ORIGINAL ARTICLE

Alveolar bone resorption and the center of resistance modification (3-D analysis by means of the finite element method)

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The main goal of this research was to study the behavior of initial tooth displacements associated with alveolar bone loss situations when loaded by a force of 1 N. The analysis of displacements was carried out by the finite element method. Six 3-dimensional models of an upper central incisor (designated Geramy 391 to 396) with 1 to 8 mm of alveolar bone loss were formulated and used by the author. Center of rotation and center of resistance were located for the various stages of alveolar bone loss. The results revealed that the moment/force ratio (at the bracket level) required to produce bodily movement increases in association with alveolar bone loss. Bone loss causes center of resistance movement toward the apex, but its relative distance to the alveolar crest decreases at the same time. Greater amounts of displacements of incisal edge and apex were observed with increased alveolar bone loss for a constant applied force. Center of rotation of the tipping movement also shifted toward the cervical line. Among the many differences between orthodontic treatment of an adolescent and an adult patient is the presence of alveolar bone loss in the adult cases. Alveolar bone loss causes center of resistance changes as a result of the alterations in bone support. This necessitates modifications in the applied force system to produce the same movement as in a tooth with a healthy supporting structure. (Am J Orthod Dentofacial Orthop 2000;117:399-405)

Although bone resorption among orthodontic patients is not usual in most patients, it can cause many problems that should be considered in force system applications. Some important points are as follows:

1. Force magnitude in relation to the amount of alveolar bone height.
2. Modification of the moment/force (M/F) ratio to produce a certain form of tooth movement.
3. The higher chances of tissue damage caused by greater amounts of tooth displacement.

There can be other clinical implications that will be discussed later.

Alveolar bone loss can be a pathologic or age-related phenomenon. Although 0.017 mm/year of alveolar bone loss is considered quite normal,[1] greater amounts of bone resorption can be found in a few adults without any diagnosable pathologic condition or postperiodontal osseous surgery. Researchers have studied the behavior of tooth movement from different points of view: histologically,[2] physiologically, and biomechanically.[3-7]

Finite element method (FEM)[8] modeling can provide insights when dealing with complex structures. This method provides us with useful findings to analyze forces, moments, stresses, etc. Although a useful method, using it with a 2-dimensional (2-D) model cannot represent the in vivo condition in many ways and may be a too simplified representation of the situation. Studies based on 2-dimensional models as well as 3-dimensional (3-D) ones[10-15] have been reported.

Table I. Characteristics of the models used in this study

Model	*Nodes*	*Elements*	*Alveolar bone height (mm)*	*Bone loss (mm)*
Geramy 391	726	470	13	0
Geramy 392	692	438	12	1
Geramy 393	658	406	10.5	2.5
Geramy 394	624	374	8	5
Geramy 395	590	342	6.5	6.5
Geramy 396	556	310	5	8

MATERIAL AND METHODS

Six 3-D models of an upper central incisor were designed by the author and used to conduct the research. Each model contained 522 to 726 nodes and 278 to 470 elements, depending on the degree of alveolar bone loss, which has been modeled (Fig 1 and Table I). Tooth morphology was based on the Ash dental anatomy[18] with minor modifications to get the best possible shape (Fig 2). The 3-D brick isoparametric element with 8 nodes was chosen to make the models.

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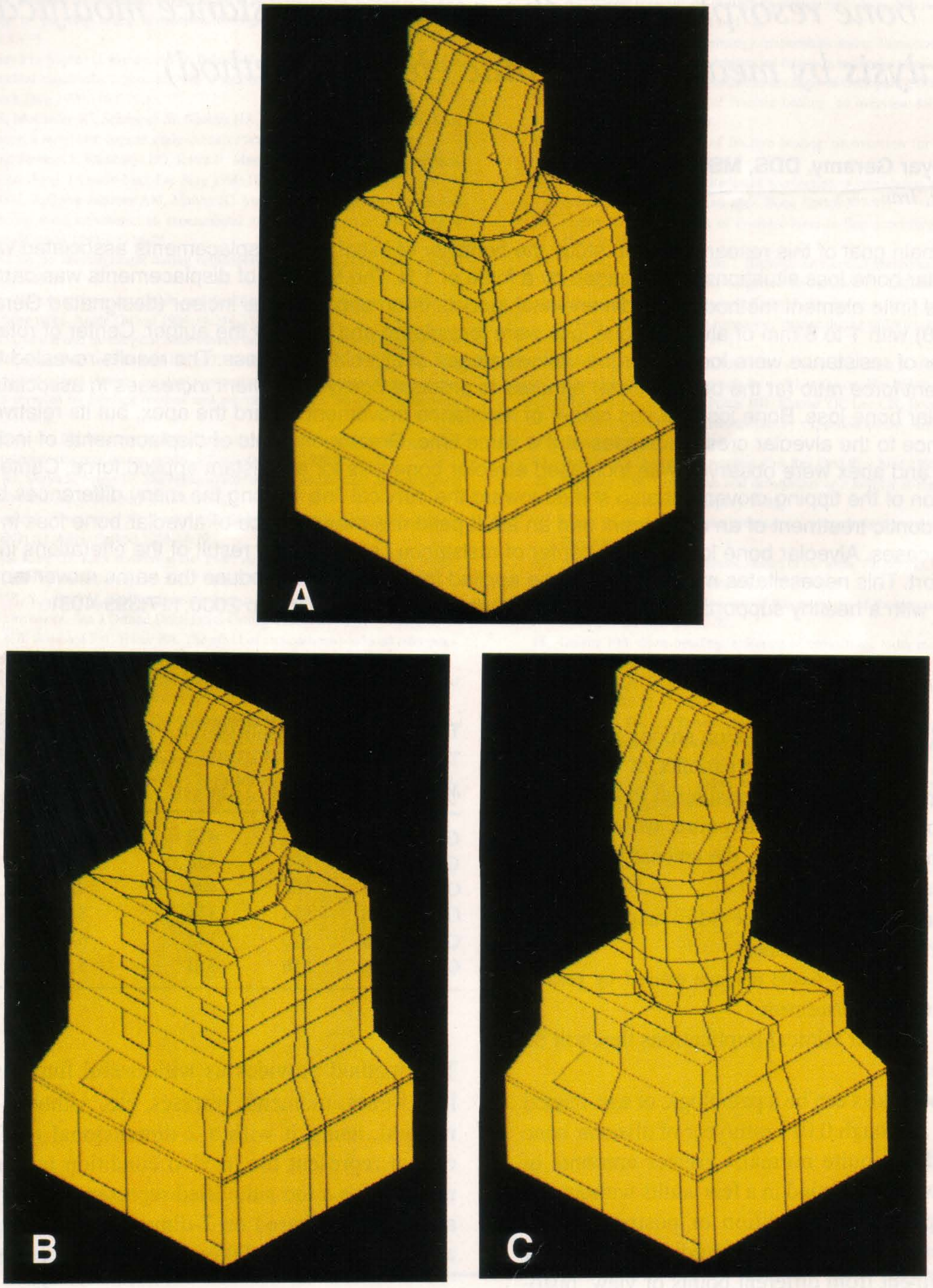

Fig 1. 3-D models used in this study with 0.5 and 8.5 mm of alveolar bone loss (Geramy 391-396).

Each model contained a tooth, its periodontal membrane (PDM), and both spongy and cortical bone. The PDM is modeled according to Coolidge[19] with various widths at different layers (Table II).

Each model was divided into 13 layers. The first layer (most apical) acted as a base; the second one formed the subapical layer. In addition, 7 layers formed the root and 4 remaining ones made up the crown. There were different vertical heights at root layers: 1 mm at the cervical; 1.5 mm at the midroot and 2.5 mm at the other layers. Designing such a meshwork with different element sizes allows the researcher to have more accurate findings where necessary and reduce node numbers where there is not an important part to be assessed. Each

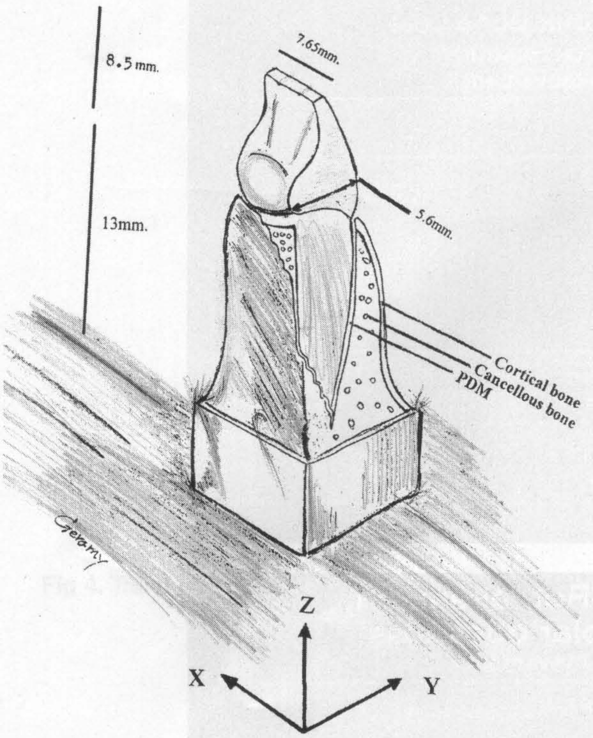

Fig 2. Structural components and the dimensions of the model.

Table II. Geometry of the PDM widths in the 3-D model according to Coolidge[19]

Distance from the alveolar crest (mm)	*Distal (mm)*	*Lingual (mm)*	*Mesial (mm)*	*Labial (mm)*
13.0	0.25	0.25	0.22	0.25
10.5	0.18	0.22	0.20	0.22
8.0	0.15	0.20	0.17	0.26
6.5	0.14	0.18	0.16	0.18
5.0	0.15	0.20	0.17	0.26
2.5	0.18	0.22	0.20	0.22
0	0.19	0.24	0.21	0.24

layer was given 14 external nodes to enable acceptable modeling. The alveolar bone, as the sole difference of these models, was considered to have 13 (normal situation), 12, 10.5, 8, 6.5, and 5 mm heights, respectively.

Physical properties of different materials have been selected from other studies[11,12,14] (Table III).

As there is not any symmetry in tooth structure in vivo, avoiding any simplification necessitates defining the location of all the nodes one by one. Sap 90 Ver. 5.20 (Computers and Structures Inc, Berkeley, Calif) was chosen to analyze the problems. The boundary condition was defined so that the models were restrained at

Table III. Mechanical properties for the structural elements

Material	*Young's modulus (N/mm²)*	*Poisson's ratio*
Tooth	20300	0.30
PDM	0.667	0.49
Cancellous bone	13700	0.38
Cortical bone	34000	0.26

Table IV. Change of the movements in different parts of an upper central incisor caused by the alveolar bone loss

Bone loss (mm)	*Incisal edge movement (mm)*	*Relative movement*	*Cervical part movement (mm)*	*Relative movement*	*Apical part movement (mm)*	*Relative movement*
0	0.0047	1	0.0020	1	–0.0018	1
–1	0.0068	1.46	0.0029	1.5	–0.0026	1.41
–2.5	0.0112	2.4	0.0050	2.56	–0.0039	2.14
–5	0.0342	7.3	0.0166	8.49	–0.0095	5.18
–6.5	0.0692	14.8	0.0350	17.88	–0.0162	8.85
–8	0.2067	44.2	0.1097	56	–0.0372	20.3

Table V. The exact location of CRes with various bone heights

Bone loss (mm)	*Alveolar bone height (mm)*	*CRes apically from alveolar crest (mm)*
0	13	5.44
1	12	4.57
2.5	10.5	3.726
5	8	2.65
6.5	6.5	1.94
8	5	1.48

Table VI. Increase of the M/F ratio to maintain bodily movement in different alveolar bone heights

Alveolar bone loss (mm)	–1	–2.5	–5	–6.5	–8
M/F ratio increment*	6%	14.46%	32.1%	41.9%	54.59%

*Needed increment of M/F ratio to maintain bodily movement.

their bases to avoid overall body motion. A force of 1 N was applied to the labial surface of the tooth crown at each phase of the study, at 5.5 mm apical in respect to the incisal edge. (This was presumed to be the location of the bracket). The point of force application was centered mesiodistally. Congruence of the line of action of the force with the long axis of the tooth avoids any rotation tendency at the models, due to the lack of any moment arm with respect to the tooth long axis.

There are 2 reliable criteria to study the behavior of tooth movement, center of resistance (CRes) and center of rotation (CRot); consequently, finding the CRot

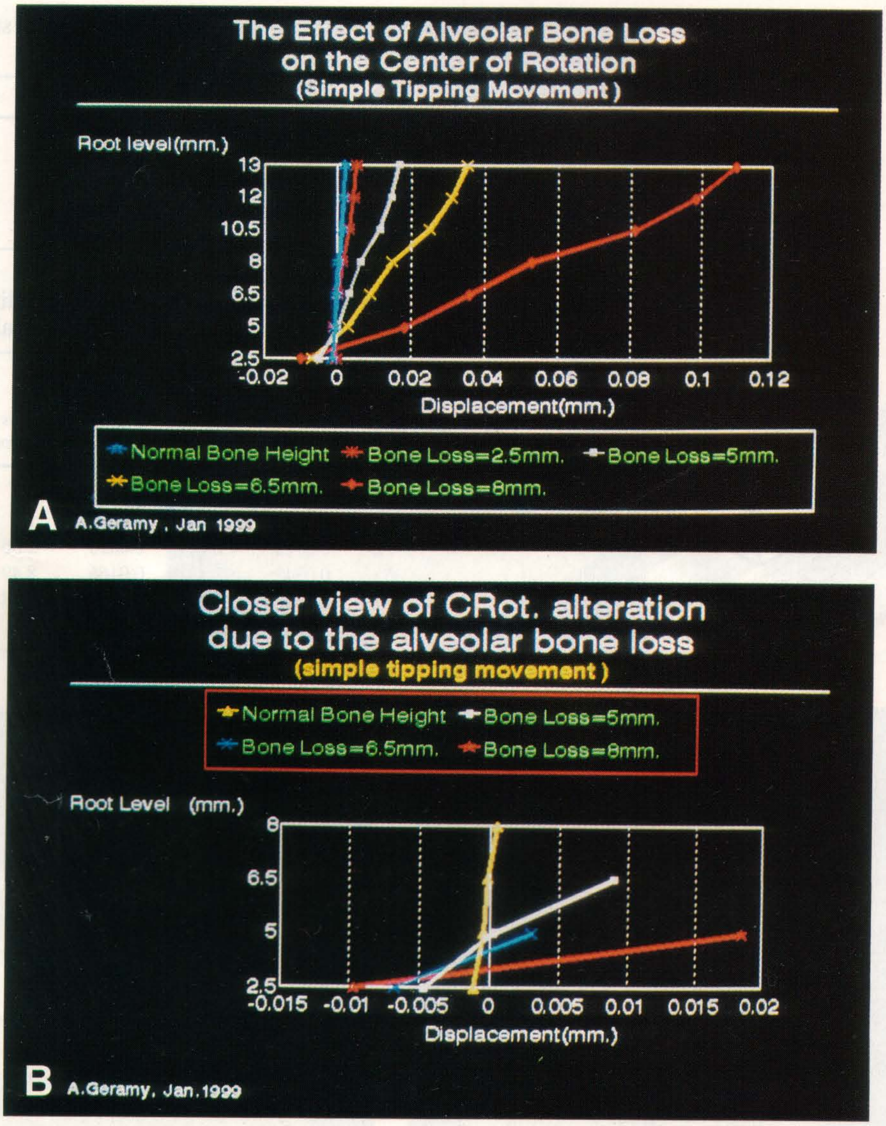

Fig 3. Root displacements in different amounts of alveolar bone loss, nearer view of **B**. **B**, Alteration of CRot (of simple tipping) under the same load with various amounts of alveolar bone loss.

of a simple tipping movement and the CRes of each model are 2 main goals of each phase of this study. Application of a point force of 1 N is suitable to find the CRot of the model. Evaluation of the displacement of the nodes at the root surface reveals that there are always 2 adjacent nodes at 2 different levels that show opposite directions of displacement. Using a simple geometric principle of right-angled triangles, the exact location of the CRot of the simple tipping movements was calculated at each model (with different alveolar bone heights).

As the second phase of the study, different M/F ratios were applied. The nearest situation to the bodily movement (being specified by the almost equal amounts of node displacements at different root levels) showed the distance apically from the bracket position to CRes.

Tooth, cortical, and cancellous bone can be considered rigid in relation to the PDM as a result of their greater differences in the Young's modulus.

Thus, their deformations were calculated yet could be ignored. The present study is limited to the elastic phase of the materials used. The models are convergent according to the criteria suggested by Zienkiewicz and Taylor.[9]

RESULTS

In simple tipping, the center of rotation lies apical to the CRes by a small amount in a healthy tooth sup-

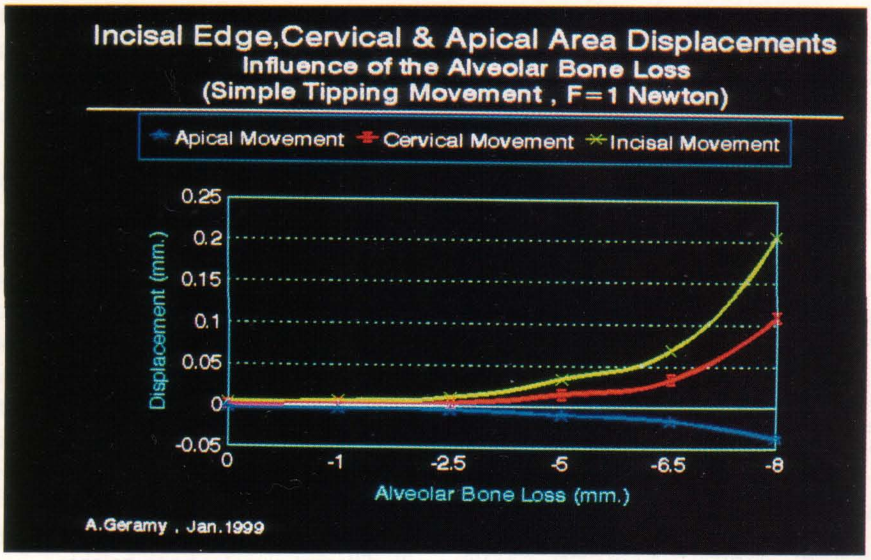

Fig 4. Trend of increase in apical, cervical, and incisal edge displacements with different alveolar bone heights.

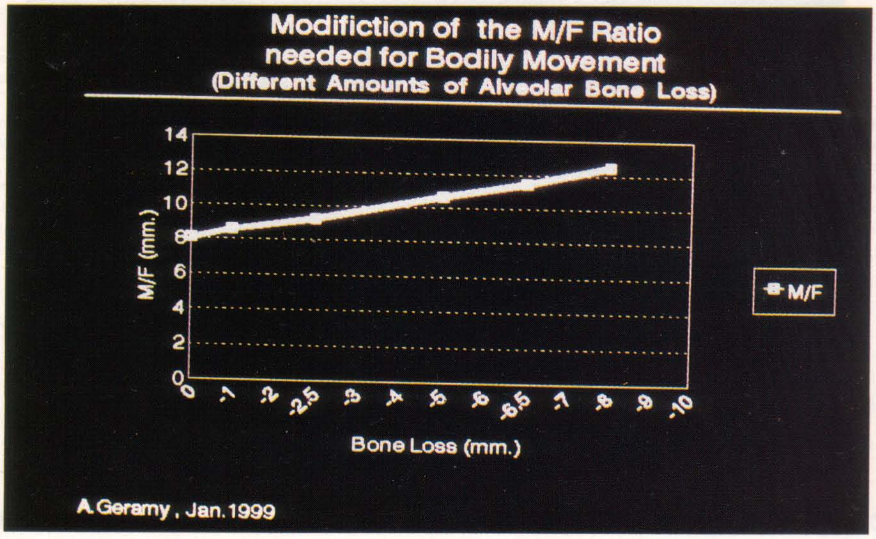

Fig 5. Change of the M/F ratio needed to maintain bodily movement with different alveolar bone heights. (All values of the M/F ratio have negative signs.)

port. As more bone loss occurs, the CRot of a simple tipping movement moves more apically (Fig 3).

An 8-mm bone loss causes up to 44 times the incisal edge movements compared with a normal condition (Table IV and Fig 4).

The M/F ratio needed to produce bodily movement without alveolar bone loss (Geramy 391) is –8.44 (point of force system application is –5.5 mm apical to the incisal edge). Bone loss causes a displacement of CRes apically. Eight millimeters of bone loss increases the M/F ratio needed to produce bodily movement to –12.46 (Fig 5).

As the CRes moves apically with the alveolar bone loss, its distance to the alveolar crest diminishes (Fig 6). Without bone loss, CRes lies approximately 5 mm apical to alveolar crest, decreasing to 1.46 mm for 8 mm of alveolar bone loss (Table V). Alveolar bone loss causes a decrease of the distance between CRes and CRot. Fig 7 shows the trend of their displacements, approximation, and shifting toward the alveolar crest.

DISCUSSION

Clinical studies report a slight loss of periodontal attachment in adults or adolescents during treatment

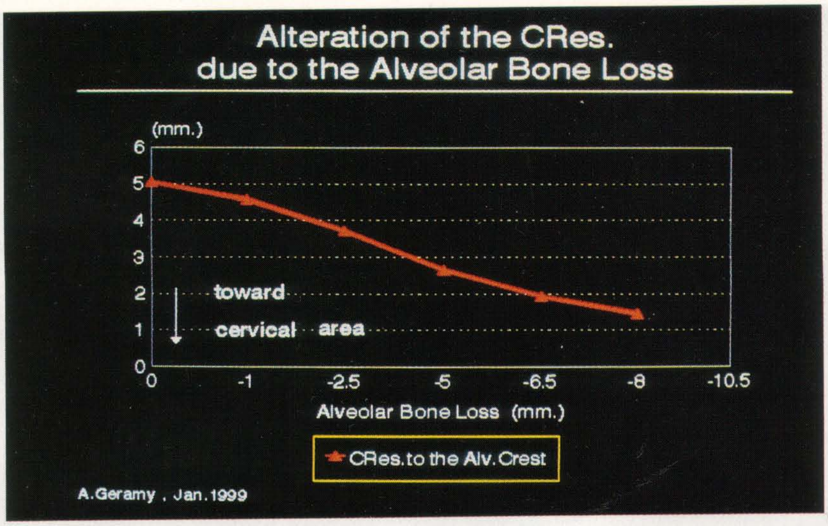

Fig 6. Change of the CRes position with different alveolar bone heights.

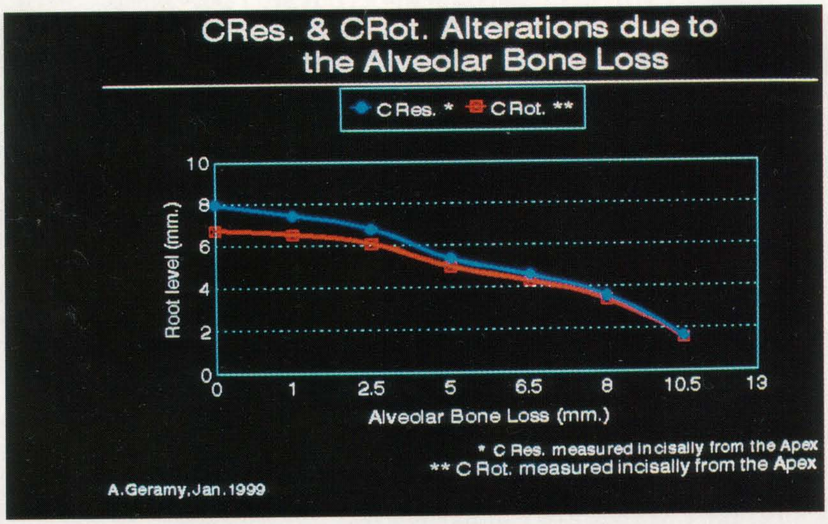

Fig 7. Change of the position and approximation of the CRes and the CRot (of simple tipping) in association with alveolar bone loss.

with fixed orthodontic appliances.[1,20,21] Using an FEM model, the present study quantifies the effects of alveolar bone loss on CRot of simple tipping movements and CRes of the tooth. Initial tooth displacement increases with increased alveolar bone loss, which is in agreement with Tanne et al[16] (Table IV). Bantleon[22] states that 3 mm of alveolar bone loss causes 20% of M/F ratio increment to maintain bodily movement. The findings of this study show 17.35% of M/F ratio increment for such a condition (Table VI). Siatkowski[17] reports an increase of 38% needed to produce bodily movement when 5 mm of marginal bone loss occurs; this study finds 32.1% for the same condition (Table VI).

Table VI shows the increase in percentage needed to maintain movement with different degrees of alveolar bone losses. Cobo et al[23] state that with alveolar bone loss, CRes can be located above the alveolar bone crest. This study shows a decrease of CRes distance to alveolar crest, but the CRes was never found beyond the alveolar bone crest.

CLINICAL IMPLICATIONS

In patients with alveolar bone loss, increased demands are placed on clinicians for careful application of the force systems used in tooth movement.

The reduced supporting PDM area and volume result in ever higher amounts of displacements in supporting structures of affected teeth for a given level of force and moment magnitude. Applied force and moment magnitudes must be reduced in proportion in order to maintain physiologically tolerable movements without further damage to these supporting structures.

CONCLUSION

1. With reduced alveolar bone heights, under the same load, the study indicated an increase of tooth movements (incisal edge, cervical part, and apical area).
2. When alveolar bone loss occurs, the M/F ratio required to produce the bodily movement is increased.
3. With continuation of alveolar bone resorption, the center of resistance ever approximates the alveolar crest.
4. With increase of alveolar bone loss, the study suggested a decrease of the distance between CRes and CRot.

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