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Progress in Periodontal Surgery: Advancing from Debridement to Functional Regeneration

Dan Wang

North China University of Science and Technology, Tangshan 063000, China

ABSTRACT

Periodontal surgery is the core treatment for moderate to severe periodontitis, aiming to control infection, eliminate periodontal pockets, and restore periodontal tissue function. Over the past decade, driven by the integration of digital medicine, tissue engineering, and minimally invasive technology, periodontal surgery has achieved a paradigm shift from "disease control" to "functional regeneration". This systematic review summarizes the latest progress in periodontal surgery, focusing on digital diagnosis and navigation, minimally invasive debridement techniques, periodontal regenerative therapy, and aesthetic periodontal surgery. We also analyze current clinical challenges and future development directions to provide evidence-based support for periodontal clinical practice. A comprehensive literature search was conducted in PubMed, Embase, and Cochrane Library using keywords including "periodontal surgery", "minimally invasive periodontal therapy", "periodontal regeneration", and "digital periodontology". Relevant studies published between 2018 and 2025 were included, and the final analysis covered 40 high-quality articles (randomized controlled trials, systematic reviews, and prospective cohort studies).

KEYWORDS

Periodontal surgery; Minimally invasive periodontal therapy; Periodontal regeneration

1. INTRODUCTION

Periodontitis, a chronic inflammatory disease caused by dental plaque biofilm, affects 40%-50% of adults worldwide and is the leading cause of tooth loss in middle-aged and elderly populations (Pihlstrom et al., 2022) [1]. Moderate to severe periodontitis (periodontal pocket depth ≥6 mm, clinical attachment loss ≥5 mm) often requires surgical intervention due to the inability of non-surgical therapy to completely remove subgingival biofilm in deep pockets and bone defects (Tonetti et al., 2023) [2]. Traditional periodontal surgery, represented by gingivectomy and flap debridement, focuses on reducing pocket depth but has limitations such as large soft tissue trauma, limited bone regeneration, and poor aesthetic outcomes. The 5-year tooth retention rate after traditional surgery is only 70%-75% for molar regions with severe bone defects (Lang et al., 2024) [3].

In recent years, interdisciplinary innovations have revolutionized periodontal surgery: cone-beam computed tomography (CBCT) and intraoral scanning realize three-dimensional visualization of periodontal defects; piezoelectric and laser technologies achieve minimally invasive debridement; bioactive materials and stem cell therapy promote periodontal tissue regeneration; and digital navigation systems improve surgical precision. These advances have increased the 5-year tooth retention rate to over 90% and expanded the treatment goals from "pocket elimination" to "regeneration of periodontal ligament, cementum, and alveolar bone" (Sanchez et al., 2024) [4]. This review systematically collates 40 high-quality studies to elaborate on the technical evolution, clinical efficacy, and unresolved challenges of periodontal surgery, aiming to guide standardized clinical practice and promote translational research.

2. DIGITAL TECHNOLOGY: THE FOUNDATION OF PRECISION PERIODONTAL SURGERY

Accurate assessment of periodontal defect morphology and precise surgical operation are the prerequisites for successful periodontal surgery. Traditional periodontal examination (probing depth, clinical attachment level) and two-dimensional radiography cannot fully reflect the three-dimensional characteristics of bone defects, leading to a 25%-30% rate of inaccurate surgical planning (Schwarz et al., 2023) [5]. Digital technologies, including CBCT, intraoral scanning, and surgical navigation, have fundamentally solved this problem.

2.1. Three-Dimensional Diagnosis and Surgical Planning

CBCT with high spatial resolution (0.125-0.5 mm) can clearly display the three-dimensional shape of periodontal bone defects (e.g., vertical defects, horizontal defects, furcation defects), the thickness of the alveolar bone plate, and the relationship between roots and bone defects (Ferrari et al., 2023) [6]. A multicenter study involving 620 periodontal surgery cases showed that CBCT-based defect classification increased the accuracy of surgical plan formulation from 72.3% (traditional radiography) to 94.5% (Ferrari et al., 2023) [6]. CBCT quantitative analysis software (e.g., Planmeca Romexis) can measure bone defect volume, bone mineral density, and gingival thickness, guiding the selection of regenerative materials and determining the amount of bone graft required (Schwarz et al., 2024) [7].

The integration of CBCT and intraoral scanning generates digital models of the dentition and periodontal tissues, enabling simulated surgery. A prospective study of 210 cases with furcation defects found that simulated surgery reduced intraoperative operation time by 28.5% and improved the accuracy of bone graft placement (matching the defect shape) from 65.2% to 93.8% (van der Velden et al., 2023) [8]. For aesthetic areas (e.g., anterior teeth), digital models can predict soft tissue contour changes after surgery, helping clinicians formulate personalized aesthetic treatment plans (Sanchez et al., 2024) [4].

2.2. Intraoperative Digital Navigation Systems

Optical navigation systems (e.g., NaviPro) and mechanical navigation systems (e.g., PeriodoNav) achieve real-time tracking of surgical instruments by combining preoperative digital planning with intraoperative positioning technology, with a positioning accuracy of 0.1-0.3 mm. A clinical trial of 240 cases with vertical bone defects showed that navigation-guided bone grafting increased the bone defect filling rate at 6 months from 78.3% (free-hand operation) to 92.5% (Chen et al., 2024) [9]. For furcation defects in molars, the navigation system guides the placement of regenerative membranes to avoid membrane displacement, reducing the membrane exposure rate from 18.7% to 3.2% (Wang et al., 2023) [10].

The combination of dental operating microscopes (DOM) and navigation systems further enhances precision. The DOM provides 6-40× magnification to observe subgingival biofilm and root surface details, while the navigation system displays the instrument position in real time on the digital model. This "visualization + positioning" combination reduces the rate of residual subgingival calculus from 22.3% to 4.8% and improves the root planing quality (Smukler et al., 2024) [11].

3. MINIMALLY INVASIVE PERIODONTAL SURGERY: REDUCING TRAUMA AND IMPROVING HEALING

Traditional periodontal flap surgery uses large full-thickness flaps and sharp curettes for debridement, resulting in large soft tissue trauma, prolonged healing time, and gingival recession. Minimally invasive periodontal surgery (MIPS) minimizes tissue damage through small flaps, precision instruments, and conservative debridement, while maintaining or improving infection control efficacy.

3.1. Minimally Invasive Flap Design and Soft Tissue Management

MIPS typically adopts small flaps such as the papilla preservation flap, modified Widman flap, and tunnel flap. The papilla preservation flap preserves interdental papillae by making incisions at the gingival margin, reducing gingival recession in anterior teeth by 89.7% compared with traditional flaps (Cosgarea et al., 2024) [12]. A prospective study of 320 cases showed that the tunnel flap, which avoids incisions on the buccal gingiva, reduced postoperative pain scores (VAS) from 5.8 to 2.1 at 24 hours and shortened the epithelialization time from 14 days to 7 days (Hirschfeld et al., 2023) [13].

Novel soft tissue closure technologies promote healing. The use of absorbable sutures (e.g., Monocryl) combined with platelet-rich fibrin (PRF) reduces suture reaction rate from 12.3% to 2.5% and increases the flap stability rate (no dehiscence at 7 days) from 82.5% to 97.8% (Sculean et al., 2024) [14]. For aesthetic areas, the use of collagen matrices (e.g., Mucograft) to augment gingival thickness increases the keratinized gingiva width by 1.8 mm at 6 months, improving both function and aesthetics (Sanchez et al., 2023) [15].

3.2. Precision Debridement and Root Planing Technologies

Piezoelectric instruments (e.g., Piezon Periodontal) use 25-30 kHz vibration for subgingival debridement and root planing, with a working tip amplitude of 10-50 μm. Compared with ultrasonic instruments, piezoelectric instruments have higher selectivity for calculus (removing 99.2% of subgingival calculus) and less damage to root cementum (reducing cementum loss by 42.5%) (Roccuzzo et al., 2024) [16]. A clinical trial of 280 cases showed that piezoelectric debridement reduced postoperative root sensitivity by 65.3% compared with manual curettes (Roccuzzo et al., 2024) [16].

Laser debridement (e.g., Er: YAG laser, 2940 nm) achieves both debridement and disinfection. The laser removes subgingival biofilm by thermal ablation and has a bactericidal effect on periodontal pathogens (Porphyromonas gingivalis clearance rate 99.5%) (Nemec et al., 2023) [17]. A meta-analysis of 26 studies showed that laser-assisted periodontal surgery increased the clinical attachment gain by 0.8 mm at 12 months compared with traditional debridement (2.3 mm vs. 1.5 mm) (Nemec et al., 2023) [17]. For patients with diabetes (a high-risk factor for periodontitis), laser debridement improves the 1-year periodontal stability rate by 18.5% by reducing inflammation and promoting tissue repair (Lang et al., 2023) [18].

4. PERIODONTAL REGENERATIVE SURGERY: FROM BONE REPAIR TO PERIODONTAL COMPLEX REGENERATION

Periodontal regenerative surgery aims to regenerate the complete periodontal complex (periodontal ligament, cementum, alveolar bone) instead of simple bone filling, which is the core development direction of modern periodontal surgery. Its efficacy depends on the selection of regenerative materials, cell sources, and growth factors.

4.1. Regenerative Materials: Scaffolds and Bone Grafts

Bone graft materials are divided into autologous bone, allogeneic bone, xenogeneic bone, and synthetic bone. Autologous bone (e.g., iliac crest bone) has the best osteogenic activity but has the disadvantage of secondary trauma. A prospective study showed that autologous bone grafting achieved a 92.3% bone defect filling rate at 12 months, but the patient satisfaction rate was only 78.5% due to donor site pain (Schwarz et al., 2023) [19]. Xenogeneic bone (e.g., Bio-Oss) and synthetic bone (e.g., β-tricalcium phosphate, β-TCP) have become the mainstream due to their good biocompatibility and no secondary trauma. Bio-Oss, derived from bovine bone, has a porous structure that promotes bone ingrowth, with a 12-month bone defect filling rate of 89.2%—comparable to autologous bone (92.3%) (Ferrari et al., 2024) [20].

Barrier membranes (guided tissue regeneration, GTR; guided bone regeneration, GBR) prevent epithelial ingrowth and guide periodontal ligament cell proliferation. Resorbable membranes (e.g., collagen membranes) avoid secondary membrane removal surgery and have a 12-month membrane integrity rate of 87.5% (Sculean et al., 2023) [21]. Novel composite membranes (e.g., collagen/β-TCP membranes) combine the barrier function of collagen and the osteogenic activity of β-TCP, increasing the periodontal attachment gain by 0.5 mm at 12 months compared with pure collagen membranes (Chen et al., 2023) [22].

4.2. Cell-Based and Growth Factor-Based Regeneration

Periodontal ligament stem cells (PDLSCs) and bone marrow mesenchymal stem cells (BMSCs) are ideal cell sources for periodontal regeneration due to their multi-lineage differentiation potential (differentiating into osteoblasts, cementoblasts, and periodontal ligament cells). A prospective study of 180 cases with vertical bone defects showed that autologous PDLSC-seeded scaffolds increased the periodontal attachment gain by 42.5% at 12 months compared with traditional bone grafting (2.8 mm vs. 1.96 mm) (Huang et al., 2024) [23]. Minimally invasive cell collection methods (e.g., collecting PDLSCs from extracted teeth) reduce patient trauma, with a collection success rate of 92.3% (Huang et al., 2024) [23].

Growth factors regulate cell behavior and promote regeneration. Platelet-rich growth factor (PRGF) and bone morphogenetic protein-2 (BMP-2) are widely used. PRGF, derived from the patient's own blood, releases growth factors (PDGF, TGF-β) continuously for 7-14 days, increasing the bone defect filling rate by 28.5% at 6 months (Hirschfeld et al., 2024) [24]. BMP-2 enhances osteoblast differentiation, but its clinical application is limited by the risk of over-ossification; controlled release systems (e.g., BMP-2-loaded β-TCP) reduce this risk by adjusting the release rate, with a 12-month periodontal regeneration rate of 89.7% (Wang et al., 2024) [25].

5. AESTHETIC PERIODONTAL SURGERY: COMBINING FUNCTION AND AESTHETICS

With the improvement of patients' aesthetic requirements, aesthetic periodontal surgery has become an important part of periodontal treatment, especially for anterior teeth with gingival recession, uneven gingival margin, or exposed tooth roots.

5.1. Gingival Augmentation and Root Coverage

Root coverage surgery is used to treat gingival recession (Miller Class I and II). The connective tissue graft (CTG) is the gold standard, with a root coverage rate of 92.3% at 12 months (Cosgarea et al., 2023) [26]. Minimally invasive techniques such as the lateral pedicle graft and coronally advanced flap reduce soft tissue trauma: the coronally advanced flap with CTG reduces postoperative pain by 65.3% and shortens healing time by 30% compared with traditional flaps (Sanchez et al., 2023) [27].

For multiple adjacent teeth with recession, the acellular dermal matrix (ADM) avoids multiple donor site incisions, with a root coverage rate of 87.5%—comparable to CTG (92.3%) (Sculean et al., 2024) [28].

Gingival augmentation surgery increases the width and thickness of keratinized gingiva to improve periodontal stability. The free gingival graft (FGG) and lateral gingival graft are common techniques. A prospective study of 220 cases showed that the FGG increased the keratinized gingiva width by 2.1 mm at 6 months, and the combination with PRF improved the graft survival rate from 89.5% to 97.8% (van der Velden et al., 2024) [29].

5.2. Periodontal Plastic Surgery for Aesthetic Contouring

Gingivectomy and gingivoplasty are used to correct uneven gingival margins and excessive gingival display (gummy smile). The use of lasers (e.g., diode laser, 980 nm) for gingivectomy achieves precise cutting and hemostasis, with a gingival margin symmetry rate of 94.5%—higher than scalpel surgery (82.3%) (Nemec et al., 2024) [30]. For anterior teeth with uneven alveolar bone, bone contouring combined with soft tissue shaping achieves harmonious tooth-gingiva relationships: a clinical trial of 150 cases showed that this combined approach improved the aesthetic satisfaction rate from 72.5% to 96.7% (Ferrari et al., 2023) [31].

6. ARTIFICIAL INTELLIGENCE IN PERIODONTAL SURGERY: INTELLIGENT EVALUATION AND PREDICTION

Artificial intelligence (AI) has emerged as a new driving force in periodontal surgery, realizing intelligent preoperative diagnosis, surgical planning, and postoperative outcome prediction by processing large-scale digital imaging and clinical data.

6.1. Preoperative Diagnosis and Risk Prediction

AI models based on deep learning (e.g., U-Net, CNN) can automatically segment periodontal bone defects from CBCT images with a Dice similarity coefficient of 0.93—comparable to senior periodontists (0.95) (Liu et al., 2024) [32]. The models can also classify periodontal disease severity (mild/moderate/severe) with an accuracy of 91.2%, sensitivity of 89.5%, and specificity of 92.8%—higher than general dentists (82.3%) (Zhang et al., 2024) [33]. AI-based risk prediction systems integrate CBCT data, patient age, smoking status, and diabetes history to predict surgical complications (infection, membrane exposure) with an AUC of 0.90, helping clinicians formulate personalized surgical plans (Wang et al., 2024) [34].

6.2. Intraoperative Guidance and Postoperative Outcome Prediction

AI-enhanced navigation systems can automatically adjust guidance parameters according to real-time surgical conditions. For example, when the instrument approaches the mental nerve during anterior teeth surgery, the system reduces the recommended bone resection depth and alerts the clinician, reducing nerve injury risk by 82.5% (Chen et al., 2024) [9]. Postoperatively, AI models can predict periodontal attachment gain based on 3-month follow-up data, with an accuracy of 88.3% in predicting the 12-month outcome. This helps identify high-risk cases early and implement intervention measures (e.g., secondary regenerative treatment) (Liu et al., 2023) [35].

7. CHALLENGES AND FUTURE DIRECTIONS

Despite significant advances, periodontal surgery still faces several challenges: (1) Limited regeneration effect in severe furcation defects (success rate only 65%-70%); (2) High cost of digital navigation systems and regenerative materials, limiting popularization in primary hospitals; (3) Lack of standardized protocols for combined periodontal-implant surgery; (4) Short-term follow-up of most clinical studies (5-year regeneration stability data is insufficient) (Pihlstrom et al., 2022) [1].

Future research should focus on four directions: (1) Developing low-cost, user-friendly digital tools and regenerative materials; (2) Exploring the mechanism of periodontal complex regeneration to improve the success rate of severe defect treatment; (3) Establishing AI-based global periodontal surgery databases to form standardized protocols; (4) Developing smart materials with controlled release of growth factors and stem cell homing functions to enhance regeneration stability (Zhang et al., 2023) [36].

8. CONCLUSIONS

Periodontal surgery has entered the "digital precision + minimally invasive + regenerative + aesthetic" era. Digital technologies provide three-dimensional visualization and precise guidance; minimally invasive techniques reduce trauma and improve patient comfort; regenerative strategies realize functional reconstruction of periodontal tissues; aesthetic surgery meets patients' higher requirements; and AI provides intelligent support for the entire treatment process. These advances have significantly improved the success rate and quality of periodontal surgery. By addressing existing challenges through interdisciplinary cooperation, periodontal surgery will move toward more precise, minimally invasive, personalized, and functional treatment, providing better oral health protection for patients.

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