Implementación de biomodelado y análisis mecanobiológico del comportamiento de un diente canino bajo efectos de una fuerza de masticación

Implementation of biomodeling and mechanobiological analysis of the behavior of a canine tooth under the influence of chewing force

Brenda Guadalupe Barrón-Rievera[1], Guillermo Urriolagoitia-Sosa[2], Beatriz Romero-Ángeles[3], Iván González-Uribe[4], Alejandro Urriolagoitia-Luna[5], Karen Paola Molina-Reyes[6], Martha Gabriela Pichardo-Almaraz[7]

Grupo de Biomecánica, SEPI ESIME Zacatenco, Instituto Politécnico Nacional
Email: 1brenda-rivera96@outlook.com, 2guiurri@hotmail.com, 3romerobeatriz97@hotmail.com, 4ing.mec.igu@hotmail.com, 5alex_ul56@hotmail.com, 6pmolinar2100tmp@alumnoguinda.mx, 7mpichardoa2000@alumno.ipn.mx

Resumen
En el presente trabajo se propone una metodología para generar un Biomodelado computacional de alta biofidelidad de un diente canino superior en programas tipo CAM/CAD con base a imágenes obtenidas por una tomografía volumétrica digital (TDC) con el sistema de tomografía computarizada cone-beam (CBCT). Esto con el fin de desarrollar un análisis numérico aplicando el Método de Elemento Finito (MEF), considerando las propiedades mecánicas de los tres principales tejidos del órgano (esmalte, dentina y pulpa) y estudiar la distribución de esfuerzos sobre el sistema biológico ante el impacto de la fuerza de oclusión propuesta durante el proceso de la Masticación a través de una simulación numérica. La metodología empleada y los resultados gráficos como desplazamientos, teoría de falla, etc. pueden servir como apoyo a investigaciones biomecánica u odontológicas.

Palabras clave: Diente canino, Biomodelado, Análisis numérico, Masticación, Simulación numérica.

Abstract
In this work, a methodology is proposed to generate a high biofidelity computational biomodelling of an upper canine tooth in CAM/CAD type programs based on images obtained by a digital volumetric tomography (TDC) with the cone-beam computed tomography system (CBCT). In order to develop a numerical analysis applying the Finite Element Method (FEM), considering the mechanical properties of the three tissues of the organ (enamel, dentin and pulp), to study the distribution of stresses on the biological system before the impact of the occlusion force proposed during the chewing process through a numerical simulation. The methodology applied and the graphic results (displacements, stress, strain, etc.) can serve as support for biomechanical or dental research.

Keywords: Canine tooth, Biomodelling, Numerical analysis, Chewing, Numerical simulation.

1. Introduction

New high-resolution imaging technologies implementation and three-dimensional modeling are applied to support the study of anatomical structures and real-scale reproduction of their morphology. It has direct application in areas of study such as; Archaeology, Paleontology, Dentistry, and Medicine. Therefore, computational biomedical programs have been developed to facilitate knowledge in professional studies, increase certainty in diagnoses, surgeries, and even design personalized devices in a virtual environment without harming a person's well-being [1]. The exact reproduction of biological structures can be developed with virtual models or prototypes. The latter are physical biomodels that serve as a tangible tool for the manipulation and analysis of an element. While virtual biomodeling helps to graphically visualize the geometry of biological data through computer programs [2]. The consummation of these models is based on a set of two-dimensional images with consecutive cross-sections according to the axial, coronal, and sagittal axes of the human body. These images are obtained through Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) which, when projected onto a screen, give three-dimensional results called volume renders [3]. In this work, the methodology for the elaboration of a high biofidelity biomodeling of an upper left canine is described step by step, which can serve as a basis for the behavior evaluation under the effect of chewing forces through numerical simulations and increase the scientific evidence in areas such as Biomechanics or Dentistry.

2. Methodology

To obtain a biological model, it is necessary to use different specialized computer programs to take a set of images to a solid element with anatomical and biological characteristics close to reality. The order of the methodology applied is described as follows.

2.1. Imaging

For the present study it was used the left-size maxillary canine of a 25-year-old female patient (healthy). The patient underwent a Digital Volumetric Tomography of the maxilla and mandible with the Cone-Beam Computed Tomography system, acquiring 449 cuts or DICOM-type images (Digital Imaging Communications on Medicine). This kind of tomography system is widely used in the dental area for its clear visualization of soft tissues and for providing high-quality images. Additionally, to the fact that the radiation dose is fifteen times lower than that of conventional tomography [4].

2.2. Importing images by CAM® computer program

The 449 DICOM-type images obtained from the tomography are imported into the ScanIP® program. This program delimited the area occupied by the tooth to be analyzed, reduces the number of cuts and condensed the computer weight.

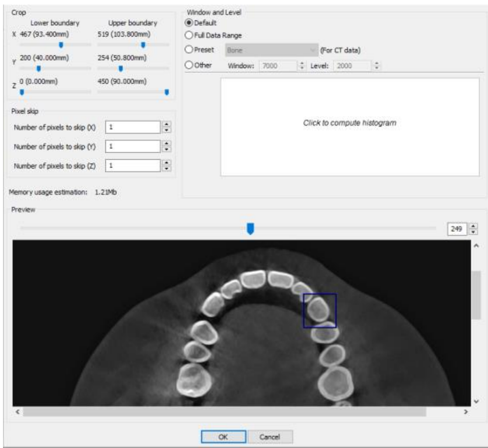


Figure 1. Study area delimitation.

The DICOM® computer program produces a four quadrants view. Three images correspond to axial views, and the fourth image is the complete component in a 3D manner (the three axial views will develop the component). This computer program display independent masks of each of the sections, in such a way that the structure to be analyzed is drawn. In this case, the enamel, dentin, and pulp of the organ were identified. Each element was drawn independently. Point clouds are formed to fill based on the overlapping cuts that were previously delimited. Finally, the three files are exported in a binary type format (.STL (Standard Triangulation Language)), saving each dental tissue separately.

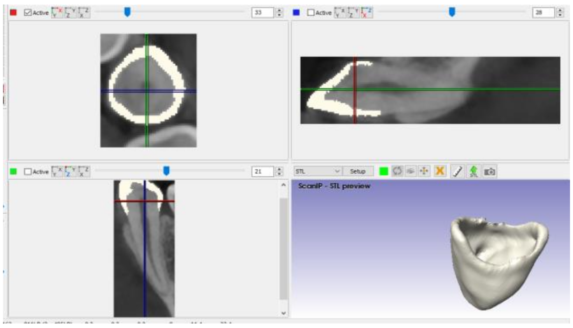


Figure 2. Delimitation of the anatomical enamel by the ScanIP® program.

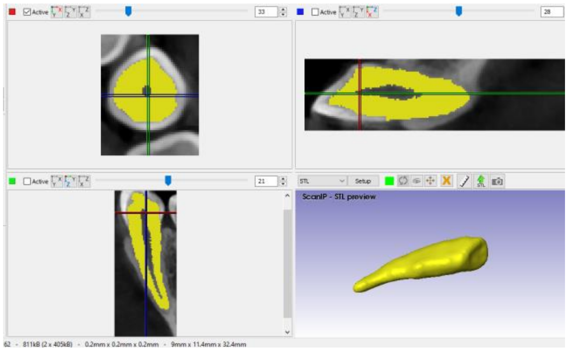


Figure 3. Delimitation of anatomical dentin by the ScanIP® program.

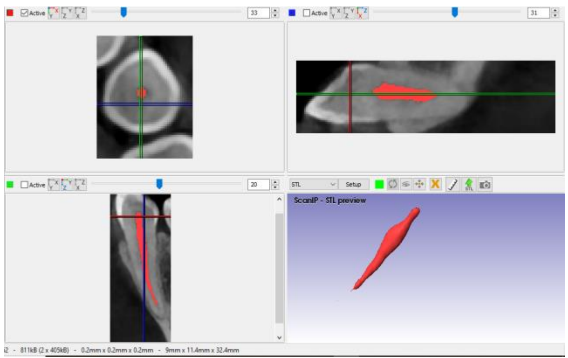


Figure 4. Delineation of the anatomical pulp in the ScanIP® program.

2.3. Solid model development

The point cloud-based models are generated by the ScanIP® computer program and are separately exported to a CAD® program (for this case Power Shape®). Where, with a set of meshing tools, a shell of closed surfaces is generated for each of the models belonging to biological tissues, and the solid tool is used once the meshing has been completed. To assemble the three solid structures, another CAD software (Solid Works®) is applied. This computer program inserts the axes and planes of elevation, ground and side view for each of the dental tissues. Later, in the computer program assembly tool the entire component will be assembled with a cavity tool. To finally export all the components successfully to the MEF computational tool in .parasolid* or .iges* format.

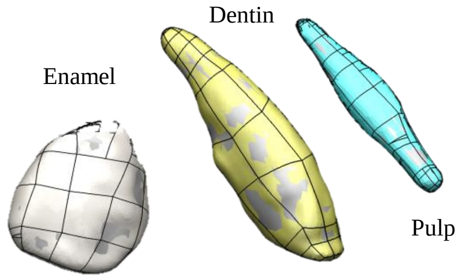


Figure 5. Surface shells.

Figure 6. Solid assembled with the cavity tool.

It should be noted, that Solid Works® is a very important tool for biomodel generation. It is used to verified that the elements are considered solid and not hollow structures.

3. Numerical analysis

The Finite Element Analysis was developed by the Ansys Workbench® version 19.2 commercial computer program. The file of the complete structure composed of the enamel, dentin, and pulp was exported in .iges format (Initial Graphics Exchange Specification).

3.1. General delimitation of the analysis

The Finite Element Method program is capable of performing endless types of analysis. For the case of the study presented in this work a structural analysis was defined. Considering a homogeneous material with the isotropic conditions. Also, continuous condition on the effects of the external agent and the analysis was carried out in a 3D manner. The numerical simulation was performed by considering the material behavior as linear-elastic. The mechanical properties of the enamel, dentin and pulp proposed in this study are described in the following table [5]:

Table 1. Propiedades mecánicas de los tejidos del diente

Tissues	Young´s modulus (GPa)	Poisson ratio	Density (g/cm^3)
Esmalte	70	0.30	0.25
Dentina	18.3	0.30	0.31
Pulpa	2	0.45	0.1

Through the Geometry in Design Modeler tool, the geometry is added to the Ansys® project, then the .iges file is imported and the program is executed to later attach it to the model.

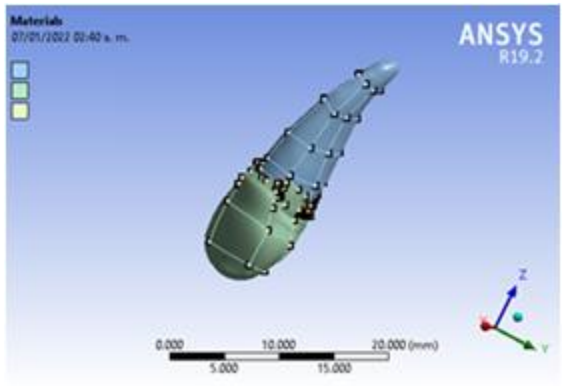


Figure 7. Geometry of the tooth in the Ansys®

3.2. Model discretization

Ansys Workbench® interprets the model as a three solid components (enamel, dentin and pulp). The discretization of the component is performed in a semi-controlled manner. Generating 3D solid high order elements. The discretization generates a total of 69 053 nodes and 44 668 elements.

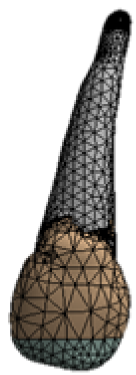


Figure 8. Model discretization.

3.3. Application of boundary conditions and external agent

It is important to state, that the application of the boundary condition and the external agent was carried out in a manner to simulate, as much as possible, the masticatory process. In this numerical evaluation was simulated the penetration of the tooth into a soft tissue (gingiva) embedded in the alveolar bone. Therefore, with the Virtual Topology tool, the displacements and rotations in the x, y and z axes and in the xy, xz and yz planes in the total area of the tooth root were delimited and restricted.

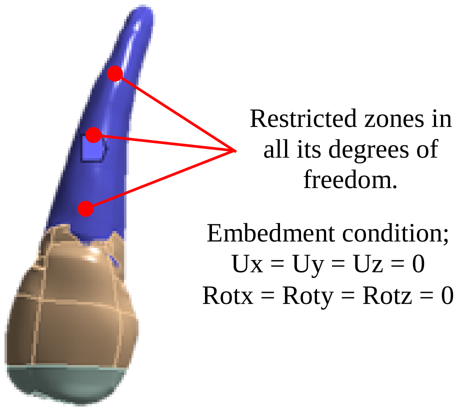
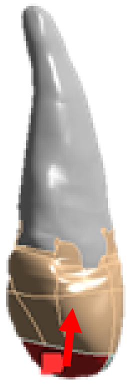


Figure 9. Border conditions (dental embedment.

When applying the externa agent (load), the surface at the canine teeth working area was considered. That is, on the incisal edge and lingual face, and not only the points of contact with the lower teeth (lateral incisor and canine). A force parallel to the z-axis with a proposed magnitude of 150 N was applied, simulating the pressure force during a healthy occlusion in the chewinr process [5-8].



External agent

Figure 10. Application of the external agent

3.4. Solution of the model and visualization of results

Once the model and external conditions are stipulated the solution is carried out. The results to be obtained are specified and display the corresponding graphs. The biomodel turned out to be viable since, through numerical simulation, results were obtained for elongations and contractions (displacements), strain, and diverse stresses (nominal, von Mises, shear, and main). The results are presented in the complete structure and for each of the components of the model.

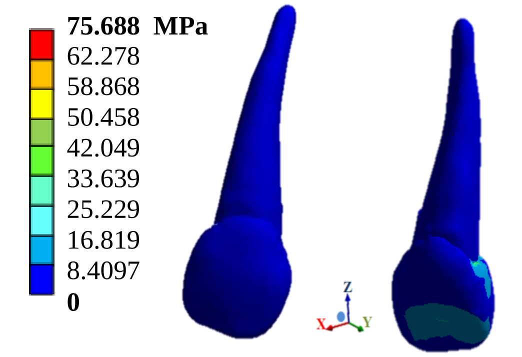


Figure 11. Von Mises stress of the complete structure (labial and lingual faces).

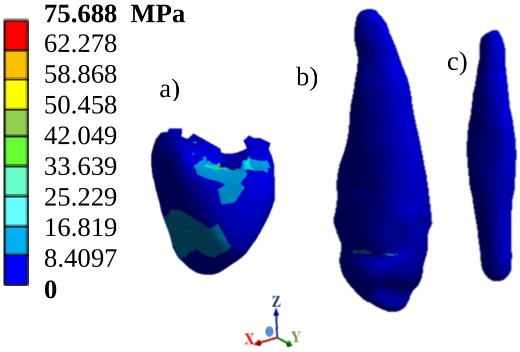


Figure 12. Von Mises stress by components. a) Enamel. b) Dentine. c) Root.

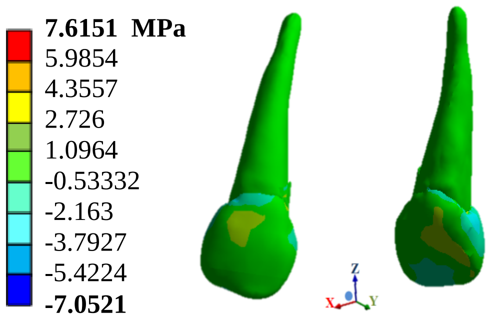


Figure 13. Shear stress xy plane complete structure (labial and lingual faces).

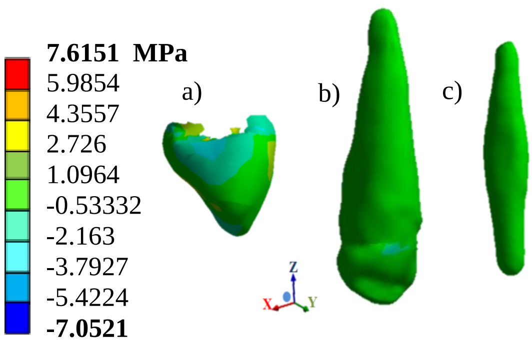


Figure 14. Shear stress xy plane by components. a) Enamel. b) Dentine. c) Root.

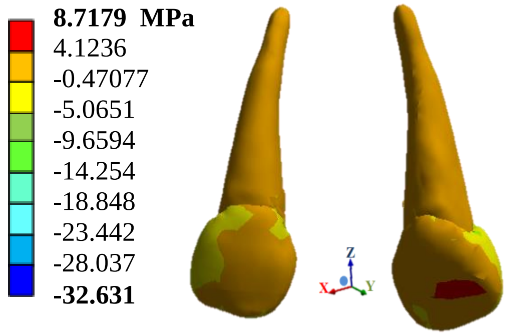


Figure 15. Shear stress xz plane complete structure (labial and lingual faces).

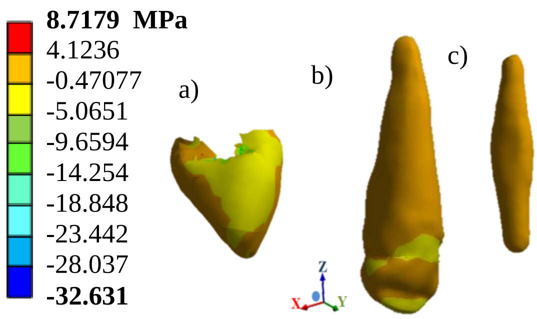


Figure 16. Shear stress xz plane by components. a) Enamel. b) Dentine. c) Root.

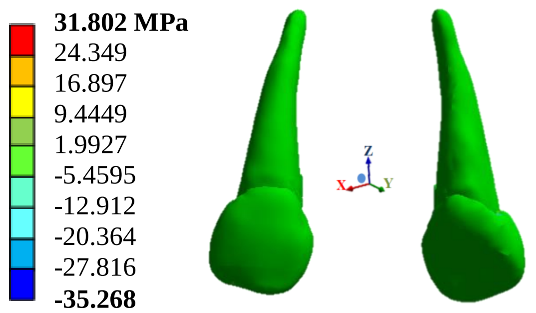


Figure 17. Shear stress yz plane complete structure (labial and lingual faces).

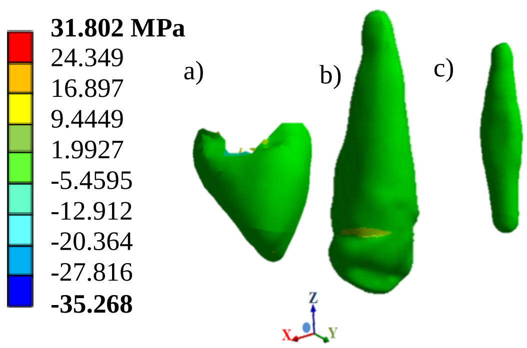


Figure 18. Shear stress yz plane by components. a) Enamel. b) Dentine. c) Root.

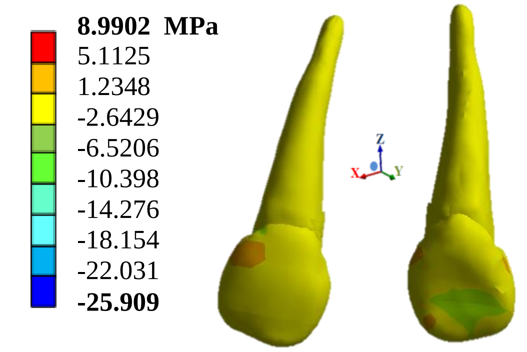


Figure 19. Nominal stress in x axis complete structure (labial and lingual faces).

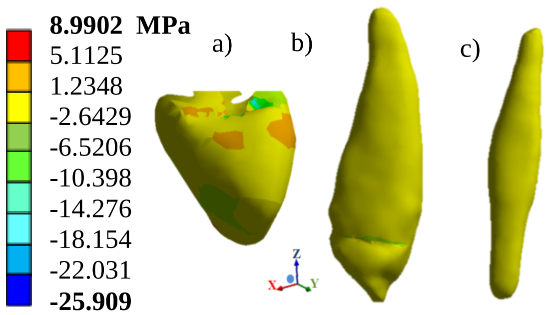


Figure 20. Nominal stress in x axis by components. a) Enamel. b) Dentine. c) Root.

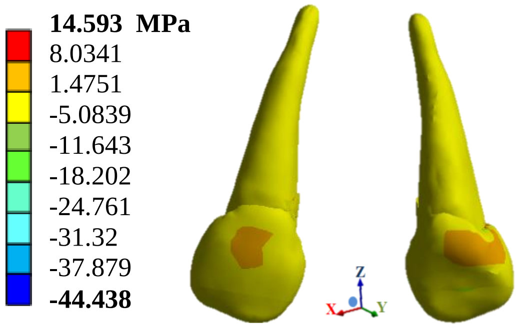


Figure 21. Nominal stress in y axis complete structure (labial and lingual faces).

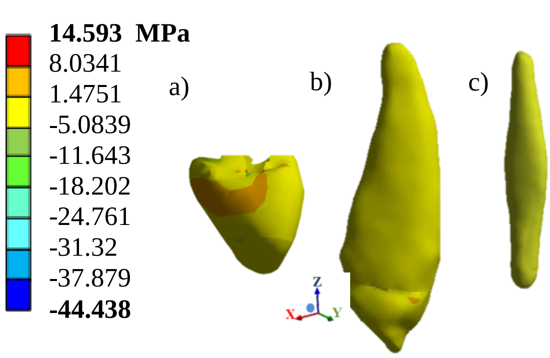


Figure 22. Nominal stress in y axis by components. a) Enamel. b) Dentine. c) Root.

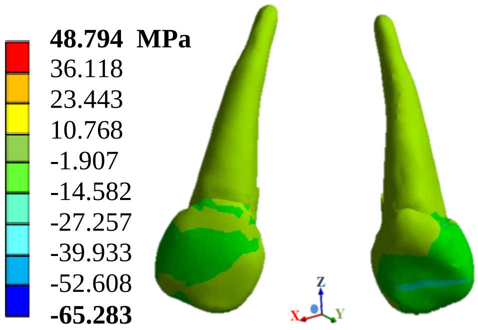


Figure 23. Nominal stress in z axis complete structure (labial and lingual faces).

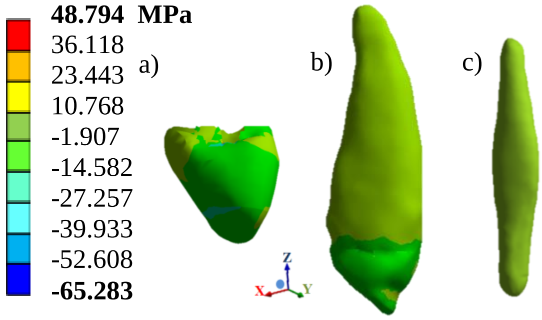


Figure 24. Nominal stress in z axis by components. a) Enamel. b) Dentine. c) Root.

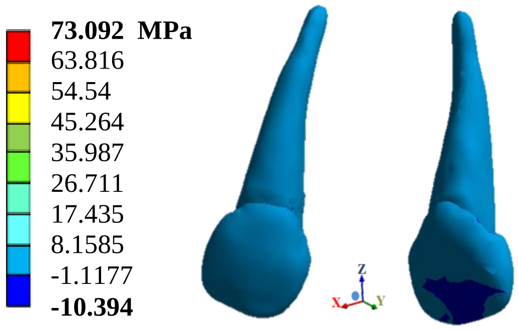


Figure 25. Maximum main stress complete structure (labial and lingual faces).

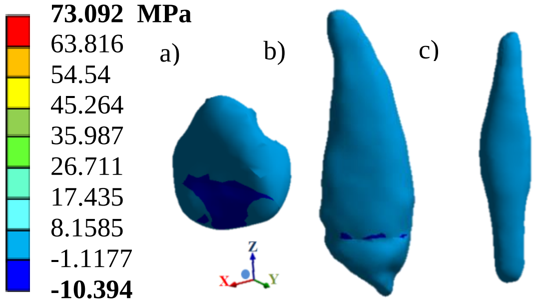


Figure 26. Maximum main stress by components. a) Enamel. b) Dentine. c) Root.

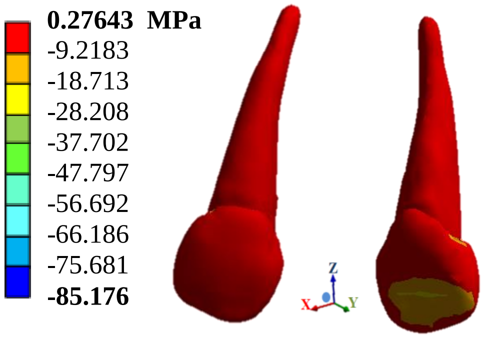


Figure 27. Minimum main stress complete structure (labial and lingual faces).

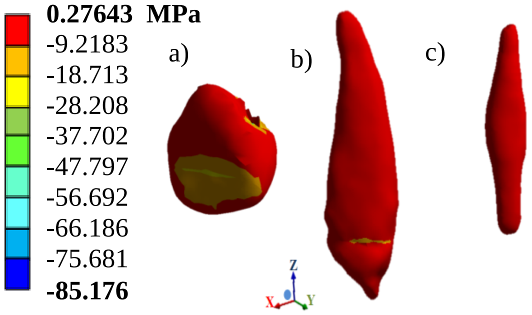


Figure 28. Minimum main stress by components. a) Enamel. b) Dentine. c) Root.

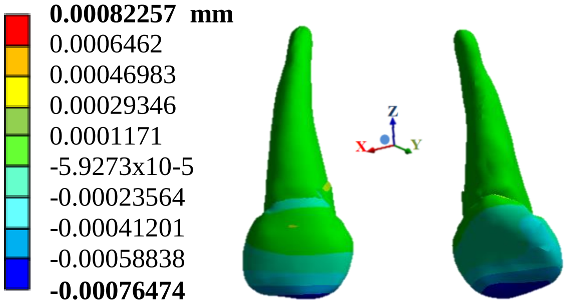


Figure 29. Displacement in x axis complete structure (labial and lingual faces).

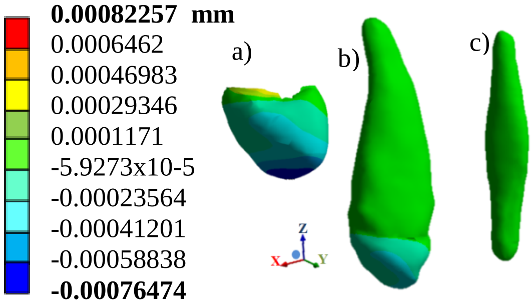


Figure 30. Displacement in x axis by components. a) Enamel. b) Dentine. c) Root.

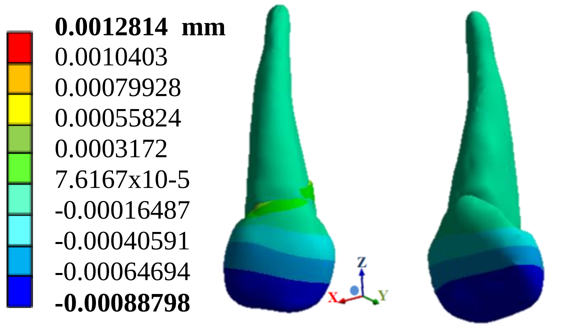


Figure 31. Displacement in y axis complete structure (labial and lingual faces).

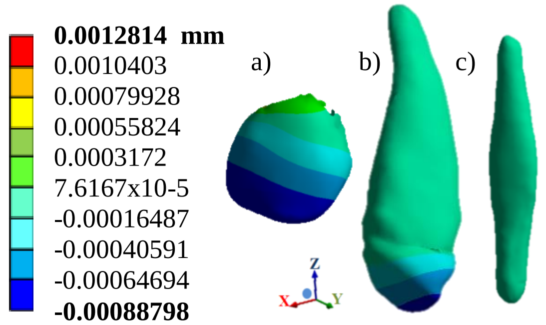


Figure 32. Displacement in y axis by components. a) Enamel. b) Dentine. c) Root.

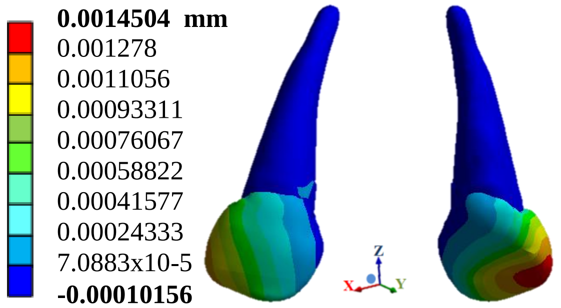


Figure 33. Displacement in z axis complete structure (labial and lingual faces).

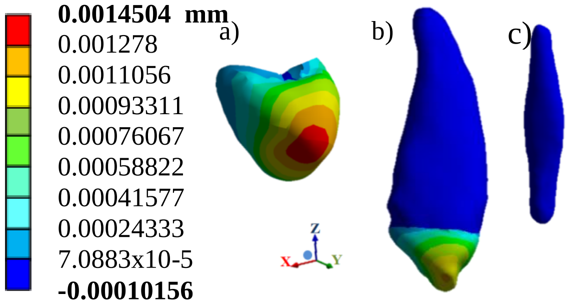


Figure 34. Displacement in z axis by components. a) Enamel. b) Dentine. c) Root.

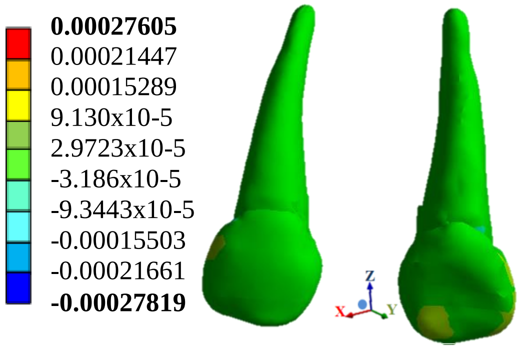


Figure 35. Strain in x axis complete structure (labial and lingual faces).

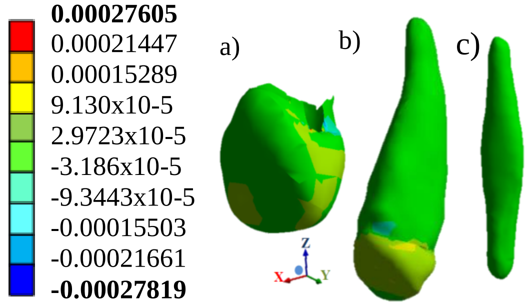


Figure 36. Strain in x axis by components. a) Enamel. b) Dentine. c) Root.

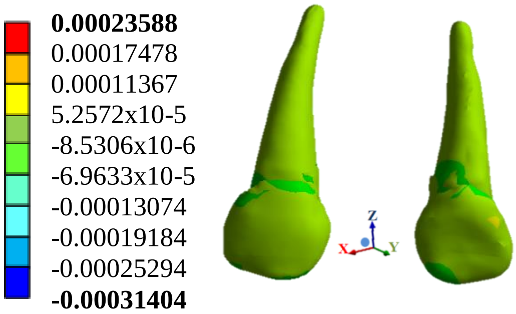


Figure 37. Strain in y axis complete structure (labial and lingual faces).

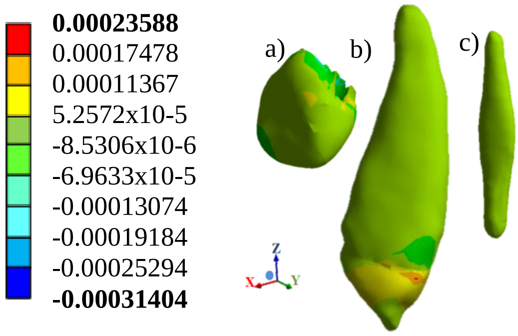


Figure 38. Strain in y axis by components. a) Enamel. b) Dentine. c) Root.

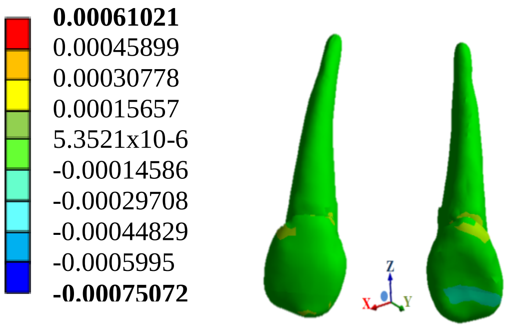


Figure 39. Strain in z axis complete structure (labial and lingual faces).

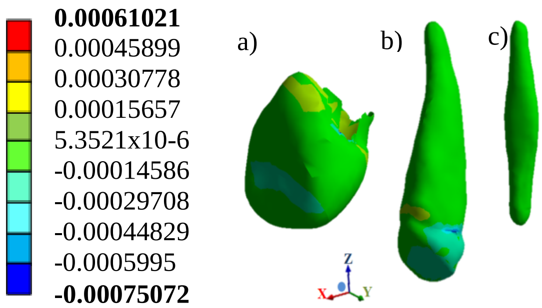


Figure 40. Strain in z axis by components. a) Enamel. b) Dentine. c) Root.

Computerized biomodeling techniques may be more relevant in practical studies because they have a broad similarity regarding practical cases in the clinical area, unlike in vitro study methods. In this research work, clear importance is shown when developing a model based on Digital Volumetric Tomography. With the help of a CAM-type software, in this case, ScanIP®, the morphology, and anatomy of each can be accurately determined. one of the tissues of the dental organ. Shows a great advantage over other non-invasive methods, such as where biomodels drawn in CAD-type programs are obtained, taking only average measurements of the teeth as references. It should be noted, that the methodology used and described in this study is not only considered for dental biomodeling and targeted analysis of healthy teeth. Nevertheless, could also serve as a reference for the modeling of other biological structures and be oriented towards different numerical analyzes that contribute to the areas of biomechanics, medical, clinic, etc. The following table shows the maximum and minimum results of each of the selected results for clear visualization.

Table 2. Numerical analysis results resumen

Value	Results	
	Maximum	**Minimum**
Nominal stress x axis (MPa)	8.9902	-25.909
Nominal stress y axis (MPa)	14.593	-44.438
Nominal stress z axis (MPa)	48.794	-65.283
Von Mises stress (MPa)	75.688	0
Shear stress xy plane (MPa)	7.6151	-7.0521
Shear stress xz plane (MPa)	8.7179	-32.631
Shear stress yz plane (MPa)	31.802	-35.268
Maximum main stress (MPa)	73.092	-10.394
Minimum main stress (MPa)	0.27643	-85.176
Displacement in x axis (mm)	0.00082257	-0.00076474
Displacement in y axis (mm)	0.0012814	-0.00088798
Displacement in z axis (mm)	0.0014504	-0.00010156
Strain in x axis	0.00027605	-0.00027819
Strain in y axis	0.00023588	-0.00027819
Strain in z axis	0.00061021	-0.00075072

4. Conclusions

The methodology used seems viable for the development of biomechanical studies, due to the high biofidelity of the components and for considering the specific mechanical properties of each component. In the same way, behavior analysis is an option for the status of pathologies and treatments in dental organs, although this proposal is made that extends the possibilities of study by changing parameters established here such as load and boundary conditions, which well adapting this methodology Depending on the needs, it can be used for personalized diagnoses and treatments by studying the teeth of each patient.

Figure 41. Biomodel generated with the proposed method of a tooth with endopost restoration.

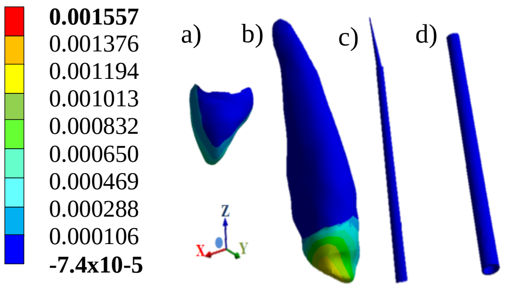


Figure 42. Result of the numerical analysis generated with the proposed method of a tooth with endopost

The programs used do not require sophisticated computer equipment, but knowledge of the computational tools of each one is required so as not to interfere with the results; the precision of the models will depend on the correct use of the programs, as well as the analysis will depend on making a correct discretization. Due to the high complexity of biomodeling, it was decided to perform the numerical analysis in Ansys Workbench®, to obtain an effective discretization in a faster and more controlled manner. Despite not considering the soft tissue (gums) and the maxillary bone where the tooth is embedded in reality, these factors were taken into account for the boundary conditions. An external inconvenience presented is the limitation of the discretization due to the low capacity of the computer used. The development of ScanIP® generates a series of disadvantages in the methodology used. The first is that the process becomes slow since in this first program used only one point cloud is obtained, for which it is necessary to export the file to the Power Shape® software to convert the point clouds to surface shells of each one. of the biological tissues and later having to unite them in a third program (SolidWorks®) and make them solid, to export them to Ansys Workbench®, and consider a single organ with three components. Another disadvantage seen is that the second software used causes a limitation in the biomodel by not considering the extremely thin parts where it is not possible to produce surface shells (part of the pulp). However, it is considered that it does not significantly compromise the accuracy of the results. results. These considerations must be taken into account when using the proposed methodology.

5. Acknowledgment

The authors thank the Instituto Politécnico Nacional and the Consejo Nacional de Ciencia y Tecnología (CONACyT) for the support provided in the elaboration of this work.

6. Referencias

[1] Chaile, S. A., Alday, A., Fernández-Álvarez, S., Defagó, V. H. and Massano, G., Cuando la gráfica se escapa del papel.... Biomodelos 3D al servicio de la medicina, *EGraFIA Argentina*, 2016.

[2] Gamarra-Rosado, V. O. and Da Silva, F. F., Propuesta de biomodelado virtual 3D utilizando software libre, *Revista de Ingeniería; Ciencia, Tecnología e Innovación*, Vol. 1, No. 2, pp 51-70, 2014.

[3] Zabala-Travers, S., Sattler, J. and Perdomo, J., Biomodelado e impresión 3D en Uruguay; Una nueva subespecialidad en imagenología, *Revista de Imagenología*, Vol. 24, No. 2, pp 21-35, 2021.

[4] Salas-Salas, C., Araneda-Silva, L. and Schott-Börger, S., Evaluación del error dimensional en la reproducción tridimensional de una mandíbula humana disecada mediante prototipado rápido de modelado por deposición fundida, *International Journal of Odontostomatology*, Vol. 14, No. 1, 2020.

[5] Hernández-Vázquez, R. A., Romero-Ángeles, B., Urriolagoitia-Sosa, G., Vázquez-Feijoo, J. A., Vázquez-López, A. J. and Urriolagoitia-Calderón, G., Numerical analysis of masticatory forces on a lower first molar considering the contact between dental tissues, *Applied Bionics and Biomechanics*, Vol. 2018, pp 1-15, 2018.

[6] Hernández-Vázquez, R. A., Urriolagoitia-Sosa, G., Marquet-Rivera, R. A., Romero-Ángeles, B., Mastache-Miranda, O. A., Vázquez-Feijoo, J. A. and Urriolagoitia-Calderón, G., High-biofidelity biomodel generated from three-dimensional imaging (Cone-Beam Computed Tomography); A methodological proposal, *Computational and Mathematical Methods in Medicine*, Vol. 2020, pp 1-14, 2020.

[7] Hernández-Vázquez, R. A., *Análisis Mecanobiológico de la Distribución de Esfuerzos Debido a Cargas Masticatorias, en los Órganos Dentales*, Tesis Doctoral, Instituto Politécnico Nacional, 2018.

[8] Esponda-Vila, R., *Anatomía Dental*, 7ª edición, Ed. Universidad Nacional Autónoma de México, pp 52-55, 170-185, 1994.