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INFLUENCE OF DIFFERENT RESTORATIVE
PROCEDURES ON STRESSES IN TOOTH TISSUES
AND RESTORATIVE MATERIALS: A FINITE
ELEMENT STUDY

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*Quel che il Sole è per i fiori, i sorrisi lo
sono per l'umanità. (J.Addison)*

*Ai miei genitori che da sempre credono
in me e a te, Luciana, che col tuo sorriso
e col tuo amore sapevi sempre
raddrizzare ogni cosa.*

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*FIRST CHAPTER:
INTRODUCTION*

1. INTRODUCTION

Endodontic treatment is indicated when the tooth is severely damaged by caries or trauma or when the pulp is nonvital or has been removed to prevent or treat apical periodontitis. The root canal treatment is used to maintain asepsis or to disinfect the root canal system, adequately.

The loss of tooth structure, due to the cause itself, and moreover, due to the access cavity preparation, leads to changes in the biomechanical properties of teeth. As a result, the risk of tooth fracture increases, and the longevity of the restoration is compromised. This is particularly the case in premolars, owing to their specific morphology and position in the tooth arch. They are subjected to higher masticatory forces than the front teeth, but their crowns are not as massive as the molar crowns. In addition, if mesial-occlusal-distal (MOD) cavity is present, the tooth susceptibility to fracture is increased due to the loss of the marginal walls, and this effect is even more severe in endodontically treated teeth due to the access cavity preparation.

Restoration of an endodontically treated premolar with a wide cavity is often complex due to biomechanical weakening of the tooth. There are no definitive recommendations on the optimal restoration in these cases.

It is necessary to consider different parameters in order to properly clean and obturate the canal. Firstly, the canals of maxillary premolars are oval in the majority of cases so it is necessary to use instruments of larger diameters. However, since the instruments have a round cross-section, and the canal is oval, this causes in certain cases excessive loss of tooth structure and could weaken the tooth. Secondly, another endodontic parameter is the apical terminus of the endodontic preparation. It has been advocated that the apical terminus should end 0-3 mm from the radiographic tooth apex, preferably at the apical constriction, depending on the diagnosis – infected canals require deeper apical terminus. Although tested from the biological aspect, this parameter has never been considered from the biomechanical point of view.

From the previous considerations it is clear that planning the restoration of such a tooth is complex and has been debated in literature. Traditionally, a full crown would be the treatment of choice for the restoration of premolars with a cavity and massive tissue loss. With the technological progress and the introduction of dental resin composite materials and adhesive systems of improved characteristics, nowadays composite resin fillings are often the restoration of choice in such cases. Furthermore, they require less chair time and are much more affordable than the indirect restorations. Despite the adequate aesthetic and mechanical properties, and affordable price, it was shown that the direct resin composite fillings alone might not be sufficient to ensure the longevity of an endodontically treated tooth.

Therefore, additional procedures, such as the palatal and buccal cusp reduction, and/or fibre-reinforced composite (FRC) posts, were suggested. Both of these procedures entail removal of additional dental tissues. Thus, the question emerges whether these procedures are beneficial for the survival of the tooth and the restorations, or whether the additional removal of healthy dental tissues only further weakens the tooth. Also, the properties of composite materials might not still be sufficiently improved to prevail over the classic crown but should be considered in terms of minimally invasive dentistry. The final restoration after an endodontic treatment should follow the principles of biomimetics, which surprisingly, does not always imply the use of materials with mechanical properties close to dentin, but stiffer materials that would provide protection to the tooth tissues.

Nowadays a widely used research method in biomedical sciences is finite element analysis (FEA), because of its precision and a variety of possibilities in the calculations of stress and strain in complex three-dimensional (3D) biomedical models. Recently, modern bioimaging techniques, such as computed tomography (CT) and micro computed tomography (μ CT), are used to gain information for the creation of high-quality 3D models of complex biostructures which contributes to the accuracy of FEA.

The aim of this FEA study was to determine the effect of different post-endodontic restoration on the von Mises stress values and distribution in dental tissues and restorative materials, using a CT-scan based 3D model of an endodontically treated upper second premolar.

SECOND CHAPTER:
ADHESION

2. ADHESION

In the restorative dentistry the first point is to rehabilitate a tooth a tooth which has lost its integrity due to different reasons. If we have an injury to the mineralized tissues, a “restitutio ad integrum” is not possible and it is important to have materials with esthetical and functional performance near to the characteristics of enamel and dentin.

The acid-etch technique for bonding composite resins to enamel has completely revolutionized the practice of restorative dentistry. The beginning of the adhesive and restorative dentistry was laid in 1955, when Buonocore experimented that “acids could be used to alter the surface of enamel to render it more receptive to adhesion. In particular, Buonocore found that acrylic resin could be bonded to human enamel conditioned with 85% phosphoric acid for 30”.¹

“Acid etching removes about 10 μm of the enamel surface and creates a porous layer ranging from 5 to 50 μm deep. When a low-viscosity resin is applied, it flows into the micro-porosities and channels of this layer and polymerizes to form a micromechanical bond with enamel. Etching also increases the wettability and surface area of the enamel substrate.” (Edward J. Swift Jr., 1995)

The introduction of this new concept changes also the preparation of the cavity from the idea of “EXTENSION FOR PREVENTION” introduced by Block to the new idea “PREVENTION OF EXTENSION”, that helps in the preservation of the healthy tissues.

2.1. DEFINITION

The American society of testing and material defines bonding as “the layer where two substrates are withheld together from strengths of the interface, which could be mechanical, chemical or a combination of these.” (Packham, 1992)

Adhesion is a measure of the force of attraction between two different materials and is differentiated from cohesion in that the latter relates to the forces of attraction within a single material, ie, the forces holding it together. (L. Breschi, 2013) Adhesion can be the result of

the formation of primary chemical bonds, like covalent, ionic or metallic and also can result from strong secondary forces, such as hydrogen bonds and Van der Waals forces. However, it is possible to say that adhesion *depends on strong molecular interactions between two surfaces in intimate contact*. Both types of interactions are evident in dental adhesive materials.

The relations between two surfaces or materials depends on many factors, and the most important one is related to energy.

In nature, there is a tendency to keep the energy state reduced because it is the most stable condition. The internal bonds have a lower energy than the one on the surfaces. This is due to the unsatisfied bonds of the molecules of the surfaces. The reason for this is that the molecules “would prefer to be covered by other molecules to satisfy their bond complexes and reduce their overall energy state.” (L. Breschi, 2013)

Surfaces are more receptive to have bonds with other materials, such as an adhesive, if they have high level of energy.

There are some practical approaches to raise the energy of a surface, in particular in dentistry, cleaning with pumice or prophylactic pastes, etching with acids or cleaning with solvents to remove contaminants are used.

When an adhesive is applied to a surface for bonding, it will spread out on the surface. This spreading is called **WETTING** and it is important to keep this physical effect in order to have a good bonding.

It is important to consider one critical property of the adhesive that affects the spreading: it is the SURFACE TENSION of the adhesive itself. If this property is very high the adhesive will bead up and not spread. “*An ideal condition for bonding is to have a substrate with high surface energy, and an adhesive with low surface tension.*” (L. Breschi, 2013)

The chemistry of the adhesive is very important and it determines how well it will wet the substrate and hence how strongly it will attach.

The adhesion is influenced by certain critical variables, such as “the surface roughness of the substrate, its cleanliness, the viscosity of the adhesive, the dimensional change occurring in the adhesive during setting and the durability of the adhesive and the new interface.” (Marshall SJ, 2010)

A rough surface, when there is microscopic roughness, may produce a very high surface area and increase surface interactions, so that the adhesive can spread onto the surface and flow into the irregularities. This is also the reason why the viscosity is important, indeed if the adhesive is too viscous it will not flow sufficiently and cannot satisfy all the theoretical bonds with the molecules present on the surface in order to create the required intimate contact. On the other hand, if the adhesive is too liquid it will not stay in place on the substrate. This is the reason why most adhesives or primers for creating bonding to dentin have solvents to reduce their viscosity.

The need for cleaning the surface depends on the possibility to have a contamination of the substrate with molecules that have a similar affinity for the surface, so that they can reduce the bonding strength, creating an unstable situation. It's possible to have a good isolation with rubber dam, cotton rolls and other techniques, which allow the removal of frequent contaminants of tooth surfaces, like water, saliva and blood.

2.2. SUBSTRATES

The enamel and the dentin react in different ways to the acid etching, because of the different compositions of these substrates. The adhesion is affected by the high concentration of organic material in dentin, specifically collagen, as well as the significant water content of the latter. (L. Breschi, 2013) Both substrates are highly hydrophilic. The development of adhesive primers with enhanced hydrophilicity as agents for preparing the surfaces for bonding to the resin, which is more hydrophobic. In the oral cavity there are some conditions that can affect the properties of the enamel and dentin and this can influence the bonding, such as caries process, developmental anomalies, such as amelogenesis imperfecta, or erosion. These substrates may be more difficult to bond to because they are weakened as a result of the hypomineralization. On the other hand exposure to mineralizing solutions, such

as fluoride, may produce hypermineralized enamel, which may requires a longer etching time to produce an adequate surface for bonding.

The tooth is composed of two morphologically different hard tissues and it influences the restorative technique.

ENAMEL

Enamel is a tissue with a high mineral content, it is composed of hydroxiapatite (95%) , water (4 %) and only 1% of organic matrix and collagen. The enamel crystals are 1 micron long and as shape they are like prisms. (Mjor IA, 2000)

The enamel is a hard tissue which does not modify itself during the entire life, while the dentin is a tissue that matures and modifies itself with the time, this is an active substrate which responds to the external stimulus.

DENTIN

The dentin is composed of a lower percentage of mineral component, and a higher percentage of the organic part compared to enamel. It is composed of 65 % hydroxiapatite, 22% of organic matrix for the and 13% of water. The crystals of this part are smaller than the enamel ones (50-60 nm) and their orientation follows the organic matrix. The matrix is composed mainly from type I collagen fibrils (90%), and the remaining 10% from proteoglycans, phosphoproteins, glycoproteins, carboxyglutaminic acid. (Mjör IA, 1986)

Dentin is characterized by the presence of dentinal tubules. The tubules are filled by the dentinal fluid, rich in protein, and the dendritic processes of the odontoblasts, called Tomes processes. These cells produce the collagen matrix that mineralizes and transforms to dentin. (Mjor IA, 2000)

The pulp-dentinal complex responds to external injuries with dentin sclerosis (DS), dead tracts (DT), or reparative dentin (RD). (Schultz, 1983)

The dentin has a physiological aging, which is called physiological dentin sclerosis and it is due to the deposition of DT until the complete closure of the tubules and the reduction of the pulp. (John Nalbandian, 1960)

When there is the deposition of the RD it leads to pathological dentin sclerosis characterized by the irregular trend of the tubules, which are often sclerotic and with low sensibility to the external injures (Lindemuth, 1991; Meerbeek, 1994; Yoshiyama M M. J., 1989; Yoshiyama M N. Y., 1990; Tagami J, 1992; Voegel, 1989; Stanley HR, 1983; Yamada T, 1983)

These structural alterations make the dentin a less receptive substrate for adhesion. (Mjor, 1987; Lindemuth, 1991; Burrow MF, 1994)

Another problem is the wetness of dentin, which makes the adhesion more difficult. The fluid quantity depends on different factors like the diameter, the length of the tubules and the dimension of the molecules inside. There is more liquid in the tubules near the pulp, because the diameter of the tubules is higher in the apical portion. (Reeder OW, 1978; Pashley, 1979)

Acid etching is used to increase the patency, because it removes the smear layer and the smear plug. The smear layer is the part full of detritus caused by dentin instrumentation during. This layer is really thin (1-5 μm), and it influences adhesion. The smear layer is incorporated within the hybrid layer (self-etch technique), or completely removed (etch-and-rinse), so that the adhesive can reach the demineralized dentin. (Pashley, 1984; Swift EJ, 1995; Pashley DH C. R., 1997)

The present water has two different roles: on one hand the humidity gets in the way of adhesion because it competes with the adhesive (Douglas, 1989; Erickson, 1992); on the other hand a wet environment, after the etching, is important to sustain the collagen fibers, really important in the adhesion. (Pashley DH C. B., 1993; Titley K, 1994)

The ADHESION will be influenced by these morphological differences, so it will change in relation to the substrate.

ADHESION ON ENAMEL

For the adhesive restoration to be successful, it is pivotal to have a strong bond between the adhesive and its substrate. The substrate has to have the surface free energy bigger than the surface tension of the adhesive. (Goracci, 1994)

The enamel is not a tissue with high surface energy, because it presents on its surface a micron of amorphous substance. It is like a cover and it is the last substance the ameloblasts make before their degeneration, which is called Nasmyth membrane and has the aim to protect the tooth from acid attack. (Goracci G M. G., 1995)

Furthermore, the presence of the smear layer reduces the surface free energy and this is the reason why on the enamel acid etching is fundamental. (Silverstone LM, 1975)

The acid etching has two aims: it removes the smear layer and the superficial cover and it makes the enamel porous and available for a micro-mechanical bond with the adhesive. (Augusti, 2006)

These microporosities allow the resin to create interdigitations called resin tags, which are divided in two groups: the macro-tags around the enamel prisms and the micro-tags in the center of the enamel prisms. (Bayne SC, 1982)

After this phase it is important to remove all the remnants of the etching gel and the degradation products rinsing with water for at least 15 seconds. (Breschi L F. P., 2009)

ADHESION ON DENTIN

Dentin for its structure is a substrate not so good to have an adhesive bond. The adhesion values are better in the superficial portion, where the mineralized is higher and the humidity is low, while near the pulp those parameters are worst. (Shams, 1995; Yoshiyama M C. R., 1995) Initially, the etching of dentin was not recommended because it seemed to cause damage to the pulp. (Michelich V, 1980; Stanford, 1985; Fusayama, 1988; Qvist V, 1989)

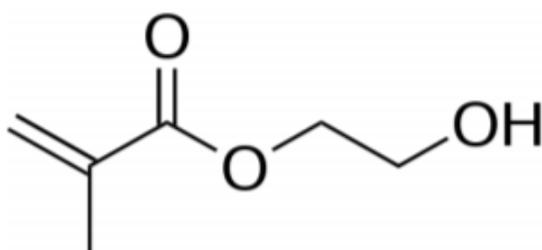
On the contrary, nowadays it was demonstrated these problems were due to contaminants or micro-gap at the restoration and that etching for 15 seconds is a fundamental step in the

adhesive procedure on dentin. (Pansecchi, 2009; Prati C, 1998; Van Meerbeek B D. M., 2003; Breschi L M. A., 2008)

The correct depth of dentin demineralization if a correct etching time is used should be 1-2 μm , because if it is greater could be more difficult the complete penetration of the resin inside the collagen matrix could be difficult, and the interface would be more vulnerable. (Erickson, 1992)

In order to envelope the collagen matrix in the adhesive it is necessary to use a primer, because the adhesive is hydrophobic while the collagen needs a wet environment. The primer is composed of amphiphilic molecules, which have an hydrophilic group to interact with the collagen of the dentin and a methacrilate group to interact with the monomers of the adhesive. (Erickson, 1992; Grandini R, 1999)

The primer is composed primary of HEMA (2-idrossietil-metacrilato) (Fig 1 (Pesce, 2010)) with an excellent wettability and depending on the formulation can have also other monomers, such as NTG-DMA (N-tolilglicin glicidil metacrilato), PMDM (Acido piromellitico dietilmetacrilato), BPDM (Bifenil dimetacrilato), PENTA (Dipentaeritritol penta acrilato monofosfato). (Nakabayashi N T. K., 1992)



*Fig 1 HEMA structure
(Pesce, 2010)*

After the phase of apposition of the primer, there is the application of the bonding. The bonding has the aim to create a solid bond between the dentin and the composite resin with a double mechanism: the infiltration of the collagen fibers, and the interdigitation inside the dentinal tubules with the formation of resin tags. The bonding is composed of hydrophobic

resinous monomers, like Bis-GMA (bisphenol A-glycidyl methacrylate) and U-DMA (uretan-di- metacrilato), viscosity regulators as TEG-DMA (Etilen glicole dimetacrilato) and a little quantity of hydrophilic monomers such as HEMA (2-idrossietil-metacrilato). (Van Meerbeek B V. L., 2006)

The bonding is applied by rubbing with a microbrush and is spreaded with the air jet, so that every anfractuosity would be reached and the solvent evaporated. (Tsai YH, 1990; Erickson, 1992)

The bonding could be self-curing or light-curing. The most used are the light-curing because the polymerization is faster and if exposed to the light of a lamp with a wavelength of 780 nm, it generates a hybrid layer resistant to polymerization shrinkage. On the other hand, the self-curing adhesive can be useful when isn't possible to reach all the surfaces of the preparation with the light of the lamp. (Fusayama, 1993; Cavalli, 2009)

The HYBRID LAYER is fundamental for the adhesion. This layer is composed of the dentinal collagen completely integrated in the resin of the adhesive and its thickness is 3-5 μm . (Nakabayashi, 1992)

The functions of the Hybrid layer are to:

- be the border resistant to the acid action, giving stability to the bond;
 - give a micromechanical retention to the restoration;
 - be a cushion between the restoration and the dentin and distribute the stress.
- (Nakabayashi N N. M., 1991)

The Hybrid layer is divided in 3 sections:

- SUPERFICIAL, composed by amorphous substance rich in electrons, because of the denaturation of the collagen;
- CENTRAL, where there the collagen fibers are longitudinal and incorporated in the resin;
- DEEP, where we can find the contact area between the dentin and the adhesive.

Moreover, the adhesive makes the resin tags, opened with the etching and closed by the bonding, with the double aim to give a mechanical interaction and to seal off the tubules and the access to the pulp, so that it is protected. The greater the number of resin tags, the greater is the contact surface for the adhesive. This influences the strength of the adhesion of the restoration for the 15%. (Pashley, 1990; Yoshiyama, 1998; Tam, 1994; Jwaku, 1981) (Tam LE, 1994)

ADHESION ON RADICULAR DENTIN

Adhesion at the radicular dentin is different from the coronal ones, because it has a minor number of dentinal tubules (Ferrari M V. A.-G., 2000) and a difference in the cross links between the collagen fibers (Miguez PA, 2004). For those reasons it is a substrate not so appropriate for the formation of a micromechanical adhesion, but the canal structure gives a surface for the adhesion larger than the coronal ones, even if within the endodontic limits (leave at least 4/5 mm of guttapercha and cement).

The accuracy of the procedures is fundamental, because it's important to have a good adhesion to avoid the possibility to have a microinfiltration and also the failure of the endodontic therapy. (Erdemir A, 2004)

Another factor that could be unfavorable for adhesion is the C-factor, but if the lodging of the post is prepared correctly, the quantity of the cement between surfaces is minimal so the contraction stress is insignificant, even if the C-factor is unfavorable. (Bouillaguet S, 2003)

2.3. CLASSIFICATION OF ADHESIVE RESINS

The adhesive system can be divided according to:

- the generation, that is the chronological order
- the type of solvent
- the mechanism of action
- the number of clinical steps:
 - 3-step: the adhesive that has etching, primer and bonding separately. Clinically it is a bit more complex but is considered the gold standard for the adhesion strength and the quality obtained. (Van Meerbeek B P. J., 1998; Van Meerbeek B D. M., 2003; Acquaviva GL, 2004; Breschi L M. A., 2008; Pashley DH T. F., 2011)
 - 2-step: can be subdivided in two categories - self-priming/adhesive and self-etching/primer. The self-priming/adhesive has one solution with primer and bonding, after etching and rinsing, while the self-etching/primer has one solution with etching and primer together, and bond in the separate bottle.
 - 1-step: adhesive in which etching, primer and bonding are in an only solution, called also all in one, or they are in three solutions which have to be united before use. However often to improve the performance a selective etching can be done before the use of these. Without this step it is called “one step pure”

2.4. CEMENTATION OF POSTS

The post can be cemented in different ways, not only using resinous cements, but also zinc oxyphosphate, CVI, CVI plus resin. Nowadays the best choice seems to be the resinous cement used with adhesive technique, because they have a good retention, a low tendency of marginal infiltration and in the first period they reinforce the radicular structure.(Mezzomo E, 2003; Mannocci F, 2001; Mannocci F, 1999; Reid LC, 2003; Nissan J, 2001; Bachicha WS, 1998.

In particular if the walls are thin, it is better to use not rigid posts and cemented with adhesive cementation, so that the stress is well distributed. (Saupe WA, 1996; Katebzadeh N, 1998)

The resin cements can be of different types with different reaction of polymerization: Self-curing; light-curing; or duals.

The self-curing cements begin the polymerization when the two pastes are mixed and have the advantage to polymerize despite the position and the possibilities of the light to reach it. Their disadvantages are the limited processing time and its technique sensitivity.

The light-curing cements contain photoinitiators, which begin the polymerization reaction after the exposition to light beams with a wavelength of 780 nm; virtually they could have an infinity processing time, but if the light doesn't reach all the surfaces it doesn't convert adequately. The dual cements polymerize with both the modalities. (Devoto W, 2009)

The preparation of the post-space has a depth that isn't reachable by the light beams with an adequate intensity. For this reason, it is necessary to use a dual cement or a self-curing cement to obtain a good grade of conversion in all the surfaces. Post in fiber that conduct the light can be useful to improve the polymerization of the light-curing and the dual cement. (Ferrari M V. A., 2001)

THIRD CHAPTER:
POST-ENDODONTIC RESTORATION

3. FRAGILITY FACTORS OF AN ENDODONTICALLY TREATED TOOTH

The endodontic treatment is clinical procedure common in the daily practice. (Weiger R, 1997) The endodontically treated tooth is often subjected to fracture and is defined breakable. (Becciani, 2004; Meister F. Jr., 1980) Initially it was thought that it was due to the dehydration because of the percentage of humidity is lower in the endodontically treated tooth of the 9%. Nowadays this hypothesis is shown not to be valid, because it seems that the external hydration of the tooth in its anatomical context is enough to replace the internal one. (Helfer A.R. 1972, Papa J. 1994, Huang 1992) Another thing to take into consideration is the Vickers hardness before and after the endodontic treatment. (Moore G.E., 1974; Grajower R, 1977; Lewinstein I, 1981) But the most important factor in the reduction of the tooth resistance is the loss of dental substance due to the endodontic treatment, the carious process and also the prosthodontic preparation. (Sedgley CM, 1992) The tooth resistance to fracture is reduced 5 % from the access cavity, while the loss of one or both marginal crests produce a loss of resistance of 46% and 63% respectively. (Reeh ES, 1989)

The elements with a high fracture risk are the endodontically treated teeth with an MOD cavity; furthermore, it was shown that in those elements apical fracture is more frequent the, which compromised tooth restoration. (Hansen EK, 1983; Lagouvaros P, 1989)

However, also the loss of the pulp chamber roof and of the interaxial dentin produces an increase of the fracture risk because of the complete change of the tooth architecture, so that it is less resistant to stress (Fuzzi, 1993).

In the end an important factor is also the age of the tooth: in the old teeth the mineralization of the dentinal tubules and the reduction of the water determine a decrease of structural resistance. (Kishen, 2006)

3.1. THE SUCCESS OF THE ENDODONTIC RESTORATION

Considering at all these unfavorable factors is important for the choice of the restoration that will maximize the chances of the survival.

As we said in the previous chapter (2nd chapter), the adhesive dentistry gives us the possibility to do conservative restoration with an optimal coronal seal, which is an important point to assure the survival of the treated element. (Ray HA, 1995; Tronstad L, 2000; Torabinejad M, 1990; (Khayat A, 1993; Cerruti A, 1998; Berrutti, 1996)

For all these reasons, the endodontically treated tooth was traditionally restored with the build-up preparation with the use of one or more posts and the cementation of a full crown. The survival of such a restoration reported in is 99% after a year; more than the 92% after 5 years and 83% after 10 years. (Yee K, 2018)

However, nowadays it is unjustified because there are partial indirect restorations that are much more conservative. (Sorensen JA M. J., 1984; Linn J, 1994; Cheung Gs, 2003; Shillimburg HT, 1985)

3.2. DIRECT VS INDIRECT RESTORATION

Nowadays the composite is the material very often used for the posterior restoration, because of the improvement of their esthetic and mechanical properties. Also, it is possible thanks to the adhesive techniques that allow a good marginal seal. (Perdigao J, 2000; Lopes GC, 2002)

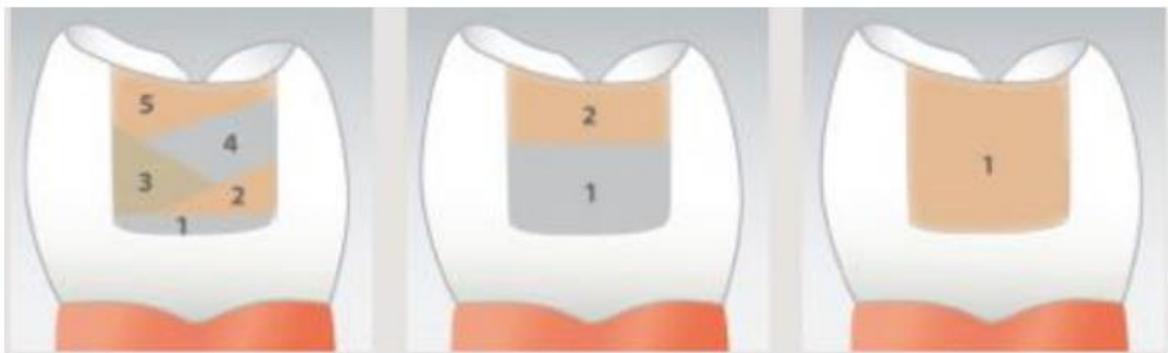


Fig 2 Possible stratification schemes (F. Brenna, 2010)

These materials can be used as a direct restoration and also as indirect restoration. It is important to understand the aim of a restoration and choose a therapeutic option based on the diagnosis: (Spreafico, 2009) (Fichera, 2003)

1. Diagnosis of the lesion
2. Elimination of the lesion
3. To restore the anatomy and function
4. To protect the pulp or to have a good canal seal
5. To have a good esthetic result
6. To facilitate good oral hygiene
7. To prevent a secondary lesion or iatrogenic damage

The direct technique is the most utilized in the posterior teeth if the element is vital. It can be used also in endodontically treated teeth if the lesion is not too large and the dental structure is maintained.

The direct technique uses the stratification system, which is necessary because during the polymerization the composite has a contraction that can make the adhesion ineffective and the marginal seal imprecise. (Lutz F, 1986; Park J, 2008)

There are different techniques of stratification, but they are of similar efficacy. (Kuijs RH, 2003; Versluis A, 1996)

Those techniques are: (Ferracane, 2008)

- Horizontal
- Oblique
- Bulk

The maximum thickness of the composite to have a good polymerization has to be of 2 mm, although the light can't reach all the parts of the material with the correct intensity. So, the maximum incrementation for the stratification must be of 2 mm. (Rueggeberg FA, 2000)

Obviously, it is different when we are going to use a bulk composite where the thickness of the layer and the depth of polymerization is higher.

The advantages are that the direct technique has a minor invasiveness during the preparation, the time necessary is only of one session and also it is the cheapest. However, this technique has some difficulties because it is difficult to reproduce the coronal anatomy and the proximal edges and if the cavity is large, it can present a high contraction stress. (Rasines Alcaraz MG, 2014)

The indirect technique uses the production of LABORATORY artefact. These inlays can be produced with ceramic or composite, both of which have an optimal success in long term. (Dietschi D H. D., 1998; Fuzzi M, 1998; Pallesen U, 2003; Otto T, 2008)

The ceramic one can be stratified by hand or produced by CAD-CAM. (Li RW, 2014)

The advantages of the indirect restorations are that they have a better occlusal anatomy, a good marginal seal and a lower polymerization stress. The disadvantages are that the preparation is much more invasive and includes the healthy tissues, besides the necessity of more than one session and an expensive cost. (Spreafico, 2009; Edelhoff D, 2002)

Recently it was demonstrated that if we have a small or medium cavity, the survival and the clinical success for indirect and direct restoration is quite similar. (Dijken, 2000; Wassell RW, 2000; Pallesen U, 2003) However, if we have a big cavity or 2nd class the indirect restoration was shown to be better than the direct ones. (Iida K, 2003)

Furthermore, when on the cervical edge there is no enamel, the indirect restoration prevents the infiltration, in particular when there is a patient with high risk of caries. (Dijken, 2000)

The direct restoration in endodontically treated tooth can be used when the cavity does not involve the cusps and the marginal crest. In any case, when there is an unfavorable C-factor it requires an evaluation of the thickness of the residual cusps, because the high stress of the polymerization could cause a fracture of the tooth.

It is important for an endodontically treated tooth to have a thickness of the residual cusp at least of 2.5 mm, against 1.5 mm which is the measure for a healthy tooth. (Feilzer AJ, 1987; Re D, 2007.)

Moreover, it was observed that the presence of marginal ridge of 2 mm increases the fracture resistance. (Shahrbaf S, 2007)

3.3. THE RESTORATION OF CHOICE

The partial restorations are nowadays the mostly used in the daily clinical routine, thanks to their advantages.

Firstly, they preserve a great percentage of the dental tissue, the prosthodontic preparation requires the loss of healthy tissue of 4.7% for a mesial or a distal inlay; of 25.5% for a MOD cavity; of the 32.5 % for an onlay; of 33.9% for an overlay and of 73.1% for a full crown. For these reasons a partial restoration allows to save more than 50% of healthy tissue (Edelhoff D, 2002) and these values do not consider the loss of tissue that we have during the endodontic therapy.

Besides, it is to consider the supragingival localization of the margins, that respects the periodontal tissue.

It is to consider also the fact that the partial restoration does not need the ferule effect to have retention and stability, considering that for a full crown a ferule of at least 2 mm is necessary. (McLean, 1998; Veneziani, 2010)

The supragingival margins allow to practice the restorative steps, using the rubber dam, improving the visibility, the precision and with a more control of the humidity and of the quality of the restoration. To those we can add the previous advantages that we mentioned in 4.2 paragraph. (Polesel, 2011)

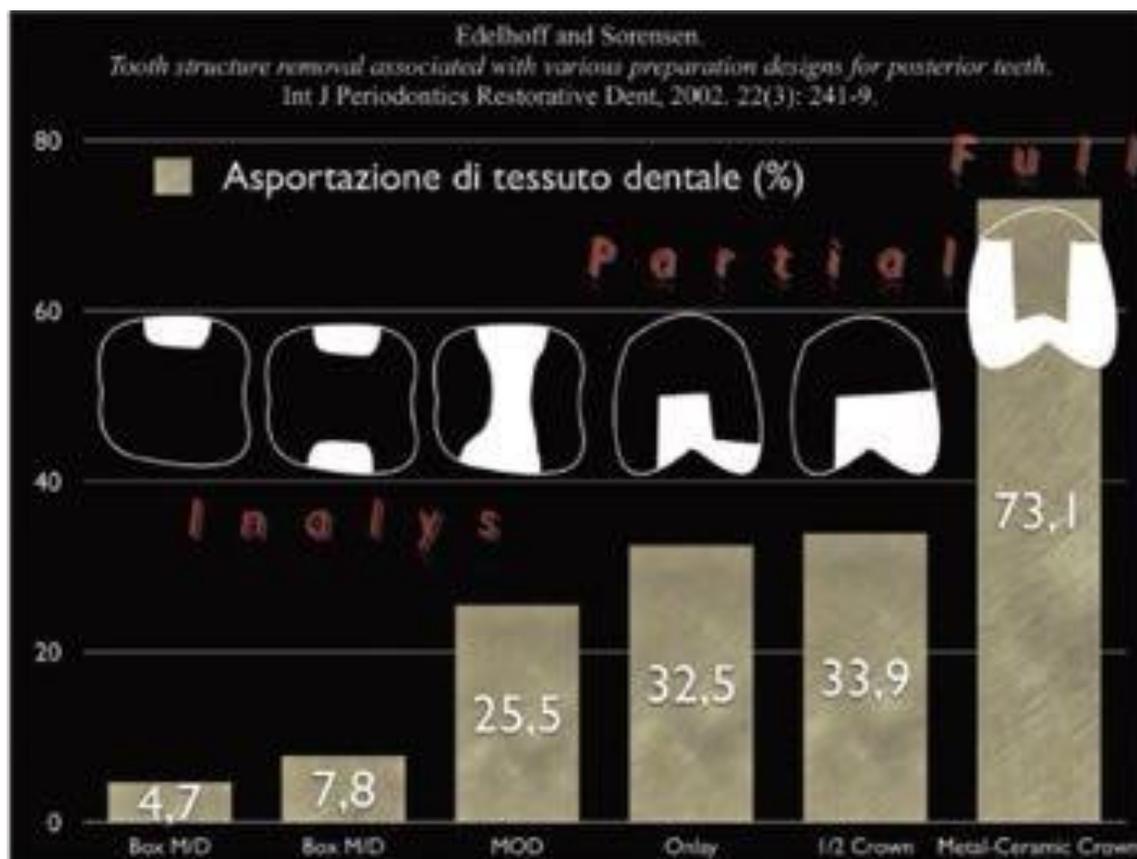


Fig.3 Schema di riduzione del tessuto dentale in base alla tipologia di preparazione. (Edelhoff D, 2002)

3.4. THE MATERIAL CHOICE

The indirect restoration can be done in different materials and clinically we have 3 groups:

1. Metal-Ceramic
2. Full ceramic
3. Full composite

In restorative world often the choice is on the ceramic with glass matrix, called also adhesive ceramic (feldspathic ceramic and lithium disilicate), or on the traditional composite or hybrid ones.

The ceramics have the translucency and hardness similar to the enamel (Federlin M, 2007) (Magne, 2006), in particular way the development of the lithium disilicate which have a compression higher than 300 MPa, but they are always etchable. Those factors extend the uses of the ceramic to the single restoration also in the posterior sectors. (Manhart J, 2004) (Tinschert J, 2001) It is also to consider that using the resinous cement the distribution of the forces is adequate. The disadvantages of the ceramic are the higher cost, the more complex procedures and the lack of possibility to have an intraoral restoration in case of a fracture.

On the other hand, thanks to the development of composites, their mechanical properties have a high performance, guaranteeing an important clinical versatility. (Manhart J, 2004; Leinfelder K. 2005; Leinfelder K., 2001; Spreafico RC, 2005)

These materials have clinical advantages such as the conservative preparation, the possibility to correct the restoration in every moment in the clinic, without compromising the mechanical properties, polishing and the lower abrasion of the antagonist and the use of only one material for the restoration, the build-up, the cement, so that the fragility due to the interfaces between different materials is reduced. (Kunzelmann KH, 2001)

Moreover, the mechanical properties of the composite (elastic modulus, compressive and tensile stress, fracture resistance) allow the stratification of the material in minimum thicknesses: (Fichera, 2001)

In the literature there is no evidence about the superiority of one or of another material, so that the choice remains to the clinician. (Morimoto, 2016)

*FOURTH CHAPTER:
ENDODONTIC POSTS*

4. ENDODONTIC POSTS

Sometimes it happens that after an endodontic therapy for a wide carious lesion, there is not enough healthy tissues to keep an adequate retention. In this case the use of a post and core build up could be indicated. (Schwartz RS, 2004)

The long-term success of the endodontic therapy depends on the quantity of the residual coronal tissues and the coronal seal: if the therapy is made by expert operators it has a success between the 70% and the 85%, while inexperienced operators only the 64 % and 75%. (Weiger R, 1997; Eriksen, 1991)

Nowadays the use of the post has to be evaluated looking at the clinical situation: the quantity of residual tooth, the occlusion, the function of the tooth and its position. (Dietschi D D. O., 2008)

4.1. INDICATION TO INSERT A POST

The aim of a post is to improve the retention of the restoration if the quantity of residual tooth is not enough. The correct position of the post cannot guarantee the success of the restoration: it is necessary to have a good ferrule effect. The length, the diameter and the material which is made influence clinical success. (Schwartz RS, 2004; Dietschi D D. O., 2007; Sahafi A, 2004)

The insertion of a post is recommended in the anteriors which have been devitalized after a caries because the remaining tooth substance is not strong enough to support the lateral and the cutting forces (Schwartz RS, 2004), whereas in the posteriors the load is vertical. However, it is also important to consider the crown-root ratio and the dimension of the crown: often the structure of the molar can be restored without the use of a post. It is different for the premolars because they are exposed to compressive forces as well as shear forces, and their crown-root ratio isn't favorable, so it is recommended in these elements. (Kane JJ, 1991; Sorensen JA M. J., 1985)

4.2. POST TYPES

The post can be divided based on the type of retention inside the canal, the longitudinal cross-section and on materials. (Schwartz RS, 2004; Felton DA, 1991)

- According to the retention inside the canal they could be active, if they engage actively in the canal with a macro-mechanical retention, like the “dentatus”; or passive, if the retention depends only of the adhesion to the radicular dentin, with a micromechanical retention, like the fiber posts. The active ones have a high retention, but they cause a high level of stress to the radicular dentin, increasing the fracture risk. (Burns DA, 1990; Standlee JP, 1992)

- According to the shape they could be divided in cylindrical and conical. The cylindrical can have a higher adhesion force and a lower risk of fracture, but they cause an important reduction of the radicular tissue, reducing the resistance. (Johnson JK, 1978; Qualtrough AJ1, 2003) The conic post can be adapted better to the natural structure of the canal, which has a descending taper in the coronal apical sense and needs less preparation. (Martínez-Insua A, 1998; Sorensen JA E. M., 1990; Isidor F, 1992)

- According to the materials the posts can be metallic or not metallic. The first can be also active or passive, conic or cylindrical or can be fabricated customized by the lab following the canal conformation. Also, ceramic posts can be used, and posts in zirconia, which have a low resistance to the fracture and need a greater preparation and also it cannot be retreated, so it is not clinically acceptable. (Schwartz RS, 2004)

The alternative choice to the metallic post nowadays is the non-metallic posts which are in carbon, glass, silicone or quartz. These posts can be cemented by the resinous cement thanks to their translucency. Moreover, in case of an endodontic retreatment, they are removable easily with the rotary and ultrasonic instruments. (Rijk, 2000)

The fiber posts are composed of quartz, carbon, glass or silica inside a methacrylic resin, which are united with a silane. The interface between those two materials allows to transfer all the stress to the post and it also can reinforce the tooth. The fibers, with a diameter between

the 6 and 15 μm , are spread longitudinally to the axes of the post. (Vichi A F. M., 2000; Vichi A G. S., 2002; Baba NZ, 2009; Grandini S, 2005)

The fundamental characteristics are its retention and its resistance. The resistance depends from the section of the post, if it is active or passive and from the cementation. The increase of the section of the post increases the retention, but it reduces the structural resistance of the root. (Standlee JP, 1992; Felton DA, 1991)

The resistance of the post depends on its length and mostly from the presence of the ferule effect; the absence of the ferule affects the success of the tooth in a long term. (Lambjerg-Hansen H, 1997)

4.3. POST PLACEMENT

The preparation of the “post-space” begins with the removal of guttapercha in the coronal and middle third of the root. To maintain a good endodontic seal, it is important to maintain at least 5 mm of guttapercha apically. The preparation is made with rotary instruments, trying to maintain the most quantity of the tooth possible. (Abramovitz L, 2001)

After the preparation of the post space, we need to cement the post, with traditional cement, as the zinc oxyphosphate, CVI classic or CVI modified with resin or resinous cement. The best choice nowadays seems to be the resinous cement associated to the fiber post, because they guarantee the increase of retention, a better seal and a reinforcement of the root. (Mezzomo E, 2003; Nissan J, 2001)

After the cementation of the post, around it and above the root we need to create a build-up, which will be the prosthetic base of the post-endodontic restoration.

*FIFTH CHAPTER:
FINITE ELEMENT ANALYSIS*

5. FEA

Finite element analysis (FEA) is nowadays a widely-used research method in biomedical sciences, due to its precision and a variety of possibilities in the calculations of stress and strain in complex three-dimensional (3D) biomedical models. Recently, modern bioimaging techniques, such as computed tomography (CT) and micro computed tomography (μ CT), are used to gain information for the creation of high-quality 3D models of complex biostructures which contributes to the accuracy of FEA.

Finite element analysis (FEA) of three-dimensional (3D) models of biomaterials and human tissues has become increasingly popular in the last years. (Maravic T., 2018) The creation of a 3D solid model based on CT scans of a second upper premolar is presented in this paper. All slices obtained from a CT scan of an intact extracted upper second premolar were imported into SolidWorks (SolidWorks Corp., USA) and the realistic 3D model was developed. After a 3D model is completed, it is possible to simulate different dental procedures and calculate values of stress and strain within the tooth and biomaterials using FEA. (Maravic T., 2018)

In recent years there has been an increasing interest in the research of mechanical aspects of biomaterials and human tissues, but the major problem is that dental and medical research is usually very expensive, ethically questionable and time consuming when conducted on live subjects. However, the use of numeric models and in vitro simulations became a valuable means of saving time and resources associated with laboratory and clinical research.

Finite element analysis (FEA) can be applied on a three-dimensional (3D) model of a biological structure and can calculate the stress and the strain within that structure, which is difficult to measure in vivo. Stress and strain within the tooth structures and biomaterials used for their reconstruction can be calculated. The influence of different restorative materials, different restoration designs and dental procedures on the tooth and the surrounding tissues, the influence of tooth anatomy and morphology of the tooth on the success of certain dental procedures, are just some of the many useful and interesting applications of FEA in dentistry.

It has been stated by many authors that Finite Element Method is an appropriate method to determine mechanical properties of materials. (Abdulaziz S. Alaboodi, 2017)

Firstly, we need to make a realistic tooth model, in order for the FEA to be as precise as possible.

Previous studies have reported different techniques to create a 3D solid models of tooth: it can be created using data collected from different sources, such as literature, data obtained through direct measurement of an extracted tooth, 3D scans of the outer surface of the tooth, or computed tomography (CT) or nuclear magnetic resonance (NMR).

In the last years these kinds of models are created using different programs, that used to gain information from CT scans.

5.1. CONSTRUCTION OF THE HUMAN MAXILLARY PREMOLAR SOLID MODEL

After the extraction a tooth is scanned using the Sensation 64 Cardiac CT scanner (Siemens, Germany). This is a 64 slice CT scanner and it is possible to obtain 110 slices along the x axis, 88 slices along y axis and 47 slices along z axis. The resolution of the CT scanner is 0.00976 mm along x and y axis and 0.5 mm along z axis. The contrast recorded by the CT scanner is from -1024 to 3071 which makes total of 4096 levels.

In this paper slices parallel to the xy plane are used for the creation of the 3D solid model. Only 42 slices contained useful information. All the slices obtained from the CT scanner are written in DICOM file format (DICOM – Digital Image and Communications in Medicine), which is a standard file format for distributing and viewing any kind of medical image regardless of the origin. The selected slices are imported to program AMIRA (Visage Imaging Inc. USA).

The **1st step** is the automatic segmentation using a threshold. In all the slices dentin has lower contrast than enamel, so the threshold is defined in the following way: exterior – dentin threshold 400 and dentin – enamel threshold 2400. There are only three thresholds because

the pulp is considered as the exterior. Pictures of one of the slices imported and segmented in AMIRA are given on Fig. **4A and 4B**.

The **2nd step**, after segmentation and definition of all the tissues, is the alignment of all imported slices. This is an important step to align all the slices that are imported to AMIRA in order to properly form the 3D solid model. The program AMIRA can use several different alignment procedures. The most important thing in the preparation for the 3D solid model is the computation of contours.

In the contour computation procedure, the program AMIRA calculates the sequence of points that make contours. It is necessary to compute contours for every entity (enamel, dentin and pulp) and along the selected axis selected (z axis). All these contours are written in series of data files. In order to make it possible to import the contours in program for 3D solid modeling, data files ought to be written in standard file format for CAD exchange. A very popular CAD exchange file formats is DXF (DXF – Drawing eXchange Format) and it is used for transferring data from the program AMIRA to the program SolidWorks (SolidWorks Corp., USA).

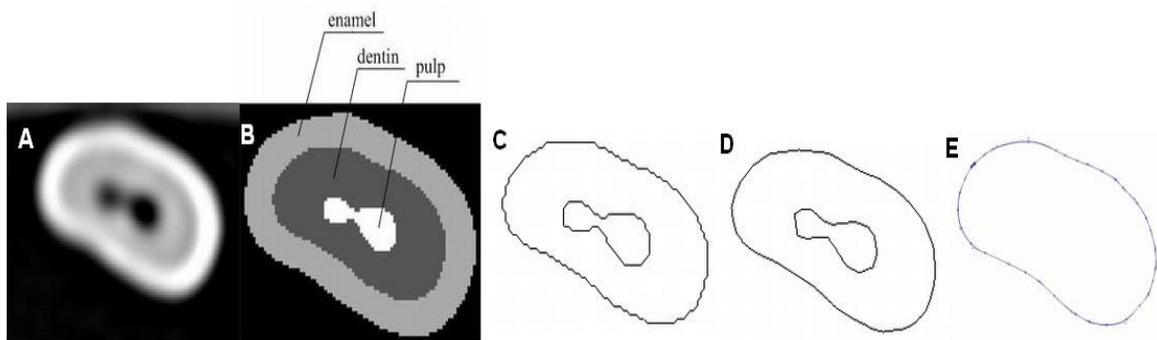


Fig 4.
A) Picture of a CT slice imported in AMIRA;
B) Picture of the same imported CT slice segmented in AMIRA;
C) The contour of dentin computed in the program AMIRA;
D) The same contour of dentin after processing in an in-house developed program;
E) The spline computed in the program SolidWorks from the outer contour of dentin

The fundamental idea of the growth of a 3D solid model is showing contours with splines and building solid model using “Loft” feature.

The dentine contour is not appropriate for definition of the spline, as it can be evaluated in the Fig.4C. Because of that is used an in-house developed program for preparing dentine contour for splines. The changing can be seen in the Fig. 4C and D that shows picture of the dentine contour before and after the use of the program. Finally, the Fig. 4E is spline constructed from the dentine contour.

The 3D solid model is developed in the program SolidWorks. The program SolidWorks is a very popular program for CAD/CAM (CAD – Computer Aided Design, CAM – Computer Aided Manufacturing). The process of developing a 3D solid model consisted of the following steps (Maravic T., 2018) (Kantardzic I., 2018) (Pegoretti A., 2002):

- definition of required number of horizontal planes (xy planes) positioned at the exact height along the z axis as the contour CT slices;
- importing adequate contours in the defined horizontal plane and definition of spline;
- building a 3D solid body from the splines positioned in horizontal planes by using the “Loft” tool (Fig. 5).

This procedure is repeated for each tooth structure: the enamel, the dentin and the pulp. The 3D solid model of the whole human maxillary premolar with the surrounding tissues is presented in the following figure. (Fig 6A, 6B, 6C and 6D)

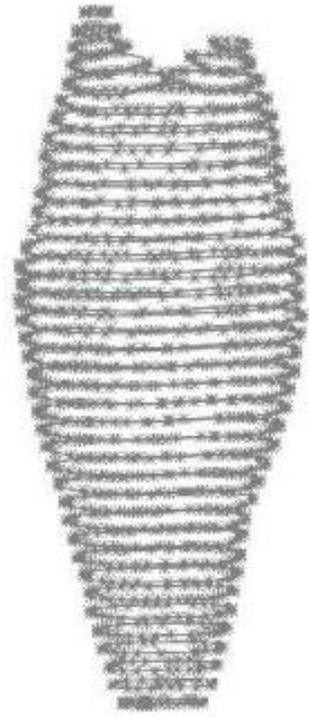


Fig. 5
The 3D solid body of dentin made from the splines positioned in horizontal planes

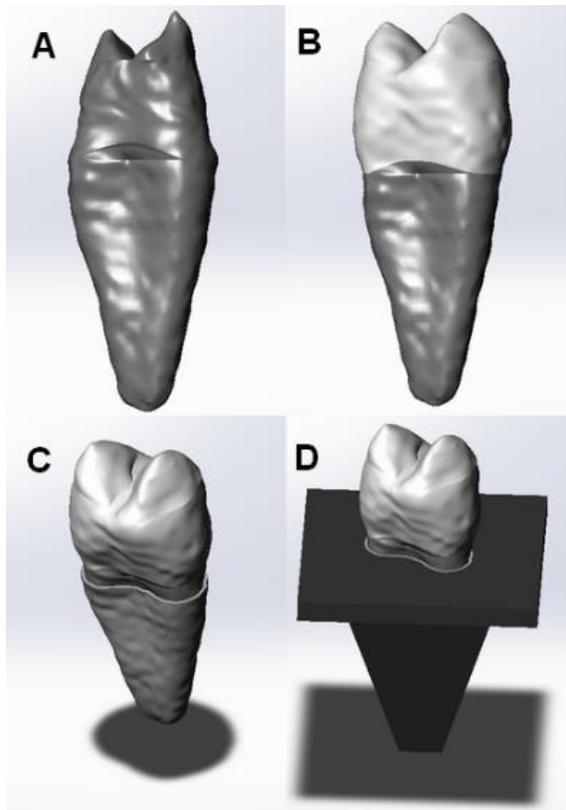


Fig. 6
3D solid model of the human maxillary premolar.
A) Dentin; B) Dentin and enamel;
C) Tooth with the PDL;
D) Tooth with the surrounding PDL and bone tissue

Consisting of several parts the human maxillary premolar is constructed as the assembly from three parts: the enamel, the dentin and the pulp. Obviously, all parts in the assembly are bonded.

5.2. FINITE ELEMENT ANALYSIS OF THE HUMAN SECOND MAXILLARY PREMOLAR

After finishing the 3D solid model of the human maxillary premolar, the next step was the definition of parameters for the finite element analysis. The first step was the assignment of material properties.

In order to be able to calculate various types of stress and strain in tooth structures, generated by different therapeutic procedures by FEA, one ought to define three necessary things: the fixture, the load and the mesh. In our case, the fixture was standard fixture with fixed geometry. The exterior nodes on all surfaces of the cortical bone were fixed in all directions so they could not move or rotate. The load was applied to the tooth at three points on the occlusal surface of the premolar (one on the palatal cusp, and the other two on the mesial and distal marginal ridge), mimicking the natural biting position with the resulting force crossing the central position. The intensity of the resulting force was 150 N. (Maravic T., 2018; Pegoretti A., 2002)

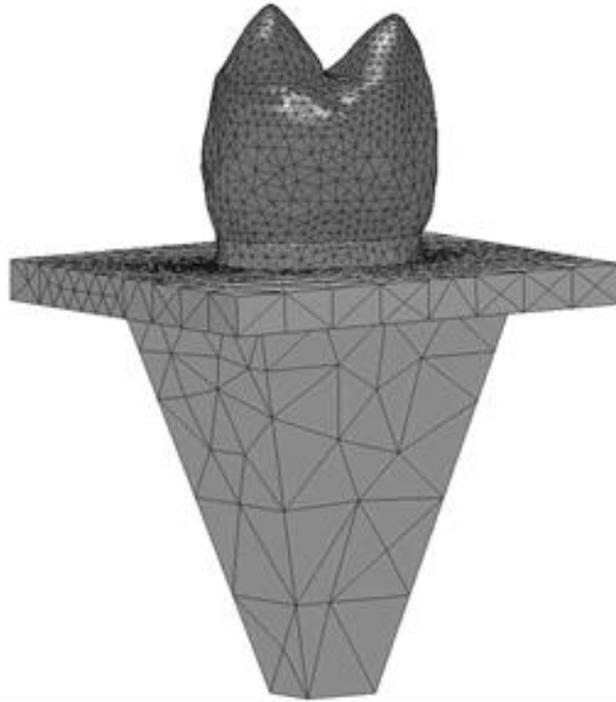


Fig. 7. The 3D solid model of the human maxillary premolar meshed in the program SolidWorks

The solid mesh, which was appropriate for complex 3D solid models, was used in this study. The standard mesher which generated parabolic tetrahedral solid elements was used for meshing in the SolidWorks program. The parabolic tetrahedral element is defined by four corner nodes, six mid-side nodes and six edges. In this paper parabolic elements were used because they represent curved boundaries more accurately and they produce better mathematical approximations. After the convergence test the resulting 3D solid model had 116244 nodes and 75231 elements. The meshed 3D solid model is presented in Fig. 7.

After the mesh is complete, stress and strain can be calculated using FEA. The program gives precise information as final result about the Von Mises stresses, principal stresses, cuspidal deflection, and the distribution of the stresses in tooth structures and biomaterials (Fig. 8)

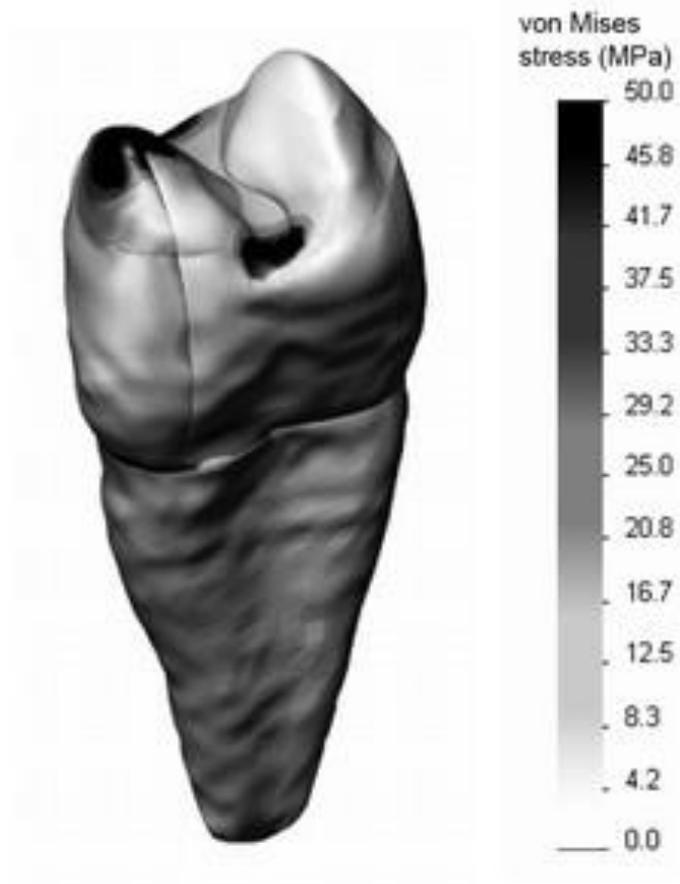


Fig. 8.
The example of the calculated Von Mises stresses using FEA on a tooth model restored with mesio-occluso-distal composite filling

*SIXTH CHAPTER:
EXPERIMENTAL PART*

6. EXPERIMENTAL PART

6.1. AIM

The aim of this FEA study is to determine the effect of variations in the restoration of endodontically treated teeth on von Mises stress values and distribution in dental tissues and restorative materials, using a CT-scan based 3D model of an endodontically treated upper second premolar. Also it is supposed to evaluate the site with the highest stress in endodontic premolar restored with different methods: restoration with an ENDOCROWN IN CERAMIC produced by CAD/CAM; restoration with A TRADITIONAL POST and a CAD/CAM CROWN IN CERAMIC and with DIRECT COMPOSITE RESTORATION with or without cuspal reduction.

The null hypotheses:

1. Different restorative procedures do not influence the stresses in tooth tissues of endodontically treated upper second premolar
2. Different restorative procedures do not influence the stresses in the restorations of endodontically treated upper second premolar

6.2. MATERIALS AND METHODS

In this study an intact second upper premolar, extracted for orthodontic reasons was used. The tooth was chosen due to lack of caries destruction, fractures and morphological abnormalities.

The extracted tooth was immediately cleaned of soft tissue residues and scanned using a multilayer CT scanner (SOMATOM Sensation 64 Cardiac, Siemens, Germany). A total of 110, 88 and 47 slices with 0.5 mm resolution were made along the x, y and z-axis, respectively. The slices along the z axis (only 42 on 47 were available), which contained useful information were imported into the AMIRA software (Visage Imaging Inc., San Diego, CA, USA), in order to carry out tooth tissue segmentation. The segmentation was enabled by the different degrees of mineralization of the enamel, dentin and the pulp, which correspond to a certain grayscale intensity. Further, the contours of the segmented tissues were imported into SolidWorks 2014 software (Dassault Systèmes SolidWorks Corp, Waltham, MA, USA), where a 3D solid model of an intact maxillary second premolar was created. Moreover, based on the contours of the generated 3D solid model, and on literature data, periodontal ligament and alveolar bone were created around the tooth.

The periodontal ligament was modeled using the “Shell” feature to follow the outer surface of the human maxillary premolar and to have thickness of 0.2 mm. The 3D solid model of the human maxillary premolar with the periodontal ligament and the cortical bone is presented in Fig. 6C and 6D. From the model of an intact premolar, 4 models were created for the present investigation.

The basis of each model was an endodontically treated tooth with a wide and deep cavity as to simulate great loss of tooth substance. The width of the cavity isthmus was simulated to be 5.35 mm, and the gingival wall of the cavity was placed 1 mm above the cementoenamel junction. Also, access cavity preparation, rotary root canal endodontic instrumentation with ProTaper Universal instruments (Dentsply Maillefer, Switzerland), and canal obturation with gutta-percha were simulated.

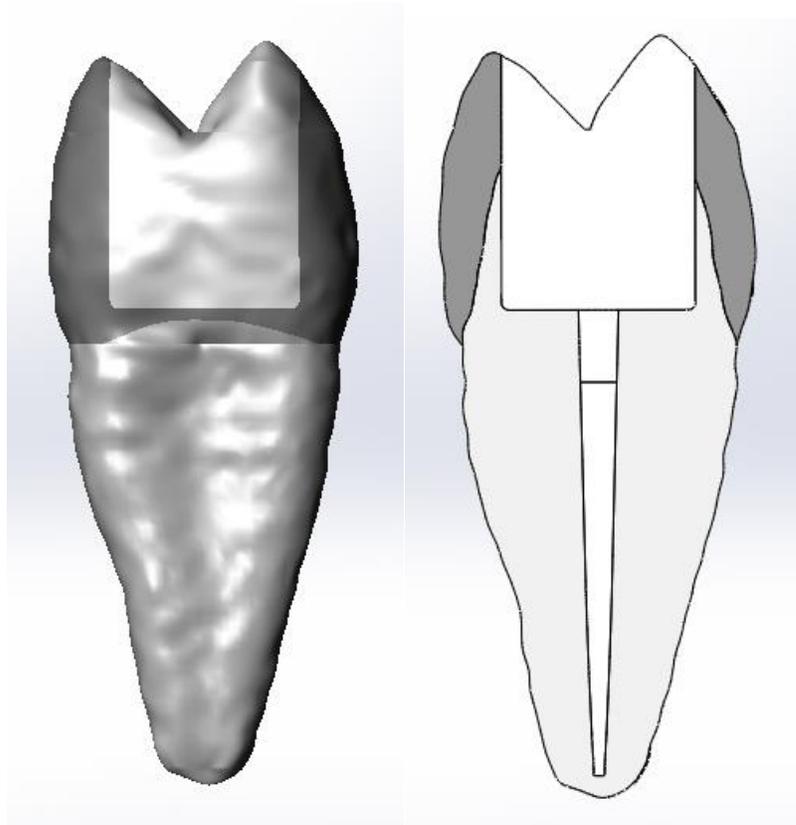


Fig 9 – Model of an MOD cavity with direct composite restoration

The restoration of the teeth was further simulated in 4 different modes:

- 1) MOD cavity restored with direct resin composite; (Fig.9)
- 2) MOD cavity restored with direct resin composite and the reduction of the buccal and palatal cusps (MODPB cavity); (Fig.10)
- 3) CAD/CAM ceramic endocrown (Empress 2, Ivoclar), with the intracoronal portion of the restoration extending 5 mm into the root canal; a 100 μ m thick layer of luting cement (Variolink, Ivoclar) was created between the endocrown and dentin. (Fig.11)
- 4) CAD/CAM ceramic crown (Empress 2, Ivoclar) with a post (Postec Plus, Ivoclar) – post insertion was simulated leaving the apical 5 mm of the gutta-percha filling intact, and a 100 μ m thick layer of luting cement (Variolink) was created between the post, crown and dentin. (Fig.12)

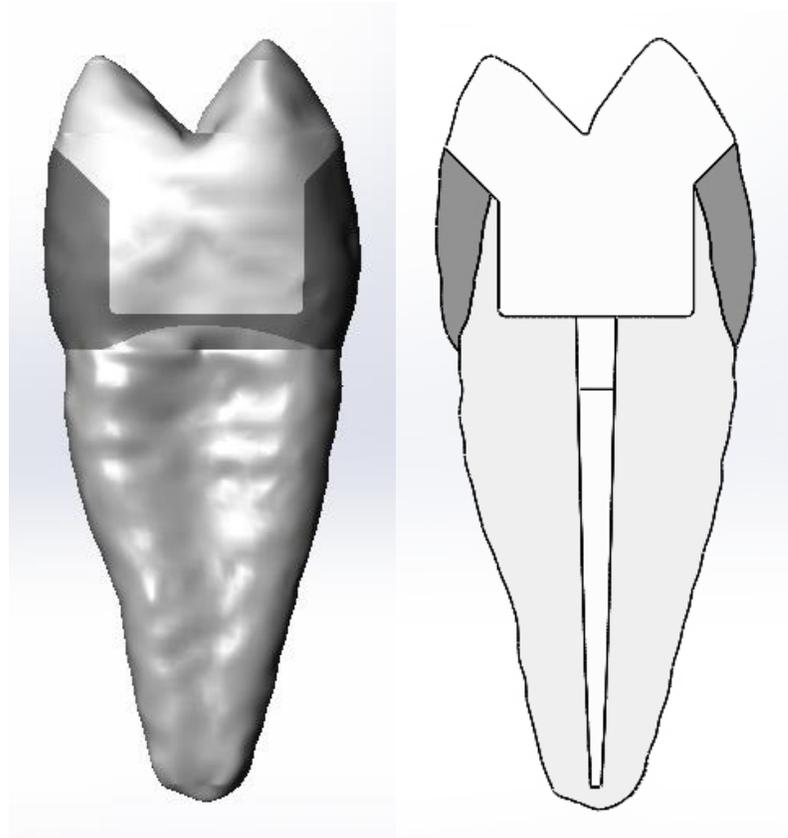


Fig 10 – Model of an MODPB cavity with direct composite restoration

Each tooth structure, as well as restorative materials, were assigned the appropriate material properties (Table 1) and were considered to be linear elastic. Further, boundary conditions were set at the outer surface of the alveolar bone and all the models were loaded at three points on the occlusal surface, the slope of the palatal cusp, and at the mesial and distal marginal ridges, simulating the normal biting pattern, with a resulting force of 150N, since the bite forces in maxillary premolars were found to be between 100 and 300N.

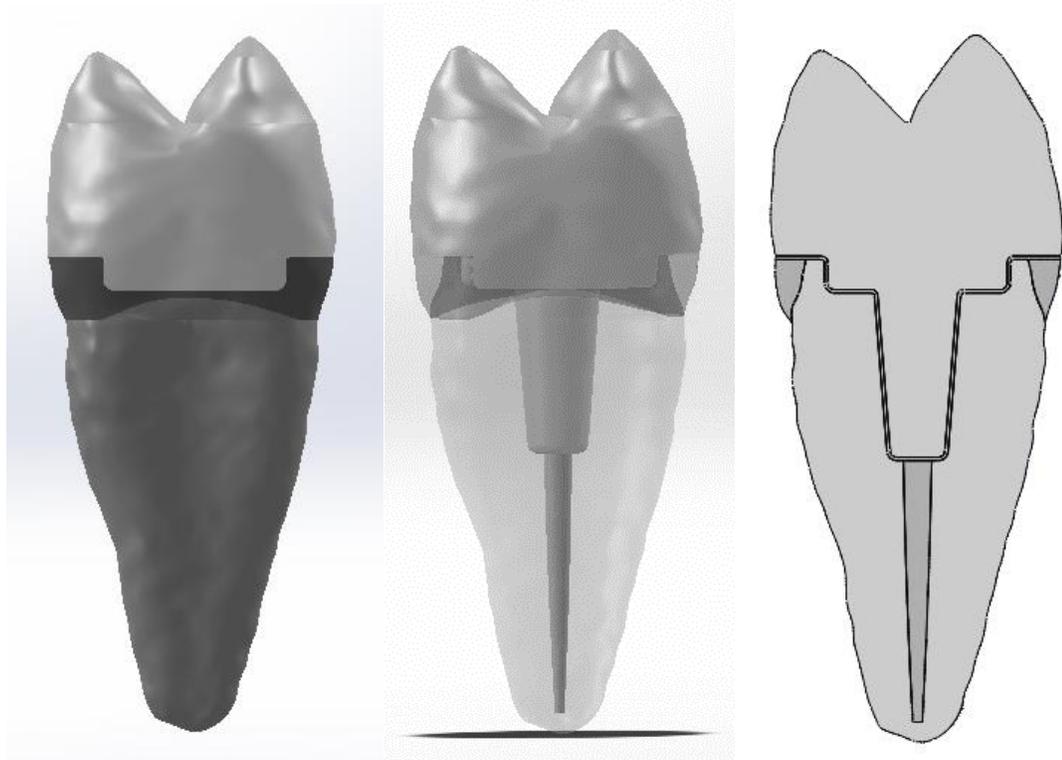


Fig 11 – Model of restoration with Endocrown

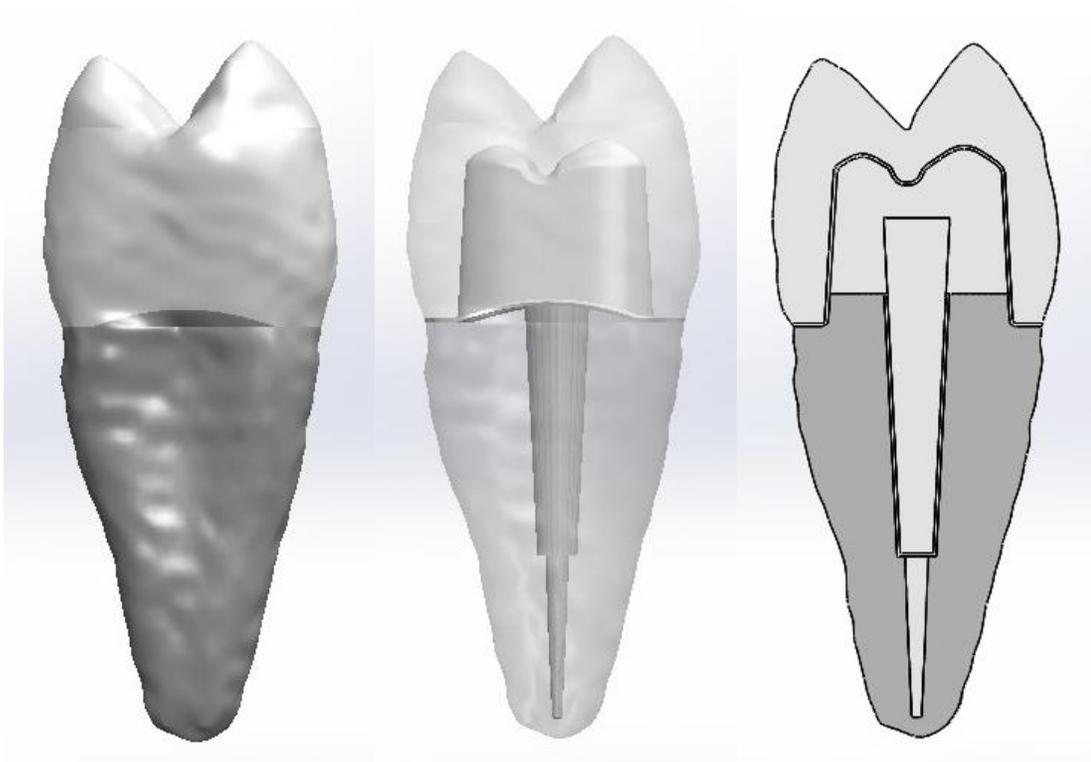


Fig 12 – Model of restoration with a full crown in ceramics

6.3. FINITE ELEMENT ANALYSIS OF THE PREMOLAR MODEL

After the creation of the 3D solid model of the human maxillary premolar, the next step was the definition of parameters for the finite element analysis. The first step was the assignment of material properties. The material characteristics are presented in Table 1.

Meshing and FE analysis was also performed in SolidWorks. SolidWorks is a general 3D design program with various add-ins, one of which is the “Simulation” package that can be used for various FEA. In this study, the classical static analysis was used.

Within “Simulation” we used solid mesh with following input parameters: Curvature based mesh, maximum element size was 2.30906 mm, minimum element size was 0.230906 mm, number of elements: 90425-132842, number of nodes: 144685-208991, mesh quality was high. 95-97,4% of elements with aspect ratio smaller than 3 and only 0,0221-0,0843% of elements with aspect ratio greater than 10 were obtained.

All elements with aspect ratio greater than 3 were in non-critical places where the stresses were low. After meshing the models, the von Mises stresses for the enamel, dentin and the restorative materials were calculated, and stress distribution was presented.

<i>Materials</i>	<i>Elastic Modulus [MPa]</i>	<i>Poisson's ratio</i>	<i>Ref.</i>
<i>Enamel</i>	84100	0,20	(Lin C-L, 2008)
<i>Dentin</i>	18600	0,31	(Lin C-L, 2008)
<i>Periodontal ligament</i>	70	0,45	(Lin C-L, 2008)
<i>Alveolar Bone</i>	15000	0,30	(Lin C-L, 2008)
<i>ParaCore (Coltene, Switzerland)</i>	7500	0,33	(Sorrentino R, 2007)
<i>Postec Plus (Ivoclar, Vivadent, Lichtenstein)</i>	48000	0,24	*
<i>Fuji II, (GS Europe, Belgium)</i>	10800	0,30	(Bowley JF, 2013)
<i>Ceramica Empress II (Ivoclar, Vivadent, Lichtenstein)</i>	120000	0,25	(Campos RE, 2011)
<i>Variolink II (Ivoclar, Vivadent, Lichtenstein)</i>	6000	0,30	(Lin C-L, 2008)
<i>Guttapercha</i>	100	0,49	(Garbin C a, 2010)

**Information provided by the manufacturer (Ivoclar, Vivadent, Liechtenstein)*

Table 1. Material characteristics

6.4. RESULTS

	Enamel	Dentin	Restoration	Post	Gutapercha	Post Cement	Crown cement	Comp. build up
MOD cavity direct composite restoration	87,6	35,5	133,9		0,1			
MODPB cavity direct composite restoration	65,8	33,4	139,0		0,2			
Endocrown ceramic	47,0	23,5	147,6		0,1		17,1	
Full ceramic crown		19,0	150,4	15,2	0,1	7,1	13,8	4,3
Table 2. Results obtained by FEA								

Maximum von Mises stress values

When comparing maximum von Mises stress values in all the tested models, it can be noticed that significantly lower stresses in dentin are recorded in indirectly restored teeth, and that the MODPB cavity design shows the lowest stresses in the directly restored group. On the other hand, the highest stresses in the restorations are recorded in the endocrowns, while the lowest stresses were found in the direct composite filling (MOD). A trend can be noted that the restorative options that are favourable for the stresses within dentin are unfavourable for

the stresses in the restoration. (Table 2) The highest stresses points were located in the restoration in all the models. It can be noticed that the values of stresses in the restoration have an ascending tendency MOD < MODPB < Endocrown < Full ceramic crown (Fig. 13).

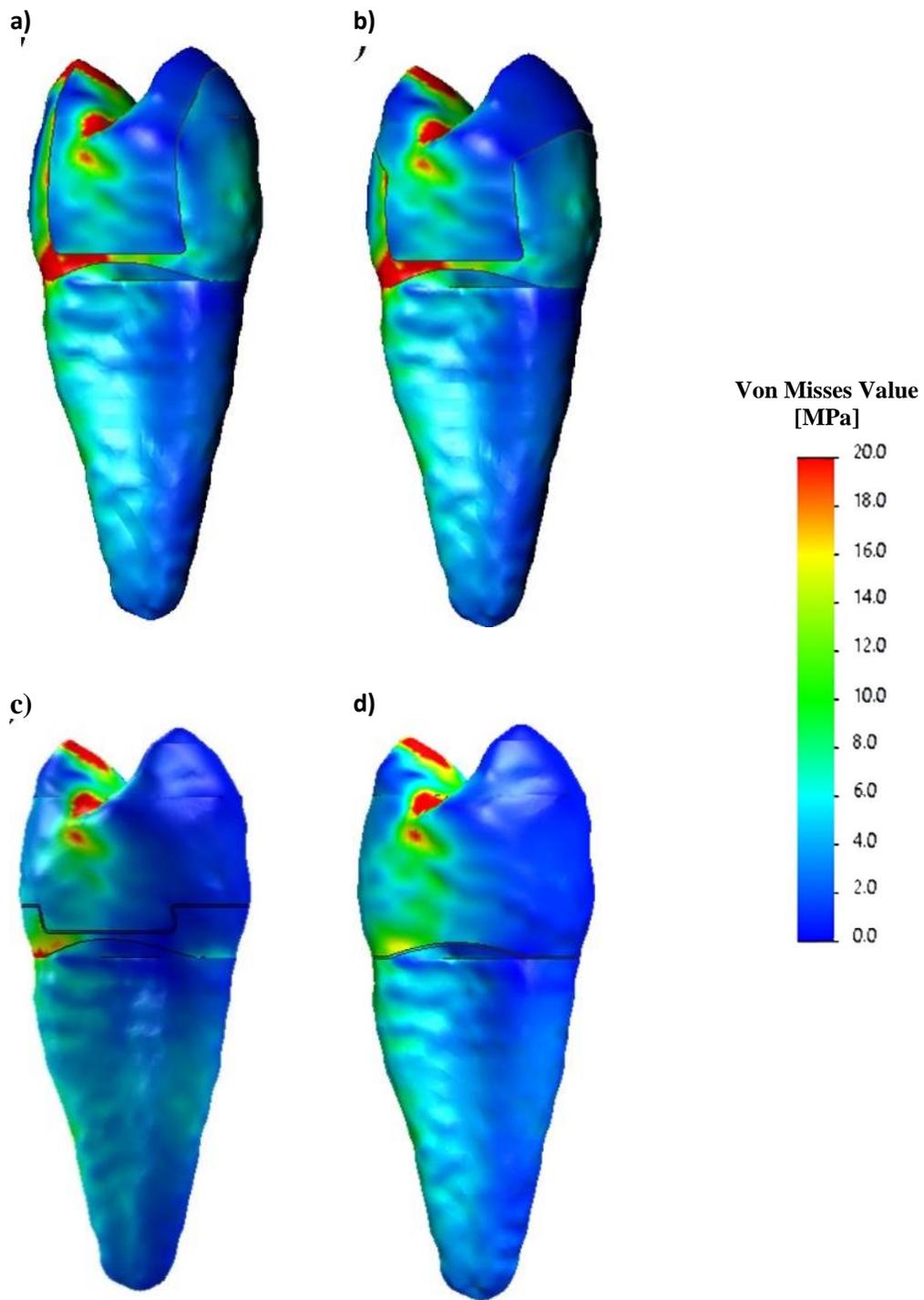
If we examine the maximum von Mises stresses in more detail within the groups, it is notable that cusp reduction influenced maximum von Mises stresses in the enamel, in the sense that the values of the stresses were lower in MODPB cavity, regardless of the use of a post.(Fig 13 a, b)

Out of the indirect restorations, endocrown caused higher stresses within the dentin, the restoration and the cement compared to classical crowns.

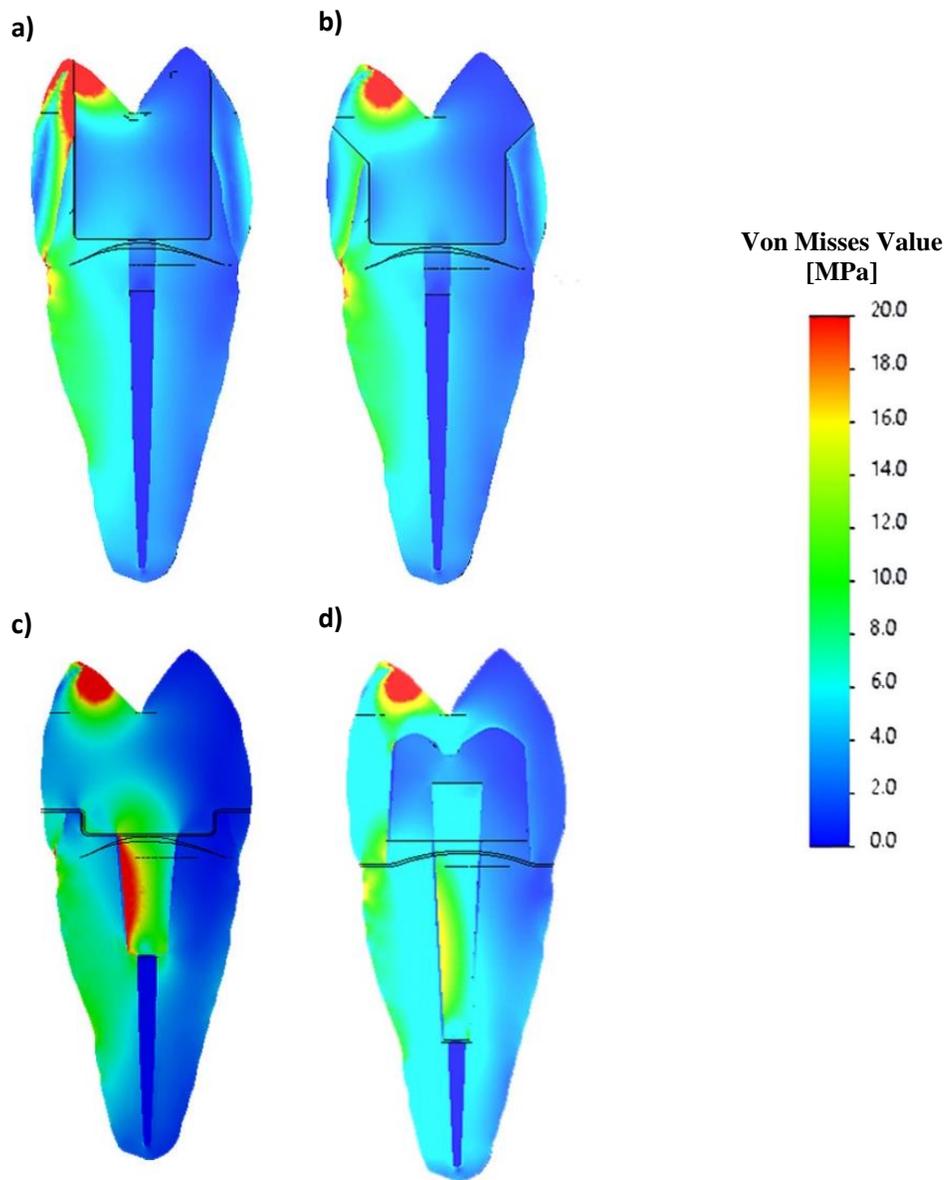
Von Mises stress distribution

Maximum stresses were mostly located in the loading areas. Another area under high stresses was the cervical portion of the palatal part of the crown (Fig. 13). High-stress areas were distributed similarly within all the tested models (Fig. 13 and 14). However, the areas of high stresses descended in all models, starting from MOD, with lower area under stresses in MODPB, followed by the indirect restorations (Fig. 15). In the endocrown, the high stresses were located at the bottom of the endodontic cavity, while in the classical crowns there were areas of slightly higher stresses in the palatal part of finishing line in dentin (Fig. 13c, d). As for the distribution of the maximum stresses in the restoration, they are similarly distributed in all the models, mostly on the points of loading (Figs 16 and 17). In crowns there are higher stresses also in the palatal portion, while the high stresses in the endocrown are also located in the palatal intracoronal part (Fig. 16c, d and 17c, d). The high stress areas in the crown cement were located in the bottom of the endodontic part in the case of endocrown, and in the palatal cervical portion in the ceramic conventional crown (Fig.18).

Moreover, the stresses distributed throughout the entire tooth models were lower in the models reconstructed with the endocrown (Fig. 13 and 14).



*Fig.13 Distribution of von Misses Stress in the models of all tested groups
a) MOD in direct composite b) MODPB in direct composite c) Endocrown
d) Full crown in ceramic*



*Fig.14 The distribution of von Misses Stress in the models of all tested groups cross sections in the sagittal plane
a) MOD in direct composite b) MODPB in direct composite
c) Endocrown d) Full crown in ceramic*

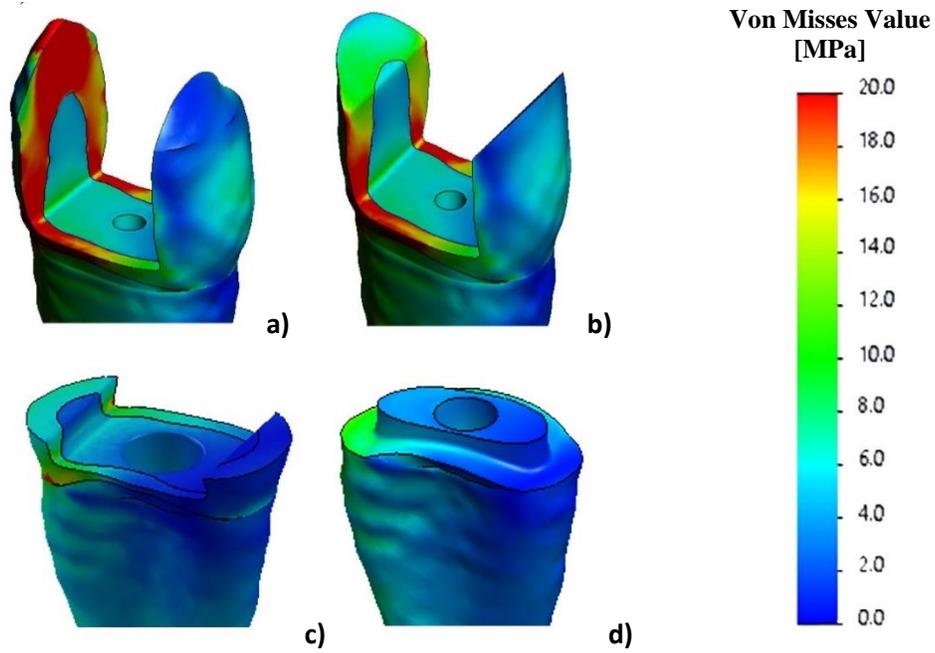


Fig. 15 Distribution of von Misses stresses in dental tissues of the studied groups:
 a) MOD in direct composite b) MODPB in direct composite c) Endocrown
 d) Full crown in ceramic

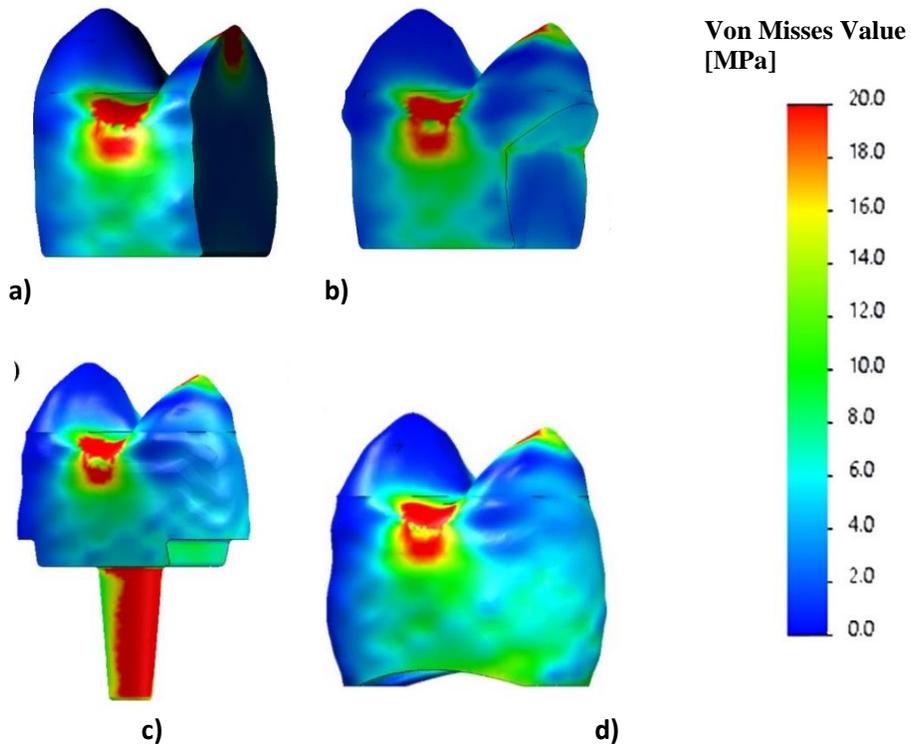


Fig. 16 Distribution of von Misses Stress in the crown compensations of all studied groups
 – Palatal side a) MOD in direct composite b) MODPB in direct composite c) Endocrown
 d) Full crown in ceramic e) Full crown in Zirconia

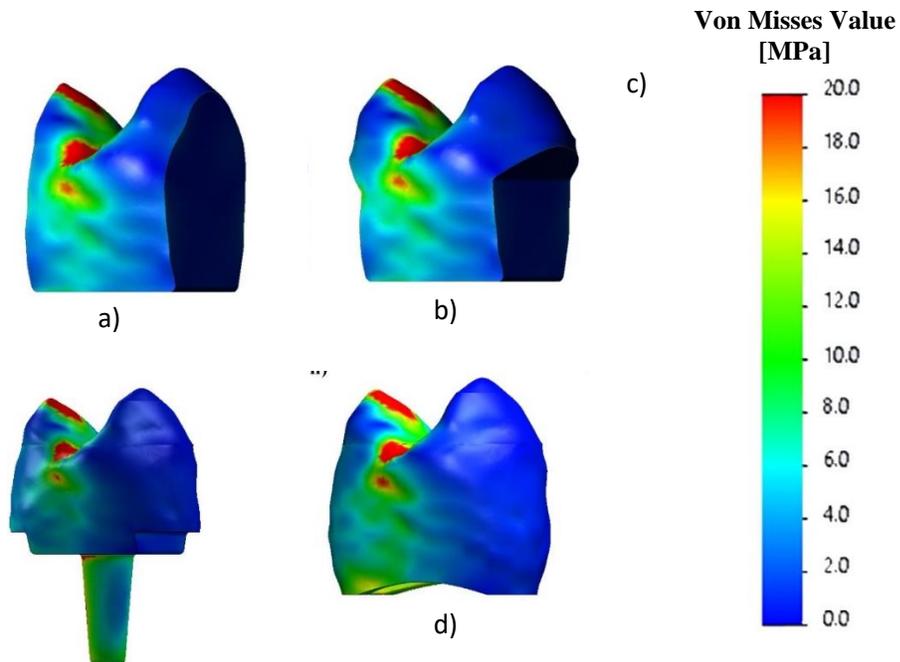


Fig.17- Distribution of von Misses Stress in the crown compensations of all studied groups – Vestibular side a) MOD in direct composite b) MODPB in direct composite c) Endocrown d) Full crown in ceramic e) Full crown in Zirconia

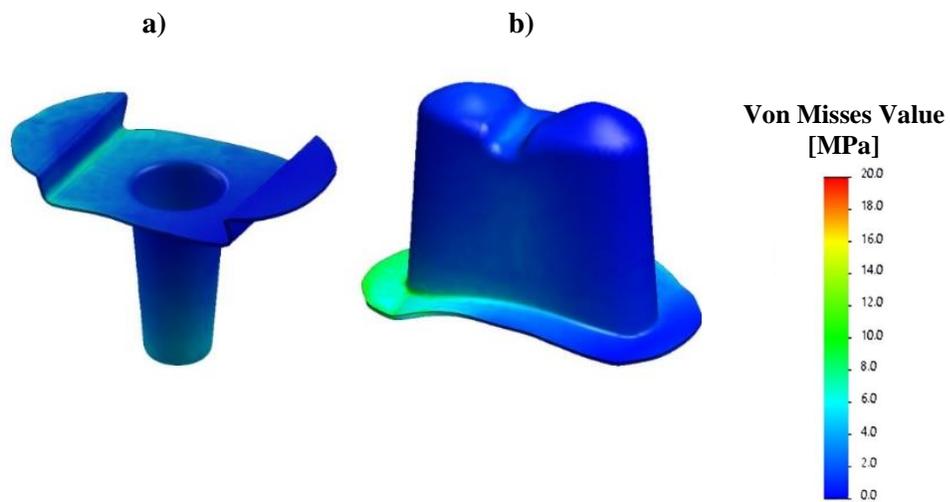


Fig. 18- Distribution of von Misses stresses in cement for the crown of groups a) Endocrown b) Ceramic crown

6.5. DISCUSSION

The aim of this study was to determine the effect of different restorative procedures in tooth tissues and in restorative materials after the endodontic treatment. This thesis researched different materials, different restorations and different preparations in numerical simulations done on 3D models of a maxillary second premolar designed using computerized tomography (CT) scan images. Based on the results of the study, the null hypotheses need to be rejected since it was shown that the different post-endodontic restorative options influence the stresses within the tooth tissues and the restorative materials.

As already discussed, the endodontic treatment is often indicated in teeth that have already been damaged by carious process and/or trauma. The biomechanical properties of tooth change for the loss of tooth structure due to the caries/ trauma itself and also due to the preparation of the restoration. (Acquaviva PA, 2011) It is also necessary to consider the increase of the risk of tooth fracture and the reduction of the long-term success of the restoration. (Dietschi D D. O., 2008)

These factors must be considered in particular when the tooth to rehabilitate is a premolar because of their morphology and their position in the tooth arch. (Tamse A, 1999) The premolars are elements with a morphology and a function which makes them vulnerable after an endodontic treatment. They also have a ratio crown-root unfavorable and they are exposed to lateral and vertical forces during the normal masticatory function. As previously mentioned, the premolar position endures high masticatory forces, but their crown is not as large as the molar ones. It is also to considered that if we have an MOD cavity, the susceptibility to fracture of the tooth increases due to removal of the marginal ridges and the endodontic treatment. (Ferrari M V. A., 2012) For all these reasons restoring an endodontically treated premolar is more difficult than any other kind of tooth.

As clinicians, our goal is not only to achieve good function and esthetics, but also to restore the mechanical properties of dental tissue and their characteristics. Every restorative procedure wants to preserve and to protect the remaining tooth structures from all the masticatory forces. It is necessary to know the critical factors in order to improve

biomechanical characteristics of tooth restoration. As shown before this study analyzes two factors: restorative materials and cavity preparation.

Moreover, as the results show us in the direct restoration it is really important and relevant to reduce the cusps: the areas of high stresses descended in all models, starting from MOD, with lower area under stresses in MODPB. The reduction of the Von Mises Stresses of the 24.8% between the forces that result in the final analysis underline the importance of the cusps reduction. This was the most influential factor in the maximum von Mises stress value changes in the enamel, in fact it is 87.6 MPa in the MOD, while it is 65.8 MPa in the MODPB.

These results are in accordance with the results of other studies. Lin et al. (Lin C-L, 2008) recommend a cusp reduction of at least 1.5 mm in order to increase the fracture resistance of premolars. Kantardžić et al. (Kantardzic I., 2018) found using the FEA method that the reduction of the palatal cusp reduces stresses in the enamel significantly. Also, certain in vitro studies showed that endodontically treated premolars restored using partial ceramic or full composite onlays had a higher fracture resistance as compared to other techniques used. Although there are other group of authors (Mohammadi N, 2009) found that cusp capping does not influence fracture resistance significantly.

Another thing to remember is the importance of the introduction in the clinical practice of the adhesion. *Adhesion* is a measure of the force of attraction between two different materials and is differentiated from cohesion in that the latter relates to the forces of attraction within a single material, ie, the forces holding it together. (L. Breschi, 2013) Adhesion can be the result of the formation of primary chemical bonds, like covalent, ionic or metallic and also can result from strong secondary forces, such as hydrogen bonds and Van der Walls forces. However, it is possible to say that adhesion *depends on strong molecular interactions between two surfaces in intimate contact*. Both types of interactions are evident in dental adhesive materials.

With the advance in materials technology, properties of the composite materials have improved significantly. Hence, dental composites are most often the material of choice in the restoration of endodontically treated teeth. Also, finishing the therapy in one session is considerably more comfortable for the patient. Further, the financial aspect plays a very important role in the choice of reconstruction, and longer chair time or laboratory procedures

elevate the costs of the intervention. Therefore, the author considered this topic to be interesting for general practitioners and restorative dentists, who are faced with a vast amount of information in the available literature, which is often confusing and non-comparable. Hence, they are more inclined to choose the therapy method based on their personal experience and in relation to the trends that are mostly present in their geographical area. (Shugars DA, 1997) Most of the available in vivo, in vitro and FEA literature on the survival and success of post-endodontic restorations investigates the classical crown restoration, so the results cannot be fully comparable to the present study. However, certain in vivo studies showed equally good or better performance of direct composite restorations as compared to metal-ceramic crowns after a 5 and 9-year follow-up. (Skupien JA, 2016; Skupien JA O. N.-C., 2013)

Another important point to analyze is the different elastic modulus between the ceramic and the composite. As can we see in the table 1, the Elastic Modulus of the ceramic is higher than the one of the composites, in particular it is much more durable and also similar to the Elastic Modulus of the enamel. The indirect restorations induced stresses of lower intensity in dentin, although endocrowns performed worse compared to full crowns. Probably due to the high elastic modulus of these materials, and consequential high stiffness, they were able to protect the weakened tooth tissue and absorb a large part of the stresses.

Stress distribution was similar in all the tested models in the present study. The maximum stresses were located on loading areas and at the cervical portion of the palatal aspect of the crown. This is again in agreement with the fact that the fracture of the palatal portion of the crown is the most often failure mode of endodontically treated upper premolars. (Salis S. G., 1987) Another interesting fact that can be seen from the results of the present study, regardless of the maximum stress values, is that von Mises stresses were slightly lower throughout the whole models with an endocrown. Although the maximum von Mises stress values showed that these restorations increased the stresses in the tooth tissue, the more favourable distribution of maximum stresses in these models could influence the longevity of the restoration over the years of use in intraoral conditions, since the maximum stresses are located only in small areas.

Strengths and limitations of the method used in this study should be mentioned. Firstly, homogeneous, linear elastic and isotropic properties were assigned to all the tooth tissues and restorative materials, while it is well known that some of these structures have neither of these properties. The non-isotropic properties of the periodontal ligament (PDL) have especially been debated in literature. However, it was found that the properties of the PDL do not influence significantly the validity nor the results of the FEA studies. Also, inhomogeneities in teeth are at nano/micro scale, while standard programs for FEA, such as Simulation package for SolidWorks can mesh only millimeter structures, so certain simplifications usually need to be applied in FEA. Further, the experiment performed in the present study was static, which means that time and temperature influence were not taken into consideration, and perfect bonding of all materials to dental tissues was assumed, which is impossible to achieve in practice. Dynamic FEA studies have been conducted which take into consideration more variables. Hence, their results are assumed to be more accurate. However, these types of studies are still very variable, and should be more standardized in order to make comparable results. Another important point to be discussed is the choice of von Mises stress criterion in the present study. Von Mises criterion is a scalar stress measure which combines the three principal stress values and identifies clearly the areas of the model that are under highest stress and are consequently more prone to fatigue failure. It is widely used in FEA studies, including a large number of published studies on the present topic. Hence, the authors have chosen this criterion as to easily compare results with other studies.

The load in this study was applied on 3 points: one on the palatal cusp and 2 on the marginal ridges, to represent the maximum intercuspitation position. In this way we could assume that our models were mostly influenced by compressive forces. Moreover, as shown in the table the compressive strength of Enamel is 384MPa and for the Dentin it is 297 MPa while the limit of proportionality is between 70-353 MPa for the enamel and between 100-190 MPa for the dentin. However, the results obtained within this study remained in the range of the limit of proportionality of the enamel and dentin. Nonetheless, for a more detailed understanding of the influence of tensile, compressive and shear stress, principal stresses could be discussed separately, which the authors intend to do in some of the following work.

Lastly, the experiment setting was made only on one model, with one type of loading, and the intraoral conditions would be much more complex. These facts could be perceived as strengths as well as weaknesses of the FEA method. The strength of FEA studies lies in the fact that it assumes constant conditions for all the investigated models, and the variables are only the features that the examiners wish to investigate. Due to this fact, the influence of a specific factor on stress and strain values and distribution can be investigated, without the influence of potential error due to the practitioner, the patient, or the variability of tooth tissues which are common in clinical and in vitro studies. Also, the values and distribution of stresses can be evaluated and visualized in every cross-section, and at every point of the complex 3D model. Since the purpose of the present FEA study was to evaluate von Mises stress values and distribution in models of endodontically treated teeth with different restoration protocols in the physiological biting position, the current experiment setting was adequate for achieving this goal. The present FEA model was validated in an experimental study with a specific setup for the measurement of strain using dual-view holographic interferometry. Due to the difficulty in collecting a homogenous sample of human premolars, it was performed on plastic tooth models created using rapid prototyping based on the FEA model. The results of the experimental study were comparable to the ones obtained in the numerical simulation, validating the accuracy of the model.

6.6. CONCLUSIONS

In conclusion, within the limitations of this study, it can be brought to the attention of a dentist that rigid restorative materials seem to cause lower stresses in dentin of an endodontically treated structurally weakened tooth. It is important to remember the importance of cusps reduction when a direct restoration is placed, because it could be beneficial for the longevity of the tooth and the restoration. The continuation of the present study could involve the use of different materials and cavity designs. Long-term influence is yet to be determined in fatigue in vitro and prospective clinical studies.

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