ANALOG AND DIGITAL MODELING OF SOUND AND IMPAIRED PERIODONTAL SUPPORTING TISSUES DURING MECHANICAL TESTING

[1]Veronika T. Szabó, [2]Balázs Szabó, [3]Tamás Tarjányi, [4]Eszter Szőke-Trenyik[3], [4]Balázs Szabó P[3], [1]Márk Fráter

[1]University of Szeged, Faculty of Dentistry, Department of Operative and Aesthetic Dentistry, Tisza Lajos krt. 64., 6726, Szeged, Hungary

[2]University of Szeged, Faculty of Dentistry, Department of Periodontology, Tisza Lajos krt. 64., 6726, Szeged, Hungary

[3]University of Szeged, Faculty of Dentistry, Department of Oral Biology and Experimental Dental Research, Tisza Lajos krt. 64., 6726, Szeged, Hungary

[4]University of Szeged, Faculty of Engineering, Department of Food Engineering, Moszkvai krt. 9., 6725, Szeged, Hungary

E-mail: tszaboveronika@gmail.com, szabobalazs77@gmail.hu, tarjanyi.tamas@stoma.szote.u-szeged.hu, szpb@mk.u-szeged.hu, meddentist.fm@gmail.com,

ABSTRACT

Periodontitis is one of the most common conditions affecting oral health among adults, posing a great challenge for both patients and also for dentists aiming to treat this disease. In severe stages such deterioration of the supporting tissues, namely the periodontal ligaments and the bone, can occur, which will affect the biomechanical behavior and therefore the longevity and survival of the affected teeth. In order to be able to plan both periodontal and subsequent restorative treatment properly, valid modelling of the current clinical situation is advised. The aim of the present article is to comprehensively discuss possible analog and digital modeling methods of periodontally affected teeth and the periodontal structures surrounding them. Modelling possibilities can serve later as the basis of mechanical load, digital finite element studies, and also aid clinical treatment planning.

Keywords: analog and digital modelling, periodontally compromised teeth, molar tooth, furcation involvement, finite element analysis

1. INTRODUCTION

Periodontitis is one of the most common conditions affecting oral health among adults, accounting for severe social and health problems [1]. Although individual differences can occur, similar results are available worldwide on disease incidence from epidemiological surveys [2].

Types of periodontal disease involving the supporting tissues usually result in irreversible destruction of the alveolar bone. In parallel with bone degradation, the periodontal ligaments that anchor the teeth are also damaged, resulting in attachment loss that –if left untreated– can lead to consequential tooth loss [3]. Deterioration of the attachment apparatus is usually a slow process and over time may show individual differences in extent and clinical appearance [4]. In case of multi-rooted teeth, this can create a special situation, so-called furcation involvement [5], the treatment of which is one of the greatest challenges among periodontal therapies.

In the treatment of periodontal diseases conservative and surgical therapeutic solutions are available. In general, we might state that the more extensive defects should be rather treated surgically [6]. Resective surgery seeks to create a stable, sustainable state by further reducing the remaining tissues, while regenerative surgery aims to restore the original structures in form and function. One type of resective procedure is root amputation, in which one or more roots are surgically removed. Restoration and maintenance therapy of teeth that have undergone root amputation poses a serious challenge in most cases to the periodontist, dentist, and patient alike.

The aim of the present article is to comprehensively discuss possible analog and digital modeling methods of periodontally affected teeth and the periodontal structures surrounding them that can serve later as the basis of mechanical load or digital finite element studies. It should be emphasized that the model created should mimic a realistic clinical situation.

1.1. Preliminary data acquisition

Anatomical, clinical, and radiological knowledge regarding teeth and periodontal tissues is essential in this topic. Although dental and periodontal anatomy has been extensively circumscribed in the literature, the present clinical state of the tooth-periodontal unit in function is more difficult to examine and evaluate, especially in the case of multi-rooted teeth.

This can be aided by the rapidly evolving CBCT technique, which is able to reveal the given clinical situation in three dimensions. This is also important in research planning as clinically relevant situations are worth examining. The majority of softwares that we use to evaluate scans, are also capable of 3D rendering of the mapped area (volume rendering), but often their quality and handling are unsatisfactory (Figure 1) [7]. Of course, the imaging technology itself is also evolving by leaps and bounds (volume ray casting, texture-based volume rendering, etc.), but has not gained in everyday dental practice as much importance as using and analyzing dental CBCTs.

In modeling, however, CBCT images can play an important role in creating a three-dimensional (3D) model based on a so-called segmentation technique. Segmentation allows different structures to be embodied in the form of different models (Figure 2) [8]. In addition, their relationship to each other and their three-dimensional position can be well observed, which is of utmost importance from the practical point of view. Without doubt, 3D visualization provides better understanding of many clinical situations, for instance the position of an inflammatory lesion in relation to a tooth (Figure 3), or periodontal and other anatomical structures, compared to two-dimensional images. However, the current state of technology has not yet allowed us to create virtual bodies of the same size and shape as real structures based on CT scans. (Figure 4, 5)

If required, the created bodies can also be printed out as scale models serving for additional source of research or mere information gathering. Printed teeth can also aid educational process, namely practicing of certain procedures (Figure 6).

It should be mentioned that certainly the two-dimensional, traditional X-rays are also used for data collection currently as well, however, they provide less and often insufficient information.

Intraorally scanned images occur predominantly in clinical usage, but can also facilitate research and educational purposes, which in several cases might be of great help in a given issue. In addition, CBCT imaging, when used in conjunction with intraoral scans, allows for special dental planning, especially in navigated treatments of implantology or endodontics.

The methods presented in a non-exhaustive way above, can help us to examine clinical situations more thoroughly and accordingly, to have realistic modeling.
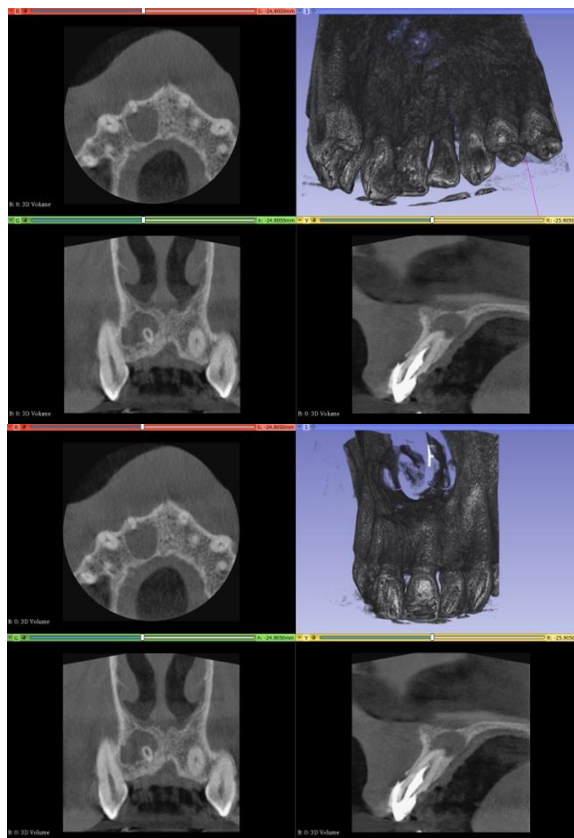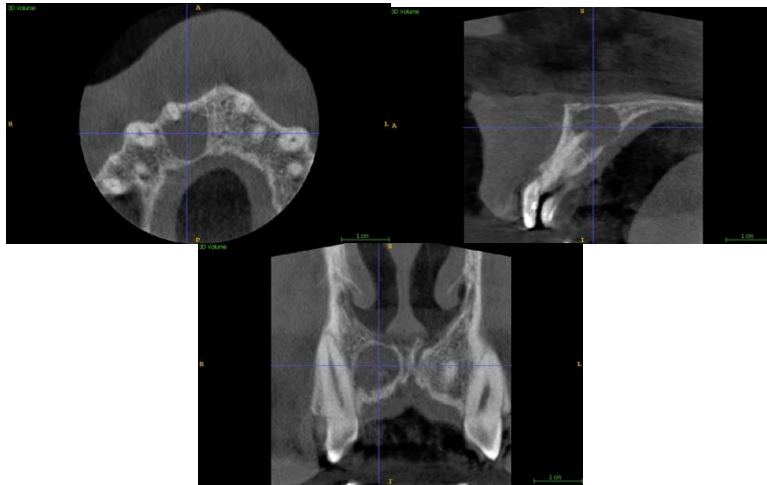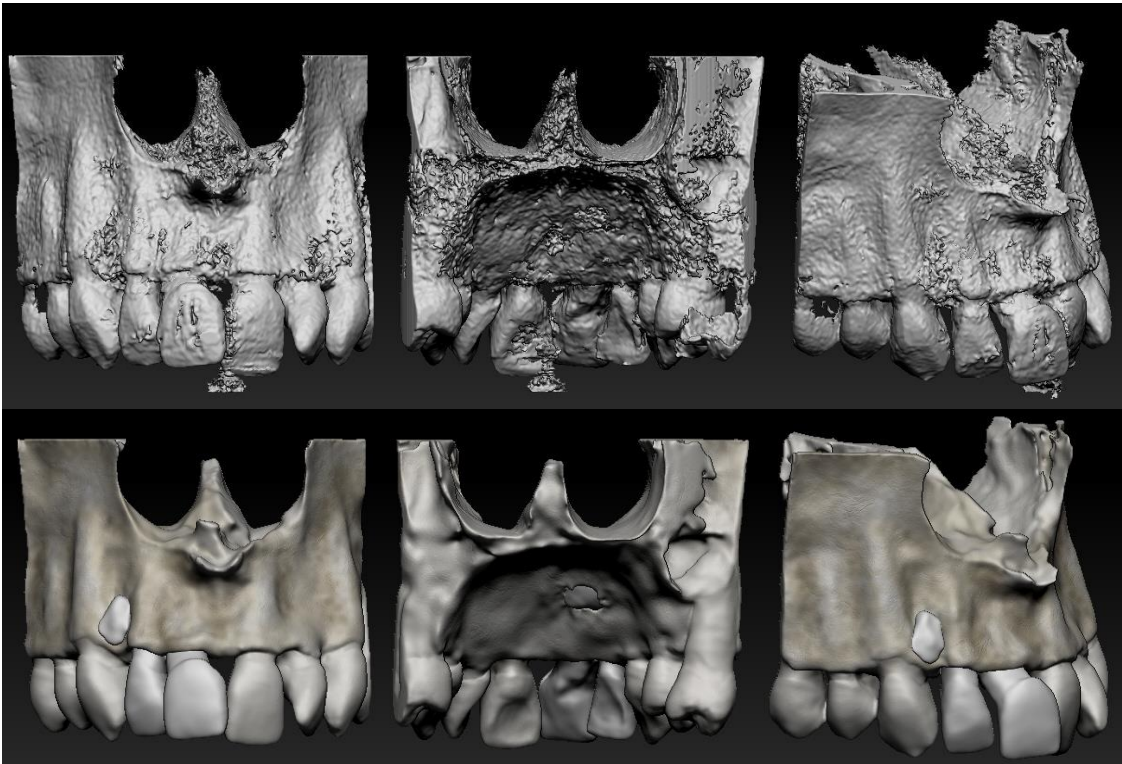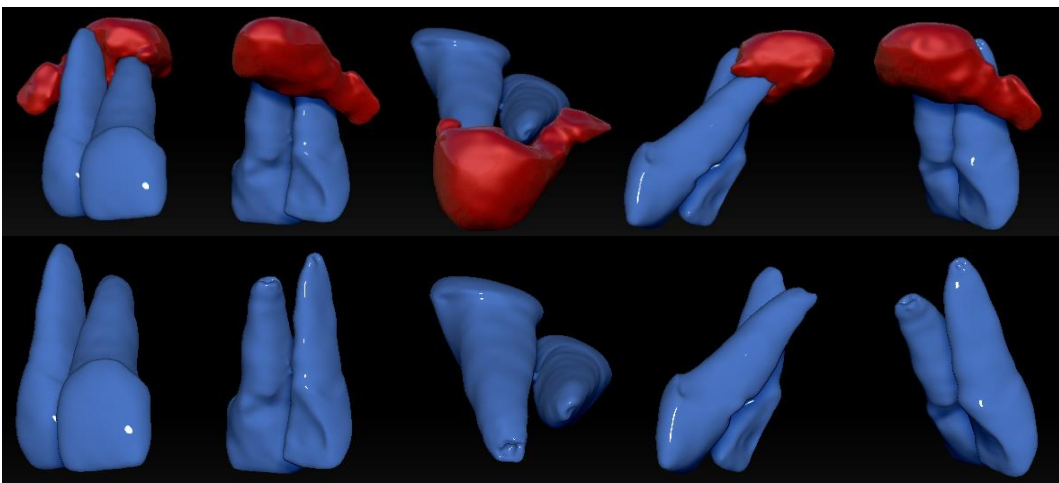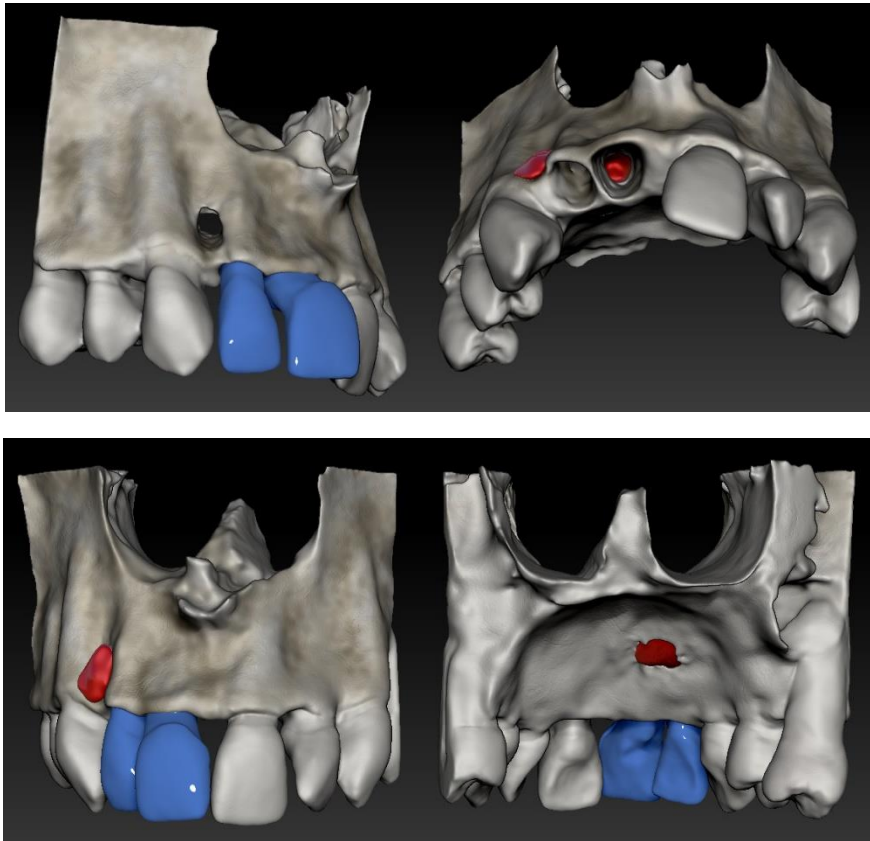
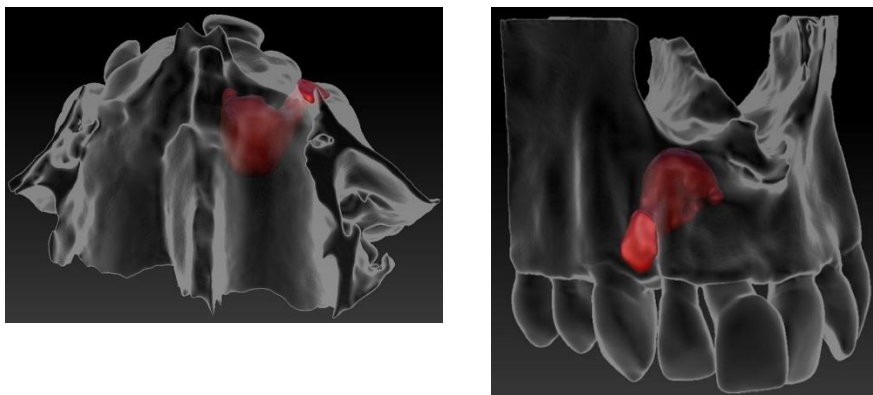*Figure 1. CBCT image and volumetric rendering*

Figure 2. Noise reduction of the CBCT image shown in the Figure 1. by segmentation technique

Figure 3. 3D visualization of the periapical inflammation of the upper right central incisor created by segmentation based on the CBCT image of Figure.1

Figure 4. 3D model of the case presented above

Figure 5. 3D model of the case presented above

Figure 6. Teeth printed with different materials and techniques

2. ANALOG MODELING

2.1. Embedding teeth

By embedding the samples, the bony support is mimicked. In normal conditions the physiological bone level is located 2 mm apically from the cemento-enamel junction (CEJ) of teeth. If we want to simulate reduced periodontal support, the level of the embedding material must be positioned even more apically from the above mentioned normal level. The simulation of furcation involvement in multi-rooted teeth, when the level of bone is withdrawn until the level of root distribution, is of particular clinical significance. As furcation-involvement can develop in varying extent and severity, only those conditions worth modeling in studies that still fall into the sustainable category. The presence of furcation involvement also depends on the anatomical parameters of the tooth, such as the apico-coronal dimension of the root trunk, which would influence the distance between the embedding material and the CEJ in any study. In case of Class I and II furcation involvement, the level of bony support is approximately 4-6 mm apically from the CEJ. During embedding of molar teeth, the occlusal surface is positioned parallel to the tabletop and is retained in this position. Accordingly, the most coronal part of the embedding material will also create a parallel surface. With this setting, we can simulate horizontal bone loss, which characterizes the clinical appearance of chronic periodontitis.

Based on the available literature, the embedding material is mainly acrylate resin in in vitro studies. For instance, Technovit 4004 (Heraeus-Kulzer) acrylate resin was used in the studies of the Biomechanical Research Group in Szeged [9-14]. The material is available in powder-liquid form. After mixing, it is poured into plastic cylinders and the teeth are embedded to the appropriate levels. Because the embedding material easily creeps on the inserted object, areas that are not intended to be embedded and are exposed to the former phenomenon should be blocked out with modelling wax. This is a particularly important step when modeling teeth with furcation-involvement (Figure 7-10).

We would like to emphasize that realistic modeling also requires the simulation of periodontal ligaments. Periodontal ligaments establish a functional connection between the alveolar bone and the cementum covering the root surface. They play crucial role in force transmission, enabling the teeth to move physiologically approximately 0.05 mm in the alveolus. In their absence, the physiological mobility of teeth, the force transmission, the local remodeling of the alveolar bone and the thickness of the cementum would change. Moreover, a model without ligaments would simulate a clinically rare, so-called ankylotic condition, which is more relevant when examining implants. In our studies, the surfaces of the roots are coated with a rubber separating agent (Rubber-Sep, Kerr, Orange, CA) according to the degree of embedding [15-17]. The separating material is applied in a single thin layer to the root surface. This can be

done with a factory-packaged nail polish brush in a single layer, thus standardizing the thickness of the separator as much as possible. There are also other material options to simulate periodontal ligaments, e.g., polyether impression material, polysulfide impression material, latex, or polyurethane. In case of the latter materials, the root is dipped into liquid, but due to the flow of the material, towards the apex of the root the separating medium will not appear evenly, but rather in excess, which makes these techniques less standard and the model less realistic.
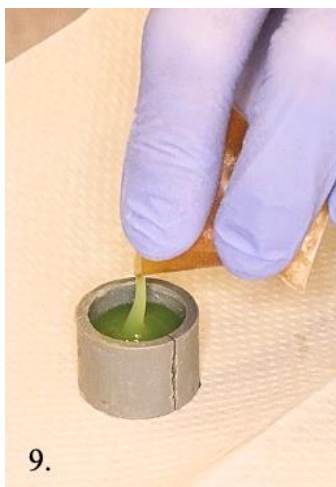
Figure 7. Application of the separator
Figure 8-9. Mixing and molding of embedding material
Figure 10. The finished sample

Embedding is followed by mechanical testing of the samples. In our previous article we have already thoroughly overviewed the advantages, disadvantages, objectives, and rationale of the static fracture test [15].

If our equipment enables us, it is always worth performing dynamic loading tests on analog samples to analyze fatigue performance. The classical dynamic loading test represents one of the most valid mechanical loading methods, as it enables us to reproduce the oral conditions during chewing almost

perfectly. This means teeth are loaded with relatively small, repetitive forces through endless cycles, simulating chewing periods and time spent in oral function up to several years. When the samples are loaded in liquid (fluid chamber), we get the currently most valid mechanical testing method possible. However, from a practical point of view it must be mentioned that the classical dynamic loading is extremely time-consuming (loading 1 sample can last up to 1 week in 0-24), so it does not only make it almost impossible to perform tests and comparisons with larger sample size and group numbers, but also requires shift work from the staff.

While static load-to-fracture tests mimic a sudden, greater force, traumatic injury, the dynamic loading is more intended to illustrate the mechanical consequences of the forces occurring during ordinary chewing. An accelerated dynamic loading test represents a realistic compromise between the two extremes. In this test, although cyclic loading occurs, the magnitude of the force is not constant (only within a given cycle) but increases after a given number of cycles for the duration of the next cycle. In this specific testing it is recommended to increase the applied force until reaching the maximum chewing force of the given tooth group or oral region. As the samples are subjected to dynamic loading, we will not be able to obtain their fracture resistance values, but rather their fatigue and survival rates, which are clinically more informative data. In addition, the great advantage of this test is that the samples can be tested within a reasonable time (hours), so in terms of time consumption, it takes place in between the static load-to-fracture test and the classical dynamic loading test [18,19].

In case of periodontally affected teeth, it is of paramount importance that a dynamic loading test (classical or accelerated) should be performed first, and after that the survived samples should undergo static load-to-fracture test also. Even if dynamic is always the best, static load-to-fracture test should also be carried out in this special situation, because clinically more mobile teeth –due to either the reduced periodontal support (furcation involvement, etc.) or root amputation– are more prone to sudden facture compared to their sound, periodontally not compromised counterparts [15,17].

3. DIGITAL MODELING

3.1. Finite element method (FEM)

Independent of which way (analog or digital) we approach the topic, preliminary information gathering is required. In the analog approach, we create real models –first a prototype in general– that allows us to perform the steps of the planned test and if it succeeds, we proceed the test with a larger sample size. Usually, creating a model/sample consumes a lot of time and energy, so the question arises, whether this time-consuming step could be replaced by a method that can substitute it or not.

The digital, finite element method (FEM) does not require the production of real models, the tests can be performed on virtually created digital models using a special software such as Comsol or Ansys, which is widely used in engineering. The FEM is a numerical method. Its operational concept is to break down the created geometries into finite number of smaller elements – hence the name 'finite element'– thus simplifying it. This means that the dimensions of spatial elements are discretized, and the equations describing the problem can be solved algebraically by specifying the geometries and meshing, then specifying the boundary conditions (for example, load, support surfaces, etc.). Analysis performed by FEM methods is called Finite Element Analysis (FEA).
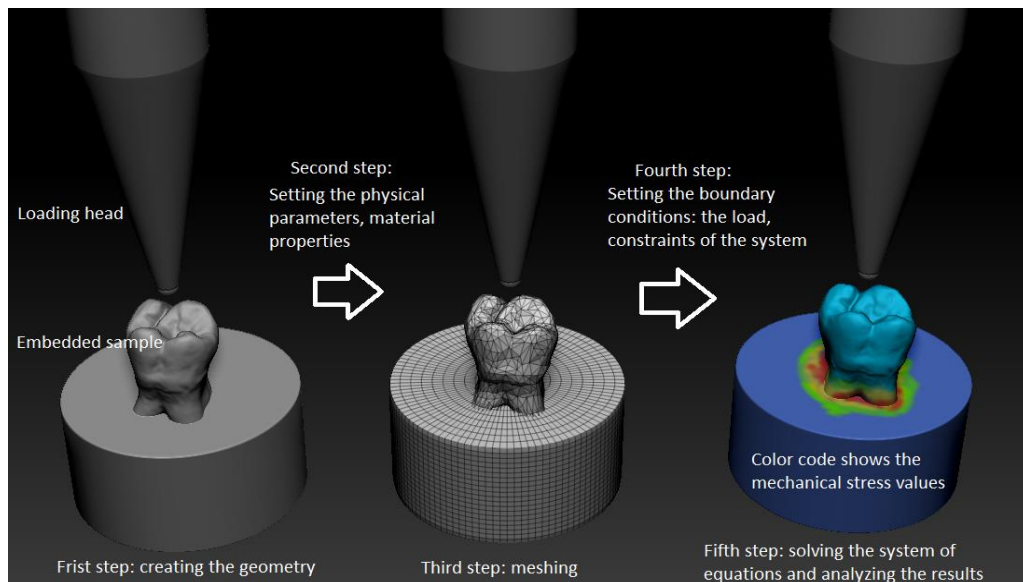
*Figure 11. Steps of FEM in our field of interest*

Its application is diverse and widespread: extremely popular in mechanical engineering but can be found in many fields of science as well. The method can even solve complex dental problems, such as deformation of a body under load or heat conduction in certain materials. It is also possible to utilize FEM in our research topic with a suitable software.

The first step in this process is to create the 3D object we want to work with, in our case it will be a 3D scanned tooth that we can import into the finite element calculation software.


Figure 12. The created 3D object that we will work with

During the experimental measurements, the teeth are embedded in Technovit poured in cylindrical holders. The level of embedding – or other parameters – can be adopted to the situation we want to reconstruct. This can also be done in the software by creating an appropriately sized cylindrical geometry of around the tooth (Figure 13).
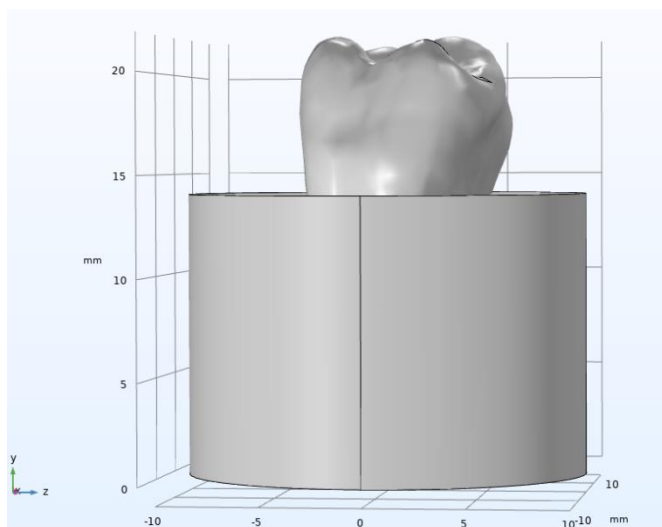
*Figure 13. The imported tooth is surrounded by the cylindrical geometry*

For subsequent calculations, it is necessary to determine what material the created geometries are made of. There is a built-in library in the programs, in which we can find the one that suits our purposes, or we can create any material constant for the program. For example, if the mechanical parameters of the tooth have been found in the literature (such as Young's modulus, density, and Poisson's ratio) (Figure 14) and parameters of Technovit from the manufacturer's site, we can enter all data using the latter method.
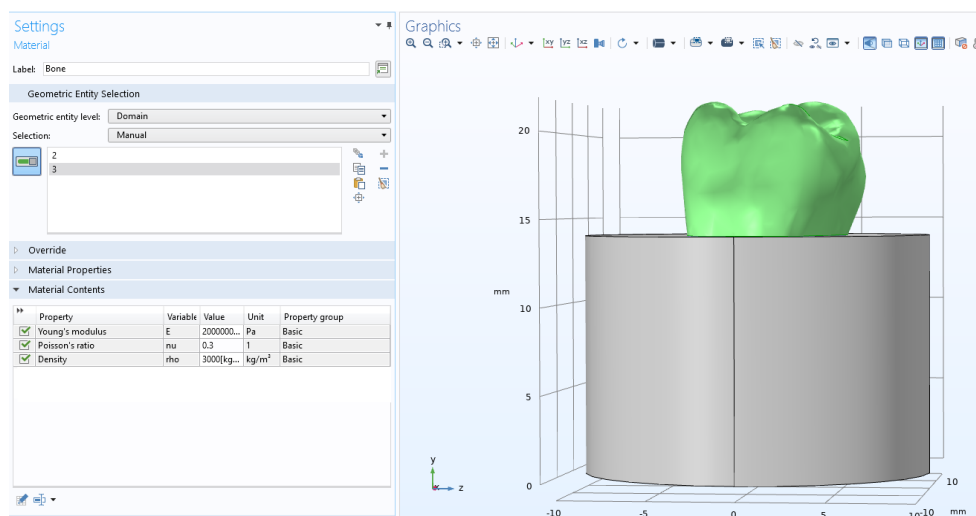
Figure 14. The material parameters of the created geometries must be determined

In the next steps, the boundary conditions must be determined, where the constraints of the system are given and the surfaces are selected, where the forces will be applied (Figure 15). In order to do this, you need to select the associated surfaces.

In our case, the bottom of the cylindrical embedding material will be the support surface. On the surface of the tooth, we can adjust how much load we want to exert (e.g., during mastication or during the experiment).
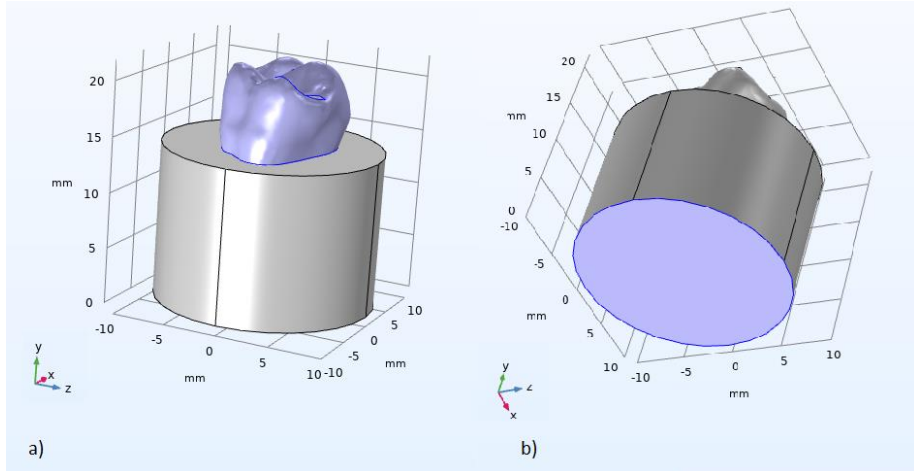

Figure 15. In the software settings we can select the loading and support surfaces. The loaded surface is on the left and the support surface is on the right.

In the case of FEM, we discretize the system and only have to solve the given problem for small surface elements. The next step, then, is to divide the surface into these smaller elements, called the mesh of the body (Figure 16).
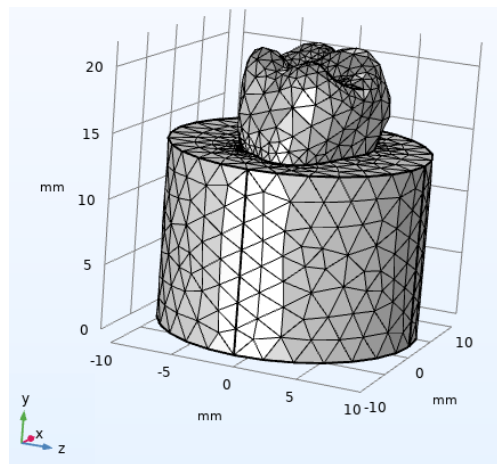
Figure 16. Mesh geometry.

Finally, we perform the calculations, in this case, we work in the mechanical module of the software. As a result, we can visualize the mechanical deformations in the material, as well as the different mechanical stress values represented by color coding. If we switch to transparent mode, we can see through the material, and the changes can be seen (Figure 17).
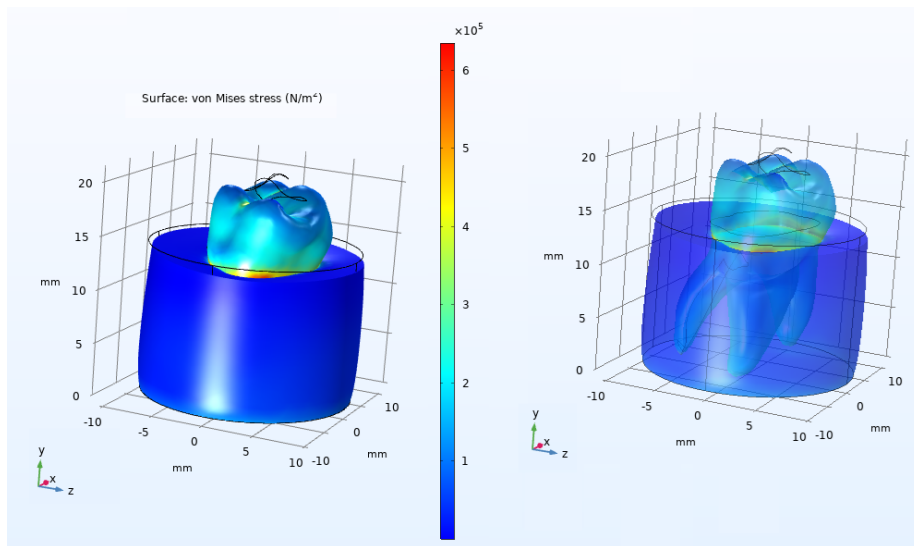
Figure 17. Distribution of mechanical stress in the material is visualized by color coding. The mechanical stress values and the deformation of the sample is shown on the left and in transparent mode on the right.

4. SUMMARY

In our article, we have generally presented our experiences in connection with the modeling of mechanical tests performed on periodontally compromised teeth. In addition, we dealt with preliminary data acquisition, which is essential for the establishment of an appropriate research plan. A significant part of dental studies is in vitro, and with the rapid development of technology we have better and better opportunities to implement them. The continuous improvements of new, up-to-date materials, techniques, equipment, and devices are available on both the analog and digital palettes. Accordingly, better and better real physical study models can be prepared, but the same can be observed in the digital world. It is extremely promising that with the help of more complex software and faster computers, real physical experiments can be simulated, but they cannot be replaced yet, maybe they never will be. We will see what the future holds, until it is essential to pay attention to the advances of both approaches and benefit from their present advantages, if possible.

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REFERENCES

[1.] Eke P. I., Wei L., Borgnakke W. S., Thornton-Evans G., Zhang X., Lu H., McGuire L. C., Genco R. J. (2016): Periodontitis prevalence in adults ≥ 65 years of age, in the USA. Periodontol 2000. 2016 Oct;72(1):76-95. doi: 10.1111/prd.12145.

[2.] Eke P. I., Dye B. A., Wei L., Slade G. D., Thornton-Evans G. O., Borgnakke W. S., Taylor G. W., Page R. C., Beck J. D., Genco R. J. (2015): Update on Prevalence of Periodontitis in Adults in the United States: NHANES 2009 to 2012. J Periodontol. 2015 May;86(5):611-22. doi: 10.1902/jop.2015.140520.

[3.] Albandar J. M. (1990): A 6-year study on the pattern of periodontal disease progression. J Clin Periodontol. 1990 Aug;17(7 Pt 1):467-71. doi: 10.1111/j.1600-051x.1990.tb02346.x.

[4.] Albandar J. M., Rise J., Gjermo P., Johansen J. R. (1986): Radiographic quantification of alveolar bone level changes. A 2-year longitudinal study in man. J Clin Periodontol. 1986 Mar;13(3):195-200. doi: 10.1111/j.1600-051x.1986.tb01459.x.

[5.] American Academy of Periodontology. Glossary of Periodontal Terms. 4th ed. American Academy of Periodontology; Chicago, LA, USA: 2001. [(accessed on 2 November 2017)].

[6.] Lindhe J., Socransky S. S., Nyman S., Haffajee A., Westfelt E. (1982): "Critical probing depths" in periodontal therapy. J Clin Periodontol. 1982 Jul;9(4):323-36. doi: 10.1111/j.1600-051x.1982.tb02099.x.

[7.] Palkovics D., Mangano F. G., Nagy K., Windisch P. (2020): Digital three-dimensional visualization of intrabony periodontal defects for regenerative surgical treatment planning. BMC Oral Health. 2020 Dec 1;20(1):351. doi: 10.1186/s12903-020-01342-w.

[8.] Palkovics D., Solyom E., Molnar B., Pinter C., Windisch P. (2021): Digital Hybrid Model Preparation for Virtual Planning of Reconstructive Dentoalveolar Surgical Procedures. J Vis Exp. 2021 Aug 5;(174). doi: 10.3791/62743.

[9.] Fráter M, Forster A, Keresztúri M, Braunitzer G, Nagy K. In vitro fracture resistance of molar teeth restored with a short fibre-reinforced composite material. J Dent. 2014 Sep;42(9):1143-50. doi: 10.1016/j.jdent.2014.05.004.

[10.] Forster A, Braunitzer G, Tóth M, Szabó BP, Fráter M. In Vitro Fracture Resistance of Adhesively Restored Molar Teeth with Different MOD Cavity Dimensions. J Prosthodont. 2019 Jan;28(1):e325-e331. doi: 10.1111/jopr.12777.

[11.] Sáry T, Garoushi S, Braunitzer G, Alleman D, Volom A, Fráter M. Fracture behaviour of MOD restorations reinforced by various fibre-reinforced techniques - An in vitro study. J Mech Behav Biomed Mater. 2019 Oct;98:348-356. doi:10.1016/j.jmbbm.2019.07.006. Epub 2019 Jul 9. Erratum in: J Mech Behav Biomed Mater. 2020 Feb;102:103505.

[12.] Fráter M, Sáry T, Vincze-Bandi E, Volom A, Braunitzer G, Szabó P B, Garoushi S, Forster A. Fracture Behavior of Short Fiber-Reinforced Direct Restorations in Large MOD Cavities. Polymers (Basel). 2021 Jun 23;13(13):2040. doi:10.3390/polym13132040.

[13.] Fráter M, Lassila L, Braunitzer G, Vallittu PK, Garoushi S. Fracture resistance and marginal gap formation of post-core restorations: influence of different fiber-reinforced composites. Clin Oral Investig. 2020 Jan;24(1):265-276. doi: 10.1007/s00784-019-02902-3. Epub 2019 May 16. Erratum in: Clin Oral Investig. 2021 May;25(5):3339-3340.

[14.] Fráter M, Sáry T, Jókai B, Braunitzer G, Säilynoja E, Vallittu PK, Lassila L, Garoushi S. Fatigue behavior of endodontically treated premolars restored with different fiber-reinforced designs. Dent Mater. 2021 Mar;37(3):391-402. doi:10.1016/j.dental.2020.11.026.

[15.] Szabó P. B., Sáry T., Szabó B. (2019). The key elements of conducting load-to-fracture mechanical testing on restoration-tooth units in restorative dentistry. Analecta Technica Szegedinensia. 13. 59-64. 10.14232/analecta.2019.2.59-64.

[16.] Szabó B, Eördegh G, Szabó PB, Fráter M. In vitro fracture resistance of root amputated molar teeth restored with overlay: a pilot study. Fogorv Szle. 2017:111-116.

[17.] Szabó B, Garoushi S, Braunitzer G, Szabó P B, Baráth Z, Fráter M. Fracture behavior of root-amputated teeth at different amount of periodontal support – a preliminary in vitro study. BMC Oral Health. 2019 Nov 27;19(1):261. doi:10.1186/s12903-019-0958-3.

[18.] Fráter M, Sáry T, Néma V, Braunitzer G, Vallittu P, Lassila L, Garoushi S. Fatigue failure load of immature anterior teeth: influence of different fiber post-core systems. Odontology. 2021 Jan;109(1):222-230. doi:10.1007/s10266-020-00522-y.

[19.] Fráter M, Sáry T, Braunitzer G, Balázs Szabó P, Lassila L, Vallittu PK, Garoushi S. Fatigue failure of anterior teeth without ferrule restored with individualized fiber-reinforced post-core foundations. J Mech Behav Biomed Mater. 2021 Jun;118:104440. doi: 10.1016/j.jmbbm.2021.104440.