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3D finite element model based on CT images of tooth: a simplified method of modeling

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Aim: This study aimed the description of a protocol to acquire a 3D finite element (FE) model of a human maxillary central incisor tooth restored with ceramic crowns with enhanced geometric detail through an easy-to-use and low-cost concept and validate it through finite element analysis (FEA). **Methods:** A human maxillary central incisor was digitalized using a Cone Beam Computer Tomography (CBCT) scanner. The resulted tooth CBCT DICOM files were imported into a free medical imaging software (Invesalius) for 3D surface/geometric reconstruction in stereolithographic file format (STL). The STL file was exported to a computer-aided-design (CAD) software (SolidWorks), converted into a 3D solid model and edited to simulate different materials for full crown restorations. The obtained model was exported into a FEA software to evaluate the influence of different core materials (zirconia - Zr, lithium disilicate - Ds or palladium/silver - Ps) on the mechanical behavior of the restorations under a 100 N applied to the palatal surface at 135 degrees to the long axis of the tooth, followed by a load of 25.5 N perpendicular to the incisal edge of the crown. The quantitative and qualitative analysis of maximum principal stress (ceramic veneer) and maximum principal strain (core) were obtained. **Results:** The Zr model presented lower stress and strain concentration in the ceramic veneer and core than Ds and Ps models. For all models, the stresses were concentrated in the external surface of the veneering ceramic and strains in the internal surface of core, both near to the loading area. **Conclusion:** The described procedure is a quick, inexpensive and feasible protocol to obtain a highly detailed 3D FE model, and thus could be considered for future 3D FE analysis. The results of numerical simulation confirm that stiffer core materials result in a reduced stress concentration in ceramic veneer.

KEYWORDS: Ceramic. Dental stress analysis. Finite element analysis. Three-dimensional imaging.

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Introduction

In dentistry, the mechanical behavior of restorative materials is a determinant factor for their clinical success. Therefore, *in vitro* tests are not only important tools to determine materials properties and resistance but also to predict stresses that could lead to clinical failure [1,2]. In these in vitro studies, when specimens that precisely simulate the restoration geometry are used, the mechanical behavior might be closer to the clinical situation[3]. However, the stress and strain distribution within complex geometries is difficult to be accessed using conventional *in vitro* approaches[4].

In this context, finite element analysis (FEA) has been used successfully to investigate stress distribution in complex structures, such as restored human teeth. In the bioengineering field, the use of computer simulations is an important instrument to measure and test the best clinical option[5]. The use of FEA in dental rehabilitation improves the understanding of biomechanical behavior of different dental restoration materials and designs, and therefore the optimal approaches that are expected to provide better clinical performance[6,7]. This experimental-numerical methodology was initially developed in the early 1960s to solve structural problems in the aerospace industry, but it has since been extended to solve problems in medical sciences, including dentistry[8]. Currently, FEA is a popular method and represents a comprehensive *in silico* method in dentistry. This method allows a better understanding of the mechanical behavior of dental restorations by testing them virtually under all conceivable loading conditions, designs and materials[3].

To conduct a FEA, the start point is the construction of an accurate model, which is the key to the analysis outcome[9,10]. Several methods have been used to generate FE models of teeth, such as the use of standard anatomical data in the literature[11], manual tracing of tooth sections from histological[12] or computer tomographic (CT) images of teeth[13-16]. These conventional methods of modeling are time-consuming and often demand labor-intensive efforts and highly skilled operators. Also, they result in geometry over simplification that might induce false predictions in the FEA[3].

To overcome this problem, previous studies have used sophisticated techniques with micro-CT images associated with costly specific medical imaging software (Mimics, Materialise, Leuven, Belgium)[3,7,17,18]. The generation of highly anatomically accurate 3D models of teeth was possible with this approach, minimizing errors in the following phases[3,17,18]. Nevertheless, despite the optimal models obtained, the combination of micro-CT with costly imaging software reduce the accessibility of many researchers. In this context, public domain medical imaging software have emerged and are available for free download, allowing the free generation of 3D surface/geometric models from a sequence of 2D Dicom files acquired through a cheaper exam, such as Cone Beam Computer Tomography (CBCT). The software explored in this study is InVesalius (Renato Archer Information and Technology Center, Campinas, Brazil). The use of InVesalius in combination with a Computer Aided-design (CAD) software allows the generation of precise 3D solid models of dental geometry based on an unaltered tooth[19-21].

Thus, this study aimed the description of a protocol to acquire a 3D FE model of a human maxillary central incisor tooth restored with ceramic crowns with enhanced geometric detail through an easy to use and low-cost concept using InVesalius and a CAD software. To demonstrate the potential of its employability, the obtained 3D model was used for a FEA of the influence of different core materials (zirconia, lithium disilicate or palladium/silver) on the mechanical behavior of veneering ceramic and core of crowns.

Materials and methods

The 3D models of a crown, with different core material (zirconia - Zr, lithium disilicate – Ds, or palladium/silver - Ps), were obtained through the 3D reconstruction from the CBCT of a sound extracted human maxillary central incisor. The process required to obtain the 3D models and FEA consists on the following stages: CBCT acquisition, 3D surface/geometric reconstruction, 3D solid modeling and finally the FEA.

Tooth FE modeling from CBCT data

This study was approved by The Ethics Committee in Research of the Piracicaba Dental School – University of Campinas (register number 106/2014). First, the CBCT acquisition of an extracted central incisor in Digital Imaging Communications in Medicine (DICOM format) was performed using a KODAK 9000 3D Extraoral Imaging System (Carestream Dental LLC, Atlanta, GA, USA). The scanning parameters used were: tube voltage of 60 kV, tube current of 2 mA, and a slice thickness of 75 μm. A total of 180 slices were provided and used for the modeling.

Subsequently, the resulted tooth images in DICOM format were imported into InVesalius, for 3D surface/geometric reconstruction in solid-display stereolithographic file format (STL). In addition, this software presents segmentation functions based on image density thresholding that allows the creation of segmented models of mineralized (enamel and dentin) or non-mineralized tissues (pulp) in STL format (Figure 1).

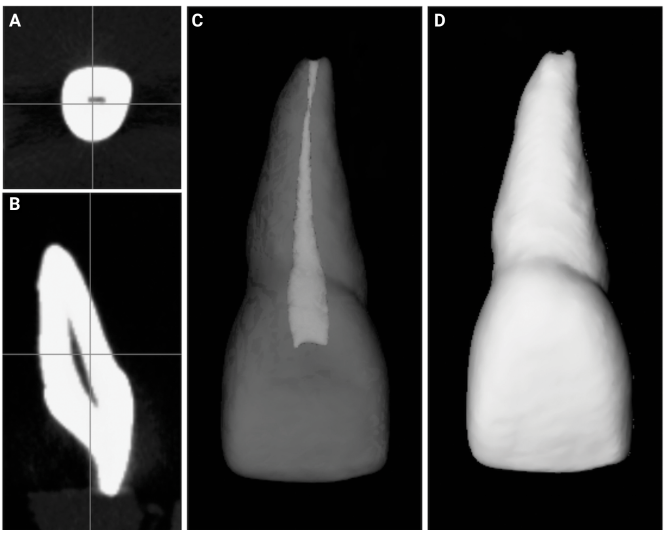

Figure 1. (A, B) CBCT data as seen in the public domain medical imaging software InVesalius. Tooth is presented in different cross-sectional views. Masks have been applied to mineralized tissues (enamel and dentin) according to the voxel density thresholding. (C, D) 3D surface model of incisor tooth in InVesalius.

Nevertheless, STL models are improper for use in FEA because of the density and quality (aspect ratio and connectivity) of the mesh[3] (Figure 2a). Moreover, using STL file prevent changes in the design or dimensions of the models, jeopardizing their use for different designs evaluation.

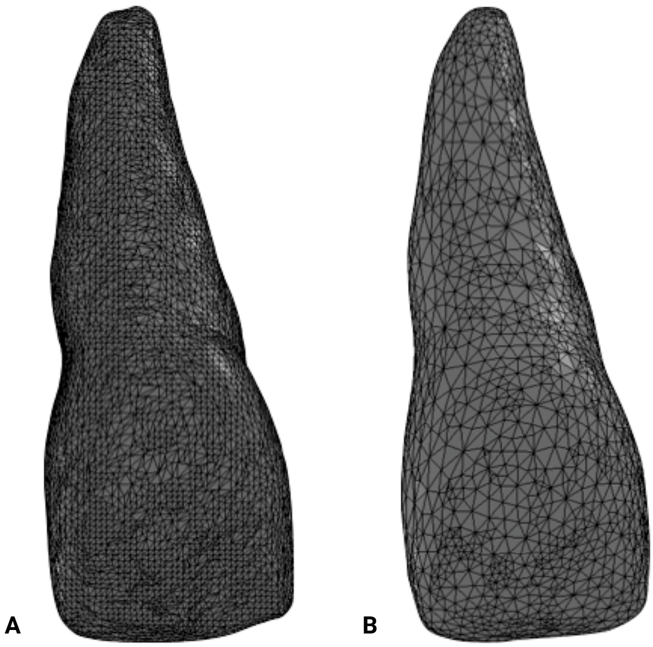

Figure 2. (A) Stereolithography triangulated (STL) file of incisor tooth obtained in InVesalius. (B) Incisor tooth STL file optimized for FEA using Mesh Prep Wizard within the CAD software SolidWorks.

For this reason, the 3D reconstructed surface of the tooth in STL format were exported to a CAD software (SolidWorks 2011, Concord, MA, USA) through its scan-to-cad plugin function (ScanTo3D). In SolidWorks software, the file was opened as mesh files (STL) and converted into a 3D solid model of a maxillary central incisor with the aid of Mesh Prep Wizard and Surface Wizard built-in tools. These tools allowed the simplification of the mesh (reduction of the number of triangles) and surface smoothing, improving the final mesh quality while the original model geometry is maintained (Figure 2b). Once the solid model is obtained and its surface smoothened, the tooth was edited by conventional CAD modeling in SolidWorks, in order to simulate complete crowns supported by tooth. For this, the tooth crown was circumferentially reduced by 2.0 mm mesiodistally and buccolingually and 3.0 mm incisally. The veneering ceramic and core (2.0 mm and 0.4 mm of thickness, respectively) were created using Boolean operations (addition, intersection or subtraction of volumes). The cementation of the crown was simulated using a resin cement (Panavia F2.0, Kuraray, Tokyo, Japan) with a 0.09 mm thick layer (Figure 3). Additionally, the root with its periodontal ligament (0.25 mm thick) was embedded in an acrylic resin cylinder, simulating the conditions of *in vitro* studies[22].

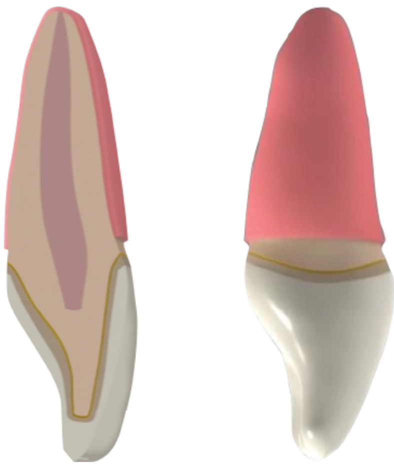

Figure 3. Tooth model with restorative crown (veneering ceramic and core), cement layer, dentin, dental pulp and periodontal ligament.

Finally, the optimized 3D solid models of the segmented tooth (dentin and pulp), restorative crown (veneering ceramic and core), resin cement layer, periodontal ligament, and cylinder support were assembled and imported into a FEA software (Ansys Workbench 13.0, Swanson Analysis Inc., Houston, USA) for the generation of a volumetric mesh, attribution of material properties, and mathematical solution (FEA) (Figure 4a). All structures were considered linearly elastic, isotropic and homogeneous. The mechanical properties of enamel[23], dentin[24], pulp[12], periodontal ligament[25], ceramic veneer[12], lithium disilicate[26], zirconia[27], palladium-silver[28], resin cement[29] and polystyrene resin[22] were taken from literature and are listed in Table 1. The mesh was generated with tetrahedral elements of 0.8 mm after a convergence analysis (5%). As a result, the models presented a number of elements and nodes of 15,378 and 29,303, respectively.

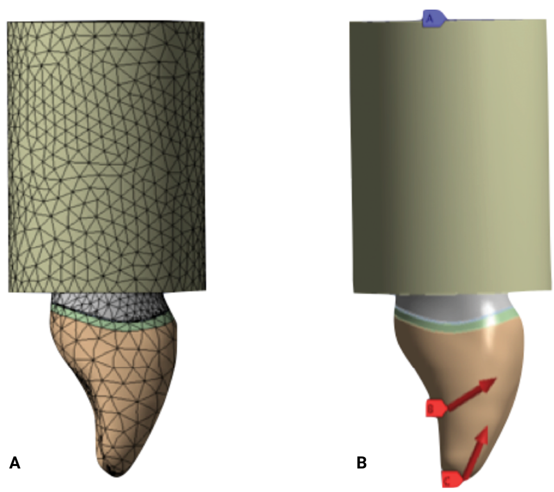

Figure 4. (A) Model with tetrahedral element of 0.8 mm. (B) Loading was performed in 2 steps: oblique load (135 degrees) of 100 N was applied to incisal third of lingual crown, and 25.5 N was applied perpendicularly to incisor crown.

Table 1. Mechanical properties of the materials included in finite element analysis.

Material	Yield Strength (GPa)	Poisson's ratio
Enamel	80	0.33
Dentin	20	0.31
Pulp	0.002	0.45
Periodontal ligament	0.0689	0.45
Ceramic Veneer	70	0.30
Litium-Disilicate	95	0.30
Zirconia	205	0.22
Palladium-Silver	95	0.33
Resin Cement	18.3	0.33
Polystyrene resin	13.5	0.31

Boundary and loading conditions

Fixed zero-displacement in the three spatial dimensions was assigned to the nodes at the bottom surface of the cylinder support. The tooth and restorative materials were considered perfectly bonded. The crowns were loaded with 100 N applied to the palatal surface at 135 degrees to the long axis of the tooth[22], followed by a load of 25.5 N perpendicular to the incisal edge of the crown[19] (Figure 4b). The maximum principal stress for the veneering ceramic and the maximum principal strain for the core were obtained as dependent variables for both quantitative and qualitative (color-coded) comparisons.

Results

The Zr model presented the lowest stress concentration in the ceramic veneer. The maximum principal stress (σ_{max}) peak was higher in Ds and Ps models (24.728 MPa and 24.711 MPa, respectively), than in Zr (23.395 MPa) even though the differences between the lowest and the highest was an increase of 5.69%. For all models, the stresses were predominantly concentrated on the external surface of the veneering ceramic, surrounding the loading area. The qualitative analysis suggests that the compression load, generated by the force application, resulted in tensile stresses also on the buccal surface and cervical area (interface with the core) (Figure 5a).

When comparing different core materials, those with lower elastic modulus presented higher values of maximum principal strain, which concentrated in the area directly below the loading site (Figure 5b). These values were 0.4 μm for Zr and 0.7 μm for Ds and Ps models. There was an increase of 75% in strain between the lowest to the highest models.

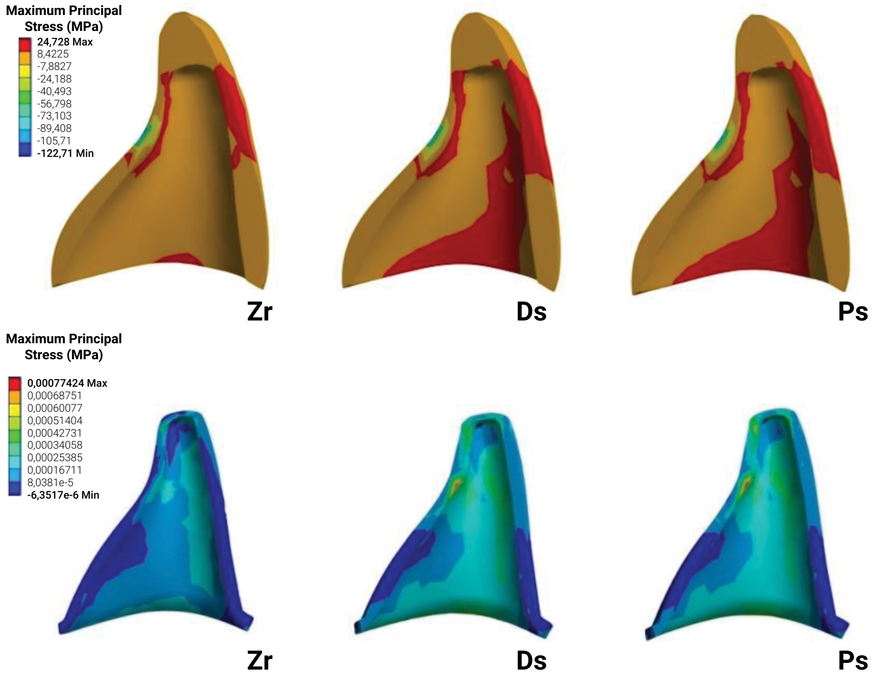

Figure 5. (A) Maximum Principal Stress in ceramic veneer and (B) Maximum Principal Strain in core of Zr, Ds and Ps groups, respectively.

Discussion

FEA represents a powerful tool to understand the mechanical behavior of all-ceramic crowns[17]. However, the analysis might be limited by difficulties related to model generation. Teeth and dental restorations are difficult to model because of their complex anatomical shape and layered structure[30]. Therefore, many studies used simplified 2D models for specific problems in dentistry, underestimating the influence of the complex geometry in the stress and strain distribution. Although 2D models are simpler and easier to be constructed compared to 3D models, the biaxial state of 2D models may compromise the results reliability as it does not take into consideration some important biomechanical aspects clinically observed[31]. Therefore, a 3D simulation should net be simplified when investigating the biomechanics of dental restorations[32].

To overcome this problem, the present study described an easy to use and low-cost modeling technique for the generation of an accurate 3D model of a maxillary central incisor using CBCT images associated with a public domain medical imaging software, InVesalius. This method is simpler when compared to other methods used in previous studies[11-13], as it consists of going through few semi-automatic steps. Furthermore, the use of public and free medical imaging software to generate 3D models from CT/CBCT images might extend access to more researches in the biomechanical field, contributing to a better understanding of restorations' mechanical behavior and consequently improving their clinical performance. Previous studies used similar approaches with micro-CT images and another interactive medical image control software (Mimics 9.0, Materialise, Leuven, Belgium), also obtaining highly detailed and accurate 3D models of dental structures or restorations[3,17,18], with the disadvantage of higher costs.

Particularly in this study, CBCT images were used instead of micro-CT images once the latter is not suitable for human teeth in live patients, which prevents the generation of instant patient-specific models for more realistic simulations. Although CBCT images of an extracted sound incisor tooth were used for generating the FE model, a similar approach could be also performed using CBCT images from living individuals in other studies. Additionally, the Kodak 9000 3D CT scanner was chosen because it provides a sub-millimeter isotropic voxel resolution that is the closest to that given by some microscale CT scanners[33]. Despite the advantages of CBCT, when this technique is applied to small structures like teeth (with thin anatomical details such as the enamel shell) it does not allow the fine control of internal boundaries (e.g. dentin-enamel junction), raising difficulties in the generation of precise 3D segmented models of enamel and dentin. It is expected that the rapid development of more precise dental CBCT scanners, computer processing power, and interface friendliness will make this approach even faster, more accurate and fully automated in the near future[3].

FEA was performed to demonstrate the applicability of the 3D FE model generated in this study. In this analysis, it was evaluated the influence of different core materials (zirconia, lithium disilicate or palladium/silver) on the mechanical behavior of the weak link of modern esthetic indirect restorations, the veneering ceramic. The introduction of zirconia and lithium disilicate as core materials makes possible to produce long-lasting all-ceramic restorations with improved esthetics with less invasiveness when compared to conventional metal-ceramic restorations. However, the stresses in the veneering ceramic could jeopardize the longevity of these bilayer ceramic restorations[34], once ceramic chipping has been reported as the most frequent failure[35]. According to the results of this *in silico* simulation, the Zr model presented lower stress concentration in veneering ceramic than Ds and Ps models. This result can be attributed to lower deformation of zirconia core, once that hard and stiff ceramic cores effectively prevents the flexure of veneering ceramic[36], decreasing the stress in this structure and consequently its risk of fracture[37].

Despite the Zr model presents the best biomechanical behavior, the other materials evaluated (Ds and Ps) also showed stress values in the veneering ceramic below the critical values described for its fracture(31-38 MPa)[38]. However, it is worthwhile to mention that clinically, zirconia restorations can fracture under low-stress values and more frequently than metal-ceramic restorations due to poor bonding on the veneer-zirconia interface[39]. Hence, future studies considering also the influence of ceramic-ceramic bonding conditions are necessary.

Besides, despite the effort on improving of reality of the present simulation, it is important to emphasize that the FEA models still present limitations when compared to the clinical conditions, as the materials were considered homogeneous, isotropic and with a linear elastic behavior. Disadvantages of FEA are known as incorrect information about mechanical properties, statistics applied to the results, and interpretation will yield misguiding results. Also, researches need to have minimum computer knowledge and information about the mechanical behavior of human models.(5)

In conclusion, the described protocol consists on a low-cost, fast and efficient method to obtain a highly detailed 3D FE model of a maxillary central incisor restored with full crowns. The numerical simulation outcomes confirm that stiffer core materials result in a reduced stress concentration in the veneering ceramic.

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