

Effect of different restorative crown design and materials on stress distribution in endodontically treated molars and peripheral bone: A finite element analysis study

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Abstract

Background: The purposes of this simulation study were to evaluate the stresses in the roots of endodontically treated molars with extensive coronal tissue loss which were restored by endocrowns (all-in-one core and crown) and traditional crowns with post-cores, during masticatory simulation using finite element analysis.

Methods: A mesio-distal cross-section of a lower right first molar was digitized and used to create 2-dimensional models of the teeth and supporting tissue; different crown designs, viz., endocrown with 2 mm occlusal clearance, endocrown with 4 mm occlusal clearance and post-core crown; different crown materials, viz., zirconia (Zr) and lithia-disilicate reinforced glass ceramic (LDRGC), and different post and core materials, viz., glass fiber (GF), stainless steel (SS) and metal cast (MC). A simulated 100 N vertical occlusal load was applied to the distal marginal ridge of the crown.

Results: The root canal inner wall stresses of SS post (maximum 33.7 MPa) and MC post (maximum 36.3 MPa) were higher than that of GF post (maximum 19.1 MPa) and endocrown (maximum 8.9 MPa).

Conclusion: Endocrown showed reduced stresses at its root canal inner wall but increased stresses at the coronal cavity inner wall when compared to post-core crowns.

Background

The decision of how to rehabilitate endodontically treated molars (ETM) with extensive loss of coronal structure is a challenge in restorative dentistry. Coronal tooth tissue is often significantly damaged after endodontic treatment and are traditionally restored with metal posts and cores and prosthetic crowns⁽¹⁻³⁾. Initially, it was believed that this procedure would provide better reinforcement of the remaining dental structure^(4, 5). However, it has been observed that the use of intracanal retainers only help in the retention of the prosthetic crown. As a result of removing a dental structure to enable the placement of rigid dental materials devoid of mechanical behaviors similar to those of the tooth, the remaining tooth is weakened⁽⁶⁾. The preparation of a molar for a post in relatively narrow root canals also involves a risk of accidental root perforation and fracture⁽⁷⁾.

In fact, minimally invasive preparations, with maximal tissue conservation, are now considered 'the gold standard' for restoring ETM⁽⁸⁾. In 1995, the endocrown was described by Pissis who is the forerunner of the endocrown technique, as the 'mono-block porcelain technique'⁽⁹⁾. Currently, due to the advances in adhesive methods and materials, endocrown type of intracoronal restorations were suggested for damaged posterior teeth as an alternative to post and core retained ones⁽¹⁰⁾. It is a method particularly indicated in cases in which there is excessive loss of hard tissues of the crown, interproximal space is limited, and traditional post-core crown is not possible because of inadequate ceramic thickness⁽¹¹⁾. Their advantages include the fact that tooth structures require little preparation, ease of preparation, demand less clinical time when compared with conventional crowns^(12,13).

Knowledge of the stress distribution within and around the roots is a key factor for understanding root fracture, which are well-known problems with ETMs. It has been proposed that molars restored with endocrowns are less prone to fracture than those with posts^(14,15). Nevertheless, so far there was no clear evidence to prove it. Dejak et al.⁽¹⁶⁾ compared equivalent stresses in molars restored with endocrowns as well as posts and cores during masticatory simulation using finite element analysis (FEA) and found the tensile stresses achieved were 4 times higher values than under endocrowns. These tensile stresses occurred in the dentin under the crown shoulder, rather than in the root. A similar study by Lin et al.⁽¹⁵⁾ showed that the stress values on the dentin and luting cement for the endocrown restoration were lower than those for the crown. However, these studies made no attempt to compare endocrowns and post-core crowns. Moreover, relatively little is known about the differences of stress distribution in the roots.

The type of restoration (endocrown or post-core crown, different crown and post materials) will provide rational stress distribution and reduce a risk of fracture in molars? Because of the absence of information about the biomechanical behavior of endocrowns and the expectation that this type of restoration would behave similarly or superiorly to post-core crowns, the present study has aims to evaluate the von Mises stresses in the roots of ETMs with extensive coronal loss, restored by endocrowns and post-core crowns, during masticatory simulation using FEA, and simulate stresses at the first molar made with different crown and post materials.

Methods

Structures and geometric conditions of the computer aided design (CAD) model

A mesio-distal cross-section of a lower right first molar was digitized and used to create 2-dimensional (2-D) models. There were three different model designs (Fig 1), *viz.*, endocrown with 2 mm occlusal clearance, endocrown with 4 mm occlusal clearance and post-core crown. The restorations used two different crown materials, *viz.*, zirconia (Zr) and lithia-disilicate reinforced glass ceramic (LDRGC), and three different post and core materials, *viz.*, glass fiber (GF), *stainless steel (SS)* and metal cast (MC). There were ten kinds of combination in this study.

Endocrown-2 mm-Zr: full zirconia endocrown with 2 mm occlusal clearance;

Endocrown-2 mm- LDRGC: full lithia-disilicate reinforced glass ceramic endocrown with 2 mm occlusal clearance;

Endocrown-4 mm-Zr: full zirconia endocrown with 4 mm occlusal clearance;

Endocrown-4 mm- LDRGC: full lithia-disilicate reinforced glass ceramic endocrown with 4 mm occlusal clearance;

GF post-Zr: glass fiber post + full zirconia crown;

GF post- LDRGC: glass fiber post + full lithia-disilicate reinforced glass ceramic crown;

SS post-Zr: *stainless steel* post + full zirconia crown;

SS post- LDRGC: *stainless steel* post + full lithia-disilicate reinforced glass ceramic crown;

MC post-Zr: metal cast post + full zirconia crown;

MC post- LDRGC: metal cast post + full lithia-disilicate reinforced glass ceramic crown.

In the GF posts and SS *posts*, the cores were made of composite, while in the MC posts they were made of metal. The model was created from radiographic image of a real tooth (Fig. 1a) using a FEA software (ANSYS v. 10; ANSYS Inc., Canonsburg, PA, USA) ⁽¹⁷⁾.

Endocrown and post-core crown designs

The Endocrown-2 mm designs were created with 2.0 occlusal clearance, 7.0 mm cavity depth, and 5.3 mm base width. The prepared cavity walls tapered with 2-5 degrees from the cavity base to the cavosurface (Fig. 1b). The Endocrown-4 mm designs were created with 4.0 occlusal clearance, 5.0 mm cavity depth, 5.3 mm base width and 2-5 degrees cavity walls taper (Fig. 1c). Jacket crown preparations were created with 2.0 mm occlusal clearance, 0.5-1.5 mm cervical clearance and shoulder margin, 2-5 degrees tapering angle for first molars, 14.0 mm post lengths. Rounded shoulder margins and anatomic occlusal reduction were incorporated in model (Fig. 1d).

The surrounding bone was modeled as cortical bone (1.5 mm thickness) and cancellous bone, which were assumed to be isotropic, homogeneous, and linearly elastic. A 0.2 mm periodontal ligament was modeled around the roots. A 0.1 mm thick cement-imitating layer was formed around the root part of the created post and under the crown. Perfect bonding was assumed at all the interfaces, including those between the teeth, the cores, the crowns, the posts and bones.

Material properties, mesh generation and boundary conditions

The elastic moduli and Poisson's ratios of the materials used are shown in Table 1. Material properties were assumed to be isotropic, homogenous, and linear-elastic, except the GF post. The material of GF post was anisotropic (Young's modulus along its long axis was 38.5 GPa, and 12.0 GPa perpendicular to that axis).

For calculation purposes, each tooth model was divided into 2-D 4-node structural solid elements (PLANE42). This element is defined by four nodes having two degrees of freedom at each node: translations in the nodal x and y directions. In model with endocrown-2 mm, 4,596 elements joined at 4,701 nodes were used. In model with endocrown-4 mm, 4,582 elements joined at 4,693 nodes were used. In model with post-core crown, 4,657 elements joined at 4,759 nodes were used. The aim of this preliminary FEA was to identify the most highly stressed regions within the restoration, especially those along the distal root inner and outer surface. These would be the regions to which shape optimization

would be applied. Thus, the mesh around the distal root inner and outer surface was made much finer than those in the other areas, with an average element edge length of 0.2 mm.

Fixed zero-displacement in both the horizontal and vertical directions was defined at the horizontal and vertical cut-planes of the supporting bone. A load was applied that corresponded to static loading, assuming no vibrational or dynamic effects in the structure. To reflect the stress distribution at the moment of equilibrium, a simulated 100 N vertical occlusal load was applied to the distal marginal ridge. The von Mises stress values were calculated by FEA along the distal root canal inner wall and the root outer surface (Fig 1: A→B→C). We focused on the distal root canal inner wall because the post was set in the distal root canal, from preliminary analysis the distal root canal inner wall was analyzed in greater detail. The stress distribution within the tooth/restoration cross-section was solved with the FEA software (ANSYS).

Results

The von Mises stress analysis for the 2 crown designs, 2 crown materials, 3 post materials tested is presented in Fig. 2. The stress distributions were similar for 2 different crown materials (Zr and LDRGC) and 2 different occlusal clearance (2 mm and 4 mm). The crown stresses of Zr were more concentrated. For the endocrown-2 mm-Zr and endocrown-4 mm-Zr (Fig. 2), a stress peak was found at the distal cavity inner wall (maximum 27.7 MPa and 17.8 MPa). Compared with the endocrown-2 mm, the endocrown-4 mm reduced the stress concentration in crown.

For the post-core crown, the main difference was found at the distal root. The low elastic modulus of the GF post showed reduced the von Mises stresses (maximum 23.6 MPa) (Fig. 2 GF post); both the SS post (maximum 62.9 MPa) and MC post (maximum 67.5 MPa) ensure a stress concentration at the post and distal root.

Differences also were found in the stresses at the alveolar bones. The endocrown showed increased and smooth stresses in the periodontal support tissue (maximum 24.2 MPa). (Fig. 2). The plots of the post-core crowns displayed only minor differences between post materials, 20.1 MPa for GF post, 17.4 MPa for SS post and 16.6 MPa for MC post.

Figure 3 shows the path plots of the interfacial von Mises stresses along the distal root canal inner wall and the root outer surface (A→B→C) in endocrown and post-core crown. No difference was found in the Zr crowns and the LDRGC crowns in the path plots. In the endocrown covered tooth, maximum von Mises stress values of 9 MPa were recorded in the distal root canal inner wall. The root canal inner wall stresses of SS post (maximum 33.7 MPa) and MC post (maximum 36.3 MPa) were higher than that of GF post (maximum 19.1 MPa) and endocrown (maximum 8.9 MPa). The behavior of the endocrown clearly differed from that of the post-core crowns. The endocrown only had one peak, nevertheless the post-core crowns had two peaks. The peak 1 was caused by the apical foramen, and the peak 2 was caused by the tip of the post. von Mises stress values around the SS and MC post tip (Peak 2) reached 12.7 MPa and 14.1 MPa. They were higher than that of GF post (7.5 MPa). In the same region, von Mises stress of

endocrown achieved a value of 5 MPa. The endocrown showed higher stresses occurred in the root outer surface than that of post-core crowns.

Discussion

The numeric FEA modeling is able to reveal the otherwise inaccessible stress distribution within the tooth-restoration complex. It has proven to be an important tool in the design process for the understanding of tooth biomechanics and the biomimetic approach^(27, 28). Although teeth are 3-D structures, important mechanical events in endocrown and post-core crown appear within the mesio-distal plane^(27, 29). These events support the use of the 2-D plane-strain model for numerical analyses. Volume meshing of 3-D teeth structures is usually restricted to tetrahedral elements. The tetrahedral element has a good ability to model irregular shapes; however, its accuracy is poor for bending and shearing dominated problems. The use of a 2-D model is also valuable because of its improved performance in terms of element number and simulation quality. Consequently, 2-D analysis was chosen in this study.

Inversely to anterior teeth, posterior cusps do not deform under load as simple cantilever beams^(30, 31). The deformation mode is complicated by the numerous possibilities in the application of loads. It is inevitable for the molar to receive non-axial force in the process of occlusion. The load configuration applied in this study was selected because it creates a maximum challenge for distal root flexure, which seems to represent an important biomechanical feature of post-core crown. Mean masticatory forces have been reported by Anderson⁽³²⁾ to be in the range of 70.6 to 146.1 N. Thus, the applied 100 N load lies within the range of these values in this study, and it has been used in a number of FE model validation studies⁽³³⁾.

Despite great variations in crown material properties, there were only minor differences in the alveolar bone. For a given load configuration, it appears that overall stress distribution within the tooth-bone complex was more influenced by geometry design of restoration (endocrown vs. post-core crown) than by composition (e.g. crown, post and core restorative material type). The endocrown showed a relatively smooth stress distribution in the root and the periodontal support tissue. This is largely due to two reasons: firstly, post-core crown applied extra-coronal retainer, while endocrown used intra-coronal retainer. Endocrown with intra-coronal retainer was more conducive to transfer the force to the wall of the pulp chamber and the periodontal tissue, rather than to the root canal wall. Secondly, endocrown geometrically reduced the rotation center of the crown restoration in comparison with the full crown (Fig. 1, Ring arrow). This also contributed to transfer the occlusal force to periodontal tissue.

The root canal after instrumentation (root canal or post preparation) is thinner and weaker than the rest of the tooth. Stress concentration at the tip of the post must therefore be regarded as most harmful. It is precisely in the area of concentrated stresses where differences were found (Fig. 3, Peak 2 of SS post and MC post). e.g. stresses in the tip of the post around MC posts achieved 3 times higher values than under endocrowns and twice higher values than under GF posts. In this specific zone, low-elastic modulus restorative materials showed reduced stresses, which can be explained by the stress redistribution into

the more flexible GF post and composite core. Stress concentration of endocrown in the root canal was relatively small, it is good to avoid the weak tip of the post. The molar post-core crown increased the risk of accidental root fracture. The highest von Mises stresses in the distal root canal occurred in molar restored with SS and MC posts. These types of restorations seem to be the least beneficial in molar teeth. Biacchi and Basting⁽³⁴⁾ found that molars with endocrowns are more fracture resistant than teeth restored with GF posts and cores and ceramic crowns. Taking into consideration the suitable stress distribution of endocrowns, minimal invasive preparation of tooth structures and no roots damage, these restorations can be recommended to use in molars.

Although von Mises stress levels in the root and the periodontal tissue of molars restored with post-core crowns were higher than stress levels in the tooth with the endocrown. Zr endocrown represented the one condition with a slightly greater amount of stresses concentration in the distal cavity inner wall when compared to the post-core crowns. Thus, this is regarded as a potential threat, knowing that remaining coronal tooth structure fractured. On the other hand, experimental strength study by Forberger and Göhring⁽³⁵⁾, have shown no significant differences between teeth restored with posts and endocrowns in terms of fracture resistance. Under the analytical conditions of this study, the results were largely dependent on the Young's modulus and Poisson ratio of the materials. However in reality there will be other dominating factors such as the bond strength, potential for micro-crack at the interface, fatigue damage potentials both for the hard tissues and the restorative materials. Further experimental studies and clinical trials are needed to validate the results of this FEA study.

Conclusions

In conclusion, posterior ceramic endocrowns bonded to the tooth substrate is a judicious way to reduce excessive tooth tissue removal and surgical crown lengthening. Within the limitations of this FEA experiment, it can be concluded that: Endocrown showed reduced stresses at its root canal inner wall but increased stresses at the coronal cavity inner wall when compared to post-core crowns. Endocrown exhibited higher stresses occurred at the root outer surface, while post-core crowns showed increased stresses at the root canal inner wall, especially SS post and MC post. The stress distributions in root were similar for 2 different crown materials (zirconia and lithia-disilicate reinforced glass ceramic) and 2 different occlusal clearance (2 mm and 4 mm).

Abbreviations

Zr: zirconia, LDRGC: lithia-disilicate reinforced glass ceramic, GF: glass fiber, SS: stainless steel, MC: metal cast, ETM: endodontically treated molars, FEA: finite element analysis, CAD: computer aided design

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and material

The complete data and materials described in the research article are freely available from the corresponding author on reasonable request.

Competing interests

The authors have no conflicts of interest relevant to this article.

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Authors' contributions

JL and ZZ conceived and designed the study. JL performed the finite element analysis. JL and ZL wrote the paper. ZZ reviewed and edited the manuscript. All authors read and approved the final manuscript.

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Table

Table 1 Properties of restorative materials and tooth tissue.

	Young's modulus (GPa)	Poisson ratio
Enamel	84.1 ⁽¹⁸⁾	0.33 ⁽¹⁸⁾
Dentin	18.6 ⁽¹⁹⁾	0.31 ⁽¹⁹⁾
Gutta-percha	0.14 ⁽²⁰⁾	0.45 ⁽²⁰⁾
Periodontium	0.05 ⁽¹⁶⁾	0.45 ⁽¹⁶⁾
Cortical bone/ Cancellous bone	13.7/ 1.37 ⁽²¹⁾	0.3 ⁽²¹⁾
Luting resin cement	8.3 ⁽¹⁶⁾	0.35 ⁽¹⁶⁾
LDRGC	96 ⁽²²⁾	0.23 ⁽²²⁾
Zirconia	205 ⁽²²⁾	0.19 ⁽²²⁾
Glass fiber post:	38.5/ 12 ⁽²³⁾	0.35/0.11 ⁽²³⁾
Fiber_longitudinal/ Fiber_transverse		
Metal cast post [Ni-Cr]	188 ⁽²⁴⁾	0.33 ⁽²⁴⁾
Stainless steel post	210 ⁽²⁵⁾	0.3 ⁽²⁵⁾
Composite resin core	7 ⁽²⁶⁾	0.3 ⁽²⁶⁾

LDRGC: lithia-disilicate reinforced glass ceramic

Figures

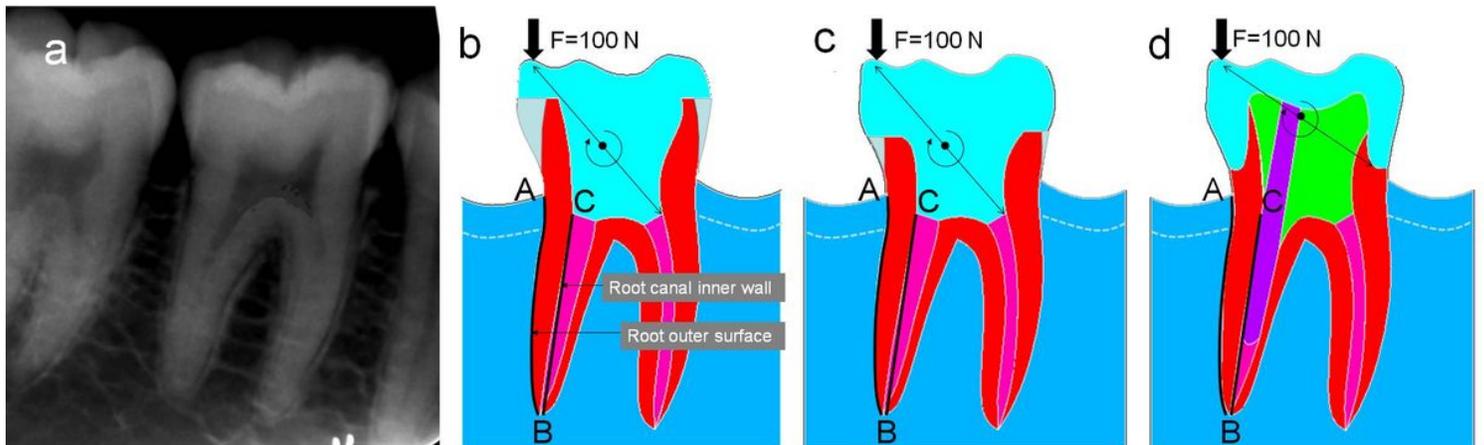


Figure 1

2-D models of first mandibular molar tooth with roots and periodontium (bucco-lingual side view). Original contours developed from radiographic image of first mandibular molar tooth. (a) radiographic image of first mandibular molar tooth, (b) endocrown, (c) post-core crown. Thick arrow: simulated 100 N vertical occlusal load. AB and BC: distal root outer surface and distal root canal inner wall. Ring arrow: rotation center. Endocrown geometrically reduced the rotation center of the crown restoration in comparison with the full crown.

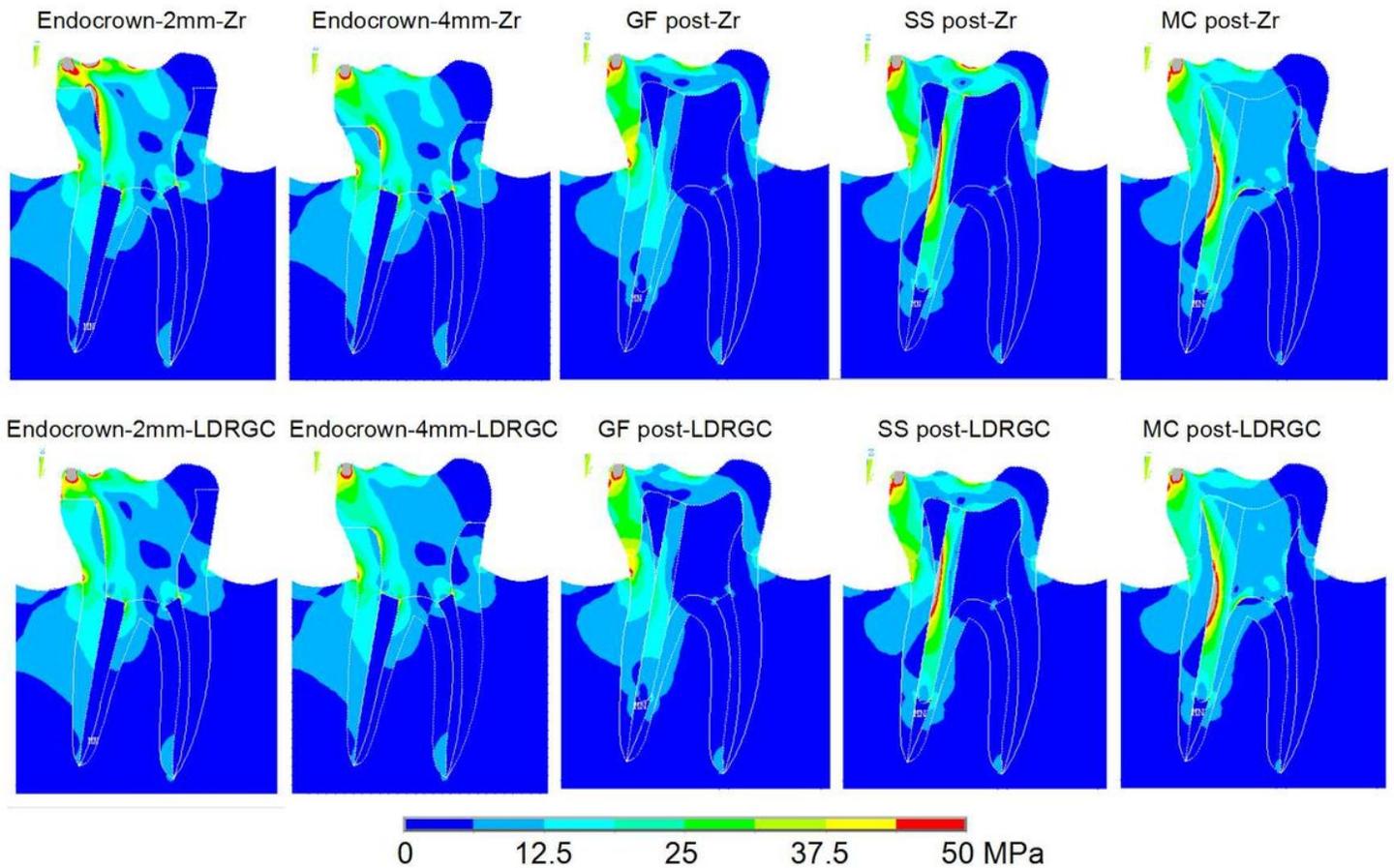


Figure 2

von Mises stress distribution maps in FE analysis results. Color bar indicates range of 0 to 50 MPa.

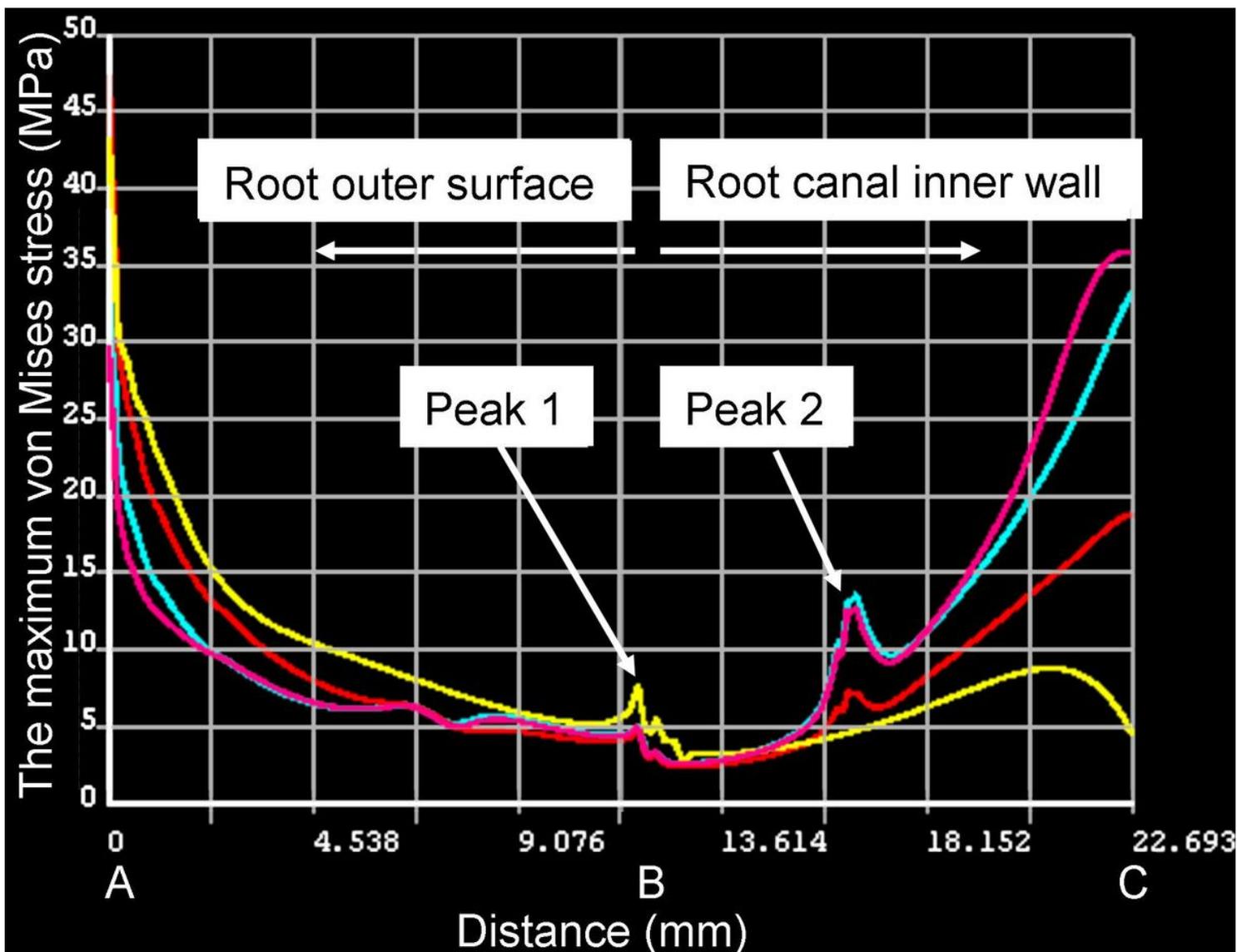


Figure 3

The path plots of the interfacial von Mises stress along the distal root canal inner wall and the root outer surface (A→B→C). Blue line: SS post-Zr and SS post-LDRGC; Pink line: MC post-Zr and MC post-LDRGC; Red line: GF post-Zr and GF post-LDRGC; Yellow line: endocrown-2mm-Zr, endocrown-2mm-LDRGC, endocrown-4mm-Zr and endocrown-4mm-LDRGC. Peak 1: apical foramen; Peak 2: tip of post.