the tested variables, only mean primary ISQ was significantly associated with ISQ gain (F = 38.73, $P < 0.001$), indicating that implants with higher initial stability tended to exhibit greater ISQ increases during the healing period. Other variables, including age, gender, systemic conditions, implant location, diameter, length, implant type, surface treatment, adjunctive procedures, and insertion torque, were not significantly associated with ISQ gain (all $P > 0.05$).

## Discussion

This study compared the effects of three surgical techniques—free-hand, static-guided, and dynamic navigation, on enhancing implant stability during osseointegration in delayed posterior maxillary placements. While all techniques demonstrated successful outcomes with increased ISQ values over time, significant improvements were observed only in the static-guided and dynamic navigation groups, with the greatest increase observed in dynamic navigation, followed by static guidance. Additionally, primary ISQ emerged as a significant predictor of ISQ gain, indicating that higher initial stability was associated with greater improvements in implant stability during the osseointegration period. In this framework, baseline ISQ primarily reflects primary stability (mechanical interlock at placement), whereas ISQ gain over time reflects secondary stability (biologic integration during healing); thus, technique-related differences are expected to appear more clearly in the change in ISQ than in the baseline value.

The primary stability in dynamic navigation group was found to be lower than the conventional free-hand and static-guided groups. This may be due to the fact that primary stability is largely influenced by quality of the bone and implant design rather than the surgical technique.[3] This finding is consistent with ITI consensus report that although dynamic navigation shows superior accuracy, primary stability may not be differ significantly from conventional techniques.[10] Mechanistically, primary stability is governed chiefly by local bone quality/density and implant macrogeometry, while osteotomy adjustments (e.g., under-preparation in softer bone; countersinking in dense cortex) modulate thread engagement.[11-13] Guided approaches do not change intrinsic density, but can standardize entry point, angulation, and depth, reducing over/under-preparation, cortical over-compression, and thermal insult. Dynamic navigation adds real-time trajectory correction that may better preserve trabecular architecture in challenging posterior sites; these features are expected to have a modest effect on primary stability but may favor secondary stability during healing.[8]

The results in our study revealed that implant placement using dynamic navigation yielded significantly higher ISQ gain when compared to the freehand and static guided approaches. This shows that the dynamic navigation group enhanced the precision in implant positioning, leading to more favorable osseointegration.[14,15] Navigation systems allow for real-time adjustments, correct insertion angles, preserve surrounding bone integrity, optimizing bone-to-implant contact during healing and potentially minimizing micromovements.[16] Accordingly, the greater ISQ gains observed with guided/dynamic techniques are consistent with an effect on secondary stability (osseointegration) rather than on the density-driven primary stability at placement.

There were no statistically significant differences in insertion torque among the three groups. This finding is consistent with the previous studies that insertion torque depends more onlocal bone density than on the surgical techniques.[10], The dynamic navigation group's mean IT was numerically lower, which could reflect reduced tactile feedback and less bone condensation during osteotomy preparation.[10,17] However, this interpretation remains exploratory given the non-significant difference. This may benefit clinically by reducing the risk of cortical bone damage, particularly in soft bone regions such as the posterior maxilla. Taken together, our data support a model in which bone density primarily determines baseline IT/ ISQ, whereas surgical guidance influences the trajectory of stability (ISQ gain) by minimizing procedural trauma and micromotion during the osseointegration period.

Guided and navigation techniques achieved ≥80% post-hoc power for the paired ISQ change, whereas the free-hand analysis did not reach 80% (power ≈0.52; MDE at n=19: $d_z$ ≈0.68). Accordingly, the smaller effect observed in the free-hand group should be interpreted cautiously given the higher risk of type II error. Despite these insights, this study has limitations. The retrospective design and sample size may limit generalizability, particularly for subgroup analyses. Although implant diameter, length, and insertion torque were controlled, other factors influencing stability, such as variations in bone quality and soft tissue conditions, were not fully assessed. It is important to note that peri-implant bone density provides additional insights into the relationship between bone quality and stability outcomes, emphasizing the necessity of comprehensive bone assessments in future researches. In this routine-care cohort, multiple operators performed ISQ measurements, and no intra-/inter-rater reliability (ICC) was assessed, which may introduce measurement variability. Additionally, the follow-up should investigate long-term outcomes, such as marginal bone loss, peri-implant bone density changes, and prosthetic success.

Further long-term studies with larger samples are recommended to confirm the benefits of digital surgical techniques on implant stability and peri-implant bone health in delayed posterior maxillary placements. Prospective studies should incorporate standardized duplicate measurements and ICCs to assess rater reliability

## Conclusion

From this, we can conclude that clinically acceptable implant stability outcomes can be achieved regardless of the surgical techniques. However, dynamic navigation demonstrated greater gains in secondary stability despite initially lower insertion torque, suggesting that its precision in implant positioning may aid favorable bone remodeling and osteointegration, particularly in the posterior maxilla.

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