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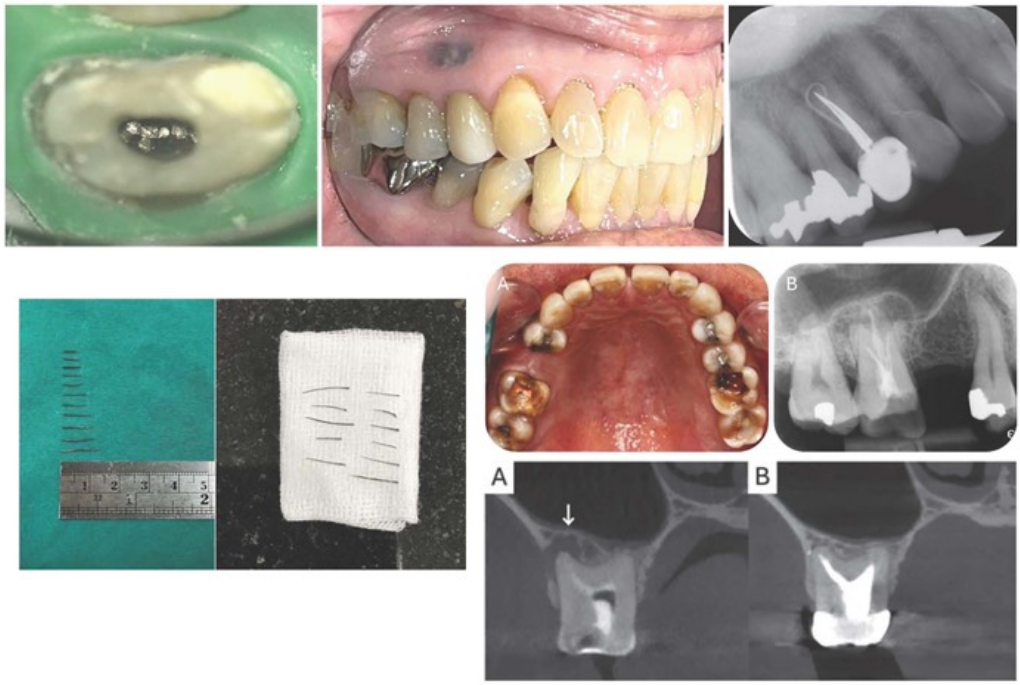

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▶ Review article ◀

Minimally invasive access cavity designs: A literature review of mechanical and biological considerations in posterior teeth

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Abstract

This literature review aimed to compile and evaluate current evidence on the different endodontic access cavity designs from both mechanical and biological perspectives, in order to identify factors relevant to access cavity selection in root canal treatment of posterior teeth. A structured search was conducted using PubMed and ScienceDirect, covering publications from 2010 to 2025.

Evidence from in vitro studies suggested that, from a mechanical perspective, conservative and ultra-conservative access designs preserved more coronal tooth structure and pericervical dentin compared with traditional access designs, and were generally associated with lower cervical stress concentration. However, their influence on fracture resistance remained inconsistent, particularly in molars, where marginal ridge integrity appeared to exert a greater influence on tooth strength than access cavity design itself. Findings on fracture mode and canal transportation were similarly inconclusive.

From a biological perspective, evidence did not demonstrate superior cleaning efficacy for conservative access designs compared with traditional designs. Most studies reported no significant differences in remaining hard tissue debris or residual pulp tissue within the root canal system, whereas findings on un-instrumented areas remained conflicting. Importantly, increased access conservatism was associated with a higher risk of missed canals, particularly the MB2 canal in maxillary molars, due to reduced visibility. Ultra-conservative access designs were also consistently associated with greater root filling remnants in the pulp chamber, potentially compromising coronal bonding and esthetic outcomes.

Overall, while MIE access designs offered mechanical advantages through dentin preservation, their biological benefits and effects on fracture resistance remained uncertain. Access cavity design should therefore be case-dependent, considering residual tooth structure, anatomical complexity, operator experience, and the availability of adjunctive technologies. Further well-designed clinical studies are needed to clarify the long-term implications of MIE approaches.

Keywords: conservative access cavity, minimally invasive endodontics, ninja access, truss access, ultra-conservative access cavity,

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Introduction

In root canal treatment, the success rate was 86% and the survival rate was 95% at a follow-up period of 4–6 years (1). However, with increasing follow-up duration, survival progressively declined to 87.1% at 10 years and further to 84.6% at 10–19 years (2). Among these endodontic failure cases, approximately 28% required tooth extraction, mainly attributed to non-restorable conditions such as caries, defective restorations, or coronal fractures. Vertical root fractures also represent a significant contributing factor in endodontically treated teeth (3-6).

Fracture susceptibility in endodontically treated teeth was influenced by several factors, including changes in dentin properties (6-8), pre-existing structural loss (9) and procedural factors related to endodontic treatment. Among these factors, structural loss, particularly loss of the marginal ridge, oblique ridge, and pericervical dentin, was identified as the most important determinant of reduced tooth stiffness (10, 11). In contrast, changes in dentin properties appeared to have a relatively minor effect (6, 12). Procedural factors are the only components that can be modified by the clinician and are therefore of particular clinical importance. Evidence from mechanical analysis suggested that access cavity preparation contributed more significantly to tooth weakening than root canal enlargement (9, 13).

Access cavity preparation may influence the amount of dentin removed in the cervical region of the tooth, which corresponds to the pericervical dentin. Pericervical dentin (PCD) is the dentin located near the alveolar crest, approximately 4 mm above and below the crestal bone level. This region plays a critical role in stress distribution by transferring occlusal loads from the crown to the root and is essential for maintaining the structural integrity of the tooth. Preservation of PCD has therefore become an important consideration in contemporary endodontic practice (14).

Concerns regarding cracks and vertical root fracture in endodontically treated teeth have led to the development of **minimally invasive endodontics (MIE)**. This concept was first introduced by Clark and Khademi in 2010 and initially focused on access cavity designs that preserve coronal tooth structure and PCD (14). The concept has since expanded to include smaller apical preparation and reduced tapers during root canal instrumentation.

Endodontic treatment requires a balance between **biological objectives** and mechanical objectives. Biological objectives involve removal of infected dentin and facilitation of effective irrigant penetration, whereas **mechanical objectives** focus on preservation of dentin to maintain tooth strength. Overall, MIE aims to preserve healthy tooth structure while maintaining adequate disinfection and treatment effectiveness (15).

Although MIE might offer advantages in preserving tooth structure and reducing the risk of cracks, fractures, and procedural errors (16), its reduced preparation size raised critical concerns for **biological effectiveness**. Limited access and canal enlargement may compromise cleaning, disinfection, and obturation, leading to an increased risk of residual debris, smear layer, bacteria, infected dentin, and pulp remnants (15). Therefore, the present literature review aims to compile and evaluate current evidence on different access cavity designs from both mechanical and biological perspectives, in order to identify factors relevant to access cavity selection in root canal treatment of posterior teeth.

Access cavity preparation

Access cavity preparation is defined as the opening prepared in a tooth to gain entrance to the root canal system for cleaning, shaping, and obturation (17). Traditionally, access cavity design focused on providing straight-line access to the canal system through complete deroofing of the pulp chamber, with smoothly divergent axial walls to facilitate visualization and reduce procedural complications (18). With the introduction of MIE, greater emphasis has been placed on preservation of sound dentin, particularly in regions such as the pulp chamber roof and PCD, as previously discussed. This shift has led to the development of more conservative access cavity designs aimed at minimizing structural loss while maintaining treatment effectiveness (14).

However, the nomenclature and classification of access cavity designs remain inconsistent in the literature, with multiple systems proposed by different authors, including Isufi et al., 2020 (19), Silva et al., 2020 (20), and Shabbir et al., 2021 (21). For the purpose of this review, the classification described by Shabbir et al., 2021 (21) is adopted. According to this classification, access cavity preparation in posterior teeth can be categorized into four main designs.

- **Traditional access cavity (TAC)**:

A conventional design involving complete deroofing of the pulp chamber to provide straight-line access to the first curvature or the apical part of the canal, with smoothly divergent axial walls.

- **Conservative access cavity (CAC)**:

A contracted form of the traditional design, extending from the central fossa only as much as necessary to locate canal orifices while preserving PCD and part of the chamber roof.

- **Ultra-conservative access cavity**: Can be categorized into two types

  - **Ninja access (NA):** A design created through the central fossa or the deepest part of the occlusal surface and advanced apically with minimal expansion, aiming to preserve as much of the pulp chamber roof as possible while still allowing access to all canals through a small single opening.

Truss access: A design that targets only the canal orifices by preparing separate small openings, thereby preserving the dentinal bridge between canals.

  - **Computer-assisted access cavity (CAAC):** An access cavity guided by software and three-dimensional imaging to create a precise pathway to the root canal system. This approach can be categorized into two types, including guided access cavity (GAC), which uses a custom-made guide stent to direct the bur to the target location, and dynamic-navigated access cavity (DNA), which uses real-time navigation technology for freehand drilling.

Materials and methods

A structured literature search was performed using PubMed and ScienceDirect databases covering publications from 2010 to 2025, with a combination of descriptive terms related to minimally invasive access cavities and root canal treatment combined using Boolean operators. Only English-language studies involving permanent posterior teeth were included. After the initial screening process, full-text articles were reviewed, and the relevant findings were critically analyzed and discussed. The final selection comprised studies comparing minimally invasive access cavities with traditional access cavities in terms of the mechanical and biological aspects of root canal treatment.

Mechanical objectives

From a mechanical perspective, root canal treatment focuses on preservation of tooth structure while maintaining the structural integrity and strength of the tooth. Excessive dentin removal may increase the risk of procedural errors (18, 21) and compromise the long-term survival of endodontically treated teeth (22). The following sections therefore review the current evidence on whether minimally invasive access designs affect these mechanical parameters.

Remaining dentin thickness

Remaining dentin thickness plays an important role in maintaining the structural integrity and fracture resistance of endodontically treated teeth. In particular, the PCD region is considered critical for stress distribution and preservation of tooth stiffness during functional loading (14).

From a total of 16 studies investigating the effects of various access cavity designs on remaining dentin thickness (Table 1), 8 studies focused on the coronal crown region (19, 23-29), 6 on the PCD (26, 27, 29-32), 1 on the dangerous zone (27), and 8 on the root canal area (23, 28, 29, 33-37). Overall, the studies consistently reported that TAC designs resulted in greater tooth structure loss compared with more conservative access designs, particularly in the coronal crown and PCD regions. Two studies further evaluated dentin thickness at different levels within the PCD region (27, 32). However, the definition of the PCD region varied between studies. Vorster et al., 2023 used the cementoenamel junction (CEJ) as the reference point and evaluated dentin thickness from 4 mm above to 6 mm below the CEJ. In contrast, Peng et al., 2022 defined the upper and lower PCD as the regions approximately 4 mm coronal and 4 mm apical to the alveolar crest, respectively. Because the alveolar crest in their model was positioned approximately 1.5 mm below the CEJ, these regions corresponded roughly to 2.5 mm above to 5.5 mm below the CEJ. Despite these methodological differences, both studies demonstrated a similar trend in that greater dentin loss associated with TAC designs was mainly observed in the coronal or upper portion of the PCD, whereas no significant difference was found in the deeper or lower PCD region between access cavity designs. Similarly, most studies evaluating the root canal region (six out of eight studies) and the dangerous zone reported no significant differences in dentin removal among access cavity designs.

Taken together, these findings suggested that the influence of access cavity design on remaining dentin thickness was more pronounced in the coronal portion of the tooth structure adjacent to the access preparation, whereas the deeper PCD and root canal regions appeared to be less affected by the access cavity design itself.

Stress distribution

Across 11 studies on stress distribution using finite element analysis (FEA) (Table 2), Jiang et al., 2018 (38) and Elkholy et al., 2021 (39) similarly reported that access cavity preparation caused stresses to migrate apically along the root surface, whereas in intact teeth, stresses remained mainly confined to the cervical area. At the occlusal surface, four of eight studies found that access cavity design had no significant effect on stress distribution (38, 40-42), while another three showed greater stress in teeth with TAC (27, 43, 44). Only one study reported opposite results (25). Six studies agreed that the highest stresses occurred occlusally

Table 1 A summary of in vitro studies evaluating remaining dentin thickness.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Krishan et al., 2014 (23)	Maxillary incisors, Mandibular premolars, and molars	90	TAC and CAC	Micro-CT	- Crown level (over CEJ)	Significantly less dentin volume removed at crown level for CAC than TAC in all tooth types.
					- Root canals	No difference in dentin volume removed between TAC and CAC in all root thirds.
Plotino et al., 2017 (24)	Maxillary and mandibular premolars and molars	120	TAC, CAC, and NA	CBCT	Coronal crown	Significantly more coronal enamel and dentin volume was removed for TAC than for CAC and NA, respectively.
Isufi et al., 2020 (19)	Maxillary and mandibular premolars and molars	120	TAC, CAC, and NA	CBCT	Coronal (over CEJ)	The volume of dentin and enamel removed was <6% in NA, up to 15% in CAC, and >15% in TAC.
Saber et al., 2020 (25)	Mandibular first molar	1	TAC, CAC, and truss access	FEA	Access cavity volume	The volumes of CAC and truss access were approximately 50% and 40% of the TAC volume, respectively, indicating greater preservation of tooth structure with more conservative access designs.
Silva et al., 2021 (28)	Mandibular first molars	60	TAC and NA	Micro-CT	Root canals	No significant differences between the groups.
					Crown level	The volume of the hard tissue removed was significantly greater in TAC than in NA.
Wang et al., 2021 (29)	Maxillary first molars	30	TAC, CAC, and GAC	Micro-CT	Crown, PCD (from the lowest point of pulp chamber roof to a level	TAC removed significantly more dentin in the crown, PCD and coronal third of the canal,

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
					2 mm below the CEJ), coronal, middle, and apical third	while no differences were found among the groups in the middle and apical thirds.
Fu et al., 2022 (26)	Mandibular first molars	20	TAC and CAC	Micro-CT	Coronal tissue (above CEJ) and PCD	CAC preserved significantly more coronal tissue and PCD than TAC.
Peng et al., 2022 (27)	Maxillary and mandibular first molar	48	TAC and NA	Micro-CT	- Coronal dentin and upper PCD (4 mm above the alveolar crest)	The volume and thickness of coronal dentin and upper PCD reduction in NA were significantly lower than in TAC.
					- Lower PCD	No significant differences between the groups.
					- Dentin thickness in the dangerous zone	No significant differences between the groups.
Vorster et al., 2023 (32)	Mandibular first molars	60	TAC and CAC	Micro-CT	PCD (4 mm above the CEJ to 6 mm below the CEJ)	No significant differences between the groups were observed from 1 mm above the CEJ to 6 mm below the CEJ. However, in the region 2–4 mm above the CEJ, the TAC group showed significantly lower remaining dentin thickness values than the CAC group.
Makati et al., 2018 (31)	Mandibular molars	60	TAC and CAC	CBCT	PCD (at CEJ level)	Significant decrease in remaining dentin thickness in TAC.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Lin et al., 2020 (30)	Maxillary and mandibular molars	36	TAC, CAC, and NA	CBCT	PCD	TAC showed the greatest cervical dentin removal, followed by CAC and NA. No difference was found between CAC and NA in mandibular distal canal.
Augusto et al., 2020 (33)	Mandibular molars	32	TAC and NA	Micro-CT	Root canals	No significant differences between the groups.
Barbosa et al., 2020 (34)	Mandibular molars	30	TAC, CAC, and truss access	Micro-CT	Root canals	No significant differences among the groups.
Lima et al., 2021 (36)	Mandibular molars	40	TAC and NA	Micro-CT	Root canals	The percentage of root dentine removed was significantly lower in NA.
Silva et al., 2022 (37)	Mandibular molars	70	TAC and CAC	Micro-CT	Coronal third of mesial root canals	No significant differences between the groups.
Chandolu et al., 2024 (35)	Maxillary molars	80	TAC and CAC	Nano-CT	Root canals	The mean dentin volume removed in TAC was significantly greater than in CAC.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access; GAC, guided access cavity; PCD, pericervical dentin

Table 2 A summary of in vitro studies evaluating stress distribution.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Yuan et al., 2016 (44)	Mandibular first molars	1	TAC and CAC	FEA	Occlusal surface and cervical regions at 3 levels below the pulp chamber floor with 0.5 mm intervals	TAC showed higher stress concentration and larger stress area in the occlusal and cervical regions compared to CAC.
Jiang et al., 2018 (38)	Maxillary first molars	1	TAC and CAC	FEA	Occlusal surface and PCD at CEJ level	Occlusal stress distribution was similar among all cavity designs, while TAC had higher stress concentration at the PCD compared to CAC. In addition, stress in root-filled models tended to shift apically along the root surface, whereas in the intact tooth model stress was mainly concentrated in the PCD region.
Zhang et al., 2019 (45)	Maxillary first molars	1	TAC, CAC, and NA	FEA	3 level at cervical region (CEJ, pulp chamber floor and root furcation)	Larger stress concentration areas at the cervical region were found in the CAC and TAC compared with NA.
Saber et al., 2020 (25)	Mandibular first molar	1	TAC, CAC, and truss access	FEA	Occlusal surface, cervical line and 1, 3 and 7 mm from the root apices	At the occlusal surface, the highest stress was recorded for CAC, followed by the truss access and TAC, whereas at the cervical line and root regions, decreasing the size of the access cavity was associated with increased cervical stress and lesser apical transmission of stresses.
Wang et al., 2020 (41)	Maxillary first molars	1	TAC and NA	FEA	Occlusal surface and PCD at pulp chamber floor and root furcation level	Occlusal stress distribution was similar among all cavity designs, while NA significantly reduced the stress in cervical region and root furcation.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Elkholy et al., 2021 (39)	Mandibular first molars	1	TAC, CAC, and truss access	FEA	Overall stress distribution throughout the entire tooth structure	The maximum increase in stress was observed with TAC, followed by CAC and truss access, with no noticeable difference between CAC and truss access, while stress patterns in all models tended to migrate apically along the root surface rather than concentrate solely in the PCD region.
Fu et al., 2022 (26)	Mandibular first molars	20	TAC and CAC	FEA	PCD	The mean maximum stress in the cervical region was significantly smaller in CAC than in TAC.
Peng et al., 2022 (27)	Maxillary and mandibular first molars	2	TAC and NA	FEA	Occlusal surface and cervical region (at CEJ, pulp chamber floor and root furcation)	TAC showed higher stress concentration in the occlusal and cervical regions compared to NA.
Alshazly et al., 2023 (40)	Three-rooted maxillary first premolars	1	TAC and CAC	FEA	Occlusal surface and entire root	The CAC exhibited higher cervical and radicular stresses compared with the TAC, with both groups showing higher stress values at the cervical cross-section that gradually decreased toward the apical region, while there was no significant difference in occlusal stress between the two designs.
Srinivasan et al., 2023 (42)	Maxillary second molars	1	TAC, CAC, and extended endodontic cavity	FEA	Occlusal surface and PCD	Access cavity design showed minimal influence on occlusal stress distribution, with peak stresses occurring near the load application site and cavity margins. Stress in the PCD increased as cavity size increased, with the extended endodontic cavity demonstrating the highest stress values.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Arıcan et al., 2025 (43)	Mandibular first molars	1	TAC-I (Class I), TAC-II (Class II) CAC, NA, caries-driven access, truss access, and caries-driven truss access	FEA	Enamel, dentin, root surface and PCD	Stress distribution increased with greater tissue loss and larger access cavity designs. Extended cavity designs demonstrated higher stress concentrations in the enamel, root dentin and PCD regions, whereas minimally invasive designs (NA, CAC, and truss access) showed lower and more favorable stress distribution patterns.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access; PCD, pericervical dentin

at the load application site, regardless of access design, with a marked increase when the load was applied near the access cavity margin or tooth–restoration interface (27, 38, 40-42, 44). In the cervical region, eight of ten studies found higher stresses in larger access cavity designs, particularly TAC (26, 27, 38, 41-45), while two showed the reverse trend (25, 40). Saber et al., 2020 (25) and Alshazly et al., 2023 (40) further noted that cervical stress was inversely related to access cavity size, and that larger cavities promoted greater apical transmission of stress. Beyond these region-specific analyses, Elkholy et al., 2021, the only study evaluating overall stress distribution throughout the entire tooth structure, reported the greatest increase in stress with TAC, followed by CAC and truss access, with no noticeable difference between the latter two. Importantly, all included studies evaluated restored access cavities, with composite resin used for cavity restoration in all models.

Fracture resistance

Fracture resistance is widely used as a mechanical indicator of the ability of endodontically treated teeth to withstand functional loading and resist structural failure over time. It also plays an important role in long-term tooth survival, as structural failure remains one of the major causes of tooth loss following root canal treatment (3-5).

A total of 27 studies involving restored teeth were included in the fracture resistance analysis, comparing TAC with conservative and ultra-conservative access cavity designs (Table 3). Among studies conducted on premolars, three of four studies reported no significant difference in fracture resistance among access cavity designs (46-48), whereas one study found significantly higher fracture

resistance in teeth prepared with CAC (49). Among studies conducted on molars, slightly more than half of the studies on molars (12 out of 23) found that fracture resistance was lower in teeth prepared with TAC compared to those with a more conservative design (24, 31, 39, 41, 45, 50-56), while the remaining studies showed no significant difference (28, 33, 34, 36, 57-63).

When fracture resistance was evaluated in teeth with varying degrees of marginal ridge loss, the available evidence suggested that fracture resistance decreased as the number of missing marginal ridges increased, regardless of the access cavity design. Furthermore, when the same number of residual walls remained, no significant difference in fracture resistance was observed among different access cavity designs in restored teeth (57).

Fracture mode

Among the 11 included studies evaluating fracture mode (Table 4), all studies were conducted on premolars and molars and assessed endodontically treated teeth with restored access cavities. Considerable heterogeneity was observed in the classification systems used. Seven studies classified fracture mode according to restorability criteria (restorable/non-restorable or favorable/unfavorable) (24, 51, 52, 55, 60, 62, 63), whereas two studies used alternative classifications based on fracture location or extent (47, 49). Two studies reported favorable and unfavorable fractures without providing explicit classification criteria and therefore were excluded from qualitative comparison of fracture mode (33, 34).

Among seven studies using restorability-based criteria, five studies evaluated teeth with access cavity preparation alone (24, 51, 52, 55, 62), whereas two studies additionally included Class II cavity preparations with varying degrees of marginal ridge loss (60, 63). Among studies evaluating teeth with access cavity preparation alone, intact or non-accessed control teeth consistently demonstrated a higher frequency of restorable fractures than access-prepared teeth. Three studies reported no significant differences in fracture mode among different access cavity designs (24, 51, 62), whereas two studies showed a higher proportion of non-restorable fractures in TAC than in more conservative access designs (52, 55). Marinescu et al., 2020 (52) reported the most pronounced difference, with all fractures in TAC being non-restorable, whereas 70% and 80% of fractures in CAC and NA, respectively, were restorable.

In contrast, two studies evaluating teeth with marginal ridge loss in addition to access cavity preparation demonstrated inconsistent findings. Ozyurek et al., 2018 (60), which involved one marginal ridge loss, reported a greater proportion of non-restorable fractures in TAC groups, whereas Abou-Elnaga et al., 2019 (63), which involved loss of two marginal ridges, found no significant differences in fracture mode among access cavity designs.

Two studies using alternative fracture classifications, although different classification systems were applied, both consistently reported no significant differences in fracture mode among different access cavity designs (47, 49). In Roperto et al., 2019 (49), TAC predominantly exhibited Type II failures (middle crown involvement), whereas CAC predominantly showed Type III failures (cervical root involvement).

Similarly, Pereira et al., 2021 (47) reported that Type I (occlusal or middle crown involvement) and Type II failures (cervical crown involvement) were the most prevalent across all groups.

Table 3 A summary of in vitro studies evaluating fracture resistance.

Authors and year	Teeth	n	Group	Methods	Loading conditions	Main results
Moore et al. (2016) (59)	Maxillary molars	39	TAC and NA	Universal testing machine after 1,000,000 fatigue cycles	Vertical compressive loading to failure following cyclic fatigue	No significant difference in fracture load was found between NA and TAC, and intact teeth showed the highest resistance.
Chlup et al. (2017) (46)	Maxillary and mandibular premolars	60	TAC and NA	Universal testing machine (compression test with acoustic-emission monitoring)	Oblique compressive loading on the occlusal surface, with the tooth inclined 30° to the long axis	No significant difference was found between NA and TAC, and mandibular teeth were more resistant than maxillary teeth.
Plotino et al. (2017) (24)	Maxillary and mandibular premolars and molars	160	TAC, CAC, and NA	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	TAC showed significantly lower fracture load than CAC and NA, while CAC, NA and intact teeth did not differ from one another.
Rover et al. (2017) (61)	Maxillary first molars	30	TAC, CAC	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference in fracture load was found between TAC and CAC.
Allen et al. (2018) (50)	Mandibular first molar	1	TAC and NA	FEA	Vertical occlusal loading on the occlusal surface	TAC produced higher dentin stress than the NA, indicating that the TAC was more prone to fracture.
Corsentino et al. (2018) (57)	Mandibular first and second molars	100	TAC, CAC, and truss access	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference was found among the TAC, CAC, and truss access, whereas loss of marginal ridges significantly reduced fracture strength.

Authors and year	Teeth	n	Group	Methods	Loading conditions	Main results
Makati et al. (2018) (31)	Mandibular molars	60	TAC, CAC	Universal testing machine after thermocycling	Compressive loading to fracture (loading site not specified)	CAC showed significantly higher fracture resistance than TAC, approximately double its value.
Ozyurek et al. (2018) (60)	Mandibular molars	100	TAC and truss access	Universal testing machine	Oblique loading at the central fossa in the lingual direction, 15° to the long axis	No significant difference was found between TAC and truss access when the same restorative base material was used, and intact teeth were the most resistant.
Abou-Elnaga et al. (2019) (63)	Mandibular first molars	66	TAC and truss access	Universal testing machine	Vertical loading at the center of the occlusal surface, contacting the buccal and lingual cusps, parallel to the long axis	Truss access showed the highest fracture resistance values and was the only experimental group not significantly different from intact controls, although no significant differences were found among the experimental groups.
Roperto et al. (2019) (49)	Maxillary premolars	1	TAC and CAC	FEA	Oblique (lateral) loading on the palatal cusp, 45° to the long axis	CAC exhibited significantly higher fracture resistance than TAC.
Zhang et al. (2019) (45)	Maxillary first molar	1	TAC, CAC, and NA	FEA	Vertical static occlusal loading on the occlusal surface	NA demonstrated the highest predicted dentin fracture load among the endodontically treated groups, followed by CAC and TAC, while TAC exhibited the lowest fracture resistance.
Augusto et al. (2020) (33)	Mandibular molars	32	TAC and NA	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference in fracture load was found between TAC and NA.

Authors and year	Teeth	n	Group	Methods	Loading conditions	Main results
Barbosa et al. (2020) (34)	Mandibular molars	30	TAC, CAC, and truss access	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference was found among TAC, CAC, and truss access.
Marinescu et al. (2020) (52)	Maxillary and mandibular molars	20	TAC, CAC, and NA	Universal testing machine	Vertical loading at the central pit, parallel to the long axis	TAC showed the lowest fracture force, CAC and NA were higher, and intact teeth were the most resistant.
Saberi et al. (2020) (54)	Mandibular first and second molars	60	TAC and truss access	Universal testing machine	Oblique loading at the central fossa along the lingual surface, 15° to the long axis	Without thermocycling the truss cavity was comparable to intact teeth. After thermocycling both TAC and truss access decreased, with TAC showing the lowest values, indicating that the truss access preserved fracture strength under thermal stress.
Silva et al. (2020) (48)	2-rooted maxillary premolars	20	TAC and NA	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference in fracture resistance was found TAC and NA.
Wang et al. (2020) (41)	Mandibular molar	1	TAC and NA	FEA	Vertical and lateral occlusal loading	NA reduced cervical stress, indicating improved biomechanical behavior and fracture resistance.
Elkholy et al. (2021) (39)	Mandibular first molar	1	TAC, CAC, and truss access	FEA	Cyclic occlusal loading on the occlusal surface until model failure	TAC showed a lower life span than CAC and truss access, which did not differ notably from each other.

Authors and year	Teeth	n	Group	Methods	Loading conditions	Main results
Karobari et al. (2021) (51)	Mandibular first molars	80	TAC, CAC and truss access	Universal testing machine	Vertical loading at the central fossa, parallel to the long axis	TAC showed significantly the lowest fracture strength, while the truss access and CAC did not differ significantly from each other.
Lima et al. (2021) (36)	Mandibular molars	40	TAC and NA	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference in fracture load was found between TAC and NA, regardless of the instrument used.
Maske et al. (2021) (58)	Mandibular molars	50	TAC and NA	Universal testing machine after thermocycling	Vertical loading on the inclined occlusal planes at the intercuspal position, parallel to the long axis	Access cavity design did not increase fracture strength, as TAC and NA did not differ at the same restoration status. Restoration significantly increased fracture strength, and intact teeth were the most resistant.
Pereira et al. (2021) (47)	2-rooted maxillary premolars	90	TAC and CAC	Universal testing machine	Vertical loading at the center of the occlusal surface, contacting the buccal and palatal cusps	No significant difference in fracture resistance was found between TAC and CAC.
Santosh et al. (2021) (55)	Mandibular first and second molars	40	TAC, CAC, and truss access	Multiaxial fatigue testing machine after thermocycling	Dynamic loading followed by vertical loading to fracture	TAC was the least resistant to fracture, the CAC and truss access were higher and did not differ from each other, and intact teeth were the most resistant.
Silva et al. (2021) (28)	Mandibular molars	60	TAC and NA	Universal testing machine	Oblique loading at the central fossa, 30° to the long axis	No significant difference was found between TAC and NA.

Authors and year	Teeth	n	Group	Methods	Loading conditions	Main results
Patil et al. (2022) (53)	Mandibular molars	50	TAC, CAC, NA, and truss access	Universal testing machine	Vertical compressive loading to fracture (loading site not specified)	Intact teeth exhibited the highest fracture resistance. Among the access cavity designs, Truss and Ninja access cavities demonstrated significantly greater fracture resistance than Traditional and Conservative access cavities, with no significant difference between Truss and Ninja designs.
Selvakumar et al. (2023) (62)	Maxillary molars	24	TAC and CAC	Universal testing machine after chewing simulation and thermocycling	Oblique loading at the central fossa, 30° to the long axis	No significant difference in fracture resistance was found between TAC and CAC, and intact teeth were the most resistant.
Vorster et al. (2023) (56)	Mandibular first molars	1	TAC and CAC	FEA	Vertical and horizontal static loading at the occlusal contact points	CAC required failure loads similar to the intact control, whereas TAC required significantly reduced loads, and the instrumentation system had no significant effect.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access

Table 4 A summary of in vitro studies evaluating fracture mode.

Authors and year	Teeth	n	Group	Methods	Definition	Main results
Plotino et al., 2017 (24)	Maxillary and mandibular premolars and molars	120	TAC, CAC and NA	Stereomicro-scope	Restorable fractures: fractures above the level of bone simulation. Unrestorable fractures: extended below the level of bone simulation.	Intact teeth exhibited significantly more restorable fractures than all prepared groups. No significant difference was observed in the frequency of restorable or unrestorable fractures among TAC, CAC, and NA groups. In all access cavity groups, unrestorable fractures were more frequent than restorable fractures.
Ozyurek et al., 2018 (60)	Mandibular first molars	100	TAC and truss access	Stereomicro-scope	Restorable fractures: Adhesive failures above bone simulation level. Non-restorable fractures: Vertical root fractures below bone simulation level.	More restorable fractures were observed in truss groups, whereas TAC groups showed a higher incidence of non-restorable fractures.
Roperto et al., 2019 (49)	Maxillary first premolars	32	TAC and CAC	Not defined	Failure modes were classified into four types: Type I: Fractures involving a small portion of the dental crown. Type II: Fractures involving the middle portion of the dental crown without root involvement. Type III: fractures involving the coronal portion with cervical root involvement Type IV severe fractures involving both crown and root.	No significant differences were observed among the groups. TAC groups predominantly presented Type II failures, whereas the CAC group predominantly showed Type III failures.

Authors and year	Teeth	n	Group	Methods	Definition	Main results
Abou-Elnaga et al., 2019 (63)	Mandibular first molars	66	TAC and truss access	Dental operating microscope	Favorable fractures: Fractures extending not more than 1 mm below the cervical margin and remaining above the pulp chamber floor. Unfavorable fractures: fracture extended more than 1 mm below the cervical margin or involving the pulp chamber floor	No significant differences in favorable or unfavorable fracture patterns were observed among the groups.
Augusto et al., 2020 (33)	Mandibular molars	32	TAC and NA	Not defined	Favorable fractures: Not defined in the study. Unfavorable fractures: Not defined in the study.	No significant differences in fracture patterns were observed among the groups. Three unfavorable fractures occurred in TAC/.03, four in TAC/.05, two in NA/.03, and four in NA/.05 groups.
Barbosa et al., 2020 (34)	Mandibular molars	30	TAC, CAC and truss access	Micro-CT	Favorable fractures: Not defined in the study. Unfavorable fractures: Not defined in the study.	No significant differences in fracture pattern were observed among the groups. Four unfavorable fractures occurred in TAC, six in CAC, and five in truss access groups.
Marinescu et al., 2020 (52)	Maxillary and mandibular molars	20	TAC, CAC and NA	Visual examination	Restorable fractures: Fractures located above the level of the acrylic plate (corresponding to the alveolar ridge level). Non-restorable fractures: Fractures located below the level of the acrylic plate.	All fractures in the TAC group were non-restorable, while 70% in CAC and 80% in NA were restorable.

Authors and year	Teeth	n	Group	Methods	Definition	Main results
Karobari et al., 2021 (51)	Mandibular first molars	80	TAC, CAC and truss access	Stereomicro-scope	Restorable fractures: Fractures above the bone simulation level (acrylic resin). Unrestorable fractures: Fractures extending below the bone simulation level.	Intact teeth showed significantly more restorable fractures, whereas all access cavity groups showed significantly more unrestorable fractures. No correlation was found between access cavity design and fracture favorability.
Pereira et al., 2021 (47)	2-rooted maxillary premolars	90	TAC and CAC	Stereomicro-scope	Type I: Crown fractures involving the occlusal or middle third. Type II: Crown fractures involving the cervical third. Type III: Root fractures involving the cervical third of the root. Type IV: Root fractures involving the middle or apical third of the root.	Type I and II failures were the most prevalent in all groups, with no significant differences in failure pattern between TAC and CAC groups.
Santosh et al., 2021 (55)	Mandibular first and second molars	40	TAC, CAC, and truss access	Stereomicro-scope	Restorable fractures: Fractures extending above the acrylic resin (above the level of bone simulation). Unrestorable fractures: Fractures extending below the acrylic resin (below the level of bone simulation).	Intact teeth showed the highest number of restorable fractures, whereas TAC showed the highest number of unrestorable fractures. No significant differences in fracture mode were observed between CAC and truss groups.

Authors and year	Teeth	n	Group	Methods	Definition	Main results
Selvakumar et al., 2023 (62)	Maxillary molars	24	TAC and CAC	Stereomicro-scope	Restorable fractures: Fractures extending above the acrylic resin (above the level of bone simulation). Unrestorable fractures: Fractures extending below the acrylic resin (below the level of bone simulation).	Intact teeth showed the highest number of restorable fractures, whereas TAC showed the highest number of unrestorable fractures. No significant differences in fracture mode were observed between TAC and CAC groups.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access

Canal transportation

Among a total of 10 studies investigating canal transportation (Table 5), most used micro-computed tomographic (micro-CT) imaging for evaluation, with only one study employing radiographic assessment. All studies were con-ducted on premolars and molars. Six out of the ten studies reported that the access cavity design did not result in significant differences in canal trans-portation or centering ratio (27, 29, 33, 34, 64, 65). In contrast, the remaining studies found that the TAC design maintained a more centralized canal pathway and provided greater preservation of the original root canal anatomy (36, 47, 61, 66).

Biological objectives

Although MIE emphasizes preservation of tooth structure, the biological objective of root canal treatment remains fundamentally important. Root canal preparation should both remove infected and/or irreversibly inflamed tissues and create a canal shape suitable for obturation. From a biological standpoint, canal preparation aims to eliminate the microbial load and its by-products, thereby creating an environment conducive to periapical healing (15). Furthermore, maintaining a clean pulp chamber after obturation is crucial to optimize the coronal seal and prevent microleakage or secondary infection. However, persistent intracanal infection and compromised coronal seals have been recognized as a major factor associated with post-treatment disease and treatment failure (22). Therefore, preservation-oriented preparation strategies should not compromise the effectiveness of canal disinfection or final restoration. To evaluate whether minimally invasive access designs impact

Table 5 A summary of in vitro studies evaluating canal transportation.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Rover et al., 2017 (61)	Maxillary first molars	30	TAC and CAC	Micro-CT	3, 5 and 7 mm from the apex of the root	Although centering ability was canal- and level-specific (TAC better in the palatal canal at 5–7 mm, CAC better in the distobuccal canal at 5 mm), CAC showed no overall benefit over TAC in preserving canal anatomy.
Alovisi et al., 2018 (66)	Mandibular molars	30	TAC and CAC	Micro-CT	1 and 3 mm from the apex	TAC **better preserved** the original canal anatomy with **less apical transportation** than CAC, particularly at the apical level.
Marchesan et al., 2018 (65)	Mandibular molars	24	TAC and NA	Radiograph	Primary canal curvature	No significant difference in primary canal curvature between TAC and NA.
Augusto et al., 2020 (33)	Mandibular molars	32	TAC and NA	Micro-CT	3, 5 and 7 mm from the apical foramen	No significant difference in canal transportation or centering ratio between TAC and NA at any level.
Barbosa et al., 2020 (34)	Mandibular molars	30	TAC, CAC, and truss access	Micro-CT	3, 5 and 7 mm from the apical foramen	Canal transportation and centering ability were **comparable** among TAC, CAC, and truss access at all levels.
Freitas et al., 2021 (64)	Maxillary molars	20	TAC and CAC	Micro-CT	3 mm from canal entrance and 3 mm from the apex	TAC and CAC produced **similar** canal transportation and centering ability.
Lima et al., 2021 (36)	Mandibular molars	40	TAC and NA (each prepared with Reciproc and XP-endo Shaper)	Micro-CT	3, 5 and 7 mm from the apex	NA with Reciproc produced the greatest canal transportation in MB and distal canals, whereas TAC with XP-endo Shaper produced the least. Transportation was influenced more by instrument type than by access design.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Pereira et al., 2021 (47)	2-rooted maxillary premolars	90	TAC and CAC	Micro-CT	Coronal, middle, and apical thirds of the root canals	CAC showed greater transportation than TAC across all root thirds (especially at cervical and middle thirds).
Wang et al., 2021 (29)	Maxillary first molars	30	TAC, CAC, and GAC	Micro-CT	1, 3, 5 and 7 mm from the apex of the root	No significant difference in canal transportation or centering ratio among TAC, CAC, and GAC at any level.
Peng et al., 2022 (27)	Maxillary and mandibular first molar	48	TAC and NA	Micro-CT	3, 5 and 7 mm from apical foramen	Canal transportation and centering ratio were **similar** between TAC and NA in both maxillary and mandibular molars.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access; GAC, guided access cavity

these fundamental biological parameters, the following sections review the current evidence on their biological efficacy.

Ability to locate the canal

Three studies compared the influence of different endodontic access cavity designs on root canal detection (Table ***6***). In maxillary molars, detection of the second mesiobuccal (MB2) canal was used for comparison. Saygili *et al. (67)* reported that, with magnification, the MB2 detection rates of TAC and CAC were significantly higher than those of NA. Conversely, Rover *et al. (61)* found no significant difference between TAC and CAC when magnification was combined with ultrasonic troughing. However, without magni-fication, TAC enabled detection of a greater number of root canals.

Only one study, by Mendes *et al. (68)*, evaluated mandibular molars using the middle mesial (MM) canal as the reference and found no significant difference between TAC and NA, regardless of whether procedures were performed without magnification, with magnification alone, or with magnification combined with ultrasonic troughing.

Un-instrumented area

Of the 11 studies employing micro-CT or nano-computed tomographic (nano-CT) imaging to evaluate un-instrumented areas in premolar (3 studies) and molar (9 studies) teeth (Table 7), two premolar studies (23, 48) and five molar studies (27, 29, 33, 59, 61) reported no statistically significant differences between access cavity designs. Conversely, the remaining studies consistently demonstrated that TAC design was associated with a lower percentage of un-instrumented area (23, 34-36, 47).

Table 6 A summary of in vitro studies evaluating the ability to locate the canal.

Authors and year	Teeth	n	Group	Detection condition	Canal assessed	Main results
Rover et al., 2017 (61)	Maxillary first molars	30	TAC and CAC	Without DOM, with DOM or with DOM combined with ultrasonic tip	MB2	TAC enabled the detection of a greater number of root canals regardless of magnification. However, when magnification was combined with ultrasonic troughing, no statistically significant difference in canal detection was found between TAC and CAC.
Saygili et al., 2018 (67)	Maxillary first molars	60	TAC, CAC, and NA	With DOM	MB2	MB2 detection rates of TAC and CAC were significantly higher than those of NA.
Mendes et al., 2020 (68)	Mandibular first molars	60	TAC and NA	Without DOM, with DOM or with DOM combined with ultrasonic tip	MM	No significant difference between the TAC and NA groups, when evaluation was performed without magnification, with DOM, or with DOM associated with ultrasonic troughing.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access; DOM, dental operating microscope; MB2, second mesiobuccal; MM, middle mesial

Table 7 A summary of in vitro studies evaluating un-instrumented area.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Krishan et al., 2014 (23)	Maxillary incisors, Mandibular premolars, and molars	90	TAC and CAC	Micro-CT	Root canals	CAC had a significantly higher percentage of untouched canal wall in molar distal canals (notably at the apical third), whereas no significant difference was found in incisors and premolars.
Moore et al., 2016 (59)	Maxillary molars	18	TAC and NA	Micro-CT	Root canals	No significant differences between the groups .
Rover et al., 2017 (61)	Maxillary first molar	30	TAC and CAC	Micro-CT	Root canals	No significant differences between the groups.
Barbosa et al., 2020 (34)	Mandibular molars	30	TAC, CAC, and truss access	Micro-CT	Root canals	CAC exhibited the largest unprepared canal areas, truss access was intermediate, and TAC showed the least.
Augusto et al., 2020 (33)	Mandibular molars	32	TAC and NA	Micro-CT	Root canals	No significant differences between the groups.
Silva et al., 2020 (48)	2-rooted maxillary premolars	20	TAC and NA	Micro-CT	Root canals	No significant differences between the groups.
Lima et al., 2021 (36)	Mandibular molars	40	TAC and NA	Micro-CT	Root canals	NA had a significantly higher percentage of unprepared area, regardless of the instrument used.
Pereira et al., 2021 (47)	2-rooted maxillary premolars	90	TAC and CAC	Micro-CT	Root canals	CAC showed a significantly higher untouched canal surface than TAC only with ProTaper Universal, with no difference between the two cavities for the other instruments.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Wang et al., 2021 (29)	Maxillary first molars	30	TAC, CAC, and GAC	Micro-CT	Root canals	No significant differences among the groups.
Peng et al., 2022 (27)	Maxillary and mandibular first molar	48	TAC and NA	Micro-CT	Root canals	No significant differences between the groups.
Chandolu et al., 2024 (35)	Maxillary molars	80	TAC and CAC	Nano-CT	Root canals	The untouched pulp canal space was significantly less for TAC.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access; GAC, guided access cavity

Remaining hard tissue debris and pulp tissue

Among studies evaluating hard tissue debris (Table 8) using micro-CT imaging, both molar studies reported no significant differences among access cavity designs (36, 61). In contrast, one premolar study demonstrated that NA resulted in a significantly higher percentage of hard tissue debris within the root canals (48). Only one study, conducted by Neelakantan et al. (69), assessed remaining pulp tissue histologically and found that truss access retained significantly more pulp tissue in the pulp chamber than the TAC design, whereas no significant differences were observed within the root canals or isthmus among the groups.

Root filling remnant in pulp chamber

Among studies evaluating root filling remnants using micro-CT imaging in premolar (2 studies) (47, 48) and molar (2 studies) (34, 36) teeth (Table 9), all demonstrated consistent findings that more conservative access cavity designs resulted in a significantly greater percentage of root filling remnants in the pulp chamber compared with TAC.

Conclusion and discussion

This review summarized the current evidence regarding different endodontic access cavity designs from both mechanical and biological perspectives, indicating that MIE access designs offered certain advantages but also presented important limitations. From a mechanical perspective, conservative and ultra-conservative access cavities consistently preserved more coronal tooth structure and upper PCD compared with TAC (19, 23-32). Most FEA studies also demonstrated lower cervical stress concentration in more conservative access designs (26, 27, 38, 41-45), suggesting that preservation of

Table 8 A summary of in vitro studies evaluating remaining hard tissue debris and pulp tissue

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Remaining hard tissue debris						
Rover et al., 2017 (61)	Maxillary first molar	30	TAC and CAC	Micro-CT	Root canals	No significant differences in hard-tissue debris accumulation between TAC and CAC.
Silva et al., 2020 (48)	2-rooted maxillary premolars	20	TAC and NA	Micro-CT	Root canals	NA showed a significantly higher percentage of accumulated hard tissue debris than TAC.
Lima et al., 2021 (36)	Mandibular molars	40	TAC and NA	Micro-CT	Root canals	No significant differences in hard-tissue debris between TAC and NA, regardless of the instrument used.
Remaining pulp tissue remnants						
Neelakantan et al., 2018 (69)	Mandibular molars	32	TAC and Truss access	Histologic evaluation	Pulp chamber, root canal, and isthmus at all root third	Truss access retained significantly more pulp tissue than TAC in the pulp chamber, while no significant differences within the root canals or isthmus at any root third.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access

Table 9 A summary of in vitro studies evaluating root filling remnants in the pulp chamber.

Authors and year	Teeth	n	Group	Methods	Region evaluated	Main results
Barbosa et al., 2020 (34)	Mandibular molars	30	TAC, CAC, and Truss access	Micro-CT	Pulp chamber	CAC and Truss access showed a significantly larger volume of filling remnants in the pulp chamber than TAC, with no significant difference between CAC and Truss access.
Silva et al., 2020 (48)	2-rooted maxillary premolars	20	TAC and NA	Micro-CT	Pulp chamber	NA showed a significantly greater volume of root filling remnants in the pulp chamber than TAC.
Lima et al., 2021 (36)	Mandibular molars	40	TAC and NA	Micro-CT	Pulp chamber	NA showed a significantly greater volume of root filling remnants in the pulp chamber than TAC, regardless of the instrument used.
Pereira et al., 2021 (47)	2-rooted maxillary premolars	90	TAC and CAC	Micro-CT	Pulp chamber	CAC showed residual root canal filling material near the region of the pulp horns and the buccal and palatal walls, whereas TAC showed none.

TAC, traditional access cavity; CAC, conservative access cavity; NA, ninja access;

structurally important dentin may contribute to more favorable stress distribution and maintenance of tooth stiffness.

Regarding remaining dentin thickness, the influence of access cavity design appeared to be more pronounced in coronal regions adjacent to the access preparation, whereas deeper PCD and root canal regions were generally less affected (27, 32). The lack of significant differences observed in lower PCD regions may be explained by their anatomical distance from coronal modifications. Similarly, dentin removal within root canals is likely governed more by instrumentation procedures than by access cavity design itself. Previous studies have demonstrated that preparation taper (70-72), apical enlargement (73, 74), and instrumentation systems (75) might significantly affect dentin removal and remaining dentin thickness, particularly within root canal regions. Therefore, although conservative access cavities consistently preserve more coronal tooth structure, their influence on dentin preservation appeared to diminish progressively toward deeper root regions. This concept is further supported by Zelic et al., 2015, who reported that access cavity preparation accounted for the greatest reduction in tooth strength, whereas canal enlargement produced only a minor additional weakening effect (13). Collectively, these findings suggested that coronal structural loss associated with access cavity preparation might have a greater influence on tooth weakening than dentin removal within the root canal space, providing a rationale for conservative access cavity designs aimed at preserving coronal tooth structure.

Although preservation of tooth structure represents one of the primary mechanical objectives of MIE, maintaining the original canal anatomy during instrumentation is equally important to minimize procedural errors and prevent excessive weakening of root dentin (15, 22). Evidence regarding canal transportation remained inconclusive. Although several studies demonstrated no significant differences among access cavity designs (27, 29, 33, 34, 64, 65), others reported greater canal transportation or reduced canal-centering ability in conservative access preparations (36, 47, 61, 66). These inconsistent findings may be influenced by differences in tooth anatomy, original canal curvature, instrumentation systems, preparation taper, and levels of measurement. Conservative access cavities may reduce straight-line access and increase coronal canal curvature, thereby increasing instrumentation difficulty, particularly in molars with complex anatomy. These findings are partly consistent with the systematic review by Shroff et al., 2023, which suggested that contracted endodontic cavities might have negatively affect instrumentation efficacy and increase the risk of canal transportation in certain anatomical conditions (76).

Despite these potential mechanical advantages, the influence of MIE access cavities on fracture resistance remained inconsistent. While several studies demonstrated improved fracture resistance in conservative access designs (24, 31, 39, 41, 45, 49-56), many others found no significant differences compared with TAC (28, 33, 34, 36, 46-48, 57-62). These inconsistent findings suggested that preservation of dentin volume through more conservative access cavity preparation alone might not necessarily translate into superior mechanical performance. Instead, fracture resistance appeared to be affected by several additional factors, including tooth type, residual tooth structure, restoration

condition, and methodological variability among studies.

One important factor contributing to these inconsistent findings may be the amount and location of pre-existing structural loss. Studies evaluating varying degrees of marginal ridge loss consistently demonstrated that fracture resistance decreased proportionally as the number of missing marginal ridges increased, regardless of access cavity design. Furthermore, when teeth with the same number of remaining walls were compared, differences among access cavity designs became less evident in restored teeth (57). These findings suggested that marginal ridge integrity might exert a greater influence on tooth strength than access cavity design itself. Because marginal ridges play a critical role in maintaining cuspal stiffness and distributing occlusal forces, extensive structural loss may reduce or override the potential biomechanical benefits associated with preservation of PCD alone.

Restoration status and restorative protocols may also substantially influence the mechanical behavior of endodontically treated teeth and partially explain inconsistencies among studies. Adhesive restorations have been shown to reinforce weakened tooth structure and reduce cusp deflection, potentially compensating for structural loss associated with cavity preparation. Supporting this concept, Maske et al., 2021 reported that restoration significantly increased fracture resistance in endodontically treated teeth compared with unrestored groups. However, pulp floor fractures remained predominant regardless of restoration status or access cavity design (58). This finding suggested that although adhesive restoration might partially recover tooth strength, it might not necessarily modify the location or pattern of structural failure.

Restoration protocols may also contribute to the variability observed in fracture mode findings. Ozyurek et al., 2018 suggested that fracture behavior might be influenced by the restorative material used, as groups restored with fiber-reinforced composite in combination with bulk-fill composite demonstrated a greater proportion of restorable fractures compared with other restorative protocols (60). In contrast, Pereira et al., 2021 found no significant differences in failure patterns among different restorative materials or access cavity designs after restoration (47). These inconsistent findings suggested that the influence of restorative materials on fracture mode remained unclear and might depend on the interaction between material properties, cavity configuration, and the amount of remaining tooth structure.

Regarding fracture mode, the majority of studies reported no significant differences among different access cavity designs (24, 47, 49, 51, 62, 63). However, in studies reporting significant differences, more conservative access cavities generally exhibited a greater proportion of restorable fractures, whereas TAC was associated with a higher proportion of non-restorable fractures (52, 55, 60). Studies using location-based classifications demonstrated that fractures most commonly involved the crown, cervical region, or coronal portion of the root, while fractures extending into deeper root structures were less frequently observed (47, 49). In contrast, differences among access cavity designs became less apparent in studies involving additional marginal ridge loss. Notably, Ozyurek et al., 2018 observed a greater proportion of non-restorable fractures in TAC when one marginal ridge was absent (60), whereas Abou-Elnaga et al., 2019 found no significant

differences in fracture mode among access cavity designs when both marginal ridges were lost (63). This pattern may suggest that as the extent of marginal ridge loss increases, the influence of access cavity design on fracture mode becomes progressively less apparent, with pre-existing structural loss becoming the dominant determinant of fracture behavior. However, this interpretation is based on only two studies and should be regarded with caution. Nevertheless, the available evidence does not permit a definitive conclusion regarding the influence of access cavity design on fracture mode. Furthermore, interpretation of the available evidence remains challenging because fracture mode classification systems varied considerably among studies.

Comparison with currently available systematic reviews and meta-analyses revealed a similar pattern of findings regarding fracture resistance. Silva et al., 2018 concluded that there was insufficient evidence to support the superiority of contracted access cavities over traditional access cavities in improving fracture resistance (77). Similarly, Nobar et al., 2023 (78) and more recent reviews by Dioguardi et al., 2024 (79), Haridoss et al., 2024 (80) and Mrinalini et al., 2024 (81) reported that although conservative access preparations might preserve more tooth structure and potentially improve biomechanical behavior, the available evidence regarding fracture resistance remains heterogeneous and clinically inconclusive.

From a biological perspective, the available evidence does not clearly demonstrate superior cleaning efficacy for MIE access cavities. Most studies reported no significant differences in remaining hard tissue debris or residual pulp tissue within the root canal system (36, 61, 69). However, findings regarding untouched canal areas were conflicting, with several studies demonstrating larger un-instrumented areas in conservative or ultra-conservative access cavities (23, 34-36, 47). These findings are consistent with Shroff et al., 2023, who concluded that contracted endodontic cavities might negatively affect instrumentation efficacy, particularly with respect to untouched canal areas and debridement effectiveness (76). Therefore, although preservation of tooth structure remains desirable, excessive access conservatism may compromise cleaning and disinfection effectiveness under certain anatomical conditions.

Furthermore, conservative access cavities may compromise canal detection, particularly in anatomically complex teeth such as maxillary molars with MB2 canals (61, 67). Reduced visibility and restricted instrumentation pathways may increase the risk of missed anatomy and incomplete debridement. These findings are consistent with the scoping review by Dioguardi et al., 2024, which suggested that conservative access cavity designs might compromise canal orifice localization and increase the likelihood of debris accumulation because of reduced visibility and restricted access pathways. The review also highlighted that adjunctive technologies might improve precision during canal localization, particularly in anatomically complex teeth (82). In addition, ultra-conservative access cavity designs consistently demonstrated greater root filling remnants within the pulp chamber, which may compromise subsequent adhesive procedures and potentially affect coronal sealing ability and esthetic outcomes (34, 36, 47, 48).

Several important limitations should be considered when interpreting the findings of the present review. First, most available studies were

conducted in vitro and may not accurately reproduce clinical conditions. Different restorative protocols, loading conditions, instrumentation systems, and preparation dimensions among studies may also have influenced the reported outcomes and complicated direct comparison of results. Second, many studies had relatively small sample sizes, particularly FEA studies that frequently used only one or a few digital models. Third, substantial heterogeneity exists in the nomenclature and classification of MIE access cavity designs. Different studies used varying definitions and classifications for conservative and ultra-conservative access cavities, which may complicate comparison and interpretation of results. This ambiguity in terminology and classification systems has also been highlighted in previous literature discussing the lack of standardized nomenclature for access cavity designs.

Overall, from a mechanical perspective, MIE access cavities generally preserved more coronal tooth structure and upper PCD and might have provided certain biomechanical advantages. However, current evidence does not consistently demonstrate superior fracture resistance, because fracture behavior appeared to be affected by factors such as marginal ridge loss, tooth type, restoration condition, and methodological variability among studies. From a biological perspective, increasing access conservatism may compromise canal detection and instrumentation efficacy in anatomically complex teeth, potentially affecting cleaning and debridement effectiveness. These biological considerations may be clinically relevant because persistent or inadequately controlled intraradicular infection remains one of the major causes of post-treatment apical periodontitis and endodontic failure. Previous studies have emphasized that the primary goal of root canal treatment is the prevention or elimination of intracanal infection and the maintenance of long-term periapical health. Taken together, these findings suggested that the theoretical benefits of MIE designs in preserving tooth structure might not necessarily translate into improved clinical outcomes and might involve trade-offs in canal detection, instrumentation efficacy, and debridement.

In the authors' opinion, access cavity design should be selected according to individual clinical circumstances, considering residual tooth structure, anatomical complexity, restorative condition, and operator experience rather than relying solely on maximal preservation. To facilitate the effective and safe application of MIE concepts, adjunctive tools such as CBCT, magnification, ultrasonic tips, and flexible rotary instruments are essential, particularly in conservative and ultra-conservative access cavities. Clinicians must also remain flexible. If anatomical difficulties or the risk of complications arise during a minimally invasive procedure, converting to a traditional access design is often necessary to achieve optimal results. Preserving tooth structure should never come at the expense of compromised cleaning efficacy or procedure errors that lower the overall prognosis.

Moreover, maximizing tooth structure preservation is no longer limited to the endodontic phase. Alongside MIE, advancements in minimally invasive restorative techniques and modern adhesive agents now play a significant role in ensuring a high-quality coronal seal without excessive tissue removal. Ultimately, the long-term survival of an endodontically treated tooth is multifactorial. It relies on a holistic approach that incorporates

periodontal health, the quality of the final restoration, patient-specific factors such as parafunctional habits, and oral hygiene. Because the current evidence remains predominantly laboratory-based and methodologically heterogeneous, further well-designed clinical studies with standardized definitions and long-term follow-up are required to determine the true clinical relevance of MIE access cavity designs.

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