Stress analysis at bone-implant interface of single- and two-implant-retained mandibular overdenture using three-dimensional finite element analysis

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ABSTRACT

Purpose: The purpose of this research was to compare stress distribution on the bone between single implant-retained and two-implant-retained mandibular overdentures using three-dimensional (3D) finite element analysis.

Materials and Methods: Two 3D finite element models were designed. The first model included single implant-supported mandibular overdenture placed in the midline of the mandible while the second model included two-implant-supported mandibular overdenture placed in the intra-foramen region, retained by ball attachment of the same diameter. The bone was modeled on the D2 bone depending on the classification given by Misch. A computed tomography scan of the mandible was used to model the bone by plotting the key points on the graph and generating the identical key points on the ANSYS Software (ANSYS, Inc., USA). The implant was modeled using appropriate dimensions as provided by the manufacturer. Stresses were calculated based on the von Mises criteria.

Results: Stresses produced in the hard bone (HB) and soft bone (SB) were higher in single implant-retained mandibular overdenture while stresses produced around the denture as well as implant were higher in two-implant-retained mandibular overdenture.

Conclusion: Within the limitations of the study, it had been seen that stresses produced were the highest on HB and SB in single implant-retained mandibular overdenture while stresses produced across the denture as well as implant were the highest in two-implant-retained mandibular overdenture.

Key words: Ball attachment, bone-implant interface, finite element analysis, mandibular overdenture, von Mises stress

Implant-retained overdenture is now a reliable and well-documented treatment option for a completely edentulous. Using a minimal number of implants which is adequate for prosthodontic support and retention can be of economic help to the patient.\(^1\)

Options for the evaluation of stress around dental implant systems include photoelasticity, finite-element analysis, and strain measurement on bone surfaces. The finite element method offers several positive aspects, including accurate representation of complex geometries, easy model modification, and representation of the internal state of stress along with other mechanical quantities.\(^2\)

This study used a finite element analysis with three-dimensional (3D) model to compare stress distribution on the bone between the single implant-retained and two-implant-retained mandibular overdentures

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within a vertical static load. Hence, single implant-retained overdenture has become popular over two-implant-retained overdenture. Besides retention, it is also worth focusing on not causing excessive stress on implants that is transmitted to alveolar bone. Hence, these stresses need to be analyzed.

MATERIALS AND METHODS

Two 3D finite element models, having single implant-supported and two-implant-supported mandibular overdentures, retained by ball attachment of the same diameter were designed for the study. The bone was modeled on D2 bone based on the classification provided by Misch. A computed tomography (CT) scan (X-force/SH spiral [Figure 1]) from the mandible was utilized to model the bone by plotting the key points on the graph and generating the identical key points on the ANSYS 12.1 Software. The implant was modeled using appropriate dimensions as provided by the manufacturer (Nobel Biocare implant system). The implant was modeled having length of 11.5 mm and diameter of 3.75 mm. The surface of the simulated implant was threaded as well as the thread pitch was 0.4 mm. The inner diameter of the implant was 2.25 mm.

The ball attachment was modeled being 2.25 mm in diameter, having a cuff height of 1 mm as well as an overall length of 3 mm for the model. The silicone O-ring attachment is an O-shaped member having an inner radius as well as an outer radius. Both models had an inner radius of 1.25 mm as well as an outer radius of 2 mm.

The mucosa was modeled on the cortical bone having a uniform thickness of 2 mm. Overdenture on the implant has been modeled. It contains an acrylic denture base and acrylic teeth. All materials utilized in this model were regarded as homogeneous isotropic and linearly elastic.

PREPROCESSING AND MESHING

The CT scan of the patient is procured, and the DICOM data are changed into geometric models using reverse engineering technique. Reverse engineering includes scanning the models, measuring the length, diameter, and other features using standard measuring instruments and scanning machines. Geometric modeling is performed using “Rapidform” software (3D systems, Geomagic, Korea), which contains only surface data. Geometric models of the edentulous mandible, overdenture, and implant abutment system are then imported to the meshing software “HyperMesh” (HyperMesh 13.0, Altair Engineering Inc., Hyperworks, America). The process of dissecting the finite element model into components of equal dimension is called meshing [Figure 2]. In HyperMesh, the individual parts such as soft bone (SB), hard bone (HB), mucosa, overdenture, implant, and abutment are then discretized (meshing) and assembled. Meshed model is classified as finite element model, and it contains nodes and element data (total nodes = 108,091, total elements = 672,663). The complete selection of elements and nodes formed by meshing is known as mesh. Tetrahedral elements were utilized since they were more harmonious with all the design structure and therefore will produce more accurate results. The material properties were included in the model after meshing.

POSTPROCESSING AND ANALYSIS

This is the final stage from the procedure, wherein two models were prepared and analyzed. The two models created were single implant placed at the center and two-implant placed in the canine regions [Figure 3]. Herein, the meshed models were afflicted by vertical (along long axis) force to evaluate the stress patterns formed within the bone. Both finite models were subsequently loaded in the vertical direction using the force of 35 N. The force was applied to the overdenture at the surface of the modeled tooth. The model is constrained in the mesial, distal, and inferior directions and was allowed movement in the buccolingual plane. Stress levels based on the von Mises criteria were calculated because von Mises stresses ($V_m$) are most frequently reported in finite element analysis studies to conclude the entire stress state with a point.
RESULTS

3D models of the mandible comprising the cortical and trabecular bone, having single implant-retained and two-implant-retained mandibular overdentures, retained by ball attachment of the same diameter were constructed. Force of 35 N was applied in the vertical direction.\(^6,7\) Stresses generated around the implant in the bone were studied.

The two models being studied are:
- Single implant-supported mandibular overdenture placed in the midline of the mandible, retained by ball attachment
- Two-implant-supported mandibular overdenture placed in the intra-foramen region, retained by ball attachment.

The material properties of the two models were from the literature.\(^5\) The \(V_s\) and their distribution were generated by the finite element software according to a stress map with various color coding. Red was the highest followed by orange, yellow light green, green, light blue, blue, and dark blue colors representing the stresses in the descending order. Using these different colors, stress distribution patterns may be analyzed in various models. Stresses produced in the HB and SB were higher in single implant-retained mandibular overdenture (Case 1) while stresses produced around the denture as well as implant were higher in two-implant-retained mandibular overdenture (Case 2) [Table 1].

DISCUSSION

In an implant-supported overdenture, two basic factors can be minimized. The first is the stress around the implants as well as the other may be the movement of the denture. Numerous methods are already followed to achieve this goal. The role of anchorage, including ball attachments, clips on the bar connecting the implants, and magnetic attachments was reported being quite important. The McGill consensus statement on implant-supported overdentures was brought out in May 2002.\(^8\) According to the consensus, two-implant-supported mandibular overdenture was considered to be the first choice of treatment for edentulous patients. Studies have shown that clear differences exist in the way stresses are transferred to the bone in a tooth-supported overdenture and an implant-supported overdenture. The load transfer at the bone–implant interface depends on (1) implant geometry, (2) type of loading, (3) material properties of implant and prosthesis, (4) nature of bone–implant interface, (5) quality and quantity of surrounding bone, and (6) implant surface structure.\(^9,10\)

Implant geometry

Cylindrical implants produce high shear stress on the bone. Studies show that stresses reach only a particular distance (approximately 10 mm in height) within the implant.

Type of overdenture attachment

There are various attachments which have been used with implant supported overdenture, the most frequent being the bar-clip attachment, ball/O-ring attachment, and also the magnet attachment. In vitro and in vivo\(^3,5\) research has shown the ball as well as O-ring attachment transferred less stress to the implants compared to the bar-clip attachment. Ball attachment are considered the simplest type of attachment for clinical application with tooth or implant supported overdentures.\(^11\) Usually, regarding tough, the precise design of the ball attachment may influence how much totally free movement thereby restricting its resiliency. When wear-induced retentive changes are manifested over time, studies have shown how the ball attachments lose about 32% to 50% of their original retentive force.

Type of loading

The degree of bite force depends on the direction of the force. In our study, vertical forces coming from different directions had been chosen. The vertical bite force was determined to be 35 N from studies which measured the bite force of edentulous patients with overdentures supported by implants in the mandible.\(^7\)

Material properties of implant and prosthesis

Implant biomaterials should have satisfactory strength and modulus of elasticity to withstand forces acting on them.

| Table 1: Result Summary and Comparison |
|--------------------------------------|
| **Stress** | **HB** | **SB** | **Denture** | **Implant** | **Mucosa** | **Around-Implant** |
|-----------|--------|--------|-------------|-------------|------------|-------------------|
| \(V_s\)   |        |        |             |             |            |                   |
| Case1     | 156.99 | 135.01 | 14.72       | 12.35       | 11.18      | 14                |
| Case2     | 162.67 | 137.92 | 15.44       | 13.19       | 13.54      | 9.11              |
| Case1     | 23.57  | 39.82  | 0.125       | 0.09        | 10.47      | 28.34             |
| Case2     | 24.09  | 41.18  | 0.117       | 0.124       | 11.23      | 15.59             |
| S1        |        |        |             |             |            |                   |
| Case1     | 145.66 | 125.43 | 11.96       | 10.49       | 18.01      | 21.33             |
| Case2     | 23.37  | 44.13  | 0.207       | 0.142       | 13.54      | 47.65             |

HB=Hard bone SB: Soft bone, \(V_s\)=Von-Mises Stress, S1=Max principle stress, S3=Min Principle Stress
Biomaterials such as silicone, hydroxyapatite, and carbon are intolerant to such forces, hence are not preferred as primary implant materials. Conversely, ceramics are avoided despite their strength due to their low modulus of elasticity. In conclusion, titanium alloys (Ti6Al4V), which offer superior strength and comparable modulus of elasticity, are preferable to transfer forces acting on them. An increase in force magnitude is deleterious to osseointegration. Hence, the above factors should be considered to plan treatment so as to minimize force magnitude.

Nature of bone–implant interface
A critical aspect affecting the success or failure of an implant is related to how the mechanical stresses are transferred from the implant to the bone. It is essential that neither implant nor bone is stressed beyond their long-term fatigue capacity. Any relative motion that can produce abrasion on the bone or progressive loosening of the implant should be avoided. These requirements are met by osseointegrated implants by virtue of close apposition of the bone to implant at the Angstrom level. The close apposition of titanium and bone at the Angstrom level means that under any subsequent loading, the interface moves as a unit without relative motion of the bone and titanium and with the possibility of transferring stress to all parts of the interface.

Quality and quantity of bone surrounding the implant
The most common bone density that is present in the anterior mandible is the D2 type. A finite element analysis conducted by Misch had predicted 100% success rate for implants placed in this type of bone. The type of bone present around the bone–implant interface spells the type of distribution of stress seen at the interface. Cortical bone can take better stresses as compared to trabecular bone. The ultimate compressive strength of cortical bone is 140–170 Mpa, whereas the compressive strength of trabecular bone is 22–28 Mpa. In all the loading conditions, the stress levels did not reach the maximum yield strength of the mandibular bone; hence, there would be no fracture of the bone. With the probability of excessive stresses being minimized, the focus of attention should be directed to the minimal amount of stress that is required to maintain a healthy bone–implant interface without causing bone disuse atrophy. The minimal stresses that are required for the deposition of the bone around the implant are about 1.3–1.7 Mpa. Ball and O-ring attachments give favorable stress distribution to the bone. This fact being laid down by the present study, the choice of the attachment now depends on the retention and stability that the attachment offers to the patient. Studies conducted on the satisfaction of the patient with implant-supported overdenture have revealed that they prefer the ball O-ring attachment as compared to the magnet attachment as far as retention and stability are concerned. Hence, the best attachment to be used for implant-supported overdenture is the small diameter ball O-ring attachment. The advantage of using finite element analysis is that accurate representation of complex geometries can be made, the models can be easily modified, and the internal state of stress and other mechanical quantities can be represented. There were certain limitations pertaining to the present study. Finite element analysis is a mathematical in vitro study that may not simulate the clinical situation completely. A state of optimal osseointegration was assumed between the cortical bone, trabecular bone, and the implant. This may not occur in clinical situations. All materials were assumed to be linearly elastic and homogeneous in nature, whereas bone is viscoelastic, anisotropic, and heterogeneous material. The resultant stress values obtained may not be accurate quantitatively but are generally accepted qualitatively. Chewing forces are dynamic in nature, but the loads applied in this study were static loads.

CONCLUSION
Within the limitations of the study, it had been seen that stresses produced were the highest on HB and SB in single implant-retained mandibular overdenture while stresses produced across the denture as well as implant were the highest in two-implant-retained mandibular overdenture.

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Conflicts of interest
There are no conflicts of interest.

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