Biomechanical effects of implant number and diameter on stress distributions in maxillary implant-supported overdentures

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In recent years, implant-supported overdentures (ISOs) have become a preferred option in edentulous patients.1,2 ISOs have advantages over conventional removable complete dentures, such as increased retention and stability and enhanced comfort, masticatory activity, and patient satisfaction.3,4

The early success of dental implants depends on the success of the surgical procedure, the quality and quantity of the bone, and the implant design, diameter, and length.5-7 Factors for long-term success include prevention of unbalanced and excessive forces on the implants.8,9 Because there is no periodontal ligament around the implant to serve as a buffer, these forces are directly transmitted to the peri-implant bone and cause stress concentrations.10,11 This situation can lead to bone resorption and thus can negatively affect the success of the implant.12-14 The stress distribution on the adjacent bone can be changed by parameters such as implant number, position, and size.6,7,15 Longitudinal studies have reported that implants for ISOs may fail because of a loss of osseointegration even without bacterial infection; thus biomechanical forces play a crucial role in long-term success.16

The optimal number of implants necessary to support a maxillary ISO is unclear. Sadowsky17 emphasized that studies on this topic are limited and that until this deficiency is overcome, decisions must be made according to patient-mediated considerations. In a systematic review, Klemetti18 reported there is no optimal number of implants or an attachment type that directly affects patient satisfaction.19

Statement of problem. Implant-supported overdentures (ISOs) are considered a good alternative to conventional removable dentures. However, varying rates of failure have been reported in some clinical studies. Excessive stress on surrounding tissues is one of the possible causes of implant failure. As stress is transmitted to the bone through the implant, careful planning, correct number of implants, and implant positioning are keys to ensuring appropriate stress distribution. However, research of the optimal number of implants necessary to support a maxillary ISO is insufficient.

Purpose. The purpose of this in vitro finite element study was to determine the optimal implant location, number, and diameter to support a maxillary ISO.

Material and methods. Three-dimensional models of an atrophic maxilla, dental implants, and ball attachments were modeled, and different loading conditions were applied to simulate realistic conditions. Six models with different numbers and diameters of implants, including mini-dental implants and differently located implants, were formed, and stress values were compared by implementing a finite element analysis.

Results. The study showed that, as the implant number increased, decreased stress values were observed in peri-implant bone and implants in the maxillary ISO prosthesis. However, changes in implant diameter had no significant effect on stresses.

Conclusions. Increasing the implant diameter was not advantageous; the use of mini-dental implants may be a viable alternative method. However, using 4 implants for maxillary ISOs is indicated. (J Prosthet Dent 2018;119:244-249)
satisfaction or maxillary ISO functionality. Gottfredsen et al\textsuperscript{19} claimed that increasing the number of implants for a mandibular ISO does not have a significant effect on its success; however, the authors are unaware of a sufficient number of studies to express an opinion for the maxilla. Based on their decade-long research, Meijer et al\textsuperscript{20} and Batenburg et al\textsuperscript{21} suggested that no significant differences could be found between patients with two-implant models (TIM) and those with four-implant model (FIM) overdentures with regard to radiographic bone loss, soft tissue health, patient satisfaction, and surgical/prosthetic applications; thus, they advocated TIM overdentures, which are cost effective.

Many attachment systems for ISOs have been developed. These systems can be divided into 2 main groups: bar-type anchorages with splints and ball attachment-type anchorages without splints. Because anchorage systems without splints occupy less space within the prosthesis and are easier to clean, more economical, and easier to construct, they tend to be used more frequently in ISOs.\textsuperscript{17,22} Trakas et al\textsuperscript{23} reported that, in terms of bone loss, there were no significant differences between ball and bar attachments. In a recent systematic review in which 4200 implants were examined, no significant differences were observed between the attachment designs with respect to marginal bone loss around the implants in ISOs.\textsuperscript{24} Arat Bilhan et al\textsuperscript{12} emphasized that the attachment type used with overdentures should be determined according to the experience and preference of the clinician. In the present study, the ball attachment was preferred because it was thought that it could be modeled more easily.

In recent years, mini-dental implants (MDIs) have been developed to avoid extra procedures such as bone grafting, especially in elderly patients. Mini-implant placement is much easier for patients with reduced horizontal bone volume and represents a less invasive surgery. However, mini-implants tend to be fragile, although more durable MDIs will be available in the future with recent developments in titanium alloys.\textsuperscript{15,25–27}

Clinical Implications

Considering that implant-supported overdentures (ISOs) are most commonly applied to systemically compromised elderly patients, applying advanced surgical options to increase the implant diameter is not necessary. The straightforward use of mini-dental implants may be an alternative approach. However, supporting maxillary ISOs with 4 implants is indicated.

The present study evaluated the optimal conditions for a maxillary ISO prosthesis, using different numbers, locations, and diameters of implants, including standard diameter implants and MDIs.

MATERIAL AND METHODS

This study was performed after obtaining institutional review board approval and computed tomography images of a patient who had indications for an ISO had been obtained and converted to Digital Imaging and Communications in Medicine (DICOM) format. As density type 3 (D3) bone is often observed in the maxilla, the model was formed to represent a 1-mm outer cortical bone thickness covering the dense trabecular bone.\textsuperscript{28} Implants and prosthetic superstructures were scanned to create 3-dimensional (3D) files with a 3D scanner (NextEngine 3D Laser Scanner; NextEngine Inc), and the dataset was obtained in a standard tessellation language (STL) format and imported into software (Rhino 5.0; Rhinoceros). For the model simulation, a computer program (MARc 2013; MSC Software Corp) was used, and 6 different models were obtained to create a virtual maxilla with different implant numbers and diameters.

Implants (XiVE; Dentsply Sirona) with diameters of 3.0, 3.4, and 3.8 mm were used. Wider diameters were not modeled, as they would not be realistic because the width of the alveolar crest in the anterior maxilla is narrow in edentulous patients. All implants created for the study were 11 mm in length. Models are labeled according to the number of implants and the diameter of the implants, respectively (Tables 1–3). For model 234, 2 implants with diameters of 3.4 mm were placed in the maxillary canine tooth region. For model 434 4 implants with the same diameter were placed in the maxillary lateral and first premolar regions. For model 238, 2 implants with 3.8-mm diameters were placed. For model 438, 4 implants with 3.8-mm diameters were placed. models 230 and 430 simulated MDI-supported overdentures; model 230 contained 2 implants, and model 430 contained 4 implants, each 3.0 mm in diameter. For the MDI models, a virtual implant was designed by protecting the features of the same implant system and by decreasing the diameter in the computer environment.

Cortical and trabecular bone were assumed to undergo load transfers in accordance with their internal properties. Implants with ball attachments and ball attachments with an ISO were designed to transfer loads in a direct manner. It was assumed that the implants were 100% osseointegrated. A bone thickness of 1 mm was formed on the neck regions of the buccal and palatal surfaces of the implants. All materials used in this study were defined as homogeneous, isotropic, and linear elastic. The material features of the denture base,
The mucosa, cortical bone, trabecular bone, and implants were determined based on similar studies. Acrylic resin was used as the denture base material.

Four different loading conditions were applied vertically and obliquely: 1 from the central incisor area (CIA) that simulated incising forces and another from the molar area (MA) that simulated masticatory forces. For vertical loading, a force was applied to an area of 2 mm² on the long axis of the modeled denture base. For oblique loading, the same forces were applied at an angle of 30 degrees. The magnitude of the force was 100 N, similar to other studies.

Principal stresses were evaluated for fragile structures such as bone. The maximum principal stress (Pmax) represents tension-type stresses, and the minimum principal stress (Pmin) represents compression-type stresses. von Mises stresses were analyzed for the evaluation of stress formations in the implants.

The present study benefited from analysis software (Algor FEMpro; Autodesk Inc). As the data obtained from the FEA were mathematical calculations without variance, the results were not statistically analyzed and were evaluated with distribution scales instead. The results were subsequently evaluated comparatively.

**RESULTS**

All stress values are shown using color and quantity scales (Supplemental Figs. 1-6). Pmax and Pmin were measured in kilopascals (Tables 1, 2) and von Mises stresses in megapascals (Table 3). When the Pmax in cortical bone was evaluated relative to vertical loading from the CIA, more stress occurred in models 230, 234, and 238 (TIMs) than in models 430, 434, and 438 (FIMs). The Pmin in cortical bone in the TIM were higher. Changes in implant diameter did not cause an effect on stress formations for either stress (Supplemental Fig. 1).

When the Pmax in trabecular bone was examined relative to that of vertical loading from the CIA, no differences were observed between TIMs and FIMs.

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**Table 1. Tension stresses in cortical and trabecular bone against vertical and oblique loading**

<table>
<thead>
<tr>
<th>Area and Loading Direction</th>
<th>Model 234</th>
<th>Model 434</th>
<th>Model 238</th>
<th>Model 438</th>
<th>Model 230</th>
<th>Model 430</th>
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<tbody>
<tr>
<td><strong>Cortical Bone (kPa)</strong></td>
<td></td>
<td></td>
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<tr>
<td>Central incisor area, vertical loading</td>
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<td>120</td>
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<td>100</td>
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<td>Central incisor area, oblique loading</td>
<td>70</td>
<td>50</td>
<td>140</td>
<td>66</td>
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<td>60</td>
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<td>Molar area, vertical loading</td>
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<td>230</td>
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<td>Molar area, oblique loading</td>
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<td>210</td>
<td>900</td>
<td>170</td>
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<td>250</td>
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<tr>
<td><strong>Trabecular bone (kPa)</strong></td>
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<tr>
<td>Central incisor area, vertical loading</td>
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<td>26</td>
<td>28</td>
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<td>Central incisor area, oblique loading</td>
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<td>100</td>
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<tr>
<td>Molar area, oblique loading</td>
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<td>35</td>
<td>78</td>
<td>28</td>
<td>90</td>
<td>50</td>
</tr>
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</table>

Pmax, maximum principal stress.

**Table 2. Compression stresses in cortical and trabecular bone against vertical and oblique loading**

<table>
<thead>
<tr>
<th>Area and Loading Direction</th>
<th>Model 234</th>
<th>Model 434</th>
<th>Model 238</th>
<th>Model 438</th>
<th>Model 230</th>
<th>Model 430</th>
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<tr>
<td><strong>Cortical Bone (kPa)</strong></td>
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<td>Central incisor area, vertical loading</td>
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<td>Central incisor area, vertical loading</td>
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<td>-20</td>
<td>-30</td>
<td>-30</td>
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<td>Central incisor area, oblique loading</td>
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<td>-20</td>
<td>-15</td>
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<tr>
<td>Molar area, vertical loading</td>
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<td>-70</td>
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<td>-100</td>
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</tr>
<tr>
<td>Molar area, oblique loading</td>
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<td>-50</td>
<td>-60</td>
<td>-40</td>
<td>-80</td>
<td>-80</td>
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</table>

Pmin, minimum principal stress.

**Table 3. von Mises stresses in implants against vertical and oblique loading**

<table>
<thead>
<tr>
<th>von Mises Stresses (MPa)</th>
<th>Model 234</th>
<th>Model 434</th>
<th>Model 238</th>
<th>Model 438</th>
<th>Model 230</th>
<th>Model 430</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central incisor area, vertical loading</td>
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<td>8.9</td>
<td>0.83</td>
<td>10.75</td>
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<tr>
<td>Central incisor area, oblique loading</td>
<td>3.9</td>
<td>0.7</td>
<td>3.6</td>
<td>0.67</td>
<td>4.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Molar area, vertical loading</td>
<td>41.5</td>
<td>3.2</td>
<td>39.7</td>
<td>3.5</td>
<td>41.8</td>
<td>3.8</td>
</tr>
<tr>
<td>Molar area, oblique loading</td>
<td>36.1</td>
<td>2.1</td>
<td>33.5</td>
<td>2.9</td>
<td>37.5</td>
<td>2.6</td>
</tr>
</tbody>
</table>

PMAX, maximum principal stress.
However, when the implant diameters were greater, the amounts of stress were lower. In terms of the Pmin in trabecular bone, no differences were observed between the models. Moreover, diametric changes did not cause a difference (Supplemental Fig. 1).

Examining the Pmax in cortical bone when a vertical force was imposed from the MA showed that the stress intensity was greater around the implants in the TIM. As for the Pmin, stress intensity also increased in the TIM. On comparing the FIM, a decreased Pmin in cortical bone was observed when the diameter of the implant increased (Supplemental Fig. 2).

When a vertical force from the MA was imposed, the tension stress intensity in trabecular bone of the TIM was greater, whereas no correlation was found between an increase in implant diameter and the Pmax in trabecular bone (Supplemental Fig. 2). When the Pmax in cortical and trabecular bone was analyzed relative to oblique forces from the CIA, no differences were found. Additionally, similar stress intensities were observed when the Pmin was analyzed (Supplemental Fig. 3).

Comparing the Pmax in cortical bone relative to an oblique force from the MA, the amount of stress was greater in the TIM; for the Pmin, the stresses in the TIM were greater as well. However, no differences were found in trabecular bone for either stress. Diametric changes in the TIM had no effect on stress intensity; conversely, in the FIM, the stress intensity decreased (Supplemental Fig. 4).

When von Mises stresses on the implants against a vertical force from the CIA were analyzed, stress intensities in the TIM were much greater. A slight decrease in von Mises stresses occurred as the implant diameter increased in the TIM; however, no differences were observed for the FIM. An increase in von Mises stress intensity was observed in the TIM relative to an oblique force from the CIA. When vertical and oblique forces from the CIA were compared, lower von Mises stress levels were observed in the TIM relative to oblique forces (Supplemental Fig. 5). The von Mises stress intensities compared with vertical and oblique forces from the MA were approximately 10 times increased in the TIM (Supplemental Fig. 6).

**DISCUSSION**

The finite element stress analysis (FEA) method in implant biomechanics is better than other methods in terms of its ability to mimic complex clinical situations. It can be used to predict the distribution stresses in jawbones and dental implants.  

An association exists between excessive and unbalanced biomechanical forces and peri-implant bone loss. Reports of differences in bone loss due to bone density in animal studies and clinical reports support the theory that excessive stresses on implants may be the main etiological factor related to peri-implant bone loss. Moreover, the importance of biomechanical stress is even greater for patients with poor bone quality, limited bone volume, and systemic diseases. The present study focused on modeling patients with edentulism, poor bone quality, and limited bone volume.

Similar to the findings of Barao et al., the greatest stress measurements were obtained from peri-implant cortical bone. The forces were directly transferred to cortical peri-implant bone, which can be associated with bone resorption in peri-implant tissue. However, the stress formed in trabecular bone was somewhat low for all models. This explains why implants have only supporting and anchoring roles in ISOs instead of compensating for forces directly.

This study showed that forces applied to the MA resulted in higher levels of stress both in implants and in peri-implant bone. Given that masticating food takes longer than incising food, this study placed greater importance on stresses formed relative to forces applied to the MA. Additionally, the results of this study showed that von Mises stresses on the implants increased by 5 times compared with oblique forces from the CIA and by approximately 10 times for all other forces in the TIMs than in the FIMs. Similarly, stress measured in cortical bone increased up to 5 times, especially compared with forces applied to the MA. Considering the stress levels obtained from the implants and cortical bone, especially compared with forces applied from the MA, the use of FIM overdentures was determined to be a reliable method for maxillary ISOs.

Although numerous studies have described FIM-supported maxillary overdentures, few studies exist regarding TIM-supported maxillary overdentures. Meijer et al. compared different numbers of implants and stated that no decrease in stress formation could be observed after increasing the number of implants. Despite this finding, the results of this study suggest that a decrease in stress intensity occurred in both the implants and bone with an increase in implant numbers. However, these findings should be supported and confirmed with clinical studies.

Himmlova et al. evaluated the effect of implant diameter and length on the stress occurring around the implant and stated that implant diameter affected stress distribution more than length. However, Holmgren et al. reported that the use of larger diameter implants was not always necessary. Moreover, within morphological limits, the most appropriate implant diameter will be the one that decreases stresses in the implant bone structure. Similarly, considering the results of this study, increasing the implant diameter in both groups separately did not significantly affect the stresses formed in the implants and peri-implant bone with a few exceptions. As the forces formed are generally...
below the level of forces that implant materials can resist, and given the advantages of MDI use in elderly patients, MDI-supported overdenture prostheses are preferable because they avoid further surgical procedures. However, in their clinical research, Jofré et al\(^{35}\) reported vertical bone loss greater than 1 mm around overdenture implants with the use of MDIs. Although the present study shows only slightly greater amounts of stress in the peri-implant bone and MDI, attention must be given to selecting patients in terms of factors such as bone quality and habits such as bruxism. Because of the existence of periodontal ligaments in natural teeth and in contrast with implants, occlusal loads are transferred to the bone tissue with buffering.\(^{10}\) Deformation may occur in peri-implant bone because of excessive stress above 2000 to 3000 microstrain. With excessive, pathological loads above 4000 microstrain, stress and tensile forces exceed physiological limits, leading to mechanical issues such as microfractures in the bone-implant interface, implant failure, fracture or loosening of the implant screw, and bone resorption. According to the results of this study, maximum equivalent strains formed on peri-implant bone were below 2500 microstrain in all models, and these measurements were not above physiologic limits.\(^{11,33}\)

In the present study, the stress values measured in implants were significantly lower than the strength of the material. However, significantly higher stress levels were found in TIM than in FIM. Increasing the implant diameter did not result in significant differences when the TIM and FIM were investigated internally. These findings suggest that MDIs and regular-diameter implants are not different in terms of hardware complications such as implant fracture and that increasing the implant diameter does not significantly affect the success of overdentures.

CONCLUSIONS

Based on the findings of this finite element study, the following conclusions were drawn:

1. Cortical bone had the highest tensile and compression stress values.
2. The von Mises stresses were most severe at the neck of the ball attachment and at the junction of the implant ball attachment.
3. The stresses that occurred against vertical loads were found to be greater.
4. The stress values that occurred as a result of masticatory forces applied from the MA were more intense than incisal forces applied from the CIA.
5. Four-implant overdentures exhibited better stress conditions than TIM overdentures for maxillary ISOs and increasing the implant diameter was not advantageous.

REFERENCES

Radiographic appearance of interocclusal record materials for cone beam computed tomography-guided implant surgeries

Mohunta VV, McGlumphy EA, Kim DG, Azer SS

Purpose. To select an ideal interocclusal record material for cone beam computed tomography (CBCT)-guided implant surgery based on the material’s radiodensity on the scan.

Material and Methods. Twelve commonly used interocclusal record materials were used for this investigation: two were waxes, one was polyether, and nine were polyvinyl-siloxane-type materials. A scan template was fabricated by duplicating existing dentures in Ortho-Jet acrylic resin mixed with 30% barium powder for the teeth and 10% barium powder for the denture base between the teeth and the tissue. An interocclusal record was fabricated with each material, and the same template was used to obtain a CBCT scan with an ICAT machine (Imaging Sciences International) at 0.3 voxel and 14-bit depth settings. Twelve CBCT scans were obtained and analyzed. The radiopacity of the barium teeth was used as a control and was compared with the opacity of the 12 materials using a paired t-test. A post hoc analysis of variance (ANOVA) test was used to compare the densities of the various materials with each other.

Results. There was a statistically significant difference between the radiopacity of barium teeth (gray value: 1,959.475) and that of Modelling Wax (gray value: 750; P=.0026), Aluwax (gray value: 795.22; P=.0022), Blu-Bite CT (gray value: 1,105; P=.005), Ramitec (gray value: 1,105.3; P=.08), Memosil 2 (gray value: 1,202; P=.01) followed by Reprosil (gray value: 1,407.73; P=.01). Compared with the barium teeth, there was no statistically significant difference between the densities of Futar D (gray value: 1,866.5; P=.51), Jet Bite (gray value: 1,660.04; P=.08), Lab-Putty (gray value: 1,402.14; P=.19), and Memoreg 2 (gray value: 1,754.72; P=.1). The highest radiodensity was seen with Blu-Mousse (gray value: 2,949; P=.007) and Take 1 (gray value: 2,229.85; P=.025), which were also significantly different from the density of the barium teeth but in the opposite direction, making them more opaque.

Conclusions. Within the limitations of this in vitro study, the most radiolucent appearance of Modelling Wax, Aluwax, Memosil 2, Blu-Bite CT, and Ramitec made them the suitable materials of choice of those tested, as the interocclusal registration record during CBCT scanning allowed clear visualization of barium teeth.

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Supplemental Figure 1. Compression and tension stresses observed in cortical bone and trabecular bone against vertical loading from central incisor area. Pmax, maximum principal stress; Pmin, minimum principal stress.
Supplemental Figure 2. Compression and tension stresses observed in cortical bone and trabecular bone against vertical loading from molar area. Pmax, maximum principal stress; Pmin, minimum principal stress.
Supplemental Figure 3. Compression and tension stresses observed in cortical bone and trabecular bone against oblique loading from central incisor area. Pmax, maximum principal stress; Pmin, minimum principal stress.
Supplemental Figure 4. Compression and tension stresses observed in cortical bone and trabecular bone against oblique loading from molar area. Pmax, maximum principal stress; Pmin, minimum principal stress.
Supplemental Figure 5. von Mises stresses observed in implants against vertical and oblique loadings from central incisor area. First and third columns: appearance of implants in alveolar crest; second and fourth columns: spatial appearance of implants after removal of alveolar crest.
**Supplemental Figure 6.** von Mises stresses observed in implants against vertical and oblique loadings from molar area. First and third columns: appearance of implants in alveolar crest; second and fourth columns: spatial appearance of implants after removal of alveolar crest.