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2D and 3D finite element analysis of central incisor generated by computerized tomography

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ABSTRACT

The purpose of this study was to compare the results of different hierarchical models in engineering analysis applied to dentistry with 2D and 3D models of a tooth and its supporting structures under 100 N occlusal loading at 45° and examine the reliability of simplified 2D models in dental research. Five models were built from computed-tomography scans: four 2D models with Plane Strain and Plane Stress State with linear triangular and quadratic quadrilateral elements and one 3D model. The finite element results indicated that the stress distribution was similar qualitatively in all models but the stress magnitude was quite different. It was concluded that 2D models are acceptable when investigating the biomechanical behavior of upper central incisor qualitatively. However, quantitative stress analysis is less reliable in 2D-finite element analysis, because 2D models overestimate the results and do not represent the complex anatomical configuration of dental structures. Therefore 3D finite element analyses of dental biomechanics cannot be simplified.

1. Introduction

The decision to use two-dimensional (2D) or three-dimensional (3D) models to investigate the biomechanical behavior of complex structures, by Finite Element (FE) Method, depends on many inter-related factors, such as the complexity of the geometry, material properties, mode of analysis, the required accuracy and the applicability of general findings and finally time and costs involved. In deciding which method to use, it is important to understand the advantages and limitations of both approaches [1].

The 2D modelling has been extensively used in dental research and was employed by many authors [2–4] due to its simplicity and it being a more effective method, relative to time and cost. Although 2D models are simpler, easier to build and less time consuming compared to the 3D model, they do not represent the complexity of the real problem and suffer several inherited limitations.

In contrast, 3D modelling has several advantages such as, better visualization of internal areas, though the 3D models require a mesh refinement, more complex analysis and full assessments which yield accurate results at greater computational cost.

The advantages of employing 3D models should be carefully weighed against the disadvantages of creating complex geometry with appropriate mesh density. Hence the more sensitive the technique is to the scan environment, the less accurate and reliable the geometry and subsequently the analyses are [5].

Khera et al. were the pioneers in the utilization of 3D models [6]. The models were obtained from sectional images of

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human mandible. Initially, a 2D model was built and, with the projection of several pictures in a magnifying monitor, a 3D model was built from the generation of a millimetric thickness and the definition of an axial z-axis. Ho et al. also constructed models in this same way, from pictures of an upper central incisor transversely sectioned [7]. Ricks-Williamson et al., with the purpose of constructing a 3D model, embedded a tooth in resin and sectioned it into thin slices perpendicularly to its longitudinal axis, with every section photographed and digitalized [8]. Other authors like Yaman et al., Lanza et al., and Zarone et al. utilized averaged teeth dimensions, obtained from the literature, to generate 3D dental model [9–11].

However, the time that was spent on these studies, during the resin embedding and slice sectioning procedures, is no longer necessary with the use of a technique that has recently gained general consensus among researchers which is the computerized tomography (CT) for 3D models creation [12].

Aside from the mathematical models that can be used, another frequent doubt arises when establishing what element type should be used, according to the problem at hand. Thus, in FE analysis choosing the appropriate mathematical model, the element type and the degree of discretization are important to turn it efficient as well as time and cost effective [13].

The purpose of this study was to compare the differences from hierarchical models in engineering analysis applied to 2D and 3D dental models for the assessment of the biomechanical behavior of a sound upper central incisor and its supporting structures under 100N occlusal loading at 45° by using finite element analysis (FEA).

2. Materials and methods

Computerized tomography (CT) image acquisition in DICOM (Digital Imaging Communications in Medicine) format was performed with a GE HiSpeed NX/i CT scanner (HiSpeed NX/I, General Electric, Denver, CO, USA) using several physical and geometrical parameters within safety limits (Protocol of the Committee of Ethics in Research of the Medicine University/Academical Hospital Antonio Pedro CEP CMM/HUP no. 213/05). The ones that yielded the best results, with respect to image quality, were obtained in the regime of 120 kV, 150 mA, 512 × 512 matrix, field of view 14 cm × 14 cm and slice thickness of 0.5 mm.

Initially, the CT images obtained from patient imaging, 165 cross sections and 123 coronal sections, were imported into Mimics/MedCAD 8.0 (Materialise, Leuven, Belgium). From this point, the segmentation process that consists of the separation an object from other adjacent anatomical structures in different groups or masks, such as enamel, dentin, pulp, cortical and spongious bone, was started. According to its radio-density, expressed in Hounsfield unities, and location, the structures were segmented (Fig. 1a).

The pulp, enamel and dentin isocurves of maxillary central incisor were imported into the MSC/PATRAN 2005 program (MSC Software Corporation, Santa Ana, CA, USA) (Fig. 1b). The upper central incisor was defined as the model for analysis and a 0.25 mm-thick periodontal ligament [14] was created from the dentin isocurves as it was impossible to generate the image of this structure from the CT images. After that, the cortical and spongious bones were also imported with the same methodology.

From the isocurves of the anatomic structures, the surfaces of each object were generated. Fig. 2a illustrates the surfaces of the complete 3D model and Fig. 2b shows the surfaces of the 2D model which was extracted from the middle plane of the 3D model (buccal–lingual section). The anatomic structures that compose the central incisor were segmented into different groups, according to Rees et al. [15], for the application of their respective mechanical properties.

2.1. Analyzed models

2.1.1. 2D FEA

The 2D FEA was performed through two Formulations, Plane Strain (STRAIN) and Plane Stress (STRESS) State. Besides the constitutive difference in the 2D models, two mesh alternatives were also applied in the STRAIN and STRESS models, one with a linear triangular element (CTRIA3) and another with a quadratic quadrilateral element (CQUAD8). These elements differ mainly in their geometry, number of connections between points in the mesh and number of integration points.

The CQUAD8 element is of a higher order and uses intermediate nodes in addition to those in the vertex, but it is not used as frequently. Such intermediate nodes increase element precision but it becomes more difficult to create a mesh in structures with irregular shape, due to its quadrilateral geometry. However, the majority of users prefer the triangular element (collapsing quadrilateral element), especially in mesh transition or when modelling parts of a structure the quadrilateral elements are impracticable.

For the 2D models with CTRIA3 elements, 9259 nodes and 18,038 elements were generated while for the CQUAD8 mesh, 24,868 nodes and 8129 elements were generated using element edge length of 0.2 mm for both element types.

In STRESS model, the thicknesses of the anatomic structures, pulp, dentin, enamel, cortical and spongious bones, and periodontal ligament, were 1.5, 4.0, 1.2, 10.0 and 0.5 mm, respectively. These values were measured in the 3D model at the bone level for pulp, dentin and cortical bone while the enamel, periodontal ligament and spongious bone thicknesses remained relatively constant.

2.1.2. 3D FEA

Due to the complexity of the geometry analyzed, a tetrahedral linear element (CTETRA) was adopted in order to minimize distorted elements and avoid compromising the geometry discretization of the structures included. CTETRA is an element of four surfaces with 4 nodes and shaped like a pyramid, used mainly for mesh transition and areas where the hexagonal elements are distorted.

Starting from the dental structure surfaces built (Fig. 2a) the superficial meshes were generated with linear triangular element (Tri3) with an edge size of 0.01 mm in regions where the curvature was high, that had a small size or within transition zones between structures like, for instance, the pulp base. In regions of low curvature, great size or distant from transition zones such as, for instance, the distal and mesial regions of the cortical bone, the edge size was of 0.05 mm. This pro-