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Eco-Friendly Dental Materials: Advancing Sustainability in Oral Healthcare

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Abstract: The growing global emphasis on environmental sustainability has extended into healthcare, including dentistry. Conventional dental materials—while effective—often involve resource-intensive manufacturing, non-biodegradable components, and mercury-containing compounds that raise ecological concerns. Eco-friendly dental materials aim to reduce environmental impact while maintaining clinical performance and patient safety. This mini review explores recent developments, material innovations, environmental implications, and future directions in sustainable dentistry.

Keywords: Eco-friendly dentistry; Sustainable dental materials; Green dentistry; Digital dentistry; Environmental sustainability.

Dentistry places an environmental burden through waste of materials, consumption of energy and water, and chemical disposal. Conventional materials comprised of heavy metals, petroleum-derived polymers, and those with minimal recyclability like amalgam, resin composites, and some impression materials pose ecological challenges. The trend toward environmentally friendly dental materials is part of a larger phenomenon called green dentistry, which encourages reducing waste, using safer chemistry and sustainability in sourcing [1].

Dental amalgam comprises about 50% mercury. Though long-lasting and cost-effective, mercury does carry risks of environmental contamination during disposal and cremation. International initiatives like the Minamata Convention on Mercury promote mercury use reduction nationwide and refer to the phase-down of amalgam from clinical use [2].

The vast majority of used composite resins originates from petrochemical sources (e.g., Bis-GMA, UDMA). The production of these products depends on fossil fuels and they are not biodegradable. Microplastics released during finishing and disposal processes also create pollution [3].

Alginate, silicone impression materials, plastic barriers, suction tips, and single-use items generate substantial non-recyclable waste in dental clinics.

Glass ionomer cements (GICs) and resin-modified glass ionomers provide fluoride release, chemical adhesion, and lower environmental toxicity compared to amalgam. Although not fully biodegradable, they avoid heavy metals and require less invasive preparation [4].

Research is advancing plant-derived monomers (e.g., from soybean oil or lignin derivatives) as substitutes for petroleum-based resins. These materials aim to reduce carbon footprint while maintaining mechanical strength and biocompatibility.

Calcium silicate–based materials used in endodontics and pulp therapy are biocompatible and often require less energy-intensive processing compared to traditional materials. Their longevity can also reduce replacement frequency, indirectly lowering material consumption [5].

Manufacturers are developing compostable cups, recyclable packaging, and biodegradable suction tips. Digital dentistry—such as intraoral scanning—reduces the need for physical impression materials, minimizing waste generation.

The adoption of CAD/CAM systems and 3D printing reduces material waste by improving precision and decreasing remakes. Digital workflows eliminate plaster models and reduce shipping-related emissions. However, energy consumption and resin waste from 3D printing must also be considered when evaluating overall sustainability [6].

Life Cycle Assessment is increasingly used to evaluate environmental impact from raw material extraction to disposal. Sustainable dental material development now considers:

Carbon footprint, energy use during production, toxicity and biodegradability, packaging waste, end-of-life recyclability, LCA-based research guides evidence-based decision-making in sustainable dental practice.

The future of eco-friendly dental materials lies in development of fully bio-based composite systems, improved recycling programs for dental plastics, mercury-free global restorative strategies, integration of circular economy principles in dental manufacturing, greater collaboration between material scientists and environmental researchers, educational reforms incorporating sustainability principles into dental curricula will also support long-term transformation [7].

Finally, Eco-friendly dental materials are essential for sustainable dentistry. Though conventional materials have provided over its decades of clinical success, emerging bio-based, mercury-free, and digitally optimized alternatives are paving paths toward reducing dentistry's ecological footprint. Further research, policy advocacy and professional dedication will be needed to align clinical excellence with environmental stewardship.

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Type of the Paper (Mini-Review)

Minimally Invasive and Regenerative Dentistry: Transforming Contemporary Oral Care

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Abstract: Minimally invasive and regenerative dentistry represent paradigm shifts in modern oral healthcare. Rather than focusing solely on surgical intervention and tissue replacement, these approaches prioritize early detection, preservation of natural tooth structure, and biological repair of damaged tissues. Advances in adhesive materials, biomimetics, stem cell biology, and tissue engineering have expanded the potential to restore form and function while maintaining biological integrity. This mini-review highlights the principles, materials, clinical applications, and future directions of minimally invasive and regenerative dentistry.

Keywords: Minimally invasive dentistry; Regenerative dentistry; Tissue engineering; Bioactive materials; Adhesive dentistry; Guided tissue regeneration; Biomimetic scaffolds.

Introduction

Conventional dentistry typically involved an aggressive mechanical excision of carious tissue, sometimes sacrificing healthy structure to achieve longevity. Today's practice tends to lean towards restoration with an emphasis on preservation and stimulating body's natural healing potential. Minimally invasive dentistry (MID) is characterized by preventive, risk-based and conservative treatment of diseases of the teeth, while regenerative dentistry is based on biological restoration of lost dental and periodontal tissues [1]. These philosophical stances align with evidence-based care and patient-centered ideology, decreasing discomfort, treatment time as well as long-term morbidity during intervention [2].

Principles of Minimally Invasive Dentistry

Minimally invasive dentistry is guided by four core principles [3]:

1. Early detection and risk assessment – Identification of caries at the non-cavitated stage using advanced diagnostic tools.
2. Remineralization strategies – Use of fluoride, calcium phosphate systems, and bioactive agents to reverse early lesions.
3. Selective caries removal – Preservation of affected but remineralizable dentin.

4. Adhesive restorative techniques – Bonded restorations that require minimal cavity preparation.

The philosophy is strongly influenced by the work of G.V. Black, whose traditional "extension for prevention" concept has largely been replaced with tissue-preserving strategies [4].

Minimally Invasive Clinical Techniques

Atraumatic Restorative Treatment (ART)

ART involves hand instrumentation and high-viscosity glass ionomer cements, reducing the need for rotary instruments and anesthesia [5].

Resin Infiltration

Micro-invasive infiltration techniques allow penetration of low-viscosity resins into early enamel lesions, arresting caries progression without drilling.

Sealants and Preventive Resin Restorations

Pit and fissure sealants prevent bacterial colonization in high-risk areas.

Adhesive Dentistry

Modern bonding systems enable smaller cavity preparations while maintaining mechanical strength and esthetics.

Regenerative Dentistry: Biological Repair and Replacement

Regenerative dentistry aims to restore damaged tissues such as dentin, pulp, periodontal ligament, and even whole teeth using biological approaches.

1. Dental Pulp Regeneration

Regenerative endodontic procedures (REPs) promote revascularization and continued root development, especially in immature teeth with necrotic pulp. Guidelines from organizations such as the American Association of Endodontists support regenerative protocols as alternatives to apexification [5].

2. Stem Cell-Based Therapies

Dental pulp stem cells (DPSCs), stem cells from apical papilla (SCAP), and periodontal ligament stem cells demonstrate the ability to differentiate into odontoblast-like and osteoblast-like cells [6].

3. Tissue Engineering Triad

Regenerative strategies rely on three core components:

Stem cells, Growth factors (e.g., BMPs, TGF-β), Scaffolds (natural or synthetic biomaterials), Biomimetic scaffolds guide cell proliferation and differentiation, enabling tissue regeneration.

Biomaterials in Regenerative Dentistry

Calcium silicate–based cements, bioactive glass, and platelet-rich fibrin (PRF) support healing and mineralization. These materials release bioactive ions that stimulate cellular activity and dentin bridge formation. Bioceramic materials used in endodontics offer sealing ability, biocompatibility, and regenerative potential compared with traditional materials [7].

Periodontal and Bone Regeneration

Guided tissue regeneration (GTR) and guided bone regeneration (GBR) use barrier membranes to facilitate selective cell repopulation. Enamel matrix derivatives and growth factors further enhance periodontal regeneration. Clinical success depends on defect morphology, patient factors, and biomaterial selection.

Future Perspectives

Emerging technologies such as gene therapy, 3D bioprinting, and nanotechnology may enable full pulp-dentin complex regeneration and even bioengineered tooth formation. Interdisciplinary collaboration between clinicians, bioengineers, and molecular biologists will accelerate progress in this field

Conclusion

Recent advancements in dental care have ushered a revolution in oral health with minimally invasive and regenerative dentistry leading the way. Through a focus on conservation, biological repair work and sophisticated biomaterials these methods are maintainable and a center of attention in cases. Further study and invention will probably revise the principles of restorative and endodontic therapy in future decades.

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Type of the Paper (Case Presentation)

Digitally Guided Flapless Atraumatic Extraction (DSG-FARE) of a Soft-Tissue–Impacted Palatal Root Fragment: A Case Report

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Abstract:

Background: Extraction of impacted or retained root fragments in the posterior maxilla may be surgically challenging due to limited access and close proximity to critical anatomical structures. Conventional flap-based approaches may increase morbidity and the risk of iatrogenic injury. **Case Presentation:** A 20-year-old healthy female presented with a soft-tissue–impacted palatal root fragment of a previously extracted maxillary first molar. Cone-beam computed tomography (CBCT), initially obtained for comprehensive digital implant planning, revealed an extremely close proximity of the fragment to the adjacent second molar root and the maxillary sinus floor. **Technique:** A digitally guided flapless atraumatic extraction technique was planned to use merged CBCT and intraoral scan data. A surgical guide was designed to allow controlled access, guided drilling, and traction-based extraction through a minimally invasive approach. **Outcome:** The root fragment was removed successfully without flap elevation or damage to adjacent structures. Postoperative healing was uneventful, with minimal discomfort and favorable soft tissue outcomes. **Clinical Significance:** This report describes a novel application of established digital planning and guided traction based atraumatic extraction techniques to enable minimally invasive removal of a retained palatal root fragment in an anatomically sensitive region.

Keywords: *Digitally guided surgery; Flapless extraction; Impacted root fragment; Atraumatic extraction; Cone-beam computed tomography; Digital dentistry; Surgical guide*.

1. Introduction

Management of impacted or retained root fragments in the posterior maxilla remains a common clinical challenge, particularly when fragments are located in close proximity to vital anatomical structures such as the maxillary sinus, adjacent tooth roots, and the greater palatine neurovascular bundle. Traditional surgical management typically involves

flap elevation, bone removal, and freehand instrumentation, which may increase operative time, postoperative discomfort, and the risk of complications [1].

The integration of cone-beam computed tomography (CBCT) and intraoral scanning into clinical workflows has transformed surgical planning in implant dentistry and guided endodontic procedures. These technologies allow precise three-dimensional visualization of anatomical relationships and enable guided surgical execution with enhanced accuracy. However, their application in guided extraction of impacted root remnants has been only sparsely reported [2].

Flapless surgical approaches have demonstrated advantages in preserving vascular supply, minimizing tissue trauma, and improving patient comfort. Nevertheless, flapless access in anatomically constrained regions is often avoided due to concerns regarding safety and control when performed without guidance [3].

This case report presents a Digitally Guided Flapless Atraumatic Extraction (DSG-FARE) technique, representing a case-selective digital adaptation of established surgical principles for the removal of a soft-tissue–impacted palatal root fragment located in extremely close proximity to adjacent vital structures.

2. Case Presentation:

A 20-year-old healthy female patient was referred for evaluation of a retained root fragment in the maxillary left posterior region. The patient's medical history was non-contributory. Dental history revealed previous extraction of the maxillary left second premolar and first molar. Clinical examination showed healed palatal mucosa with no signs of acute infection or sinus involvement.

Cone-beam computed tomography (CBCT) imaging was originally obtained as part of comprehensive digital implant planning for the replacement of teeth 25–26, 15–14, and 36. Review of the same dataset revealed the presence of a soft-tissue–impacted palatal root fragment of the maxillary first molar, requiring further clinical management.

CBCT assessment demonstrated the following critical measurements:

Axial CBCT view:
The coronal portion of the palatal root fragment was located at a distance of 0.42 mm from the mesial surface of the adjacent maxillary second molar root.

Sliced panoramic reconstruction:
A radiolucency consistent with chronic periapical inflammation was present around the apical portion of the root fragment. The minimum distance between the root tip and the cortical floor of the maxillary sinus measured 1.14 mm.

Soft tissue assessment:

Palatal soft tissue thickness covering the coronal surface of the impacted root fragment ranged between 3.0 and 3.33 mm, indicating a thick palatal mucosal phenotype.

Given the extremely limited anatomical clearances and the thick palatal soft tissue, a digitally guided flapless approach was selected to minimize surgical morbidity and reduce the risk of iatrogenic injury.

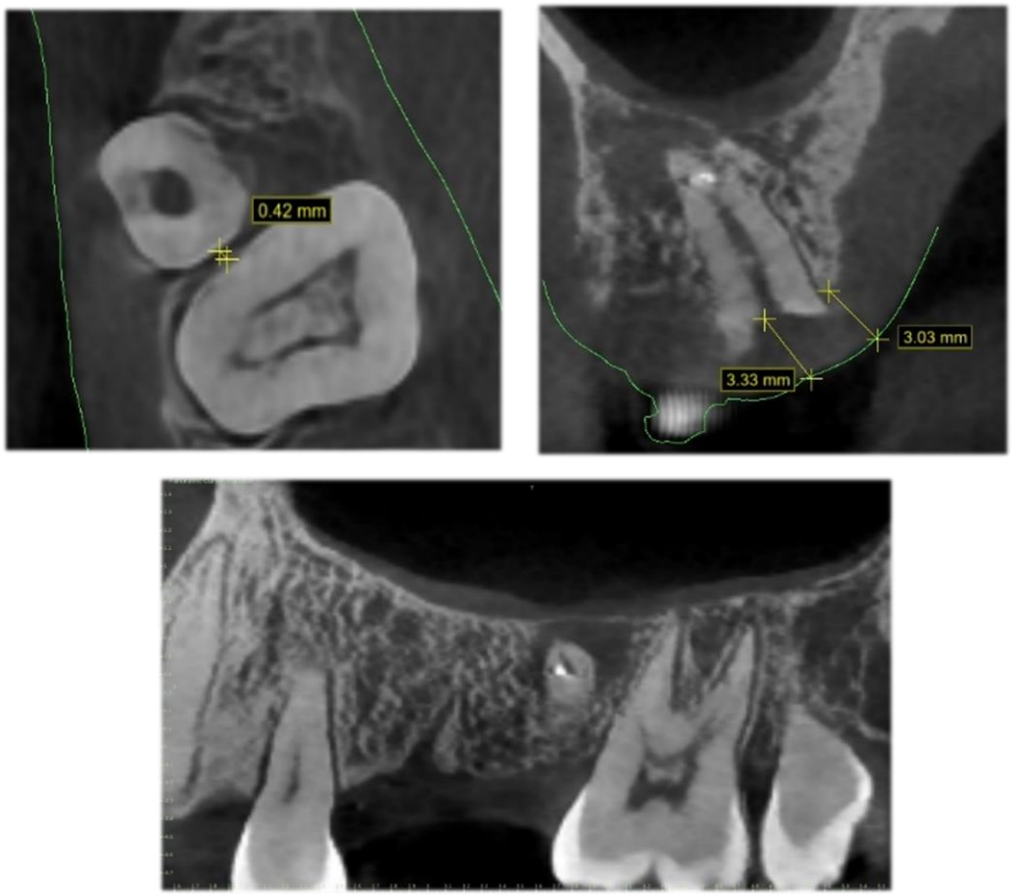


Figure 1. Preoperative CBCT demonstrating proximity of the palatal root fragment to the adjacent second molar and maxillary sinus floor.

Digital Planning and Surgical Guide Design

CBCT and intraoral scan (IOS) data were merged using digital planning software (exoplan, exocad GmbH, Germany).

Virtual planning focused on:

- Identification of the fracture surface of the palatal root fragment.
- Establishment of a safe access trajectory avoiding the adjacent second molar root and maxillary sinus floor.

- Control of drilling angulation and depth.

A tooth-supported surgical guide was designed incorporating a titanium sleeve with a 4-mm height and 5-mm internal diameter.
The guide was fabricated using a three-dimensional printing workflow. The guide was manufactured using a biocompatible photopolymer resin suitable for intraoral surgical use (Senertek-Turkey). The guide was then verified intraorally for stability and accuracy prior to surgery.

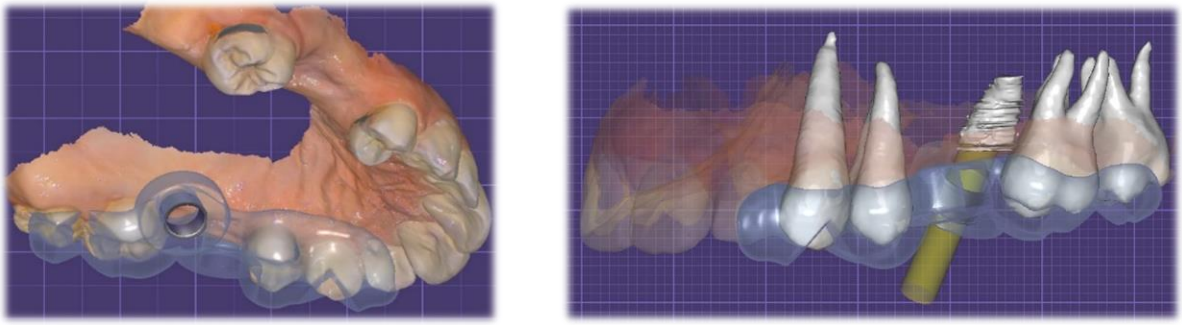


Figure 2. Digital planning and trajectory design for guided access.

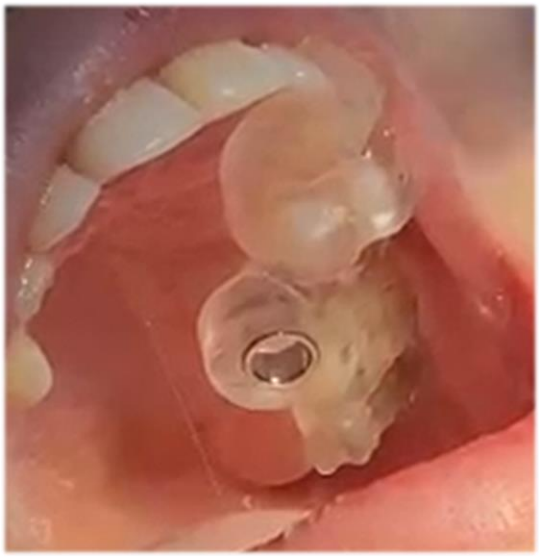
Surgical Technique: DSG-FARE Technique

Guided access was performed using a tooth-supported surgical guide incorporating a titanium sleeve and tissue punch (MODE Dental Implant System, Turkey). Guided drilling was carried out using a 1.5-mm tapered reamer derived from a commercial fiber post system, followed by insertion of a threaded attachment. Controlled axial traction was then achieved using a specialized traction device.

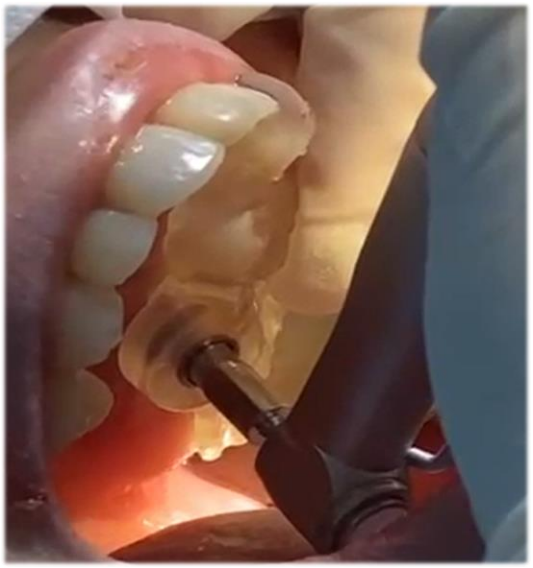
The procedure was performed under local anesthesia using a flapless approach. A soft tissue punch was used to remove the palatal mucosa overlying the fracture surface of the root fragment, providing direct access without flap elevation, using the surgical guide to ensure precise localization.

Drilling was performed using a post drill to prepare an internal channel within the coronal portion of the root fragment. A threaded traction post with an attachment mechanism was then inserted.

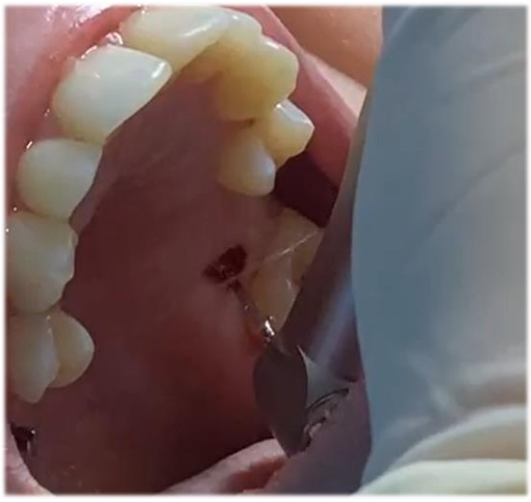
Using a specialized traction device, controlled axial traction was applied through the surgical guide, allowing removal of the root fragment without lateral luxation forces. The extraction was completed without sinus membrane perforation or injury to adjacent teeth.



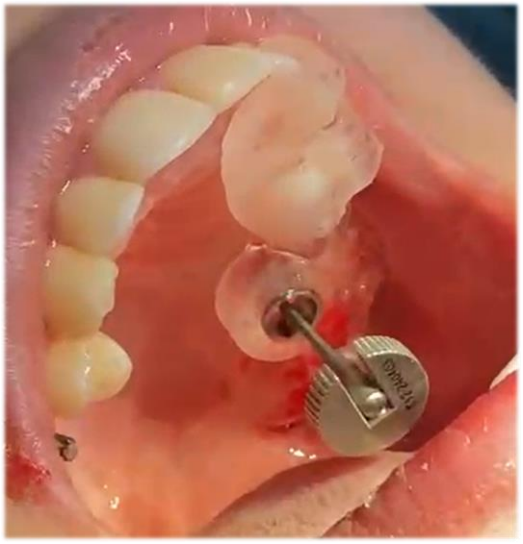
1-Surgical Guide positioned prior to access



2 – Guided Tissue punch

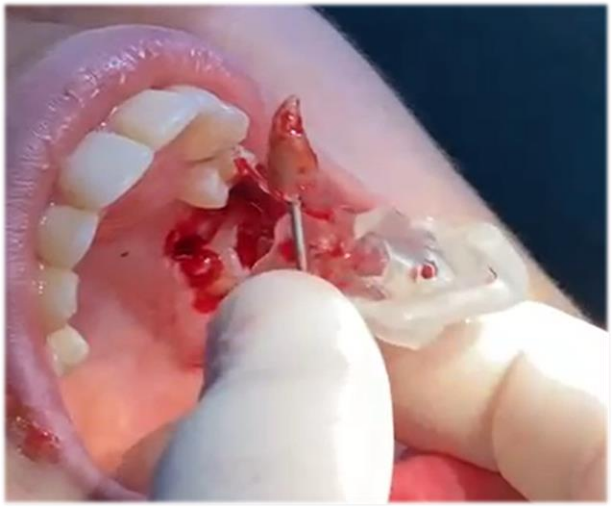


3-Preparing the root canal.

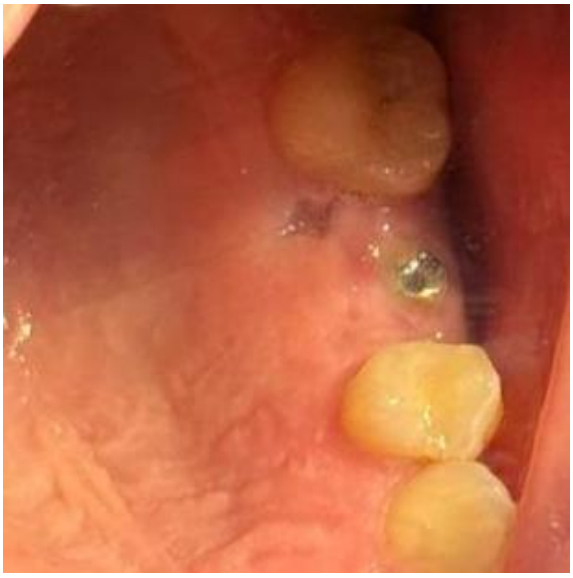


4-Securing the surgical guide with traction post in place.

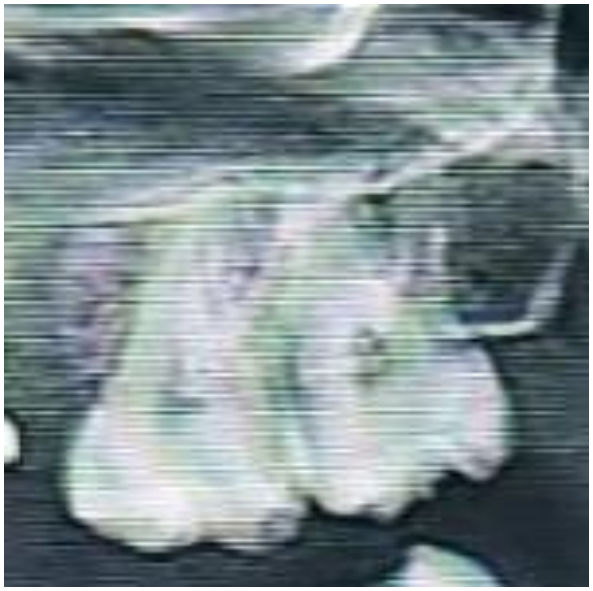
5-Traction-based Extraction plier



6- Removing the Root.



7-Postoperative clinical view – after seven days.



8-Postoperative radiographic confirmation.

Figure 3. Clinical sequence of the DSG-FARE technique.

3. Postoperative Outcome:

Postoperative healing was uneventful. The patient reported minimal discomfort and no swelling, bleeding, or sinus-related symptoms. Clinical follow-up demonstrated favorable palatal soft tissue healing with preservation of mucosal contour.

Postoperative radiographic assessment confirmed complete removal of the root fragment and preservation of surrounding anatomical structures.

4. Discussion:

In the present case, CBCT analysis demonstrated critically limited anatomical clearances, with less than 0.5 mm separation from the adjacent tooth root and approximately 1 mm from the maxillary sinus floor. Such conditions render conventional freehand surgical extraction particularly hazardous [4,5].

The DSG-FARE technique illustrates how established digital surgical principles may be adapted beyond implant placement and guided endodontic access to manage complex extraction scenarios. Digital planning enabled precise trajectory control, while guided drilling and traction-based extraction minimized lateral forces on adjacent teeth and alveolar bone [6].

The flapless approach preserved palatal vascular supply and reduced the risk of injury to the greater palatine neurovascular bundle. Additionally, utilization of an existing CBCT dataset originally obtained for implant planning avoided the need for additional imaging, adhering to the ALARA principle [7].

Limitations of the technique include the requirement for advanced digital infrastructure and operator experience. Ankylosed root fragments or cases with dense cortical bone may not be suitable for traction-based removal. Further studies are required to assess reproducibility and broader clinical applicability.

This report highlights the potential of digital workflows to extend minimally invasive surgery into situations traditionally considered high risk. With appropriate planning and case selection, guided traction-based extraction may reduce morbidity while preserving anatomical integrity.

Conclusion

The DSG-FARE technique represents a digitally guided, flapless adaptation of established surgical principles for the extraction of impacted palatal root fragments in anatomically sensitive regions. Precise digital planning and guided execution enabled safe removal despite extremely limited anatomical clearances, while preserving adjacent structures and enhancing patient comfort. This report describes a novel application of established digital planning and guided traction based atraumatic extraction techniques to enable minimally invasive removal of a retained palatal root fragment in an anatomically sensitive region.

Author Contributions

Ahmed Z. Rajab conceptualized the treatment approach, performed the digital planning and surgical guide fabrication, and supervised the clinical surgical procedure.
Moftah Alsharif provided surgical supervision and validated the clinical applicability of the technique.
Shahd Tushani, Internship Dentist, participated in the surgical procedure under direct supervision and assisted during the surgical workflow when required.
All authors critically revised the manuscript and approved the final version for publication.

Ethical Statement and Patient Consent

Written informed consent was obtained from the patient for all clinical procedures and for publication of clinical and radiographic images. No additional CBCT imaging was required for the extraction procedure, as the existing dataset obtained for digital implant planning was utilized in accordance with the ALARA principle. According to institutional policy, formal ethical committee approval was not required for this anonymized case report.

Conflict of Interest

The authors declare no conflict of interest.

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