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Safe and Accurate Immediate Implant Placement in the Posterior Maxilla: The Role of Dynamic Navigation in Transcrestal Sinus Augmentation

PhD Thesis

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LIST OF PUBLICATIONS PROVIDING THE BASIS OF THE THESIS

Jain S, Solanki A. A dynamic surgical navigational approach for immediate implantation and transcrestal sinus augmentation. *J Indian Soc Periodontol*. 2021;25(5):451-6. doi:10.4103/jisp.jisp_581_20

SJR rank: Q2

Jain S, Nagy K, Bhalerao A. Accuracy and safety of dynamic navigation vs. freehand approach in indirect sinus lift and immediate implant placement: A split-mouth clinical study. *J Dent*. 2025;160:105866. doi:10.1016/j.jdent.2025.105866

SJR rank: Q1/D1

ABBREVIATIONS

AAOMR	American Academy of Oral and Maxillofacial Radiology
AI	Artificial Intelligence
AR	Augmented Reality
CAIS	Computer-Assisted Implant Surgery
CBCT	Cone Beam Computed Tomography
CT	Computed Tomography
dCAIS	Dynamic Computer-Assisted Implant Surgery
DICOM	Digital Imaging and Communications in Medicine
DNS	Dynamic Navigation System
EPHD	Entry Point Horizontal Deviation
MSFE	Maxillary Sinus Floor Elevation
OD	Osseodensification
OSFE	Osteotome Sinus Floor Elevation
sCAIS	Static Computer-Assisted Implant Surgery
SFE	Sinus Floor Elevation
VAS	Visual Analog Scale

I. INTRODUCTION

I.1. A Brief Historical Background of Dental Implants

The evolution of dental implantology is rooted in the principle of osseointegration, introduced by Brånemark in the 1960s, which transformed implants from experimental devices into predictable clinical solutions [1, 2]. Early implant systems, often subperiosteal or blade-form, were progressively abandoned due to biomechanical and biological shortcomings. The introduction of endosseous, screw-shaped titanium implants established the basis of modern implantology, with long-term clinical data confirming survival rates exceeding 90% in favorable conditions [3].

A persistent clinical challenge, however, has been the posterior maxilla, where tooth loss is frequently accompanied by sinus pneumatization and vertical ridge resorption. Immediate implant placement in fresh extraction sockets, introduced by Schulte and Heimke [4] and first systematically described by Lazzara in 1989 [5], represented an important step toward reducing treatment time. However, its application in the posterior maxilla was limited by insufficient bone height and quality. The pioneering work of Boyne and James in 1980, who described sinus floor augmentation with autogenous bone grafts, marked a milestone in addressing this anatomical limitation [6]. Building on this, Tatum further refined the lateral window approach for sinus grafting, which became a cornerstone of reconstructive implant dentistry [7], and Smiler and colleagues in 1992 broadened its clinical application, establishing the sinus lift as a predictable treatment option for the atrophic posterior maxilla [8].

Subsequent decades witnessed the development of less invasive transcrestal methods. Summers introduced the osteotome sinus floor elevation technique in 1994, emphasizing preservation of bone and atraumatic membrane elevation [9]. Modifications to this method, including the use of hydraulic pressure and osteotome variants, aimed to improve predictability and reduce complications [10]. Later systematic reviews demonstrated high implant survival rates with both lateral and transcrestal techniques, though the latter was generally associated with reduced morbidity [11].

Parallel to surgical innovations, implant placement philosophy evolved from a bone-driven to a prosthetically driven approach, emphasizing three-dimensional positioning for aesthetic and functional outcomes [12]. The posterior maxilla became a proving ground for these concepts, as prosthetically ideal positioning was often constrained by anatomical risk factors such as sinus septa and vascular structures [13].

Technological advances in imaging, particularly the widespread adoption of cone-beam computed tomography (CBCT), further supported this paradigm shift. CBCT provided detailed visualization of sinus anatomy, bone availability, and potential hazards, becoming a standard of care in preoperative planning for sinus floor elevation procedures [14].

In summary, the historical trajectory of implantology reflects a progressive refinement of surgical techniques and diagnostic tools to overcome the anatomical limitations of the posterior maxilla. From the early lateral window grafts of Boyne and Tatum to minimally invasive transcrestal approaches and prosthetically guided placement, each development has addressed the persistent challenge of limited bone height beneath the sinus. These historical foundations frame the contemporary exploration of computer-assisted and biologically optimized techniques, which this thesis builds upon.

I.2. Sinus Floor Elevation

The posterior maxilla remains one of the most challenging regions for implant rehabilitation due to its unique anatomical and biological constraints. Following tooth loss, progressive alveolar ridge resorption is compounded by sinus pneumatization, often leaving residual bone heights insufficient for predictable implant anchorage [13]. As early as the 1980s, Boyne and James described grafting of the maxillary sinus floor with autogenous bone, demonstrating the feasibility of augmenting the subantral space to support endosseous implants [6]. Shortly thereafter, Tatum's lateral window approach was popularized as the standard technique, involving the creation of a bony window to access and elevate the Schneiderian membrane [7].

While the lateral approach provided predictable vertical bone gain, it was associated with surgical morbidity, risk of membrane perforation, and extended healing periods. In the 1990s, Summers introduced the transcrestal osteotome technique as a less invasive alternative, designed to elevate the sinus membrane through the implant osteotomy itself [9]. This technique was further refined by Davarpanah and colleagues with modified osteotomes, improving tactile control and reducing the risk of perforation [10]. The evolution of these techniques reflects a broader clinical trend toward minimally invasive procedures that preserve native bone architecture and shorten rehabilitation times [15].

Systematic reviews have confirmed high implant survival rates in conjunction with sinus floor elevation. Pjetursson and colleagues reported survival exceeding 90% with both lateral and transcrestal techniques, though the latter was associated with lower patient morbidity and shorter chairside times [16]. Wallace and Froum corroborated these findings in an earlier systematic review, demonstrating that sinus augmentation procedures consistently improved implant survival across different grafting approaches [17]. More recent meta-analyses have indicated that implants can achieve predictable osseointegration even when grafting materials are omitted, provided primary stability is obtained. This graftless approach has been supported by radiographic and histologic studies, showing sufficient spontaneous bone formation in the elevated sinus cavity [18]. Similarly, Del Fabbro and colleagues confirmed high long-term implant survival in grafted maxillary sinuses, underscoring that both grafted and graftless approaches can yield favorable outcomes depending on case selection [19].

Despite these encouraging outcomes, sinus augmentation procedures are not without risk. Membrane perforation remains the most common intraoperative complication, reported in up to 30% of lateral window cases, with sequelae including graft infection and maxillary sinusitis [11]. The Cochrane review by Esposito et al. [20] further highlighted the heterogeneity of available studies, concluding that while sinus lift procedures are generally effective, the evidence quality remains moderate and long-term comparative trials are needed.Anatomical variations such as sinus septa, alveolar antral arteries, and thickened Schneiderian membranes further complicate surgery, increasing the risk of hemorrhage or incomplete elevation [13]. To mitigate such risks, the 1996 Sinus Consensus Conference established guidelines emphasizing preoperative radiographic evaluation, atraumatic membrane handling, and appropriate case selection [21].

The integration of cone-beam computed tomography (CBCT) into routine diagnostics has significantly advanced surgical planning. CBCT enables accurate assessment of sinus morphology, membrane thickness, and residual bone height, thereby improving risk stratification and reducing intraoperative surprises. Current recommendations by the American Academy of Oral and Maxillofacial Radiology include CBCT imaging as a standard of care for complex sinus augmentation cases [14].

In addition to imaging, surgical innovations have expanded the armamentarium for sinus floor elevation. Piezoelectric devices, for instance, have been shown to reduce membrane perforation rates during lateral osteotomy by providing micrometric and selective bone cutting [22]. Similarly, osseodensification with densifying burs has enhanced the safety of transcrestal approaches by compacting bone apically while gently elevating the sinus floor, a technique explored further in Section I.3.

I.3. Osseodensification and Transcrestal Sinus Augmentation

Conventional implant osteotomies are subtractive and can reduce trabecular support in low-density posterior maxillae; osseodensification (OD) was introduced to compact—rather than remove—bone using densifying burs operated in a non-cutting, counter-clockwise mode, thereby aiming to increase primary stability and preserve osteotomy wall vitality [23]. In the seminal animal work underpinning the concept, sheep ilium models showed higher initial stability and improved early osseointegration for OD versus conventional drilling in low-density bone, supporting its biological plausibility for maxillary applications [24].

Beyond biomechanics, OD has been framed as a platform technology that can facilitate indirect sinus lifting and controlled crest expansion where ridge width or residual height are limiting, by virtue of compaction autografting and lateral bone deformation [25]. Within maxillary sinus surgery, this is clinically relevant because the classic osteotome sinus floor elevation (OSFE) introduced by Summers remains less invasive than lateral windows yet demands careful manipulation to avoid Schneiderian perforation [9-11], and OD-mediated compaction through the osteotomy offers an alternative mode of crestal elevation that may reduce reliance on percussive osteotomes [25, 26].

Clinical and radiographic studies focused specifically on transcrestal sinus elevation with densifying burs report feasible membrane elevation with simultaneous implant placement and measurable bone-height gain—supporting OD as a practical adjunct to crestal approaches [26]. Comparative work is also emerging: recent analyses have examined Densah burs vs. osteotomes in transcrestal lifting, assessing radiographic outcomes rather than asserting superiority without data [27]. In parallel, contemporary systematic reviews/meta-analyses on OD (not limited to sinus lifts) suggest higher primary stability metrics and favorable crestal bone behavior versus conventional drilling, while emphasizing the heterogeneity of protocols and the need for controlled trials in indication-specific settings [28].

These OD data should be interpreted within the broader evidence on transcrestal sinus augmentation itself: long-standing systematic reviews indicate high survival with crestal elevation when adequate primary stability is achieved [11], and more recent syntheses report that graftless crestal elevation can still yield predictable bone formation under the elevated membrane in selected cases [18]. In this context, OD does not replace the classic OSFE paradigm so much as it modifies the mechanics of crestal elevation—compacting and autografting bone chips apically to help stabilize the implant and support the membrane [23, 25].

From a risk perspective, OSFE remains technique-sensitive, and membrane perforation is still the key intraoperative concern [11]. OD-mediated crestal elevation has been investigated with the specific aim of minimizing perforations by relying on densifying contact rather than chiseling; early clinical series describe transcrestal elevation with simultaneous placement and low reported perforation rates, but these findings warrant cautious generalization until head-to-head trials standardize endpoints [26, 29].

Summarizing the above, osseodensification provides a biologically coherent and practically usable adjunct to transcrestal sinus augmentation. Preclinical evidence supports improved primary stability in low-density bone [24], clinical case-series and cohorts show feasible crestal elevation and simultaneous placement with densifying burs (Shalash et al., 2023), and early comparative/radiographic studies plus systematic reviews point toward favorable stability metrics while calling for rigorous, indication-specific trials [27, 28]. In this thesis, OD is therefore treated as a mechanical adjunct to the crestal approach, to be evaluated alongside our navigation-guided workflows rather than as a replacement for established sinus elevation principles [9, 18, 23].

I.4. Computer-Assisted Implant Surgery (CAIS)

Computer-aided implant surgery (CAIS) aims to align prosthetically driven planning with precise intraoperative execution by using CBCT-based 3D datasets and guidance technologies [14]. In implant rehabilitation of the posterior maxilla—especially when sinus augmentation or immediate placement is planned—CAIS seeks to reduce operator variability and proximity-related risks while preserving prosthetic goals [30].

Static systems transfer a virtual plan to the mouth via a stereolithographic guide (tooth-, mucosa-, or bone-supported) that constrains drills through sleeves/keys, thereby controlling entry point, angulation, and depth [14]. sCAIS has been widely studied; a landmark systematic review concluded that accuracy is clinically acceptable across indications and recommended a ≥2 mm safety margin to account for residual deviations [31].

Pooled analyses report mean linear deviations ≈1–1.5 mm at entry and ≈3–4° angular deviations in clinical settings, with variability from support type, sleeve offset, jaw position, and mouth opening [31, 32]. In one, randomized, controlled trial, the increasing level of static guidance increased the accuracy of the procedure in a stepwise manner [33]. In edentulous/mucosa-supported guides, deviations tend to be higher due to tissue resiliency and guide micromobility—an effect demonstrated clinically [34].

sCAIS can reduce gross positioning errors and standardize workflows, but intraoperative plan changes are not possible and irrigation around sleeves may be restricted, raising theoretical heat-generation concerns; moreover, cumulative tolerances from imaging, guide fabrication, and sleeve-tool play can degrade precision [31, 32]. In posterior maxillary cases with sinus septa or variant vasculature, lack of real-time adaptability can be a practical limitation when the intraoperative reality diverges from the plan [14].

Dynamic navigation uses optical tracking to display the drill/osteotome relative to the CBCT plan in real time, allowing the surgeon to adjust trajectory and depth as anatomy is encountered (JISP 2021, 13; JISP 2021, 14; JDENT, 10–12). Clinical series and trials consistently show lower deviations than freehand and, in several analyses, slightly lower angular deviations than sCAIS [12, 35-38]. Meta-analysis of dynamic systems reports mean clinical angular deviation ~3.7° and entry 3D global ~1.0 mm, again recommending a 2 mm safety margin [12].

Accuracy depends on the registration step (matching jaws/instruments to the CBCT volume). Besides stent-based fiducials, trace registration ("trace-and-place") eliminates a thermoplastic stent and has shown clinically acceptable accuracy *in vivo* [39]. Reviews of dynamic guidance highlight advantages (intraoperative adjustability, no guide bulk, easier access in limited mouth opening) and considerations (equipment, calibration steps, team training) [40, 41].

Although navigation is operator-dependent, controlled studies suggest rapid proficiency gains, and comparative trials show accuracy improvements independent of surgeon experience once basic training is completed [38, 42]. Broader medical simulation evidence supports the benefit of simulation-based training [43].

Head-to-head evidence indicates both sCAIS and dCAIS outperform freehand, while differences between sCAIS and dCAIS are small and domain-specific: dynamic tends to show lower angular deviation and better intraoperative adaptability, whereas static can be efficient for straightforward cases [12, 44]. A 2024 umbrella review spanning static, dynamic, and robot-assisted workflows confirms overall accuracy advantages of CAIS with indication-dependent trade-offs, underscoring the need for safety margins across modalities [45].

Dynamic navigation has been integrated with piezoelectric osteotomy to design and execute precise lateral windows, tailoring window size/shape to avoid septa and vessels while maintaining visibility; clinical technical notes and case-based studies report accurate window placement with simultaneous implant insertion [46, 47].

Real-time trajectory control is particularly helpful as the drill approaches the sinus floor; a 2024 clinical study evaluating dynamic navigation for MSFE reported favorable safety and placement accuracy, reinforcing its suitability for complex posterior maxillae with limited operative visibility [48].

Dynamic systems can be coupled with osseodensification burs to control apical approach during crestal elevation, or with piezoelectric tips during lateral windowing, providing a navigated pathway rather than a fixed sleeve [23, 43, 46]. In all such scenarios, a 2 mm safety buffer to critical boundaries remains prudent, mirroring recommendations from both static and dynamic meta-analyses [12, 31].

For sinus procedures, dCAIS offers error-detect-and-correct capability when encountering septa, variable membrane thickness, or altered floor contours, whereas sCAIS affords predictable transfer in straightforward anatomy when the intraoperative field closely matches the plan. Choice of modality should weigh anatomical complexity, need for intraoperative flexibility, and team training/throughput [14, 40].

I.5. Dynamic Navigation in Sinus Augmentation and Immediate Implant Placement

Implant rehabilitation in the posterior maxilla is complicated by sinus pneumatization, ridge resorption, and variable anatomy such as septa or vascular structures [13]. Conventional sinus floor elevation techniques achieve predictable survival when primary stability is achieved [11, 18]. However, the transcrestal osteotome method is technique-sensitive and carries a risk of membrane perforation [9, 10], whereas the lateral window approach is more invasive and associated with longer healing [7, 21].

Dynamic computer-aided implant surgery (dCAIS) addresses these challenges by providing real-time correlation of the drill trajectory with CBCT data, permitting intraoperative adjustments [40].

Dynamic navigation is particularly valuable in transcrestal sinus lifts, where membrane perforation is a concern as the osteotomy nears the sinus floor. dCAIS provides continuous control of depth and angulation, reducing risk while maintaining prosthetic positioning [12]. Meta-analyses report angular deviations typically under 4° and emphasize a 2 mm safety buffer to accommodate outliers [12, 31].

Randomized controlled trials demonstrate significantly lower deviations with dynamic navigation compared with freehand placement [38]. Clinical studies also show that accuracy improves rapidly with training, suggesting a short learning curve [37, 42].

In transcrestal approaches, combining dCAIS with osseodensification enhances both stability and safety. Preclinical work has shown that densifying burs increase peri-implant bone density and implant stability [23, 49], providing a biological complement to the spatial accuracy afforded by navigation.

The lateral window technique remains an important option when residual bone is very limited but carries a higher complication risk [11]. Dynamic navigation has been adapted to improve precision in lateral osteotomies, often paired with piezoelectric devices. Zhou et al. demonstrated that dCAIS permitted accurate design and execution of lateral windows in anatomically complex cases [46]. Similarly, Dotia et al. presented a navigated lateral window protocol with simultaneous implant placement, illustrating its feasibility [47].

Systematic reviews conclude that navigation enhances predictability in complex cases but emphasize that evidence for lateral window applications is still limited and largely based on feasibility reports [30, 41].

Immediate placement requires exact three-dimensional positioning to avoid labial plate perforation or prosthetic compromise [50, 51]. Dynamic navigation provides intraoperative trajectory control within extraction sockets, facilitating maintenance of prosthetic alignment. In vivo evaluations confirm clinically acceptable accuracy for dCAIS in private practice settings [37]. Comparative studies also demonstrate significantly lower entry and angular deviations compared with freehand [35, 36].

Systematic reviews indicate that navigation reduces operator-dependent variability, which is especially important in immediate placement where sockets constrain implant trajectory [12, 44].

Across applications, dynamic navigation consistently improves accuracy compared with freehand and performs comparably or slightly better than static guides in some scenarios [12, 42]. Reported mean angular deviations are ~3–4° and global entry deviations around 1 mm, but all reviews stress maintaining a ≥2 mm safety margin to vital structures such as the Schneiderian membrane [12, 31].

Dynamic systems also allow intraoperative correction when anatomical variations are encountered, unlike static templates [40]. Nevertheless, accurate registration and adequate operator training remain prerequisites for reliable performance [37]. Reviews emphasize that the advantages of dCAIS are most relevant in complex cases such as posterior maxilla with sinus augmentation or immediate implants, where precision is critical [30, 41].

I.6. Knowledge Gaps and Rationale

Dynamic navigation has become an increasingly adopted adjunct in implant dentistry, with systematic reviews confirming improvements in accuracy compared with freehand placement [12, 44, 52]. Despite this progress, several important knowledge gaps remain, particularly regarding its role in sinus augmentation and immediate implant placement in the posterior maxilla.

First, long-term outcome data are scarce. Most studies focus on short-term metrics such as angular and linear deviations [12, 42], while few extend to survival, marginal bone levels, or sinus health beyond the early healing phase. Recent trials of immediate implant placement under dynamic navigation have reported improved stability and accuracy with follow-up to 30 months [53], yet systematic, multicentre data remain limited.

Second, reporting of intraoperative complications is inconsistent. Schneiderian membrane perforation remains the key risk in sinus augmentation, yet most studies rely on small cohorts or case reports and often describe only the absence of perforations [46, 48]. A pilot study of transcrestal sinus floor elevation under navigation provided promising accuracy data [54], but larger controlled trials are needed to assess whether dynamic navigation consistently lowers complication rates.

Third, there is insufficient clarity regarding the comparative performance of static vs. dynamic navigation. Meta-analyses confirm both are more accurate than freehand, with dynamic systems showing marginally lower angular deviation in some scenarios [12, 44], but outcomes remain heterogeneous and protocol-dependent. Evidence from lateral window procedures shows feasibility when dCAIS is combined with piezoelectric devices [55], yet systematic reviews emphasize that clinical validation is still at an early stage [30, 41].

Fourth, the learning curve and operator training require better definition. Experimental and early clinical work suggests rapid proficiency gains [37, 39], but little is known about how training affects complication avoidance or efficiency in sinus augmentation specifically. Moreover, cost–benefit considerations are rarely quantified [30].

Finally, there is a paucity of data on the integration of dynamic navigation with adjunctive techniques such as osseodensification and piezoelectric osteotomy. Preclinical models and case reports indicate potential for enhanced implant stability and controlled sinus elevation [23, 49, 55], but robust clinical trials are lacking.

In summary, while dynamic navigation offers clear advantages in accuracy and intraoperative adaptability, evidence remains limited regarding its broader clinical role in sinus augmentation and immediate implant placement. The present thesis sought to contribute to this field by (i) introducing and demonstrating the technical feasibility of a novel workflow combining dynamic navigation with osseodensification for transcrestal sinus augmentation, and (ii) systematically evaluating, in a split-mouth randomized clinical trial, the accuracy, safety, procedural efficiency, and patient-reported outcomes of dynamic navigation compared with the freehand technique in the posterior maxilla.

II. OBJECTIVES

This thesis draws on two clinical studies that investigated the accuracy, safety, and clinical feasibility of dynamic navigation in the posterior maxilla, particularly in cases requiring transcrestal sinus augmentation and immediate implant placement.

The primary objective of the first study [56] was to introduce and describe a novel workflow that combined dynamic surgical navigation with osseodensification burs for transcrestal sinus augmentation performed simultaneously with immediate implant placement. The focus was on demonstrating the technical feasibility and clinical safety of this approach in a patient case, highlighting the potential advantages of dynamic navigation over conventional fiducial-based methods and the benefits of osseodensification for enhancing implant stability.

As a secondary objective, the study also aimed to document the stepwise protocol and its practical applicability, establishing a framework for subsequent clinical evaluation.

The primary objective of the second study [57] was to evaluate, in a prospective split-mouth clinical design, the accuracy and safety of dynamic navigation compared to the freehand technique in indirect sinus lift and immediate implant placement. The main outcomes included angular deviation, deviation at entry, and deviation at the apex, assessed by comparing preoperative planning with postoperative implant positions.

As secondary objectives, the study investigated procedural efficiency, measured by intervention time, and patient-reported outcomes, including satisfaction levels, in order to assess the overall clinical value of dynamic navigation.

Both studies aimed to determine whether dynamic navigation could provide a safe, accurate, and clinically feasible alternative to freehand implant placement in the posterior maxilla, particularly in cases complicated by limited residual bone height and the need for sinus augmentation.

III. METHODS

III.1. Case Report: Dynamic Navigation and Osseodensification in Transcrestal Sinus Augmentation

III.1.1. Patient Selection and Ethical Considerations

A 39-year-old female patient with no relevant medical history presented with a fractured maxillary first molar. Dental records indicated that the tooth had undergone root amputation five months earlier. At the time of consultation, an intraoral periapical radiograph confirmed the previous removal of the mesiobuccal root of tooth 16 (Figure 1).

Figure 1. Periapical radiograph showing the initial situation

The patient gave written informed consent for the surgical and prosthetic treatment, as well as for the use of anonymized clinical data and images for scientific reporting. Because the present work describes a single patient case, additional approval from an institutional ethics committee was not required.

III.1.2. Preoperative Imaging and Virtual Planning

Clinical photographs were obtained at baseline to document the condition (Figure 2). Cone-beam computed tomography (CBCT) was performed with a Kavo OP 3D Pro unit (KaVo Kerr, India), which provided a detailed three-dimensional view of the region (Figure 3). The scan demonstrated adequate healing in the mesiobuccal socket of tooth 16, consistent with the previous root amputation.

The DICOM dataset was transferred into the Navident navigation platform (Navident R2.0, ClaroNav Inc., Toronto, Canada). Prosthetically driven virtual planning was carried out within the software, taking into account the anatomical landmarks, available bone, local tissue topography, and the relationship to adjacent and opposing dentition. The crown's buccolingual and mesiodistal orientation, as well as the apico-coronal position of the implant, were defined using sagittal, coronal, and axial CBCT views.

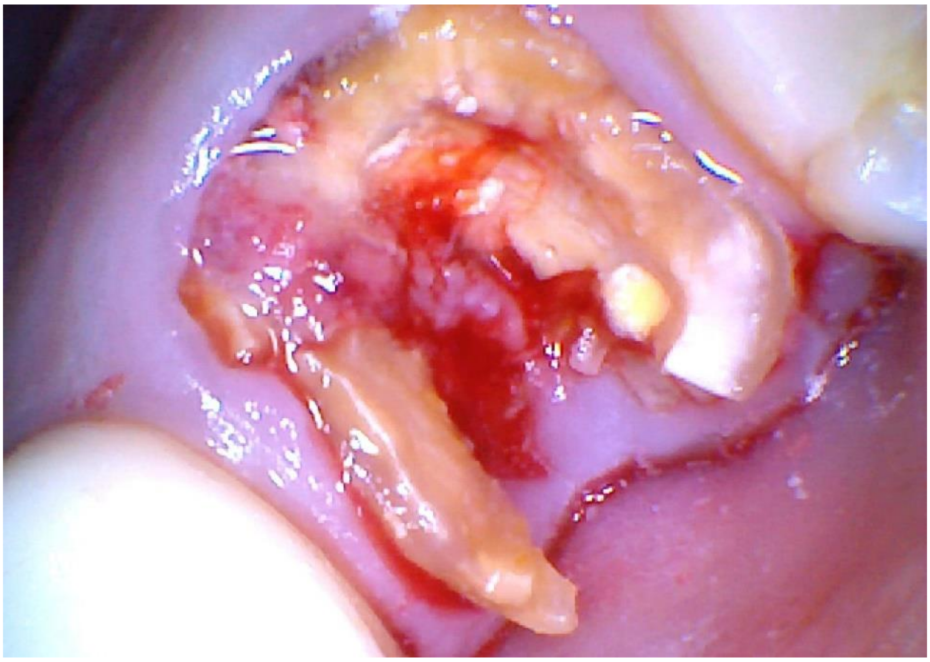

Figure 2. Clinical photograph showing the missing mesiobuccal cusp.

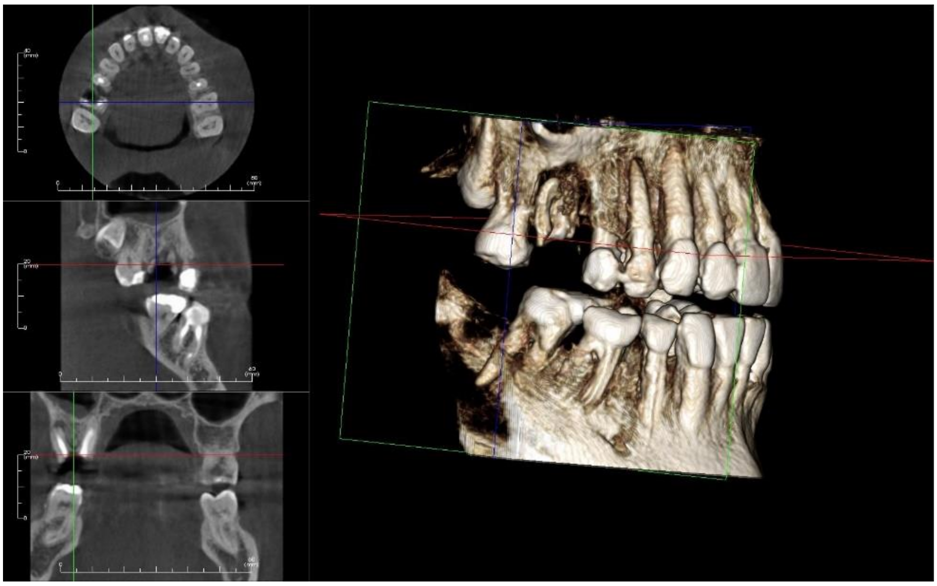

Figure 3. CBCT images showing adequate healing in the mesiobuccal socket.

Because no fiducial markers were available in the CBCT scan, the trace-and-place workflow was initiated. The maxilla and the region of interest were localized by adjusting the line of reference to the occlusal plane and selecting the upper arch in the software. The jaw centerline curve, required for generation of a panoramic view, was subsequently defined.

Following this, the definitive implant plan was generated. A 10.5-mm long, 4.6-mm diameter implant was selected, positioned in accordance with the anticipated prosthetic contours (Figure 4). For registration, trace-and-place mapping was performed across both sides of the arch, moving from right to left, and included reproducible landmarks on the buccal surfaces of teeth adjacent to the surgical site.

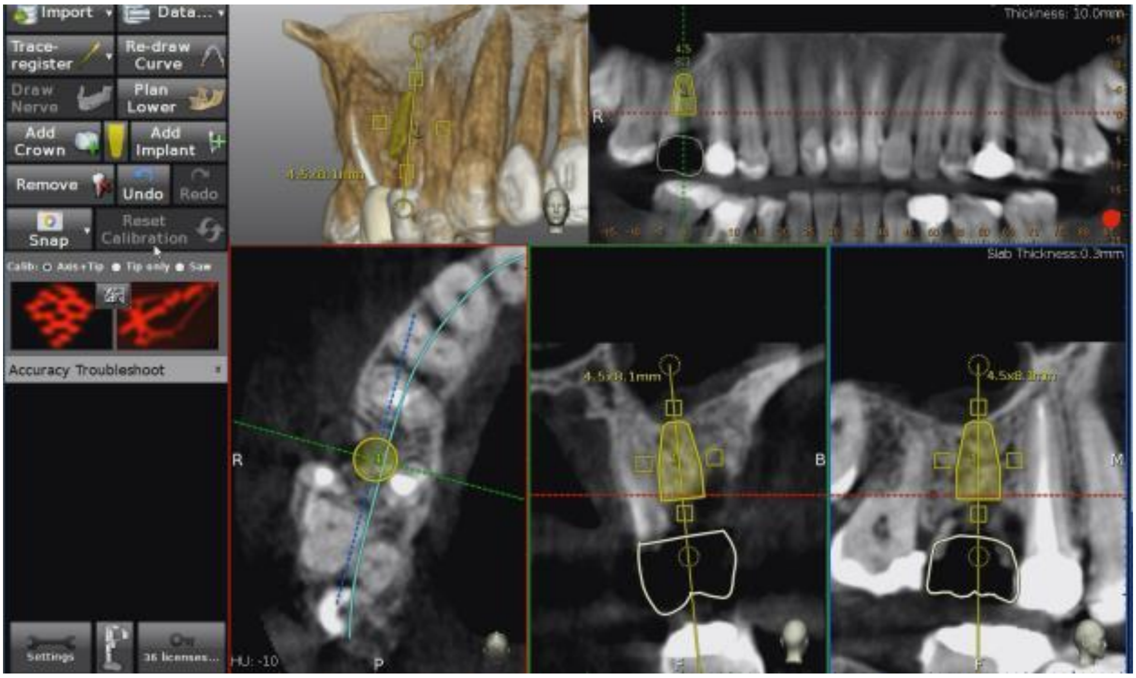

Figure 4. Prosthetically driven digital implant planning.

III.1.3. Registration

Dynamic navigation was performed using the trace-and-place (TaP) registration protocol. A head-mounted tracking device was positioned with ear hooks and nasal support, allowing the MicronTracker stereoscopic camera system to continuously monitor the maxilla throughout the procedure.

Calibration began with the tracer tool, which was linked to the head tracker. The tracer was first placed on the dimple of the jaw tag, serving as a calibration reference. This was performed at a working distance of approximately 50 cm from the optical camera. Once recognized by the navigation system, the tracer tip was applied to the buccal aspect of the first tooth selected for registration. Tracing was performed by sliding the tip along the buccal, palatal, proximal, and incisal surfaces while maintaining continuous contact. A score of 100 indicated successful capture of the landmark. This process was repeated for all preselected teeth, moving sequentially across the arch. Figures 5 and 6 demonstrate this procedure.

Following completion of the registration process, calibration of the surgical handpiece was performed. The drill tag was attached to a contra-angled 20:1 surgical handpiece, which was then positioned onto the pin of the jaw tag calibrator and rotated to accurately establish the instrument axis within the navigation system.

Each drill intended for use during the procedure was subsequently inserted into the handpiece and calibrated individually by placing the drill tip into the dimple of the jaw tag. This calibration step ensured that the navigation system precisely recognized both the spatial orientation and the tip location of the surgical instruments during navigation.

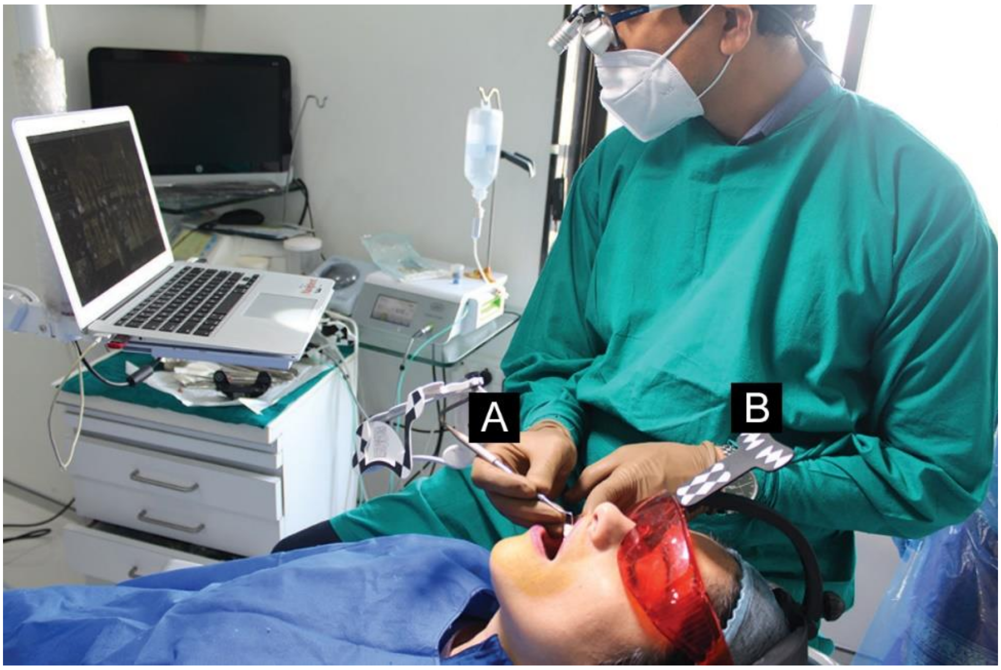

Figure 5. Tracing and registration. A: tracer tool; B: head tracker.

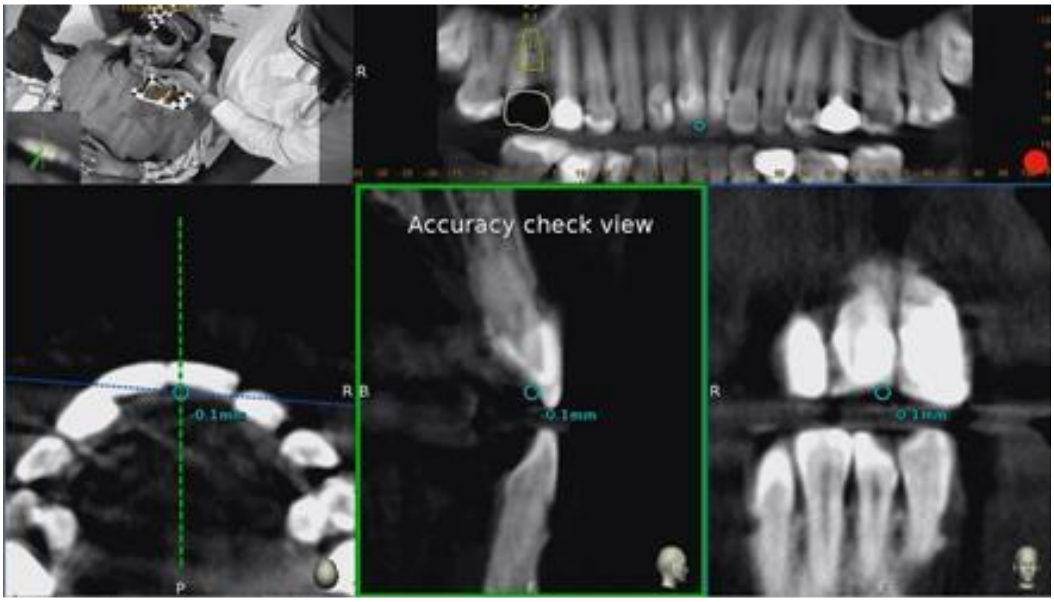

Figure 6. Obtaining landmarks for accurate navigation.

III.1.4. Osteotomy Preparation and Sinus Elevation

Local anesthesia was administered prior to extraction of the maxillary first molar. The tooth was sectioned at the furcation using a carbide tooth-splitting bur (Strauss and Co., bur no. FG-ZEKRYA 28), and the individual roots were removed with a DE3 luxator (SS White) to preserve the interradicular bone. The extracted palatal and distobuccal roots measured 12 mm and 10.5 mm, respectively, when evaluated with a Williams graduated probe. Clinical and radiographic assessment confirmed that the socket walls remained intact.

The buccolingual width of the socket was measured clinically and correlated with CBCT cross-sectional imaging. Based on these measurements, an implant diameter was selected to maintain a 3 mm gap between the buccal plate and the implant fixture. A full-thickness mucoperiosteal flap was then elevated buccally and palatally to provide access.

According to the virtual plan, an implant 10.5 mm in length and 4.6 mm in diameter had been selected, with placement at least 3 mm subcrestal to achieve primary stability in an immediate implant setting. As the residual bone height measured 8 mm, a sinus elevation of approximately 5.5 mm was required.

A flapless crestal approach was not adopted; instead, a transcrestal sinus augmentation was performed with Versah (Densah) burs. Each drill was calibrated in the navigation system prior to use, as described in the registration procedure. Osteotomy preparation began with a 2 mm Densah drill in clockwise rotation at 1200 rpm, advancing to 1 mm short of the sinus floor. A 3 mm Densah drill was then used in counter-clockwise densifying mode, extending 3 mm beyond the sinus floor.

Sinus augmentation was carried out with Rocky Mountain allograft material (Rocky Mountain Tissue Bank, USA). Grafting was performed using a 4.3 mm Densah drill operated at 600 rpm in counter-clockwise direction without irrigation, which allowed placement of graft material 3 mm above the sinus floor (Figure 7).

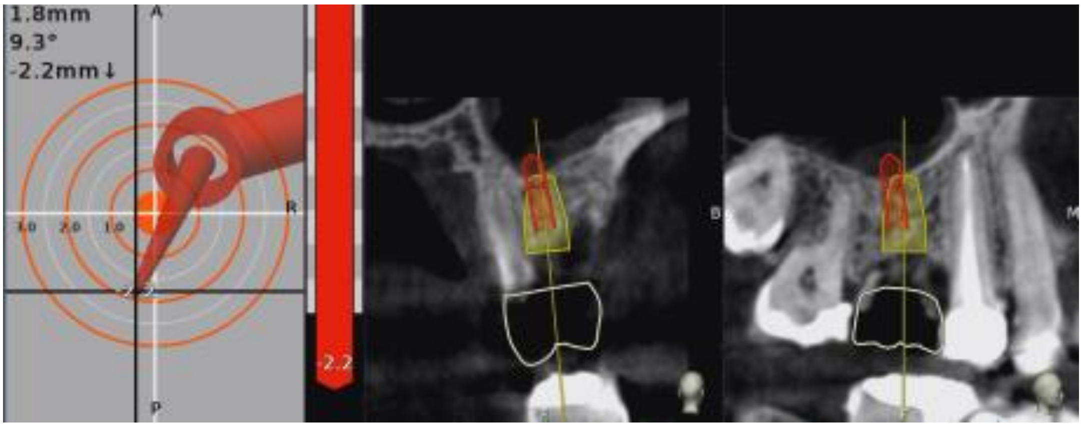

Figure 7. The 4.3 mm drill 3.9 mm beyond the sinus floor; The grafted bone is readily detectable.

III.1.5. Implant Placement

Following osteotomy preparation and sinus augmentation, the planned implant was calibrated within the navigation system and placed under continuous navigational guidance. A tapered implant measuring 10.5 mm in length and 4.6 mm in diameter was inserted in the prosthetically determined trajectory.

The implant was positioned 3 mm subcrestally, consistent with the preoperative plan, and achieved adequate primary stability at placement. A healing abutment was connected, and closure was completed with 4-0 silk sutures.

III.1.6. Postoperative Management and Prosthetic Rehabilitation

The postoperative phase was uneventful. The patient was recalled after a standard healing period of four months. At that time, implant-level impressions were obtained, and a screw-retained prosthesis was fabricated in the laboratory. The restoration was torqued to 30 Ncm, after which the abutment screw channel was sealed with Teflon tape and composite resin.

Clinical and radiographic follow-up confirmed stable osseointegration and functional rehabilitation of the implant without complications.

III.2. Randomized Split-Mouth Trial: Dynamic Navigation versus Freehand Approach

III.2.1. Study Design and Ethical Approval

This investigation was conducted as a prospective, randomized, split-mouth clinical trial designed to compare the accuracy and clinical outcomes of immediate implant placement with indirect sinus lift performed under dynamic navigation (dCAIS) versus the conventional freehand approach.

Sample size calculation was carried out using G*Power software (Version 3.1.9.7). Based on a two-tailed analysis with $\alpha = 0.05$, $\beta = 0.20$, and 80% statistical power, it was determined that a minimum of 64 implants would be required. Accordingly, 28 patients were recruited, contributing 64 implant sites; of these, 62 implants were ultimately included in the final analysis.

Ethical permission was obtained from the Institutional Ethics Committee of the Maharashtra Cosmpolitan Education Society (Ref. No.: EC/MCES/958/2024), and all procedures were performed in accordance with the Declaration of Helsinki (1975, revised 2013). Written informed consent was obtained from all participants after a detailed explanation of the study design, interventions, and possible risks and benefits.

III.2.2. Participants and Randomization

A total of 28 adult patients were enrolled, each of whom required bilateral indirect sinus lift procedures with immediate implant placement in the posterior maxilla. This yielded 64 implant sites, of which 62 were included in the final analysis.

Inclusion criteria were:

- Age between 24 and 60 years.
- Partially edentulous maxilla with at least four healthy anterior teeth.
- Residual bone height of 6–7 mm and width of 4.0–4.5 mm, as assessed by CBCT bilaterally.
- Willingness to provide informed consent and undergo repeat CBCT scans for postoperative evaluation.

Exclusion criteria were:

- Smoking more than 10 cigarettes per day.
- Metabolic bone disorders.
- Diabetes with HbA1c > 7.5%.
- History of radiotherapy to the head and neck.
- Requirement for additional bone or soft tissue grafting.

- History of chronic sinusitis.
- Fully edentulous maxilla.

Site allocation to treatment modality was randomized in a split-mouth fashion. Randomization was performed using a sealed opaque envelope method: following local anesthesia and surgical preparation, an envelope was opened to determine whether the side would be treated with dynamic navigation or by the freehand technique.

A flowchart of the study is presented in Figure 8.

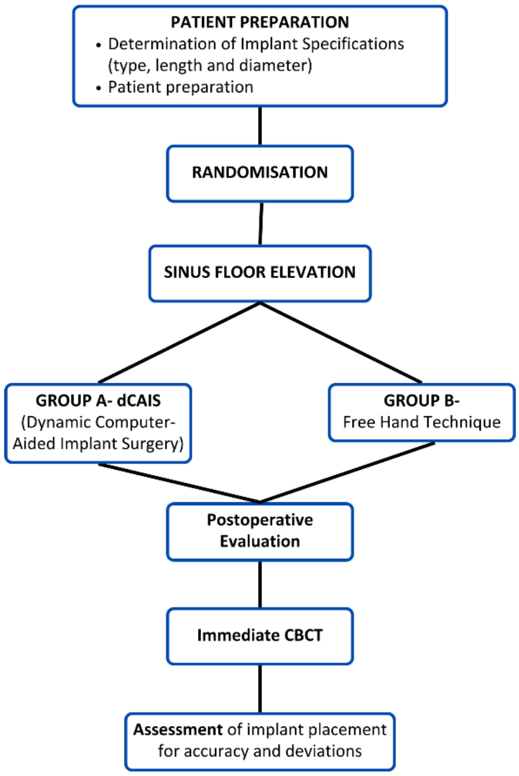

Figure 8. A flowchart of the study

III.2.3. Procedures

Implant surgeries were carried out by a single clinician who possessed extensive implantology experience, including four years of working with dynamic navigation systems and eighteen years of general implant surgery practice. Both preoperative and postoperative CBCT examinations were obtained with the KaVo OP 3D Pro unit (KaVo Kerr), using uniform exposure parameters of 0.2 mm voxel size, 100 kV, and 10 mA.

The study employed a split-mouth design in which each participant contributed one site to the dynamic navigation arm and one site to the freehand arm. Allocation was randomized using sealed opaque envelopes to ensure appropriate concealment. Once virtual planning had been completed and the operative field had been prepared, local anesthesia was administered (2% lignocaine hydrochloride with 1:80,000 adrenaline; Septodont, France, USP), after which the envelope corresponding to that patient was opened to determine whether the side in question would be treated with dynamic navigation or by freehand placement.

Because of the inherent differences between the two surgical approaches, neither the operator nor the patient could be blinded to treatment assignment. Nevertheless, all primary outcome measures were recorded by an independent implant surgeon who remained blinded throughout the evaluation process. Preoperative CBCT data and implant planning were undertaken through Navident software (ClaroNav Technology Inc., Canada).

III.2.3.1. The Dynamically Navigated Arm (dCAIS)

For sites allocated to dynamic navigation, optical tracking markers were positioned according to manufacturer recommendations, and the registration phase was performed prior to surgery. Because all implants were placed in the maxilla, the required optical headgear was secured over the nasion and stabilized with ear hooks. The Navident 2.0 platform employs the Trace-and-Place (TaP) method, which registers the patient's anatomy by selecting four reproducible landmarks on the CBCT scan and tracing those same sites intraorally with a calibrated tracing instrument. Through this process, the software aligns CBCT data with the physical maxilla. Upon successful completion of the registration, its accuracy was verified by touching various anatomical points intraorally and confirming their correspondence on the system display. After registration validation, calibration of the handpiece—equipped with its optical mount—was carried out according to manufacturer protocol. Each bur intended for use (including all osseodensification burs) was also calibrated individually. The indirect sinus elevation was then performed in accordance with the dimensions of the planned implant, and implant placement proceeded immediately afterward. A flapless approach was selected whenever adequate visibility and access permitted.

In the absence of fiducial markers on the CBCT images, the maxilla and the operative region were initially identified by adjusting the occlusal plane reference line within the software interface and selecting the upper arch (Fig. 8A). Following this step, a center-line curve was outlined to enable generation of the panoramic reconstruction required for subsequent planning (Figure 8B).

Prosthetically driven virtual planning was then completed using the Navident software, during which relevant anatomical structures, hard- and soft-tissue contours, available bone volume, and spatial relationships with adjacent and opposing teeth were carefully evaluated. Based on this assessment, the ideal buccolingual, mesiodistal, and apico-coronal orientation of the implant was determined using the sagittal, coronal, and axial CBCT views provided by the software (Figure 9).

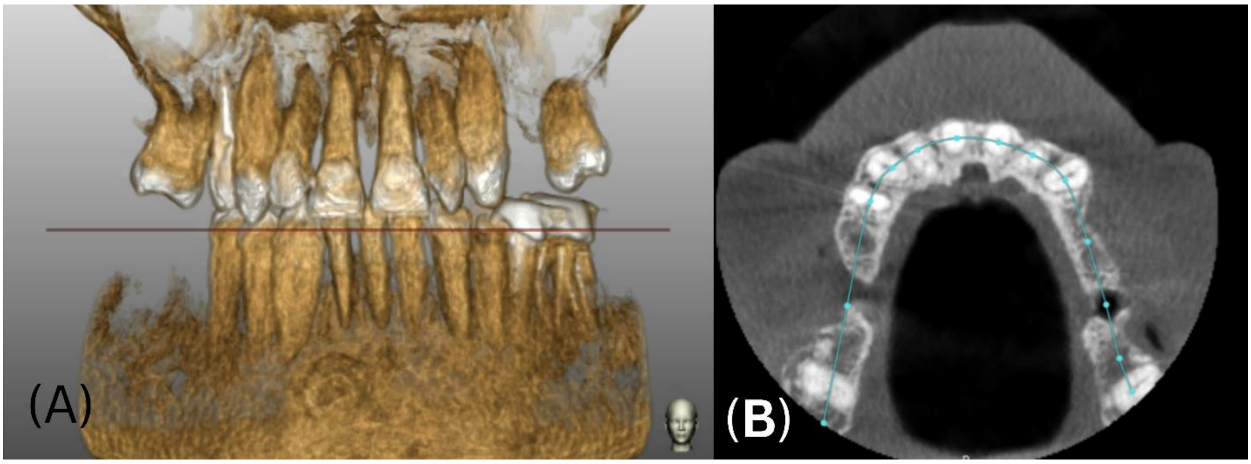

Figure 8. A- The maxilla and the area of implant surgery are located by dragging the red line to the occlusal plane; B- The jaw centerline curve required for the generation of the panoramic view.

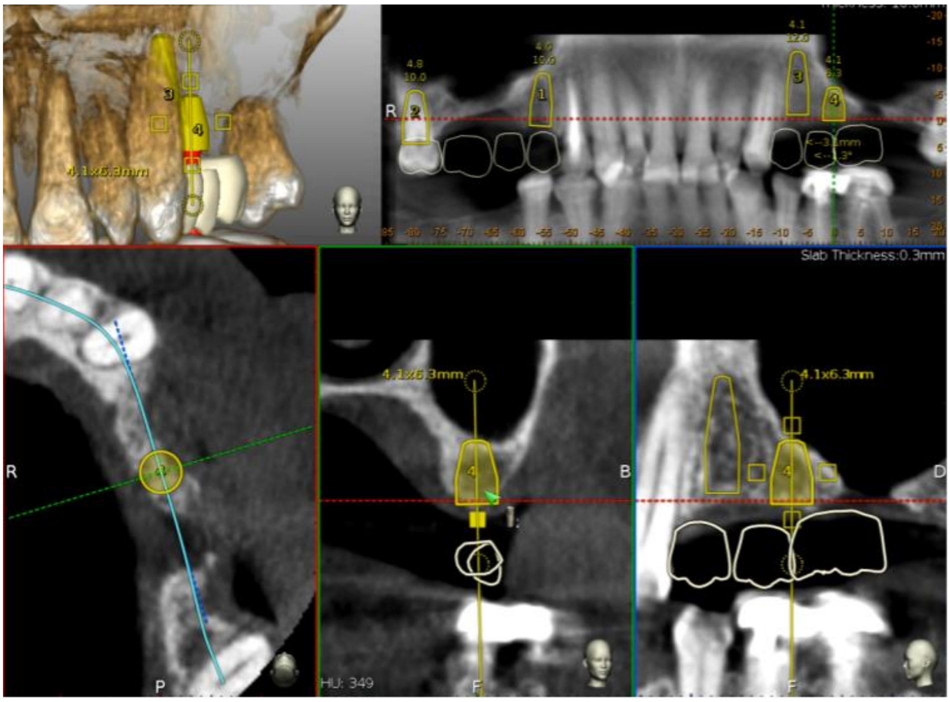

Figure 9. Prosthetically driven implant planning in the Navident software.

Trace registration was subsequently performed across both sides of the operative region. Anatomical landmarks easily identifiable on the buccal surfaces of the teeth were traced from right to left using the calibrated tracer tool.

Calibration of the tracer tool was initiated by placing the tracer tip into the dimple of the jaw-tag calibrator at an approximate distance of 50 cm from the MicronTracker camera. Once calibration was confirmed by the navigation system, the tracer tip was positioned against the buccal surface of the first selected tooth intended for landmark registration.

Tracing was performed by maintaining continuous contact between the tracer tip and the tooth surface while sliding it along the buccal, palatal, proximal, and incisal aspects in a smooth and uninterrupted motion until a score of 100 was achieved for each designated site (Figure 10). This tracing procedure was then repeated sequentially on adjacent teeth to register additional anatomical landmarks. Upon completion of tracing for all selected sites, an audible signal indicated successful registration, at which point the system finalized the alignment of the patient's anatomy with the corresponding CBCT dataset.

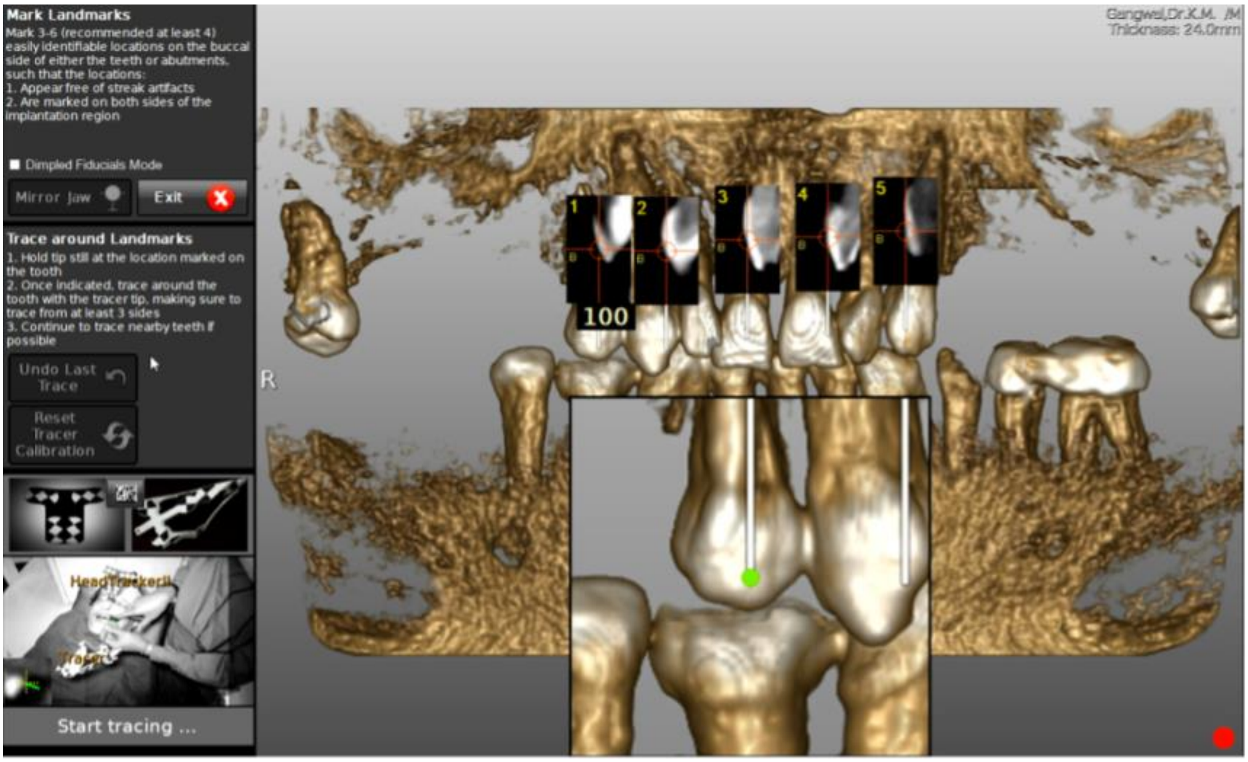

Figure 10. Trace registration was performed on both sides of the region of interest from right to left, marking landmarks that were easily identifiable on the buccal sides of the teeth.Tracing was done until a score of 100 was achieved for each selected tracer site.

Accuracy verification followed, after which the DrillTag was attached to the 20:1 contra-angled handpiece. The handpiece chuck was circled around the jaw-tag calibration pin to establish its axis, and each drill intended for use was calibrated by placing its tip in the jaw-tag dimple. This set the drill's tip location and axial alignment relative to the DrillTag.

Intraoperative navigation guided the drill tip to the planned position by mapping its real-time spatial location onto the CBCT dataset. Registration served to align the patient's actual maxilla with the CBCT volume. A head tracker equipped with MicronTracker-compatible markers was positioned to enable continuous tracking of maxillary movement using stereoscopic vision. The setup included protective glasses and ear- and nose-supported hardware.

Transcrestal sinus elevation was undertaken using Densah burs. Following calibration of the handpiece and drills, osteotomy preparation began with the pilot bur, used under copious irrigation at 1200 rpm in a clockwise direction until reaching a depth 1 mm short of the sinus floor (Figure 11). Subsequent drills corresponding to the planned implant dimensions were operated in reverse (counterclockwise) rotation. The 2 mm Densah bur initiated the densifying phase (Figure 12), followed by the 3 mm bur advanced approximately 3 mm beyond the sinus floor after calibration, also at 1200 rpm in anticlockwise rotation. The 4 mm Densah bur was then used under irrigation at 1200 rpm in densifying mode for an additional 3–4 mm elevation. No grafting material was used, and membrane elevation followed the preplanned trajectory.

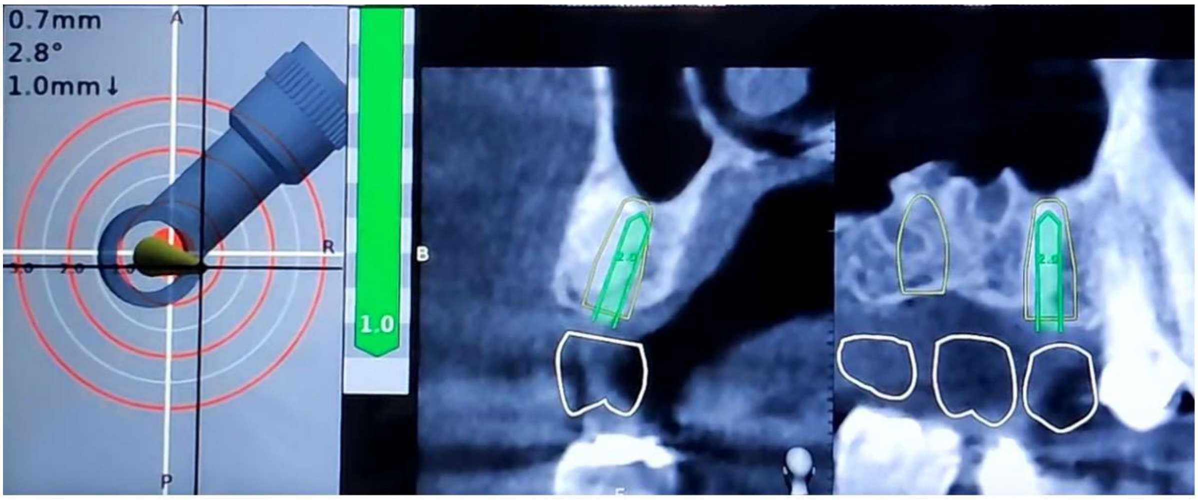

Figure 11. Osteotomy performed with the pilot drill, carried out in a clockwise direction, to a depth of 1 mm short of the sinus floor.

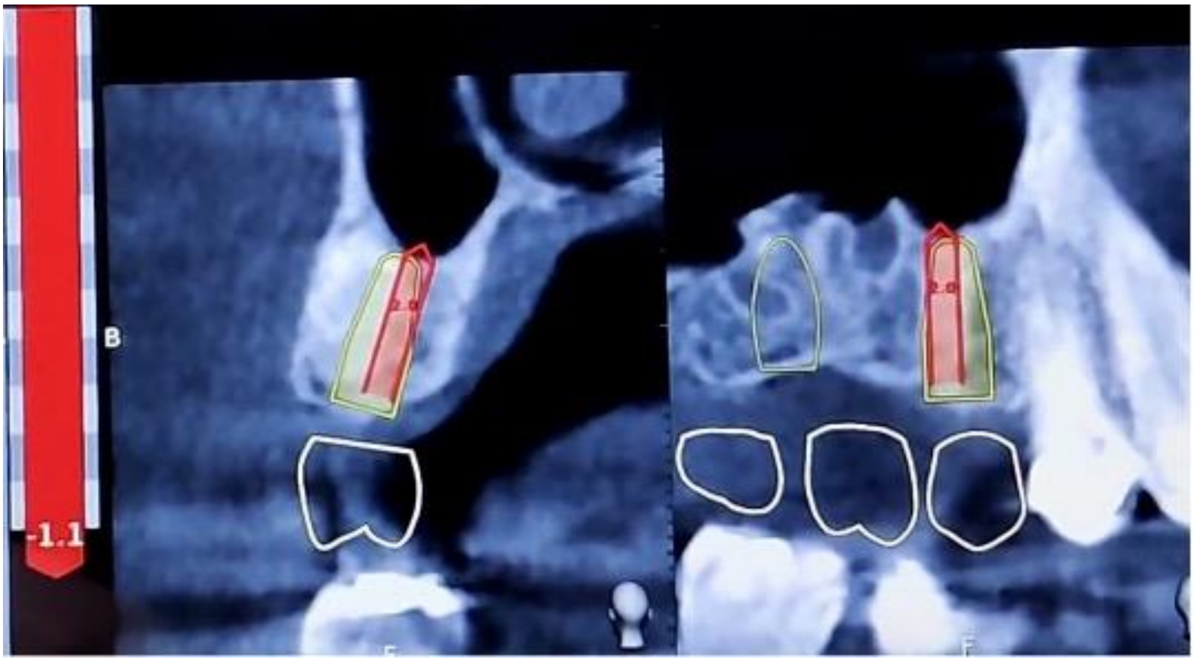

Figure 12. Osteotomy performed with Densah burs, in an anticlockwise direction, to a depth of 2.2 mm beyond the sinus floor.

III.2.3.1. The Freehand Arm

Once the dynamic navigation equipment, including the handpiece mount and headgear, had been removed, the contralateral site was treated freehand. The indirect sinus lift was completed following the osseodensification manufacturer's recommended protocol, and implants were placed according to the dimensions established during virtual planning. A flapless technique was used whenever feasible.

Immediate postoperative CBCT imaging was performed for all patients, and the resulting DICOM datasets were transferred to the EvaluNav software for subsequent analysis.

III.2.4. Outcome Variables

Evaluation of implant placement accuracy was performed by comparing the virtually planned implant positions generated from the preoperative CBCT scans with the actual implant positions recorded on the postoperative scans. This analysis was conducted using the EvaluNav software (Navident, ClaroNav Technology Inc.), which enabled precise superimposition of the preoperative and postoperative datasets. Three deviation parameters were assessed: angular deviation, horizontal deviation at the implant entry point, and horizontal deviation at the implant apex.

The characteristics of the implants—including type, diameter, and length—were selected based on software-driven planning and prosthetic, anatomical, and clinical considerations. Standard preoperative preparation included cleansing of extraoral regions with Betadine surgical scrub solution and instructing patients to perform a 30-second rinse with a 2% chlorhexidine mouthwash (Colgate Max Fresh Plax, India).

Measurements of procedural time and patient satisfaction constituted the secondary outcome variables. Procedural duration was recorded using a stopwatch, beginning at the administration of local anesthesia and concluding upon completion of the navigation setup and tracing sequence. Patient satisfaction was assessed after treatment using a standardized ten-point visual analog scale (VAS), where scores ranged from 0 (no satisfaction) to 10 (maximum satisfaction).

III.2.5. Statistical Analysis

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS, Version 21.0; IBM Corp., USA). The normality of the continuous variables was examined using both the Shapiro–Wilk and the Kolmogorov–Smirnov tests. Descriptive statistics, including means and standard deviations, were generated for all primary and secondary outcome measures. Because of the split-mouth design, comparisons between the dynamic navigation and freehand groups were carried out using paired t-tests to evaluate intra-patient differences in accuracy parameters, procedural time, and patient-reported satisfaction. P-values of less than 0.05 were considered statistically significant.

IV. RESULTS

IV.1. Case Report: Dynamic Navigation and Osseodensification in Transcrestal Sinus Augmentation

The procedure was completed uneventfully under local anaesthesia. Dynamic navigation using the trace-and-place registration protocol remained stable throughout the intervention and enabled continuous real-time tracking of the osteotomy and implant insertion.

The maxillary first molar was extracted atraumatically following sectioning of the roots, which preserved the interradicular bone. The distobuccal and palatal socket walls remained intact. Clinical and radiographic measurements confirmed an available bone height of 8 mm. Based on the prosthetically driven treatment plan, a sinus augmentation of 5.5 mm was required in order to place a 10.5 mm implant 3 mm subcrestally.

The osteotomy was prepared flaplessly with osseodensification burs in sequential diameters under copious irrigation. Drilling was performed in densifying mode, compacting the trabecular bone laterally and apically. This facilitated controlled elevation of the Schneiderian membrane. During the procedure, no perforation of the sinus membrane was detected.

A tapered titanium implant, 4.6 mm in diameter and 10.5 mm in length, was inserted into the predetermined trajectory with the assistance of dynamic navigation. The implant achieved satisfactory primary stability, and a healing abutment was placed immediately. The surgical site was closed with interrupted 4-0 silk sutures.

Postoperative healing was uneventful. The patient reported no significant discomfort, and there were no clinical or radiographic signs of infection, sinus complications, or peri-implant inflammation. After a four-month osseointegration period, implant-level impressions were made, and a screw-retained prosthesis was fabricated and delivered. The abutment screw was torqued to 30 Ncm, and the access channel sealed. Follow-up confirmed stable osseointegration, functional prosthetic rehabilitation, and absence of adverse events.

IV.2. Randomized Split-Mouth Trial: Dynamic Navigation versus Freehand Approach

A total of 28 patients were treated, contributing 64 implant sites. Two implants (one in each arm) failed to osseointegrate and were excluded from the analysis, leaving 62 implants for evaluation.

IV.2.1. Accuracy Outcomes

Dynamic navigation demonstrated significantly higher accuracy compared with freehand placement across all measured parameters. The mean horizontal deviation at the implant entry point was 1.510 ± 0.425 mm in the navigation arm and 2.687 ± 0.507 mm in the freehand arm ($p < 0.0001$). The mean angular deviation was 2.768° ± 0.627° with navigation, compared to 11.094° ± 3.390° with freehand ($p < 0.0001$). At the apex, the mean deviation was 2.719 ± 0.674 mm for navigation and 3.913 ± 0.888 mm for freehand placement ($p < 0.0001$). These results are summarized in Table 1 and illustrated in Figure 9.

Table 1. Descriptive statistics of the measured parameters across the arms of the study.

ARM		DEVIATION AT ENTRY	ANGULAR DEVIATION	DEVIATION AT EXIT
FREEHAND	Mean	2.687	11.094	3.913
	SD	0.507	3.390	0.888
	SEM	0.091	0.609	0.159
	95% CI	0.40515 to 0.67769	2.70900 to 4.53132	0.70961 to 1.18697
DNS	Mean	1.510	2.768	2.719
	SD	0.425	0.627	0.674
	SEM	0.076	0.113	0.121
	95% CI	0.33962 to 0.56809	0.50104 to 0.83809	0.53860 to 0.90092

SD: standard deviation; SEM: standard error of the mean; 95%CI: 95% confidence interval; DNS: Dynamic Navigation System

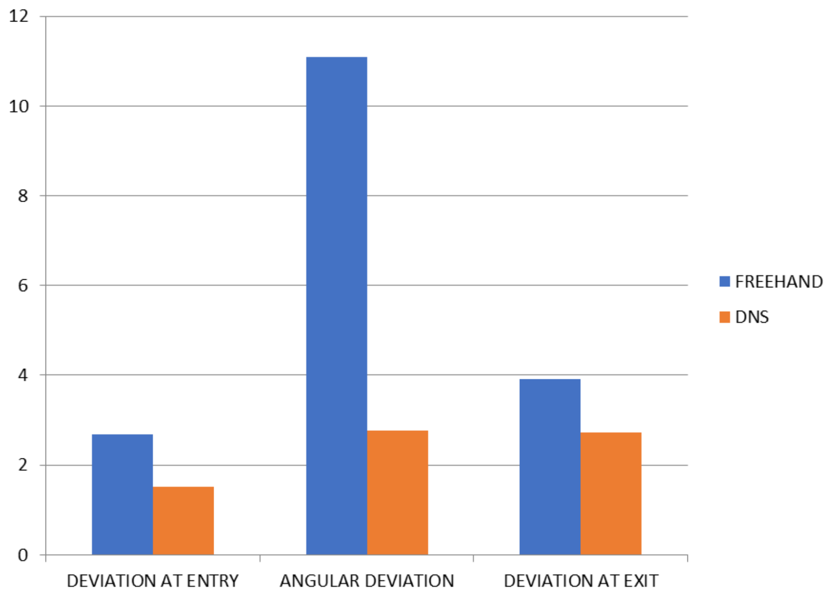

Figure 13. Mean deviation at entry, angular deviation, and deviation at exit for implants placed using the freehand technique and the dynamic navigation system (DNS).

IV.2.2. Secondary Outcomes

The mean procedural time in the navigation arm was 37.43 ± 7.01 minutes, significantly longer than in the freehand arm (34.04 ± 6.65 minutes; $p < 0.0001$). Patient satisfaction, assessed on a 10-point VAS, was slightly higher with navigation (7.96 ± 0.88) compared with freehand placement (7.61 ± 0.96; $p = 0.0155$). No sinus membrane perforations were observed in either arm. These findings are presented in Table 2 and Figure 14.

Table 2. Descriptive statistics of the secondary outcome variables.

ARM		PROCEDURAL TIME (MINUTES)	PATIENT SATISFACTION (VAS)
FREEHAND	Mean	34.04	7.61
	SD	6.65	0.96
DNS	Mean	37.43	7.96
	SD	7.01	0.88

SD: standard deviation; DNS: Dynamic Navigation System

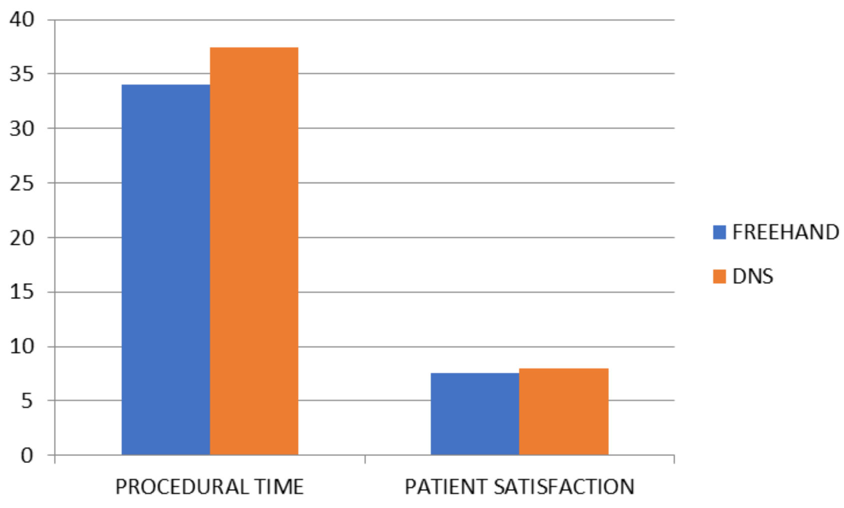

Figure 14. Comparison of procedural time and patient satisfaction between freehand implant placement and the dynamic navigation system (DNS).

V. DISCUSSION

V.1. General Considerations

In this thesis, we sought to investigate a novel surgical workflow combining dynamic navigation with osseodensification-assisted transcrestal sinus augmentation in immediate implant placement in the posterior maxilla. The overarching aim was to address well-recognized challenges in this region — limited residual bone height, limited surgical visibility, risk of membrane perforation, and the difficulty in precise implant positioning.

The case report demonstrated the technical feasibility and clinical success of using dynamic navigational guidance together with osseodensification in a transcrestal sinus augmentation and immediate implant placement. That case served as a proof of concept, illustrating how real-time guidance might mitigate risks in delicate anatomical zones. The clinical study then provided controlled comparative evidence on dynamic navigation vs. freehand technique in indirect sinus lift with immediate implants. Together, these two studies represent complementary contributions: one exploring innovation in a single patient, the other evaluating performance in a clinical cohort under controlled design.

In the broader literature, dynamic navigation (i.e. real-time guidance) in implantology has been increasingly evaluated. A systematic review and meta-analysis by Schnutenhaus et al. reported mean angular deviations of ~4.1° (95% CI, 3.12–5.10) in clinical studies, and global apex deviations of ~1.0 mm (95% CI, 0.83–1.16) in clinical settings using dynamic navigation [58]. That review concluded that dynamic navigation yields clinically acceptable accuracy, albeit with notable heterogeneity across systems. Moreover, Knipper et al. in 2024 concluded that dynamic navigation is a valid alternative to static guiding, and that freehand placement tends to have worse accuracy metrics [59]. Takács and co-workers contributed a meta-analytic overview of computer-assisted implant surgery modalities, further contextualizing the performance of navigational systems across in vitro conditions [60]. These meta-analyses establish benchmarks against which our empirical results may be compared.

Simultaneously, osseodensification (OD) has emerged as a bone instrumentation technique that preserves and compacts trabecular bone during osteotomy preparation rather than removing it. A classic review by Padhye et al. outlined the rationale, mechanism, and early clinical applications of OD in dental implants [61]. Retrospective clinical data from de Carvalho Formiga et al. on 211 implants placed with OD (some immediately loaded) showed a total survival rate of 98.1%, with 99.2% survival in the subset of immediate implants under load [62]. Later *ex vivo* studies [63] demonstrated that osseodensification enhances insertion torque (IT), removal torque (RT), and resonance-frequency-based stability (ISQ) compared with conventional drilling for both cylindrical and conical implant designs. Recent comparative trials by Fu and colleagues suggest that OD may lead to improved implant stability and reduced marginal bone loss compared to conventional drilling in adjacent implants [64]. However, a recent work by Politi et al. reported no significant superiority of OD in some contexts, highlighting that the benefits may depend on bone quality, implant macrogeometry, and surgical technique [65].

Thus, the current discussion must situate our results against this evolving evidence base. We must ask: does combining dynamic navigation and osseodensification produce additive or even synergistic improvements in safety, accuracy, primary stability, and predictability — beyond what each technique might deliver separately?

In what follows, we will (i) analyze lessons from the case study, (ii) interpret the findings of the randomized clinical study, and (iii) synthesize a comparative view, while critically assessing strengths, limitations, and future directions.

V.2. Insights from the Case Study

In the case study, we demonstrated the feasibility of combining dynamic navigation with osseodensification-assisted transcrestal sinus augmentation for immediate implant placement. Dynamic navigation has previously been shown to achieve accuracy comparable to static guides and clearly superior to freehand placement [35-37]. Our experience confirmed this potential, while also emphasizing that the system requires a period of training: the learning curve is real, but hands-on practice improves both ease of use and accuracy. This is consistent not only with dental navigation studies, but also with broader medical education research. For example, simulation training in other specialties such as gastrointestinal endoscopy has been shown to enhance performance and shorten the learning curve [43].

Compared with static guides, dynamic navigation offered several practical advantages. It provided real-time intraoperative guidance, allowing us to make alterations in the surgical plan when necessary. It required no special surgical instrumentation, could be used in situations with limited mouth opening, and offered the precision to detect and correct even minor deviations from the preoperative plan.

A novel element in our workflow was the use of the trace-and-place registration method, which differs from the fiducial stent technique described in earlier navigation protocols. Trace-and-place avoids the need for an additional CBCT scan with fiducials, thereby eliminating extra cost and radiation exposure. It also prevents errors linked to stent placement during scanning and surgery, reduces treatment costs by eliminating stent fabrication, and simplifies intraoperative handling. These advantages were confirmed in the clinical setting of our case study.

The use of osseodensification burs provided enhanced primary stability through the spring-back effect, while the compacted bone created close interlocking contact between the implant and its osteotomy walls. This compacted bone also acted as a nucleation site for new bone formation [23, 49]. Transcrestal sinus augmentation with immediate implant placement is already well accepted, with survival rates comparable to implants placed under conventional protocols [50, 51]. Our findings align with these outcomes, while showing that osseodensification can further improve bone–implant contact and stability.

A further advantage of integrating navigation with densah burs was the ability to calibrate and visualize the burs on-screen in real time as they approached the sinus floor. This provided an additional layer of safety and precision not available with other sinus elevation techniques.

Taken together, the case study established the technical feasibility and potential clinical advantages of this novel workflow. At the same time, it highlighted the need for broader evaluation: a single patient cannot answer questions of generalizability, complication risk, or long-term stability. For this reason, we extended our investigation into a randomized split-mouth clinical trial, designed to systematically compare dynamic navigation with the conventional freehand approach in a larger patient cohort.

V.3. Findings from the Randomized Split-Mouth Trial

In the randomized split-mouth clinical study, we systematically compared dynamic navigation with the freehand approach for indirect sinus lift and immediate implant placement. The results confirmed that dynamic navigation provides a significant improvement in the accuracy of implant positioning while maintaining comparable procedural efficiency and patient satisfaction

Implant deviation at entry, apex, and angulation were all significantly lower with dynamic navigation than with the freehand technique. The mean angular deviation in the navigation arm was approximately 2.8°, compared with more than 11° in the freehand arm, while entry and apex deviations were reduced by more than 1 mm each [35, 36, 38]. These results correspond closely with previous reports showing that dynamic systems consistently achieve mean angular deviations below 4°, confirming a clinically acceptable level of accuracy [12].

Our findings therefore support the consensus that computer-assisted implant surgery—particularly dynamic systems—reduces variability and improves positional precision compared with manual placement. This improvement has direct clinical implications: smaller angular errors limit prosthetic discrepancies, reduce the risk of sinus or cortical perforation, and improve esthetic and functional outcomes. Comparable findings were reported in other split-mouth designs, such as that of Aydemir and Arısan [38], who observed similarly reduced deviations in dynamically guided implants.

The navigation arm exhibited no instances of Schneiderian membrane perforation, and all implants remained within safe anatomical boundaries. This observation emphasizes that real-time guidance and visualization of the drill trajectory near the sinus floor enhance intraoperative control. Previous studies have highlighted that dynamic navigation enables continuous visualization and adjustment, minimizing the risk of perforation during sinus elevation [48].

Dynamic navigation also facilitated more consistent implant angulation and parallelism, particularly in sites with limited residual bone height. By ensuring congruence between preoperative planning and intraoperative execution, the system reduced operator-dependent variability—a key advantage in posterior maxillary implantology.

The total procedure time was slightly longer in the dynamic navigation arm (mean ≈ 37 min) compared with the freehand arm (mean ≈ 34 min), mainly due to registration and calibration steps. This marginal increase is a reasonable trade-off for the substantially improved precision. From a patient perspective, satisfaction scores were slightly higher in the navigation arm, likely reflecting both perceived technical sophistication and the absence of complications.

These findings align with other clinical evaluations in which dynamic navigation achieved enhanced accuracy without major increases in operative time. Stefanelli et al. and Block et al. reported similar trends in their comparative analyses of navigation systems in private practice [35-37].

Both arms of the study employed osseodensification burs for transcrestal sinus elevation and implant osteotomy preparation. This design allowed us to isolate the contribution of navigation from that of the densifying technique. While osseodensification improves primary stability through bone compaction, dynamic navigation ensures optimal three-dimensional implant placement. The combination of these two modalities thus produced superior accuracy without compromising mechanical stability—a synergy that represents a contemporary evolution of the transcrestal sinus lift procedure.

Comparable findings have been reported in recent systematic reviews suggesting that the densifying approach improves torque and bone-to-implant contact [23, 62], while navigation improves spatial fidelity [12]. Our study therefore bridges these two areas under controlled clinical conditions.

The significant reductions in deviation parameters, absence of sinus complications, and high patient satisfaction indicate that dynamic navigation offers both quantitative and qualitative benefits in sinus-related implant surgery. These results validate the technique first explored in the case study, extending its proof of concept to a statistically supported clinical comparison.

V.4. A Comparative Overview

The two investigations that form the basis of this thesis—the case study and the randomized split-mouth clinical trial—represent sequential stages in the assessment of a combined workflow for transcrestal sinus augmentation and immediate implant placement using dynamic navigation and osseodensification. Considered together, they provide a coherent body of evidence for the accuracy, safety, and clinical applicability of the approach.

The case study introduced the combined use of dynamic navigation with trace-and-place registration and osseodensification in a single-tooth immediate implantation scenario. This integrated approach was grounded in prior evidence demonstrating the accuracy of dynamic navigation, the influence of structured operator training on performance, and the biological and clinical advantages of osseodensification in transcrestal sinus elevation [23, 35-37, 43, 49-51]. These prior studies established the reliability of dynamic guidance for precise implant placement, the importance of hands-on training for mastering navigation workflows, and the biological rationale for densification-assisted transcrestal sinus elevation. The case study demonstrated that these principles could be successfully integrated into a single procedure, achieving precise, minimally invasive implant placement while maintaining the integrity of the Schneiderian membrane and achieving primary stability.

The subsequent randomized split-mouth clinical trial extended this approach to a controlled comparative design, in which the same densification protocol was applied in both arms, isolating navigation as the primary variable. Previous investigations have shown that dynamically guided implant placement achieves significantly lower angular and linear deviations than freehand surgery, supporting the rationale for including navigation as the test modality in this study [35, 36, 38]. The consistent absence of membrane perforation and the uniform stability of the implants across both investigations indicate that the workflow is transferable from individual feasibility to a broader clinical context.

Across both investigations, dynamic navigation and osseodensification addressed distinct yet interrelated objectives. Navigation ensured three-dimensional precision in implant positioning, whereas osseodensification enhanced the biomechanical quality of the osteotomy through bone compaction. The integration of these techniques produced complementary effects: improved spatial accuracy, as evidenced by significantly lower entry, apex, and angular deviations in the dynamically guided arm, consistent with earlier reports on navigated implant placement [35, 36, 38], and enhanced primary stability resulting from densification-mediated bone condensation, a phenomenon well documented in previous investigations of the osseodensification technique [23]. Together, these mechanical and geometric advantages contributed to a reproducible and safe clinical outcome. Both studies confirmed that dynamic navigation requires initial calibration and verification steps that extend operative time but provide measurable improvements in precision. The learning curve observed during the development of the workflow was consistent with previous reports that emphasize the effect of structured training on navigational accuracy [35-37, 43]. Comparable findings have been reported by Ma et al., who demonstrated a progressive reduction in angular deviation with increasing operator experience [66]. Despite the additional preparation time, the overall procedural efficiency and patient satisfaction were preserved, confirming the clinical practicality of the method.

The outcomes obtained in both studies align with the pooled evidence on guided implant surgery. A recent meta-analysis reported mean angular deviations of approximately 3.8° and global entry deviations near 1 mm for dynamic navigation systems, values that are markedly superior to freehand placement and comparable to static surgical guides [58]. Other prospective comparisons have reached similar conclusions, indicating that both static and dynamic systems significantly outperform freehand approaches in terms of positional accuracy [45].

In relation to bone preparation, clinical data continue to substantiate the advantages of osseodensification over conventional drilling. Veluri et al. found greater insertion torque and improved graft stability in transcrestal sinus lift procedures performed with densifying burs, while volumetric analysis of 3D-guided densification protocols has confirmed predictable bone gain and implant stability in the posterior maxilla [67]. These findings support the rationale for combining navigation and densification in a single operative sequence.

The parallel consistency of results between the case study and the split-mouth trial supports the reliability of the combined workflow. The evidence indicates that navigated osseodensification allows transcrestal sinus elevation to be performed with high precision and minimal risk of membrane perforation, while achieving mechanical conditions favorable for immediate implant placement. Further research should aim to validate these findings in multicentre settings and to quantify the long-term biological and prosthetic outcomes. The trace-and-place registration protocol, by reducing radiation exposure and eliminating stent fabrication, merits particular attention for standardization and external verification.

V.5. Strengths and Limitations

The present work is built on two methodologically related investigations. Both the case study and the randomized split-mouth trial were conducted by the same operator using identical radiographic equipment and planning software, which ensured a uniform technical standard and minimized inter-operator and inter-equipment variability. The use of the trace-and-place registration protocol eliminated the need for additional fiducial scans, thereby reducing radiation exposure and patient cost while simplifying workflow [35-37, 49]. This registration method, together with real-time navigational tracking, allowed consistent alignment between virtual planning and intraoperative execution across all treated sites.

The split-mouth design represented a key methodological strength by providing internal control within each patient. This configuration minimized biological variability and enabled direct comparison between the navigated and freehand procedures under identical anatomical and systemic conditions [35, 36, 38]. Moreover, the identical osseodensification protocol applied in both arms ensured that mechanical variables related to bone preparation remained constant, isolating dynamic navigation as the independent variable.

The use of CBCT for both planning and postoperative evaluation provided three-dimensional accuracy assessment with standardized voxel size and exposure parameters, contributing to reliable quantitative comparison [36, 37]. Consistency in surgical protocol, implant design, and operator expertise further enhanced the reproducibility of the results.

Despite these strengths, several limitations should be acknowledged when interpreting the findings. The overall sample size of the clinical trial, although statistically powered for accuracy outcomes, remains limited for detecting less frequent complications or subtle biological differences. Larger multicentre cohorts are required to confirm the generalizability of these results. The single-operator design simultaneously constitutes a strength and a limitation. While it ensures procedural consistency, it also restricts external validity because the outcomes may partly reflect individual operator skill and familiarity with the navigation system. As highlighted in previous evaluations of learning curves for dynamic navigation, operator experience exerts a measurable influence on accuracy [66]. Broader validation across surgeons with varying levels of experience is therefore necessary.

Another limitation relates to the comparative framework: the absence of a static-guide control arm limits conclusions about the relative performance of dynamic versus static systems. Although previous research suggests comparable accuracy between these approaches [42, 58], direct comparison within the same clinical setting would enhance interpretability.

Accuracy assessment in this thesis relied on CBCT superimposition, which, despite standardized parameters, carries inherent registration and segmentation error. Minor voxel-based mismatches may introduce sub-millimetric deviations independent of true surgical inaccuracy [35, 36].
The clinical follow-up period was limited to early postoperative assessment. While this interval suffices for evaluating positional accuracy and short-term stability, it does not capture long-term biological parameters such as marginal bone maintenance, prosthetic success, or sinus membrane health. Longitudinal data are needed to establish whether the early accuracy advantages of dynamic navigation translate into sustained functional and aesthetic outcomes.
Finally, patient inclusion criteria restricted the trial to anatomically favourable cases with residual bone height between six and seven millimetres. As a result, the findings may not fully extend to more complex scenarios involving extreme pneumatization, sinus septa, or compromised bone quality. Future studies should examine these variables to delineate the true boundaries of the technique's applicability.
The limitations identified here are consistent with those noted in other early-phase clinical studies on dynamic navigation. They reflect the progressive nature of innovation in guided implantology, where feasibility and accuracy typically precede long-term outcome research. Importantly, none of these constraints compromise the internal validity of the findings. The data collectively demonstrate that within the defined clinical indications, dynamic navigation integrated with osseodensification is a precise, safe, and reproducible workflow for transcrestal sinus augmentation and immediate implant placement.

V.6. Future Directions and Clinical Implications

Dynamic navigation integrated with osseodensification has demonstrated precision, safety, and clinical feasibility; however, further research is required to consolidate these findings.

Future investigations should aim to validate these results in multicentre settings with larger and more diverse patient populations. Multicentre collaboration would allow comparison across different levels of surgical experience, equipment configurations, and anatomical variations, thereby improving external validity. Such studies should also incorporate different navigation systems and implant designs to verify whether the accuracy and safety benefits observed are system-independent.

In addition, the inclusion of a static surgical guide arm in future randomized trials would provide a complete comparative framework. While meta-analyses have indicated comparable accuracy between static and dynamic modalities [45, 58], head-to-head trials under identical conditions would clarify the specific advantages of dynamic navigation, particularly its intraoperative adaptability and reduced need for template fabrication.

Further refinement of navigation systems is expected through the integration of artificial intelligence (AI), augmented reality (AR), and robotic assistance. Real-time motion compensation and AI-driven registration algorithms may reduce calibration errors and enhance intraoperative stability [68]. Robotic-assisted implantology, which offers automated execution within navigational parameters, has already achieved sub-millimetric accuracy in early studies [45]. Hybrid workflows combining dynamic navigation with robotic guidance or piezoelectric instrumentation could expand precision-based approaches to more complex anatomical situations, including severely pneumatized sinuses and atrophic maxillae.

To date, the evidence on dynamic navigation has primarily focused on positional accuracy and short-term safety. Longitudinal follow-up is necessary to determine whether the improved accuracy observed translates into superior biological stability and prosthetic longevity. Future studies should therefore assess marginal bone levels, peri-implant soft-tissue response, sinus membrane integrity, and prosthetic alignment over extended periods. In addition, patient-reported outcomes should be incorporated systematically, as improved accuracy and less invasive procedures may correlate with enhanced comfort, recovery, and satisfaction [35, 38].

Another priority is the standardization of training in dynamic navigation. Structured, simulation-based learning programs have proven effective in reducing the learning curve for other surgical navigation applications [37, 43]. Similar curricula adapted to dental navigation could facilitate skill acquisition and make the technology more accessible to practitioners with varying levels of experience.

Cost-effectiveness analyses are also warranted. Although dynamic navigation systems require initial investment, their potential to prevent complications, shorten treatment timelines, and reduce the need for prosthetic corrections may offset expenditure in the long term. Comparative economic evaluations between navigated, static, and freehand workflows would provide valuable guidance for evidence-based adoption in clinical practice.

The integration of navigation with osseodensification represents a shift toward mechanically and geometrically optimized implantology. The combination of spatial guidance and bone preservation aligns with the broader paradigm of biologically oriented, minimally invasive surgery. The approach may be particularly valuable in anatomically challenging sites, where bone quality and spatial limitations coincide, and where precise sinus management is essential for long-term success.

VI. CONCLUSIONS

Based on the presented studies, we draw the following conclusions, which we consider as the new scientific findings of the thesis:

1.Dynamic navigation can be successfully combined with osseodensification for transcrestal sinus augmentation and immediate implant placement. The case study demonstrated that this integrated workflow is technically feasible, enables controlled transcrestal membrane elevation, and preserves the integrity of the Schneiderian membrane while achieving adequate primary stability.

2. Trace-and-place registration provides a reliable and radiation-free method for dynamic navigation in posterior maxillary implant surgery. Its clinical application in the case study confirmed accurate intraoperative tracking without the need for fiducial markers or additional CBCT scans, thereby simplifying workflow and reducing patient exposure.

3. Dynamic navigation significantly improves the accuracy of implant placement compared with freehand surgery in indirect sinus lift procedures. In the randomized split-mouth trial, dynamically guided implants exhibited substantially lower entry, apex, and angular deviations, indicating that navigation enhances the fidelity of transferring the preoperative plan to the surgical field.

4. The use of osseodensification in both study arms establishes that improvements in spatial accuracy are attributable to navigation rather than mechanical preparation of the osteotomy.
The consistent primary stability across arms confirms that densification provides a uniform biomechanical baseline, isolating navigational guidance as the determinant of positional precision.

5. Dynamic navigation supports safe transcrestal sinus augmentation when residual bone height is limited. Across both studies, no Schneiderian membrane perforations were observed, suggesting that real-time trajectory control contributes to procedural safety in anatomically constrained regions.

6. Dynamic navigation does not compromise procedural efficiency or patient experience. Although calibration and registration require additional steps, total operative time remained comparable between navigated and freehand approaches, and patient satisfaction scores were high in both arms of the split-mouth trial.

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REFERENCES

1. Adell R, Lekholm U, Rockler B, Branemark PI. A 15-year study of osseointegrated implants in the treatment of the edentulous jaw. *Int J Oral Surg* 1981;10(6):387-416.10.1016/s0300-9785(81)80077-4

2. Branemark PI, Hansson BO, Adell R, Breine U, Lindstrom J, Hallen O, et al. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. *Scand J Plast Reconstr Surg Suppl* 1977;16:1-132

3. Albrektsson T, Zarb GA. Current interpretations of the osseointegrated response: clinical significance. *Int J Prosthodont* 1993;6(2):95-105

4. Schulte W, Heimke G. [The Tübinger immediate implant]. *Quintessenz* 1976;27(6):17 - 23

5. Lazzara RJ. Immediate implant placement into extraction sites: surgical and restorative advantages. *The International journal of periodontics & restorative dentistry* 1989;9(5):332-43

6. Boyne PJ, James RA. Grafting of the maxillary sinus floor with autogenous marrow and bone. *Journal of Oral Surgery* 1980;38(8):613-6

7. Tatum H. Maxillary and sinus implant reconstructions. *Dental clinics of North America* 1986;30(2):207-29.10.1016/s0011-8532(22)02107-3

8. Smiler DG, Johnson PW, Lozada JL, Misch C, Rosenlicht JL, Tatum OH, et al. Sinus lift grafts and endosseous implants. Treatment of the atrophic posterior maxilla. *Dental clinics of North America* 1992;36(1):151-86;discussion87.10.1016/s0011-8532(22)02464-8

9. Summers RB. A new concept in maxillary implant surgery: the osteotome technique. *Compendium (Newtown, Pa)* 1994;15(2):152,4-6,8passim;quiz62

10. Davarpanah M, Martinez H, Tecucianu JF, Hage G, Lazzara R. The Modified Osteotome Technique. *International Journal of Periodontics and Restorative Dentistry* 2001;21(6):599-607

11. Tan WC, Lang NP, Zwahlen M, Pjetursson BE, editors. A systematic review of the success of sinus floor elevation and survival of implants inserted in combination with sinus floor elevation Part II: Transalveolar technique. Journal of Clinical Periodontology; 2008.

12. Jorba-García A, González-Barnadas A, Camps-Font O, Figueiredo R, Valmaseda-Castellón E. Accuracy assessment of dynamic computer–aided implant placement: a systematic review and meta-analysis. *Clinical Oral Investigations* 2021;25(5):2479-94.10.1007/s00784-021-03833-8

13. Iwanaga J, Tanaka T, Ibaragi S, Okui T, Hamaguchi J, Min S, et al. Revisiting major anatomical risk factors of maxillary sinus lift and soft tissue graft harvesting for dental implant surgeons. *Surgical and Radiologic Anatomy* 2020;42(9):1025-31.10.1007/s00276-020-02468-w

14. Morgan N, Meeus J, Shujaat S, Cortellini S, Bornstein MM, Jacobs R. CBCT for Diagnostics, Treatment Planning and Monitoring of Sinus Floor Elevation Procedures. *Diagnostics* 2023;13(10).10.3390/diagnostics13101684

15. Al-Dajani M. Recent Trends in Sinus Lift Surgery and Their Clinical Implications. *Clinical Implant Dentistry and Related Research* 2016;18(1):204-12.10.1111/cid.12275

16. Pjetursson BE, Tan WC, Zwahlen M, Lang NP. A systematic review of the success of sinus floor elevation and survival of implants inserted in combination with sinus floor elevation. *J Clin Periodontol* 2008;35(8 Suppl):216-40.10.1111/j.1600-051X.2008.01272.x

17. Wallace SS, Froum SJ. Effect of maxillary sinus augmentation on the survival of endosseous dental implants. A systematic review. *Ann Periodontol* 2003;8(1):328-43.10.1902/annals.2003.8.1.328

18. Moraschini V, Uzeda MG, Sartoretto SC, Calasans-Maia MD. Maxillary sinus floor elevation with simultaneous implant placement without grafting materials: a systematic review and meta-analysis. *International Journal of Oral and Maxillofacial Surgery* 2017;46(5):636-47.10.1016/j.ijom.2017.01.021

19. Del Fabbro M, Wallace SS, Testori T. Long-term implant survival in the grafted maxillary sinus: a systematic review. *Int J Periodontics Restorative Dent* 2013;33(6):773-83.10.11607/prd.1288

20. Esposito M, Grusovin MG, Rees J, Karasoulos D, Felice P, Alissa R, et al. Effectiveness of sinus lift procedures for dental implant rehabilitation: a Cochrane systematic review. *Eur J Oral Implantol* 2010;3(1):7-26

21. Jensen OT, Shulman LB, Block MS, Lacono VJ. Report of the sinus consensus conference of 1996. *International Journal of Oral and Maxillofacial Implants* 1998;13(SUPPL.):11-32

22. Vercellotti T, De Paoli S, Nevins M. The piezoelectric bony window osteotomy and sinus membrane elevation: introduction of a new technique for simplification of the sinus augmentation procedure. *Int J Periodontics Restorative Dent* 2001;21(6):561-7

23. Huwais S, Meyer EG. A novel osseous densification approach in implant osteotomy preparation to increase biomechanical primary stability, bone mineral density, and bone-to-implant contact. *International Journal of Oral and Maxillofacial Implants* 2017;32(1):27-36.10.11607/jomi.4817

24. Lahens B, Neiva R, Tovar N, Alifarag AM, Jimbo R, Bonfante EA, et al. Biomechanical and histologic basis of osseodensification drilling for endosteal implant placement in low density bone. An experimental study in sheep. *J Mech Behav Biomed Mater* 2016;63:56-65.10.1016/j.jmbbm.2016.06.007

25. Pai UY, Rodrigues SJ, Talreja KS, Mundathaje M. Osseodensification - A novel approach in implant dentistry. *J Indian Prosthodont Soc* 2018;18(3):196-200.10.4103/jips.jips_292_17

26. Shalash M, Mounir M, Elbanna T. Evaluation of crestal sinus floor elevation in cases exhibiting an oblique sinus floor with a residual bone height of 4.0-7.0 mm using Densah burs with simultaneous implant placement: a prospective clinical study. *Int J Implant Dent* 2023;9(1):41.10.1186/s40729-023-00510-1

27. Elghobashy MTM, Shaaban AM, Melek LNF. Radiographic comparison between Densah burs and osteotome for graftless internal sinus lifting with simultaneous implant placement: a randomized clinical trial. *Int J Oral Maxillofac Surg* 2023;52(3):388-95.10.1016/j.ijom.2022.06.020

28. Gaikwad AM, Joshi AA, Nadgere JB. Biomechanical and histomorphometric analysis of endosteal implants placed by using the osseodensification technique in animal models: A systematic review and meta-analysis. *J Prosthet Dent* 2022;127(1):61-70.10.1016/j.prosdent.2020.07.004

29. Alajami MM, Elsheikh HA, Abo El-Farag SA, Mansour NA. Antral membrane balloon technique versus Densah bur in crestal sinus lift with simultaneous implant placement: a randomized clinical trial. *BMC Oral Health* 2024;24(1):916.10.1186/s12903-024-04609-8

30. Oillic A, Varazzani A, Fitouchi B, Carlier A, Bouletreau P. Navigation in oral surgery: a systematic review. *Journal of Oral Medicine and Oral Surgery* 2023;29(4).10.1051/mbcb/2023039

31. Tahmaseb A, Wu V, Wismeijer D, Coucke W, Evans C. The accuracy of static computer-aided implant surgery: A systematic review and meta-analysis. *Clin Oral Implants Res* 2018;29 Suppl 16:416-35.10.1111/clr.13346

32. Vercruyssen M, Hultin M, Van Assche N, Svensson K, Naert I, Quirynen M. Guided surgery: accuracy and efficacy. *Periodontol 2000* 2014;66(1):228-46.10.1111/prd.12046

33. Varga E, Jr., Antal M, Major L, Kiscsatari R, Braunitzer G, Piffko J. Guidance means accuracy: A randomized clinical trial on freehand versus guided dental implantation. *Clin Oral Implants Res* 2020;31(5):417-30.10.1111/clr.13578

34. Van de Wiele G, Teughels W, Vercruyssen M, Coucke W, Temmerman A, Quirynen M. The accuracy of guided surgery via mucosa-supported stereolithographic surgical templates in the hands of surgeons with little experience. *Clin Oral Implants Res* 2015;26(12):1489-94.10.1111/clr.12494

35. Block MS, Emery RW, Cullum DR, Sheikh A. Implant Placement Is More Accurate Using Dynamic Navigation. *Journal of Oral and Maxillofacial Surgery* 2017;75(7):1377-86.10.1016/j.joms.2017.02.026

36. Block MS, Emery RW, Lank K, Ryan J. Implant placement accuracy using dynamic navigation. *International Journal of Oral and Maxillofacial Implants* 2017;32(1):92-9.10.11607/jomi.5004

37. Stefanelli LV, DeGroot BS, Lipton DI, Mandelaris GA. Accuracy of a dynamic dental implant navigation system in a private practice. *International Journal of Oral and Maxillofacial Implants* 2019;34(1):205-13.10.11607/JOMI.6966

38. Aydemir CA, Arısan V. Accuracy of dental implant placement via dynamic navigation or the freehand method: A split-mouth randomized controlled clinical trial. *Clinical Oral Implants Research* 2020;31(3):255-63.10.1111/clr.13563

39. Stefanelli LV, Mandelaris GA, DeGroot BS, Gambarini G, De Angelis F, Di Carlo S. Accuracy of a Novel Trace-Registration Method for Dynamic Navigation Surgery. *Int J Periodontics Restorative Dent* 2020;40(3):427-35.10.11607/prd.4420

40. D'Haese J, Ackhurst J, Wismeijer D, De Bruyn H, Tahmaseb A. Current state of the art of computer-guided implant surgery. *Periodontol 2000* 2017;73(1):121-33.10.1111/prd.12175

41. Gargallo-Albiol J, Barootchi S, Salomo-Coll O, Wang HL. Advantages and disadvantages of implant navigation surgery. A systematic review. *Ann Anat* 2019;225:1-10.10.1016/j.aanat.2019.04.005

42. Wu D, Zhou L, Yang J, Zhang B, Lin Y, Chen J, et al. Accuracy of dynamic navigation compared to static surgical guide for dental implant placement. *Int J Implant Dent* 2020;6(1):78.10.1186/s40729-020-00272-0

43. Koch AD, Ekkelenkamp VE, Haringsma J, Schoon EJ, De Man RA, Kuipers EJ. Simulated colonoscopy training leads to improved performance during patient-based assessment. *Gastrointestinal Endoscopy* 2015;81(3):630-6.10.1016/j.gie.2014.09.014

44. Younis H, Lv C, Xu B, Zhou H, Du L, Liao L, et al. Accuracy of dynamic navigation compared to static surgical guides and the freehand approach in implant placement: a prospective clinical study. *Head Face Med* 2024;20(1):30.10.1186/s13005-024-00433-1

45. Khaohoen A, Powcharoen W, Sornsuwan T, Chaijareenont P, Rungsiyakull C, Rungsiyakull P. Accuracy of implant placement with computer-aided static, dynamic, and robot-assisted surgery: a systematic review and meta-analysis of clinical trials. *BMC Oral Health* 2024;24(1):359.10.1186/s12903-024-04033-y

46. Zhou W, Tao B, Wu Y, Wang F. Novel use of dynamic navigation for guiding a piezoelectric device during window osteotomy for maxillary sinus floor elevation in complex clinical scenarios. *International Journal of Oral and Maxillofacial Surgery* 2024;53(12):1068-72.10.1016/j.ijom.2024.09.013

47. Dotia A, Selvaganesh S, Abhinav R, Nesappan T, Abhinavch R. Dynamic navigation protocol for direct sinus lift and simultaneous implant placement: a case report. *Cureus* 2024;16

48. Yang M, Ma Y, Han W, Qu Z. The safety of maxillary sinus floor elevation and the accuracy of implant placement using dynamic navigation. *PLoS ONE* 2024;19(5 May).10.1371/journal.pone.0304091

49. Trisi P, Berardini M, Falco A, Podaliri Vulpiani M. New osseodensification implant site preparation method to increase bone density in low-density bone: In vivo evaluation in sheep. *Implant Dentistry* 2016;25(1):24-31.10.1097/ID.0000000000000358

50. Barone A, Toti P, Quaranta A, Derchi G, Covani U. The Clinical Outcomes of Immediate Versus Delayed Restoration Procedures on Immediate Implants: A Comparative Cohort Study for Single-Tooth Replacement. *Clinical Implant Dentistry and Related Research* 2015;17(6):1114-26.10.1111/cid.12225

51. Tarnow DP, Chu SJ. Human histologic verification of osseointegration of an immediate implant placed into a fresh extraction socket with excessive gap distance without primary flap

closure, graft, or membrane: A case report. *International Journal of Periodontics and Restorative Dentistry* 2011;31(5):515-21

52. Werny JG, Frank K, Fan S, Sagheb K, Al-Nawas B, Narh CT, et al. Freehand vs. computer-aided implant surgery: a systematic review and meta-analysis-part 1: accuracy of planned and placed implant position. *Int J Implant Dent* 2025;11(1):35.10.1186/s40729-025-00622-w

53. Deng H, Geng N, Yang S, Dou X, Wang H, Chen S, et al. Clinical study of dynamic navigation-assisted immediate implant placement in posterior maxillary alveolar bone defects. *BMC Oral Health* 2025;25(1):617.10.1186/s12903-025-05976-6

54. Wu BZ, Ma FF, Sun F. Analysis of the accuracy of a dynamic navigation system when performing dental implant surgery with transcrestal sinus floor elevation: A pilot study. *J Dent Sci* 2023;18(4):1747-55.10.1016/j.jds.2022.12.014

55. Zhou W, Tao B, Wu Y, Wang F. Novel use of dynamic navigation for guiding a piezoelectric device during window osteotomy for maxillary sinus floor elevation in complex clinical scenarios. *Int J Oral Maxillofac Surg* 2024;53(12):1068-72.10.1016/j.ijom.2024.09.013

56. Jain S, Solanki A. A dynamic surgical navigational approach for immediate implantation and transcrestal sinus augmentation. *Journal of Indian Society of Periodontology* 2021;25(5):451-6.10.4103/jisp.jisp_581_20

57. Jain S, Nagy K, Bhalerao A. Accuracy and safety of dynamic navigation vs. freehand approach in indirect sinus lift and immediate implant placement: A split mouth clinical study. *J Dent* 2025;160:105866.10.1016/j.jdent.2025.105866

58. Schnutenhaus S, Edelmann C, Knipper A, Luthardt RG. Accuracy of Dynamic Computer-Assisted Implant Placement: A Systematic Review and Meta-Analysis of Clinical and In Vitro Studies. *J Clin Med* 2021;10(4).10.3390/jcm10040704

59. Knipper A, Kuhn K, Luthardt RG, Schnutenhaus S. Accuracy of Dental Implant Placement with Dynamic Navigation-Investigation of the Influence of Two Different Optical Reference Systems: A Randomized Clinical Trial. *Bioengineering (Basel)* 2024;11(2).10.3390/bioengineering11020155

60. Takacs A, Hardi E, Cavalcante BGN, Szabo B, Kispelyi B, Joob-Fancsaly A, et al. Advancing accuracy in guided implant placement: A comprehensive meta-analysis: Meta-Analysis evaluation of the accuracy of available implant placement Methods. *J Dent* 2023;139:104748.10.1016/j.jdent.2023.104748

61. Padhye NM, Padhye AM, Bhatavadekar NB. Osseodensification -- A systematic review and qualitative analysis of published literature. *J Oral Biol Craniofac Res* 2020;10(1):375-80.10.1016/j.jobcr.2019.10.002

62. de Carvalho Formiga M, Grzech-Leśniak K, Moraschini V, Shibli JA, Neiva R. Effects of Osseodensification on Immediate Implant Placement: Retrospective Analysis of 211 Implants. *Materials (Basel)* 2022;15(10).10.3390/ma15103539

63. de Carvalho Formiga M, da Silva HDP, Ghiraldini B, Siroma RS, Ardelean LC, Piattelli A, et al. Effects of Osseodensification on Primary Stability of Cylindrical and Conical Implants-An Ex Vivo Study. *J Clin Med* 2023;12(11).10.3390/jcm12113736

64. Fu PS, Du JK, Tseng FC, Hsu HJ, Lan TH, Kung JC, et al. Comparison of implant stability and marginal bone loss between osseodensification and conventional osteotomy at adjacent implant sites. *J Dent Sci* 2025;20(2):1002-7.10.1016/j.jds.2024.11.019

65. Politi I, Honari B, Winning L, Polyzois I. The Effect of Osseodensification on Implant Stability and Marginal Bone Levels: A Randomized Control Clinical Trial. *Clin Exp Dent Res* 2025;11(1):e70126.10.1002/cre2.70126

66. Ma L, Ye M, Wu M, Chen X, Shen S. A retrospective study of dynamic navigation system-assisted implant placement. *BMC Oral Health* 2023;23(1):759.10.1186/s12903-023-03481-2

67. Veluri S, Gottumukkala S, Mantena SR, Penmetsa GS, Ramesh K, Pasupuleti MK, et al. Clinical and radiological outcomes of osseodensification and crestal approach sinus kit for transcrestal sinus elevation - A randomized clinical trial. *Dent Res J (Isfahan)* 2025;22:17.10.4103/drj.drj_711_23

68. Pisla D, Bulbucan V, Hedeșiu M, Vaida C, Cailean A, Mocan R, et al. Real-Time Motion Compensation for Dynamic Dental Implant Surgery. *Journal of Clinical Medicine* 2025;14(18):6429

APPENDIX