Finite Element Stress Analysis of Dental Prostheses Supported by Straight and Angled Implants

Mauro Cruz, DDS, MSc, PhD[1]/Thomaz Wassall, DDS, MSc, PhD[2]/Elson Magalhães Toledo, Eng, MSc, DSc[3]/
Luís Paulo da Silva Barra, Eng, MSc, DSc[4]/Silvia Cruz, DDS[5]

Purpose: *A three-dimensional finite element analysis was conducted to evaluate and compare the stress distribution around two prosthesis-implant systems, in which implants were arranged in either a straight-line or an intrabone offset configuration.* ***Materials and Methods:*** *The systems were modeled with three titanium implants placed in the posterior mandible following a straight line along the bone. The straight system was built with three straight implants (no offset). The angled system was built as follows: the first implant (mesial) was an angled implant inclined lingually, the second (median) was straight, and the third (distal) was another angled implant inclined buccally. This buccal incline created an intrabone implant offset owing to the inclination of the angled implants' bodies. Each system received a metal-ceramic prosthesis with crowns that mimicked premolar anatomy. In both systems, an axial load of 100 N and a horizontal load of 20 N were applied on the center of the crown of the middle implant.* ***Results:*** *In both systems, the major von Mises stresses occurred with vertical loading on the mesial and the distal neck area of the first and third implants, respectively: 6.304 MPa on the first implant of the straight system and 6.173 MPa on the third implant in the angled system. The peak stress occurred for the minimum principal stress (S3) on the neck of the first implant for both systems at the level of −8.835 MPa for the straight system and −8.511 MPa for the angled system. There was no stress concentration on the inner or outer angles of the angled implants, on the notches along the implant body, or on any apex.* ***Conclusions:*** *In this analysis, the angled system did not induce a stress concentration in any point around the implants that was different from that of the straight system. The stress distribution was very similar in both systems.* INT J ORAL MAXILLOFAC IMPLANTS 2009;24:391–403

Key words: *angled implants, dental implants, dental prosthesis, finite element analysis, offset implants*

An implant-supported prosthesis is a predictable means of treating tooth loss.[1–3] Although the implant prosthetic designs are often used to replace completely edentulous arches, they are also used in the rehabilitation of partially edentulous jaws.[4–8] In complete edentulism, the biomechanical situation is likely to be favorable, as implants are placed in a curvilinear pattern following the dental arch. In contrast, implants used to support prostheses in the partially edentulous jaw are normally placed in a relatively straight alignment. Rectilinear arrangements of implants have been shown to create forces that cause adverse effects on the supporting implants; this situation could result in damage to the prosthetic components, the implants, or the surrounding bone.[9–14] Eckert et al[15] found a fivefold increase in the incidence of implant fractures in the partially edentulous jaw compared to the edentulous jaw. Because the edentulous jaw generally provides a curvilinear arrangement for implants, it may be hypothesized that this factor is responsible for the lower implant fracture rate in this patient group.

For these reasons, Rangert et al[10,13,16–19] suggested that when three or more implants are planned, the implants should be placed in such a way as to create an intentional offset rather than in a straight-line configuration. The offset is thought to

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[1] Director, Clinical Center of Research in Stomatology, Juiz de Fora, MG, Brazil; Researcher and Professor, São Leopoldo Mandic Research Center, Dental School, Campinas, SP, Brazil.
[2] Director, São Leopoldo Mandic Research Center, Dental School, Campinas, SP, Brazil.
[3] Researcher, Computational Mechanics Coordination, National Laboratory for Scientific Computing, Petrópolis, RJ, Brazil; Professor, Federal University of Juiz de Fora, School of Engineering, Campus Cidade Universitária, Juiz de Fora, MG, Brazil.
[4] Professor, Federal University of Juiz de Fora, School of Engineering, Campus Cidade Universitária, Juiz de Fora, MG, Brazil.
[5] Director, Clinical Center of Research in Stomatology, Juiz de Fora, MG, Brazil.

Correspondence to: Dr Mauro Cruz, Av. Rio Branco, 2288/1205 Juiz de Fora, MG, 36016-310 Brazil. Phone/Fax: +55-32-3215-3957. Email: maurocruz@clinestpq.com.br

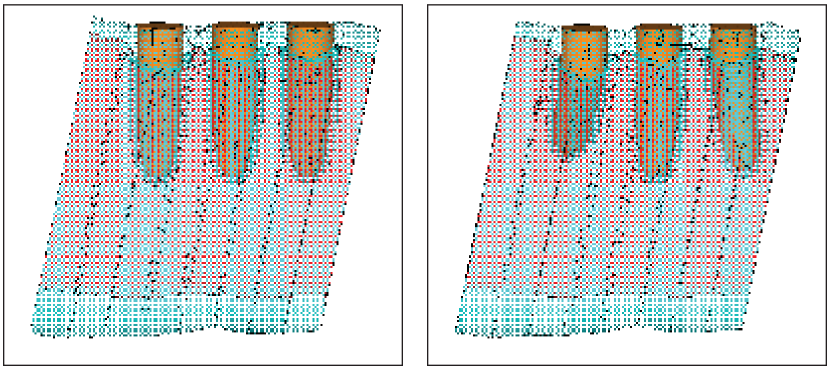


Fig 1a Section of the bone and the implants. Cortical bone, medullary bone, and compact bone layer (lamina dura) around the implants.

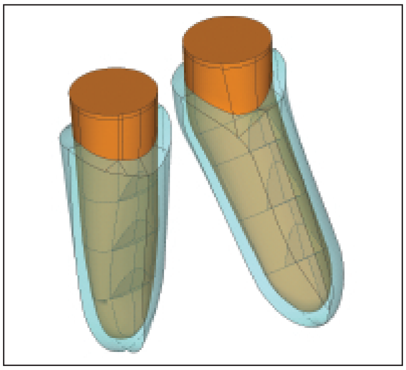


Fig 1b Detail of the lamina dura modeled.

create a more favorable distribution of forces within the prosthesis/implant/bone system because of its triangular base.[20] The rationale is that such a base is more stable than one that has all its supports in a straight line. While this line of thought makes sense from the biomechanical point of view, an offset may be difficult to achieve because of anatomic limitations,[21–23] because in many cases the alveolar crest is narrow.

There is little information on the magnitude of the effect when the offset is within the anatomic confines of the natural teeth. This phenomenon was examined by Sütpideler et al,[24] whose study recommended a maximum offset of 3 mm for anatomic reasons and demonstrated that such an offset effectively reduced the stress under inclined loads. However, Akça and Iplikçioglu[25] found limited advantage in nonlinear arrangements of standard-diameter implants compared to wider implants placed along a straight line. Iplikçioglu and Akça[26] assessed the stress distribution in the bone caused by this kind of implant configuration supporting a three-unit fixed partial prosthesis by evaluating the effect of diameter, length, and number of implants used to support the prosthesis.

In designing any prosthesis, the clinician endeavors to recreate the natural anatomy. With an implant-supported prosthesis, the implants should follow the angulation of the roots. Also, the coronal tooth structures should be aligned with the supporting implants to avoid overcontours that otherwise alter the tooth anatomy[27] and create unfavorable stresses.[24] The hypothesis is that a tripod configuration and the small crowns can compensate for the moment that is created when occlusal forces are applied to the prosthesis.[18,20,24]

The use of angled implants has been recommended to permit implant placement that matches the contours of anatomic structures[28–30] or to enhance esthetic conditions.[28] The biomechanical behavior of angled implants is similar to that of straight implants placed at an inclination.[31,32] Canay et al[33] found a considerable difference among straight and angled implants for horizontal loads; this finding has not been replicated by other authors.[34,35] Angled implants can be placed in a straight line following the alveolar crest but can create an offset inside the alveolar bone, where the crest is thicker.

The distribution of forces in peri-implant bone has been investigated by finite element analysis (FEA) in several studies.[36–40] FEA is an engineering method that allows investigators to assess stresses and strains within a solid body. Studies comparing the accuracy of these analyses found that, if detailed stress information is required, then three-dimensional (3D) modeling is necessary.[41–44] The 3D FEA is considered an appropriate method for the investigation of stresses throughout a structure, therefore, this method was selected to evaluate bone and implant stresses in this study.

The purpose of this study was to evaluate, through FEA, the stress distribution around two prosthesis-implant systems with implants aligned in a straight line over the alveolar crest and arranged within the bone in either a straight-line configuration (straight implants) or an offset configuration (angled implants).

MATERIALS AND METHODS

A 3D finite element model was constructed to evaluate the stress distribution around two prosthesis-implant systems, in which implants were arranged in either a straight-line or an offset configuration. The offset configuration was obtained by means of arranging angled implants with straight ones. The straight implants were 4 mm in diameter and 13 mm in length, and the angled implants were 4 mm in diameter and 14 mm in length and had a 35-degree slope. Both had a wedge-shaped basic geometry. The model of the mandible simulated the outer and inner anatomic structure of an actual human mandible obtained from

Table 1 Mesh Data

Model	Domain	Elements	Nodes
Straight system	Complete model	243,621	339,164
	Prosthesis/implant system + surrounding region	137,044	188,839
Angled system	Complete model	246,477	343,302
	Prosthesis/implant system + surrounding region	141,140	194,535

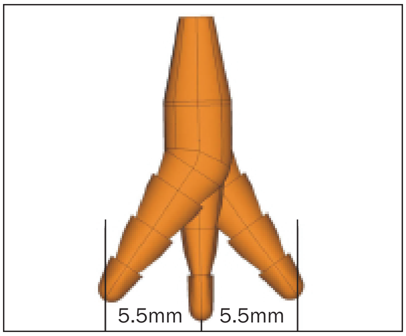


Fig 2a Angled system. Frontal view of the offset.

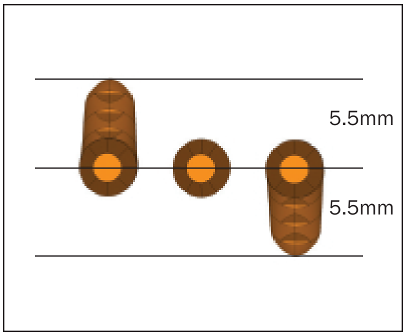


Fig 2b Angled system. Horizontal view of the offset.

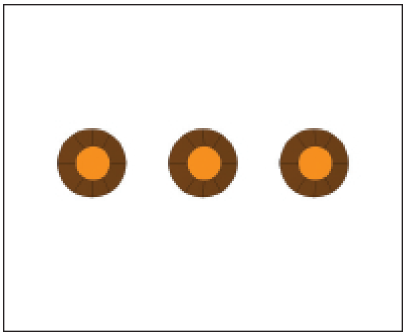
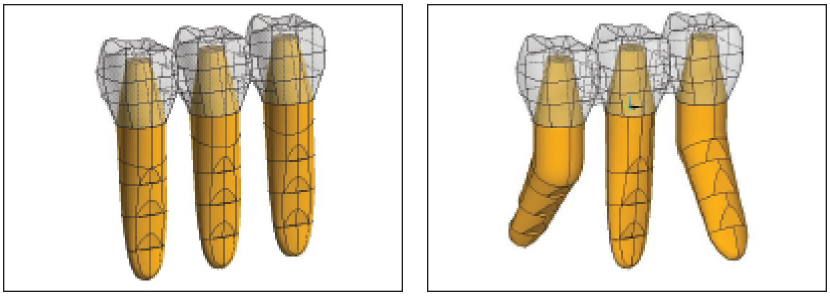


Fig 2c Straight system. Horizontal view, no offset.



Figs 3a and 3b Geometric models of the implant-supported prosthesis. Straight system and angled system.

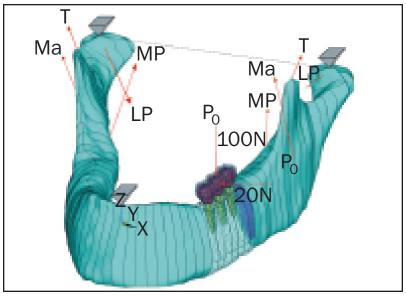


Fig 4 Model with restraints adopted and the direction of the applied muscular forces. LP = lateral pterygoid; Ma = masseter; MP = medial pterygoid; P_0 = implant load; T = temporalis.

computerized tomography data. The dimensions of the mandible body and of the cortical and medullary bone followed the measurements of the actual model used. All implants were surrounded by a layer (1 mm) of compact bone to simulate the lamina dura–like structure that is encountered in successful osseointegrated functional implants (Figs 1a and 1b).[45–49] Two FEA models representing two different implant-prosthesis systems were created and meshed with tetrahedral isoparametric quadratic elements consisting of four triangular faces, four vertices, and 10 nodes using the commercial finite element code Ansys (Ansys, Canonsburg, PA) and processed in a personal computer (Table 1). Each system was modeled with three titanium endosseous implants placed in the posterior region of the mandible following a straight line along the bone. The straight system was built with three straight implants (no offset). The angled system was built as follows: the first implant (mesial) was an angled implant inclined lingually, the second (median) implant was straight, and the third (distal) was another angled implant inclined buccally. This buccal incline created an intrabone implant offset because of the inclination of the angled implants' bodies. The offset obtained was 5.5 mm for each side (buccal/lingual) from the center, for a total offset of 11 mm, measured from the center of each implant in the apex region (Fig 2). Both systems received a metal (titanium)-ceramic prosthesis with crowns that followed the premolar anatomy (Figs 3a and 3b). The cement layer between the crown and the abutment was not considered in the model. In both systems, an axial load of 100 N was applied on the center of the crown of the second implant and a horizontal load of 20 N was applied on the same tooth, on the buccal side, in the buccolingual direction.

Table 2 Distance Vector Components (mm)

Vector distance	x-axis	y-axis	z-axis
r_M	0.0	28.07	33.01
r_{MP}	0.0	27.67	38.97
r_{LP}	0.0	9.56	6.31
r_T	0.0	30.61	5.27
r_{P_0}	0.0	80.63	23.89

Table 3 Director Cosines of the Resultant Muscular Forces (Right Side)

Muscle	Cos (α)	Cos (β)	Cos (γ)
Masseter	−0.043	−0.011	0.999
Medial pterygoid	0.587	−0.165	0.792
Lateral pterygoid	0.714	−0.692	0.106
Temporalis	−0.325	0.219	0.920
P_0 horizontal	−0.907	0.420	0
P_0 vertical	0	−1	0

Table 4 Resultants of the Muscular Forces for Vertical and Horizontal Loads

Load direction	M	MP	LP	T
Vertical (100 N)	49.251	32.626	28.634	28.348
Horizontal (20 N)	1.787	1.195	1.039	1.029

Table 5 Material Properties

Material	Modulus of elasticity (E)	Poisson ratio (ν)
Cortical bone	13,700 MPa	0.30
Medullary bone	1,370 MPa	0.30
Titanium	110,000 MPa	0.33
Ceramic	82,800 MPa	0.28

The final model was supported by force vectors simulating the actions of the muscles of mastication (masseter, medial pterygoid, lateral pterygoid, and temporalis) and the temporomandibular joints[50] (Fig 4). The acting forces generated by the masticatory muscles and transferred to the vectors were calculated based on the transverse sections, as proposed by Inou et al.[51] The data obtained from this work indicate the following relationships between the muscle actions, based on the average size of their cross-sectional areas at the mandibular interface:

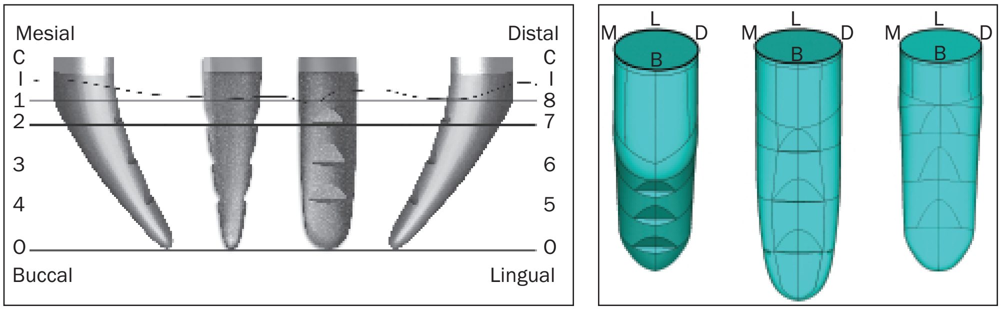
- M = 1.72 LP
- T = 0.99 LP
- MP = 1.15 LP

where M is the masseter, LP is the lateral pterygoid, T is the temporalis, and MP is the medial pterygoid. For horizontal and vertical loading, both condyles were completely restrained. The values of the muscular forces for both loading cases were determined by the moment equilibrium equation around the axis connecting the condyles, which is given by the expression:

$$\left(\vec{r_M} \times 2\vec{M} + 2\overrightarrow{MP} \times \vec{r_{MP}} + 2\overrightarrow{LP} \times \vec{r_{LP}} + 2\vec{T} \times \vec{r_T} + \vec{P_0} \times \vec{r_{P_0}}\right) \bullet \vec{e} = 0$$

The variables r_M, r_{MP}, r_{LP}, r_T, and r_{P_0} are the distance vectors from the load application points of the muscles forces *M*, *MP*, *LP*, and *T* and of the axial implant loads *(P_0)* to the (1–2) axis passing through the tops of the condyles, respectively. The same equation was used for axial and horizontal loads, with the distance varying accordingly. The symbol × denotes the vector product, the symbol (•) denotes the inner vector product, and $\vec{e}$ is the unit vector in the condylar axis direction. The positions of the muscular forces and axial load are given in vector form in Table 2. This model resulted in symmetric muscle forces, not including the effect of the nonsymmetry of implant location. Under the assumption of symmetric muscular loads, the asymmetry is generated by the reaction forces in the condyles. Moment equilibrium in the y-axis, obtained by the FEA, results in different condyle forces and thus an asymmetric stress distribution in the model. The locations and directions of the muscle force vectors were obtained from the literature.[35,51–53] Their resultants were considered to be acting on the centroid of the elements included in the areas of muscular action. Force directions are described in terms of director cosines, as given in Table 3. Obtained values for each muscular force, considering both vertical and horizontal loads, are listed in Table 4. Elastic properties for cortical bone, medullary bone, titanium, and ceramic were extracted from the current literature[35,37,54] and are listed in Table 5. Thicknesses of the cortical and medullary bone were based on computerized tomographic sections of the mandible. The bone was assumed to be isotropic, homogeneous, and linearly elastic, which allowed immediate extrapolation of the obtained results for different load levels.

Stresses were analyzed in the superior surface of the simulated bone adjacent to the implant platform, along the implant body (mesiodistal and buccolingual contouring), and in the apical region. Stresses were analyzed as well at specific points such as the outer and inner angles of the angled implants and the inner surface of the cortical bone surrounding the implants (Figs 5a and 5b). The data obtained were used to determine maximum and minimum principal stresses. The von Mises (VM) stress field, under the loading conditions simulated, was also used in deciphering these stresses.



Figs 5a and 5b Areas analyzed around the implants. References lines for the stress charts. Body lines and cervical line. B = buccal; L = lingual; M = mesial; D = distal.

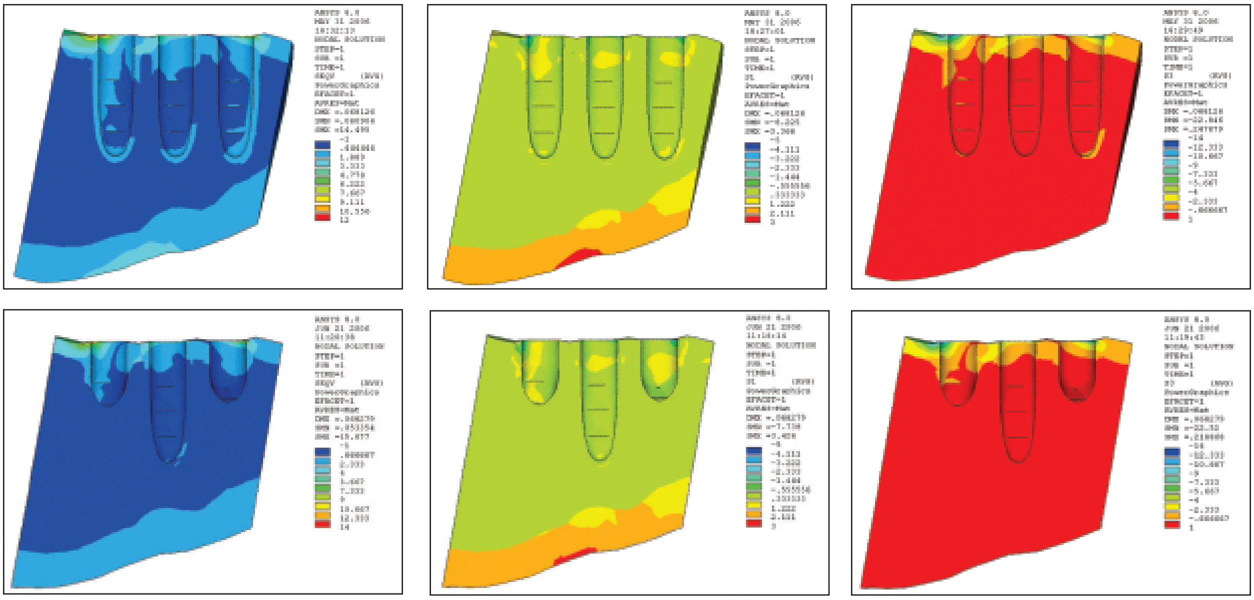


Fig 6 Diagram of stresses around the implants under vertical load. (*Left*) VM, Von Mises. (*Center*) S1, maximum principal stress. (*Right*) S3, minimum principal stress. (*Top*) Straight system. (*Bottom*) Angled system.

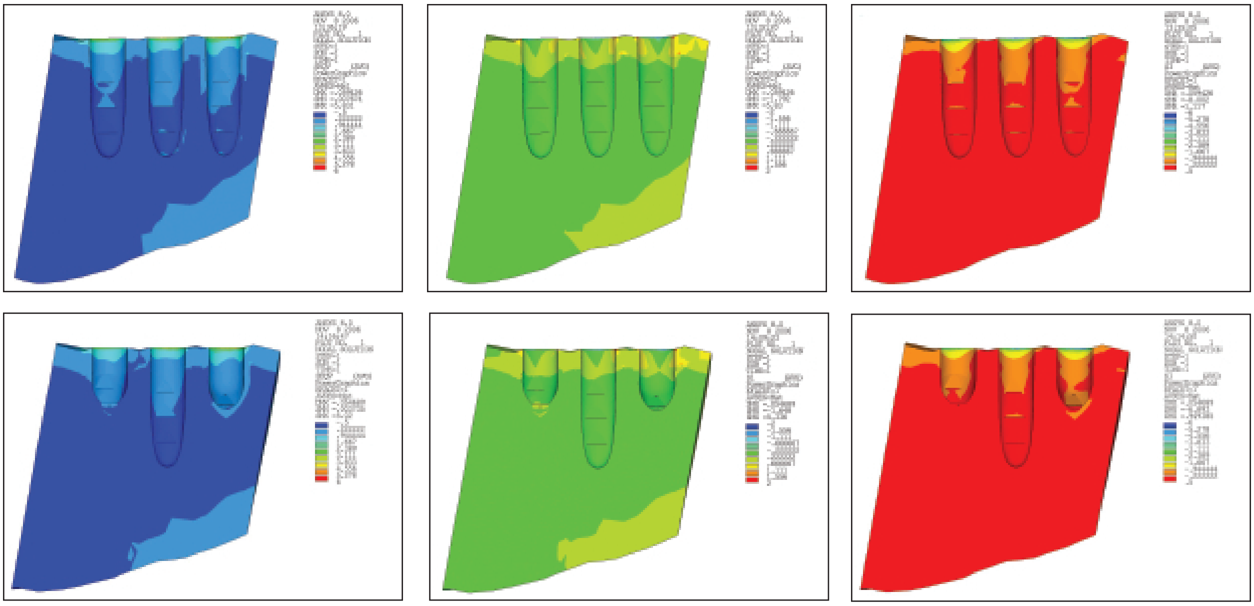


Fig 7 Diagram of stresses around the implants under horizontal load. (*Left*) VM, Von Mises. (*Center*) S1, maximum principal stress. (*Right*) S3, minimum principal stress. (*Top*) Straight system. (*Bottom*) Angled system.

Table 6 Stresses Reported in Neck and Apex Region (MPa)

Stresses	Straight system									Angled system								
	1			2			3			1			2			3		
	Neck		Apex	Neck		Apex	Neck		Apex	Neck		Apex	Neck		Apex	Neck		Apex
	Max	Min		Max	Min		Max	Min		Max	Min		Max	Min		Max	Min	
Von Mises stress																		
VL	6.304*	0.418	0.432	2.957	1.401	0.446	5.766	0.220	0.782	6.108	0.312	0.474	2.951	1.253	0.483	6.173*	0.327	0.634
HL	1.959	0.897	0.115	2.148*	0.739	0.139	2.467	0.836	0.138	1.676	0.798	0.534	1.953	0.666	0.148	2.096	0.779	0.105
Maximum principal stress (S1)																		
VL	−2.463	0.395	−0.071	−0.745	0.012	−0.089	−2.324	0.246	−0.144	−2.331	0.394	0.153	−0.914	0.032	−0.116	−1.954	0.303	−0.016
HL	1.493	−0.195	−0.001	2.397	−0.233	−0.016	2.902	−0.331	−0.001	1.366	−0.125	0.256	2.239	−0.225	0.001	−0.262	2.496	0.088
Minimum principal stress (S3)																		
VL	−8.835*	−0.479	−0.523	−3.940	−1.872	−0.551	−8.010	−0.277	−0.954	−8.511*	−0.712	−0.353	−3.924	−1.467	−0.612	−8.319	−0.489	−0.713
HL	−2.281	0.024	−0.129	−2.522	0.180	−0.159	−2.398	0.480	−0.152	−1.918	0.022	−0.360	−2.079	0.144	−0.154	−2.484	0.338	−0.027

VL = vertical load; HL = horizontal load. *Major/peak stress.

RESULTS

The stress distribution was virtually identical in both systems (Figs 6 and 7; Tables 6 to 8). A slight difference was seen in the first and third implants (when compared to the second implants), which showed a stress concentration on the neck area (Figs 8 to 11). The major stress occurred for the vertical load on the mesial and on the distal neck area of both implants: 6.304 MPa (VM) on the first implant for the straight system, and 6.173 MPa (VM) on the third for the angled system (Table 6). The peak stress occurred for the minimum principal stress (S3) on the neck of the first implant for both systems at the level of −8.835 MPa for the straight system and −8.511 MPa for the angled system (Table 6). To compare the stress distribution along the bodies of the straight and angled implants, points were selected in each model where stress concentration could occur, such as the angles, the notches in the body, or the apex. No considerable stress concentration was found along the body, on the inner or outer angles, or on the apices of any implant in either system (Figs 8 to 11).

DISCUSSION

At present, implant-supported prostheses are commonly used in partially edentulous jaws. When three or more implants are used, Weinberg and Kruger[20] and Rangert et al[13,18] suggested that the implants be placed in such a way as to create an intentional offset on the middle implant, generating a tripod condition that minimizes the moment. This design is suggested to improve the biomechanical stability of the prosthesis and to reduce the risk of fractures of the prosthetic components and implants. Akça and Iplikçioglu[25] performed FEA with an offset limited to 1.9 mm and demonstrated that such a limited offset was of no advantage compared to a system with wider-diameter implants placed along a straight line. Sütpideler et al[24] not only recommended a 3.0-mm offset (to mimic the natural anatomy of the teeth), but also indicated that other works[25,26] failed to assess the maximum offset possibility, taking into account the limits of natural tooth anatomy and alveolar bone crest dimensions. According to them, these works discussed the offset condition in terms of an engineering concept and did not consider the limits established by natural tooth anatomy[13,18] and the dimensions of the alveolar bone crest. The average buccolingual dimension of posterior teeth is 8 mm or less,[27] and in posterior restoration designs, the distances from the center of the implant to the buccal or lingual surface of the restoration should be

Table 7 Stress Reported Around the Implant Body, Mesiodistal Contouring (MPa)

	Straight system						Angled system					
	1		2		3		1		2		3	
Stresses	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Von Mises stress												
VL	6.220	0.208	2.825	0.183	4.627	0.158	5.979	0.290	2.901	0.187	4.850	0.123
HL	1.311	0.067	1.174	0.105	1.613	0.106	1.534	0.075	1.066	0.083	1.472	0.043
Maximum principal stress (S1)												
VL	−1.925	0.314	−0.697	0.269	−1.380	0.470	−1.860	0.648	−0.702	0.311	−1.253	0.494
HL	0.969	−0.015	0.949	−0.024	1.209	−0.015	1.554	0.064	0.859	−0.019	0.944	0.001
Minimum principal stress (S3)												
VL	−8.178	−0.210	−3.804	−0.202	−6.393	−0.159	−7.797	−0.139	−3.857	−0.219	−6.370	−0.095
HL	−0.541	0.104	−0.397	0.098	−0.651	0.141	−0.469	0.318	−0.365	0.071	−0.751	0.129

VL = vertical load; HL = horizontal load.

Table 8 Stress Reported Around the Implant Body, Buccolingual Contouring (MPa)

	Straight system						Angled system					
	1		2		3		1		2		3	
Stresses	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**
Von Mises stress												
VL	3.680	0.186	1.789	0.157	3.542	0.222	3.206	0.169	1.699	0.158	3.456	0.203
HL	1.928	0.053	2.114	0.043	2.399	0.058	1.676	0.082	1.865	0.046	2.059	0.032
Maximum principal stress (S1)												
VL	0.713	−0.109	0.600	−0.160	0.618	−0.147	0.792	−0.198	0.597	−0.154	0.854	−0.129
HL	1.248	−0.058	2.333	−0.227	2.788	−0.065	1.219	−0.090	2.134	−0.212	2.391	−0.059
Minimum principal stress (S3)												
VL	−3.764	−0.118	−2.012	−0.104	−3.649	−0.136	−3.226	−0.031	−1.988	−0.119	−3.555	−0.018
HL	−2.248	0.074	−2.507	0.113	−2.392	0.132	−1.895	0.071	−2.079	0.103	−2.140	0.124

VL = vertical load; HL = horizontal load.

considered, because overcontouring may occur if the implant is placed too far from the buccal or the lingual surface of the tooth. This situation, therefore, may also limit the amount of offset that can be achieved. Unfortunately, bone resorption generally occurs very quickly after tooth loss,[22] thereby making the residual ridge narrower and either limiting the implant offset or making it impossible. The current study aligned the implants over the bone crest and reduced the crowns to the dimensions of the premolar teeth to try to overcome these limitations. In the angled system, the angled implants had their platforms arranged in a straight line over the bone (without the necessity of a large crest) and also had their bodies arranged in an offset configuration (4.3 mm for each side) inside the bone, creating a true tripod effect that could be an effective biomechanical and prosthetic solution.

This study analyzed and compared two prosthesis-implant systems with the implants arranged in a rectilinear configuration over the alveolar ridge. In both systems, an axial load of 100 N was applied at the center of the crown of the second implant and a horizontal load of 20 N was applied to the buccal face of the crown of the same implant. In normal chewing, however, it is unlikely that force would be concentrated in this way. Instead, mastication would produce complex patterns of force vectors, making the results of this type of analysis appear to be an anomaly. Although FEAs examine forces applied in isolation, results nonetheless mirror reality very closely.[42,43,54] Nevertheless, the clinician must consider this limitation when a clinical application is being discussed.

The results unexpectedly showed the same stress distribution pattern for both systems: the use of angled implants did not induce stress concentration in critical points, such as the outer or inner angles, for vertical or horizontal loads. The data obtained confirmed the results of Ferreira,[34] who found no difference in the distribution patterns of angled and straight implant geometries. The data also contradicted the results of Canay et al,[33] who observed a fivefold increase in stress in the platform of the angled implant compared to that of the straight implant under a vertical load. It must be noted, however, that this work studied hollow-cylinder implants, a geometry that differs considerably from the wedge-shaped geometry examined in this study.

The stress distribution in the angled system in this study was quite similar to that seen in the straight system. This permitted an intrabone offset, creating a tripod configuration that is purported to improve the biomechanical stability[10,13,17–19] of an implant-supported prosthesis and reduce the average rate of the stress under inclined loads.[24]

CONCLUSIONS

Stress analysis of two different implant/prosthesis system designs (straight and angled) using the finite element method led to the following conclusions:

1. The angled system, with an intrabone offset, did not experience a stress concentration at any point around the implants that was different from that seen in the straight system.
2. Both prosthetic-supported implant systems presented a similar stress distribution pattern.
3. The intrabone offset created by the angled system did not alter the stress distribution pattern and can be an option to increase biomechanical stability.

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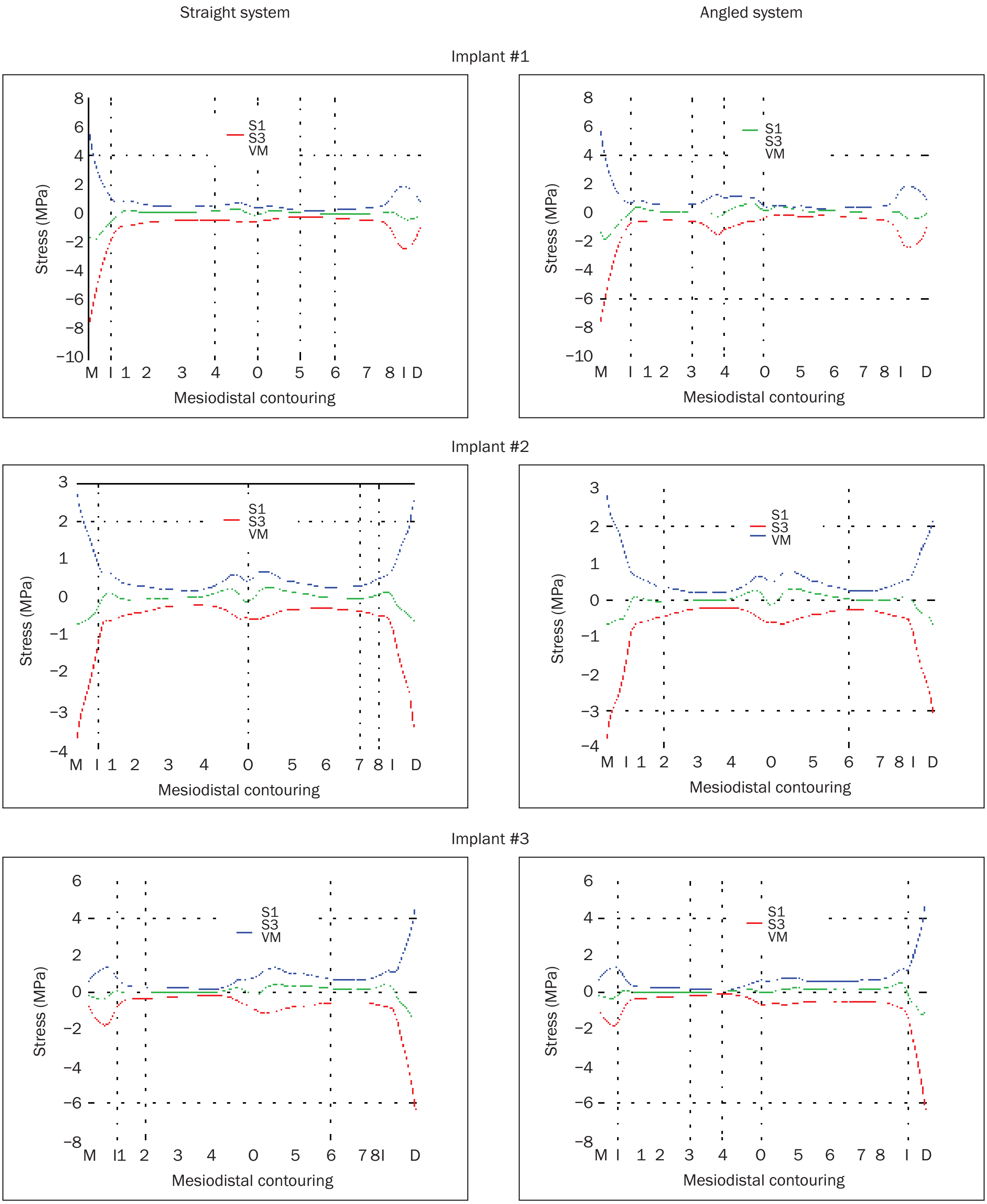

Fig 8 Stresses around the implants under vertical load. Mesiodistal contouring (MPa). S1 = maximum principal stress; S3 = minimum principal stress; VM = von Mises.

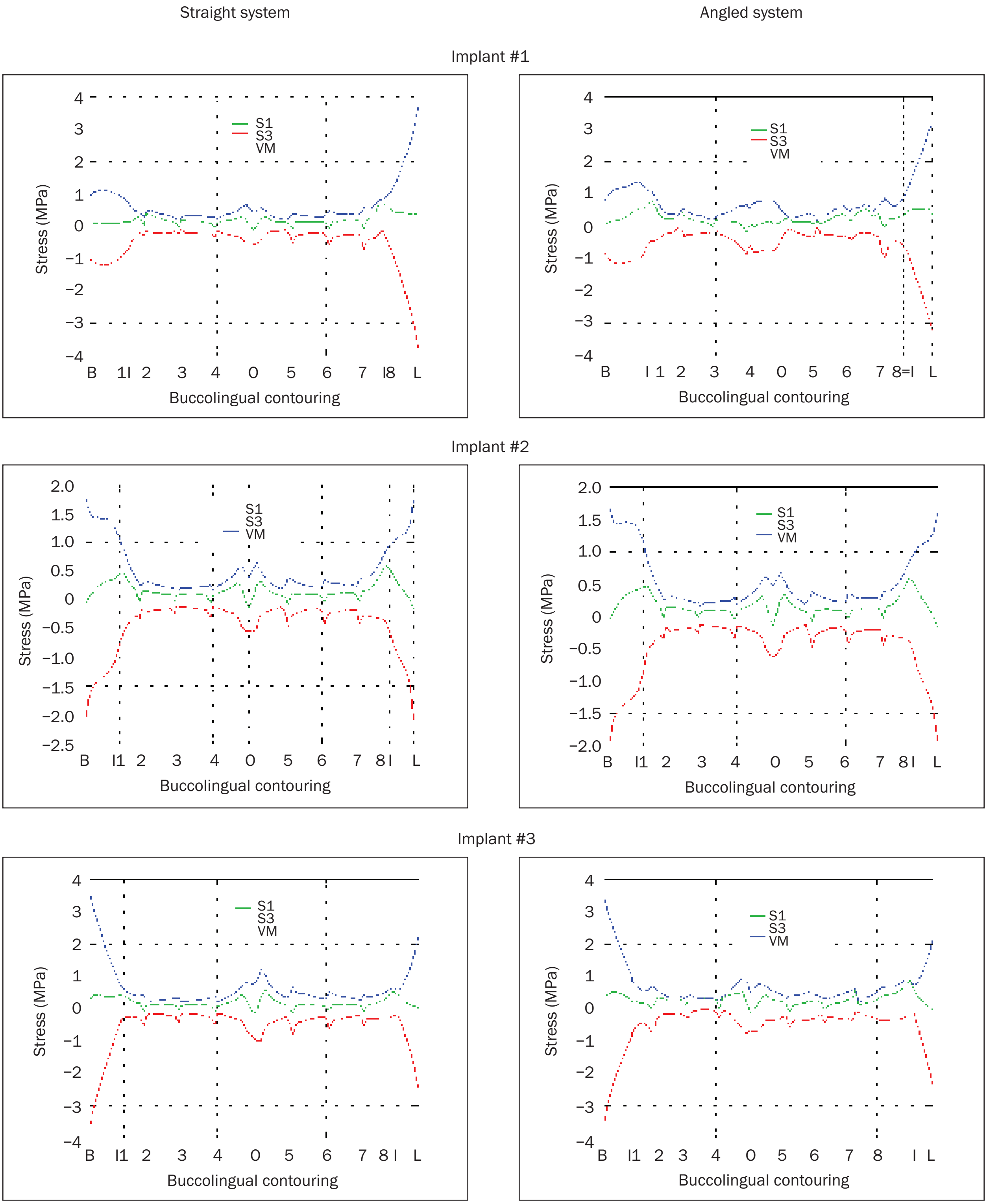

Fig 9 Stresses around the implants under vertical load. Buccolingual contouring (MPa). S1 = maximum principal stress; S3 = minimum principal stress; VM = von Mises.

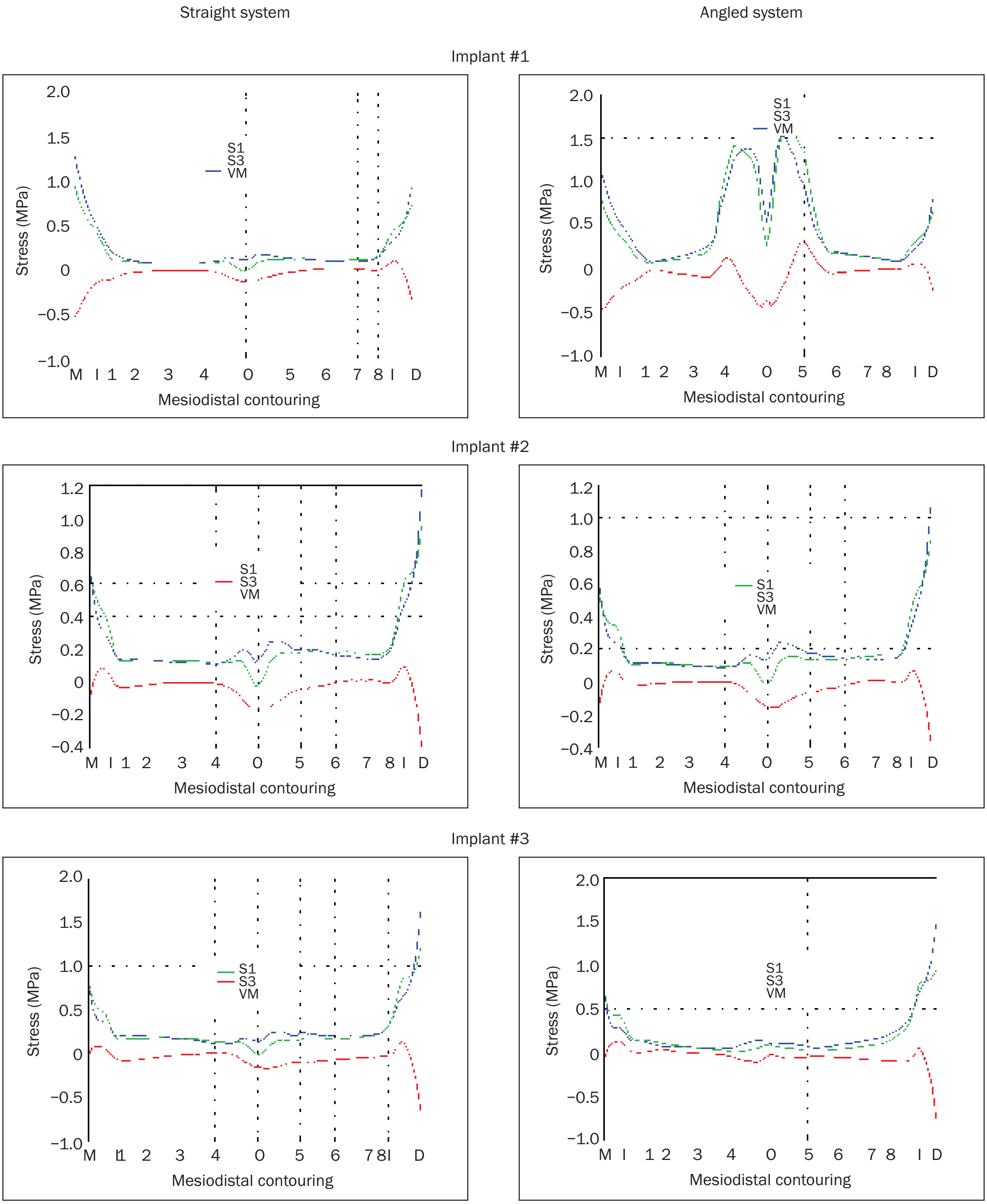

Fig 10 Stresses around the implants under horizontal load. Mesiodistal contouring (MPa). S1 = maximum principal stress; S3 = minimum principal stress; VM = von Mises.

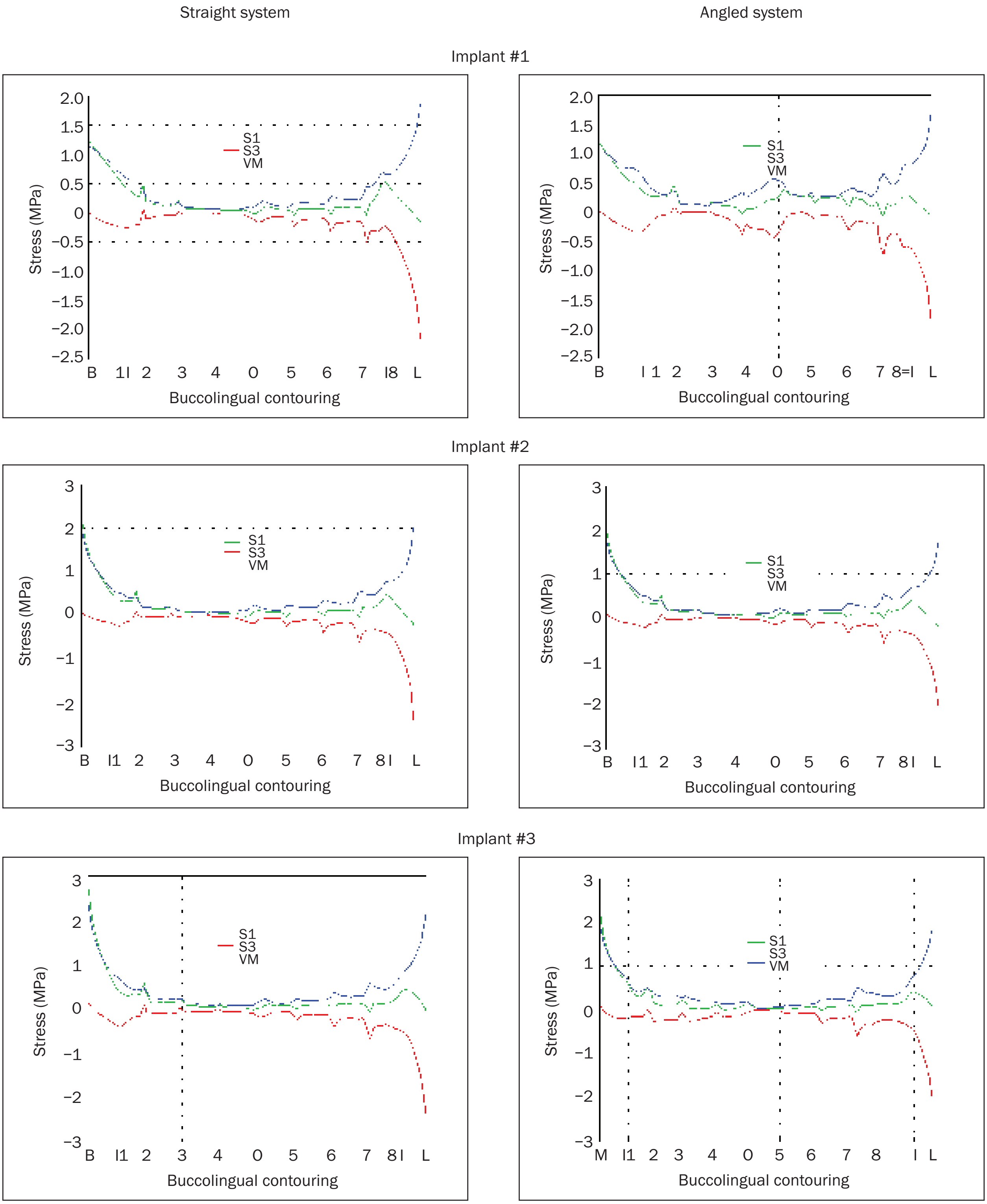

Fig 11 Stresses around the implants under horizontal load. Buccolingual contouring (MPa). S1 = maximum principal stress; S3 = minimum principal stress; VM = von Mises.