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RESEARCH

Intra-operative navigation systems: advancing precision and safety in oral and maxillofacial surgery

Savitha Lakshmi Raghavan[1*]

[1] Department of Oral and Maxillofacial Surgery, Sree Balaji Dental College and Hospital, Bharath institute of Higher Education and Research, Chennai, India

[*]**Correspondence:**
Savitha Lakshmi Raghavan,
savitharaghav15@gmail.com

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Since their initial introduction in neurosurgical applications approximately two decades ago, computer-assisted surgical navigation systems have progressively been adopted within the domain of craniomaxillofacial surgery. The intricate anatomy of the oral and maxillofacial region is characterized by its proximity to vital adjacent structures, necessitates heightened precision during operative procedures. Surgical navigation technologies facilitate real-time intraoperative localization and enable accurate translation of preoperative planning into the surgical field, thereby enhancing procedural accuracy and patient safety. Surgical navigation enable surgeons to navigate complex anatomical regions while assessing the accuracy and effectiveness of preoperative planning, intraoperative execution and postoperative outcomes. Within the field of oral and maxillofacial surgery, these systems have emerged as indispensable adjuncts, enhancing both the safety and precision of surgical interventions. Clinical applications include management of maxillofacial trauma such as complex midfacial fracture repair and reconstruction of orbit, removal of foreign bodies, complex dentoalveolar procedures, skull base and temporomandibular joint surgery, orthognathic surgeries and dental implant placement. Collectively, these applications underscore the proven efficacy of navigation systems in optimizing outcomes across a broad spectrum of oral and maxillofacial surgical procedures. Literature reveals numerous studies with significant statistical data which highlight the significant role of navigation in improving the overall surgical outcome. This review provides a comprehensive overview of navigation technologies and their diverse applications within the field of oral and maxillofacial surgery.

Keywords: navigation, craniomaxillofacial surgery, complex, safe, precise

Introduction

Traditionally, maxillofacial surgeries have required large incisions and extensive dissections due to the region's complex anatomy and restricted operative field. Such approaches have been associated with considerable surgical morbidity, increased intraoperative blood loss and extended postoperative hospitalization (1). To overcome this, Image guided surgery and augmented reality guided surgery were developed. Commonly employed image-guided surgical modalities include intraoperative computed tomography (CT) and intraoperative ultrasonography. While intraoperative CT offers high-resolution imaging, its use is limited by exposure to ionizing radiation and the relatively cumbersome nature of the procedure. Also setting up the infrastructure is more expensive. Nevertheless the margin of error was more and surgical results were less predictable (2). Hence various navigation systems were introduced, which had a great potential for achieving precision in surgical procedures. Neuronavigation systems were initially developed in the field of neurosurgery for accurate resection of brain tumors. Spiegel and Wycis in 1947, originally performed the stereotactic thalamotomy in humans (3). Computer-assisted navigational surgery was initially used by Watanabe in 1987 in neurosurgical procedures (4).

Intra-operative navigation is a trend towards minimally invasive surgical technique which helps to visualize the

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TABLE 1 | Applications of intra-operative navigation in oral & maxillofacial surgery.

Surgery type	Benefits	Limitations
Trauma (orbital, zygomatic, midfacial fractures)	• Precise 3D reconstruction • Accurate plate/mesh positioning • Avoid large incisions • Improves facial symmetry • Safer near optic canal	• Increased surgical time • Cost of navigation setup
Orthognathic surgery	• Accurate osteotomy placement (IVRO, Le Fort, BSSO) • Reduced nerve damage risk • Eliminates intermediate splint • Real-time repositioning of jaws • Higher accuracy in vertical dimension	• Learning curve • Setup time • Difficulty guiding movable mandible
Temporomandibular joint (TMJ) surgery (gap arthroplasty, ankylosis)	• Precise ankylotic bone removal • Maintains safety margin from cranial fossa & ear canal • Reduced risk to nerves/vessels • Real-time 3D visualization	• Longer planning time • High system cost
Pathology (tumors, skull base, retromaxillary, intraorbital)	• Safer resection near vital structures • Less invasive for benign tumors • Helps in re-operations (altered planes) • Useful in oncological follow-up • Enables prefabricated implant/flap placement	• Requires computed tomography/magnetic resonance imaging (CT/MRI) imaging • Higher cost • Prolonged setup
Implants	• Sub-millimeter accuracy (<0.73 mm error) • Prosthetic-driven planning • Safer near sinus, nerves, roots • Minimal flap surgery, less morbidity • Increased patient satisfaction	• High equipment cost • Requires cone beam computed tomography (CBCT)/CT planning
Foreign body removal	• Minimally invasive access • Faster surgery (~40% time saved) • Safer in complex/deep sites • Useful for multiple objects • Increased precision	• Expensive • Requires pre-op imaging & registration
Dentoalveolar surgery (impacted, supernumerary teeth)	• Accurate localization • Protects adjacent structures • Reduces bone loss & surgical trauma • Transfers pre-op design precisely	• Costly • Setup time • Not always practical for simple cases

surgical site as well as instruments with simultaneous correlation with diagnostic images of patient (5).

In recent times, Oral and maxillofacial surgery has witnessed varied applications of surgical navigation in different procedures such as trauma, reconstruction of temporomandibular joint (TMJ), orthognathic surgeries, resection of tumors, endoscopic sinus surgeries, foreign body removal and dental implants (5–8). Literature reveals numerous studies with significant statistical data which highlight the significant role of navigation in improving the overall surgical outcome (**Table 1**).

This review offers a concise synthesis of navigation technologies and their clinical applications within oral and maxillofacial surgery.

Components of surgical navigation

Surgical navigation, analogous to the global positioning system (GPS) used in automobiles, comprises three primary components are

1. The localizer functions analogously to a satellite in space, serving as the reference source for tracking and positional data.
2. The surgical probe emits signals via infrared diodes, analogous to the tracking signals transmitted by a vehicle's GPS.
3. Computerized tomography scan data set is comparable to a road map (4).

This system is more reliable with accuracy and facilitates perfect execution of pre-operative plan, minimizes the intraoperative time and allows safer manipulations in anatomic zones which are closer to vital structures (9, 10).

Each surgeon's navigation requirements vary depending on the specific surgical indications and functional demands. To accommodate this diversity, a broad spectrum of navigation platforms has been developed. These systems may be permanently integrated within the operating theatre or configured as mobile units, allowing transportation and utilization across multiple hospital settings (11).

Principle of intraoperative navigation

There are two different principles of intraoperative navigation are

- **Electromagnetic navigation** involves the use of an emitter attached to the operating table, which generates an electromagnetic field surrounding the surgical site. The navigation probe determines its position based on its relative location within this field. However, the reliance on electromagnetic fields poses limitations, as many surgical instruments possess ferromagnetic properties that can interfere with the field resulting in signal disturbances and imaging artifacts.
- **Optical-guided navigation systems** use light sources such as infrared cameras or light-emitting diodes (LEDs), to emit beams that are detected by optical sensors. These sensors track the reflected signals from the navigational probe, thereby determining its precise position in real time (12).

Armamentarium of navigation

1. The instrument console includes the operating software, display screen and instrument panel.
2. The operating software which comprises the navigation mapping modules and planning elements.
3. The patient tracker is securely attached either directly to the patient or to a rigid fixation device such as the "Mayfield" neurosurgical clamp, thereby ensuring stable and reliable tracking of the patient's anatomical position throughout the procedure.
4. During surgery, a handheld sensor known as a pointer sensor is employed (12).

Navigation in oral and maxillofacial surgery

Trauma

The navigation system facilitates intraoperative reconstruction of complex orbital anatomy by enabling precise three-dimensional imaging through processes such as imaging acquisition, validation and registration. High-velocity impacts often lead to comminuted orbital fractures, increased orbital volume, herniation of periorbital soft tissues into the adjacent sinuses and associated cranial neuropathies (13). Despite advancements in biocompatible materials and the expertise of skilled surgeons, achieving precise and predictable restoration and recontouring of anatomical landmarks remains a significant challenge (13, 14).

Metzger et al. described a semi-automated technique involving the fabrication of titanium meshes that were mirror-imaged from the unaffected side. These custom-designed meshes were inserted with the aid of frameless stereotaxy, using three infrared cameras and integrated LEDs for precise intraoperative control during CT-guided navigation. The proper positioning of plates in less visible anatomical areas has been made possible by the use of intraoperative navigation along with adequate preoperative planning (15).

Surgical navigation is used repeatedly throughout the procedure to evaluate the ongoing reconstruction of the orbital floor and to verify accurate positioning of the fixation plates.

However, accurate reconstruction of orbit is only possible with the aid of a navigation system, even though orbital reconstruction can be obtained to the point where no functional impairement manifests clinically when using the traditional method (16).

On the CT scan, graphic lines were drawn at the zygomatic arch to guide the computer navigation and employing virtual mid-sagittal plane to reflect from the healthy side. Reduction accuracy was confirmed when the virtual line representing the zygoma's pre-osteotomy position intersected with the preoperatively designated target line. This approach offers significant advantages as it allows avoidance of coronal and subciliary incisions and eliminates the need for complete exposure of the zygomatic bone (17).

The surgeon's view point on the repair can be improved by the use of surgical navigation systems. Using intraoperative navigation, the zygomaticomaxillary complex was accurately repositioned to within 2 mm of the corresponding anatomical landmarks on the contralateral side. Improved facial symmetry resulted from the precise positioning of the mobilized bony fragments made possible by intraoperative navigation (18).

Navigation systems facilitate precise and safe surgical interventions in patients with severe orbital wall fractures, particularly those involving regions adjacent to the optic canal. By using the system's visualization capabilities to accurately identify anatomical landmarks with the pointer, surgeons can achieve successful dissections and implant placements near the optic canal. Clinical outcomes indicate that orbital wall reconstruction aided by navigation systems is highly effective in managing deep and extensive orbital wall fractures (19).

Orthognathic surgery

Navigation systems play a valuable role in orthognathic surgery, offering enhanced safety and precision even when the operative site is located in deep or otherwise obscured anatomical regions.

Navigation systems assist in accurately identifying anatomical landmarks and determining both the depth and extent of the osteotomy during intraoral vertical ramus osteotomy procedures for mandibular setback, thereby enhancing surgical precision and safety (20). This approach offers the benefit of reducing the risk of injury to the inferior alveolar nerve; however, it does not completely eliminate the possibility, as the ramus osteotomy must still be performed posterior to the lingula. Enhanced anatomical verification through navigation could potentially limit the need for endoscopic access and usage in intraoral vertical ramus osteotomy procedures (21).

Brown et al. reported the use of surgical navigation to accurately localize osteotomy sites during a Le Fort III procedure combined with bilateral sagittal split osteotomy as part of a facial transplantation. Navigation was applied to both donor and recipient sites and following harvest of the composite tissue, final positioning was confirmed using the navigation system (22).

Intraoperative navigation can serve as an adjunctive technique during the execution of the surgical treatment plan, enabling highly precise outcomes by assessing horizontal, vertical and sagittal relationships of the jaws and dentition. This technology is particularly advantageous for performing planned osteotomies such as those indicated for hemimandibular hyperplasia and for intraoperative evaluation of vertical skeletal relationships. However, due to the difficulty of guiding a movable structure, navigated surgery in the mandible warrants special consideration (23).

Navigation technology enables intraoperative repositioning of the entire maxillomandibular complex without the use of an intermediate splint, thereby overcoming the limitations associated with the conventional two-splint technique. This approach provides an efficient means of translating virtual surgical planning directly into the operative setting without requiring intraoperative image registration. By visually tracking the real-time position of the maxillomandibular complex on a monitor, the surgeon can achieve highly precise repositioning. Consequently, traditional model surgery and intermediate splints are rendered unnecessary, significantly streamlining preoperative preparation (24).

When compared with computer-designed surgical planning using specialized software, simulation-guided navigation offers highly accurate postoperative outcomes for maxillary repositioning in orthognathic surgery particularly in the vertical dimension which remains the most challenging to control. However, this technique is not without limitations including the high cost of navigation equipment, the additional time required for system setup and intraoperative use and the learning curve necessary to achieve proficiency with the technology (25).

As the real-time navigation system advances into anatomically complex and visually inaccessible deep regions, structures such as the canal of the descending palatine artery and the tips of surgical instruments can be visualized on the monitor, ensuring safe execution of all procedures. Additionally, other surgical instruments including osteotomes and chisels can be registered and tracked within the system. The integration of navigation technology in orthognathic surgery thus provides a high degree of precision, enabling exceptionally accurate surgical outcomes (26).

TMJ

Intraoperative real-time visualization of the surgical field and its spatial relationship to adjacent anatomical structures significantly enhances surgical accuracy and minimizes risk. This is particularly valuable in high-risk interventions such as gap arthroplasty for TMJ ankylosis, where precise navigation is vital for optimal outcomes and complication avoidance (27).

Navigation-assisted surgery has been shown to result in a significantly lower postoperative skull base thickness compared to procedures performed without navigation, indicating that joint ankylosis can be managed more effectively by facilitating the excision of a greater volume of ankylosed bone. Furthermore, navigation systems aid surgeons in accurately assessing and controlling the amount of bone removed during the procedure, thereby enhancing surgical precision and safety (27).

Open TMJ surgery carries an elevated risk of injury to adjacent structures including the middle ear, middle cranial fossa as well as nearby arteries and nerves, particularly when relying solely on subjective visual assessment. Moreover, the confined visual field necessitates highly precise surgical maneuvers for the TMJ capsule. The incorporation of real-time three-dimensional navigation provides valuable guidance, enabling more accurate and safer execution of open TMJ surgery (28).

The navigation-guided technique was developed to assist in lateral gap arthroplasty by enhancing consistency through the identification of safety margins, safeguarding vital anatomical structures and providing improved visualization for increased operative accuracy and safety (29).

When designing navigation protocols for TMJ ankylosis surgery, two vital factors must be considered are the maximal safe range of ankylosed bone excision and the safety margins between the surgical site, the middle cranial fossa and the external auditory canal. During the procedure, direct visualization of the osteotomy and bone removal on the mandibular ramus is essential. The principal objective of surgical navigation is to ensure a safe distance from these vital structures, a principle that applies to both unilateral and bilateral TMJ ankylosis cases (27).

The implementation of computer-assisted surgery with navigation facilitates safe excision of ankylosed TMJ structures at the skull base by ensuring adequate resection margins toward the middle cranial fossa and enabling precise intraoperative identification of vital anatomical landmarks such as the foramen ovale (30).

Preoperatively, the navigation system converts digital imaging and communications in medicine (DICOM) imaging data into a proprietary format and displays it across coronal, sagittal, axial and three-dimensional reconstructions. The volume of ankylotic bone scheduled for removal is estimated and highlighted in a distinct color to aid planning. Virtual surgical planning typically requires approximately 40–60 minutes. Intraoperatively, navigation systems enhance the safety and precision of ankylotic tissue resection during gap arthroplasty by providing real-time instrument tracking and accurate anatomical identification (31).

Pathology

In 1994, the first report detailing the application of a mechanically coupled navigation system in craniomaxillofacial surgery was published. This system was utilized for skull base tumor excisions, removal of foreign bodies and the precise transfer of osteotomy lines (32).

Navigation is particularly valuable in previously operated regions where normal anatomical planes have been disrupted resulting in the absence of a clear surgical plane. In such cases, navigation assists surgeons by delineating a distinct separation between vascular and avascular planes, thereby enhancing surgical safety and precision (33). Yang et al. reported a diagnostic accuracy of approximately 90% for skull base and parapharyngeal pathological lesions over a 5-year study period (34).

Computer-assisted navigation technology is particularly recommended for the excision of benign tumors located in close proximity to vital anatomical structures, as it enhances surgical precision and minimizes the risk of injury to adjacent tissues. The necessity for extensive resection can be avoided by treating these neoplasm with a less invasive method.

Navigation facilitates precise identification of both the tumor and adjacent anatomical structures, even in cases where the lesion cannot be directly or indirectly visualized. This capability is particularly advantageous for managing lesions such as retromaxillary and intraorbital osteomas.

In oncological follow-ups, intraoperative navigation is helpful for evaluating the tumor recurrence. Navigation offers further assistance because it can be supported endoscopically and microscopically (35).

Gunkel et al. reported an accuracy range of 1–2 mm after evaluating five different navigation systems for preoperative planning and intraoperative guidance in procedures involving the frontal and lateral skull base, paranasal sinuses and petrous bone. In a series of 250 head and neck surgeries, they also noted improved safety in manipulating delicate anatomical structures and a positive impact on surgical efficiency (36).

Navigation aid in enhancing tumor resection efficiency while reducing the extent of unaffected tissue. Furthermore, surgery involving the pterygomaxillary fossa, infratemporal fossa or skull base may be executed with greater safety in relation to surrounding vital structures (37). Finally, osteotomies can be precisely positioned using a presurgical imaging, allowing prefabricated implants, free flaps or bone grafts to be inserted into the defect to improve surgical accuracy and precision (4).

Implant

The use of navigation leads to decreased postoperative morbidity, precise angulation and greater time efficiency. Furthermore, it enables minimal flap surgery, which decreases patient discomfort as well as postoperative complications. Navigation systems are considered safe for use in proximity to bones, adjacent tooth roots, nerves and sinus cavities. When applied to guided implant surgery, they are regarded as more precise, accurate and reliable than conventional freehand techniques with the added benefit of reducing complication rates. Patient satisfaction and acceptance were higher with guided implant surgery. It has lowered the probability of surgical complications and decreased surgical time. It enables implant positioning to be planned and optimized (38).

Navigation systems facilitate continuous monitoring of the drilling process by providing real-time imaging of the dental drill throughout the procedure. Image-Guided Implantology systems have demonstrated high accuracy with reported deviations of less than 0.73 mm. Such precise control over the drilling bur's position minimizes the risk of injury to vital anatomical structures (8).

Intraoperative computer navigation systems have been developed to enable surgeons to track the continuously updated positions of surgical instruments and the operative field in real time, using three-dimensional reconstructed patient imaging data displayed on a monitor. When performing implant dentistry, an image-guided navigation system has proven to be more effective than traditional implant surgery, especially in challenging anatomical areas (39).

Implant position can be planned preoperatively and simulated using navigational assistance, allowing both tumor resection and implant insertion to be performed in the same surgery. Implant placement can be preoperatively planned based on prosthetic requirements and accurately translated to the patient intraoperatively, ensuring optimal functional and aesthetic outcomes (35).

Removal of foreign bodies

Navigation system is employed in situations such as fragments that could create challenges, use of less-invasive procedures, presence of several foreign bodies, objects situated within important areas and failure of earlier attempts with traditional techniques. Image-guided navigation is a valuable tool for surgeons in removing foreign bodies due to enhanced surgical precision, minimally invasive access and reduced surgical time (40).

A study by Siebegger et al. involving patients with foreign body complications in the head and neck region demonstrated that navigation-assisted surgery enabled effective removal of the foreign bodies with minimal intervention. Moreover, the use of navigation reduced surgical time by more than 40% compared to conventional techniques (41).

The stereotactic navigation system (STN) navigation system was used both for preoperative surgical planning and for intraoperative navigation, enhancing precision and procedural efficiency. Foreign bodies were removed without difficulties in five cases using minimally invasive method. Image-guided navigation reduced surgical time by approximately 40% compared to conventional techniques. Navigation-assisted removal of foreign bodies in complex and deep maxillofacial regions particularly near vital anatomical structures represents an effective and advantageous approach (40).

A computer-assisted navigation system was employed during surgery on a girl presenting with 24 foreign bodies in her left lower face and neck. Using the system, the appropriate bony anatomical landmark for each "buckshot" on the mandible was identified and served as a reference point for precise removal. The foreign bodies were extracted sequentially from anterior to posterior using palpation and targeted mini-incisions. This approach is facilitated by navigation technology and is particularly suitable for the safe and effective removal of multiple foreign bodies in the craniofacial region (42).

A 78-year-old Japanese woman presenting with pain in the left upper molar region was referred for evaluation. The lesion abutted the maxillary sinus and its precise location was difficult to determine due to the absence of clear anatomical landmarks. Consequently, an optical navigation system was employed. Preoperative registration was reliably achieved using a splint embedded with reference points, allowing the procedure to be performed accurately without compromising the maxillary sinus. Additionally, this simplified registration method reduced surgical time while maintaining precision (43).

Dentoalveolar surgery

Navigation systems facilitate precise localization of supernumerary teeth and their spatial relationships with adjacent anatomical structures. By providing real-time visualization that correlates the intraoperative scenario with preoperative CT or cone beam computed tomography (CBCT) sectional imaging, these systems enhance surgical accuracy and increase the surgeon's confidence throughout the procedure (43).

Wang observed that navigation offers significant advantages in the complex extraction of deeply impacted teeth including

1. Accurate identification of the position of deeply impacted teeth, allowing precise localization of the surgical site and minimizing bone loss and damage to surrounding structures.
2. To differentiate between permanent tooth germs and deeply impacted teeth.
3. Ensuring that the preoperative surgical plan is accurately translated into the intraoperative procedure.
4. Defining safe margins to protect adjacent structures such as the apical papilla and the incisive canal thereby minimizing the risk of complications (44).

Drawbacks of navigation

Navigation systems are expensive. In addition to equipment expenditures, other hidden expenses include increased surgical time and requirement for skilled assistant. Preoperative planning is required for surgical navigation. This approach necessitates preoperative CT imaging, access to a navigation system within the surgical theatre and accurate transfer of the imaging data to the intraoperative setting. Intraoperative CT scanning further reduces registration errors, particularly when performed with fiducial markers in place.

Immobilization of patient's head during the navigation is the complicating factor which is impossible for the patient and considered as a disadvantage as compared to other systems that allow head movement. Head immobilization throughout the procedure is not practical for orthognathic surgery because of the difficulties of the surgery and its limited access (45).

Conclusion

In craniomaxillofacial surgery, navigation-assisted technology improves reliability by enabling accurate safety margins and protecting important structures. Furthermore, it promotes radiotherapy planning precision and enhances the reconstructive process. Despite the relatively high cost of navigation systems and the longer preparation time compared to conventional techniques, their use offers substantial benefits. Navigation provides enhanced safety, particularly in complex cases, and can contribute to improved clinical outcomes. In challenging surgical approaches and anatomically sensitive areas, navigation increases surgeon confidence. Overall, the integration of navigation technology in craniofacial surgery has the potential to significantly enhance the precision and predictability of surgical results.

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