Effect of 125–150 Hz Vibrational Frequency Electric Toothbrush on Teeth and Supporting Structures: A Finite Element Method Study

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ABSTRACT

Aim and objective: The aim of this finite element method (FEM) study was to assess the safety of 125–150 Hz vibrational frequency electric toothbrush on teeth and associated structures.

Materials and methods: A three-dimensional (3D) geometric model of entire skull having maxilla, mandible, and their dentitions was created using a computed tomography (CT) image of a healthy male patient. Linear static analysis was carried out by applying 15 g of force on anterior part of maxilla and mandible from labial and lingual sides each to calculate the primary displacement (sagittal, vertical, and transversal) and principal stress levels generated on the maxillary and mandibular dentition, on the maxilla and mandible and on the whole skull.

Results: A force of 15 g applied to maxillary anterior teeth from labial side caused a mean deflection of 0.003 mm and stress of 0.004 MPa on the teeth and supporting structures. A force of 15 g applied to maxillary anterior teeth from palatal side caused a mean deflection of 0.017 mm and stress of 0.017 MPa on the teeth and supporting structures. A force of 15 g applied to mandibular anterior teeth from labial side caused a mean deflection of 0.078 mm and stress of 0.051 MPa on the teeth and supporting structures. A force of 15 g applied to mandibular anterior teeth from lingual side caused a mean deflection of 0.077 mm and stress of 0.051 MPa on the teeth and supporting structures.

Conclusion: For the applied loads and boundary conditions, very small or negligible amount of stresses were observed in maxilla, mandible, and their dentitions. The vibrational frequency of 150 Hz producing 15 g of force did not produce any harmful effects on maxilla, mandible, and their dentitions. Hence, 125–150 Hz of vibrational frequency can be considered optimum.

Clinical significance: An electric toothbrush using the vibration of 125–150 Hz produces negligible stress on teeth and associated structures.

Keywords: Electric toothbrush, Finite element analysis, Finite element model, Mechanical vibration, Safe range, Vibrational frequency.

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INTRODUCTION

Orthodontic treatment duration can be reduced by accelerating the tooth movement since long treatment time is associated with iatrogenic side effects like periodontal issues, demineralization, and root resorption. The mechanical stimulation caused by the appliances used in orthodontic treatment causes remodeling of the bone, adaptation of the periodontal tissues, and consequently, tooth movement takes place.¹

Many attempts were made to accelerate the tooth movement such as physical trauma by surgical methods (piezopuncture, alveolar corticotomy, micro-osteoperforation, etc.) and by the use of drugs (corticosteroids, vitamin D3, and prostaglandins).² The techniques used previously had disadvantages such as localized pain, decalcification, resorption of roots, and other side effects induced by drugs.³ Considering the harmful effects of the previously attempted techniques, a noninvasive method to accelerate the tooth movement was needed. Mechanical vibration is one such method that caused an increase in the rate of orthodontic tooth movement. Literature search revealed that very few studies have been done on mechanical vibration as a means to accelerate tooth movement, and the few which were done were on animals.^{4–9}

Low-magnitude and higher frequency mechanical vibration accelerated orthodontic tooth movement without any damage to the periodontal tissues in humans.¹⁰

It is very important to understand the response of oral biological structures to the applied mechanical loads such as

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vibrations in complex stomatognathic systems which can be done more efficiently using computational techniques before using it to accelerate tooth movement in conjunction with orthodontics.¹¹ Finite element analysis (FEA) has been widely used in many fields, and it helps in providing concrete information on various aspects. Very few *in vitro* studies have been done in this regard, and the outcome has been less than satisfactory.^{11–13}

The trend of orthodontics practice has evolved from opinion-based practice to evidence-based practice. It has become necessary to plan treatment modalities based on scientific rationale evidence of tissue response to them.^{12,14,15} The advances in modern

technology aid the dental profession in carrying out risky and complex procedures in a very reliable and safe manner.¹⁶ Medical phenomena can be investigated or simulated accurately using this technology, and it is also minimally invasive to the patient.¹⁷ FEA is a useful mathematical instrument to determine the amount of stress, strain, and displacement in the dentoalveolar complex after using different loading conditions of force.¹⁸ In orthodontics, FEM has been used in various situations, such as to study the alveolar bone loss, root resorption, changes in the center of rotation, and stress/strain distribution during the tooth movement.^{19–25}

Limited information is given in the literature regarding the safe ranges within which vibrations could be applied to the teeth through an electric toothbrush. Hence, with the help of FEA, we have tried to determine the safe span of vibrational frequency for designing a time-controlled multifunctional electric toothbrush.

MATERIALS AND METHODS

In this study, the computed tomography (CT) scan of the entire skull of a 22-year-old nonsyndromic, periodontally healthy male patient was used. The CT scan image was obtained using an X-force/SH spiral CT scan machine. Medical modeling software (Materialise's Interactive Medical Image Control System—MIMICS 8.11) was used for the visualization and segmentation of CT images.

The CT image was procured and processed, and the three-dimensional (3D) geometric data were constructed using reverse engineering by importing the obtained Digital Imaging and Communications in Medicine (DICOM) data into Rapidform software. An individual geometry consisting of only the surface data of the entire skull including the maxilla, mandible, and its dentition was created. Geometric models of the maxilla and mandible including all the teeth were then imported into the meshing software "HyperMesh 13.0." The individual parts like soft bone, hard bone, teeth, and periodontal ligament (PDL) were discretized (meshing was carried out) and assembled in the HyperMesh software. This meshed model consisting of nodes and element data was the final finite element model (Fig. 1).

The 3D FEA was conducted using a Workstation Intel Core 2 Duo computer (2.1 GHz). The 3D tetrahedral elements were used to create the FE-model. In this study, 378,719 tetrahedral elements and 87,313 nodes were used. The material properties, loads, and boundary conditions were assigned to the FE-model (Fig. 2). The finite element model details (material properties) of the full skull with mandible, maxilla, all teeth, PDL, bones, and sutures are shown

in Table 1. The boundary conditions were defined, and the model was fixed to have a zero movement at each degree of freedom.

In a study done by Takano-Yamamoto et al., the acceleration of tooth movement due to supplementary high-frequency vibration was evaluated, and it was found that 150 Hz produced a static force of 15 g.²⁶ Hence, in this study, we have assumed that the toothbrush vibrating at 150 Hz frequency would produce a force of 15 g. The following four situations were considered (Fig. 2):

- Situation 1: Force of 15 g was applied to maxillary anterior teeth from labial side
- Situation 2: Force of 15 g was applied to maxillary anterior teeth from palatal side
- Situation 3: Force of 15 g was applied to mandibular anterior teeth from labial side
- Situation 4: Force of 15 g was applied to mandibular anterior teeth from lingual side

Linear static analysis was carried out to calculate the primary displacement (sagittal, vertical, and transversal) and the minimum and maximum principal stress levels generated by the force on the maxillary and mandibular dentition, on the maxilla and mandible, and on the whole skull. Although the load was applied to the maxillary and mandibular dentition, we intended to study its effects on not just the dentition, but also on the maxilla, mandible, and the entire skull. The forces applied to the dentition get transmitted to all the three dimensions. They propagate through the jaws and reach the bones of the skull. Hence, the entire skull model was taken into consideration.

RESULTS

While studying the effects of the force applied to the skull, we observed a minimal displacement of 0.000 mm and a maximum displacement of 0.004 mm at the base of the skull in both the situations 1 and 2 (Fig. 3). In situation 1, the maxilla showed a minimal displacement of 0.001 mm in the pterygoid region (Fig. 4) and maximum displacement of 0.003 mm (Figs 4A and C). In situation 2, a maximum displacement of 0.004 mm was seen on the maxillary central and lateral incisor (Figs 4B and D). In both situations 3 and 4, a minimal displacement of 0.000 mm and a maximum displacement of 0.003 mm were observed in the condyles (Fig. 5).

In situations 1 and 2, a minimal stress of 0.000 MPa was seen on the entire skull except at the base of the skull (0.003

Figs 1A to C: Hypermeshed model of skull with maxilla, mandible, and their dentitions

Figs 2A to D: (A) Force of 15 g applied to maxillary anterior teeth from labial side (situation 1); (B) Force of 15 g applied to maxillary anterior teeth from palatal side (situation 2); (C) Force of 15 g applied to mandibular anterior teeth from labial side (situation 3); (D) Force of 15 g applied to mandibular anterior teeth from lingual side (situation 4)

Table 1: Material properties used for FEA study

Part	Elastic modulus (MPa)	Poisson's ratio
Cortical bone	13,700	0.3
Cancellous bone	1,370	0.3
Suture	10	0.49
PDL	0.069	0.49
Tooth	20,700	0.3

and 0.004 MPa for labial and palatal applications, respectively) (Fig. 6). In situations 1 and 2, when the effects on the maxilla and its dentition were studied, a maximum stress of 0.017 MPa was seen in both the situations 1 and 2 at the palatal area between the maxillary lateral incisor and canine of both the sides and a minimal stress of 0.000 MPa was seen in both the situations in the rest of the maxilla (Fig. 7).

In situation 3 (Fig. 8), a minimal displacement of 0.000 mm was seen in the base of the skull and a maximum displacement of 0.004 mm was seen at the vertex of the skull. Also, minimal displacements were seen at the condyles, and maximum displacement of 0.087 mm for labial force and 0.086 mm for lingual force were seen at the mental protuberance (Figs 9A and B). In

situation 3, the displacement ranged from a minimum of 0.024 mm to a maximum of 0.078 mm distal to the molars, and in situation 4, the displacement ranged from a minimum of 0.077 mm to a maximum of 0.025 mm in the mandibular incisors (Figs 9C and D).

In situation 3, the stresses generated on the mandible at the ramus were a minimum of 0.00 MPa and a maximum of 0.085 MPa. When we studied the effects on the mandibular dentition, a minimum stress of 0.00 MPa was seen on the molars and incisal surfaces of mandibular incisors (Fig. 10).

Table 2 shows the displacements and stresses produced after the load application on the maxillary anteriors in situations 1 and 2. The displacements and stresses produced after the load application on the mandibular anteriors in situations 3 and 4 are shown in Table 3.

DISCUSSION

Bone is a dynamic tissue that is subjected daily to a variety of mechanical loading. It has the capacity to structurally adapt by changing its mass, morphology, architecture, and density, in response to mechanical loading through the process of bone remodeling. Since the bone cells are sensitive to their environment, they can detect chemical and mechanical signals.²⁶

Figs 3A and B: (A) Displacement contours on whole skull (situation 1); (B) Displacement contours on whole skull (situation 2)

Figs 4A to D: (A) Displacement contours on maxilla (situation 1); (B) Displacement contours on maxilla (situation 2); (C) Displacement contours on maxillary dentition (situation 1); (D) Displacement contours on maxillary dentition (situation 2)

Orthodontic appliances apply forces on the tooth crown, and this is transferred to the surrounding periodontal tissues. The magnitude of force applied is crucial since high forces may lead to root resorption and such damage is irreversible.^{27,28}

A large number of manual and electronic toothbrushes are available in the market today. There has not been any detailed evaluation on the effect of the forces applied by such devices. According to a study done by Burgett and Ash, the hard manual toothbrush created an *in vivo* mean maximum pressure of 19.53 ± 6.48 g/mm², the soft manual toothbrush applied 11.32 ± 5.32 g/mm², whereas the powered toothbrush applied 11.29 ± 5.02 g/mm² pressure.²⁹ There have been a few studies

conducted on the effects of forces generated by toothbrushing. They have reported that the mean maximum brushing force varies a great deal, but they have not assessed if the forces produced any detrimental effects.^{30–38}

Several engineering fields use numerical simulations (FEA) to research certain problems. FEA is a well-known method used to solve the problems of complex geometry and loading conditions that are not solved analytically. In FEA, the structure is divided into various small elements that are connected by mesh intersections or nodes, and this process is called meshing. The forces are applied to simulate applied loads and boundary conditions are defined to constrain the structure.³⁹ Studies have shown that the finite element

Figs 5A and B: (A) Displacement contours on mandible (situation 1); (B) Displacement contours on mandible (situation 2)

Figs 6A to D: (A and C) Stress contours on whole skull (situation 1); (B and D) Stress contours on whole skull (situation 2)

method (FEM) can be applied to the study of the stress and strain levels induced in internal structures.^{40,41} FEM offers a useful method for accurate modeling of the tooth-periodontium system with its complicated 3D geometry.⁴⁰

A study was conducted by Wiegand et al. to determine the forces applied during toothbrushing with manual and sonic toothbrushes. Their results showed that the average force applied by the manual toothbrush (1.6 ± 0.3 N) was higher than that applied by the sonic

Figs 7A to D: (A) Stress contours on maxilla and its dentition (situation 1); (B) Stress contours on maxilla and its dentition (situation 2); (C) Stress contours on maxilla and its dentition (situation 1); (D) Stress contours on maxilla and its dentition (situation 2)

Figs 8A and B: (A) Displacement contours on whole skull (situation 3); (B) Displacement contours on whole skull (situation 4)

toothbrushes (0.9 ± 0.2 N), but the difference was not significant. The brushing force was measured by an experimental model designed by the authors.⁴²

According to a study done by Muneer et al., forces of 5, 15, 24, and 29 kg applied to the middle third of the crown on the palatal

surface of incisor tooth at an angle of 50° in palato-labial direction represented the forces of normal occlusion. Force values of 5 kg (50 N) represented hypofunction as it was very minimal compared to the average force on the tooth while 24 kg (240 N) and 29 kg (290 N) represented hyperfunction.⁴³

Figs 9A to D: (A) Displacement contours on mandible (situation 3); (B) Displacement contours on mandible (situation 4); (C) Displacement contours on mandibular dentition (situation 3); (D) Displacement contours on mandibular dentition (situation 4)

At a load of 15 kg (150 N) (normofunction), the minimum stress was -1.18 MPa and the maximum stress was -10.93 MPa. Similarly, the minimum and maximum stresses of -0.39 and -3.64 MPa were seen with 5 kg load, -1.88 and -17.49 MPa with 24 kg load, and -2.28 and -21.13 MPa with 29 kg load. In this study, at all values of loading, the maximum tooth displacement was noted at the incisal edge and minimum tooth displacement was at the cervical third of the root.⁴³

Reddy and Vandana studied the von Mises stresses using a 3D FEM model of the maxillary central incisor tooth, its PDL, and alveolar bone due to a higher load of 24 kg applied to its palatal surface in palato-labial direction at the level of the middle third of crown at an angle of 50° to the long axis of the tooth. The maximum stress measured was 21.676 MPa.⁴⁴

The teeth and the jaws are subjected to the opposing forces from the buccal tissues and the tongue. Valentim et al.⁴⁵ evaluated the physiological forces applied by the tongue and lip on maxillary central incisor tooth. At rest, the force exerted by the lip on the maxillary central incisor was 0.02 ± 0.02 N and this was higher than the force exerted by the tongue (0.00 ± 0.00 N). During swallowing, the forces exerted by the lip on the tooth were 0.03 ± 0.38 N and the forces exerted by the tongue were 0.15 ± 0.14 N, and there was no significant difference between them. It can be concluded that these forces are very too small to cause any displacement or stress on the dentition or the jaws.

Therefore, in our study, these physiological forces would not affect our observations.⁴⁵

In a study by Takano-Yamamoto et al.²⁶ where they evaluated in rats that the acceleration of tooth movement induced by supplementary high-frequency vibration, it was observed that at 150 Hz vibration, a static force of 15 g was produced. Hence, in our study, we have assumed that a toothbrush producing up to 150 Hz of vibration frequency would generate a force magnitude of around 15 g.

In this study, we have evaluated the effect of the vibrations from the brushing forces applied to maxillary and mandibular anteriors by analyzing the stresses and displacements on the skull using 3D FEM.

The forces applied from the labial and palatal sides produced a minimal displacement at the base of the skull (0.000 mm) and a maximum displacement at the vertex of the skull (0.004 mm) (Fig. 3). The force's effect on the maxilla was a minimal displacement of 0.001 mm in the pterygoid region (Fig. 4) and a maximum displacement of 0.003 mm on the maxillary central and lateral incisors when labial brushing forces were applied from labial aspect (Figs 4A and C). The maximum displacement of 0.004 mm was seen on the maxillary central and lateral incisors when brushing forces were applied from palatal direction (Figs 4B and D). The effects of brushing forces in both the situations involving the mandible

Figs 10A to D: (A) Stress contours on mandible (situation 3); (B) Stress contours on mandible (situation 4); (C) Stress contours on mandibular dentition (situation 3); (D) Stress contours on mandibular dentition (situation 4)

Table 2: Load on maxillary anterior region (situations 1 and 2)

Loading direction	Deflection (mm)	Stress (MPa)
Buccal side	0.003	0.004
Lingual side	0.017	0.017

Table 3: Load on mandibular anterior region (situations 3 and 4)

Loading direction	Deflection (mm)	Stress (MPa)
Buccal side	0.078	0.051
Lingual side	0.077	0.051

showed that the minimal displacement of 0.000 mm was seen in the condyles and the maximum displacement of 0.003 mm was seen on the mandibular central and lateral incisors (Fig. 5).

The stresses produced on the skull were also evaluated. We observed very minimal stress (0.000 MPa) on the entire skull except at the base of the skull (0.003 and 0.004 MPa for labial and palatal application, respectively) (Fig. 6). The applied forces also produced stresses on the maxilla and its dentition. A maximum stress of 0.017 MPa was seen at the palatal area between the maxillary lateral incisor and canine of both the sides and in the rest of the entire maxilla minimal stress of 0.000 MPa

was seen in both the situations (Fig. 7). When we studied the effects of brushing force on the anteriors of mandible, a minimal displacement of 0.000 mm was seen in the base of the skull and a maximum displacement of 0.004 mm was seen at the vertex of the skull. Also, minimal displacements were seen at the condyles and maximum displacements of 0.087 mm for labial force and 0.086 mm for lingual force were seen at the mental protuberance (Figs 9A and B). Also, in situation 3 in the mandibular teeth, the displacement distal to molars was found to be a minimum of 0.024 mm and a maximum of 0.078 mm. In situation 4, it ranged from 0.025 to 0.077 mm at the mandibular incisors (Figs 9C and D).

The stresses generated on the mandible in both situations were a minimum of 0.00 MPa at the ramus and a maximum of 0.085 MPa for labial force and 0.084 MPa for lingual force at the condylar neck bilaterally. When we studied the effects of brushing forces only on the mandibular dentition, a minimum stress of 0.00 MPa was seen on the molars and incisal surfaces of mandibular incisors (Fig. 10).

The displacements and stresses produced after the load application on the maxillary anteriors in situations 1 and 2 as shown in Table 2 were very minimal. The displacements and stresses produced after the load application on the mandibular anteriors in both the situations 3 and 4 as shown in Table 3 were also very minimal. Comparing the loads during the normofunction as stated

in the previous studies,^{43–46} the effects of the loads obtained in our study were extremely minimal or negligible.

CONCLUSION

Force of 15 g applied to maxillary anterior teeth from labial side caused a mean deflection of 0.003 mm and stress of 0.004 MPa on the teeth and supporting structures. Force of 15 g applied to maxillary anterior teeth from palatal side caused a mean deflection of 0.017 mm and stress of 0.017 MPa on the teeth and supporting structures. Force of 15 g applied to mandibular anterior teeth from labial side caused a mean deflection of 0.078 mm and stress of 0.051 MPa on the teeth and supporting structures. Force of 15 g applied to mandibular anterior teeth from lingual side caused a mean deflection of 0.077 mm and stress of 0.051 MPa on the teeth and supporting structures.

For the applied loads and boundary conditions, we found out that very small or negligible amounts of stresses were observed in maxilla, mandible, and their dentitions. The vibrational frequency of 150 Hz producing 15 g of force did not produce any harmful effects on the maxilla, mandible, and their dentitions.

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