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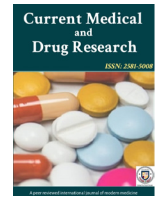

Comparison of minimally invasive access cavity designs using finite element analysis and long-term clinical outcomes

Divya Gupta

BDS, India

*Corresponding author. E-mail: Div19.gupta@gmail.com

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ABSTRACT

Minimally invasive access cavity designs have emerged as an important advancement in endodontics, aiming to preserve maximum tooth structure while maintaining adequate access for effective root canal treatment. Various designs, including conservative, ninja, and truss access cavities, have been proposed to enhance the biomechanical integrity of treated teeth without compromising clinical outcomes. Finite element analysis (FEA) has become a valuable computational tool for evaluating stress distribution, fracture resistance, and structural behavior under simulated functional loading conditions. This review examines the biomechanical performance of different minimally invasive access cavity designs through FEA and compares these findings with available long-term clinical outcomes. The relationship between tooth structure preservation, canal accessibility, instrumentation efficiency, and restorative success is critically discussed. Clinical evidence indicates that while conservative access designs may improve fracture resistance by preserving pericervical dentin, their effectiveness depends on appropriate case selection, operator expertise, and the ability to achieve thorough canal debridement and disinfection. Long-term treatment success is influenced by multiple factors, including restoration quality, occlusal loading, and patient-specific characteristics, in addition to cavity design. Integrating computational modeling with clinical follow-up provides a more comprehensive understanding of the strengths and limitations of minimally invasive approaches, supporting evidence-based decision-making and guiding future innovations in endodontic treatment planning and restorative strategies.

INTRODUCTION

Minimally invasive endodontics has transformed contemporary root canal therapy by emphasizing the preservation of healthy tooth structure while maintaining the biological and mechanical objectives necessary for successful treatment. Traditional endodontic access cavities provide wide visibility and instrument accessibility but often require extensive removal of coronal dentin, potentially weakening the remaining tooth and increasing susceptibility to fracture. Consequently, conservative access cavity designs, including conservative, ninja, and truss access cavities, have been introduced to preserve pericervical dentin, which plays a critical role in maintaining the structural integrity and long-term survival of endodontically treated teeth (Zhou, Pu, & Liu, 2024).

Finite element analysis (FEA) has become an essential computational method for evaluating the biomechanical performance of different access cavity designs. By simulating functional occlusal forces and stress distribution within dental tissues, FEA enables researchers to predict fracture resistance and identify areas susceptible to mechanical failure without

Table 1: Finite Element Comparison of Different Access Cavity Designs

Access Cavity Design	*Tooth Structure Preservation*	*Stress Distribution*	*Fracture Resistance*	*Clinical Consideration*
Traditional Access	Low	Higher cervical stress	Moderate	Excellent canal visibility and instrumentation
Conservative Access	Moderate	Reduced stress concentration	High	Good balance between preservation and access
Ninja Access	Very High	Low localized stress	High	Limited visibility; technically demanding
Truss Access	Very High	Favorable stress dispersion	High	Difficult canal negotiation in complex anatomy

invasive laboratory testing. Recent evidence indicates that preserving strategic dentin may reduce stress concentration and improve resistance to catastrophic fractures, although these computational findings must be interpreted alongside long-term clinical outcomes (Zhou et al., 2024). Effective access cavity preparation must also preserve adequate irrigation pathways and facilitate complete debridement of the root canal system, as successful disinfection remains fundamental to favorable endodontic outcomes (Singh, 2020).

Clinical success is influenced by numerous restorative and patient-related factors beyond cavity design. The quality of definitive restorations, adhesive performance, periodontal health, and postoperative biological responses collectively determine tooth longevity following root canal treatment (Singh, 2025; Papapanou et al., 2018; Isola et al., 2019). Furthermore, advances in artificial intelligence and digital imaging have improved diagnostic precision, treatment planning, and restoration assessment, providing complementary tools for evaluating structural preservation and treatment outcomes (Gonzalez et al., 2024; Rohrer et al., 2022). Predictive modeling approaches widely adopted in dentistry further support individualized risk assessment and long-term prognosis, reinforcing the integration of computational simulations with evidence-based clinical decision-making (Feher et al., 2020; Ravera et al., 2021).

Finite Element Analysis of Access Cavity Designs

Finite element analysis (FEA) has become an essential computational method for evaluating the biomechanical behavior of endodontically treated teeth restored with different access cavity designs. By generating three-dimensional digital models and simulating occlusal loading, FEA enables detailed assessment of stress distribution, cuspal deflection, and fracture susceptibility without the variability associated with laboratory testing. Recent evidence indicates that conservative access cavity designs preserve greater amounts of pericervical dentin, thereby reducing stress concentration and improving structural integrity compared with traditional access cavities (Zhou et al., 2024). Nevertheless, the biomechanical benefits of tissue preservation must be balanced against adequate canal visibility and instrumentation to ensure effective cleaning and shaping of the root canal system (Singh, 2020).

Studies comparing traditional, conservative, ninja, and truss access cavities consistently demonstrate that stress is primarily concentrated around the cervical region and cusp inclines during masticatory loading. Designs preserving more coronal dentin generally exhibit lower peak stress values and improved fracture resistance, although excessively restricted access may increase procedural complexity and compromise canal debridement. Restoration quality also influences stress transfer, as adhesive restorative materials with superior bonding properties enhance structural reinforcement following endodontic treatment (Singh, 2025). Advances in artificial intelligence and digital image segmentation further improve the accuracy of three-dimensional tooth modeling used in FEA, supporting more realistic biomechanical simulations and individualized treatment planning (Gonzalez et al., 2024; Rohrer et al., 2022).

Although FEA provides valuable biomechanical insights, simulated conditions cannot fully replicate biological responses, occlusal variability, periodontal support, or patient-specific healing factors. Therefore, computational findings should be interpreted alongside clinical evidence, periodontal status, restorative prognosis, and patient risk assessment to optimize long-term treatment outcomes (Feher et al., 2020; Papapanou et al., 2018; Isola et al., 2019; Ravera et al., 2021).

Long-Term Clinical Outcomes

Long-term clinical outcomes of minimally invasive access cavity (MIAC) designs depend on achieving an optimal balance between preserving tooth structure and maintaining sufficient access for effective cleaning, shaping, and obturation of the root canal system. Conservative cavity designs preserve greater amounts of pericervical dentin, which is considered essential for resisting functional stresses and reducing the likelihood of catastrophic fractures. Nevertheless, long-term success is influenced by several interrelated factors beyond cavity geometry, including irrigation efficiency, restorative quality, occlusal loading, and patient-specific oral conditions (Singh, 2020; Zhou, Pu, & Liu, 2024).

Clinical studies indicate that although minimally invasive designs improve structural preservation, restricted access may increase procedural complexity and challenge complete canal debridement in anatomically complex teeth. Adequate irrigation protocols and meticulous instrumentation remain essential to eliminate microorganisms and prevent persistent

Table 2: Factors Influencing Long-Term Clinical Outcomes of Minimally Invasive Access Cavities

Clinical Factor	*Influence on Long-Term Outcome*	*Supporting Reference*
Tooth structure preservation	Improves fracture resistance and tooth longevity	Zhou et al. (2024)
Irrigation effectiveness	Enhances disinfection and periapical healing	Singh (2020)
Coronal restoration quality	Reduces stress concentration and restoration failure	Singh (2025)
AI-assisted radiographic evaluation	Improves follow-up diagnosis and restoration monitoring	Gonzalez et al. (2024); Rohrer et al. (2022)
Periodontal and systemic health	Influences healing potential and prognosis	Papapanou et al. (2018); Isola et al. (2019); Feher et al. (2020)

infection, thereby ensuring favorable healing and treatment longevity (Singh, 2020). Furthermore, the durability of the final coronal restoration significantly influences tooth survival, as restorations with superior adhesive performance help distribute occlusal stresses and minimize structural failure (Singh, 2025).

Recent advances in artificial intelligence have enhanced radiographic interpretation and restoration assessment, facilitating earlier detection of restorative defects and recurrent disease during follow-up examinations. These technologies may improve long-term monitoring and support evidence-based clinical decision-making (Gonzalez et al., 2024; Rohrer et al., 2022). Patient-related variables, including periodontal status, systemic health, antioxidant balance, and risk profiles for postoperative complications, also contribute substantially to treatment prognosis and should be considered during comprehensive treatment planning (Papapanou et al., 2018; Isola et al., 2019; Feher et al., 2020). Although evidence from other dental disciplines highlights the importance of standardized clinical protocols and long-term follow-up for evaluating treatment stability, similar principles are equally applicable in endodontic outcome assessment (Ravera et al., 2021).

CONCLUSION

Minimally invasive access cavity designs represent an important advancement in contemporary endodontics by emphasizing preservation of healthy tooth structure while maintaining the biological objectives of root canal therapy. Evidence from finite element analysis consistently demonstrates that conservative, ninja, and truss access cavities reduce stress concentration and improve fracture resistance through preservation of pericervical dentin, although the magnitude of these benefits varies according to tooth morphology, cavity design, restorative approach, and loading conditions (Zhou et al., 2024). Nevertheless, biomechanical advantages predicted through computational modeling must be interpreted alongside long-term clinical evidence, which indicates that treatment success is also dependent on complete canal debridement, effective irrigation, and high-quality obturation. Adequate irrigation protocols remain essential for eliminating microorganisms regardless of cavity design, ensuring that structural preservation does not compromise disinfection efficiency (Singh, 2020). Likewise, durable coronal restorations with appropriate bonding characteristics contribute significantly to the longevity of endodontically treated teeth (Singh, 2025). Emerging digital technologies, including artificial intelligence for radiographic interpretation and restoration assessment, may further improve treatment planning and postoperative evaluation, supporting more individualized clinical decision-making (Gonzalez et al., 2024; Rohrer et al., 2022). Patient-specific biological factors, periodontal health, and risk prediction models should also be incorporated into treatment planning because these variables influence long-term prognosis beyond access cavity configuration alone (Papapanou et al., 2018; Isola et al., 2019; Feher et al., 2020). Although advances in digital dentistry and predictive analytics continue to refine minimally invasive strategies, clinicians must carefully balance conservative access preparation with adequate visibility and instrumentation to ensure predictable clinical outcomes. Future well-designed prospective clinical studies with extended follow-up are needed to validate finite element predictions and establish standardized guidelines for selecting the most appropriate access cavity design across different tooth types and clinical scenarios. Such an evidence-based approach will optimize both structural preservation and long-term endodontic success while enhancing patient-centered care (Ravera et al., 2021).

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