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Three-Dimensional Finite Element Analysis of Custom-Made Ceramic Dowel Made Using CAD/CAM Technology

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Keywords
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Abstract

Purpose: This study compares the stress distribution in the structure of a loaded endodontically treated maxillary extracted canine restored with either custom-made zirconia (Cercon) or cast gold dowel and core.
Materials and Methods: Standard treatments were implemented to prepare the gutta-percha-filled root canal and dowel space. The tooth along with the dowel and core fabricated pattern resin were prepared to receive an all-ceramic (Cercon) crown. An impression was made for the tooth preparation with the zirconia milled dowel and core in place to fabricate the Cercon crown using CAD/CAM. The restored canine was scanned, and from the scan two models were constructed with the surrounding ligament and bone. Three-dimensional finite element elastic analysis was then carried out for the stress distribution within the different regions of the two models due to a concentrated force of 100 N applied at the mid-lingual area. Analyses were made for three load angulations, vertical, buccolingual horizontal, and an in-between oblique force at 45°. Each region of the models was assumed isotropic and homogeneous. The two restored canines with zirconia and gold were compared in terms of the resulting maximum tensile, compressive, and Von Mises stresses.
Results: Generally, there were no significant differences in the maximum stresses in most regions for both models. Von Mises stresses for zirconia dowel and core was 8.966 MPa and for cast gold dowel and core was 8.752 MPa. The maximum tensile stress for zirconia dowel and core was 9.326 MPa, and for cast gold dowel and core was 8.166 MPa.
Conclusions: The present work validates the use of CAD/CAM zirconia material for ceramic dowel and cores. *Clinical implications:* CAD/CAM Zirconia can be used for a custom-made dowel and core in an esthetically demanding zone as an esthetic replacement for a metal cast dowel and core when restoring endodontically treated teeth.

Endodontically treated teeth often lose a large portion of their structure either due to the removal of existing caries or the access opening preparation.[1] Moreover, the additional tooth preparation, especially if the marginal ridges are involved, will result in the largest reduction in tooth stiffness.[2,3] These teeth are generally more fragile than vital teeth and, at times, may be more predisposed to fracture.[4–6] In a study using the unconstrained punch shear test,[7] the dentin of endodontically treated molar teeth was found to be weaker and more brittle than that of vital teeth. This could be attributed to moisture loss,[8–11] architectural changes,[2,12,13] altered biomechanical behavior,[14] changes in the physical properties of dentine,[15] collagen alteration,[16] and loss of "Dome Effect."[17] To restore these weakened teeth, reconstruction of lost tooth structure is performed using a single material or a combination of available materials; a dowel is placed to help retain the core, which is essential for crown retention.[18] Subsequently, a prosthetic crown with an optimal ferrule design is made to ensure the tooth's resistance to fracture.[19-30] There are many causes of failure of endodontically treated teeth, including root fracture, caries, dowel distortion, and loss of retention of the dowel and/or crown.[12,31-33] The use of cast metal dowels and cores is advocated because they are effective retaining artificial prostheses for teeth with large coronal defects, and they have a well-established high success not matched by nonmetallic systems[34-36] as reported in retrospective studies over a long period of time. Fiber dowels with composite cores are claimed as a better esthetic alternative because they have flexural strength almost equal to dentin,[35,37] improving fracture resistance.[29,38-43] Furthermore, the repair of a failed fiber dowel and composite core can be easily performed.[44]

A new method of fabricating custom-made, all-ceramic dowels and cores using CAD/CAM technology was described by Awad and Marghalani.[45] In the current study, an analysis was completed to evaluate the effect of two dowel and core materials, CAD/CAM tetragonal zirconia poly-crystals (Cercon, DeguDent, Hanau-Wolfgang, Germany), and gold, on stress distribution in the following regions: crown, dowel, core, root, and surrounding bone. The tooth was subjected to different loading conditions using 3D finite element analysis (FEA).

Materials and methods

An extracted right maxillary canine was chosen for this study. The tooth was endodontically treated and filled with gutta-percha. Part of the gutta-percha was removed to allow for dowel space. Dowel space was prepared using a number 3 Gates Glidden drill (Dentsply, Addlestone, UK) and Peeso reamer (Pulpdent, Watertown, MA) leaving 5-mm of gutta-percha in the apical portion of the root as an apical seal. A large portion of the coronal part of the crown was removed to simulate the tooth loss to be replaced with the dowel and core. A pattern resin (GC America, Alsip, IL) was made to form the custom-made dowel and core. The tooth was prepared to receive a Cercon all-ceramic crown with a 2-mm ferrule design included in the preparation (Fig 1). The dowel and core were fabricated using Awad and Marghalani's method:[45] the pattern was scanned and milled into the presintered form using the Cercon machine and sintered in the Cercon Heat oven; the dowel and core were fitted into the maxillary canine. An impression was made for the tooth preparation with the dowel and core in place, using polyvinyl siloxane (3M ESPE, St. Paul, MN) to fabricate the master die. The crown was fabricated as all-ceramic using a CAD/CAM machine (Cercon). The prepared maxillary canine, the finished crown, and the zirconia dowel were scanned and modeled three-dimensionally. Bone was also modeled. The outer surfaces of four regions were selected to be geometrically identified and were scanned four times; the mold (representing bone), the root, the dowel and core, and the crown (Fig 1).

The scanning accuracy was 0.5 mm. The resulting scans were exported as CAD files and imported by FEA software (ANSYS, Swanson Analysis Inc., Canonsburg, PA). Volumes were generated from the imported surface areas. ANSYS was manipulated to complete the tooth preparations not scanned by the 3D scanner. To resemble biologic width, a cylindrical block resembling surrounding bone and the marginal crest located 2 mm apical to the cementoenamel junction was also scanned. The ANSYS file was expanded to include all needed data for the FEA, including the periodontal ligament area, which was taken as 300 μm, and the adhesive resin cement surrounding the dowel and core, which was taken as 50 μm (Table 1).

A 100-N concentrated load was applied to the crown at the mid-lingual area in three directions: axial (vertical), inclined at a 45° angle, and horizontal. Resemblance of the regular mastication load was achieved. Boundary conditions served as supports located at the base of the bone cylinder. The analysis was completed for the dowel and core two times: once run with the zirconia material and then run with type II gold material. In both cases, the crown material remained Cercon. The distribution of compressive, tensile, and von Mises stresses was calculated in all regions.

Results

The distribution of principal stresses and Von Mises stresses is illustrated in Figs 2–5. The values of the principal stresses and Von Mises stresses are summarized in Table 2. The stress distribution in the root was similar for both materials (gold and zirconia). The stress distribution was in a more favorable pattern than other systems.

The Von Mises stresses for the zirconia dowel and core were 4.81% lower than that of the gold dowel and core (difference of 3.7 MPa). Regarding crown Von Mises stresses, the zirconia dowel and core experienced 2.78% less stress (difference of 4.9 MPa) than the gold dowel and core (Fig 6).

In general, there were no differences in the maximum compressive stresses of bone, periodontal ligaments, and root structure when the tooth was restored by either gold or zirconia dowels and cores (Fig 7). The only difference in compressive stresses between gold and zirconia was found within the dowel and core, and crown. Similar results are observed in Figure 8 in relation to the maximum tensile stresses. In general, there were no significant differences in the maximum stresses in most regions for both materials; the difference in the dowel and core region was due to the difference in the modulus of elasticity between the two materials.

Discussion

Three methods have been used to investigate the stress/strain in tooth structure and dental appliances. Photoelasticity provides good qualitative information in relation to the overall location of stresses; however, only limited quantitative information is obtained. Strain-gauge measurements provide accurate data pertaining to strains only at the location of the gauge. FEA is an analytically powerful tool that provides detailed quantitative data at every location within a mathematical model that simulates the mechanical behavior of the system. Thus, FEA has become valuable in the assessment of various systems in dentistry.

By definition, the present FEA gives an accurate solution for the present model, which is an approximation of loaded endodontically treated maxillary extracted canines restored with dowel and cores made of two materials. Thus, the outcome

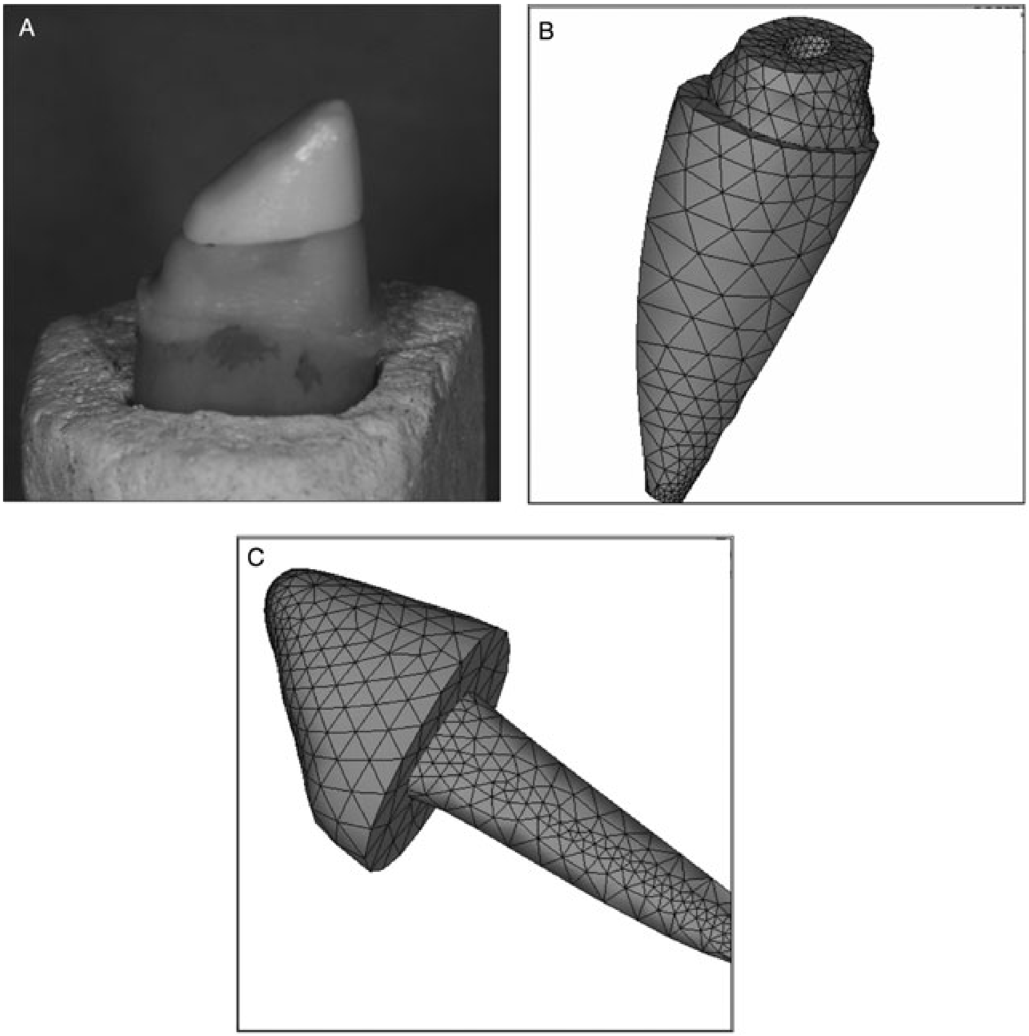


Figure 1 (A) Dowel and core and tooth; (B and C) 3D image of scanned tooth and dowel.

solution is approximate, and the closer the model to the analyzed system, the closer the solution is to reality. To approach the actual system, the present modeling invoked some assumptions that potentially influenced the accuracy of the results. Modeling approximation was related to (1) detailed geometry of the analyzed system, (2) boundary conditions, (3) material properties, (4) loading conditions, (5) convergence, and (6) validation.

Table 1 The moduli of elasticity and Poisson's ratios used in the analysis

Material	Gold	Cercon	Cement	Periodontal ligament	Dentin	Bone
Elastic modulus E (GPa)	100	210	2.6	0.0000689	18.6	3.7
Poisson's ratio (ν)	0.31	0.3	0.36	0.4	0.31	0.35

The present work qualitatively compares the effect of two dowel and core materials. For such an objective, the present 3D FEA is efficient, provided that the analyzed system is satisfactorily modeled. Standard treatments and procedures were implemented to prepare the analyzed restored canine for 3D scanning to identify the outer surfaces of the tooth with its different regions with an accuracy of 0.5 mm. Bone level, periodontal ligament, and cement were taken into account in this FEA study.

Periodontal ligament with a realistic 300 μm thickness[46] was generated to surround the outer surface of the tooth root. In the literature, the thickness with the closest strain values to the experimental values were an isometric voxel size of 0.44 mm,[47] which is close to the thickness chosen for this study based on the average obtained from findings of the PDL thickness for humans, ranging between 0.2 mm and 0.5 mm.[46] Although periodontal ligaments' modulus of elasticity values in most of the literature was taken as 6.89×10^2 GPa, the value used in this study was 3 orders less than the one indicated in the literature, as indicated by Ruse.[48]

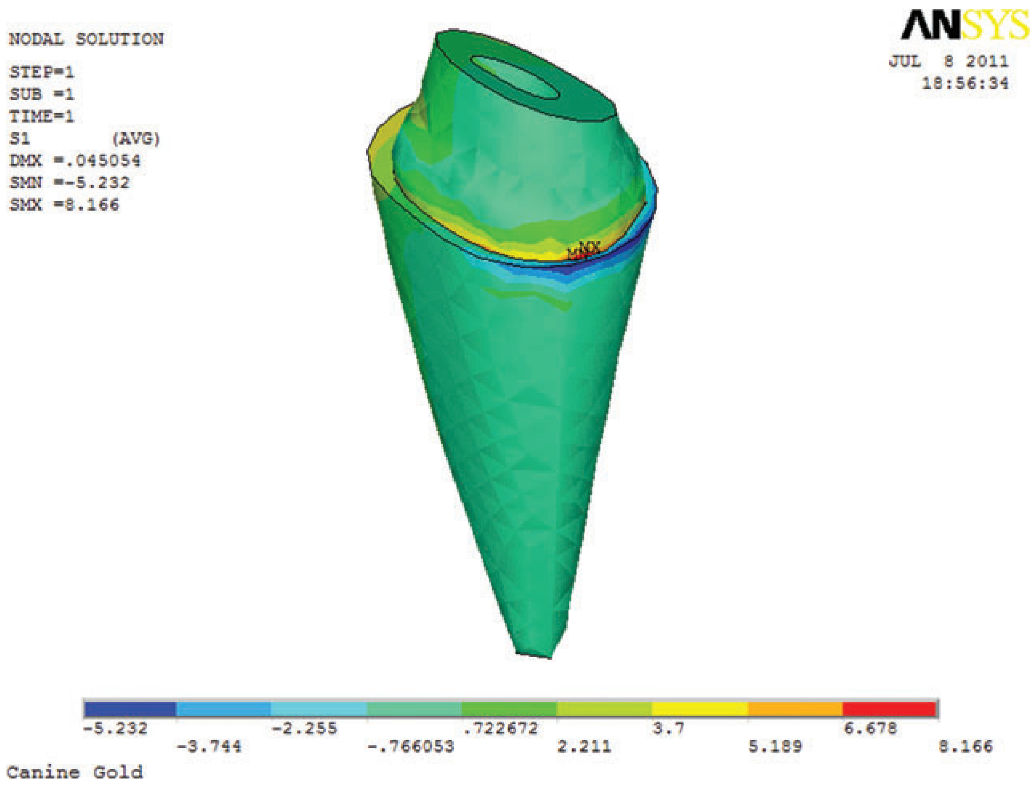


Figure 2 Root maximum tensile stress (MPa) (gold).

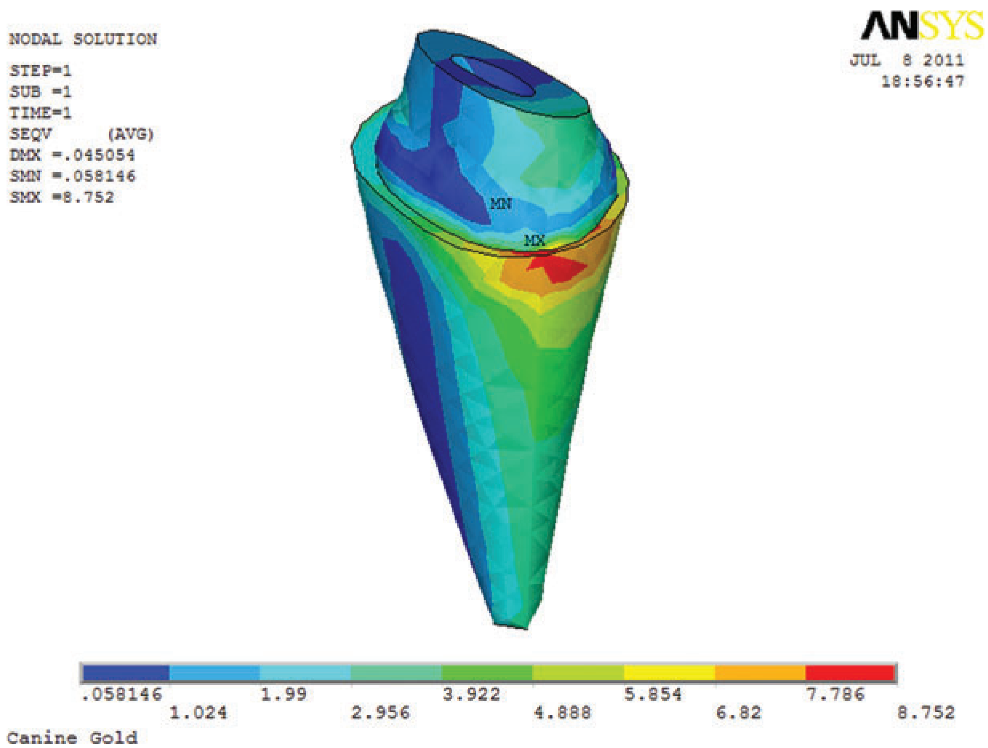


Figure 3 Root maximum Von Mises stress (MPa) (gold).

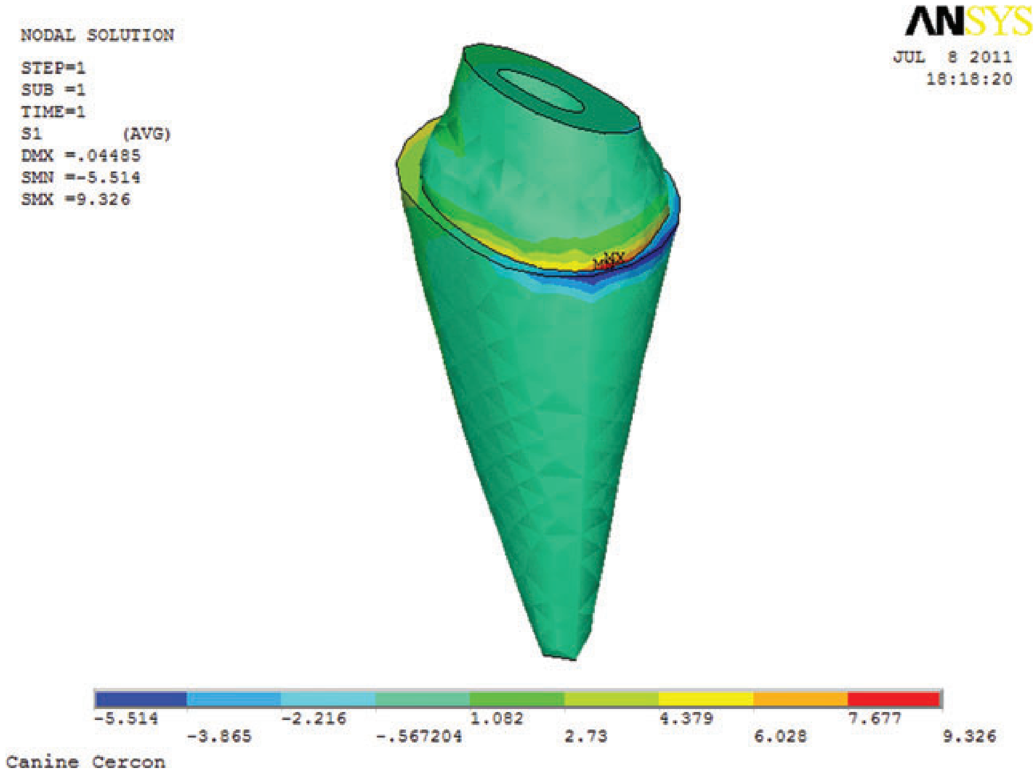


Figure 4 Root maximum tensile stress (MPa) (Cercon).

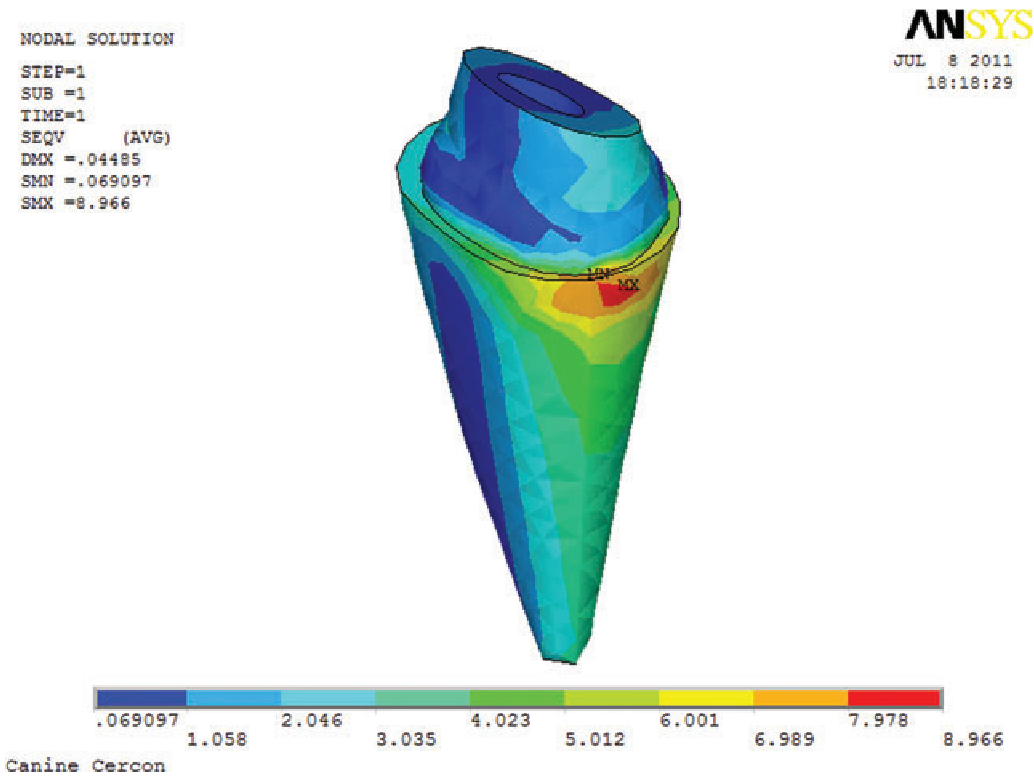


Figure 5 Root maximum Von Mises stress (MPa) (Cercon).

Table 2 Maximum stress, Von Mises stress, and displacement of different components

	Lateral movement (μm)		Maximum tensile stresses (MPa)		Maximum compressive stresses (MPa)		Maximum shear stresses (MPa)		Von Mises stresses (MPa)	
	Gold	Cercon	Gold	Cercon	Gold	Cercon	Gold	Cercon	Gold	Cercon
Root	45.1	44.9	8.166	9.326	13.69	13.621	4.8235	4.8245	8.752	8.966
Crown	55.6	55.2	88.154	74.93	215.916	207.301	99.3165	96.837	176.485	171.576
Dowel and core	53.9	53.4	23.213	19.809	91.494	96.132	43.3295	40.5255	76.78	73.083
Bone	34.3	34.3	4.87	4.827	9.279	9.237	3.0905	3.075	5.698	5.653
Periodontal ligament	34.3	34.3	0.00002	0.00002	0.00004	0.00004	0.00002	0.00002	0.000038	0.000036

The model was further justified by surrounding the dowel and core with a realistic 50-μm thick adhesive resin cement, while in the literature, a reported cement film thickness as high as 41.7 μm for Bis-GMA resin cement[49] and above 25 μm for more recent cements was used.[50] Whether this difference in film thickness will affect the FEA study results is not known and could be a subject for future research. Leary et al speculated that the cement layer would act as a stress breaker.[51] Further, they indicated that if there was any cement present at the apex of the dowel, it might act as a detrimental effect to the cement integrity due to tensile stresses.

The cylindrical bone block has been frequently used in the analysis of similar problems.[52-55] If the bone level support diminished, the stresses in dentin were found to increase dramatically and concentrate in the small amounts of remaining dentin close to the apex.[56] Zero displacement constraints were placed on the bottom of the bone block. Such an assumption has frequently been adopted in similar studies.[53,57]

The present work assumed homogeneous and isotropic linear elastic materials as reported in similar studies.[52,53,55,58] In reality, enamel and dentin are anisotropic structures containing tubules and prisms. Although this anisotropy is at a microscopic scale, the tooth is modeled at a macroscopic scale; therefore, the isotropic consideration is a valid point.[59]

Material properties greatly influence the stress distribution in the analyzed system. The modulus of elasticity and Poisson's ratio used in the present work for the material of each analyzed region were extracted from documented sources.[60-63]

In the present analysis, the canine was subjected to a concentrated force with a reference magnitude of 100 N, which was not guaranteed as an actual magnitude of the biting force experienced by that tooth. Mastication involves repeated cyclic impacts. Further, bite force studies indicated considerable variations from one area of the mouth to another and from one individual to the next, and the variation may be related to many factors such as muscle size, bone shape, sex, age, degree of edentulism, and parafunction; however, the assumption of a concentrated force with a certain magnitude is satisfactory to achieve the comparison objective of the present elastic FEA. The present analysis further recognized the importance of not considering only axial forces and horizontal forces but also combined oblique forces, since the latter represents more realistic mastication.[57] The selection of the mid-lingual area as a load application site is realistic for the canine.[52-55] The mesh of the analyzed system was consistently refined to the level of obtaining a suitably converged analysis with a tolerance of less than 1% in terms of elastic strain energy.

In this FEA study, a ferrule effect was designed in the tooth preparation. Teeth with cast dowels and cores have fewer root fractures and better fracture resistance if a sufficient ferrule effect is included in preparation design.[19-30] Eraslan et al reported that von Mises stresses were reduced when ferrule design was included in the restoration of endodontically treated teeth.[64] In comparison, one FEA study showed that stresses accumulate within the cast dowel system and that the transmission of stress to supporting teeth and tissues is low, although no ferrule design was included in the FEA model.[53] The current study shows favorable stress distribution that can be attributed to the use of the ferrule effect principle in the preparation design.

Yaman et al, in a 3D FEA, compared different combinations of prefabricated dowel and core materials to cast gold dowels and cores. They found that the cast dowels and cores yielded the best results; they had lower stress values than the prefabricated dowels and cores.[65] The current study also demonstrates that the new ceramic dowel and core have a similar stress distribution to the cast gold dowel and core.

Esthetic dowels and cores are made to improve the esthetic and optical qualities of overlying ceramic crowns. Most of the alloys used for cast dowels and cores are often dark in color, and they often produce dark shadows around the gingival third of the ceramic crown and marginal gingiva covering the root. These results can compromise the final esthetic outcome of the crown. Using yellow alloys was suggested to give a warm, yellowish hue of gold under the ceramic crown. This may produce better esthetic outcomes.[66-68] Custom-made zirconia CAD/CAM dowels and cores offer an esthetic alternative to the metallic dowel and core.[45] The zirconia dowels and cores have a white and ivory color that serves as a better background for the translucent ceramic crowns, producing a better esthetic outcome.

Cast gold dowel and cores have superior mechanical properties and are rich in yellow color and produce good esthetic results;[66,68] however, they are expensive. Although prefabricated dowels and composite cores are easier to apply and practical to use, they have porous characteristics that cause the materials to absorb water and expand.[65,69,70] The composite cores also have

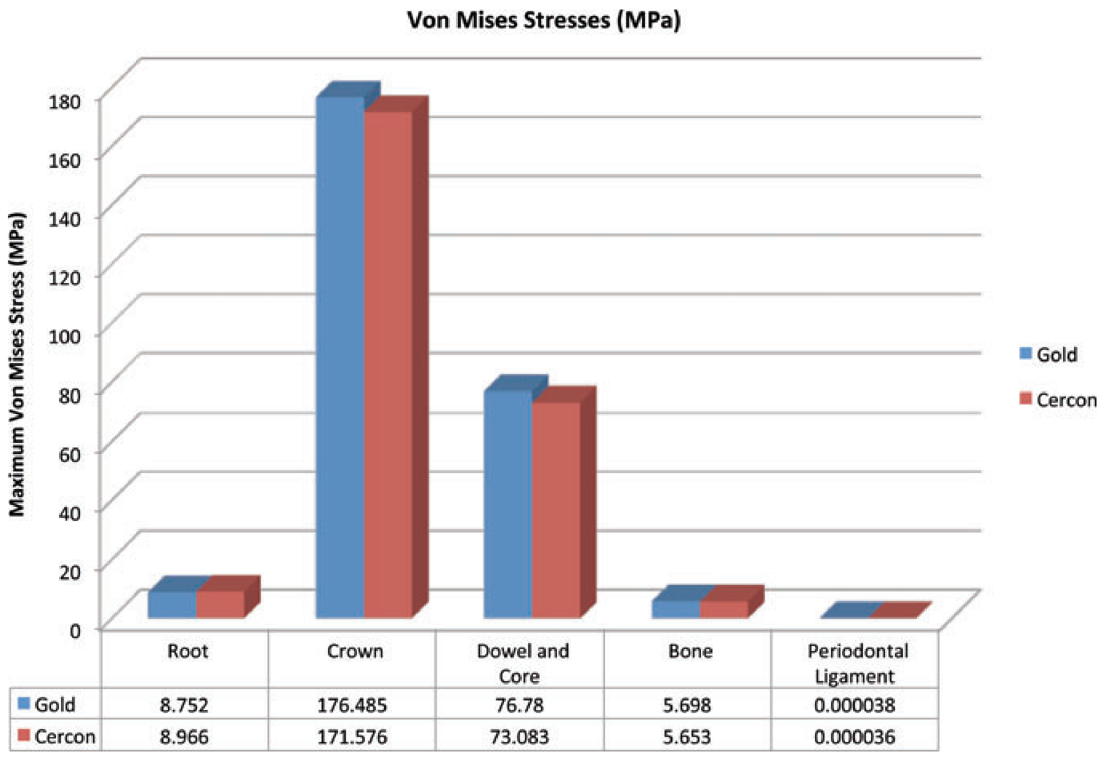


Figure 6 Von Mises stresses (MPa).

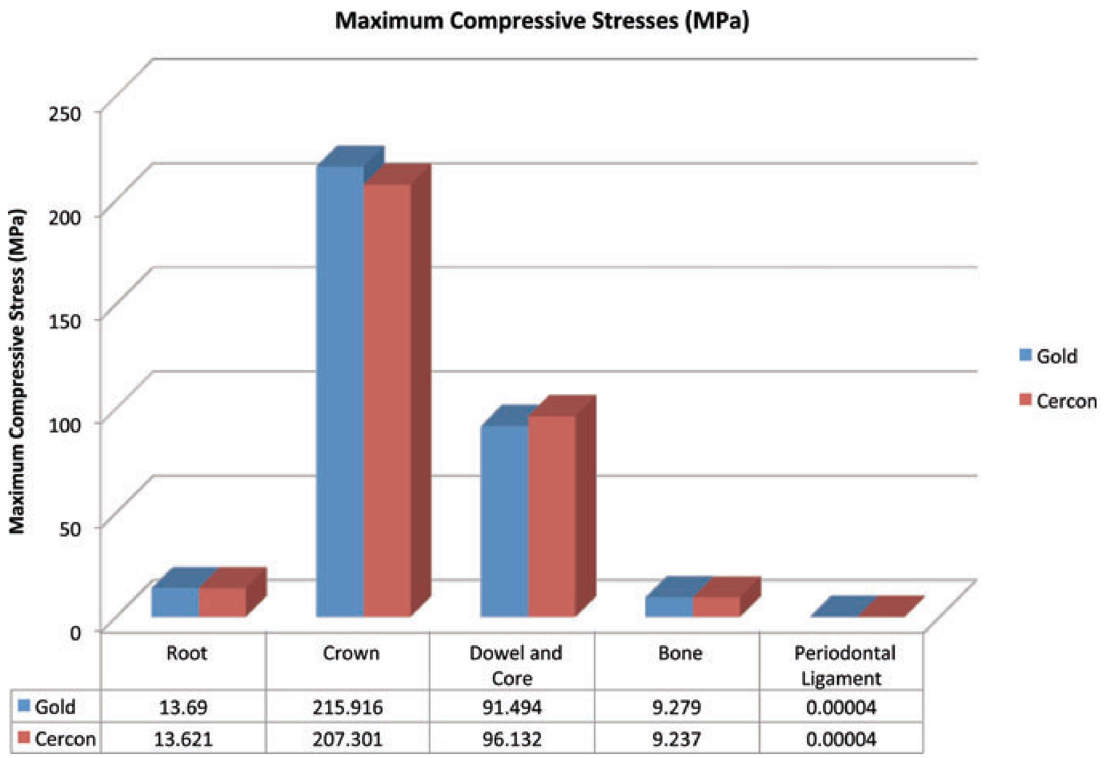
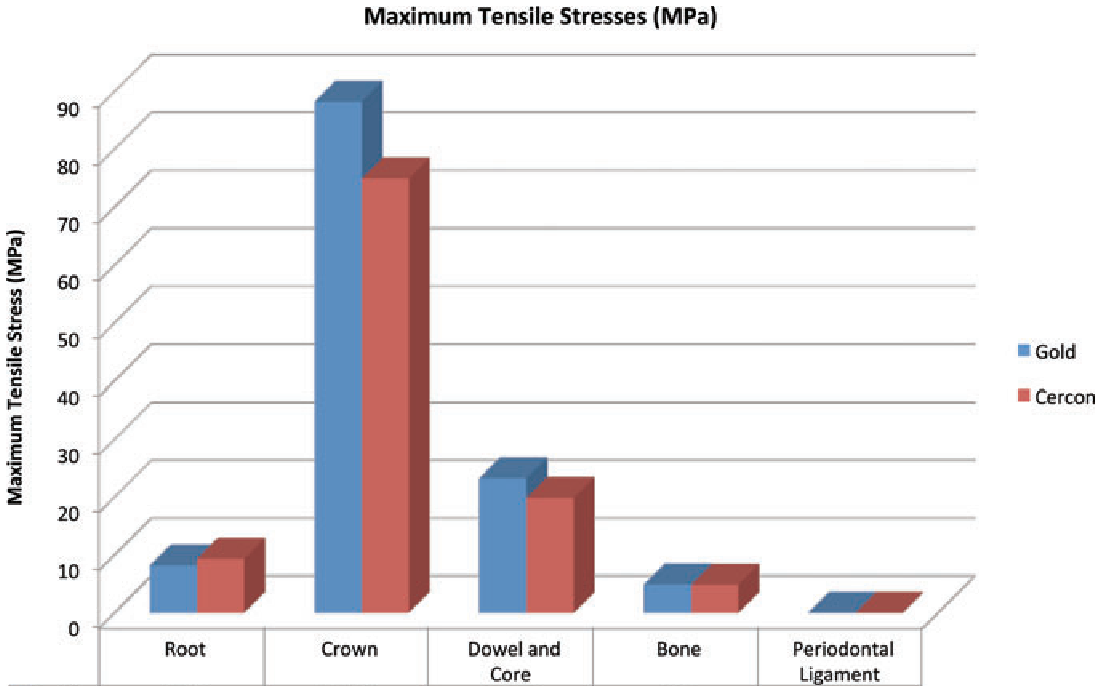


Figure 7 Maximum compressive stresses (MPa).



	Root	Crown	Dowel and Core	Bone	Periodontal Ligament
Gold	8.166	88.154	23.213	4.87	0.00002
Cercon	9.326	74.93	19.809	4.827	0.00002

Figure 8 Maximum tensile stresses (MPa).

less structural durability. Prefabricated dowels do not take into account the individual shape of the root canal, and their adaptation to the canal is not ideal.[71] Dowel adaptation is important for successful dowel and core systems.[71-75] The new ceramic dowel system offers better adaptation to the root canal.

The problem with having a flexible material such as a fiber dowel and composite core is that it will flex to various degrees when subjected to eccentric forces. A continued application of force can lead to either debonding at the interface and/or microleakage, resulting in recurrence of caries; the dowel and core can also loosen and cause the restoration to fail. Loosening of either carbon and glass fiber-reinforced epoxy resin dowels have been reported in several studies,[76-87] whereas dowel loosening was not reported in several other studies.[76,82,88-92]

One of the problems of the zirconia dowel and core is its retrievability in case of failure. The authors suggest the use of a nonadhesive cement, like zinc phosphate cement, for two reasons. One reason is that the bond of adhesive cements to zirconia is an issue, and the other is that the use of zinc phosphate cement would allow the safe removal of the dowel using ultrasonic instruments used to remove broken dowels.

Flaws in the dowel materials and the supporting tooth and tissue structures were not considered in the FEA modeling. This study helps to visualize and quantify stress distribution regarding selected strain levels and directions without the influence of other variables present in the biological materials.

Many studies using experimental and theoretical techniques have focused on stress distribution.[53,64,65,93-98] However, the comparison of these studies is difficult due to the lack of load value standardization. A thorough search in the literature concluded that no relevant 3D FEA results on the present analyzed system exist for comparison. The only data found were in several studies[95,99-101] in which other dowel and core systems were investigated, and in one study a new composite dowel was investigated. Only one in vitro study compared a one-piece milled zirconia dowel with cast gold dowel and core and showed no significant difference between the two systems.[102] Clinical validation of the present numerical analysis is one of the objectives of future research.

Conclusions

Within the limitations of the study it can be concluded that there were no significant differences in the maximum stresses in most of the regions for both models. Thus, the present work validates the use of CAD/CAM zirconia material as a dowel and core similar to gold.

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