A two-dimensional finite element method was used to analyze the changes in mechanical behavior of the supporting structures when a fixed prosthesis replaced a mandibular first molar. In the unrestored situation, as the degree of bone resorption increased there was a corresponding increase in stress in the periodontium. Tilting of the molar abutment induced additional stress on the mesial side of the root. The presence of a fixed prosthesis markedly reduced the magnitude and distribution of stress in the periodontium. The mechanical advantage obtained by a fixed prosthesis was greater in the situation of a tilted second molar with reduced bone support than with higher bone levels. Int J Prosthodont 1991;4:416-424.

A mandibular molar abutment that has tilted mesially into the edentulous space is a common problem in fixed prosthodontics. Although the ideal abutment for a fixed prosthesis is an upright, sturdy tooth that is well supported by a healthy periodontium, such a situation is rare, and the dentist must decide whether the extent of the bone resorption and degree of abutment tilting is acceptable for a fixed retainer.

Some authors\(^1\)\(^2\) claim that the tilted molar abutment for a fixed prosthesis will induce an unusual strain in the periodontium and will eventually destroy the supporting tissues. However, Hood et al\(^3\) suggested that mesial tilting of less than 30° should not be a limiting factor for the molar abutment, since the stresses induced in the periodontium were markedly reduced following the placement of a fixed partial denture. Many textbooks\(^4\)-\(^6\) propose that a crown/root ratio of more than 1:1 should be avoided for abutments. Another study\(^7\) has shown that teeth with considerably reduced bone support can be successfully used as abutments for fixed prostheses. There are some arguments\(^8\)-\(^9\) regarding these theories on abutment selection. No clearly examined scientific guidelines have been presented for the selection of abutments with reduced alveolar bone level and/or severe inclination of one of the abutment teeth.

The purpose of this study was to analyze the stress levels in the supporting structures with increasing bone loss and abutment tilting and to ascertain how the addition of a fixed prosthesis modified these stresses and their distribution. A two-dimensional finite element method was used to determine the stresses in the prosthesis and surrounding structures as well as the displacement of the abutment teeth by forces of occlusion.

**Materials and Methods**

The finite element model was constructed of a mandibular posterior segment that included a canine, premolars, (first molar missing), second molar, and supporting structures. A standard intraoral radiograph was made of a periodontally healthy mandibular premolar-molar area using the paralleling technique. There was no bone resorption and no abutment tilting. The radiograph was used to trace the outlines of each of the components and to construct the standard model (OH). Three variations of the two-dimensional finite element models were made: two with upright abut-
Symbols for Finite Element Designs

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>OH</td>
<td>No restoration, high bone level (C/R ratio 1:1.5)</td>
</tr>
<tr>
<td>OL</td>
<td>No restoration, low bone level (C/R ratio 1:0.6)</td>
</tr>
<tr>
<td>OTL</td>
<td>Gold crown on second molar, tilting of second molar, low bone level</td>
</tr>
<tr>
<td>3H</td>
<td>Three-unit restoration, high bone level</td>
</tr>
<tr>
<td>3L</td>
<td>Three-unit restoration, low bone level</td>
</tr>
<tr>
<td>3TL</td>
<td>Three-unit restoration, tilting of second molar, low bone level</td>
</tr>
<tr>
<td>4H</td>
<td>Four-unit restoration, high bone level</td>
</tr>
<tr>
<td>4L</td>
<td>Four-unit restoration, low bone level</td>
</tr>
<tr>
<td>4TL</td>
<td>Four-unit restoration, tilting of second molar, low bone level</td>
</tr>
</tbody>
</table>

Mechanical Properties of Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Young's modulus (kg/cm²)</th>
<th>Poisson's ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enamel</td>
<td>$8.26 \times 10^6$</td>
<td>0.33</td>
</tr>
<tr>
<td>Dentin</td>
<td>$2.14 \times 10^6$</td>
<td>0.31</td>
</tr>
<tr>
<td>PDL</td>
<td>$7.03 \times 10^4$</td>
<td>0.45</td>
</tr>
<tr>
<td>Compact bone</td>
<td>$1.45 \times 10^3$</td>
<td>0.30</td>
</tr>
<tr>
<td>Cancellous bone</td>
<td>$2.15 \times 10^3$</td>
<td>0.30</td>
</tr>
<tr>
<td>Casting gold</td>
<td>$8.46 \times 10^3$</td>
<td>0.40</td>
</tr>
</tbody>
</table>

In all models, the lower border of the mandible was considered fixed and the mesial border was supported, allowing movement in the mesiodistal direction. A 1-kg unit occlusal force with a 15° mesial vector was applied on all of the fossae, marginal ridges, and cusps of the occlusal surface of each tooth (Fig 1). When a prosthesis was present, loading of its fossae and cusp tips was added to the total loading of the structures (compare Figs 15 and 16). Mechanical properties of the materials were taken from the previous literature (Fig 2 and Table 2). The amount of tooth mobility reported in the model after finite element analysis calculation was compared to the actual amount of mobility observed in the mouth. The elastic modulus for the periodontal ligament (PDL) was selected from several available to give model results that best correlated with this literature value. The elastic constant and Poisson’s ratio of the materials (Table 2) as well as the data concerning coordinates and geometry of each node and element were recorded in a personal computer. The basic finite element model (Fig 1) was composed of 413 elements and 476 nodes, which varied with bone level and restoration. The linear plane stress analysis program of Supersap version 9.01/387E (Algor Inc, Pittsburgh, Pa) was used to solve the two-dimensional static stress analysis problems. The calculated numeric data were transformed into color graphics to better visualize mechanical phenomena and a crown/root ratio for each tooth of either 1:1.5 or 1:0.6, and the other with upright premolars but with 35° of mesial tilt of the second molar and all teeth with a crown/root ratio of 1:0.6. Each of these three models was considered and analyzed with the following variations: (1) no restoration, (2) a three-unit fixed prosthesis, and (3) a four-unit fixed prosthesis. Additionally, a model of a gold crown on the tilted second molar (OTL) to restore the normal occlusal plane was analyzed. The designs and their symbols are given in Table 1.
Fixed Prosthodontic Approaches to the Tilted Molar Abutment

Yang/Thompson

Fig 3 (Left) Shear stress magnitude and associated color for Figs 4 through 12. (Units are kg/cm².)

Fig 4 (Right) Stress distribution with no restoration and ideal bone height (0H). Stresses are widely distributed in the cortical bone.

Fig 5 Stress distribution with no restoration and low bone level (0L). Stress concentration is observed in the periodontium around the root apex.

Fig 6 Stress distribution with low bone level, a gold crown, and tilting of second molar (0TL). Additional high stress is generated in the periodontium on the mesial side of the second molar.

nomena in the models. The maximum compressive stress, maximum tensile stress, and maximum shear stress in each element of the models were calculated and plotted.

To verify convergence of the finite element model, the number of elements was increased in the basic model (0H) and in the four-unit fixed prosthesis model with low bone level (0L). The number of elements was increased in the basic model (0L) to 3,042 (3,282 nodes) and to 3,078 elements (3,322 nodes) in the four-unit fixed prosthesis model (0L). The calculated results were almost identical to those shown below, indicating convergence for this model.

Results

The stress distribution patterns for each type of stress were similar. Maximum shear stress was selected for presentation, as it well represented the other stress patterns. Only plots of maximum shear stress are presented in this paper (Figs 3 through 12).

In the supporting structures, relatively high stresses were found in the cortical bone. As the height of alveolar bone around the freestanding teeth was reduced, the localized stress in the periodontium increased (Figs 4 and 5). There were some differences in the location and distribution of the localized stress concentration between the upright and tilted abutments. The freestanding, mesially tilted molar abutment induced additional stress on the mesial side of its root and in the associated periodontium (Fig 6).

All of the fixed partial dentures modified and reduced the stress in the periodontium, but high stress concentrations were observed within the metal structure, particularly in the connector areas.
Fig 7  Stress distribution with high bone level and a three-
unit restoration (3H). Stress is relieved in the periodontium 
but stress concentration is seen in the connectors of the fixed 
prosthesis.

Fig 8  Stress distribution with low bone level and three-unit 
prosthesis (3L). The fixed restoration markedly reduced the 
stress in the periodontium.

Fig 9  Stress distribution with low bone level, tilted second 
arch, and three-unit fixed restoration (3TL). The fixed rest-
oration not only reduces the stress level but also modifies 
the pattern of stress distribution. No stress concentration is 
found in the periodontium around the tilted molar.

Fig 10 Stress distribution with ideal bone height and four-
unit fixed prosthesis (4H). Splinting increases the stress in 
the gold restoration but decreases the stress in the sup-
porting structures.

Fig 11 Stress distribution with low bone level and four-unit 
prosthesis (4L). Stress level in the periodontium is reduced 
in both premolars by using a second abutment.

Fig 12 Stress distribution with low bone level, tilted molar, 
and four-unit fixed restoration (4TL). The fixed prosthesis 
fores the tilted abutment with reduced bone support. No 
stress concentration occurs in the periodontium around the 
abutments. (Compare to Fig 6.)
Table 3  Maximum Stresses in the Material of Each Design (kg/cm²)

<table>
<thead>
<tr>
<th>Stress</th>
<th>0H</th>
<th>0L</th>
<th>0TL</th>
<th>3H</th>
<th>3L</th>
<th>3TL</th>
<th>4H</th>
<th>4L</th>
<th>4TL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Compressive</td>
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<td>225</td>
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<td>177</td>
<td>195</td>
<td>113</td>
<td>112</td>
<td>125</td>
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<tr>
<td>Tensile</td>
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<td>157</td>
<td>197</td>
<td>94</td>
<td>152</td>
<td>160</td>
<td>63</td>
<td>79</td>
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<tr>
<td>Shear</td>
<td>64</td>
<td>112</td>
<td>113</td>
<td>73</td>
<td>89</td>
<td>97</td>
<td>56</td>
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<td>63</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>17</td>
<td>21</td>
<td>8</td>
<td>13</td>
<td>17</td>
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<tr>
<td>Tensile</td>
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<td>15</td>
<td>17</td>
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<td>12</td>
<td>12</td>
<td>2</td>
<td>7</td>
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<tr>
<td>Shear</td>
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<td>16</td>
<td>17</td>
<td>5</td>
<td>9</td>
<td>11</td>
<td>5</td>
<td>8</td>
<td>10</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
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<td>116</td>
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<td>165</td>
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<td>124</td>
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<td>149</td>
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<tr>
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<td>74</td>
<td>55</td>
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<td>78</td>
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<tr>
<td>Shear</td>
<td>33</td>
<td>58</td>
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<td>67</td>
<td>83</td>
<td>84</td>
<td>62</td>
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<td>156</td>
<td>148</td>
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<tr>
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<td>104</td>
<td>87</td>
<td>100</td>
<td>114</td>
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</table>

(Figs 7 through 12). To compare the magnitude of stress in each model, the peak stress for each material in each model was tabulated (Table 3). The maximum compressive stresses for the freestanding teeth in the normal (0H) and reduced bone models (0L) were 129 and 225 kg/cm² in the bone and 9 and 32 kg/cm² in the PDL, respectively. In the restored situation, the maximum compressive stresses for the four-unit fixed partial denture with reduced bone level (4L and 4TL) were 112 and 126 kg/cm² in the bone and 13 and 17 kg/cm² in the PDL, respectively. The maximum compressive stresses of the three-unit and four-unit fixed partial dentures in the high bone level group (3H and 4H) were 136 and 148 kg/cm² in the bone and 10 and 8 kg/cm² in the PDL, respectively.

To compare the mobility of an abutment tooth from model to model, the deflections were traced (Figs 13 through 16). The displacements were all magnified by a factor of 10 for ease of visualization. The greatest mobility of the second molar abutment was observed with tilting and no fixed partial denture (Fig 14). A marked reduction in mobility was observed in this abutment after placement of a fixed partial denture (Fig 16). The mesial and apical displacements in micrometers at the mesial cusp tip of the second molar and the cusp tip of the second premolar when subjected to the standard loading conditions are listed in Table 4.

The displacements of the freestanding molar abutment with normal bone level, low bone level, and tilted molar abutment (0H, 0L, and 0TL) were 87, 225, and 408 μm in the mesial direction and 64, 155, and 365 μm in the apical direction, respectively. The mesial displacement of the molar abutment after placement of a three-unit fixed partial denture with reduced bone level and upright molar abutment (Figs 13 through 16). The displacements were all magnified by a factor of 10 for ease of visualization. The greatest mobility of the second molar abutment was observed with tilting and no fixed partial denture (Fig 14). A marked reduction in mobility was observed in this abutment after placement of a fixed partial denture (Fig 16). The mesial and apical displacements in micrometers at the mesial cusp tip of the second molar and the cusp tip of the second premolar when subjected to the standard loading conditions are listed in Table 4.
Fixed Prosthodontic Approaches to the Tilted Molar Abutment

Table 4 Displacement of Mesial Cusp Tip in Each Design (µm)

<table>
<thead>
<tr>
<th>Design</th>
<th>Second molar</th>
<th>Second premolar</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mesial</td>
<td>Apical</td>
</tr>
<tr>
<td>OH</td>
<td>287</td>
<td>64</td>
</tr>
<tr>
<td>OL</td>
<td>255</td>
<td>155</td>
</tr>
<tr>
<td>OTL</td>
<td>408</td>
<td>365</td>
</tr>
<tr>
<td>3H</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>3L</td>
<td>55</td>
<td>43</td>
</tr>
<tr>
<td>3TL</td>
<td>75</td>
<td>55</td>
</tr>
<tr>
<td>4H</td>
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<td>30</td>
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<td>4L</td>
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<td>37</td>
</tr>
<tr>
<td>4TL</td>
<td>52</td>
<td>40</td>
</tr>
</tbody>
</table>

The finite element method of stress analysis is a mathematical engineering method of approximation that divides a structure into a finite number of elements whose mechanical behavior is specified by a finite number of parameters. If input data and assumptions in making a finite element model are appropriate, the output will be more accurate than is possible with other stress analysis methods. The finite element method has long been used in the field of biomechanics, and its validity in designing and analyzing prostheses has been established in dentistry.13

The stresses that occur in the periodontium are an important factor in regulating the remodeling process of the alveolar bone. It is a well-accepted theory that excessive compressive stress reduces the blood supply in the periodontal membrane, leading to bone resorption, while tensile stress leads to bone deposition.14 Although they were well distributed, high stresses in the cortical bone surrounding the abutment teeth were found in the model. The highest stresses for upright teeth occurred in the periodontium around the root apex, not at the crestal bone. The tilted molar induced an additional stress concentration in the periodontium around the alveolar crest on the mesial side of the mesial root. As the height of the alveolar bone decreased around the abutment without a fixed prosthesis, there was a corresponding increase in the magnitude of all stresses. The major differences between the tilted and upright abutment at the same bone height were the location and the distribution pattern of the stress concentration (Figs 4 through 6, Table 3).

The maximum compressive stresses for the four-unit prosthesis in the low bone level group (4L and 4TL) were 112 and 126 kg/cm² in the bone and 13 and 17 kg/cm² in the PDL, respectively. These values were similar to those calculated for the high bone level model without a fixed prosthesis. When comparing the stresses between the unrestored group and the four-unit fixed restoration, the mag-

![Fig 15](image1) Deflection with reduced bone level and tilting of the molar. The greatest mobility of the second molar is seen. (Magnitude of displacement × 10.)

![Fig 16](image2) Deflection after the placement of a fixed prosthesis on tilted abutment with reduced bone support. A marked reduction in the abutment mobility is seen compared to Fig 15. (Magnitude of displacement × 10.)
magnitude of compressive stress in the periodontium
was reduced approximately 50% by the placement
of a prosthesis in the low bone level model (4L and 4TL), while a 10% reduction was seen in the
high bone level model (4H) (Figs 10 through 12,
Table 3). A fixed prosthesis not only reduced the
stress level but also more uniformly distributed
stresses in the periodontium. This result complements
other stress analysis research on fixed prostheses.\textsuperscript{13,17} These results also support the clini-
cal report of Nyman and Ericsson,\textsuperscript{7} who ques-
tioned the validity of "Ante's law."\textsuperscript{16}

Note that when a prosthesis was present, a major
portion of the masticatory forces applied were dis-
tributed within the metal structures.

Relatively high principal stress ranging from 128
to 173 kg/cm\textsuperscript{2} was seen in the region of the con-
nectors (Figs 7 through 12). When a fixed prosth-
esis was present, the 1-kg load was applied to all
cusps, fossae, and marginal ridges of the pros-
thesis (note the vectors in Fig 16). This increased
the total force borne by the abutments, yet deforma-
tion in the prosthesis absorbed and distributed
the forces and reduced the overall stress level
within the periodontal structures in comparison to
the unrestored situation.

When a tilted abutment was present, stress con-
centration occurred within the gold alloy at the
occlusal half of the mesial surface of the molar
abutment and the connector area between the
pontic and the second premolar (Figs 9 and 12).
No stress concentration was observed in the peri-
dontium including the region of the alveolar
bone crest. This suggests that a molar abutment
with 35° of mesial tilting may not be detrimental
to the periodontium, as the magnitude of stresses
in the periodontium was reduced by approximately
50% after placement of a fixed prosthesis. Addi-
tionally, no stress concentration was observed on
the lateral side of the root. Although high stress
concentrations were found at the connector areas,
a fixed prosthesis markedly reduced the stress level
in the supporting periodontal structures in all sit-
uations. The mechanical advantage (reduction of
peak stress level in the periodontium and reduction
of tooth mobility) afforded by a fixed prosthesis
was greatest for the tilted molar with a reduced
bone level as compared to a normal bone level.

Nyman and Ericsson's long-term study\textsuperscript{7} of fixed
partial denture abutments with reduced bone sup-
port indicated that none of the patients exhibited
recurrent periodontal breakdown or occlusal over-
loading. Only 8% of the 332 restorations had failed
by the 5- to 8-year recall. All of recorded failures
were from either loss of retention of the retainer
to its abutment (3.3%), fracture of the fixed re-
stitution (2.1%), or fracture of abutment teeth
(2.4%).

Based on this stress analysis, the possible prob-
lems associated with a fixed restoration using the
tilted molar abutment with reduced bone support
would be (1) breakage of the prosthesis at the con-
ector area and (2) failure of cementing media at
the second molar as a consequence of the high
stress concentrations in those regions. Deteriora-
tion of the periodontium as a result of increased
occlusal loading seems unlikely.

Stress distribution patterns were similar in the
three-unit and four-unit fixed restorations. When
the first premolar was included as a second abut-
ment, lower stress was observed in each tooth and
periodontium around the premolars than before
splinting (Figs 7 through 12). Splinting of the pre-
molars increased the peak stress level in the inter-
nal structure of the fixed prosthesis but decreased
the stresses in the abutment teeth, PDL, and sup-
porting bone (Table 3).

The mesial and apical displacement of the teeth
increased with increasing bone resorption and
abutment tilting, and it decreased after placement
of a fixed prosthesis (Fig 13 through 16). The four-
unit prosthesis exhibited slightly less displacement
than the three-unit prosthesis (Table 4). At the
same bone level but without a fixed restoration,
the tilted molar exhibited greater mobility than the
upright molar. This implies that the PDL supports
the load more efficiently when the force is applied
along the long axis of the root. The tilted second
molar without a prosthesis exhibited the greatest
mobility when occlusal force was applied. This ver-
tical displacement of the tilted second molar sup-
porting the three-unit prosthesis was less than that
calculated in the presence of a normal bone level
without a restoration.

Limitations of the Study

To construct a finite element model, it is usually
necessary to simplify the system by making several
assumptions. The assumption required for analysis
of stress distribution by using a two-dimensional
finite element method was that the stresses in a
buccolingual direction were negligible and stress
components in any direction were independent of
the buccolingual dimension. In this regard, the
above analysis is a first approximation and the
result should be interpreted as qualitative. In addi-
tion, although biological materials such as dentin,
PDL, and bone are anisotropic and inhomoge-
neous, and usually exhibit nonlinear stress-strain
relationships, the materials involved were idealized as homogeneous, isotropic, and linearly elastic. The lack of good characterization data on biological materials limits the accuracy of these results. Particularly, the physical properties for the PDL available in the literature exhibit a large variation. The PDL has viscoelastic properties and tooth mobility varies considerably with the individual. The mechanical behavior of PDL changes nonlinearly depending on the magnitude and duration of the load applied. Also, the PDL has different properties in compression than in tension, and these are not well described in the available literature. As was recently noted, progress in finite element analysis will be limited until better defined physical properties for enamel, dentin, the PDL, and cancellous and cortical bone are available. We are not in a position to verify the model developed other than to note clinical data supporting these results.

Although these two-dimensional models of dental structures were not an exact representation of the clinical situation, the results obtained may have significant clinical implications. The better distribution of the occlusal forces achieved with the fixed prosthesis compared to the freestanding teeth is noteworthy. Even in the extreme event of a crown/root ratio of 1:0.6 and 35° molar abutment tilting, a fixed prosthesis markedly reduced the amount of abutment displacement and the stress level in the periodontium by splinting the isolated abutment teeth. The fixed prosthesis appeared to have a functionally favorable effect on the abutment teeth and supporting structures.

Based on the above analysis, it would appear that a fixed prosthesis can be a successful restoration with a tilted molar abutment tooth having severely reduced bone support. It must be assumed that in such a situation the periodontium is healthy, long-term maintenance has been assured, and connector areas are of adequate depth.

It is clear that a three-dimensional model would yield more accurate stress values and distributions, and further study is needed in this area. Only clinical trials can ultimately confirm the predictions made from the finite element analysis presented here.

Conclusions

Based on a two-dimensional finite element analysis, the following conclusions are made:

1. Reduction of alveolar bone support around freestanding teeth caused a corresponding stress concentration in the periodontium.
2. The freestanding tilted molar induced additional stress on the mesial side of the roots and in the local periodontium.
3. A fixed restoration reduced and modified the stresses in the periodontium by distributing the major portion of occlusal force within the metal structure.
4. The greatest improvement in stress reduction and distribution in the periodontium and a concomitant marked reduction of tooth mobility were achieved by the fixed prosthesis on the tilted molar abutment with reduced bone support.
5. Multiple abutments more uniformly distributed the stresses than the single abutment and reduced the amount of cusp displacement.

References

The Effect of Some Chlorhexidine-Containing Mouthrinses on Salivary Bacterial Counts

This study evaluated the effect of four chlorhexidine mouthwash formulations on salivary bacterial counts after a single rinse. Ten healthy young adult volunteers rinsed with the 0.2%, 0.12%, and two 0.1% formulations (all except for one of the two 0.1% formulations commercially available) according to manufacturers' instructions. The 0.2%, 0.12%, and commercially unavailable 0.1% formulations produced similar large and prolonged reductions in salivary bacterial counts during a 7-hour period. The commercially available 0.1% formulation produced minimal effects on salivary bacterial counts not much different than the saline rinse control. The results were consistent with comparative plaque inhibitory studies of the formulations and suggest that the described method is a quick and simple way of screening products for antimicrobial and antiplaque potential.