Chapter

Finite Element Analysis and Its Applications in Dentistry

Vinod Bandela and Saraswathi Kanaparthi

Abstract

Finite Element Analysis or Finite Element Method is based on the principle of dividing a structure into a finite number of small elements. It is a sophisticated engineering tool, which has been used extensively in design optimization and structural analysis first originated in the aerospace industry to study stress in complex airframe structures. This method is a way of getting a numerical solution to a specific problem, used to analyze stresses and strains in complex mechanical systems. It enables the mathematical conversion and analysis of mechanical properties of a geometric object with wide range of applications in dental and oral health science. It is useful for specifying predominantly the mechanical aspects of biomaterials and human tissues that cannot be measured *in vivo*. It has various advantages, can be compared with studies on real models, and the tests are repeatable, with accuracy and without ethical concerns.

Keywords: finite element analysis, finite element method, stress, dentistry, implants

1. Introduction

Dentistry is the fastest growing branch of medical field, deals with the study of diagnosis, prevention, and treatment of diseases, disorders, and conditions of the oral cavity. Although primarily associated with teeth, the field of dentistry is not limited to teeth but includes other aspects of the craniofacial complex including the temporomandibular joint (TMJ) and other supporting, muscular, lymphatic, nervous, vascular, and anatomical structures.

Virtually, every phenomenon in nature; whether biological, geological or mechanical, can be described with the aid of law of physics, in terms of algebraic, differential or integral equations relating various quantities of interest. Finite Element Analysis (FEA) or Finite Element Method (FEM) is a computer-based numerical method to analyze the structure based on the principle of dividing a structure into a finite number of small elements that are connected with each other at the corner points called nodes. For each element, its mechanical behaviour can be written as the function of displacement of the nodes. These nodes when subjected to certain loading conditions results in behaviour of the model similar to the structure it represents. When a computer analysis is performed on this, a system of simultaneous equations can be solved to relate all forces and displacement of the nodes. From this, stress and strain can be established in each element and the whole structure can be evaluated [1].

There were many articles published before on FEA and their uses, this chapter mainly focus on the brief application of FEA in dentistry, apart from the historical perspective, planning of analysis, workflow of FE study, merits, shortcomings, and future of FEA.

2. Historical perspective

The first researcher who developed this technique was Richard Courant, a mathematician with the main goal of minimizing the calculative procedures in gaining absolute solution to bio-mechanical system in early 1940's. Turner et al., in 1956 attempted to describe this method by developing broader definition of these numeric analyses in aeronautical engineering. Ioannis Argyris and R.W Clough coined the term 'Finite Element' in 1960. Weinstein et al., in 1976 used this technique in implant dentistry to evaluate various loads of occlusion on implant and adjacent bone. Since then, evolution of this technique has been observed in a very rapid and sophisticated scale in micro-computer as well as analysis of large-scale structural system [1, 2].

3. Planning of analysis

3.1 Pre-processor

In this stage, the material properties are assigned (**Figure 1**) [1, 2].

3.1.1 Specifying the title

It is specifying the name of the problem. This is optional but very useful, especially if a number of design iterations to be completed on the same base model.

3.1.2 Setting the type of analysis

In this, the type of analysis that is going to be used is done. Eg: structural, fluid, thermal or electromagnetic etc.

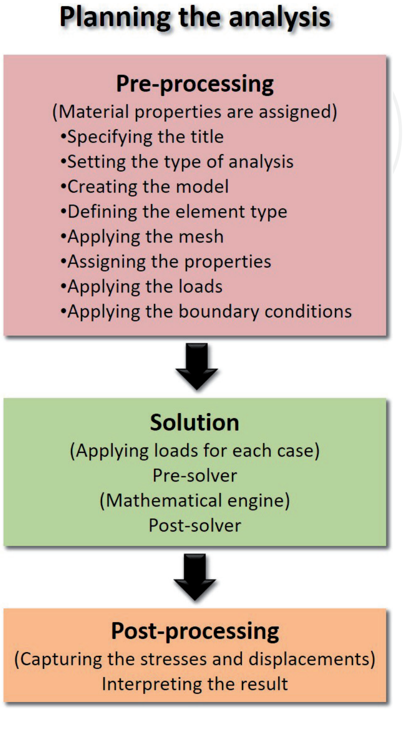

Figure 1.
Planning of analysis.

3.1.3 Creating the model

The model is drawn in 1-D (dimensional), 2-D, or 3-D space in the appropriate units (M, mm, inch etc.).

3.1.4 Defining the element type

This may be 1-D, 2-D, or 3-D.

3.1.5 Applying a mesh

Mesh generation is the process of dividing the analysis continuum into a number of discrete parts or finite elements. The finer the mesh, the better is the result but longer the analysis time.

3.1.6 Assigning properties

Material properties (Young's modulus, Poisson's ratio, density and if applicable coefficient of expansion, friction, thermal conductivity, damping effect, specific heat etc.) have to be defined in this step. In addition, element properties may need to be set.

3.1.7 Applying loads

Usually, some type of load is applied to the analysis model. The loading may be in the form of a point load, a pressure or a displacement in a stress (displacement) analysis. The loads may be applied to a point, an edge, a surface or even a complete body.

3.1.8 Applying boundary conditions

When applying a load to the model, in order to stop accelerating infinitely through the computer's virtual ether, at least one constraint or boundary condition must be applied. A boundary condition may be specified to act in all directions - axes (x, y, z) or in certain directions only. They can be placed on nodes, key points, areas or on lines.

3.2 Solution

This part is fully automatic and it can be logically divided into three main parts: the pre-solver, the mathematical engine and the post-solver. The pre-solver reads the model created by the pre-processor and formulates the mathematical representation of the model. The results are returned to the solver and the post-solver is used to calculate strains, stresses, etc., for each node within the component or continuum.

3.3 Post-processor

Here the results of the analysis are read and interpreted. They can be presented in the form of a contour plot, a table, deformed shape of the component or the mode shapes and natural frequencies if frequency analysis is involved. Most post-processors provide an animation service, which produces an animation and brings the model to life. All post-processors now include the calculation of stress and strains in any of the x, y or z directions or indeed in a direction at an angle to the co-ordinate axes. The principal stresses and strains may also be plotted or if required the yield stresses and strains according to the main theories of failure.

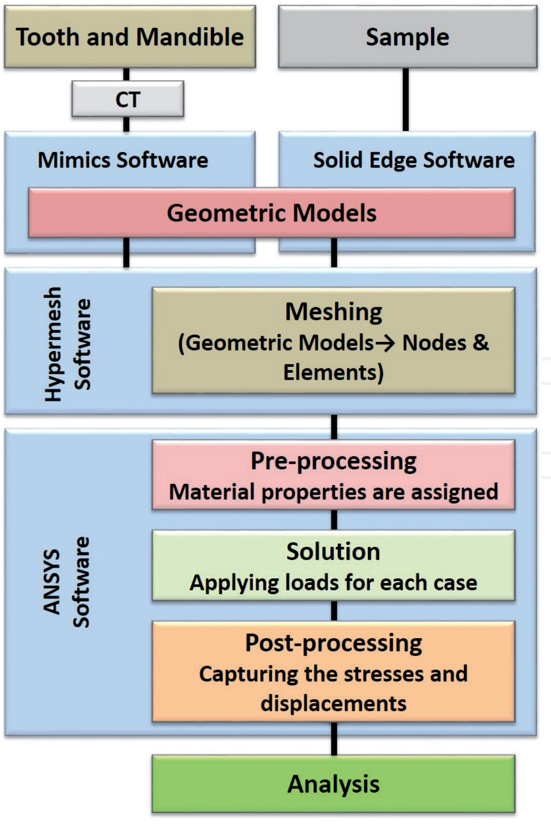

Figure 2.
Workflow of FE analysis.

In brief, the FE is a mathematical method for solving differential equations. It has the ability to solve complex problems that can be represented in differential equation form that occur naturally, in virtually all fields of the physical sciences. Accurate modeling is essential to ensure the relevance of the result for the corresponding FEA. The results solely depend on the model that has been created. Workflow of the entire finite element study is shown in **Figure 2**.

4. Application of FEA in oral radiology

Oral and maxillofacial radiology is the specialty of dentistry concerned with performance and interpretation of diagnostic imaging used in examining the dental, craniofacial, and adjacent structures. Use of FEA in this specialty helps for proper diagnosis and possibility of knowing iatrogenic effects.

Szücs et al., in 2010 analyzed the effect of removing various amounts of bone around an impacted mandibular third molar and predicted the possibility of iatrogenic fracture. FEA was used to generate 3-D models of a human mandible with impacted third molars. They found highest stress occurred during normal clenching if the surgical procedure involved the external oblique ridge. The peak stress occurred at the site of removal of the third molar, during contralateral loading of the mandible. They concluded that with FEA they could able to identify the accumulation of stress and strain at specific parts of the mandible and predicted the responses of bone to mechanical activity. FEA could prove to predict the likelihood of iatrogenic fracture of the jaws after surgical removal of mandibular bone, such as occurring during the extraction of third molar. This allow the dentists to change/modify their approach to tooth removal in certain cases [3].

Oenning et al., in 2018 simulated functional forces in a mandible model by means of FEA and then assessed the biomechanical response produced by impacted third molars on the roots of the second molar. They found areas of high-energy dissipation and compression stress in the second molar root, independently of the inclination of the impacted third molar. They concluded that, impacted third molars in close proximity with the adjacent tooth can generate areas of compression concentrated at the site of contact, suggesting an involvement of mechanical factors in triggering of resorption lesions [4].

Kihara et al., in 2019 evaluated the longitudinal change quantitatively in mandibular volume and configuration in a patient with craniofacial fibrous dysplasia (FD). The 3-D models were analyzed morphologically and volumetrically using FEA. They found FD lesion in the mandible enlarged non-uniformly and had site specificity. They suggested that compression stress induced by the occlusal force through the denture may have influence on the direction of enlargement in FD [5].

5. Application of FEA in restorative dentistry

Restorative dentistry refers to the diagnosis and integrated management of diseases of the teeth and their supporting structures and rehabilitation of the dentition for functional and esthetic requirements of an individual. Restorative dentistry. It is a broader term encompasses the dental specialties of endodontics, prosthodontics, and periodontics.

Many newer materials have been developed owing to the increasing interest in the field of esthetic dental restorations. In order to minimize the stress concentration of the restorative materials and to decrease the incidence of restorative failure; physical properties like modulus of elasticity should be near or equal to that of the natural dental tissue. Due to the lack of proper understanding on the biomechanical principles of the materials involved in restorative procedure, lead too many detrimental effects causing a restorative failure. Therefore, in order to know the behaviour of materials and dental tissue, biomechanical studies are very crucial [6, 7].

Goel et al., in 1991 investigated stress variation in the enamel and dentin adjacent to the Dentinoenamel Junction (DEJ) on FEM of maxillary first premolar. The results suggested that, because of mechanical interlocking between enamel and dentin in the cervical region is weaker than in other regions of the DEJ, enamel in this region may be susceptible to belated cracking that could eventually contribute to the development of cervical caries than other areas of tooth [8].

Rees in 2002 examined the effect of varying position of an occlusal load on the stress contour in the cervical region of a lower second premolar using a 2-D plane strain FEM. A 500 N load was applied vertically to either of the cusp tips or in various positions along the cuspal inclines. He found that, loads applied to the inner aspects of the buccal or the lingual cuspal inclines produced maximum principal stress values of up to 358 MPa, which is exceeding the known failure stresses for enamel [9].

Ausiello et al., in 2002 conducted a 3-D FEA study to identify the thickness and flexibility of the teeth adhesively restored with resin-based material. No difference in the stress relief between the application of a thin layer of more flexible adhesive with low elastic modulus and thick layers of less flexible adhesive of high-elastic modulus was found. They observed a relatively small cuspal deformation in all the models with increased cusp-stabilizing effect of ceramic inlays compared to composite restorations [10].

Ausiello et al., in 2004 investigated the composite inlay restored class-II MOD cavities the effect of differences in the resin-cement elastic modulus on stress-transmission to ceramic or resin-based during vertical occlusal loading. They found better stress dissipation in indirect composite resin-inlays. Glass ceramic inlays transferred stresses to the resin cement and adhesive layer [11].

Magne et al., in 2006 described a rapid method of generating FE models of dental structures and restorations. They evaluated five models: natural tooth, mesial-occlusal (MO), and mesial-occlusal-distal (MOD) cavities, MO, and MOD endodontic access preparations and found a progressive loss of cuspal stiffness in MO to MOD to endodontic access, as there is loss of tooth structure with these type of restorations. The natural tooth and the tooth with the MOD ceramic inlay retained 100% cuspal stiffness [7].

Ichim et al., in 2007 investigated the influence of the elastic modulus (E) on the failure of cervical restorative materials (Glass ionomer cement (GIC) and composite) and identified an E value that minimizes the mechanical failure under clinically realistic loading conditions. They found that the materials used in non-carious cervical lesions are unsuitable for restorations as they are less resistance to fracture and suggested that the elastic modulus of a restorative material to be in the range of 1 GPa [2].

Asmussen et al., in 2008 analyzed the stresses generated in tooth and restoration by occlusal loading of Class-I and Class-II restorations restored with resin composite; suggested that the occlusal restorations of resin composite should have a high modulus of elasticity in order to reduce the risk of marginal deterioration [12].

Coelho et al., in 2008 conducted a study to test the hypothesis that micro-tensile bond strength values are inversely proportional to dentin-to-composite adhesive layer thickness through laboratory mechanical testing and FEA. They found micro-tensile bond for Single Bond as increased adhesive layer thickness did not reduce Clear fil SE Bond strength [13].

Magne and Oganesyan in 2009 measured cuspal flexure of intact and restored maxillary premolars with MOD porcelain, and composite-inlay restorations and occlusal contacts (in enamel, at restoration margin, or in restorative material). They found a relatively small cuspal deformation in all the models and an increased cusp-stabilizing effect of ceramic inlays compared with composite ones [9].

5.1 Dental composites

Composites are the resin restorative materials developed to overcome the disadvantages of amalgam restorations, which are unaesthetic and toxic. Composites are filled resins, exhibit high compressive strength, abrasion resistance, ease of application, and high translucency. FEA has been in use to analyze stresses generated in teeth and restorations. It is a proven useful tool in understanding biomechanics of tooth and the biomimetic approach in restorative dentistry [14].

Lee et al., in 2007 conducted a study to measure the cusp deflection by polymerization shrinkage during composite restoration for MOD cavities in premolars, and examined the influence of cavity dimension, C-factor, and restoration method on the cusp deflection. They found that, the cusp deflection increased with increasing cavity dimension and C-factor and suggested the use of an incremental filling technique or an indirect composite inlay restoration to reduce the cuspal strain [15].

Choi et al., in 2011 analyzed the disintegration of a dental composite restoration around the margin due to contraction stress by measuring the circumferential strain on the outer surface of a ring-type dental substrate. They found increase in the marginal gap size representing the increase in the number of cracking's along the margin due to polymerization contraction [16].

Jongsma et al., in 2011 studied to find out the rationale of using whether 60% increase in push-out strength with a two-step cementation procedure of fiber posts is equivalent to the layering technique of composite restorations or not. They found two-step cementation of fiber posts lead to a decrease in internal stresses in the restoration, resulted in higher failure loads and less microleakage [17].

5.2 Dental ceramics

Dental ceramics are in-organic, non-metallic, and brittle restorative materials producing dental prosthesis that are used to replace missing or damaged dental structures which has high compressive strength and low tensile strength. FEM provides a mathematic analysis to predict strength values without the potential for errors in dental ceramics [18].

Tensile stresses tend to be more critical than compressive stresses for ceramic materials. The strength of ceramic restorations is significantly affected by the presence of flaws or other microscopic defects. Tensile stress concentration at cementation surface of the ceramic layer suggested as the predominant factor controlling ceramic failure [6].

Belli et al. in 2005 evaluated the effect of hybrid layer on distribution and amount of stress formed under occlusal loading in a premolar tooth restored with composite or ceramic inlay. They concluded that the hybrid layer has an effect on stress distribution under loading in restored premolar tooth model with composite or ceramic inlay [19].

Rezaei et al., in 2011 determined the effect of buccolingual increase of the connector width on the stress distribution in posterior FPDs made of IPS Empress. Three models of three-unit bridges replacing the first molar were prepared with the buccolingual connector width varied from 3.0 to 5.0 mm. They were loaded vertically with 600 N at one point on the central fossa of the pontic and a load of 225 N at 45° angle from the lingual side. They concluded that, increasing the connector width decreases the failure probability when a vertical or angled load is applied [20].

Thompson et al., in 2011 compared the inlay supported all-ceramic bridge with that of traditional full crown supported all-ceramic bridge. They demonstrated peak stresses in the inlay bridge around 20% higher than in the full crown supported bridge. They suggested the use of an ideal inlay preparation form and an optimized bridge design emphasizing on broadening of the gingival embrasure, so that the forces derived from mastication can be distributed adequately to a level that are within the fracture strength [21].

Matson et al., in 2012 compared the stress distribution generated in a veneer restoration of an upper central incisor to intact teeth by applying a 10 N lingual buccal load at the incisal edge. Veneers used in restorative rehabilitations for anterior teeth are retained by the adhesive systems and resin cements. These restorations are mechanically not strong, because they are made of brittle materials, but they have good retention due to the resin-dentine bonding. They recommended the use of veneers to replace enamel for rehabilitation [22].

6. Application of FEA in endodontics

Endodontology/Endodontics is the branch of dental sciences concerned with the form, function, health, injuries to and the diseases of the dental pulp and periradicular region, and their relationship with systemic health and well-being. Endodontic therapy involves either root canal filling techniques by conventional methods; or endodontic surgery with the use of biocompatible restorative materials, instruments, and techniques performed. The objective of endodontic instrumentation is to produce a tapered continuous preparation that should preserve the anatomy of root canal and maintain a good apical seal and foramen as small as possible, without any deviation from the original canal curvature [23].

During canal instrumentation, pressure is generated against the dentinal walls that may lead to inappropriate canal preparation or microcracks. These microcracks may lead to vertical fracture - one of the cause for tooth loss. During instrumentation, nickel-titanium (NiTi) are the commonly used for shaping the root canal. So, in order to perform well and avoid instrument breakage inside the canal, the material used and the technique performed should be followed meticulously. FEA helps to analyze and predict the treatment outcome [24].

Satappan et al., in 2000 analyzed the type and frequency of defects in NiTi rotary endodontic files after routine clinical use and reasons for their failure. They found torsional failure by using too much apical force during instrumentation as the more frequent cause than flexural fatigue, which resulted from the use in curved canals [25].

Hong et al., in 2003 analyzed the stress variations by vertical and lateral condensation on mandibular first molar mesio-buccal root canal by step-back technique. They found vertical condensation technique generating high stresses and the reason for vertical root fracture was due to over-force and improper operation [2].

Subramaniam et al., in 2007 compared the torsional and bending stresses in two simulated models of Ni-Ti rotary instruments, ProTaper and ProFile. They found the distribution of stresses was uniform in ProTaper model and stiffer by 30% than ProFile model, which shows ProFile is more flexible than ProTaper [26].

Kim et al., in 2008 compared the stress distribution during root canal shaping and estimated the residual stress in three brands of Ni-Ti rotary instruments: ProFile, ProTaper, and ProTaper Universal (Dentsply Maillefer). They found that the original ProTaper design showed greatest pull in the apical direction and highest reaction torque from the root canal wall while, ProFile showed the least. The residual stress was highest in ProTaper followed by ProTaper Universal and ProFile. In ProTaper, stresses were concentrated at the cutting edge [27].

Lee et al., in 2011 investigated on cyclic fatigue resistance of various Ni-Ti rotary files in different root canal curvatures by correlating cyclic fatigue fracture tests. They concluded that stiffer instrument had the highest stress concentration and the least number of rotations until fracture in the cyclic fatigue test. Increased curvature of the root canal generated higher stresses and shortened the lifetime of Ni-Ti files [28].

Belli et al., in 2011 evaluated the effect of interfaces on stress distribution in incisor models of primary, secondary, and tertiary monoblocks generated either by adhesive resin sealers in combination with a bondable root filling material or by different adhesive posts. The concept of creating mechanically homogenous units within the root dentine is theoretically excellent, but accomplishing in the canal space is challenging because bonding is compromised by volumetric changes in resin-based materials to dentine, debris on canal walls, configuration factors, and differences in bond strengths. They found stresses within roots increased with an increase in the number of the adhesive interfaces [29].

6.1 Application of FEA in post and core

A considerable amount of tooth structure lost due to caries, endodontic therapy, and placement of previous restorations will compromise the tooth structure to resume its full function to serve satisfactorily. The type of the tooth restoring and the amount of remaining coronal tooth structure are the two factors that influence the choice of technique. The second factor is probably the key important indicator in determining the prognosis a tooth that is restored. If a substantial amount of coronal structure is missing, a cast post and core is indicated [30].

The method of restoring a structurally weakened tooth is post and core system, which is most common and widely used. This system can be categorized into two; custom cast metal posts and cores that are single piece, and a two component design comprising a prefabricated post to which other core materials is subsequently adapted. While fabricating a custom post and core, the difference in the elastic modulus of dentine and post material may be a source for root structure because of stress and debonding of posts due to stress contraction of the cement. Design of the post also effects the stress distribution, which was found as the most common mode of failure. Ferrule preparation creates a positive effect in reducing the stress concentration in an endodontically treated tooth. FEM can be used in various types of materials like carbon, metal, glass fiber, and zirconia ceramic and different configurations of dowel like smooth and serrated on the stress distribution of the teeth [6, 7].

Studies have showed that the increase in elastic modulus of post material cause decrease in the stress in dentin. However, Boschian et al., in 2006 have reported that higher the elastic modulus of post material than dentin can cause a dangerous, non-homogenous stress in root dentin. Also Silva et al., in 2009 reported that the stress distribution is more related to endodontically treated teeth restored with a post than the post's external configuration. Therefore, whenever the clinician is planning to use a post he has to choose a post material, which has the stiffness similar to dentin. They evaluated the stress distribution in maxillary central incisor, which is endodontically treated and restored with fiberglass and metallic prefabricated posts [7].

Necchi et al., in 2008 conducted a study on rotary endodontic instruments to demonstrate the usefulness of the FEM in improving the knowledge of the mechanical behaviour of Ni-Ti and stainless steel ProTaper F1 instrument during root canal preparation. The results found the radius and position of the canal curvature as the most critical parameters in determining the stress whilst high stress levels are produced by decrease in the radius and instrumenting apical to the mid root position. They advised to discard the instrument after its use in those type of root canals [31].

The use of glass fiber dowels showed less stress than the metal, carbon, and ceramic posts which few researchers found. However, there are some differences in the material properties, boundaries and loading conditions. A study by Eraslan et al., in 2009 showed a reduction in VM stress in an endodontically treated tooth restored with all-ceramic post and core than with zirconium oxide ceramic post and fiber post at the dentin wall and within the post [32].

In a study by Zhou et al., in 2009 a mandibular second premolar was used to evaluate the stress distribution restored with fiber post and core with various shapes and diameter in axial and non-axial loads. They found no significant change with the increase in post diameter irrespective of the shape. They recommended trapezium and cone fiber posts as the ideal design for restoring the crown and root portion as they produced least maximum stress in non-axial loads than in axial load [33].

For fixation of post and core to the remaining tooth structure cements like zinc-phosphate, glass ionomer, resin-modified glass ionomer, and resin cement are used. The difference in elastic modulus of these cements, post materials and dentin results in stress concentration under function. In 2010, Soares et al., found zinc-phosphate and conventional glass ionomer cement producing high stress concentrations at dentin-cement interface. They also demonstrated that resin cement recorded higher fracture resistance values than other cements, which was in accordance with the study done by Suzuki et al., in 2008 [7].

A systematic review in 2010 by Al-Omiri et al., discussed the importance of ferrule and emphasized the use of adhesive resin-fiber posts and composite cores as the best luting technique with respect to the biomechanical behaviour and tooth fracture resistance [34].

Al-Omiri et al., in 2011 conducted a study on 3-D FEM of maxillary second premolar restored with an all-ceramic crown supported by a titanium post and a resin-based composite core to analyze the stress concentration areas. They found higher incidence of deep root fractures in teeth restored with post-retained crowns below the level of crestal bone due to the increase in intracanal stresses with horizontal loads generating more dentinal stress than vertical loads. Though endodontic posts provide retention for coronal restoration, the dentinal stress value was higher than those without posts were. Smaller diameter posts with modulus of elasticity similar to dentine were associated with better stress distribution. More the amount of radicular dentin around the post better/reduced dentinal stress concentration within the root [35].

7. Application of FEA in prosthodontics and implantology

The branch of dentistry pertaining to the restoration and maintenance of oral function, comfort, appearance, and health of the patient by the restoration of natural teeth and/or the replacement of missing teeth and craniofacial tissues with artificial substitutes. FEA helps in studying the stress patterns and their distribution between the tooth and the material used in restoring the natural or missing tooth/teeth structure and predicting the favorable outcome with least chance of failure.

Zarone et al., in 2005 conducted a study on maxillary central incisor, the influence of tooth preparation design restored with alumina porcelain veneer on the stress distribution under functional load. They suggested the use of chamfer with palatal overlap design when restoring with porcelain veneers as it restored the natural distribution of stress than window technique [9].

FEA has been extensively used in implant dentistry to predict the biomechanical behaviour of various dental implant designs, as well as the effect of clinical factors for predicting the clinical success. Stress patterns in implant components and surrounding bone are well studied. The achievement of any FE study depends on the accuracy of simulating structures used. They are the material properties of implant and bone, surface characteristics and geometry of the implant and its components, loading method and support conditions, and the biomechanical behaviour of implant-bone interface. The prime difficulty in simulating the living tissues and the responses to the applied load can be successfully achieved with the use of advanced imaging techniques [36].

FEA gives an in-depth idea about the patterns of stress in the implant and more importantly in the peri-implant bone and this helps in the betterment of the implant design and implant insertion techniques. Several studies had been put forward on the effect of material properties of implant, implant number, size (length and diameter), thread profile, and on the quality and quantity of surrounding bone on stress distribution. The stresses of various kinds such as von Mises stress, maximum shear stress, maximum and minimum principal stress are used to assess the mechanical stress on the bone, implant, and bone-implant interface. Amongst, von Mises stress is most frequently and mainly used scalar-valued stress invariant to evaluate the yielding, and or failure behavior of dental materials. While minimum principal stress gives an idea on the compressive stress, maximum principal stress gives on tensile stress. Principal stress is used to study both ductile and brittle properties of a bone [36].

Siegele and Soltesz in 1989 conducted a study using implants of various shapes to evaluate the patterns of stress generation in the jawbone found that different shapes produced different stress patterns and conical implant showed higher stress than screw shaped and cylindrical implants [2].

Mailath et al., in 1989 evaluated the stress values at the level of bone while placing implants with different designs and shapes (cylindrical and conical). They found more desirable stress patterns in the cylindrical implants than conical implants, large implant diameters provides more favorable stress distributions and implant materials should have a modulus of elasticity of at least 110,000 N/mm^2. Slipping between implants and cortical bone is desirable [37].

Geng et al., in 2001 did literature review on the application of FEA in implant dentistry. They advised the use of advanced digital imaging technique for preparing the models with high accuracy, considering anisotropic and non-homogenous material and simulating the exact boundary conditions and mimicking the implant and its components [7].

Chun et al., in 2002 found that the square thread shape filleted with a small radius was more effective in stress distribution than other dental implants used in the analyses also maximum effective stress decreased not only as screw pitch decreased gradually but also as implant length increased [38].

Himmlova et al., in 2004 conducted a study by taking implants of various lengths and diameters to evaluate the stress values produced at implant-bone interface. They found maximum stress at the collar of the implant and an increase in the implant diameter decreased the maximum von Mises equivalent stress around the implant neck more than an increase in the implant length [39].

Ding et al., in 2009 conducted a study on immediate loading implants showed that the masticatory force around the implant neck was decreased with increased diameter of an implant. Several studies found higher risk of bone resorption occurring in the implant neck region. By using FEM, authors could able to compare the elastic modulus and deformation with different types of bone, and implant materials which helps clinicians to better understand the process of bone remodeling, and for further improvements in surgical techniques [40].

Eraslan et al., in 2009 evaluated the effects of different implant thread designs on stress distribution characteristics at supporting structures. Four different thread-form configurations for a solid screw implant was prepared with supporting bone structure. V-thread, buttress, reverse buttress, and square thread designs with a 100-N static axial occlusal load applied to occlusal surface of abutment to calculate the stress distribution. They found that the implant thread forms has no effect on von Mises stress distribution in the supporting bone, but produced dissimilar compressive stress intensities in the bone [7].

Dos Santos et al., in 2011 conducted a study to evaluate the influence of height of healing caps and the use of soft liner materials on the stress distribution in peri-implant bone during masticatory function in conventional complete dentures during the healing period in submerged and non-submerged implants. They found non-submerged implants with higher values of stress concentration and soft liner materials gave better results. They stated that use of soft liners with submerged implants to be the most suitable method to use during the period of osseointegration [41].

Demenko et al., in 2011 emphasized that, selecting an implant size is one of the important factor in determining the load bearing capacity. The most common reason of mandibular implant supported overdenture failure was peri-implantitis due to the loss of osseointegration without any sign of infection [42].

The increase risk of mechanical failure can occur with the increase in crown to implant ratio, which was substantiated by many FE studies. A study by Verri et al., in 2014 found an oblique loading induced high stress on the abutment screw when the crown:implant ratio was 1.5:1 which is in agreement with the study done by Urdaneta et al., in 2010 on correlation between screw loosening, fracture of prosthetic abutments, and crown to implant height [36].

7.1 Prosthesis for maxillectomy or hemi-mandiblectomy

FEA is important in predicting the success of implant supported prosthetic rehabilitation of maxillectomy patients. In case of maxillary or partial mandibular resection patients, FE models can be used to simulate the resection areas and biomechanics of maxillary obturator or mandibular partial or implant supported prosthesis can be studied. de Sousa and Mattos in 2014 conducted a study to evaluate the stability and functional stress caused by implanted-supported obturator prostheses in simulated maxillary resections of an edentulous maxilla corresponding to Okay Classes Ib, II, and III, with no surgical reconstruction. They found that the implant-supported obturator prostheses tended to rotate toward the surgical resection site, the region where there is no osseous support. As the osseous support and the numbers of implants and clips diminished, the tensile and compressive stresses in the gingival mucosa and in the cortical bone increased. They concluded that the osseous tensile and compressive stresses resulting from the bar-clip retention system for Okay Classes Ib, II, and III maxillectomy may not be favorable to the survival rate of implants [36].

8. Application of FEA in trauma and fractures

Oral and maxillofacial surgery is one branch of dentistry, which has always been associated with biomechanics. Trauma surgery, orthognathic surgery, reconstructive surgery are the subdivisions where understanding the mechanism of fractures and its biological response to the biomechanical change are worth knowing for optimal treatment method and outcome [43].

When present technology was not available in the past, cadaveric studies were the only way of information and it is not possible to carry out designing and executing which at present times have ethical issues often challenging to have valid and reliable results. Furthermore, post mortem alterations and the age do not match in a typical facial trauma cadaver. One such example was René Le Fort, a French army surgeon, conducted a series of thorough experiments on the heads of cadavers. His work gave rise to a system of classifying facial fractures, now known as Le Fort types I, II and III [36, 43].

Since the maxillofacial region has vital anatomical structures, intervention in this region needs precise work to be carried out in restoring function and esthetics of the tissues in obtaining predictable and favorable long-term outcomes. In the field of trauma surgery, to identify the craniofacial region that are potential prone to fracture, FEA enables precise mapping of the maxillofacial region to know the biomechanics and stress pattern distribution of trauma that helps in evaluation of patient and optimizing the surgical protocol for treating the fractures [43].

Today, with the help of FEA mechanical properties of facial hard and soft tissues, osteosynthesis materials, implant components for fixing the fractured parts, and various biological and synthetic bone substitutes can be easily generated and determined due to the advancement in the computing and virtual analysis. It allows the testing of various fixation system to prevent the future failure due to its improper selection or inappropriate positioning. It made us possible to know the impact in biomechanical behaviour of testing materials on the biological responses of the bone tested as well as adjacent anatomical structures more accurate, repeatable, time saving, and cost-effective way regardless of their complexity [43].

Isolated orbital floor fracture (IOFF), zygomatic bone fracture are the examples of more complex traumas occurring frequently in contact sports and their pathomechanism were also studied with the aid of FEA. In relatively rare facial traumas like in case of blast or gunshot wounds, FEA helps in exploring, analyzing and determining the mechanism of anatomical structures damaged and ways in reconstructing them. The pathomechanism underlying the type and method of fracture is exceptionally important as it may help in designing the helmets, other protecting devices. Rigid fixation is one of the key element in determining the long-term success for osseointegration. Inappropriate selection of an osteosynthesis component for the biological tissues can cause complication in fusion of bone. Therefore, FEA helps in determining and designing various fixation systems and methods [44, 45].

Osteosynthesis of condylar fracture and fixing the element is a challenging aspect for a maxillofacial surgeon due to its specific anatomy and surgical access. Through FEA, it has become possible for the researchers to find the better way and an exceptionally handy, easy mountable and durable element for optimal stabilizing and fixing the fractured fragments. A new type of "A-shape condylar plate" was designed for all levels of neck fractures and it can be used for stabilization of existed coronoid process fracture. FEA has proved to be a useful tool in investing and thorough evaluation of newer materials and solutions, which are more optimized, durable and light weight components before they can be used in the clinical situations [46].

Bujtár et al., in 2010 analyzed the stress distribution in detailed models of human mandibles at 3 different stages of life (12, 20, and 67 years) with simulation of supra normal chewing forces at static conditions. They found higher elasticity in younger models in all regions of the mandible whereas higher levels of stress in a 67 year old at the mandibular neck region of edentulous mandible [47].

Huempfner-Hierl et al., in 2014 showed a pattern of von Mises stresses beyond the yield point of bone that corresponded with fractures commonly seen clinically. They found Naso-orbitoethmoid fractures account for 5% of all facial fractures. They concluded that, FEM can be used to simulate the injuries occurring to the human skull that provides information about the pathogenesis of different types of fracture [48].

Murakami et al., in 2014 evaluated the strength of mandible after removal of a lesion to illustrate the theoretical efficacy of preventive measures against pathologic fracture. They found plate application is effective to decrease the stress on the mandible after surgical removal of a cyst including third molar [43].

Santos et al., in 2015 analyzed the stress distributions on the symphyseal, parasymphyseal, and mandibular body regions in the elderly edentulous mandible under applied traumatic loads, which enabled precise mapping of the stress distribution in a human elderly edentulous mandible (neck and mandibular angle) [49].

9. Application of FEA in orthodontics and dentofacial orthopedics

Orthodontics is a specialty of dentistry, which deals with the diagnosis, prevention and correction of malpositioned teeth and jaws. It also focuses on determining and modifying the facial growth, known as dentofacial orthopedics. Abnormal alignment of the teeth and jaws is common. In the field of Orthodontics and Dentofacial Orthopedics, FEM has proved to be a reliable and valid procedure in evaluating the applied orthodontic forces.

Tanne et al., in 1995 did a 3-D FE study to investigate the location of nasomaxillary complex centre of resistance (CRe). 9·8 N of force directed anteriorly and inferiorly were applied at five different levels, parallel and perpendicular to the occlusal plane. When a horizontal force was applied at a point in the horizontal plane, passing through the superior ridge of the pterygomaxillary fissure, the complex exhibited a translatory displacement of 1·0 μm approximately in forward direction. Whereas, clockwise or counter clockwise rotation when the forces were applied at the remaining levels suggesting that CRe of the nasomaxillary complex is located on the postero-superior ridge of the pterygomaxillary fissure, registered on the median sagittal plane [2].

Many researchers have developed various FE models in order to understand the interaction between tooth mobility and periodontal ligament. Jones et al., in 2001 validated an FE model and found PDL as the main mediator for orthodontic tooth movement and the material properties of PDL are difficult to quantify [7].

The use of the lingual orthodontic technique has increased over time, as adults dislike the visibility of orthodontic appliances. Sung et al., in 2003 evaluated the effect of compensating curves on canine retraction between the lingual and the labial orthodontic techniques. The compensating curve was increased on the .016-in stainless steel labial or lingual archwire, and a 150-g force was applied distally on the canine. The pattern of tooth movement (with or without a compensating curve) was found to be different between labial and lingual techniques. As the amount of compensating curve increased (0, 2, and 4 mm) in the archwire, the rotation and the distal tipping of the canine was reduced. The anti-tip and anti-rotation action of compensating curve on the canine retraction was greater in the labial archwire than in the lingual archwire [50].

Cattaneo et al., in 2009 studied on Orthodontic tooth movement (OTM) which occurs when an orthodontic force is applied to the brackets. The modeling and remodeling process of the supporting structures occurs by alteration in the distribution of stress/strain in the periodontium. As per the classical OTM theories, symmetric zones of compression and tension are present in the periodontium. However, they did not consider the complex mechanical properties of the PDL, the morphology of alveolar structures', and magnitude of the applied force. The authors could not confirm the classical ideal of symmetrical compressive and tensile areas in periodontium as per the OTM scenarios. They found light continuous orthodontics forces will be perceived as intermittent by the periodontium. They expressed that, as the roots and alveolar bone morphology are patient-specific, FEA should not be based on general models [51].

Lingual orthodontics has developed rapidly in recent years; however, research on torque control variance of the maxillary incisors in both lingual and labial orthodontics is still limited. Liang et al., in 2009 generated maxilla and maxillary incisors models to evaluate the torque control during retraction in labial and lingual orthodontic technique for maxillary incisors. They found loads of the same magnitude produced translation of the maxillary incisor in labial orthodontics but lingual crown tipping in lingual orthodontics. This suggested the loss of torque control during retraction of the maxillary incisors in extraction patients is more likely in lingual orthodontic treatment [52].

Field et al., in 2009 investigated the stress–strain responses of teeth to orthodontic loading. Two cases were analyzed, consisting of a single-tooth system with a mandibular canine, and a multi-tooth system with mandibular incisor, canine, and first premolar that are subjected to orthodontic tipping forces. They found stress levels greater in the multi-tooth system than in the single-tooth system also, elevated distortion strain energies at the alveolar crest area and tensile and compressive stresses at the apical sites clinically associated with root resorption [22].

9.1 Orthognathic surgery

Orthognathic surgery also known as corrective jaw surgery or simply jaw surgery is aimed to correct the conditions of jaw and face. They relate to correct the structure, growth modification, disorders of TMJ, sleep apnea, malocclusion problems owing to skeletal disharmonies, or other orthodontic problems that cannot be treated with orthodontic braces. It involves the surgical manipulation of the structures of the facial skeleton in restoring the suitable anatomy and their functional relationship with dentofacial skeletal abnormalities for the patient's sense of self and well-being. Successful outcome depend on meticulous preoperative planning until finalization of occlusion. Virtual planning promotes a more accurate analysis of dentofacial deformity and preoperative planning with the help of computer-based technique like FEA, an invaluable tool in providing comprehensive patient education. Today's orthognathic treatment consists of standard orthognathic procedure in correcting jaw deformities like maxillary and mandibular prognathism, open bite, difficulty in chewing and swallowing, TMJ dysfunction pain, excessive wear of the teeth, and receding chins. It includes adjunctive procedures like genioplasty, septorhinoplasty, and lipectomy of the neck to improve hard and soft tissue contours [53].

Chabanas et al., in 2002 presented their study on the treatment protocol – a computer aided maxillofacial sequence for orthognathic surgery in the patients with large gnathic defects because the treatment protocol is difficult and time consuming [43].

Erkmen et al., in 2005 conducted a study and found that the use of 2.0 mm lag screws placed in a triangular configuration provided most sufficient stability and lesser stress fields at the osteotomy site compared to other rigid fixation methods [54].

For successful outcome in any orthognathic surgeries, selection of an appropriate bridging element is a key determinant, corrective mandibular surgery like bilateral sagittal split osteotomy (BSSO) is not an exception to stabilize the bony segments with different fixing elements and FEA is an important tool [43].

Stróżyk et al., in 2011 compared three types of fixation during BSSO using 3-D FE model divided into 3 segments with 5 mm gap in between according to BSSO line. Three fixation systems were bridged to the osteotomized fragments, a 20 N and 80 N force applied at the incisor and molar area respectively. They concluded that the most stable bridging after BSSO can be obtained with bicortical screw fixation [55].

Surgically Assisted Palatal Expansion (SARPE) is an orthognathic surgical procedure that is performed frequently in the patients with narrower maxilla. De Assis et al., in 2014 investigated the stress distribution in maxillae that underwent SARPE. They constructed five maxillary models with no osteotomy, Le Fort I osteotomy with a step in the zygomaticomaxillary buttress, Le Fort I osteotomy with a step in the zygomaticomaxillary buttress and the pterygomaxillary disjunction, Le Fort I osteotomy without a step, and Le Fort I osteotomy with pterygomaxillary disjunction and no step. The distribution of tensions in maxillae that underwent SARPE was simulated by the FEM and they revealed that the steps in the zygomaticomaxillary buttress and the pterygomaxillary disjunction seems to be important in decreasing the harmful dissipation of tensions during SARPE [56].

A more complex surgery involving correction of deformation of both the jaws simulating the maxillary and mandibular jaw osteotomy using FEA was also executed. Fujii et al., in 2017 conducted a study to determine whether non-linear 3D-FEA can be applied to simulate pterygomaxillary dysjunction during Le Fort I osteotomy (LFI) not involving a curved osteotome (LFI-non COSep), and to predict potential changes in the fracture pattern associated with extending the cutting line. In their study, the rate of agreement between the predicted pterygomaxillary dysjunction patterns and those observed in the postoperative 3D-CT images was 87.0%. The predicted incidence of pterygoid process fracture was higher for cutting lines that extended to the pterygomaxillary junction than for conventional cutting lines. They also added that, 3-D FEA can be a useful tool in predicting pterygomaxillary dysjunction patterns and provides useful information in selecting safe procedures during LFI-non-COSep [57].

Knoops et al., in 2019 conducted a study to compare the soft tissue prediction accuracy of several available computer programmes like Dolphin, ProPlan CMF, and Probabilistic Finite Element Method (PFEM) in patients with Le Fort I osteotomy. They concluded that patient or population-specific material properties can be defined in PFEM, while no soft tissue parameters are adjustable in ProPlan. Therefore, PFEM provides accurate soft tissue prediction and can be a useful tool in preoperative patient communication [58].

10. Application of FEA in reconstructive surgery

The FEM technique can also be used in oncosurgeries and reconstructive surgery where an extensive resection is needed and reconstruction of jawbones are done. The crucial parameter form the postoperative point of view is the amount of bone segment removed from the surgical site, which includes size, shape, and location. The aim of reconstructing the bone defect should result in restoration of the integrity, its anatomy and the functionality of stomatognathic system. With the aid of digital technology; modeling, simulation and analysis, it is possible to know and compare the stress levels and distribution on and at the bone-graft interface and predictable behaviour of the reconstructed site to identify the most suitable transplant for a given clinical situation and to find the appropriate bone fusion under favorable conditions in the reconstructed area [43].

Moiduddin et al., in 2017 studied to present an integrated framework model in designing and analyzing customized porous reconstruction plate based on the selection of implant design techniques. Reconstruction of large mandibular defects often leads to complications while using reconstruction plates. Studies proved that implants with porous structures can effectively enhances the biological fixation to the bone but, no study reported on the design and analysis of the customized porous mandibular reconstruction. In their study, two customized implant design techniques; mirroring and anatomical were compared. They recommended the use of mirror design reconstruction technique in mandibular bone repair, which not only improves the stability but also the flexibility of mandibular reconstruction under chewing conditions [59].

Hu et al., in 2019 performed a study to characterize the mechanical behaviour of 3-D printed anisotropic scaffolds as bone analogs by fused deposition modeling (FDM). Using topological optimization and 3-D printing technology, designing and manufacturing of a customized graft with porous scaffold structure is necessary in repairing large mandibular defects. They used CBCT images of an edentulous 50-year-old patient. The topological optimized graft provided the best mechanical properties. They highlighted the use of numerical simulations and 3-D printing technology in designing and manufacturing the artificial porous graft [60].

11. Application of FEA in periodontics

PDL is a highly specialized soft connective tissue that is present between the tooth root and the alveolar bone. The primary function is to support the tooth and is the most important component of periodontium. Various studies included and investigated on its biomechanics and stress distribution under normal, masticatory, and traumatic loads. PDL is the crucial aspect in designing as it influences the properties of a 3-D model, though it is difficult in modeling and not a concern for the study. Ignoring the PDL may result in inaccurate values of stress and strain distribution [36].

Tuna et al., in 2014 conducted a study and pointed out the advantage of simulating as a contact model at the interface of tooth root and alveolar process instead of a solid meshed FE model with poor geometric morphology or very dense mesh to save the time. They reinforced the use of PDL in designing the tooth model and its associated structures that increases the accuracy and contribution to the smoothness of interface stress distributions [61].

12. Merits of finite element method

- FEA is a non-invasive method [1, 2, 9, 62].
- Results can be easily interpreted in physical terms as well as it has a strong mathematical base.
- Non-homogenous structures also can be dealt by merely assigning different properties to different elements.
- It is even possible to vary the properties to different elements and within an element according to the polynomial applied.
- It minimizes the requirement for laboratory testing, but not replaces entirely.
- Applicable to linear and non-linear as well as solid and fluid structural interactions.
- Any problems can be split into smaller number of problems.
- It is very easy to simulate any biological condition in pre-operative, intra-operative, and post-operative stages for more accurate and reliable results.
- Reproducibility of the results does not affect the physical properties of the materials involved.
- It can replace stereo lithographic models for pre-surgical planning.
- With FEA, static and dynamic analysis is possible.
- It is less time consuming even with the complex structures.
- No extensive instrumentation is required.
- The study can be repeated as many times as the operator wants.
- The systematic generality of finite element procedure makes it a powerful and versatile tool for a wide range of problems.

13. Shortcomings of FEM

- The solution obtained from FEM can be realistic if and only if the material properties are known precisely [1, 2, 9, 62].
- The major drawback is sensitivity of the solution on the geometry of the element such as type, size, number, shape and orientation of element used.
- FEM programs yield a large amount of numerical data as results and it is very difficult to separate out the required results from the pile of numbers.
- Inability to simulate the biological dynamics of the tooth and its supporting structure accurately. For example, in non-carious cervical lesions, due to the exposure to oral environment the structure of dentin (tertiary or reparative dentin) undergoes variable amount of changes such as attrition, erosion or abrasion, which has formed as a response to stimulus.
- Misguided results due to inaccurate data or information or interpretation.
- Due to their complex anatomy and lack of complete knowledge about the mechanical behaviour, modeling of human structures are extremely difficult.
- The results depend on the personnel involved in the process due to assumptions.
- Until well-defined physical properties of enamel, dentin, PDL, cancellous, and cortical bone are available, the progress and the process in the FEA will be limited.

14. Advances in FEM

- Early FE models had the difficulty in allocating physical characteristics to the different constituent parts of the tooth, as they were considered as isotropic which in real are not [1, 2, 9, 62].
- The non-linear simulation and dynamic behaviour of PDL and other soft tissue properties has become an increasingly powerful approach that provides precision and reliability in calculating stress and strain with a wide range of tooth movements.
- The transient and residual stresses in dental materials are also included in non-linear FEM calculations also include. Residual stresses in ceramic and metal restorations, contraction stresses in composites, and permanent deformation prediction of materials are some to mention for non-linear application to be applied and investigated.
- The phenomena of sliding and friction critically affect the stress and strain created on the contact surfaces between teeth that play a major role in the mechanical behaviour. This non-linear property can be solved by contact analysis depend various factors like region of contact, load, material, and environment that are highly unpredictable. The frictional response depends on the pair of surfaces in contact, temperature, and humidity.

- Research is also going on polyhedral meshing and mesh-less (or mesh-free) analysis for reducing the meshing time. Advantages of polyhedral meshing being; less meshing time, high accuracy, and too less number of degrees of freedom (DOF).

- Hybrid meshing (hex-pyram-tetra) is a very special option but not all software supports its application.

15. Conclusion

The power of the Finite Element Method is its versatility. It is a well-established numerical analysis used not only in aerospace, automotive industry and civil engineering, but also in health care. It addresses the biomedical problems that are challenging due to structural complexity. The structure analyzed may have arbitrary shape, arbitrary support, and arbitrary loads therefore; it is ideally suited for the analysis of bibliographical structures, which are non-homogeneous. The modeling and simulation of the structures and or materials saves time and money in conducting the experiment. Therefore, this tool has been successfully employed in various areas of dentistry.

A finite element analysis does not produce formula as a solution, nor does it solve a class of problems. This method is a way of getting a numerical solution to a specific problem. Finite element analysis is an accurate tool in assessing stress distribution, only of the given set of values are effective. However, it varies from person to person as the situation and biomechanical properties of living structures interpretation differs. Hence, the obvious shortcomings should be kept in mind before any decision making procedure in experimental as well as clinical dentistry. The experiments done are repeatable with no ethical concern and study designs can be modified as per the requirement. Certain limitations of FEA do exist. Keeping in mind the limitations, FEA research should be accompanied with clinical evaluation.

Conflict of interest

The authors declare no conflict of interest.

Author details

Vinod Bandela[1]* and Saraswathi Kanaparthi[2]

1 Fixed Division, Prosthetic Dental Sciences, College of Dentistry, Jouf University, Kingdom of Saudi Arabia

2 Department of Pedodontics and Preventive Dentistry, St. Joseph Dental College and Hospital, Andhra Pradesh, India

*Address all correspondence to: vinod.bandela@gmail.com

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