

Beyond the Ferrule Effect: Artificial Intelligence, Adhesive Biomaterials, and Structural Preservation for Predicting the Restorability of Endodontically Treated Teeth

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Abstract

The restoration of endodontically treated teeth is challenging because the long-term prognosis depends on the interaction of biological, biomechanical, and restorative factors. Although the ferrule effect has long guided restorability, emerging evidence supports a broader approach incorporating minimally invasive dentistry, adhesive biomaterials, and artificial intelligence. This narrative review examined their role in predicting restorability beyond the ferrule effect, synthesizing peer-reviewed studies from PubMed, Scopus, and Web of Science. Long-term restorability is determined by the interaction of structural preservation, biomechanical behavior, adhesive strategies, and patient-related factors rather than by the ferrule alone. Preservation of residual pericervical dentin consistently emerged as one of the strongest predictors of fracture resistance and longevity, while minimally invasive access, adhesive biomaterials, and endocrown approaches conserve sound tooth structure. Machine-learning models showed promising accuracy for estimating restorability, survival, and fracture risk, with revised FDI criteria enabling validation. Restorability assessment is shifting toward a holistic, individualized, evidence-based paradigm.

Keywords: Endodontically treated teeth; restorability; ferrule effect; structural preservation; adhesive biomaterials; artificial intelligence; biomimetic dentistry; precision restorative dentistry

INTRODUCTION

The loss of tooth structure associated with endodontic treatment is a multifactorial process resulting from pre-existing caries, previous restorations, access preparation, canal instrumentation, and the restorative procedures required to rehabilitate the tooth [1]. The cumulative removal of enamel and dentin reduces the biomechanical strength of the remaining tooth structure, increasing its susceptibility to crack formation and fracture under functional loading [2].

One of the primary objectives of endodontic treatment is the effective cleaning and disinfection of the root canal system to eliminate infected pulp and organic debris; achieving a predictable outcome requires adequate access for the complete

removal of pulp tissue and thorough instrumentation [1]. However, creating sufficient access often requires sacrificing a considerable amount of sound structure, particularly dentin from the roof of the pulp chamber and the pericervical region, thereby facilitating visualization but compromising structural integrity [3].

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The loss of healthy dental tissue has been associated with reduced biomechanical strength and fracture resistance, making endodontically treated teeth more susceptible to structural failure under functional and parafunctional loading [2]. The removal of dentin during access preparation and instrumentation alters the natural distribution of occlusal forces, resulting in increased stress concentration within the remaining tooth structure [3].

The amount of residual tooth structure is recognized as one of the most important determinants of long-term prognosis and functional survival. Consequently, contemporary restorative and endodontic therapies aim not only to eliminate disease but also to preserve biomechanical integrity by maintaining sufficient strength and stiffness [4].

Restoration of endodontically treated teeth is a crucial stage, with the primary goals of reestablishing function, esthetics, and structural integrity in teeth compromised by caries, trauma, or endodontic procedures [5]. Because the extent of structural loss varies considerably among patients, restorative strategies should be selected according to the amount of residual sound tooth structure and the functional demands of each case; the cumulative loss associated with these conditions can reduce tooth strength by up to 60% [4,5]. An ideal restoration should provide an effective coronal seal to prevent microbial reinfection while preserving the maximum amount of remaining sound structure: direct adhesive restorations are indicated for minimal coronal destruction, whereas indirect restorations, including full-coverage crowns and onlays, are recommended for extensive loss [5].

METHODS

A narrative review was conducted to examine contemporary evidence regarding the restorability of endodontically treated teeth, with particular emphasis on the ferrule effect, adhesive biomaterials, structural preservation, and artificial intelligence (AI)-assisted decision-making. Literature searches were performed in PubMed, Scopus, and Web of Science using combinations of keywords including endodontically treated teeth, ferrule effect, restorability, adhesive dentistry, adhesive biomaterials, fiber posts, endocrowns, structural preservation, fracture resistance, artificial intelligence, and clinical decision support [6,7].

Publications considered eligible included systematic reviews, meta-analyses, randomized clinical trials, observational studies, in vitro investigations, and relevant narrative reviews. Priority was given to articles published within the last five years to reflect current concepts; however, landmark and foundational publications describing the ferrule effect and biomechanical principles were also included when essential for historical context [6]. Articles were selected for their relevance to the review objectives, with emphasis on studies

addressing the biomechanical, restorative, and technological factors influencing restorability and long-term prognosis [9,11].

The selected literature was synthesized qualitatively using a thematic approach rather than quantitative analysis. Major themes included the historical evolution and contemporary reinterpretation of the ferrule concept, preservation of residual tooth structure, advances in adhesive restorative materials, minimally invasive restorative strategies, and emerging applications of artificial intelligence in restorative treatment planning [6,8,10]. Given the narrative nature of this review, no formal quality assessment or quantitative meta-analysis was performed. By integrating evidence from endodontics, prosthodontics, restorative dentistry, biomaterials science, biomechanics, and artificial intelligence, this review provides a contemporary overview of restorability assessment and explores how modern adhesive strategies and AI-assisted predictive models may complement traditional restorative principles [11].

BIOMECHANICS OF FRACTURE AND THE FERRULE EFFECT

Tooth fractures result from a complex biomechanical process in which repetitive occlusal forces produce stress concentrations within enamel and dentin that initiate and propagate microscopic cracks. A thorough understanding of the biomechanical behavior of dental tissues is therefore essential for predicting fracture risk, selecting appropriate restorative strategies, and improving the long-term prognosis of endodontically treated teeth [12]. The fracture-resistant nature of enamel and dentin under physiological loading is attributable not only to their material properties but also to their hierarchical organization, which enables them to absorb, redistribute, and dissipate mechanical energy during function [13].

Crack initiation represents the first stage of this process, in which localized stress concentration exceeds the ability of dental tissues to absorb and redistribute mechanical energy; at this stage, the defect may remain limited to enamel or dentin and be difficult to detect clinically [14]. Understanding crack initiation and propagation is therefore essential for predicting fracture risk and for supporting restorative strategies focused on preserving tooth structure [14,15]. Consequently, the quantity and quality of residual sound dentin have become the principal predictors of restorability and long-term survival, and among the biomechanical factors influencing longevity, the ferrule effect remains one of the most extensively investigated and clinically relevant concepts [16,9].

Mamoun proposes that the ferrule transforms multiple independent restorative components into a mechanically continuous unit; under functional loading, this continuity

reduces bending moments, decreases root flexure, and redistributes tensile and compressive stresses more uniformly around the cervical dentin, so that the likelihood of vertical root fracture is significantly reduced when an adequate ferrule is present [9].

Recent studies also demonstrate that endocrowns provide favorable biomechanical performance by using the pulp chamber for retention while preserving more sound tooth structure than conventional restorations [16]. Moderate reductions in the thickness or number of pulp chamber walls do not necessarily compromise fracture resistance when appropriate adhesive protocols and materials are used, reinforcing the importance of conservative preparation designs and effective adhesive bonding rather than excessive removal of healthy dentin [17]. Finally, artificial intelligence is becoming an increasingly valuable tool in restorative dentistry: machine-learning and deep-learning algorithms can assist in predicting fracture risk, detecting vertical root fractures, and supporting restorative treatment planning, and future integration with digital dentistry, computer-aided design and manufacturing (CAD/CAM), and finite element analysis may enable highly personalized restorative strategies that optimize biomechanical performance while preserving healthy tooth structure [18,19].

ARTIFICIAL INTELLIGENCE FOR RESTORABILITY PREDICTION

Artificial intelligence has the potential to transform the assessment of restorability in endodontically treated teeth from a subjective decision based on clinical experience into a reproducible predictive model [20]. Historically, restorability has relied on multiple biological and restorative variables, including the ferrule effect, remaining coronal structure, periodontal support, tooth position, occlusal loading, cracks, remaining pericervical dentin, and clinician judgment [21]. Structural preservation has long been a fundamental principle: Schilder emphasized that canal preparation should be as small as practicable and as large as necessary, advocating maximal dentin preservation while maintaining adequate debridement, a concept central to minimally invasive endodontics [22]. Because clinicians weigh these variables differently, treatment decisions vary; AI offers the possibility of integrating heterogeneous parameters into reproducible models that classify teeth as restorable, restorable with risk, or non-restorable while estimating the probability of long-term success [22,23].

For clinical translation, AI prediction should not rely solely on radiographic interpretation, ferrule height, or cone-beam computed tomography (CBCT) findings [24]. Predictive algorithms should incorporate standardized clinical outcome measures such as the revised FDI criteria for restoration

evaluation, which assess esthetic, functional, and biological performance; particularly relevant domains include restoration fracture and retention, marginal adaptation, recurrent caries, postoperative sensitivity, periodontal response, and restoration-related biological complications [20]. These standardized parameters provide reproducible outcome labels for supervised machine-learning models, facilitating objective training, validation, and comparison across datasets [21].

Recent evidence supports the use of machine learning to predict the longevity of restorations in endodontically treated teeth [24]. Chisini and colleagues developed a survival prediction model based on randomized clinical trial data, demonstrating that AI can estimate the longevity of restoration rather than simply classify structural characteristics [25]. This distinction is clinically important because restorability is fundamentally a prognostic concept that depends on the probability of long-term survival rather than a single cross-sectional evaluation, shifting decision-making from subjective structural assessment toward individualized prediction of clinical outcomes [26].

AI models in endodontics can integrate numerous clinical and radiographic variables, including periapical radiographs, CBCT imaging, remaining dentin thickness (particularly in the pericervical region), ferrule height, number of residual coronal walls, presence and type of intraradicular posts, restorative materials, periodontal health, occlusal loading, parafunctional habits, caries risk, and patient-related factors. [21] Contemporary reviews show that machine-learning and deep-learning algorithms can assist diagnosis, treatment planning, prognosis estimation, and automated image interpretation, and convolutional neural networks have shown promising performance in detecting periapical lesions on CBCT, an important predictor of healing and success that directly influences restorability [26,27].

Future AI-based restorability prediction should evolve toward multimodal models that integrate clinical examination, radiographic findings, periodontal status, restorative variables, and standardized FDI outcome measures [24]. Rather than a binary recommendation to restore or extract, clinically useful systems should generate individualized, risk-stratified prognostic categories, such as favorable prognosis, guarded prognosis requiring cuspal coverage or adhesive reinforcement, and poor prognosis due to structural, biological, periodontal, or restorative limitations, supporting interdisciplinary communication and evidence-based tooth preservation [28]. Artificial intelligence should nonetheless be regarded as a clinical decision-support tool rather than a replacement for clinician judgment; before widespread implementation, predictive models require rigorous external validation across populations and settings and calibration against decisions made by experienced multidisciplinary teams. When combined with

adhesive biomaterials and the minimally invasive structural-preservation principles advocated by Schilder, AI has the potential to redefine restorability beyond the ferrule concept through more objective, biologically based, and personalized prognostic assessment [29].

DIGITAL DECISION-MAKING

The paradigm shift in the evaluation and restoration of endodontically treated teeth is increasingly driven by digital technologies that substitute subjective estimation with objective, quantifiable data. Traditionally, restorability of a non-vital tooth was assessed by visual inspection, with wide variability in treatment planning between practitioners [30]. Digital scanning and three-dimensional modeling software now allow assessment of the exact volumetric loss of tooth structure, and intraoral scans can be imported into computer-aided design (CAD) software for quantitative evaluation of the remaining tissue, providing a data-driven comparison of tooth volume before and after preparation as a reliable basis for choosing the restorative approach [31,32].

Accurate quantification of residual tooth structure is important because it is the main predictor of long-term survival, and the decision to use direct or indirect restorations depends on the presence of adequate coronal tissue and the ferrule effect [33]. Digital decision-making platforms must consider complex biomechanical parameters such as the uniformity of the remaining ferrule; in vitro studies show that a uniform, continuous ferrule best increases fracture resistance, but non-uniform ferrule designs still offer relevant mechanical protection compared with no ferrule, and such configurations can be mapped using advanced CAD algorithms, enabling clinicians to simulate stress distributions and predict fracture resistance before fabrication [34].

Once the structural assessment has been digitized, CAD/computer-aided manufacturing (CAM) workflows allow highly conservative restorative solutions [35]. Digital impressions and CAD software enable the design of custom monoblock

restorations, such as endocrowns, that rely on adhesion rather than mechanical retention, thereby maximizing preservation of tooth structure and providing a durable alternative to conventional full-coverage crowns supported by a post and core [36].

Digital decision-making also improves the accuracy and clinical outcomes of the final restoration. Clinically detectable, non-exact coronal margins have been shown to increase the hazard ratio for complications almost sevenfold in long-term evaluations over an 18-year period; CAD/CAM systems reduce this risk through excellent marginal adaptation and seal, which are crucial to preventing bacterial microleakage and ensuring long-term survival regardless of the presence of an intraradicular post [37,38]. Finally, digital workflows shorten treatment timelines: indirect restorations inherently have a longer interval from completion of endodontic therapy to final cementation, extending the opportunity for coronal leakage or catastrophic fracture, whereas intraoral scanners and chairside CAM units simplify decision-making and fabrication, removing conventional impressions and laboratory turnaround and facilitating rapid delivery while maintaining biomechanical integrity [39].

A CONCEPTUAL FRAMEWORK: THE AI RESTORABILITY SCORE (AIRS)

Building on the evidence above, we outline a conceptual framework for an AI Restorability Score (AIRS) to formalize the integration of heterogeneous clinical data into a reproducible prognostic assessment. Rather than relying on ferrule height alone, the model would receive multiple structured inputs spanning structural, endodontic, periodontal, restorative, functional, radiographic, and patient domains and would be trained on standardized, revised FDI outcome labels [37]. The framework is conceptual and requires development and validation before any clinical use; it is presented to illustrate how the variables discussed throughout this review could be organized for predictive modeling (Table 1)

Table 1. Proposed input variable domains and standardized outcome labels for a conceptual AI Restorability Score (AIRS).

Variable domain	Representative inputs
Structural	Number of remaining coronal walls (0-4); ferrule height; ferrule continuity (360 vs partial); remaining pericervical dentin thickness; root dentin thickness; crown-root ratio; cracks; suspected vertical root fracture; previous restorations; pulp chamber volume
Endodontic	Quality of obturation; apical seal; missed canals; periapical lesion size; previous retreatment; procedural errors (ledge, perforation, transportation, separated instrument)
Periodontal	Probing depth; clinical attachment loss; mobility; furcation involvement; bone loss (%); crown-root support
Restorative	Adhesive restoration; fiber post; cast post; endocrown; overlay; full crown; restorative material; marginal adaptation (FDI); secondary caries (FDI)

Variable domain	Representative inputs
Functional	Bruxism; occlusal loading; tooth position; opposing dentition; number of contacts; guidance; age; salivary risk; caries risk
Radiographic / CBCT	Periapical lesion; root length; root curvature; root thickness; external and internal resorption; bone support; cortical integrity
Patient	Diabetes; smoking; xerostomia; periodontal susceptibility; compliance; recall attendance
Outcome labels (revised FDI)	Esthetic (surface luster, marginal staining, color match); functional (fracture, retention, marginal adaptation, wear); biological (secondary caries, periodontal response, tooth vitality, postoperative sensitivity)

CONCLUSIONS

The way restorability of endodontically treated teeth is evaluated is evolving, prompting reconsideration of concepts derived from classical biomechanical principles. Although the ferrule effect has long been regarded as key to biomechanical stability, current evidence shows that it cannot be viewed as a standalone factor nor as the sole indicator of long-term restorative success; its value must be interpreted within a comprehensive, individualized framework in which additional clinical and structural variables collectively determine prognosis.

Advances in adhesive dentistry, new restorative biomaterials, and the growing adoption of biomimetic strategies have shifted the traditional emphasis on mechanical retention toward preservation of remaining tooth structure, which often carries more prognostic weight than a ferrule of specific dimensions. This assessment must also incorporate patient-specific factors such as occlusal load, functional risk, parafunctional habits, and individual biological conditions, enabling a more realistic prognosis and restorative decisions tailored to each case.

The rapid development of artificial intelligence and machine learning creates new opportunities to enhance decision-making in restorative dentistry. Current evidence shows these tools can support diagnostic interpretation, detection of structural defects, prediction of outcomes, and restorative planning with increasing precision and reproducibility, without replacing professional judgment. Within this landscape, precision restorative algorithms represent a logical evolution: conceived as dynamic clinical decision-support systems, they could integrate structural-preservation metrics, adhesive biomaterial properties, patient-specific risk factors, and AI-based predictive tools, facilitating a transition from standardized protocols toward personalized therapeutic strategies.

Clinical implementation nonetheless faces significant challenges, including methodological heterogeneity across studies, a lack of standardized databases, limited external validation, and low interpretability in certain AI models. Future research must therefore focus on robust, multicenter, clinically validated predictive models that improve diagnostic

accuracy and therapeutic predictability. In conclusion, the future of restoration in endodontically treated teeth will likely depend less on isolated restorative principles and more on the integration of maximal structural preservation, advanced adhesive biomaterials, individualized risk assessment, and predictive technologies, a shift beyond an exclusive emphasis on the ferrule effect that may represent one of the most significant advances in contemporary restorative and endodontic dentistry.

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