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Influence of Crown Ferrule Heights and Dowel Material Selection on the Mechanical Behavior of Root-Filled Teeth: A Finite Element Analysis

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Abstract

Purpose: This study used the 3D finite element (FE) method to evaluate the mechanical behavior of a maxillary central incisor with three types of dowels with variable heights of the remaining crown structure, namely 0, 1, and 2 mm.
Materials and Methods: Based on computed microtomography, nine models of a maxillary central incisor restored with complete ceramic crowns were obtained, with three ferrule heights (0, 1, and 2 mm) and three types of dowels (glass fiber = GFD; nickel-chromium = NiCr; gold alloy = Au), as follows: GFD0 – restored with GFD with absence (0 mm) of ferrule; GFD1 – similar, with 1 mm ferrule; GFD2 – glass fiber with 2 mm ferrule; NiCr0 – restored with NiCr alloy dowel with absence (0 mm) of ferrule; NiCr1 – similar, with 1 mm ferrule; NiCr2 – similar, with 2 mm ferrule; Au0 – restored with Au alloy dowel with absence (0 mm) of ferrule; Au1 – similar, with 1 mm ferrule; Au2 – similar, with 2 mm ferrule. A 180 N distributed load was applied to the lingual aspect of the tooth, at 45° to the tooth long axis. The surface of the periodontal ligament was fixed in the three axes (x = y = z = 0). The maximum principal stress (σ_{max}), minimum principal stress (σ_{min}), equivalent von Mises (σ_{vM}) stress, and shear stress (σ_{shear}) were calculated for the remaining crown dentin, root dentin, and dowels using the FE software.
Results: The σ_{max} (MPa) in the crown dentin were: GFD0 = 117; NiCr0 = 30; Au0 = 64; GFD1 = 113; NiCr1 = 102; Au1 = 84; GFD2 = 102; NiCr2 = 260; Au2 = 266. The σ_{max} (MPa) in the root dentin were: GFD0 = 159; NiCr0 = 151; Au0 = 158; GFD1 = 92; NiCr1 = 60; Au1 = 67; GFD2 = 97; NiCr2 = 87; Au2 = 109.
Conclusion: The maximum stress was found for the NiCr dowel, followed by the Au dowel and GFD; teeth without ferrule are more susceptible to the occurrence of fractures in the apical root third.

The recovery of function by direct and/or indirect restorations in endodontically treated teeth is still challenging,[1] especially due to the reduced fracture resistance after endodontic treatment.[2,3] Endodontic treatment changes the tooth's architecture secondary to removal of decayed dental tissue, as well as endodontic access and root canal instrumentation,[4] which is associated with the greater induction of stress in these teeth.[5,6]

This is especially critical when there is large destruction of the remaining tooth structure, because the reduced height of this remaining structure[7] increases the probability of fracture compared to teeth with a greater height of intact remaining tooth structure.[8] Some authors have shown that the fracture resistance of dentin is directly proportional to the volume of remaining tooth structure.[5,9,10]

It is believed that the presence of ferrules protects the restored teeth, because it reinforces the tooth/prosthesis assembly.[11,12] This portion of dental tissue adjacent to the core increases the fracture resistance,[12] providing a positive effect by reducing the stress concentration on the tooth.[13-18]

The biomechanics of these teeth is also influenced by the placement of dowels.[8,19] According to some authors, the use of a metallic dowel with a high modulus of elasticity concentrates the stresses on the apical root third, thereby being associated

Figure 1 Crown ferrule heights. (left to right): A – 0 mm ferrule; B – 1 mm ferrule; C – 2 mm ferrule.

with a higher frequency of vertical fractures of the remaining root structure, often precluding the use of these roots.[1,20] The use of dowels, such as glass fiber dowels (GFDs), with a modulus of elasticity similar to dentin, has been associated with better stress distribution on the remaining tooth structure.[1,4,20,21] However, there is little information on the influence of ferrule height on the stress distribution and concentration on tooth reconstructions.[18] There are still doubts on the selection of dowels and type of material that should be used according to ferrule height.

Therefore, this study used the 3D finite element (FE) method to evaluate the mechanical behavior of a maxillary central incisor with three types of dowels with variable heights of the remaining crown structure, namely 0, 1, and 2 mm. The following hypotheses were tested: 1 – the increase in ferrule height does not reduce the stress concentration in the crown and root dentin in the simulated models; 2 – there is no difference in stress concentration on the tooth with different types of dowels, regardless of the ferrule height.

Materials and methods

This study was approved by the Human Research Ethics Committee. A maxillary central incisor from the human tooth bank of the Department of Dental Materials and Prosthodontics was used to develop the models.

Based on computed microtomography images (μCT), 720 transverse sections were obtained after tooth scanning (CT40, Scanco Medical, Bassersdorf, Switzerland). The 3D models were reconstructed using 82 μCT sections and finalized on SolidWorks 2007 software (SolidWorks Corp., Concord, MA). All tooth structures (enamel, crown and root dentin, dental pulp, and the periodontal ligament) were included in the solid model.

Table 1 Study models, crown ferrule heights, and dowel materials

Crown ferrule heights	Dowel material	Models
0 mm, 1 mm, 2 mm	Glass fiber	GFD0, GFD1, GFD2
0 mm, 1 mm, 2 mm	NiCr alloy	NiCr0, NiCr1, NiCr2
0 mm, 1 mm, 2 mm	Gold alloy	Au0, Au1, Au2

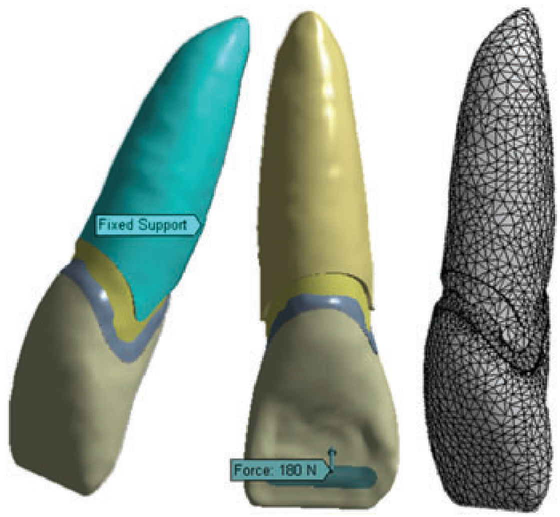

Figure 2 Boundary condition, loading, and FE mesh. Left: The surface of periodontal ligament was constrained on three axes (x = y = z = 0). Center: A 180 N load was applied on the loading area, at 45° to the tooth long axis. right: FE mesh.

Nine models were obtained based on this initial model. The root canal was considered endodontically treated in all models. Three models received a GFD; three models had an NiCr cast metallic dowel (NiCr); and three received a gold alloy cast metallic dowel (Au).

All models had a homogeneous tooth reduction of 1.0 mm on the buccal and lingual surfaces and 2.0 mm on the incisal surface. The ceramic veneer thickness followed the tooth's reductions: 1.0 mm on the buccal and lingual surfaces and 2.0 mm on the incisal surface. The thickness of periodontal ligament (0.25 mm) was the same for all models, as was a 50-μm layer of cementing agent. The models presented differences concerning the size of remaining crown structure (ferrule) and type of dowel and cast.

To evaluate the influence of ferrule height on the tooth behavior, variable heights of remaining crown structure were used, namely 0, 1, and 2 mm of height, maintaining the same design (size and shape) of the remaining tooth structure in all models, regardless of core reconstruction with composite resin (GFD) or metal (NiCr and gold) (Fig 1) (Table 1). After model development, the IGS extension files were imported in Ansys Workbench 10.0 FE software (Swanson Analysis Inc., Houston, PA) to recognize the structures of models and generate the FE mesh.

Mechanical properties (elastic modulus [E] and Poisson's ratio [ν]) were obtained from the literature, for considering all model structures to be homogeneous, isotropic, and linear elastic, except for the GFD (Table 2),[22-28] which was considered orthotropic, homogeneous, and linear elastic, according to Lanza et al[29] (Table 3). All structures of the models were considered perfectly joined.[22,30]

According to Rocha et al,[31] as boundary condition, the external surface of the periodontal ligament was fixed on x, y, and z coordinates for all models ($x = y = z = 0$).[31] A 180 N distributed load (approximately 10 mm^2)[31] was applied to the

Table 2 Elastic properties of isotropic materials. Young's modulus (E), Poisson ratio (v)

Materials	E (GPa)	Ref.	v
Enamel[22]	84.1	17	0.33
Dentin[22]	18.6	17	0.32
Periodontal ligament[23]	6.89×10^{-5}	18	0.45
Gutta-percha[24]	1.4×10^{-1}	20	0.45
Resin cement[22]	18.6	17	0.28
Ceramic[25]	69	17	0.30
Composite resin[26]	16	17	0.3
Gold alloy[27]	89.5	22	0.33
NiCr alloy[28]	200	23	0.33

lingual surface, in the incisal third, 45° to the long axis of the tooth for all models (Fig 2).[32]

To achieve convergence of analysis (6%),[31] the mesh was composed of 3 mm tetrahedral elements (ANSYS Workbench 10.0; ANSYS, Inc., Canonsburg, PA). The models had up to 64,650 elements and up to 115,881 nodes (Fig 2).

Numerical analysis was performed using FE software (ANSYS Workbench 10.0) to obtain the stress fields. After loading, the maximum principal stress (σ_{max}), minimum principal stress (σ_{min}), shear stress (σ_{shear}), and von Mises stress (σ_{vM}) were obtained for crown and root dentin, and for the dowel. According to Dejak and Mlotkowski,[25] the criterion σ_{max} is adequate to evaluate non-ductile materials like dentin, as well as to predict failures that may affect small areas at the interface.[33,34] The values for these structures were also analyzed according to the criteria of minimum principal stress (σ_{min}), shear stress (σ_{min}), and equivalent von Mises stress (σ_{vM}).[35,36]

Results

Stress on the remaining crown and root dentin with different ferrule heights (0, 1, 2 mm) and type of dowel (GFD; NiCr; Au)

When using the GFD and core, the σ_{max} of the remaining crown and root dentin were higher when the ferrule height was smaller (Fig 3), being more evident in GFD0, followed by GFD1 and GFD2. In the remaining crown dentin, the stress was located on the incisal region of the core, while in the root dentin it was observed on the apical region of the GFD in all models (Fig 4).

When the NiCr cast metallic dowel was used, the stresses in the remaining crown dentin increased with the increase in ferrule height, with maximum tension in NiCr2, in contact with the coronal portion of the metallic dowel (Fig 3). The opposite was observed for the root dentin; σ_{max} was higher in NiCr0,

Table 3 Orthotropic properties of the GFD, according to Lanza et al[29]

Young's modulus (GPa)	Poisson ratio	Shear modulus (G)
X = 37	Xy = 0.27	Gxy = 3.1
Y = 9.5	Xz = 0.34	Gxz = 3.5
Z = 9.5	Yz = 0.27	Gyz = 3.1

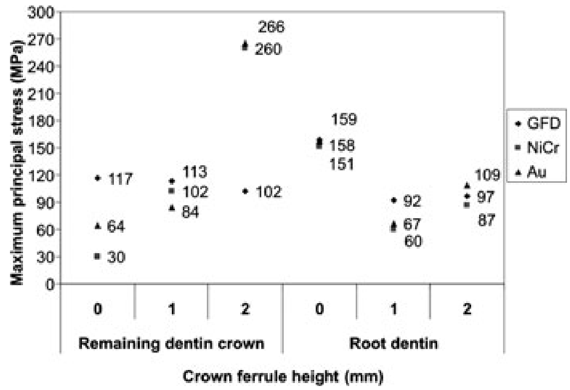

Figure 3 Maximum principal stress (MPa) on the remaining crown dentin and root dentin, varying the crown ferrule heights (0, 1, 2 mm) and dowel material (GFD, NiCr, Au).

followed by NiCr2 and NiCr1, located at the apical region of the metallic dowel (Fig 4).

For the gold alloy cast metallic dowels, the behavior of the remaining crown and root dentin was similar to the NiCr cast metallic dowel. The σ_{max} in the remaining crown dentin increased with the increase in ferrule height (Fig 3). Concerning the root dentin, the σ_{max} was more concentrated with the decrease in ferrule height (Fig 3). The stresses were located on the cervical end of the remaining crown dentin and at the apical region of the dowel in the root dentin (Fig 4).

The analysis of dentin by the criterion of σ_{min} revealed that the stress in the remaining crown dentin increased with the increase in ferrule height, being higher in NiCr2 (Table 4). In the root dentin, the σ_{min} increased with the decrease in ferrule size (Table 4).

With regard to the σ_{vM} and σ_{shear} stresses, the remaining crown and root dentin also exhibited different behaviors with the increase in ferrule size (Table 4). For the crown dentin, the stresses in all models were increased with the increase in ferrule size. Concerning the root dentin, the stresses were increased in all models without the ferrule (GFD0, NiCr0, Au0). For all models, the maximum stress was observed for simulations of NiCr metallic alloy.

Stress on the dowels (GFD; NiCr; Au) with different ferrule heights (0, 1, 2 mm)

The analysis of the σ_{max} in the three types of dowels revealed different mechanical behaviors with regard to the stress concentration in the root and coronal regions of the dowel. The models using GFD associated with composite resin core exhibited high stress concentration at the coronal region of the dowel when the GFD0 condition was simulated, followed by GFD1 and GFD2 (Fig 5). Regarding the root region of the dowel, the stress was more concentrated when there was no remaining crown structure (GFD0), with a higher concentration on the palatal aspect, in contact with the cervical region of the remaining crown dentin (Fig 6).

Conversely, for the NiCr cast metallic dowel, the highest stress concentration was on the coronal region of the dowel with a remaining structure of 2 mm (NiCr2), followed by NiCr1

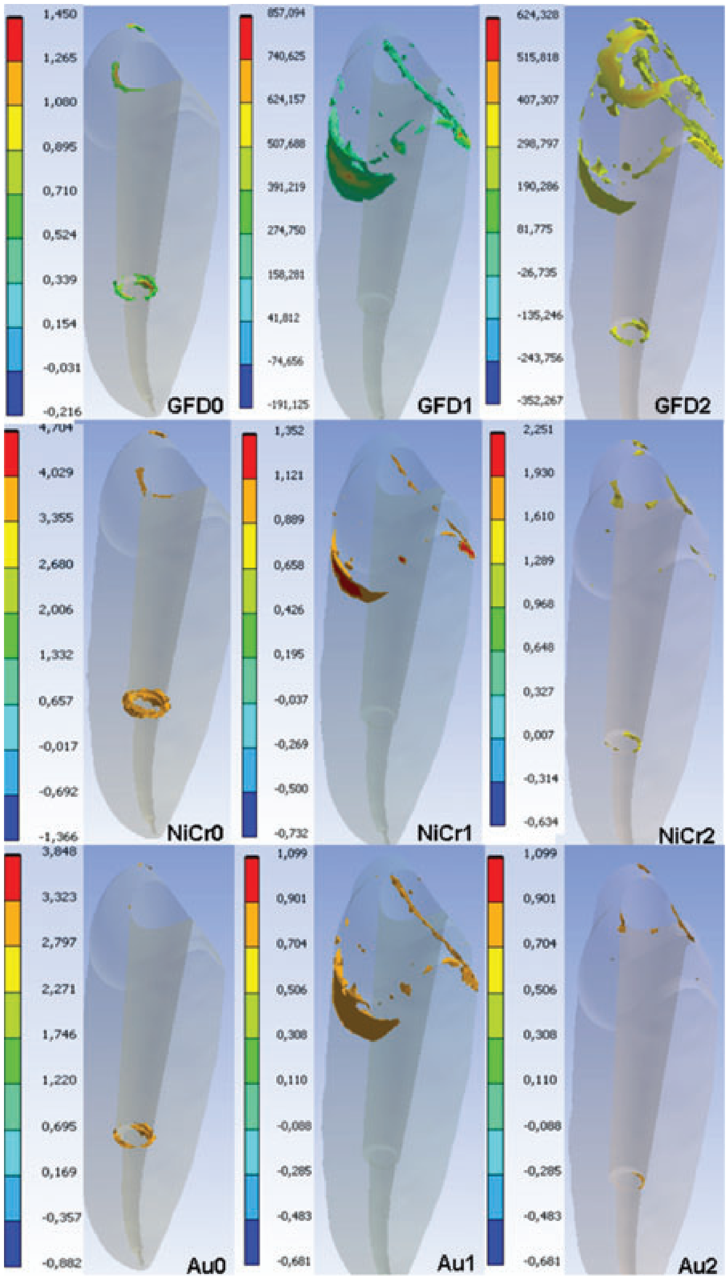

Figure 4 Location of maximum stress (σ_{max}) on the remaining dentin and root dentin for all models; GFD0 – level of the dowel apex; GFD1 – cervical region of the mesial aspect; GFD2 – distal aspect on the dowel/dentin interface; NiCr0 – level of the dowel apex; NiCr1 – level of the end of the dowel on the mesial aspect; NiCr2 – dowel/dentin interface on the cervical region of the root; Au0 – level of the dowel apex; Au1 – cervical dentin on the buccal aspect; Au2 – level of the end of the dowel.

and NiCr0 (Fig 5). Concerning the intra-radicular region of the dowel, the most evident stress concentration occurred in the NiCr0 simulation and was located below the cementoenamel junction (CEJ) (Fig 6). After NiCr0, the highest stress concentration occurred in NiCr1 and NiCr2.

In the simulations for the gold alloy cast metallic dowel, the stress distribution was similar to the GFD, yet it was higher for the gold alloy dowels. In the coronal region of the dowel, the highest σ_{max} concentrations occurred in Au0, followed by Au2 and Au1, located at the region contacting the remaining crown structure (Fig 5). For the intra-radicular region of the gold alloy dowel, the highest stress concentration occurred in Au0, followed by Au2 and Au1. The stress was located on the cervical region of the root in Au0 and Au1 and at the apical region in Au2 (Fig 6).

Regarding the criteria σ_{min} and σ_{vM}, the highest stresses in the coronal and intra-radicular regions of the dowel occurred in all models for the situation with 0 mm of ferrule (GFD0, NiCr0, Au0) (Table 4). Similarly, it was observed that the maximum stress in dentin occurred in the NiCr model.

Concerning the σ_{shear} stress, different behaviors of the dowel were observed between the models (Table 4). For the simulations of GFD, the stresses were reduced with the increase in ferrule size, with observation of lowest stresses in GFD2. For

Table 4 Minimum principal stress ($\sigma_{\min}$), von Mises stress (σ_{vM}), and shear stress (σ_{shear}) for remaining dentin (CD), root dentin (RD), dowel abutment (PA), and dowel retainer (PR)

	$\sigma_{\min}$ (MPa)				σ_{vM} (MPa)				σ_{shear} (MPa)			
Models	CD	RD	PA	PR	CD	RD	PA	PR	CD	RD	PA	PR
GFD0	−108	−125	−670	−70	128	208	1001	80	23	30	161	4
GFD1	−162	−122	−434	−3	144	113	494	5	35.6	31	8	8
GFD2	−191	−113	−460	−34	360	108	380	36	50	15	10	6
NiCr0	−44	−146	−3,940	−608	75	260	3,700	560	11	47	450	83.5
NiCr1	−146	−80	−1,900	−124	115	97	1,880	115	33	24.5	330	8
NiCr2	−622	−120	−2,140	−190	600	120	2,940	180	56	15	555	98
Au0	−64	−124	−1,970	−276	82	246	2,700	273	17	54.3	254	29.5
Au1	−150	−93.5	−1,610	−60	122	92	1,500	50	33	28	177	10
Au2	−520	−120	−1,750	−200	473	130	2,040	150	56	20	266	79

the NiCr and Au models, the stress tended to increase with the increase in ferrule size, both in the coronal and in intra-radicular regions of the dowel (Table 4). Figure 7 illustrates the possible sites of initiation and propagation of failures in the study models.

Discussion

The findings of this study revealed different mechanical behaviors of teeth when using different restorative materials for the dowels and different ferrule heights. The simulations using GFDs revealed that with the variation in ferrule height, the stress distribution in the remaining crown and root dentin were more homogeneous compared to simulated models using NiCr and gold alloy cast metallic dowels. Also, the stresses in the remaining crown dentin, root dentin, GFD, and core were gradually reduced with the increase in ferrule size for GFD0, GFD1, and GFD2. The first hypothesis of the study was partially accepted, because the stress in the root dentin was reduced for all study models, while the stress in the remaining crown dentin was reduced in GFD1 and GFD2; however, in simulations with metallic dowels, there was increased stress on the remaining

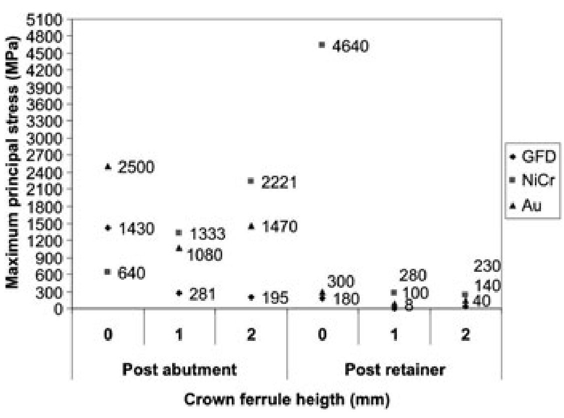

Figure 5 Maximum principal stress (MPa) on dowel abutment and dowel retainer, varying the crown ferrule heights (0, 1, 2 mm) and dowel material (GFD, NiCr, Au).

crown dentin with the increase in ferrule size. Except for the core, the mechanical behavior between dentin and GFD was similar, without variations in the $\sigma_{\max}$ concentration. According to some authors, this may occur due to the similar elasticity modulus of the dentin and GFD.[8,21]

Concerning the cores for the GFD0, GFD1, and GFD2 models, the maximum principal stress concentration was higher compared to the other aforementioned structures (dentin and GFD), especially for GFD0. This behavior of the core may be related to the direction of the simulated incisal load in the present study.[4] Since the forces on the maxillary central incisors are mainly oblique to the tooth long axis during masticatory movements, the dowel tends to present a rotational movement with the fulcrum on the cervical region of dentin. The smaller the rigidity of the dowel/cement assembly (lower elasticity modulus), the higher the tendency of dowel flexure, thus causing stress concentration on the external surface.[4]

Also, it should be highlighted that the lever arm is increased when the resistance moment arm is reduced with the reduction in ferrule size, increasing the compression stresses on the cervical region of dentin (buccal aspect) in the apical root third (and palatal aspect), also increasing the tensile stresses in the cervical region of dentin (palatal aspect) and apical region of the root on the buccal aspect. Consequently, these two factors (flexibility of the assembly, moment arm) in combination increased the stress in the resin cement for the model GFD0 compared to the other simulated models. Concerning the simulations of cast metallic dowels (NiCr and Au), the stresses were lower in root dentin than in GFD0, GFD1, and GFD2, except for the crown dentin in NiCr2 and Au2.

Similar to GFD, with an increase in ferrule height, lower stress concentration occurred on root dentin for NiCr0, NiCr1, NiCr2, Au0, Au1, and Au2. Conversely, increasing the ferrule, the stresses were increased in the remaining crown dentin for these models.

This probably occurred due to the high elasticity modulus of the metallic alloys employed to fabricate the NiCr and gold alloy metallic dowels (200 and 89.5 GPa, respectively). According to some authors, the stresses tend to be transferred from structures with lower elasticity modulus to structures with

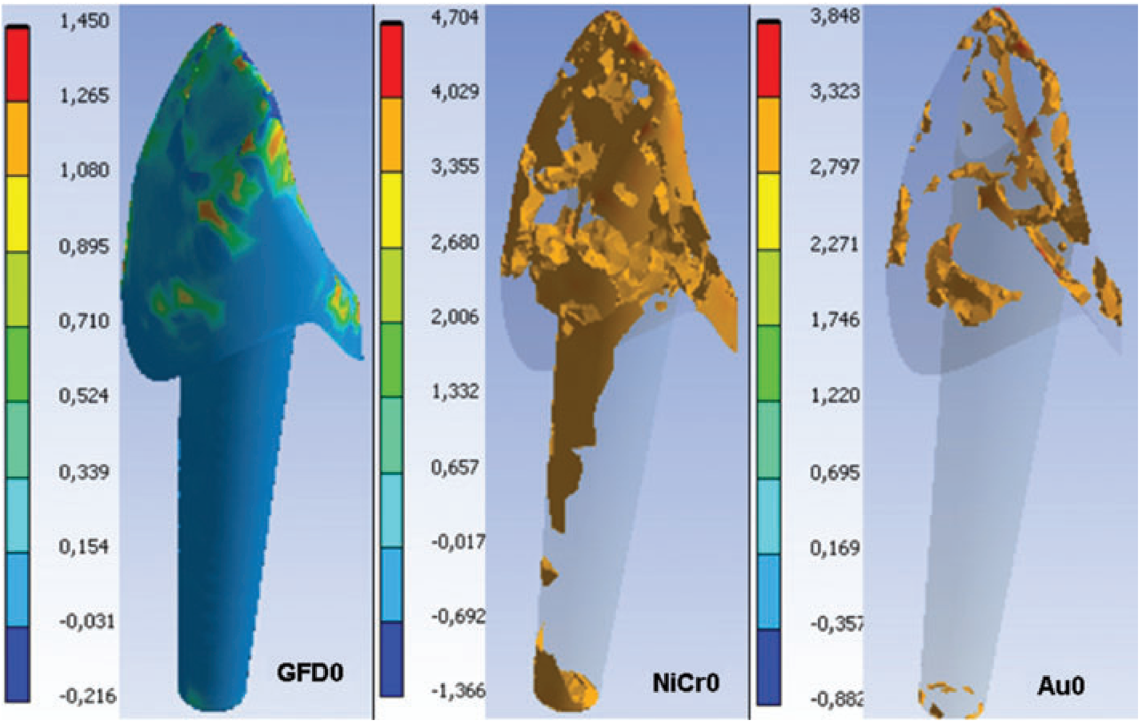

Figure 6 Location of maximum stress (σ_{max}) on the dowel for GFD0, NiCr0, and Au0. GFD0 – maximum stress on incisal dowel abutment; NiCr0 – maximum stress on apical region; Au0 – maximum stress on apical region.

higher elasticity modulus.[33] Since there were differences in stress concentration in the tooth structures for the same ferrule height and different dowel materials, the second hypothesis of the study was rejected.

In the simulations with cast metallic dowels (NiCr and Au), both the crown and root dentin presented lower stress concentration on the surface compared to simulations with GFDs; however, different from GFDs, the cast metallic dowels presented a high stress concentration when exposed to masticatory forces,[18,37] without homogeneous distribution of forces to the tooth.[18,37] This mechanical behavior is evidenced by the analysis of stress concentrations (σ_{max}, σ_{min}, σ_{shear}, σ_{vM}) in the cast metallic dowels (NiCr and Au) compared to the GFD, regardless of the height of the simulated ferrule.

The high elasticity modulus and high fracture resistance of cast metallic dowels[6,9] make the teeth highly susceptible to catastrophic fractures, especially in the absence of ferrule in the remaining crown structure and under intense occlusal forces. The stress concentration occurs at the apical level of the metallic dowel,[4] as observed in NiCr0 and Au0 (Fig 7).

Vertical fractures are more frequently observed in roots with metallic dowels, often precluding use of the tooth for future restorative treatments.[37] These characteristics make the GFDs interesting from a biomechanical standpoint.[1]

Some studies indicate the good mechanical resistance of resin-reinforced GFDs when submitted to forces along the long axis of reinforcement fibers.[38] However, under oblique forces, the fracture resistance of dowels is smaller, and thus the material may present fracture before the occurrence of damage to the remaining crown and root dentin,[38] thereby preventing damage to the crown or root dentin.

Also, there may be fracture of the cement line between the fiber dowel and dentin before the occurrence of a problem to the tooth structures,[15] because the cement line is characterized as

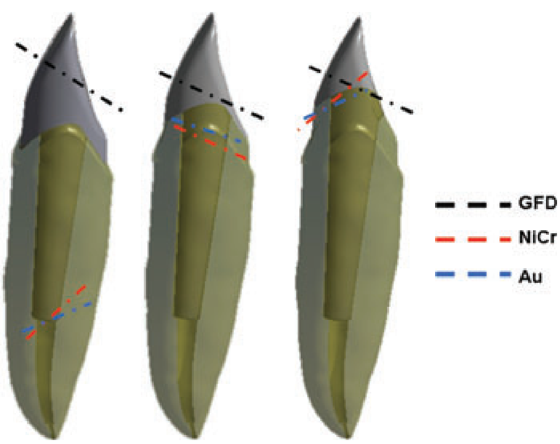

Figure 7 Probable site of crack initiation and propagation of failure on dentin for 0, 1, and 2 mm of crown ferrule. The black lines are probable planes of failure for models of GFDs; the red lines are probable planes of failure for models of cast NiCr alloy (NiCr); the blue lines are probable planes of failure for models of cast gold alloy (Au).

the weakest part of the dentin/cement/dowel interface.[29] This is observed under cyclic stresses, because this type of mechanical demand is associated with a higher number of adhesive failures in these types of restorations.[3]

This is worse for maxillary central incisors, which are exposed to repeated oblique stresses due to their position in the dental arch. These stresses lead to tensile areas on the cervical region of the buccal aspect and compression areas on the cervical region of the palatal aspect, considering a case with Angle Class I occlusion.[39] In this study, the results revealed that the presence of a ferrule in the remaining crown structure acts by reducing the stresses on the restorations in most tooth structures, which is more evident when the ferrule size is greater.[18]

Although there was no reduction of stresses in the crown dentin for NiCr1, NiCr2, Au1, and Au2, as observed in the other models, when the ferrule was present there were higher stresses in structures closer to the CEJ, favoring the prognosis of restorations if the ultimate tensile strength of dentin is reached.[40] In these cases, instead of a fracture at the medium/apical root thirds, the fracture may occur in a plane closer to the cervical third or closer to the coronal region of the restoration.[17]

This study evidenced the mechanical behavior of teeth restored with different dowel systems and different ferrule heights; however, the results should be extrapolated with caution. Although a detailed 3D FE model of the tooth was constructed based on μCT images in this study, and the literature shows a good relationship between the results of virtual simulations based in μCT data and laboratory tests,[41,42] there was no experimental validation of the models. Furthermore, other limitations should be addressed: (1) characterization of the dentin substrate as an anisotropic material,[43] according to the orientation and density of dentinal tubules; (2) evidence of different bonding degree between the cement and dentin, according to the type of cement used.

Future studies should be conducted considering the dentin substrate as anisotropic, according to the density and orientation of tubules, and non-linear, so that differences between adhesive and conventional cementation may be analyzed to establish the influence of these factors for restorations, according to the restorative material and ferrule size. Standardized longitudinal clinical studies must be carried out to evaluate the effect of ferrule heights and dowel material, to know the survival rates of each situation and allow better clinical indication.

Conclusion

Within the limitations of this study, it was concluded that the increase in ferrule size reduced the σ_{max} concentration in all structures of models with GFDs. For models with NiCr and gold alloy cast metallic dowels, the increase in ferrule height reduced the σ_{max} in the root dentin and intra-radicular region of the dowel, and increased the σ_{max} in the remaining crown dentin; the maximum stress was observed for the NiCr dowel, followed by the gold alloy dowel and the GFD. Teeth without ferrule are more susceptible to fractures on the apical root third.

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