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Review Article

Intraoperative navigation in craniofacial surgery

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Craniofacial surgery requires comprehensive anatomical knowledge of the head and neck to ensure patient safety and surgical precision. Over recent decades, there have been significant advancements in imaging techniques and the development of real-time surgical navigation systems. Intraoperative navigation technology aligns surgical instruments with imaging-derived information on patient anatomy, enabling surgeons to closely follow preoperative plans. This system functions as a radiologic map, improving the accuracy of instrument placement and minimizing surgical complications. The introduction of first-generation navigation systems in the early 1990s revolutionized surgical procedures by enabling real-time tracking of instruments using preoperative imaging. Initially utilized in neurosurgery, intraoperative navigation has since become standard practice in otolaryngology, cranio-maxillofacial surgery, and orthopedics. Since the 2000s, second-generation navigation systems have been developed to meet the growing demand for precision across various surgical specialties. The adoption of these systems in craniofacial surgery has been slower, but their use is increasing, particularly in procedures such as foreign body removal, facial bone fracture reconstruction, tumor resection, and craniofacial reconstruction and implantation. In Korea, insurance coverage for navigation in craniofacial surgery began in 2021, and new medical technologies for orbital wall fracture treatment were approved in August 2022. These technologies have only recently become clinically available, but are expected to play an increasingly important role in craniofacial surgery. Intraoperative navigation enhances operative insight, improves target localization, and increases surgical safety. Although these systems have a steep learning curve and initially prolong surgery, efficiency improves with experience. Calibration issues, registration errors, and soft tissue deformation can introduce inaccuracies. Nonetheless, navigation technology is evolving, and the integration of intraoperative computed tomography data holds promise for further enhancements of surgical accuracy. This paper discusses the various types and applications of navigation employed in craniofacial surgery, highlighting their benefits and limitations.

Abbreviations: CT, computed tomography; MRI, magnetic resonance imaging; ZMC, zygomaticomaxillary complex

Keywords: Blow-out fracture / Craniofacial / Surgical navigation systems

INTRODUCTION

Craniofacial surgery requires detailed anatomical knowledge of the head and neck to ensure patient safety and surgical precision. Over the past few decades, imaging techniques for the preoperative identification of craniofacial lesions have significantly advanced. Additionally, navigation systems that track the real-time position of surgical instruments during procedures have evolved alongside these advancements [1,2]. The concept of stereotactic surgery, which involves using a stereotactic frame to precisely locate a target within the brain, was first conceived in the 1940s [3,4]. However, it was not until the late 1980s that attempts were made to perform stereotactic surgery using computed tomography (CT) or magnetic resonance imaging (MRI). In the early 1990s, the introduction of first-generation navigation systems enabled the real-time tracking of surgical instruments based on preoperative MRI and CT scans in clinical settings [1,3]. Over the past 20 to 30 years, these first-generation three-dimensional navigation systems, utilizing CT and MRI

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images, have been widely adopted. Since the 2000s, image guidance has evolved to meet the increasing demands for accuracy in surgical procedures, with various models of second-generation navigation systems being developed for different surgical specialties (Table 1). Looking ahead, third-generation navigation systems are expected to further develop and increase their use across various fields by incorporating new technologies such as augmented reality and robotics.

Intraoperative navigation is a surgical technique that integrates real-time feedback on the location of surgical instruments with CT or MRI scans of the patient's anatomy [5]. This technology enables surgeons to follow a preoperative plan closely and confirm that the patient's anatomy corresponds with the imaging data displayed on a monitor. Utilizing radiologic data as a guide, the system aids in the precise placement of surgical instruments relative to critical structures, thereby reducing complications and enhancing surgical outcomes [1,2]. Intraoperative navigation increases precision and accuracy, making surgery safer and more effective. It proves especially beneficial in complex anatomical procedures or when accurate preoperative anatomical information is necessary, such as in craniofacial surgery [3,4]. Initially developed for neurosurgery, this navigation system has since been adopted in various surgical specialties, including otolaryngology, cranio-maxillofacial surgery, and orthopedics [1]. While its integration into craniofacial surgery has been gradual, its use is growing in procedures such as foreign body removal, facial bone fracture reconstruction, tumor resection, and craniofacial reconstruction and implantation [1,2].

Table 1. Commercially available navigation systems by year of manufacture

Generation	Device	Manufacturer	Year of production
First	Insta Trak	GE Healthcare	1990
	Stealth Station	Medtronic	1995
	VectorVision	Brainlab	1996
	Stryker Navigation	Stryker	1997
	OrthoPilot	Aesculap	1997
Second	O arm	Medtronic	2005
	Navigation system II	Stryker	2005
	Mako	Mako/Stryker	2006
	NAV3/eNlite	Stryker	2010
	Curve/Kick	Brainlab	2011
	Naviol	Mega Medical	2016
Third	Mazor X Stealth	Medtronic	2019
	ROSA	Zimmer Biomet	2016, 2019, 2024
	TruDi	Brainlab	2021

In Korea, insurance coverage for the use of navigation in certain craniofacial surgical procedures began in 2021. Subsequently, government approval for new health technologies employing navigation for the treatment of orbital wall fractures was granted in August 2022. These technologies have only recently become available for clinical use (Fig. 1). The use of navigation in craniofacial surgery is anticipated to grow, and this paper aims to summarize its applications in this field.

NAVIGATION-GUIDED ORBITAL FRACTURE SURGERY

Blowout fractures are deep defects within the bony orbit that involve critical structures such as the optic nerve and extraocular muscles [6,7]. The area behind the eyeball is densely packed with sensory and motor nerves, vasculature, and extraocular muscles, making reconstruction particularly challenging, especially when fractures extend to the posterior optic canal [6]. The primary surgical goal in treating blowout fractures is to restore ocular motility and the original shape of the orbit, thereby

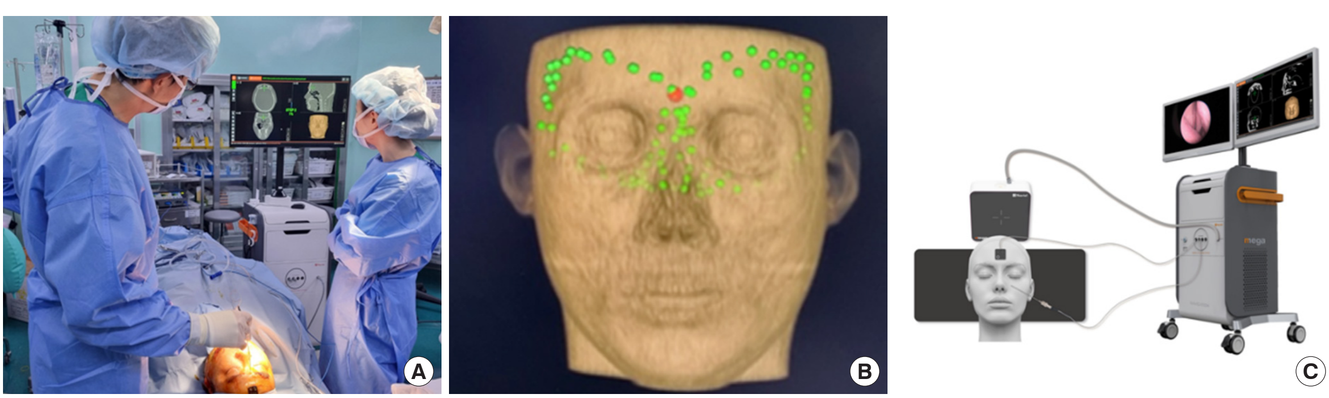

Fig. 1. (A) The intraoperative registration of a reference point on the patient's computed tomography image is integrated into the navigation system. This system, an electromagnetic navigation system, tracks instruments by generating an electromagnetic field. It functions with a generator that produces this electromagnetic field beneath the patient's head. (B) Preparation for registration involves using the reference points (red point). (C) The Naviol navigation system (Mega Medical; photo used with permission) [9].

preventing enophthalmos [7]. This involves carefully repositioning the herniated orbital contents and the fractured orbital wall back to their original locations. However, many complex cases remain challenging due to the intricate anatomy of the orbit and the difficulty in accurately visualizing intraorbital structures [7]. Incorrect positioning of bony structures during restoration can increase the volume of the orbital cavity, potentially leading to enophthalmos. Post-traumatic enophthalmos and diplopia, common sequelae of complex orbital reconstructions, often result from inaccurate restoration of orbital anatomy. Therefore, precise restoration of the orbital wall and appropriate implant placement are critical in returning the bony orbit to its normal volume and function [5,7].

The most common application of intraoperative navigation in craniofacial trauma is during orbital fracture surgery. Orbital wall fractures near the optic canal are particularly challenging due to the limited space for operation and the risk of severe postoperative complications, including optic nerve damage and blindness [6]. Intraoperative navigation facilitates real-time tracking, allowing for precise assessment of the orbital cavity's geometry, especially its posterior extent [6]. This technology enables the accurate localization of the optic nerve's complex trajectory throughout its course. Utilizing intraoperative navigation in orbital fracture repairs enhances the precision of implant or graft placements without increasing the risk of complications. It also permits multiple assessments of the orbital floor reconstruction and precise positioning of the plate during the surgery [6].

The primary challenges in orbital fracture surgery include reconstructing the orbital wall and precisely positioning the implant. The use of navigation guidance in cases of orbital trauma can significantly enhance the accuracy of implant placement, facilitating the customization and adjustment of malleable implants during the procedure [5]. It can be particularly difficult to determine whether the orbital contents are fully repositioned, whether the posterior edge of the fracture is adequately bridged, and whether the implant maintains a safe distance from the optic nerve, especially in severe fractures that involve multiple orbital walls [5]. After positioning an orbital implant, it is crucial to use navigation across its entire surface to verify its placement and to identify any necessary modifications to its shape [8]. The implant must then be re-navigated to confirm that the desired contour has been achieved (Fig. 2). Employing navigation-guided reduction with titanium-reinforced porous polyethylene plates can lead to predictable and reliable outcomes when treating orbital fractures that involve the inferomedial orbital strut. This technique ensures precise three-dimensional orientation of the implant and optimal orbital reconstruction, achieving the intended volumes [5].

The navigational sinus approach in ENT (ear, nose, and throat) surgery marks a significant advancement in the treatment of complex sinus conditions. This method is also applicable to orbital fracture surgery. A technique has been outlined for repairing the orbital wall, which involves repositioning the

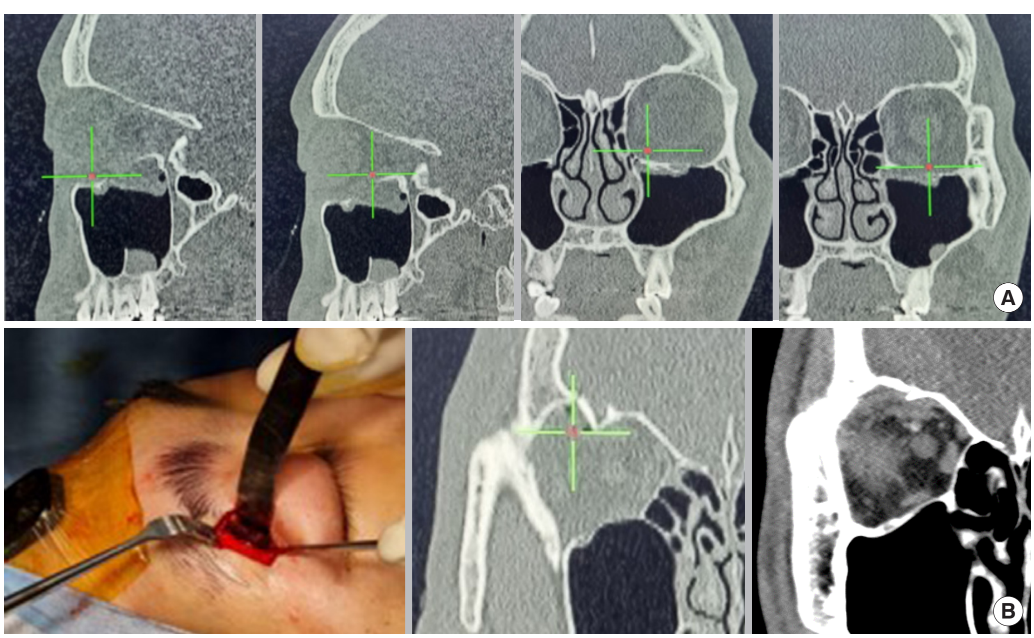

Fig. 2. (A) Intraoperative navigation is employed to verify the anterior, posterior, medial, and lateral boundaries of the orbital floor fracture and entire surface of implant. After positioning the orbital implant, navigation utilized to confirm its placement and to verify that the intended contouring iss achieved. (B) Intraoperative navigation is utilized to confirm the reduction of orbital roof fracture.

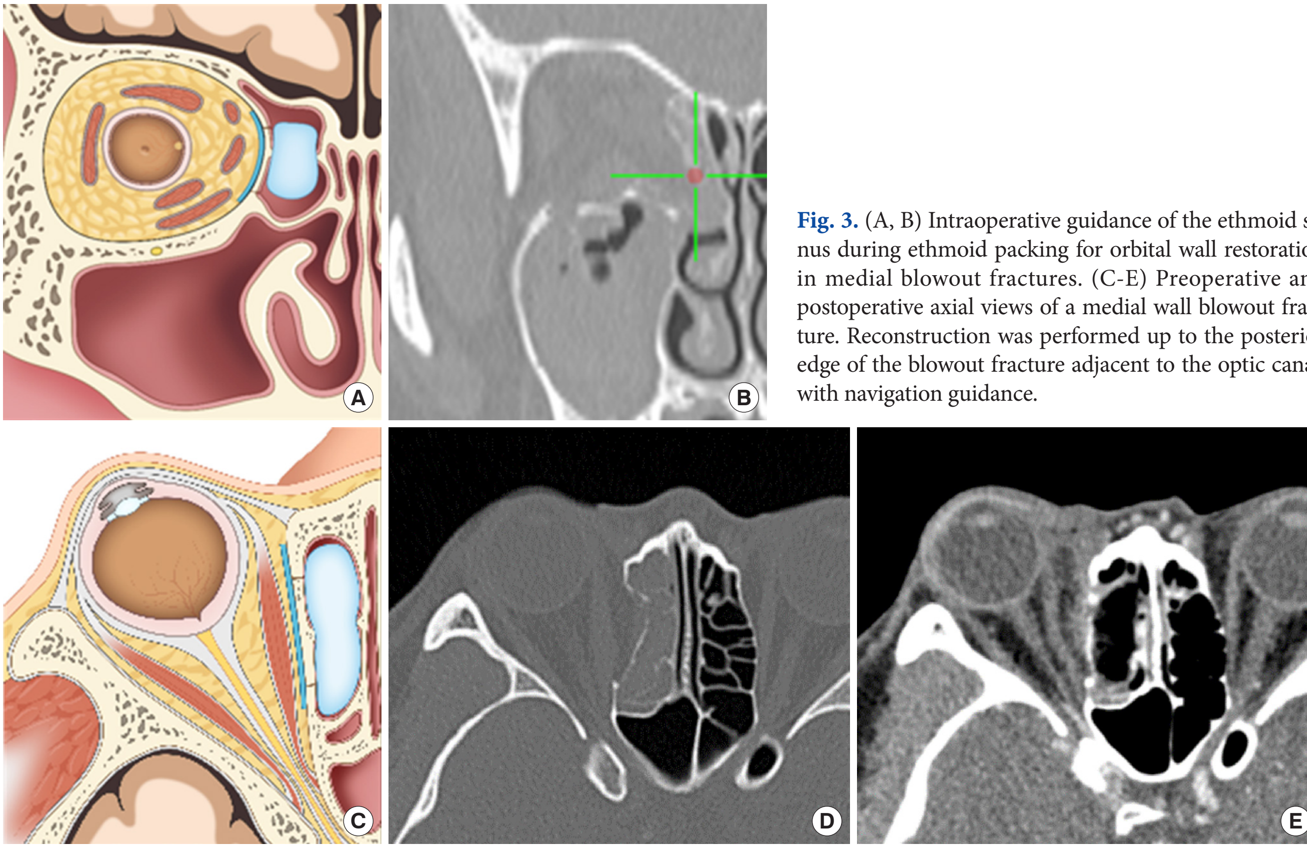

Fig. 3. (A, B) Intraoperative guidance of the ethmoid sinus during ethmoid packing for orbital wall restoration in medial blowout fractures. (C-E) Preoperative and postoperative axial views of a medial wall blowout fracture. Reconstruction was performed up to the posterior edge of the blowout fracture adjacent to the optic canal, with navigation guidance.

primary orbital wall fragment to its original location using both transorbital and transantral approaches, supported temporarily by extraorbital structures in the maxillary and ethmoid sinuses [7]. To strengthen the reconstructed medial wall of the orbit, Nasopore (Polyganics B.V.) should be inserted into the ethmoid sinus through a transnasal route, targeting the medial aspect of the reconstructed orbital wall [7]. Navigation plays a vital role in this procedure to ensure accurate placement of the medial orbital wall or skull base during dissection and to facilitate the placement of Nasopore packing within the ethmoid sinus without damaging the skull base (Fig. 3).

Although intraoperative navigation is not yet routinely used for small blowout fractures, it has been successful in managing complex orbital fractures, providing accurate and predictable outcomes. This technology offers detailed anatomical representations, enhances precision, and reliably restores orbital volume and globe projection to pre-traumatic states [8]. This makes it useful for reconstructing complex orbital injuries and post-ablative defects.

NAVIGATION-GUIDED ZYGOMA SURGERY

The reduction of complicated zygomaticomaxillary complex (ZMC) fractures poses significant challenges due to the critical role the ZMC plays in maintaining facial structure. Achieving precise reduction is crucial for restoring the face's anatomical contour and aesthetic appearance. If the ZMC is not accurately realigned, it can lead to midface asymmetry, a serious complication that might require revision surgery [10]. Common indicators of this asymmetry include a flattened cheek and an increased facial width, which results from the rotation of the zygomatic complex. The primary goals of ZMC surgery are to reestablish facial symmetry, restore orbital volume, and accurately reposition the skeletal elements in optimal anteroposterior, vertical, and sagittal orientations [10]. Repairing complex facial fractures requires a systematic approach, and determining the optimal sequence for treating these fractures presents a significant challenge, even for experienced surgeons. This difficulty arises from the absence of stable buttresses essential for restoring bone continuity. Limited visibility due to traumatic exposure further complicates the accurate confirmation of bone restoration, often necessitating additional large or multiple incisions [11]. Although surgery can be performed through a small incision, the outcomes are heavily dependent on the surgeon's anatomical knowledge and expertise. This dependency limits their ability to immediately confirm the correct repositioning of bone fragments. While intraoperative X-rays offer some guidance, they frequently fail to provide precise confirmation, particularly as the complexity and severity of the fractures increase [10].

Three-dimensional reconstruction is crucial for treating zygomatic complex fractures. However, intraoperative navigation, which provides only one-dimensional information about the position of the instrument during surgery, has limitations in confirming accurate fracture reduction. Although not yet established as a standard of care, intraoperative navigation is invaluable for achieving precise reduction of ZMC fractures. This technology allows craniofacial surgeons to reconstruct fracture fragments without needing large incisions, such as coronal incisions. Intraoperative navigation offers real-time positioning of instruments and clear identification of anatomical structures, which is especially useful in restoring the zygomatic arch [11]. By aligning the zygomatic arch accurately with the mirror image of the unaffected side from the preoperative CT scan, surgeons can achieve precise anatomical reduction and reduce the risk of malposition complications. This method of verifying exact reduction by referencing the contralateral mirror image can also be applied to other structures, such as the infraorbital rim and maxillary buttress.

Navigation aids assist surgeons in planning, executing, and evaluating operations postoperatively, thereby enhancing surgical outcomes and reducing the risk of complications and the need for secondary procedures. However, in cases involving multiple fractures, relying solely on navigation may be insufficient to ensure accurate reduction. In such situations, the combined use of portable X-rays, intraoperative CT scans, and other imaging techniques is beneficial [12].

Intraoperative navigation enables the immediate evaluation of fracture reduction by superimposing preoperatively planned positioning with intraoperatively acquired images. This provides instant feedback on the results of the fracture reduction, allowing the surgeon to make minor adjustments as necessary and thus avoiding further interventions. This technique has the potential to decrease the need for revision surgery, which is associated with additional costs, risks of complications, and increased morbidity [1].

Furthermore, intraoperative navigation significantly increases the accuracy of fracture reduction and orbital volume reconstruction in ZMC fractures. It provides real-time guidance for surgical instruments, which reduces treatment time and enables more precise, less invasive procedures by controlling bone fragments after reduction. This technique also proves valuable in orthognathic surgery, malarplasty, and mandibular angle ostectomy. It assists in determining the depth and extent of the osteotomy, adjusting the position of the zygoma and mandible, and ensuring that the contour of the mobile segment aligns with the preoperative plan. The introduction of third-generation navigation systems, which include intraoperative CT imaging, is expected to become an essential component of ZMC surgery [10].

TUMOR AND MASS EXCISION

Neurosurgical procedures necessitate precise localization and targeting of intracranial structures. Neurosurgery was the first surgical discipline to successfully integrate navigation into clinical practice. Stereotactic surgery, a cornerstone of navigation, utilizes a stereotactic frame to accurately pinpoint targets within the brain [1,13]. Navigation systems enhance the visualization of tumor borders, offering real-time guidance for precise tumor localization and resection. This approach minimizes the risk of damaging healthy brain tissue and leads to shorter operation times, smaller craniotomies, reduced blood loss, lower risk of postoperative swelling, and shorter hospital stays. The application of navigation in neurosurgery has expanded to include craniofacial surgery, particularly for tumor removal. Managing tumors in craniofacial regions demands detailed anatomical knowledge and meticulous planning of the tumor resection margin [3]. This process requires careful consideration of potential injuries to structures within the head and neck and the preservation of vital structures in a confined space. For simple facial or encapsulated masses, distinguishing the margins is straightforward, rendering navigation unnecessary. However, in surgery for recurrent tumors or conditions like fibrous dysplasia, accurately delineating tumor boundaries is challenging. In these instances, the navigation system aids in identifying radiologically suspicious tissue, facilitating error-free biopsies and precise tumor localization and resection with adequate safety margins, thereby minimizing the risk of damaging healthy surrounding tissue [1,13]. Navigation provides precise information about local anatomy and tumor margins, enabling smaller, more accurate incisions, resulting in less trauma, reduced blood loss, and faster recovery times.

The management of craniofacial fibrous dysplasia typically involves surgical debulking and contouring of proliferative fibro-osseous tissue. The primary objectives are to alleviate symptoms caused by the mass effect, restore craniofacial symmetry, and enhance cosmetic outcomes. When fibrous dysplasia involves the orbit and intracranial area, radical excision is often not feasible, necessitating decompression of the optic nerve while safeguarding vital structures [14]. In rare cases, the surgeon may be able to visualize both the affected and unaffected sides. Preoperative imaging and clinical judgment are crucial in guiding the removal of fibro-osseous tissue to restore facial symmetry, aesthetics, and function. Navigation aids transfer a map of depth markings onto the patient, enabling precise removal of diseased bone, better matching the unaffected anatomy, and decreasing the risk of injury to critical structures. By providing detailed anatomical information and continuous feedback, the navigation system helps to avoid critical facial structures, thereby reducing the risk of cosmetic deficits. Intraoperative navigation facilitates the exact anatomical reconstruction of the three-dimensional anatomy involved in tumor resection. Tumors are visualized in CT slices, which aids in planning radial tumor removal. During surgery, the navigation system guides the resection, ensuring that necessary margins are maintained. This precise orientation of local anatomy and tumor margins offers significant benefits, including smaller, more precise incisions, reduced trauma, less blood loss, and faster recovery times [14].

NAVIGATION FOR FOREIGN BODY REMOVAL

Trauma surgeons often encounter penetrating injuries and residual foreign bodies in the facial area, often resulting from traffic accidents, sports incidents, and other mishaps. For craniofacial surgeons, the removal of these foreign objects from the soft tissues of the face poses significant challenges, particularly in terms of minimizing incision scars. These difficulties arise from limited access and the necessity to avoid large scars or damage to the complex vital structures of the head and neck. Foreign bodies in the facial area can include materials such as metal, plastic, and glass. Although various imaging tests can confirm the presence of a foreign object, accurately pinpointing its exact location remains challenging, especially when it is deeply embedded in the facial tissues [1,2].

Conventional radiography and ultrasound effectively identify foreign bodies, whereas CT and MRI provide more precise detection and localization. C-arm fluoroscopy is especially valuable for pinpointing the exact location of foreign bodies within the complex anatomy of the face and neck. However, these conventional imaging techniques face limitations in accurately determining the spatial location of foreign bodies, particularly when they are situated near critical nerves and blood vessels. For instance, if a foreign body is embedded in a sensitive structure such as the eye or orbit, it must be removed safely with minimal damage to the surrounding tissues [3,4].

Intraoperative navigation systems provide a valuable solution

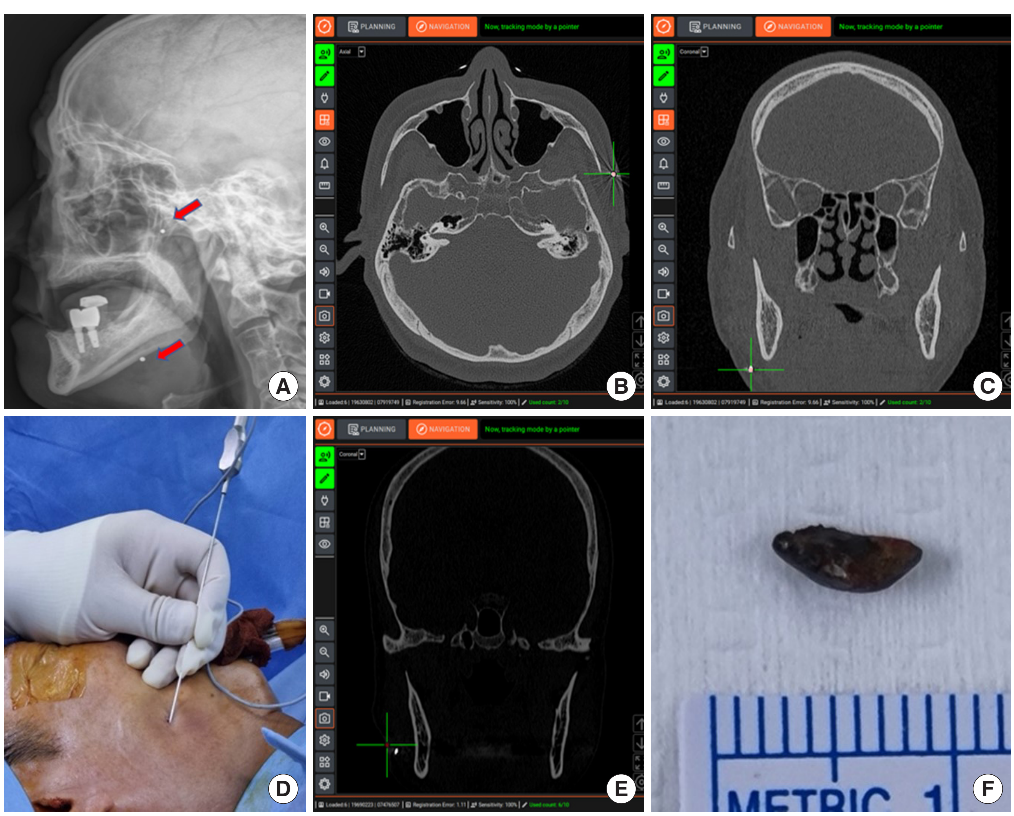

Fig. 4. Case 1: (A) a shotgun blast injury was identified in the patient's left temporal region and right chin area (red arrows); (B, C) intraoperative navigation facilitated precise localization. Case 2: (D, E) a foreign object that had entered the right cheek while weeding is being localized using intraoperative navigation through a small open wound; (F) the object was removed through a minimal incision.

for the removal of foreign bodies while minimizing major complications, such as collateral tissue damage (Fig. 4). This navigation-guided surgery is an effective, safe, and reliable method for detecting and extracting foreign bodies from the head and neck region. Even when these bodies are difficult to detect with general radiography, they can be identified through CT or MRI and then precisely located using navigation. These systems help determine the most effective removal approach, providing precise intraoperative guidance, enhancing surgical accuracy, and reducing operating time. Additionally, they improve safety by facilitating a minimally invasive approach and reducing the risk of complications, such as damage to surrounding blood vessels and nerves.

Despite its numerous advantages, navigation faces significant challenges, including the mobility of soft tissue and the difficulty of updating images during surgery. Current navigation systems depend on preoperative images for precise localization [4]. These systems utilize preoperative CT and MRI images to determine the location of foreign bodies before surgery. However, extensive manipulation of soft tissue during the procedure can shift the position of the foreign body, potentially compromising the accuracy of the navigation. Since these systems are unable to accommodate changes in soft tissue structure during surgery, minimal manipulation of soft tissue is advised.

Recent technological advances have enabled the use of intraoperative CT imaging alongside navigation systems, facilitating real-time evaluations after segmental movement [1,2]. Modern intraoperative CT scanners allow surgeons to monitor their progress and automatically update the navigation in real-time. This development enables surgeons to see the precise location of surgical instruments on a monitor that displays real-time CT or MRI data of the patient.

DISCUSSION

Surgical navigation systems operate in a manner akin to automotive navigation systems. While automotive systems pinpoint location using multiple geostationary satellites, surgical navigation employs stereoscopic cameras that emit infrared light and track reflective markers, allowing for the precise localization of instruments during surgery. This technology facilitates real-time tracking [1,2]. Decades ago, before the advent of car navigation systems, people depended on maps for directions. As car navigation technology has evolved, it has become the primary means of guidance while driving. Similarly, intraoperative navigation is progressing with advancements in imaging technology. It is anticipated that, in the coming decades, these systems will play an increasingly essential role in surgical procedures. Intraoperative navigation provides surgeons with real-time, interactive access to their patients' diagnostic imaging. This technology enables precise anatomical localization, which aids in intraoperative planning and diagnosis [1,2]. Navigation-guided surgery increases operative precision, improves target localization, enhances anatomical orientation, minimizes collateral damage, and ultimately improves both patient safety and surgeon comfort during procedures [3,4]. Initially introduced in neurosurgery, the use of navigation has expanded to include spine surgery in orthopedics and endonasal surgery in otolaryngology. Advances in related technologies have broadened the application of intraoperative navigation to nearly all surgical subspecialties, including craniofacial surgery for head and neck procedures [3].

In addition to improving surgical outcomes, intraoperative navigation also serves as a valuable educational tool for less experienced surgeons, helping them build confidence as they navigate the complex anatomy of the head and neck [13]. Even for experienced surgeons, procedures involving deep structures can be challenging. Navigation systems address these challenges by providing real-time displays of tracked instruments on multiplanar reconstructed images that are aligned with the surgical perspective [1,2]. This not only improves anatomical understanding but also boosts surgeon confidence and enhances the perceived safety of the operation.

Although surgical navigation offers numerous advantages, it also presents some limitations. These systems require significant training for both surgeons and staff due to a steep learning curve [4]. Integrating them into existing surgical workflows is complex and often necessitates additional calibration and alignment steps. The preparation and calibration of the navigation system can prolong the duration of surgery, and any necessary adjustments or recalibrations may further increase operating times, potentially affecting overall surgical efficiency. A critical preparatory step is registration, which ensures accurate alignment between the patient's actual anatomy and the navigation system's CT scans. This synchronization is achieved by registering preoperative CT images with the patient's anatomy during surgery. Once registration is complete, the positions of tracked instruments are displayed on-screen, showing real-time relationships to both the preoperative images and the actual surgical anatomy [4,15]. Although these systems may initially lengthen surgery time, efficiency typically improves with experience, eventually reducing overall operating time [1,3]. Despite their general precision, intraoperative navigation systems can sometimes be inaccurate due to improper calibration or technical issues. The technical accuracy of the system is typically less than 1 mm, while intraoperative precision for a patient ranges from

1 to 2 mm. Registration error refers to inaccuracies in aligning preoperative CT imaging data with the patient's actual anatomical structures during surgery, which is crucial for accurate surgical guidance.

While surgical navigation systems significantly enhance precision and safety, they also introduce challenges such as complexity, potential technical issues, and other factors. To fully benefit from these advanced technologies, it is crucial to consider these drawbacks carefully. Factors affecting the accuracy of navigation systems include the resolution of the CT dataset, the precision of data registration, and soft tissue deformation during surgery. The system depends on high-quality CT imaging for accurate functioning. If the resolution of available CT images is inadequate, obtaining a new high-resolution CT scan may be necessary to improve navigation accuracy. Another issue is the potential for registration errors, which can arise from patient movement or inaccurate placement of fiducial markers. Even with meticulous initial registration and landmark identification, intraoperative manipulation of facial structures can cause soft tissues and fractured bone fragments to shift. This creates discrepancies between the patient's intraoperative anatomy and the preoperative CT datasets. Since the navigation images are based on preoperative data, they fail to reflect these real-time changes, leading to guidance errors [1,4]. These inconsistencies can lead to precision issues that are difficult to correct through re-registration. However, recent advancements in navigation technology now allow the use of intraoperative CT data. In the future, it is anticipated that surgeons will be able to correct these inaccuracies by frequently adjusting the system with intraoperative CT data.

NOTES

Conflict of interest

Dong Hee Kang is an editorial board member of the journal but was not involved in the peer reviewer selection, evaluation, or decision process of this article. No other potential conflicts of interest relevant to this article were reported.

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Patient consent

Photographs were provided by the author after obtaining informed consent from patients.

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