Review

Advances in Minimally Invasive Approach for Impacted Mandibular Third Molar Extractions: From Incision Design to Dynamic Navigation

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The application of the minimally invasive concept in the extraction of impacted mandibular third molars has significantly improved surgical outcomes and patient prognosis. This review systematically examines the up-to-date research advances in various methods used for the extraction of impacted mandibular third molars within the context of the minimally invasive concept. Modified incision and flap designs have effectively reduced tissue damage. Ultrasonic bone knife technology has proven to reduce intraoperative bleeding and the risk of thermal injury, and its combined use with a dental electric motor further enhances procedural precision and efficiency. Dynamic navigation technology holds significant potential in improving surgical accuracy, facilitating precise debridement and distraction techniques, and reducing the risk of nerve injury and postoperative complications. Future integration of dynamic navigation with preoperative artificial intelligence assessment will further advance the minimally invasive approach, making it more widespread and cost-effective. Minimally invasive techniques are not only the starting point but also the means to achieve functional objectives, propelling the development of minimally invasive alveolar surgery to new heights.

Keywords: minimally invasive concept; impacted mandibular third molars; incision design; ultrasonic bone knife; dynamic navigation technology; precise debridement

Introduction

The extraction of the impacted mandibular third molar is a common procedure in oral and maxillofacial surgery. However, their proximity to the inferior alveolar nerve and the highly vascularized posterior region often leads to complications during extraction, such as postoperative pain, swelling, nerve injury, and alveolar dysfunction [1,2]. Conventional surgical techniques relying on hammer and chisel gap augmentation and extensive debridement can exacerbate tissue trauma and increase the risk of temporomandibular joint injury or mandibular fractures [3,4]. In the context of modern, patient-centered care, clinical research focuses on reducing surgical trauma and accelerating postoperative recovery through technological innovation.

The advent of minimally invasive approaches has revolutionized the management of impacted tooth extractions. Since the concept of minimally invasive medicine emerged in the late 20th century [5], impacted teeth extraction methods have undergone considerable advancements. These in-

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clude the application of a turbine drills instead of a hammer chisel by Kilpatrick (1958) [6], the solution of subcutaneous emphysema using powered systems in the 1990s [7], and the incorporation of innovative technologies such as ultrasonic bone knives, water lasers, and dynamic navigation systems in the 21st century [8,9]. Recent research focuses on optimizing procedural elements to reduce the risk of trauma. Improved flap designs have been reported to substantially reduce soft tissue injury and postoperative pain by 30%–45% [10]. Ultrasonic bone knives, which utilize the piezoelectric effect, enable precise bone cutting while reducing the risk of thermal and nerve damage; when combined with dental motors, they can alleviate operative time by 40% [11]. Dynamic navigation systems achieve sub-millimeter accuracy (error $<$1.35 mm), reducing the nerve injury rate during complex extractions to as low as 1.8% [12–14]. Additionally, adjunctive therapies such as platelet-rich fibrin (PRF) and low-energy laser procedure accelerate wound healing and reduce the duration of postoperative swelling by 50% [15,16]. These innovations in minimally invasive techniques have significantly improved clinical outcomes, reducing tissue damage, postoperative discomfort, and recovery time for patients undergoing impacted tooth extraction.

Despite significant technological advancements, several challenges remain. The high cost of dynamic navigation limits their broader adoption [17], and there is a lack of robust long-term functional evidence supporting minimally invasive extraction approaches [18,19]. Additionally, the lack of standardized, artificial intelligence (AI)-assisted difficulty prediction systems limits procedural planning and optimization [20,21]. This review aims to systematically summarize recent developments in extraction approaches guided by the concept of minimally invasive dentistry impacted mandibular third molars and to provide an evidence-based basis for enhancing clinical practice.

Basic Concept and Evolution of Minimally Invasive Techniques

Basic Concept of Minimally Invasive Techniques

The concept of minimally invasive surgery, first introduced by Payne *et al.* [5] in the late 20th century, has gradually expanded into the broader field of minimally invasive medicine. Historically, oral surgical procedures, such as tooth extraction, relied primarily on primitive tools like hammers and chisels. However, the development of innovative approaches and specialized instruments has led to the increasing adoption of minimally invasive methods in oral surgery. The term "minimally invasive" encompasses both clinical and psychological aspects. Clinically, although procedures like tooth extraction and alveolar surgery are inherently invasive, the minimally invasive approach aims to minimize tissue trauma through specialized techniques and precision instruments. The essence of the "minimally invasive" approach is to reduce postoperative discomfort and adverse reactions, promote wound healing, and preserve the integrity of hard and soft tissues to enhance subsequent repair, reconstruction, and aesthetic outcomes. From a psychological perspective, minimally invasive care focuses on patient-centered communication and emotional support. Preoperative anxiety is relieved or eliminated through effective doctor-patient communication, fostering trust and enabling patients to face recovery with a positive and stress-free outlook.

Traditional tooth extraction techniques often involve the use of invasive instruments such as dental forceps, bone chisels, and hammers to widen the socket, remove bone, and section the tooth. In contrast, tooth extraction techniques guided by the minimally invasive concept represent a crucial technical innovation that aligns with the modern principles of "patient-centered" and compassionate care [22]. This method employs specialized instruments and surgical techniques to minimize both the physiological and psychological burden on the patient during the extraction procedure. By reducing damage to hard and soft tissues, limiting bone removal, shortening the operation time, and alleviating anxiety associated with traditional percussive tools, this method offers a more patient-friendly alternative. Recent advancements in oral surgery and extraction instruments have led to the widespread adoption of minimally invasive tooth extraction, making it the preferred option among both clinicians and patients. As this approach becomes increasingly favored, it is rapidly advancing, replacing traditional methods and has emerged as the predominant practice in oral surgical extractions. This advancement marks the rise of what is now widely known as the minimally invasive tooth extraction technique or simply the minimally invasive technique [23].

The Evolution in Minimally Invasive Techniques

The extraction of impacted mandibular third molars often requires extensive surgical intervention, including large incisions, substantial tissue removal, and the use of hammering to expand the surgical field. However, this approach is associated with significant postoperative complications, including pain, swelling, and temporomandibular joint dysfunction. Moreover, the vibration and noise generated during hammering can exacerbate patient anxiety. Inappropriate or prolonged hammering may also lead to serious complications, such as temporomandibular joint injuries or mandibular fractures [7]. Additionally, the lack of ability to control intraoperative trauma and the increased risk of soft tissue injury with traditional methods contribute to a higher incidence of postoperative infections and nerve injuries [24].

The core premise of minimally invasive techniques is to minimize damage to surrounding hard and soft tissues, particularly the inferior alveolar nerve, through precise tooth sectioning, small incision design, and maximal preservation of bone structures. This technique significantly reduces in-

Table 1. Key advancements in minimally invasive techniques for dental surgery.

Technical name	Application effects	References
Laser technology	Reduced soft tissue damage and promotes healing	[25]
Ultrasonic bone knife	Improved debridement accuracy and reduced postoperative swelling	[8]
Dynamic navigation system	Improved surgical precision and reduced risk of nerve damage	[30]
Three-dimensional imaging	Improved preoperative evaluation and surgical planning	[31]

traoperative and postoperative discomfort, while alleviating patient anxiety and fear [24]. As early as 1958, Kilpatrick [6] pioneered the use of a turbine drill for impacted teeth extraction, substantially reducing the mechanical impact of traditional percussion and significantly decreasing patient anxiety. Subsequently, researcher experimented using implant devices for tooth extraction, though their widespread use was limited by low cutting efficiency and high cost. In the 1990s, researchers introduced surgical power systems to address the significant limitations of earlier methods, including the high trauma associated with the bone chisel, the risk of subcutaneous emphysema from the turbine, and the inefficiency of implant machines [7]. The use of surgical drills and pins in tooth extraction procedures has been reported to reduce operative time ((22.285 ± 12.025) vs (16.115 ± 12.078) minutes) and decrease the incidence of intraoperative and postoperative complications, such as dry socket syndrome, restricted mouth opening, and temporomandibular joint pain, compared to conventional bone chisel and crown-sectioning techniques [24]. The advent of minimally invasive surgical approaches has also enabled the integration of advanced tools, such as lasers and ultrasonic bone knives. These innovations have substantially reduced the risk of bone trauma and postoperative complications [25]. Notably, ultrasonic bone knives enable precise bone removal with minimal impact on surrounding soft tissues, making them the preferred option for procedures in anatomically sensitive areas [8].

Furthermore, advancements in computer technology have significantly improved the precision and success of the minimally invasive approach by using digital imaging. The integration of three-dimensional imaging, computer-aided simulation, and dynamic navigation enables oral surgeons to plan procedures with high accuracy, thereby minimizing the risk of intraoperative complications and accidental events [26].

A growing body of clinical evidence supports the quantifiable advantages of minimally invasive techniques over traditional approaches. Patients who underwent tooth extraction using ultrasonic bone cutters reported significantly lower pain 48 hours after surgery compared to those treated with conventional rotary instruments [27]. Similarly, the combination of a power system (e.g., dental electric motor) and ultrasonic bone knife substantially reduced pain, swelling, and trismus on postoperative day 1 to 3 relative to high-speed turbine handpieces or conventional bone chisels ($p < 0.05$) [11]. Flap design also plays a pivotal role, with envelope flaps exhibiting significantly lower postoperative pain compared to standard triangular flaps (mean difference = 8.92, 95% CI 1.71–16.73, $p = 0.02$) [10]. While ultrasonic bone knives may slightly elevate procedure times compared to conventional rotary instruments [28], their integration with dental electric motors enhances surgical efficiency by 40% [11]. Moreover, optimized tooth splitting methods, such as the three-piece technique, have demonstrated a significant reduction in operative time compared to the conventional "T" split approach (14.73 ± 3.21 min vs. 19.25 ± 4.29 min, $p < 0.05$) [29]. The primary objective of minimally invasive techniques, such as corpectomy and precision segmentation, is the preservation of the inferior alveolar nerves. The use of a dynamic navigation system has achieved sub-millimeter accuracy (error <1.35 mm), significantly reducing the rate of nerve injury in complex tooth extractions to just 1.8% [12–14].

Additionally, the ultrasonic bone knife has been found to be more effective than conventional rotary instruments in reducing the risk of postoperative sensory abnormalities of the inferior alveolar nerve [2,9]. Regarding postoperative recovery and bone healing, ultrasonic bone cutting technology not only reduces swelling and pain but also demonstrates favorable outcomes in bone healing. Studies have shown that patients treated with piezoelectric bone tools (piezosurgery) show significantly enhanced alveolar bone healing at 3 and 6 months postoperatively compared to those treated with conventional rotary instruments [2,9,28]. Moreover, the combination of biomaterials, such as PRF, further enhances soft tissue healing and reduces postoperative swelling duration by up to 50% [15] (Table 1, Ref. [8,25,30,31]).

The minimally invasive extraction of impacted mandibular third molars is progressively replacing conventional surgical techniques. This approach has demonstrated several advantages, including reduced intraoperative trauma, lower complications, and enhanced postoperative recovery. However, further evidence-based investigation is required to rigorously validate the predictability, reproducibility, and long-term reliability of these clinical outcomes.

Key Applications for Minimally Invasive Techniques

Optimized Incision Design

Basic Principles of Incision Design

In the extraction of impacted mandibular third molars, the design of the incision and flap plays a crucial role in deter-

Table 2. Common flap designs and their characteristics.

Flap design program	Vantage	Drawbacks	References
Standard triangular flap	The surgical field is fully exposed	It may leave a gum tear	[33]
Szmyd flap	Postoperative pain is mild	The operator requires high experience	[34,35]
Standard envelope flap	Easy to operate	If exposure is insufficient, additional incisions are required	[33,35,36]
Kruger envelope flap	The trauma was minor	Insufficient exposure of the lower teeth	[33]
Comma-shaped flap	Exposure is high	The incision design is complex	[37,38]
Bayonet-shaped flap	Expose superior to standard envelope flap	Suturing technology requires high	[39,40]
Lingual flap	Applicable to specific scenarios	The risk of tongue nerve injury is high	[34,41,42]
Linear flap	Minimal invasive	The risk of postoperative infection is high	[43,44]
Pedicle flap	Good blood supply	The operation is complex, and the clinical evidence is limited	[45]

mining surgical field visibility, procedural complexity, and postoperative outcomes. Guided by the concept of minimally invasive surgery, the primary goal of flap design is to maximize surgical access, minimize soft tissue damage, and preserve periodontal integrity. Selecting the appropriate incision and flap design not only facilitates the extraction process but also significantly impacts postoperative healing and the risk of complications.

An effective flap design should offer adequate exposure of the tooth and surrounding anatomy while minimizing disruption to adjacent tissues. It must also support predictability and optimal recovery and reduce the risk of postoperative wound infection [32].

Comparative Analysis of Different Incision Design Options

The design of the incision and flap is crucial in the surgical extraction of impacted mandibular third molars. An ideal flap should provide adequate surgical access to facilitate the procedure, while minimizing trauma and promoting postoperative healing. Among the most commonly employed flap designs are triangular and capping flaps, along with their modified versions. Triangular flaps (e.g., standard triangular flap [33] and the Szmyd flap [34,35]) and capping flaps such as the standard capping flap [33] and the Kruger capping flap [33,35,36] are widely used in clinical practice. However, triangular flaps may pose challenges in suturing and wound healing due to tissue laxity, whereas envelope flaps offer easier handling but may limit surgical exposure. Other designs, such as lingual and linear flaps, are less frequently utilized due to their association with high trauma or inadequate visibility of the surgical field.

The meta-analysis [10] revealed that the envelope flap was associated with significantly less postoperative pain compared to the standard triangular flap (mean difference [MD] = 8.92, 95% confidence interval [CI] [1.71, 16.73], p = 0.02), potentially due to reduced soft tissue trauma. However, no significant difference in postoperative pain was reported between the envelope flap and the Szmyd flap (MD = –3.27, 95% CI [–8.12, 1.57], p = 0.19). The envelope flap was also considered easier to perform. Additionally, one study found that the Kruger envelope flap led to significantly reduced pain levels compared to the no-flap approach (MD = –45.00, 95% CI [–53.97, –36.03]). In clinical practice, flap design, such as triangular or modified capping flaps, is usually preferred for the extraction of impacted mandibular third molars, as they provide adequate surgical exposure. Ultimately, flap selection should be based on the surgeon's experience and the individual clinical characteristics, with the capping flap potentially offering practical advantages due to its relative ease of use. Commonly used flap designs are summarized in Table 2 (Ref. [33–45]).

The Szmyd and capping flaps have been demonstrated to have superior efficacy in reducing postoperative pain than the standard triangular flap following mandibular third molar extraction. For low-positioned third molars, flap design should ensure adequate surgical exposure. Both the triangular and capping flaps provide distinct advantages and drawbacks; the choice of an appropriate flap should be based on the surgeon's experience, clinical judgment, and preferred surgical approach.

Innovative Applications of Ultrasonic Bone Scalpels

Ultrasonic Bone Knife vs. Conventional Rotary Instrumentation

Ultrasonic osteotome technology represents a significant advancement in minimally invasive techniques for mandibular third molar extraction. Unlike traditional rotary instruments, the ultrasonic bone knife, which is based on piezoelectric vibration, enables highly precise bone removal while generating less heat, thereby minimizing adjacent tissue damage and reducing postoperative complication risk [2,9].

Evidence has shown that ultrasonic bone cutters markedly decrease postoperative pain, swelling, and incidence of trigeminal nerve palsy compared to traditional rotary tools. In a randomized controlled trial, patients treated with ultrasonic scalpels reported significantly lower pain indices 48 hours after surgery than those treated with conventional rotary instruments. Although the ultrasonic bone knife may slightly elevate operative time, its minimally invasive nature leads to faster postoperative recovery and an enhanced overall quality of life [27,46].

A randomized, split-mouth study comparing the extraction of impacted mandibular third molars using piezosurgery versus conventional rotary instruments showed that piezosurgery required more surgical time. However, postoperative swelling subsided more rapidly by day 7 in the piezosurgery group, while the conventional group exhibited prolonged edema. Mandibular-auricular measurements were significantly higher on postoperative days 1, 3, and 7 with conventional tools. Although piezosurgery initially reduced mouth opening, normal function returned by day 7, outperforming recovery with conventional methods. Postoperative pain was significantly higher during the first 4 days in the conventional group, with no substantial difference after day 5. Additionally, piezosurgery also led to significantly enhanced alveolar bone healing at 3 and 6 months after surgery. When used appropriately, piezosurgery can mitigate postoperative complications compared to conventional methods. Clinicians should carefully assess the indications, benefits, and potential challenges to optimize patient outcomes [28].

Combined Application of Ultrasonic Bone Knife and Dental Electric Motor

The integration of ultrasonic bone knives and dental electric motors has substantially advanced the surgical management of impacted mandibular third molars. In complex cases, relying on a single technique may be inadequate to achieve optimal surgical outcomes. Combining the precise bone-cutting capabilities of an ultrasonic bone knife with the powerful force of the dental electric motor enhances the efficiency and safety of the procedure while mitigating surgical risks. A study by Wang and Zhang [11] evaluated the clinical efficacy of using an ultrasonic bone cutter in combination with a dental motor for the extraction of impacted mandibular third molars. In this randomized trial involving two hundred patients, participants were assigned to three groups: ultrasonic bone cutter with dental motor, ultrasonic bone cutter with high-speed turbine handpiece, and traditional bone chisel. The researchers assessed operative time, intraoperative psychological responses, postoperative outcomes, including pain, swelling, mouth opening limitation, on days 1, 2, and 3 after the procedure. The results showed that the operative time was significantly shorter in the group treated with the ultrasonic bone cutter and dental motor (17.06 $\pm$ 2.25 minutes) compared to the ultrasonic bone cutter high-speed turbine handpiece group (23.43 $\pm$ 2.18 minutes) and the traditional bone chisel group ($p < 0.05$). The intraoperative psychological status was also significantly superior in the ultrasonic bone cutter and dental motor group compared to the other two groups ($p < 0.05$). Furthermore, this group also had significantly lower postoperative pain, swelling, and mouth opening limitation ($p < 0.05$).

Additionally, the use of an ultrasonic bone knife in conjunction with a dental motor has demonstrated efficacy in cases with low to moderate impaction. This approach is associated with a favorable prognosis, high safety profile, reduced surgical duration, improved patient psychological well-being, and a lower incidence of postoperative complications. Consequently, this technique represents a preferred option for the extraction of impacted mandibular third molars in suitable cases.

The electric motor-driven micro-power system offers surgeons with robust and reliable cutting power, particularly when managing dense osseous structures, and demonstrates significantly higher cutting efficiency compared to the ultrasonic bone cutter alone. In cases involving deeply embedded or severely impacted roots, the combined use of these technologies enhances surgical efficiency while mitigating intraoperative trauma to periodontal tissues, thereby facilitating rapid postoperative healing. Concurrently, this integrated approach promotes patient comfort during postoperative recovery and reduces the incidence of postoperative complications, representing a substantial innovation in contemporary dental surgical practice [11,47,48].

Comparison of Efficiency and Postoperative Pain in Different Tooth Sectioning Techniques

The tooth extraction approach should be tailored to the specific type and position of impaction. The overarching goal of minimally invasive techniques is to minimize both tooth sectioning and bone removal. Adhering to the principles of minimally invasive surgery can reduce surgical trauma and minimize operative duration. Hence, careful planning of cutting techniques, enhancement of cutting efficacy, optimization of surgical outcomes and postoperative recovery, as well as enhancement of patient satisfaction, are crucial factors in the effective management of impacted tooth extractions.

Crown sectioning methods typically include three-piece sectioning and "T"-shaped sectioning approaches. Zheng *et al*. [49] assessed the clinical outcomes of three-piece tooth sectioning in extracting horizontally impacted mandibular third molars. In a cohort of 60 patients with bilateral mandibular third molar horizontal and buccal low impaction, one side underwent three-piece tooth sectioning, where each molar was divided into three pieces and extracted in the sequence of middle portion, root, and crown. The contralateral side was treated one month later using a conventional approach, removing the crown first, followed by the remaining parts using the same instruments. The findings revealed that the three-piece approach substantially alleviated operative time (10.05 (0.51) min) compared to the traditional method (20.15 (0.88) min, $p < 0.01$). Furthermore, patients in the three-piece sectioning group reported less severe postoperative swelling, pain, and trismus ($p < 0.01$). The findings suggested that the three-piece sectioning approach can effectively remove low-level and buccally impacted mandibular third molars, reducing surgery duration, minimizing trauma, and decreasing the risk of postoperative complications.

In another study, He *et al*. [29] comparatively evaluated the efficiency and postoperative pain associated with the three-piece and "T"-shaped cutting methods for extracting horizontally impacted mandibular third molars. Their findings revealed that the three-piece sectioning technique exhibited a significantly shorter operation duration (14.73 $\pm$ 3.21 min) than the "T"-shaped method (19.25 $\pm$ 4.29 min) ($p < 0.05$). Pain scores on postoperative days 3 and 7 were substantially lower in the three-piece approach (visual analogue scale (VAS): 2.24 $\pm$ 1.89 and 0.15 $\pm$ 0.40, respectively) compared to the "T"-shaped method (VAS: 3.95 $\pm$ 2.44 and 0.48 $\pm$ 0.68 ($p < 0.05$). Moreover, the VAS score for patient satisfaction were higher on day 7 in the three-piece sectioning group (6.05 $\pm$ 1.29) compared to the "T"-shaped group (4.90 $\pm$ 1.05) ($p < 0.05$).

Overall, the three-piece sectioning approach offers several apparent advantages, including reduced surgery time, decreased postoperative complications, and enhanced patient satisfaction, making it a preferred option for extracting impacted mandibular third molars. In cases where adjacent teeth obstruct crown removal and pose a risk of damage, it is advisable to first expose the roots by selectively removing bone and creating space. The affected teeth should then be divided into crown and root portions, with the roots extracted first, followed by the crowns [50].

Clinical Applications of Water Laser Technology

Basic Principles and Mechanisms of Water Laser Technology

Water laser technology is an advanced approach that leverages the interaction between laser energy and water to achieve precise tissue cutting with minimum damage to surrounding tissues. This method typically uses Erbium: Yttrium-Aluminum-Garnet (Er: YAG) or Er, Chromium: Yttrium Scandium Gallium Garnet (Cr: YSGG) lasers in conjunction with a fine water mist to facilitate the efficient cutting of both hard and soft tissues at lower temperatures, thereby minimizing the risk of thermal damage and carbonization [51]. The fundamental principle underlying this technique is the synergistic effect of water and laser energy, where the laser beam atomizes water to induce a micro-explosion effect, enabling the precise removal of tooth structure or soft tissue. Operating within the wavelength range of 2940 nm to 2780 nm, water lasers take advantage of their pronounced water absorption capacity by water-rich tissues to enhance cutting efficiency [52]. Compared to conventional laser technologies, water lasers exhibit substantially reduced thermal impact on adjacent tissues, thereby significantly mitigating postoperative discomfort, such as pain and swelling.

Application and Comparative Study of Water Laser Technology

The application of water laser technology in mandibular third molar extraction offers considerable advantages, particularly in the realm of minimally invasive and precise surgery. This approach minimizes damage to adjacent healthy tissue, consequently accelerating the postoperative healing [53]. Unlike conventional mechanical techniques such as rotary drills, which often cause thermal damage and create microcracks in bone, water lasers effectively eliminate these risks [54]. Furthermore, the decrease in intraoperative burning odor contributes to enhanced patient comfort during the procedure. A comparative analysis involving 57 cases of impacted mandibular third molar extractions evaluated osteotomies performed using rotary instruments, piezoknives, and Er: YAG lasers. The results indicated that both piezosurgery and Er: YAG lasers represent viable alternatives to rotary instruments, albeit with slower operating speeds compared to traditional rotary instruments [55]. The burgeoning adoption of this laser technology is being propelled by a growing number of oral surgeons who recognize its benefits in improving surgical accuracy, safety, and patient satisfaction.

Breakthroughs in Dynamic Navigation Technology

The Basic Principle of Dynamic Navigation Technology and Its Superiority

Dynamic navigation technology is increasingly adopted in dentistry and oral surgery due to its ability to allow for precise surgical procedures through real-time tracking and 3D imaging based on preoperative planning. This approach is particularly beneficial in the extraction of mandibular third molars, where it substantially enhances both surgical precision and safety [54]. Using computer-assisted technology, dynamic navigation offers continuous 3D positional feedback by integrating preoperative imaging data with reference marker plates and surgical instruments fixed within the patient's oral cavity.

Using dynamic navigation systems in surgical interventions offer several advantages. Firstly, it reduces localization errors and minimizes the risk of inadvertent injuries to adjacent structures, thereby enhancing procedural safety. Secondly, it significantly improves surgical efficiency by providing real-time, precise intraoperative guidance, which helps minimize the risk of postoperative complications, such as nerve damage and alveolar bone injury [12]. Furthermore, the flexibility and adaptability of this approach also allow for personalized surgical planning, ultimately contributing to improved patient recovery outcomes.

During implant surgery, Pellegrino *et al*. [13] reported a case involving a 75-year-old male with severe maxillary atrophy who received the placement of four zygomatic implants using a dynamic navigation system. This approach employed an intraoral anchored reference tool and three datum markers to facilitate a minimally invasive surgery with immediate load-bearing restoration. A 12-month follow-up revealed that all implants remained stable without complications. The provisional implant served as the anchoring reference, and an ultrasonic bone knife was used to prepare the implant sockets. Real-time tracking of the drill position ensured a final angular deviation of $2.05° \pm 1.02°$, with inlet and outlet position deviations of less than 1.35 mm and 2.15 mm, respectively, outperforming the precision achieved by the traditional static guide technique.

Examples of Dynamic Navigation Techniques Used in Actual Surgeries

Dynamic navigation techniques have demonstrated considerable clinical significance in extracting impacted mandibular third molars. Research has reported that using dynamic navigation significantly reduces gingival injury, postoperative pain and swelling [14]. In clinical practice, these systems support detailed preoperative imaging and surgical planning, followed by precise real-time intraoperative guidance to enhance accuracy during incisions and tooth removal. A study [56] highlighted the application of a computer-assisted navigation system under general anesthesia to precisely localize and extract an 8-mm root fragment displaced to the floor of the mouth during the extraction of a right mandibular third molar. This procedure was conducted invasively and without causing postoperative lingual nerve damage or sensory disturbances.

Furthermore, dynamic navigation techniques have demonstrated evident advantages over traditional surgical approaches, particularly in reducing postoperative pain and mitigating the risk of complications [1,57,58].

The Role of Dynamic Navigation Techniques in Improving Surgical Accuracy

Dynamic navigation technology has significantly enhanced the precision and safety of impacted mandibular third molar extractions. By offering high-precision three-dimensional image guidance, this system enables surgeons to execute efficient and accurate procedures within constrained visual fields. This technology is particularly valuable for precise tooth segmentation, allowing for targeted removal while preserving the integrity of the inferior alveolar nerve [58,59].

Technology offers real-time intraoperative calibration and feedback, helping surgeons to optimize the surgical pathway, reduce unexpected complications, and enhance procedural success. Its improved precision minimizes postoperative complications and reduces operative time, establishing dynamic navigation technology as a crucial tool in the extraction of impacted mandibular third molars [12,14,56].

Overall, dynamic navigation technology not only improves the safety and precision of impacted mandibular third molar extractions but also facilitates superior postoperative recovery. As clinical advantages become increasingly recognized, it is anticipated to gain broader adoption in oral surgery, further advancing the field of minimally invasive techniques.

Concepts of Minimally Invasive Assistive Technology and Postoperative Management

Preoperative Sedation and Analgesia

Effective preoperative sedation and analgesia are crucial for ensuring patient comfort during the extraction of impacted mandibular third molars. In clinical practice, sedation approaches are commonly classified into pharmacological methods and psychological reassurance. Pharmacological sedation involves the use of oral or intravenous agents, such as benzodiazepines (e.g., diazepam), to alleviate tension and anxiety in patients [60]. These medications have proven efficacy in reducing anxiety and improving patient cooperation and comfort during the surgical procedure.

The management of perioperative pain remains a central focus in clinical practice. Beyond conventional local anesthetic techniques, multimodal analgesic regimens incorporating agents such as lidocaine and the more potent dexmedetomidine have demonstrated efficacy in reducing postoperative pain [61]. Specifically, the combined administration of dexmedetomidine and lidocaine significantly reduced postoperative pain scores at 6, 12, and 24 hours after surgery (all $p < 0.05$). This analgesic effect was also extended to the intraoperative period, with a strong association observed between reduced pain scores and the combination regimen ($p < 0.05$) [61]. Overall, this combination has been shown to be more effective in pain control compared to lidocaine alone, thereby enhancing patient comfort and promoting a smoother postoperative recovery.

Intraoperative Minimally Invasive Technology and Corticosteroid Injection

The minimally invasive approach to mandibular third molar extraction prioritizes preventing nerve injury, with particular focus on protecting the inferior alveolar nerve. Conventional extraction methods can inadvertently damage this nerve, potentially resulting in altered sensations or even permanent numbness in the lower lip. To minimize this risk, several studies have recommended crown sectioning, which involves removing only the crown while leaving the root, thereby avoiding direct trauma to the nerve [31,62].

In anatomically complex cases, where the tooth root lies in close proximity to the inferior alveolar nerve canal, crown dissection combined with microscrew traction has emerged as a viable alternative. This technique optimizes the direction of tooth removal, minimizes surgical trauma, and enhances nerve protection [63]. Clinical evidence supports the efficacy of this modified procedure, reporting superior outcomes and lower complication rates [3,64,65].

Furthermore, topical corticosteroid injections are commonly used in minimally invasive extraction of mandibular third molars to mitigate postoperative inflammation and expedite the healing process. By inhibiting the release

Table 3. The various postoperative management strategies and their clinical outcomes.

Technology/strategy	Clinical effectiveness	References
Combined sedation and analgesia program	Enhanced intraoperative comfort and reduced postoperative pain	[60,61]
Corticosteroid local injection with laser therapy	Reduced postoperative swelling and pain, accelerated healing, efficient and comprehensive treatment	[15,16]
Optimization of platelet-rich fibrin (PRF) with analgesics	Reduced postoperative complications, improved speed of recovery, and reduced the need for analgesic medications	[15,70]

of inflammatory mediators, corticosteroids effectively reduce postoperative pain and swelling, thereby enhancing patients' recovery and quality of life [66,67].

Postoperative Drug Intervention and Physical Therapy

Postoperative infection and periodontal tissue defects are common sequelae following the extraction of impacted mandibular third molars. To mitigate these complications, the use of antimicrobial agents and adjunctive therapies, such as PRF, has become a standard component of postoperative care. PRF, extensively utilized for its regenerative properties, enhances postoperative healing by releasing growth factors that accelerate soft tissue regeneration, significantly reduces postoperative pain and swelling, and expedites overall recovery. A study demonstrated that patients treated with PRF experienced significantly less pain and swelling, allowing them to resume activities more quickly by the seventh day after surgery [15].

Furthermore, low-energy laser therapy has emerged as a valuable adjunctive treatment modality. By augmenting cellular activity and enhancing blood circulation, low-level laser irradiation significantly promotes soft tissue healing and reduces postoperative complications [16]. This therapy presents new strategies for comprehensive postoperative management [68,69]. A previous study compared the efficacy of a combined treatment regimen comprising corticosteroid injections and low-energy laser therapy with conventional postoperative care. The findings revealed that patients receiving the combined intervention exhibited significantly reduced swelling and pain scores on the third postoperative day, indicating the superior clinical efficacy of this integrated approach [16].

The integration of homeopathic remedies with conventional pharmacological treatments represents a novel approach in analgesic selection. Growing evidence supports the effectiveness of multimodal analgesia, such as the concomitant administration of celecoxib and tramadol or acetaminophen, in managing moderate to severe postoperative [70]. This synergistic strategy, which harnesses distinct mechanisms of action, has been shown to improve pain control while reducing the overall dosage of analgesics and alleviating the risk of adverse effects (Table 3, Ref. [15,16,60,61,70]).

The application of these techniques and strategies has substantially improved clinical outcomes in impacted mandibular third molar extraction, demonstrating strong support for the adoption of minimally invasive treatment approaches in oral surgery. Aligned with the concepts of minimally invasive treatment, which aim to minimize surgical trauma, a range of advanced techniques, tools, pharmacological agents, and biomaterials are employed. This comprehensive approach effectively mitigates postoperative pain, minimizes adverse reactions, and preserves both soft and hard tissues, thereby creating optimal conditions for healing, reconstruction, and aesthetic outcomes. Furthermore, it enhances patients' psychological and emotional well-being, underscoring the importance of comprehensive, patient-centered care. Further comprehensive clinical investigations are crucial to evaluate the long-term effects and broader applications of these approaches, which will be critical for advancing the clinical utilization and evolution of minimally invasive techniques in managing complex oral surgery cases.

Future Directions and Challenges

Popularity and Cost Constraints of Dynamic Navigation Technologies

The advent of dynamic navigation technology has substantially enhanced the precision of mandibular third molar extractions by enabling accurate localization and execution, thereby reducing procedural complexity and minimizing complications. However, its widespread adoption remains constrained by several cost-related factors. The significant financial investment required for acquiring and maintaining the equipment, the need for specialized training, and the potential for extended procedure duration pose significant challenges for many healthcare organizations. Consequently, the use of dynamic navigation techniques is often limited to particular complex cases where their benefits justify the associated expenses [1,17].

Despite current cost constraints, dynamic navigation technology demonstrates substantial economic potential. By minimizing postoperative complications and shortening hospital stays, dynamic navigation technology can gradually decrease overall healthcare expenditures. Technological advancements and market competition are anticipated to reduce the costs associated with equipment acquisition and maintenance, making this approach more accessible to a broader range of healthcare institutions and patients.

Application of Artificial Intelligence in Surgical Difficulty Prediction

Emerging artificial intelligence (AI) methods are increasingly being applied to predict the complexity of impacted mandibular third molar extractions. Recent studies have leveraged machine learning algorithms to analyze preoperative imaging data, aiming to forecast procedural difficulty and the risk of postoperative neurological complications [20,21]. This data-driven approach, which is based on large datasets of historical cases and radiographic analyses, has demonstrated potential in enhancing prediction accuracy and supporting more informed preoperative decision-making by surgeons.

The Maglione classification system is widely employed to evaluate the complexity of impacted mandibular third molar extractions. When integrated with AI technology, this system can be considerably enhanced to support personalized surgical planning. AI can identify key factors that affect surgical difficulty, such as root morphology, bone density, and nerve proximity, offering individualized risk assessments. With growing development, the AI-assisted approach has the potential to emerge as a standard tool in preoperative assessment and decision-making.

Evidence-Based Medicine

The growing adoption of minimally invasive dental procedures underscores the need for robust empirical evidence to substantiate their long-term efficacy and safety. In the case of impacted mandibular third molar extractions, numerous short-term clinical studies have documented benefits, such as reduced postoperative pain, swelling, and functional impairments [30,71]. However, the long-term outcomes, particularly the incidence of implications and their impacts on alveolar function, remain underexplored [18,19].

Robust evidence-based medicine necessitates rigorously designed randomized controlled trials, particularly those involving long-term follow-up across diverse patient populations and surgical techniques. Moreover, using standardized assessment indicators is essential to confirm whether minimally invasive techniques not only offer short-term efficacy but also ensure sustained alveolar integrity and effective long-term management for complications.

From Minimally Invasive to Functional: The Evolution in Alveolar Surgery

The adoption of minimally invasive techniques in the extraction of impacted mandibular third molars has significantly transformed traditional surgical practices, providing patients with a more comfortable surgical experience by minimizing intraoperative trauma and postoperative complications. However, the ultimate goal of medical advancement is to safeguard and enhance patients' functional well-being. In this context, alveolar surgery must prioritize minimally invasive incisions while shifting towards functional restoration and optimization [19,72].

Ensuring long-term postoperative functionality depends on comprehensive preoperative planning, appropriate procedural selection, and effective postoperative management. Future research should focus on evaluating the long-term impacts of various minimally invasive techniques on alveolar function and assessing the development of innovative materials and technology-assisted devices to enhance postoperative healing and recovery. As scientific evidence and clinical experience continue to grow, a more comprehensive pathway will emerge, shifting from minimally invasive to functionally transformative alveolar surgery, ultimately improving overall patient health outcomes and quality of care.

Conclusions

This review systematically outlines the clinical applications and recent advancements in the minimally invasive approach for impacted mandibular third molar extractions. Research indicates that a well-designed incision can minimize soft tissue damage. Ultrasonic osteotome technology has proven effective in reducing intraoperative bleeding and thermal injury. When combined with dental electric motors, it further enhances surgical precision and efficiency. Water laser technology offers a precise cutting alternative. Dynamic navigation technology has shown promise in improving surgical accuracy by providing real-time guidance, facilitating precise bone removal and tooth sectioning, and reducing the risk of nerve injury and postoperative complications. Additionally, incorporating preoperative sedation and analgesia, intraoperative neuroprotective strategies, and comprehensive postoperative management, among other auxiliary techniques, contributes to an extensive, minimally invasive tooth extraction that enhances the perioperative experience and patient prognosis.

Future advancements in dynamic navigation technology, the integration of artificial intelligence for preoperative planning and risk assessment, and the accumulation of long-term outcome evidence and functional recovery data are expected to further optimize and expand the application of minimally invasive techniques. These developments will enhance more precise, accessible, and cost-effective care. Minimally invasive tooth extraction not only minimizes trauma but also plays a crucial role in preserving and restoring alveolar function, making significant progress toward functionally oriented alveolar surgery.

Availability of Data and Materials

Not applicable.

Author Contributions

Conceptualization, YHW, QJ and ZYS; methodology, YHW, LDL, MYJ, QJ and ZYS; writing-original draft preparation, YHW and LDL; investigation, TYZ; resources, MYJ; data curation, XQ; writing-review and editing, QJ and ZYS; visualization, YHW, LDL and TYZ; supervision, XQ, QJ and ZYS. All authors have been involved in revising it critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

Not applicable.

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Conflict of Interest

The authors declare no conflict of interest.

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