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

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\textbf{A B S T R A C T}

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 100N 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.

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\section{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 inherent 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 spongy 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 spongy 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 spongy 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 spongy 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 (TH3) 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-
procedure was adopted to assure a perfect discretization of the structures.

After the generation of a surface mesh for every structure, a volumetric mesh with tetrahedral elements was generated. The elements used in the volumetric mesh had edge size ranging from 0.01 to 0.05 mm, which is compatible with the procedure described previously.

However, in the creation of the volumetric meshes it was necessary to generate first the small dimension or the innermost meshes, and from these to proceed to generate the larger or the more external meshes, following the procedures in Poiate et al. [16].

The degree of discretization of the model was established from convergence studies of the results in computer modelling (Pentium 4 3.2 GHz computer with 2.0 GB RAM memory) to ensure that a proper FE model mesh density was generated. The converged model included 43,934 nodes and 331,887 elements.

### 2.2. Load, boundary conditions and properties

In order to determine the exact location of load application in the models, the maximum intercuspal occlusal contact point on upper central incisor was determined in a volunteer using articulating paper (Fig. 3). This area (0.6 mm × 1.2 mm) was subsequently digitized and its coordinates mapped, by means of a program especially developed for this purpose.

In the 2D models, an occlusal load equally divided onto 4 nodes and 7 nodes of the CTRIA3 and CQUAD8 elements, respectively (Fig. 4a and b), and in the 3D model, 12 nodes were...
used (Fig. 4c). The load intensity of 100 N applied to the upper central incisor [4,17,18] is most-frequently recommended at an angle of 45° to the longitudinal axis of the tooth [2].

In order to better simulate real clinical conditions, the nasal lamina of the incisor (Fig. 4) was considered to be constraint for all models. However, since the model only represented the upper central incisor, “springs” with fixed ends were inserted in the mesial and distal extremities of the nodes in the cortical and spongious bones of the 3D model (Fig. 4c). The purpose of these springs was to represent an equivalent stiffness to the
remaining structures (truncation model), thus reproducing the reactions generated by the remaining structures [16,19].

All the structures in the models were assumed to be homogeneous, isotropic and display linear elastic behavior as characterized by two physical properties, Young's modulus (E) and Poisson’s ratio (ν) (Table 1). The interfaces between the structures were perfectly united, as the aim was to provide a comparison to our approach.

To guide the biomechanical behavior assessment in the hierarchical modelling the comparison of the results was undertaken in four main regions, circled in Fig. 4b, and considered critical to analysis of the tooth. The regions indicate materials with different mechanical properties and high-stress areas, due to the load and boundary conditions of the problem.

The solution of all analyses was obtained using MSC/NASTRAN 2005 software (MSC Software Corporation, Santa Ana, CA, USA). The pre and post-processing, visualization, and evaluation of the results were performed with MSC/PATRAN 2005 software.

3. Results

The results of the stress distribution of the maximum principal stress are plotted in Figs. 5 and 6. On the right of Figs. 5 and 6 a color scale is displayed, in which each color represents a stress value interval given in MPa unit, the positive value is tensile and negative is compression.

Fig. 5a and b illustrates the results for the 2D/STRAIN models with element CTRIA3 and CQUAD8, respectively. Fig. 5c and d illustrates the results for the 2D/STRESS models with element CTRIA3 and CQUAD8, respectively. Fig. 6a (buccal) and b (palatal) illustrates the results in a panoramic view for 3D model, while Fig. 6c shows the results in the analyzed slice used in the 2D models.

Table 2 shows the maximal principal stress results at regions 1–4 for the analyzed models.

In the dentin root (region 2) there is a tensile stress concentration, the maximum being 64.1 MPa in 2D/STRAIN/CQUAD8 model (Fig. 5b) followed by 33.8 MPa in 2D/STRESS/CQUAD8 model (Fig. 5d), 32 MPa in 2D/STRESS/CTRIA3 model (Fig. 5a), 17 MPa in 2D/STRESS/CTRIA3 model (Fig. 5c) and 4 MPa in the 3D model (Fig. 6c).

It is important to observe that there is a higher tensile stress concentration at a larger area in the cervical dentin (region 3). These stresses can be explained by the proximity of the region to the bone crest, which functions as a fulcrum defined by the load applied to the palatine surface of the incisor modelled. In the lingual cement–enamel junction (CEJ) there is a concentration of tensile stresses, the maximum being 173 MPa in 2D/STRAIN/CQUAD8 model (Fig. 5b) followed by 112 MPa in 2D/STRAIN/CTRIA3 model (Fig. 5a), 68.5 MPa in 2D/STRESS/CQUAD8 model (Fig. 5d), 57.1 MPa in 2D/STRESS/CTRIA3 model (Fig. 5c) and ranging from 5 to 17.6 MPa in a small mesial-to-distal band in the 3D model (Fig. 6b).

Under the area where the load was applied (region 4) there is a higher compressive stress concentration, the minimum being −154 MPa in 2D/STRAIN/CQUAD8 model (Fig. 5b) followed by −127 MPa in 2D/STRAIN/CTRIA3 model (Fig. 5a), −123 MPa in 2D/STRESS/CQUAD8 model (Fig. 5d), −103 MPa in 2D/STRESS/CTRIA3 model (Fig. 5c) and −33 MPa in the 3D model (Fig. 6b and c). The compressive stresses were point-like and dissipated radially from the load application area.

4. Discussion

Studies examining the biomechanical behavior of oral structures require sophisticated simulations of the fundamentals of the stomatognatic system. Such analyses are critical to learn how these elements function jointly, to provide an insight into the biomechanical behavior of dental restorative treatments and to optimize future clinical outcomes. These studies frequently involve modelling of masticatory forces which might be simulated and examined by using FE Method in 2D or 3D models [16].

The decision to employ 2D or 3D modelling to investigate the biomechanics of the biological structures depends on many inter-related factors, such as the complexity of the geometry, the mechanical properties, the analysis type, time and cost involved, the required accuracy and the

Table 1 – Mechanical properties and reference of the anatomical structures.

<table>
<thead>
<tr>
<th>Anatomical structures</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson’s ratio</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulp</td>
<td>0.02</td>
<td>0.45</td>
<td>[20]</td>
</tr>
<tr>
<td>Dentin</td>
<td>18.6</td>
<td>0.31</td>
<td>[21]</td>
</tr>
<tr>
<td>Enamel</td>
<td>41.0</td>
<td>0.30</td>
<td>[21]</td>
</tr>
<tr>
<td>Spongy bone</td>
<td>1.37</td>
<td>0.30</td>
<td>[21]</td>
</tr>
<tr>
<td>Cortical bone</td>
<td>13.7</td>
<td>0.30</td>
<td>[21]</td>
</tr>
<tr>
<td>Periodontal ligament</td>
<td>0.0689</td>
<td>0.45</td>
<td>[22]</td>
</tr>
</tbody>
</table>

Table 2 – Maximum principal stress (MPa) results at regions 1–4 in a 2D and 3D models.

<table>
<thead>
<tr>
<th>Region</th>
<th>2D STRAIN</th>
<th>3D STRAIN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CTRIA3</td>
<td>CQUAD8</td>
</tr>
<tr>
<td>1</td>
<td>−21</td>
<td>−8.7</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>64.1</td>
</tr>
<tr>
<td>3</td>
<td>112</td>
<td>173</td>
</tr>
<tr>
<td>4</td>
<td>−127</td>
<td>−154</td>
</tr>
</tbody>
</table>
applicability of the general findings. Although 2D models are simpler and easier to be constructed comparing to 3D models, it is natural that the biaxial state may compromise reliability of the results because of its simplifications, which do not take into consideration some important biomechanical aspects observed clinically [23]. Given that 2D simulation presents the same geometry at all of its sections parallel to the plane defined by the 2D model, this simplification results in more tooth tissues and less supporting structures than the 3D model when a tooth is simulated.

The present study was carried out to compare and emphasize the differences from hierarchical models in engineering analysis applied to dentistry with 2D and 3D models of a sound upper central incisor to assess its biomechanical behavior in order to verify whether 2D simplifications are reliable alternatives in investigations of teeth biomechanics.

It was observed that the stress distribution was qualitatively similar in all models but the stress magnitude was quite different. Comparing the maximum principal stress results in the 2D models to 3D model it was observed that the stress generated in the STRAIN models was higher than in the STRESS models. Dentin and enamel structures suffered high level of stress concentration which exceeded the tensile strength limit of 103 and 16.7 MPa [24], respectively, in both STRAIN and STRESS models. Such stresses do not usually occur in a real clinical situation within a masticatory load of 100 N. Therefore, it might be extrapolated that these 2D mathematical models overestimate the stress levels and do not represent the clinical performance of an upper sound central incisor. Based on the presented results the simulation might not be represented and simplified by 2D models to investigate such clinical situation in particular that could be justified by the presence of distinct structures with varied configurations, dimensions and Young’s modulus of up to 3 orders of magnitude.

However, the 2D/STRESS models indicated results that were closer to the 3D model than 2D/STRAIN models. This could be due to the stress decrease in the distal and mesial directions apart from the center (bucco-lingual slice) of the 3D model, which was produced by the applied load in small thickness, an approximation of the Plane Stress state.

As to the element type used in 2D models, it was verified that the models with CTRIA3 elements obtained better results than the ones with CQUAD8 elements in all 2D models. This can be explained by the fact that elements with the same edge length were used, producing a number of elements in the CTRIA3 models higher than in the CQUAD8
models. Even though the latter have a higher integration order, their results were not better than that of a model with an element of lower order, with a greater number of elements.

The results presented in this study are in disagreement with Romeed et al. [1] which compared 2D and 3D FE analysis of the maxillary second premolar restored with a full veneer gold crown. In that study small differences in the numerical results between the 2D and 3D analyses were revealed and the author justified the use of appropriate 2D models in investigating key aspects of the biomechanics of dental restorations. However, the present investigation and its conclusions differ from that of Romeed et al. [1]. In their study, they used approximate tooth geometries whereas we used CT derived geometries, they used a simplified mesh generation and boundary conditions whereas we used a finer mesh and more realistic boundary conditions. Thus, when comparing 2D and 3D it is important the high quality simulations are used in each case, because 2D and lesser quality 3D will yield results that differ from high quality 3D simulations, as 2D can be valuable if it really does reflect what is going on in 3D.
5. Conclusions

The 3D model was simulated from CT images with high fidelity to the anatomical dimensions and configuration of all the oral structures and the load and boundary conditions of human maxilla.

The findings in the present study concluded that 2D models might be considered for a sound upper central incisor when studying the qualitative biomechanical behavior. However, for the quantitative stress analysis the 2D models overestimate stress magnitudes and do not represent the real model and its biomechanical behavior, therefore 3D simulation cannot be simplified at least in investigating the biomechanics of a sound upper central incisor.

A concerted effort to develop other FE models may provide more reliable data that more accurately represent non-linear periodontal ligament and an anisotropic bone, dentin, and enamel. These developments will inevitably increase analysis time and cost. However the outcomes will accurately represent the clinical situation.

Conflict of interest

There is no conflict of interest.

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