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Original Research Article

Evaluation using finite element analysis of three root canal preparation tapers on stresses within the roots

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ABSTRACT

The stress distribution on endodontically treated teeth varies with different tapers of root canal preparation and thus the fracture resistance. The objective of this study was to evaluate the stress distribution on endodontically treated teeth between three different tapers of root canal preparation during simulated application of loads on the teeth. In this study, mandibular incisors with straight and mature canals were chosen, cleaning and shaping was done using Hyflex Nickel Titanium (NiTi) rotary instruments. The enlargement was done till 4%, 6% and 8% for design 1, 2, and 3 respectively following which cone beam computed tomography (CBCT) scans were taken. Three finite element analysis models were designed by using three taper designs of root canal superimposed on the same external morphology of a single mandibular incisor. These generated models were assigned to a total force of 70N and 100N which was applied parallel to the long axis of the tooth and at 45 degrees to the long axis of the tooth respectively. The von Misses stresses (VM) throughout the tooth structures were calculated and compared. The results showed that the peak VM stress on all models were at the site of incisal load points. The area of peri-cervical dentin experienced highest VM stresses in all the three designs. This study concluded that highest enamel stress at the incisal load points was seen in all three canal preparation and with increasing taper of the canal, the VM stresses increased.

1. Introduction

The ultimate goal of root canal treatment is biological healing and tooth retention. As early as 1931, it was suggested that root canal treatment was a factor influencing the incidence of vertical root fractures.[1]

Rotary systems facilitate debridement of canals, and higher instrument tapers lead to better canal wall cleanliness and decrease the concerns regarding microbial removal of canal walls.[2] It has been seen that an increase in root canal taper improved irrigant replacement and wall shear stress whilst reducing the risk of irrigant extrusion. It has also been shown that chemo-mechanical instrumentation was more efficient at reducing E. faecalis when the taper of root canals increased from 4% to 8%.[3]

However, there have been some concerns when it comes to excessive removal of radicular dentin because of increased instrumentation taper. Generally, taper should be sufficient enough to permit deep penetration of spreaders or pluggers during filling but should not be excessive to the point where procedural errors occur, and the root is unnecessarily weakened.[2,4] Fundamentally, any removal of hard tissue from the canal walls increases the chance of root fracture.[5,6] Factors potentially influencing the location and direction of root fracture include root canal shape,[7] external root morphology,[8] and dentin thickness.[9,10] Thus a clear understanding of dental root anatomy, external and internal,

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is an essential prerequisite to all dental procedures.

Although several studies have focused on fracture resistance amongst different canal preparation tapers of endodontically treated teeth,[11–14] no studies have evaluated the same in mandibular central incisors. Even though, mandibular incisors are not used regularly for chewing purposes, it can have a biting force ranging from 70N to 110N and may experience excessive forces in cases of traumatic bite and bruxism.

Various methods available to assess fracture resistance and stresses generated on teeth are universal testing machine,[2,15] strain gauge,[16] microscope,[17,18] and finite element analysis.[19,20] Cone beam computed tomography (CBCT),[19] micro computed tomography,[20] have helped to create Finite element analysis (FEA) models.

Therefore, the purpose of this in-vitro study, based on the FEA model, is to evaluate the stress and its distribution on endodontically treated teeth with three different root canal preparation tapers on mandibular incisors. Null hypothesis states that radicular stress as well as the stress distribution does not change with different root canal preparation tapers.

2. Materials and Methods

This in-silico study, stress analysis was performed in the mandibular central incisor after ethical committee clearance from the institution. Human permanent intact mandibular central incisors, with mature apices extracted for therapeutic reasons were selected. Teeth with calcified canals and curved canals were excluded. Thus three mandibular incisors similar in external morphology were chosen. Access opening was made using a No.1 round diamond bur. A size-10 K file was placed in the canal to check the patency. The working length (WL) was determined visually, a 10 K file was inserted from access cavity until the tip just appeared at the foramen, under magnification. The WL was set 1 mm short of this length. Glyde path was established using 15k file, till full WL, followed by canal preparation. Copious irrigation with 3 % sodium hypochloride (NaOCl) was used throughout the procedure. Hyflex Nickel Titanium (NiTi) rotary instruments (Coltene, Switzerland-Batch no.H825ASST) along with Dentsply X-smart endomotor (speed of 500rpm and torque of 2.4 Ncm^{-2}) were used according to the manufacturer's instructions, and the following sequence was used for each tooth no :

Tooth no. 1- 15-4%, 20-4%, 25-4%

Tooth no. 2- 15-4%, 20-4%, 25-4%, 20-6%, 25-6%

Tooth no. 3- 15-4%, 20-4%, 25-4%, 20-6%, 25-6%, 25-8%

2.1. *Modeling of mandibular central incisor tooth*

The selected mandibular incisors, with the three different canal preparation tapers (4%, 6% and 8%), were fixed with wax to maintain its position during scanning. CBCT (Planmeca Finland using CS3D software) operating at 90 kV, 12 mA with a voxel dimension of 75 μm, was used for generating images that were stored in a Digital Imaging and Communications in Medicine (DICOM) format for this study.

Images were processed using the materialize interactive medical image control system (MIMICS 19.0; Materialise, Leuven, Belgium) to identify enamel and dentin, then produce three dimensional (3D) objects. The data were reconstructed to obtain the canals with the tooth.(Figure 1) The three designs of canal preparations were then superimposed on a single tooth model that is Tooth no. 1 to obtain three 3D models with smooth external surface and a mostly centred canal as follows :

Design 1- 4% canal preparation taper

Design 2- 6% canal preparation taper

Design 3- 8% canal preparation taper

An opening was set in the middle of the lingual fossa, with its end connected to the orifice of the canal. The canal was filled with gutta-percha from the apex to root canal orifice followed with composite coronally, till the external surface. The thin cementum was neglected and the wall of the root was assumed to be dentine only.

Different parts of the tooth including periodontal ligament (PDL) and alveolar bone were designed. The PDL was assumed to have 0.25mm uniform thickness. The mandibular alveolar bone that supports the tooth was also reconstructed. The alveolar bone was assumed to have a thickness of 1.4mm all around. Thus, a virtual model of mandibular central incisor with its supporting structures was obtained.

2.2. *Meshing*

All models were imported into Cosmos software package (Solid works software package, Dassault Systems, Cedex, France) for meshing. The finite element model was divided into several finite elements with tetrahedral as the chosen element. The elastic properties namely the young's modulus and the Poisson's ratio were defined for different parts of the tooth, obturating materials, access restoration and the neighbouring anatomical structures (Table 1). Thus, finite element models of teeth were realized by changing the element material properties in the zone of canal preparations.(Figures 2 and 3)

The generated models with above mentioned materials were transferred to HyperMesh v 11.0 ANSYS R 18.1 software for the calculation of Von Misses (VM) equivalent stresses.

These generated models were assigned to a total force of 70N (applied parallel to the long axis) and 100N (applied 45 degrees to the long axis of the tooth) to simulate a normal vertical masticatory load as well and loads applied in cases of traumatic bite or bruxism. The distribution of VM stress on the models were obtained, tabulated and graphically presented.

3. Results

The VM equivalent stresses for the models with different canal preparation tapers were obtained, tabulated and graphically represented. The Finite element analysis stress values are presented in the form of a colour chart with different colours representing the stress values, blue representing lowest stress value and red representing highest stress values.

The peak VM stresses in all the 3 designs occurred at the sites of the force load. Within the designs, as the taper increased the stress values increased, with the maximum stress seen in Design 3 (8% canal preparation taper), and the minimum stress seen in Design 1 (4% canal preparation taper).(Tables 2 and 3)

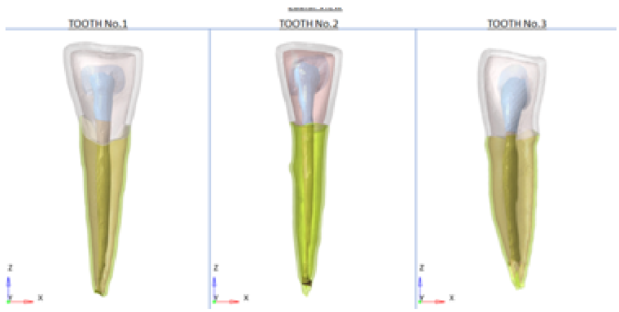

Fig. 1: Labial view of fea models

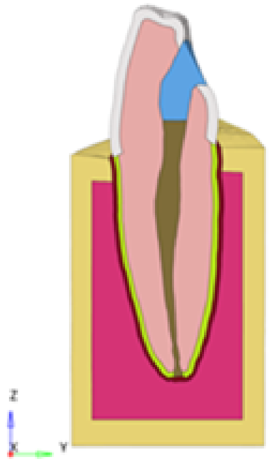

Fig. 2: Longitudnal view of superimposed model (Design 1)

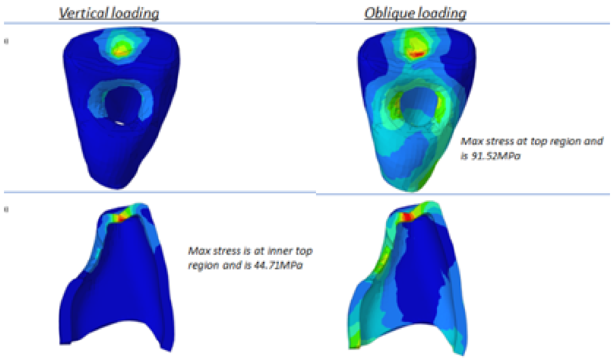

Fig. 3: Peak stress in enamel in design 1

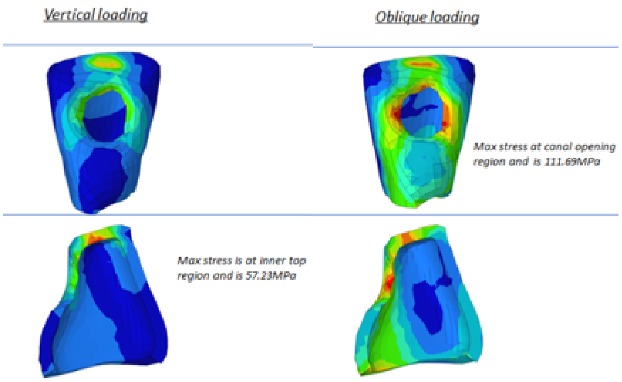

Fig. 4: Peak stress in enamel in design 2

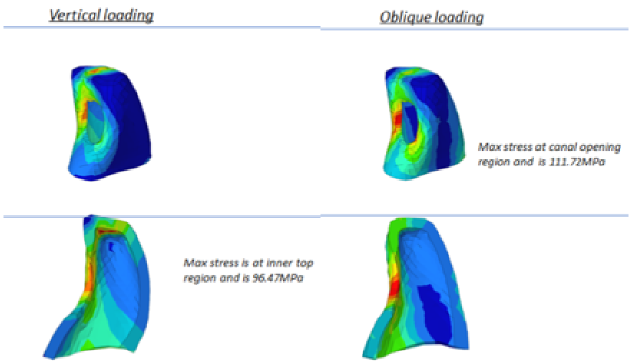

Fig. 5: Peak stress in enamel in design 3

Table 1: Young's modulus and poisson's ratio for various parts of the tooth

Material	Young's Modulus	Poisson's ratio
Enamel	84100	0.33
Dentin	20000	0.31
PDL	5000	0.45
Mandibular alveolar bone (average of cancellous and compact bone)	14000	0.30
Cold gutta-percha	30000	0.485
Composite resin	8620	0.30

Table 2: Peak stress values in different canal preparation tapers (enamel and dentin)

Maximum stress values in enamel and dentin (Mpa)				
Part	**Loading**	**Design no.1**	**Design no.2**	**Design no.3**
Enamel	Vertical	44.71	57.23	96.47
	Oblique	91.52	111.69	111.72
Dentin	Vertical	14.93	17.94	26.56
	Oblique	38.65	46.83	49.34

Table 3: Peak stress in different parts of the tooth

Stress contours in dentin (Mpa)				
Part	**Loading**	**Design no.1**	**Design no.2**	**Design no.3**
Coronal third	Vertical	7.93	12.03	10.82
	Oblique	46.83	49.34	38.65
Middle third	Vertical	5.03	7.23	8.08
	Oblique	26.67	42.19	29.56
Apical third	Vertical	3.29	3.99	4.94
	Oblique	12.61	21.67	23.10

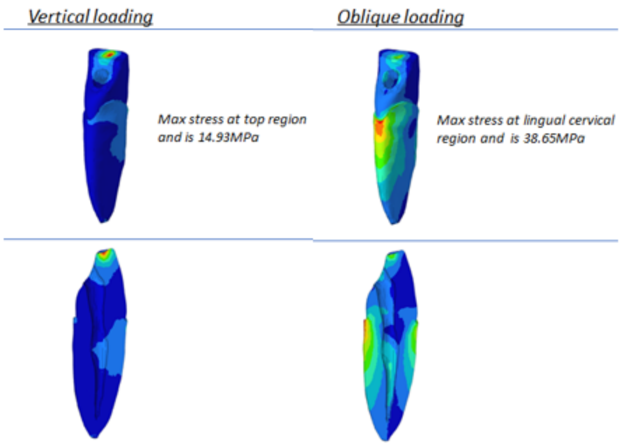

Fig. 6: Peak stress in dentin in design 1

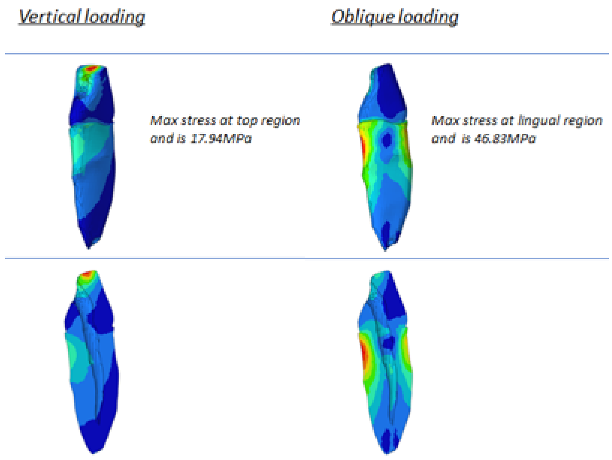

Fig. 7: Peak stress in dentin in design 2

4. Discussion

The ultimate goal of root canal treatment is biological healing and tooth retention. Preparation of the root canal system is considered one of the most important stages in root canal treatment. Since the limiting factor for fracture is the remaining hard substance of the tooth, any system will presumably prove effective if they afford no or only minimal invasive preparation procedures.[1]

However enlargement of the coronal third of the root canal space is considered important to support root canal length measurement, debris removal, and canal obturation. Extensive use of rotary instruments during preparation of the canal weakens the root structure. At the same time choosing a smaller taper may reduce the risk of procedural accidents and untoward events during cleaning and shaping,

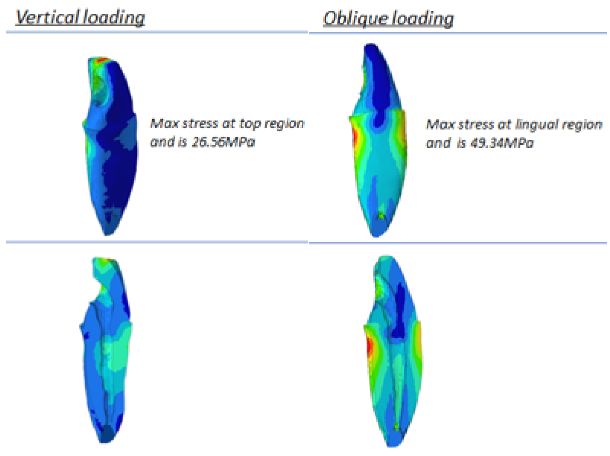

Fig. 8: Peak stress in dentin in design 3

and it may compromise the cleanliness of the canal system and placement of obturating material.[5]

As stated, a greater taper may weaken the tooth and studies have shown that the amount of remaining dentin thickness significantly affects the resistance to fracture of prepared root canals.[3,4,10] Extracted human mandibular central incisors were used for the study.

Hyflex NiTi (Coltene, Switzerland) rotary files are a new generation of NiTi heat treated files, manufactured utilizing a unique process that controls the material's memory thus making the files extremely fracture resistant and flexible. It retains its shape after bending and has good superior canal tracking ability. This system also had files with all the three canal preparation tapers required for this study (4%, 6% and 8%).

There are various methods available to check fracture resistance and stresses generated on teeth. A universal testing machine offers enhanced control and stability and ensures accuracy and repeatability. But the preparation of the samples can be time consuming and expensive, due to the destruction of the specimen. Strain gauges are used for many applications and are often used with other sensors to measure the strain or stress. The advantage of a strain gauge is the ease with which it can be used and the fact that they are reusable. However, the direction of strain which is measured cannot measure multi direction loads.[20] Microscope dentistry utilizes high-tech microscopes to provide detailed images of dental structures. Dentinal defects due to the usage of rotary files can be evaluated. Presence of these defects gives us an idea about the areas of crack initiation and propagation. A CBCT scan helps in in-vitro studies for the evaluation of dentin removal after various cleaning and shaping techniques, before and after instrumentation. Micro-CT is an imaging device with higher resolution, that produces 3D images of a biological structure, like a tooth. CBCT and Micro-CT can assist in modelling for FEA

An important advantage of using a FEA is that all the conditions can be kept exactly identical (such as tooth anatomy, mechanical properties, compaction loading, root support, temperature profiles and incremental procedures) whilst only the taper can be varied. Furthermore, the FEA offers the advantage that individual variables and combinations of variables can be tested systematically in a way that is not possible experimentally. This study used finite element analysis to show the effects of canal preparation taper on radicular stresses.

FEA studies mostly use either tetrahedral/ triangular or hexahedral/quadrilateral element shapes, with them being tailored to certain specific problems. The tetrahedral elements fit very well and are more efficient in arbitrary shaped geometries than hexahedral meshes. Combined with available state-of-the-art robust meshing techniques, quadratic tetrahedral elements can be used without sacrificing performance compared to hexahedral elements.[10] This study also used tetrahedral elements to create meshing.

To simulate clinical situation the FEA models were designed with addition of PDL and alveolar bone. Since the cementum is usually very thin, it was neglected and the wall of the root was assumed to be dentin only. Young's modulus and Poisson's ratio were applied to all the elements of the FEA models. These properties define strength of the material and how it deforms when subjected to different loads acting on it.[9,21]

In the present study the stress values on the tooth were higher, as the taper of the canal preparation increased 4% to 8%. However the stress pattern in different parts of the tooth was similar. Therefore the null hypothesis was accepted partially. The null hypothesis that stated that radicular stress does not change with different root canal preparation tapers, was rejected. The other part of null hypothesis that stated that area of radicular stress distribution does not change with different root canal preparation tapers was accepted.

Previous studies with similar methodology done on other teeth (premolars, molars) showed that, an increased degree of taper in the cervical region resulted in slightly higher stresses under both vertical and oblique loading conditions.[5,19,20]

Other studies which used universal testing machine to evaluate the effect of taper on the fracture resistance of roots showed that larger tapers can cause a higher risk of fracture.[14,22,23] It can be inferred that increasing the taper of the root canal preparation can reduce fracture resistance.

The maximum stress values were seen in enamel at the point of loading (44.71MPa, 57.23MPa and 96.47MPa respectively, for the three designs) and next maximum stress was seen around the access cavity preparation in all the three designs in case of vertical loading (70N). For oblique loading (100N), design 2 and 3 had maximum stress values in the enamel which were 111.69 MPa and 111.72MPa respectively, in the mesial and distal cavosurface margins of the access preparation. Enamel is a more brittle and stiff structure when compared to dentin, and this leads to localized tensile stress concentration and micro crack initiation. It is inferred that the access restoration should be done following all bonding procedures in order to avoid failure in this area.

For oblique loading (100N) for the three designs, the peak VM stress values in dentin were 38.65 MPa, 46.83MPa and 49.34MPa respectively, in the lingual cervical region below the CEJ. This was consistent with previous FEA studies[5,20,23,24] that showed that external cervical regions was the most important region in terms of susceptibility to maximum stresses. Greater loss of dentin in the cervical region may be the reason for comparatively higher stresses. Similar result was found in a study showing maximum stress values in the clinical crown with the greatest stress present at the CEJ.[19]

In cases of vertical loading of 70N the maximum stress in dentin was seen in the coronal third in the pericervial area (7.93MPa, 12.03MPa, 10.83MPa for the three designs respectively), followed by middle third (5.03MPa, 7.23MPa, 8.08MPa for the three designs respectively) and was seen to be the least in the apical third (3.29MPa, 3.99MPa, 4.94MPa for the three designs respectively). Higher stress in the middle third in comparison to apical third was also shown in other studies. Dang & Walton 1989 suggested that most vertical root fractures occurred in the middle third of the root. In contrast other studies (Harvey et al. 1981) reported that stresses were localized in the apical third of the root, and decreased coronally. The different findings are not necessarily conflicting because they can indicate that there are numerous methods involved in root fracture. Root fractures originating in the apical third is more likely initiated during filling, while fracture originating in the cervical portion is caused by occlusal loads which justifies the higher stress values seen in the cervical region in this study.[5,19,23]

The stress distribution was seen to be more in case of oblique loading (100N) representing pathological forces seen in cases of traumatic bite and bruxism compared to vertical loading (70N) which represented physiological masticatory forces. This showed that the forces on mandibular incisor, even though not involved in regular biting actions, may be excessive and the stresses caused thereof in cases of pathological conditions.

FEA is a very useful technique, but it possesses certain limitations. The FEA system works on many assumptions. Firstly, it assumes that dentin is a uniform, isotropic material whereas in reality, dentin is a biomaterial created and changed over time. Different areas may have different Poisson's ratio and Young's modulus, depending on factors such as mineral content.[10]

Future in-vitro studies can be done, using other techniques such as strain-gauge which could validate results obtained from FEA. The combination of modelling and strain-gauge measurement could give more information regarding the stress generated and mechanisms of vertical root fracture.

5. Conclusion

Within the limitations of this study, it was concluded that:

Stresses increased with increase in canal preparation taper in mandibular central incisor when force was applied. Stress concentration was seen to be highest on the point of loading in the enamel region for all the three designs. Stress distribution was seen to be maximum in the cervical area around the CEJ for all the three designs. Stress distribution was seen to be more in cases of oblique loading (100N) compared to vertical loading (70N).

6. Conflict of Interest

The authors declare that there is no conflict of interest.

7. Source of Funding

None.

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