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Comparative study about generation methods of geometric models by finite element analysis

Estudo comparativo sobre métodos de geração de modelos geométricos por análise de elementos finitos

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Abstract

The aim of this study was to assess the influence of different methods for generating geometric models on stress values and distributions of endodontically treated teeth using a three-dimensional finite element analysis (3D-FEA). An endodontically treated human maxillary canine restored with glass fiber post and ceramic-fused-to-metal crown was scanned by microcomputed tomography and three-dimensionally reconstructed. Based on the microcomputed tomography images, 2 geometric models were generated and divided into the following groups: Group GCAD - only the root dentine was reconstructed based on a microcomputed tomography image while the remaining structures were generated by GCAD software simulation, and Group GTC - the whole assembly was obtained from scanning and rehabilitated by microcomputed tomography. Loading of 180N at 45° of the tooth long axis was applied on the lingual surface of the incisal third and the models were supported by a periodontal ligament fixed into the 3 axes of the Cartesian system (x=y=z=0). von Mises stress (VMS) were calculated. Differences in stress value and distribution between the generation methods of the geometric models were found. The lowest ratio difference in GTC/GCAD was for resin cement and core. Thus, the method for generation of the geometric model in finite element analysis was found to influence the research results, suggesting better results for GCAD method.

Keywords: CAD; CAM; endodontically treated teeth; finite element analysis.

Resumo

O objetivo deste estudo foi avaliar a influência de diferentes métodos para a geração de modelos geométricos em valores de tensões e distrubuições de dentes tratados endodônticamente, utilizando-se uma análise tridimensional de elementos finitos (3D-FEA). Canino superior humano tratado endodonticamente, restaurado com pino de fibra de vidro e coroa metalocerâmica foi escaneado por meio de microtomografia computadorizada e reconstruído tridimensionalmente. Baseadas nas imagens de microtomografia computadorizada, foram gerados 2 modelos geométricos e divididos nos seguintes grupos: grupo GCAD-apenas a dentina radicular foi reconstruída baseada na imagem obtida por meio de microtomografia computadorizada, enquanto as estruturas remanescentes foram geradas por simulação de software de CAD, e grupo GTC-todo conjunto inteiro foi obtido do escaneamento e reabilitado pela microtomografia computadorizada. O carregamento de 180N em 45° do longo eixo do dente foi aplicado na superfície lingual do terço incisal e os modelos foram suportados por um ligamento periodontal fixado nos 3 eixos do sistema cartesiano (x = y = z = 0). Tensões equivalents de von Mises (VMS) foram calculados. Foram encontradas diferenças no valor de tensões e distribuição entre os métodos de geração dos modelos geométricos. A menor razão entre GTC/GCAD foi para o cimento de resinoso e núcleo. Assim, verificou-se que o método de geração do modelo geométrico na análise de elementos finitos influenciou os resultados da pesquisa, sugerindo melhores resultados para o método GCAD.

Palavras-chaves: CAD; CAM; dentes tratados endodonticamente; análise de elementos finitos.

Introduction

Finite element analysis (FEA) is a computer analysis in which scientific questioning, represented by a physical problem, is transformed into a virtual model that is interpreted by the finite element software as mathematical equations (1). However, the reliability of FEA results is known to be strictly related to some factors, such as the quality of the geometric representation, the properties of the materials, the boundary and loading conditions (2-4), and the proper selection of software used to solve the problem.

Assuming the complexity of oral cavities, it is difficult to achieve accurate representation using FEA (5). Thus, images from micro-computed tomography (μCT), computed tomography (CT) and magnetic resonance have been used as tools to generate geometric models in order to simulate the real clinical features of the patient. Therefore, the 3D model provides high accuracy for the anatomic dimensions and configuration of all oral structures. However, the processing techniques used to obtain the medical images from CT can lead to errors in several steps of the model generation, influencing its accuracy (6).

The BioCAD was developed (7-10) as a CAD tool (computer-assisted design) for complex structures, mainly biological structures, to transform an anatomic model into a 3D CAD model. In the BioCAD software, the geometry is designed in another source based on medical images from tomography, microcomputed tomography or magnetic resonance. Then, the reference of the anatomic geometry with proper quality is obtained. The main purpose of BioCAD is to create a conceptual base that allows the use of any CAD tool to unify the information and integrate engineering and health sciences (9). In addition, BioCAD aims to simplify the finite element model through reduction of image noise for better quality of finite element mesh and solving of mathematical answer.

The restoration of endodontically treated teeth is a challenge in restorative dentistry due to the loss of coronal structure (11-13), which requires core build-up and restoration with prosthetic crowns (14,15). Thus, assuming the complexity of tooth anatomy associated to new technologies for generation of finite element model and poor reports in the literature about the best generation method, the aim of this study was to evaluate the influence of generation methods of geometric models (computer-assisted design and μCT-based condition) on stress values and distribution in an endodontically treated tooth restored with glass fiber post and ceramic-fused-to-metal crown through a 3D-FEA. The null hypothesis assumed that there is no difference in stress value and distribution between the generation methods of the geometric models.

Materials and Methods

This study was approved by the Research Ethics Committee (C.A.A.E.: 22249113.7.0000.5498). The variation in this FEA study involved a different generation conditions of geometric models in two levels: models generated strictly from µCT scanning of structures and models generated from structures created in CAD software. In total, two groups were tested, including: GTC – structures created from µCT scanning and GCAD – structures created from CAD software. The response variable was the stress value and distribution of the different generation conditions of geometric models.

For standardization of this study, groups GTC and GCAD were obtained from the same sound maxillary canine and they had the same endodontic treatment and prosthetic rehabilitation. For group GTC, the sound maxillary canine was submitted to in vitro endodontic treatment and restoration with glass fiber post, resin core and a ceramic-fused-to-metal crown. A working distance of 14.0 mm was established, remaining 1.0 mm away from the root apex. Then, obturation with gutta-percha and restoration of the root canal with a 10.0 mm glass fiber post were performed, preserving 4.0 mm of gutta-percha at the apical region and cementation layer of approximately 50 µm in thickness (16). Additionally, the resin core was standardized based on tooth preparations of 1.5 mm in buccal and lingual surfaces and 2.0 mm in the incisal edge (16). The coronal portion of the core was a built-in composite resin with 4.0 mm in height, which was restored with a ceramic-fused-to-metal crown being made in feldspatic porcelain and nickel chrome alloy. The coping presented 0.5 mm in thickness, while the ceramic veneering presented 1.0 mm in thickness at the buccal and lingual surface and 1.5 mm at incisal edge. Then, the restored tooth was scanned in µCT (SkyScan 1174v2; Bruker-microCT, Kontich, Belgium) (0.05 mm tomographic slides throughout the tooth were collected, totaling 994 transversal sections) and the. stl files were obtained individually for each structure (porcelain veneer, copping, resin core, glass fiber post, gutta-percha, and root dentine).

In group GCAD, only the image of the root dentine generated in a .stl file aforementioned was used. The endodontic treatment and prosthetic rehabilitation including glass fiber post, resin core and ceramic-fused-to-metal crown were simulated in CAD software (SolidWorks 2007, SolidWorks Corp., Concord, MA, USA), with the similar dimensions that were made for the GTC group.

For both groups, the .stl files were transferred to the Simpleware 4.1 software (Simpleware Ltd, Rennes Drive, Exeter, UK) to generate the 3D solid models. The periodontal ligament with 0.2 mm in thickness was included in both 3D models (17) based on Boolean operations of addition and subtraction.

In the Simpleware software, ScanFE was used to determine the mechanical properties of the materials (elasticity modulus [E] and Poisson's ration [v]), which are presented in Table 1. All materials were assumed to be homogeneous, isotropic and linearly elastic except for the glass fiber post (GFP), which was assumed to be orthotropic, homogeneous and linearly elastic (18). The GFP was assumed to be orthotropic since its mechanical properties differed along the fiber direction (x direction) and the two normal directions (y and z directions). Thus, the mechanical properties of those materials were represented by the elasticity modulus along 3 directions (Ex, Ey, Ez), the Poisson's ratio (vxz, vxz, vyz) and the shear modulus (Gxz, Gxz, Gyz) in the orthogonal planes (xy, xz, yz) (Table 1) (18). All structures of the models were assumed to be completely joined, which means no failures in bonding and interposition (16).

Table 1. Mechanical properties of materials

Material	E (GPa)	v	Shear modulus (GPa)	Reference
Resin cement	11.54	0.24	-	4
Ceramic	73.19	0.4	-	4
Metallic coping	209.20	0.24	-	4
Composite resin	19.16	0.5	-	4
Dentin	18.6	0.31	-	4
Periodontal ligament	6.89×10^{-5}	0.45	-	18
Gutta-percha	1.4×10^{-1}	0.45	-	19
	X = 37.0	Xy = 0.27	Gxy = 3.1	
Glass fiber post	Y = 9.5	Xz = 0.34	Gxz = 3.5	20
	Z = 9.5	Yz = 0.27	Gyz = 3.1	

The finite element mesh was generated using linear tetrahedral elements type C3D4 and refined according to a convergence analysis of 6% (19). The group GTC presented with 234,824 nodes and 1,243290 elements; the group GCAD presented with 59,145 nodes and 216,793 elements. Then, the finite element mesh of each group was imported to the finite element software (Abaqus 6.10-EF1, Dassault Systèmes Simulus Corp., Providence, RI, USA) to simulate static occlusal loading of 180 N at the incisal third of tooth lingual surface at 45° of its long axis (16). The nodes of the periodontal ligament were fixed in the three axes of Cartesian system (x, y and z), assuming values of x = y = z = 0.

Results generation

The results were provided by the finite element software for qualitative analysis through stress maps (hot colors represent the highest stress values while cold colors represent the lowest stress values) and quantitative numeric analysis. After loading, the maximum von Mises stress (VMS) was calculated since it is a failure criterion that is widely used as an indicator of failure predictability by evaluating the combination of stress (tensile, compression and shear) in each structure.

Results

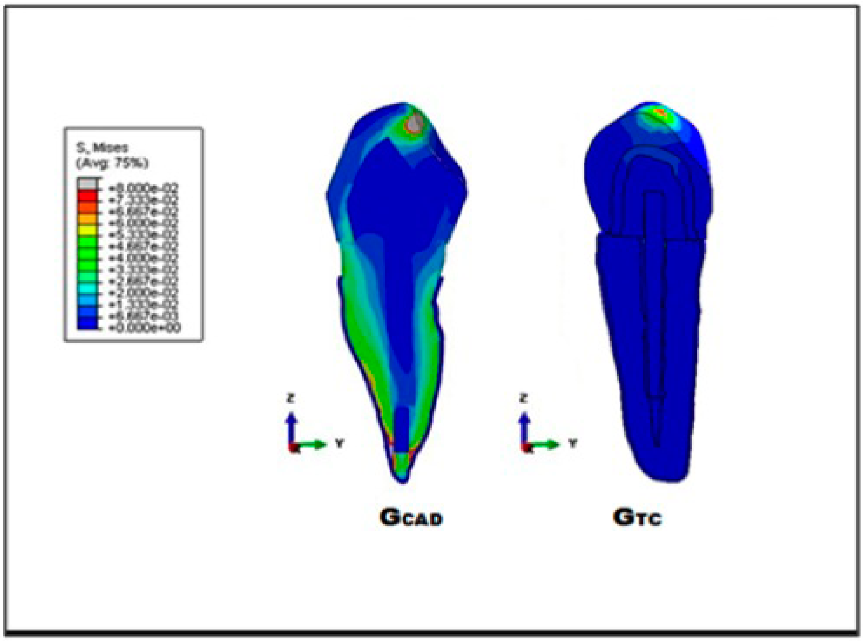
The different methods for generating the geometric models showed differences in both stress distribution and VMS values (MPa) between the groups (GCAD and GTC). Group GTC exhibited the lowest maximum VMS values compared to GCAD for all structures. The ratio (R) between the values found for each structure of each group (R = stress value of the GCAD structure ÷ stress value of the GTC structure) is shown in Table 2.

Table 2. Maximum von Mises stress values (MPa) and ratio differences between the groups

Groups / Structures	GTC	GCAD	RATIO (GCAD/GTC)
Ceramic	0.1	7.478	74.78
Resin cement	0.165	0.605	3.66
Metallic coping	0.013	0.973	74.84
Root dentine	0.016	1.975	123.43
Periodontal ligament	1×10^{-7}	0.077	770.00
Core	0.0053	0.026	4.90
Glass fiber post	0.0043	0.513	119.30

The stress maps (Figure 1) showed greatest differences between GTC/GCAD. Although both groups showed VMS stress concentration (MPa) at the loading point, the group GTC presented higher intensity. In relation to the tooth apical, medium and cervical region; only GCAD showed stress maps with different intensity and the highest stress (red tension) was noted at the apical region of gutta-percha.

Figure 1. VMS stress distribution (MPa) in all groups



Discussion

The null hypothesis of this study was rejected since quantitative and qualitative differences were found between the generation methods of the geometric models.

The finite element analysis requires the appropriate design of the experimental structures to obtain accurate results (20). Detailed models can be difficult to simulate due to their greater complexity in obtaining the finite element mesh. Furthermore, models with too much detail can influence data processing, resulting in incomplete findings (10).

In the present study, the increase in the number of nodes and elements of the group GTC compared to GCAD may have influenced the qualitative and quantitative differences between the geometric models. The detailed 3D image from the µCT .stl file is thought to potentially increase the number of elements in the group TC and influence the generation of an appropriate mesh. Therefore, a high number of elements can be assumed to not represent a more stable finite element model; an appropriate finite element mesh without distorted elements depends on the operator's experience and skills.

In addition, those results can also be a consequence of the difficulty in converting µCT medical images into .stl files. Even assuming a high level of standardization during µCT imaging, its 3D reconstruction depends on the differences in the gray tones in the structures. Furthermore, any technique artifact or noise can influence the 3D reconstruction, thereby increasing model complexity.

Another factor that probably had influenced stress distribution in this study was the generation method of models, since in the group GTC the tooth was completely scanned (endodontic treatment and prosthetic restoration) while in the group GCAD only the root was scanned because the remaining structures were designed by the software. Figure 1 shows that software designing does not provide similar accuracy of dimensions as in GTC. It was found that the dimension of gutta-percha in GCAD is longer than in GTC, which means that a thinner root dentine at apical region was designed in GCAD and resulted in higher stress concentration.

It is noteworthy that the 3D model generated after the reconstruction of the μCT images is usually in a .stl file, which is a 3D file representing the surface geometry of the object in three dimensions of triangles mesh and a difficult file to be edited. Thus, the BioCAD concept translates a .stl file into a CAD file, allowing editing of images into more versatile geometric models (9).

Furthermore, considering the different software packages available in the market, the professional must be trained to precisely use the tool to convert CT or μCT images into finite element models (5).

According to the Saint-Venant's principle, the stress at the loading point and surrounding area must be disregarded since a higher perturbation will occur in this region, which makes its analysis difficult unless advanced mathematic methods are used (21). This statement must be considered to evaluate the high stress found in veneering ceramic in both groups of this study since it corresponds to the loading area.

Therefore, prior to generating finite element models, it is important to evaluate the amount of information required for model representation. The sensitivity on determining if the information is excessive or too simple is relevant since both conditions can influence virtual simulation. Too much information can overload the system, generating more variables and noise in the model. Conversely, lack of information can cause poor simulation of the real scenario and doubtful answers.

In dentistry, 3D-FEA allows a non-destructive study in 3 dimensions, providing assessment of problems prior to the clinical procedures to avoid several undesirable situations. However, despite of technological advancement, this method remains as a limited representation of reality that cannot always accurately reproduce the clinical condition, potentially influencing the interpretation of the results. Additionally, this is just an example of how obtaining the models can influence the results, when using the finite element methodology. So, it is clearly insufficient to deduct any kind of conclusion but just assumption. In this way, more analyzes are suggested in future studies, using other teeth, types of rehabilitation as well as other bone structures.

Conclusions

Within the limitations of the present study and according to the stress values and maps generated by the finite element software, the method for generating the geometric models in the finite element analysis influences the research results, suggesting better results for GCAD method.

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