Introduction: The purpose of this study was to analyze photoelastically the stress distribution around teeth in the simulated distal movement of mandibular molars with the skeletal anchorage system. Methods: Two types of the photoelastic mandibular dentition models were used, 1 before and 1 after distal movement of the second molar. The experiment was performed with 3 forms of traction—first-molar single traction, second-molar single traction, and simultaneous first- and second-molar traction. The direction of traction was set parallel to the occlusal plane and at an angle of 30° downward to the occlusal plane. Results: In the first-molar single traction model, extremely high stress was generated around the first molar with traction parallel to the occlusal plane. With the traction 30° downward to the occlusal plane, all models showed the stress around the molars extended distally and downward. Conclusions: Simultaneous traction of the first and second molars might be preferable to the sequential traction of each molar to prevent the unfavorable distal tipping of the first molar. Regardless of whether simultaneous or sequential traction is used, the downward traction to the occlusal plane seems to induce intrusion of the molars as well as their distal movement. (Am J Orthod Dentofacial Orthop 2007;132:624-9)

The distal movement of mandibular molars is often required to reduce mandibular anterior crowding and to retract protruded anterior teeth without extracting premolars. Several orthodontic appliances have been used to move the mandibular molars distally, including headgear,1,2 the lip bumper,3,4 the Jones jig,5 and the Franzulum appliance.6 However, effectiveness of these appliances can be compromised by limited patient cooperation or reciprocal forces that cause inappropriate anchor-tooth movement.

Recently, Sugawara7,8 and Daimaru et al9,10 developed the skeletal anchorage system (SAS) that uses pure titanium anchor plates and screws as orthodontic anchorage units. The SAS permits rigid anchorage via osseointegration of both anchor plates and screws. Clinical reports described the distal movement of the mandibular molars with anchor plates placed at the anterior border of the mandibular ramus or the mandibular body.11-16 Prefferable ages for SAS treatment were not indicated. However, the SAS is used mostly for adult patients because osseointegrated implants can inhibit surrounding bone growth in children.17,18 For mandibular molar distalization, extraction of the third molars is frequently required to create sufficient space behind the second molar.15

Although the SAS is becoming popular in orthodontic practices, few published studies have focused on distal movement of the mandibular molars in SAS treatment.15,16 Furthermore, no biomechanical studies have demonstrated the stresses produced in the periodontal tissues around teeth from SAS use. The purpose of this study was to photoelastically analyze the initial stress distribution around the teeth in the simulated distal movement of mandibular molars with the SAS to increase our understanding of its likely effects in the clinical setting.

MATERIAL AND METHODS

Two photoelastic models of a mandibular dentition were used in this study, 1 simulating the position of the second molar before its distal movement, and the other simulating its position after distal movement. The photoelastic models was fabricated as follows. First, a
A plaster model of a mandible with dentition (P10-SB.1; Nissin, Kyoto, Japan) was created by using a silicon impression (Duplicone; Shofu, Kyoto, Japan). The plaster models were then set up to simulate the postleveling stage with no crowding, spacing, or flattening of the curve of Spee. In 1 model, the second molar was positioned distally to simulate its completed distal movement. An impression was then taken by using silicon impression material, and anatomic models of the mandibular teeth (B2-306; Nissin) were adapted to the impression surface. Finally, urethane (Soli-thane C113-300; Thiokol Chemical Corporation, Trenton, NJ) was infused into the impression with the model teeth. The fabricated photoelastic models were divided on the left side in the sagittal plane to permit stress evaluation. The models were fixed on an acrylic plate, and it was confirmed that no initial stress had been induced. The physical properties of each component material of the model are shown in the Table.

**Table.** Physical properties of each component material of the model

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ (MPa)</th>
<th>$v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tooth Epoxy resin</td>
<td>2,930</td>
<td>0.36</td>
</tr>
<tr>
<td>Surrounding tissue</td>
<td>Urethane (solithane)</td>
<td>6.9</td>
</tr>
</tbody>
</table>

$E$: Young’s modulus; $v$: Poisson’s ratio.

![Fig 1. Two photoelastic mandibular dentition models: a, before distal movement of second molar, and b, after distal movement.](image1)

plaster model of a mandible with dentition (P10-SB.1; Nissin, Kyoto, Japan) was created by using a silicon impression (Duplicone; Shofu, Kyoto, Japan). The plaster models were then set up to simulate the postleveling stage with no crowding, spacing, or flattening of the curve of Spee. In 1 model, the second molar was positioned distally to simulate its completed distal movement. An impression was then taken by using silicon impression material, and anatomic models of the mandibular teeth (B2-306; Nissin) were adapted to the impression surface. Finally, urethane (Soli-thane C113-300; Thiokol Chemical Corporation, Trenton, NJ) was infused into the impression with the model teeth. The fabricated photoelastic models were divided on the left side in the sagittal plane to permit stress evaluation. The models were fixed on an acrylic plate, and it was confirmed that no initial stress had been induced. The physical properties of each component material of the model are shown in the Table.

Figure 1 shows the 2 photoelastic mandibular dentition models, 1 before and 1 after distal movement of the second molar. A preformed $0.019 \times 0.025$-in stainless steel archwire was adapted to the mandibular dentition model, and $0.022 \times 0.028$-in preadjusted edgewise brackets were fixed to each archwire with elastic modules. The brackets were then bonded to the model teeth with light-curing adhesive. The distal ends of the archwire were adjusted to be less than 1 mm behind the molar tube.

A bar was fixed behind the model to vary the direction of the distalizing forces. The force was applied to a tooth through a coil spring, by using an elastic chain extending from the bar (Fig 2). The experiment was performed with 3 forms of traction—first-molar single traction, second-molar single traction, and simultaneous first-and-second molar traction. First-molar single traction was performed on the model, simulating the second molar position after its distal movement. The other tractions simulated the second molar position before its distal movement. The direction of traction was set parallel to the occlusal plane and at an angle of $30^\circ$ downward to the occlusal plane (Fig 3). A force of 250 g was selected because this is similar to that used in a clinical situation for single molar traction, and it provided a suitable response in the model without causing undue deformation.

In this study, a quasi 3-dimensional technique was used for the photoelastic observations. Figure 4 shows the circular polariscope arrangement used to observe isochromatic fringes. In an area of stress, the fringe appears as a repeated pattern of yellow, blue, and red. A cycle from yellow to red is called 1-fringe order, and it is used as an index to judge the level of stress. The isochromatic fringes occur 3-dimensionally in response to the intensity of the internal stress generated in the model. When the overall isochromatic fringe pattern is considered, interpretation is based on the following principles: (1) the more fringes, the higher the stress intensity; and (2) the closer the isochromatic fringes are to each other, the higher the stress concentration. To observe isochromatic fringes easily by preventing light reflection and refraction, the model was soaked in a mineral oil with a refractive index equal to that of the model material.

**RESULTS**

In the photoelastic analysis of the first-and-second molar simultaneous traction model (Fig 5), when the force was applied parallel to the occlusal plane, stress was generated along the mesial and distal root surfaces of the first and second molars. In the second molar, the stress was distributed along the entire root surface, whereas, in the first molar, the stress was concentrated on the cervical half of the mesial root surface and along the apical half of the distal root surface (Fig 5, a).

With the traction $30^\circ$ downward to the occlusal plane, the stress was generated along the distal root surface of the first and second molars, and extended distally and downward (Fig 5, b).
In the photoelastic analysis of the second-molar single traction model (Fig 6), with traction parallel to the occlusal plane, the stress was generated along the entire distal root surface of the second molar and extended distally with the intensity of 2-fringe order (Fig 6, a).

With the traction 30° downward to the occlusal plane, the stress was generated around the apex and along the distal surface of the distal root of the second molar and extended distally and downward (Fig 6, b).

In the photoelastic analysis of the first-molar single traction model (Fig 7), with traction parallel to the occlusal plane, extremely high stress was concentrated on the middle part of the mesial root surface of the first molar with the intensity of a 3-fringe order. Stress of a 2-fringe order was observed along the apical half of the distal root surface of the first molar (Fig 7, a).

With the traction 30° downward to the occlusal plane, the stress was less on the mesial root surface of the first molar compared with when traction was applied parallel to the occlusal plane. High stress was generated around the apex of the first molar and extended distally and downward (Fig 7, b).

**DISCUSSION**

Photoelastic stress analysis allows visualization of internal stresses with colored patterns. In this study, we used the quasi 3-dimensional photoelastic technique devised by Caputo and Standlee. This technique has the advantages of using models with good geometric fidelity and of being able to apply multiple complex force systems to the models. Moreover, the models can be used repeatedly because they are not destroyed when obtaining the photoelastic data. With this technique, some studies showed stress distributions in the craniofacial complex or the periodontal tissues induced by orthodontic forces.

Using the photoelasticity modeling concept, Caputo and Standlee demonstrated that it is impossible to model all mechanical properties of a structural element;
they proposed that a decision must be made about which properties are most pertinent to the clinical question at hand. In the photoelastic model used in this study, the periodontal membrane and the alveolar bone were not assembled separately, and the entire periodontal structure was made from urethane with a low elastic modulus and a high optical sensitivity, so that the internal stress induced by several hundred grams of orthodontic force would be easily detectable.

The anchor plate was not assembled directly in the model to avoid undue deformation of the model and disturbance of the stress generated around the plate that could influence stress distribution around the teeth.

In the first-and-second molar simultaneous traction and the first-molar single traction models, the stress around the first molar appeared to induce distal tipping when the force was applied parallel to the occlusal plane. The intensity and the concentration of the stress around the first molar were both higher in the first-molar single traction model than in the 2-molar simultaneous traction model, supposedly because of lack of contact with the second molar in the single traction model. When the force was applied at an angle of 30° downward to the occlusal plane in both models, the stress appeared to induce intrusion of the molars as well as their distal movement; the horizontal component of the force appeared to move the molars distally, whereas the vertical component acted to intrude them via archwires. The 30° downward traction reduced the distal tipping effects of the force, and this might be in part the result of the downward deflection of archwires occurring at the mesial side of the first molars; this acts to resist their distal tipping.

In the second-molar single traction model, the stress appeared to induce bodily movement when the force was applied parallel to the occlusal plane. A similar stress distribution was found around the second molar as in the first-and-second molar simultaneous traction model. In both models, the distal tipping of the second molar appeared to be prevented by the posterior part of an archwire, which was not easily deflected because of its short length. The 30° downward traction in the

![Fig 5. First- and second-molar simultaneous traction model: a, parallel; b, 30° downward.](image)

![Fig 6. Second-molar single traction model: a, parallel; b, 30° downward.](image)

![Fig 7. First-molar single traction model: a, parallel; b, 30° downward.](image)
second-molar single traction model appeared to show stress distribution with an intrusive effect resulting from the downward component of the traction force.

For the distal movement of the mandibular molar with the SAS, there are 2 kinds of procedures: first-and-second molar simultaneous traction and sequential traction when the first molar is moved distally after the second molar has been moved. The stress analysis in this study suggested that, irrespective of the traction direction, there are no differences in tooth movement between simultaneous and sequential traction of each tooth, except for the distal tipping of the first molar. Based on these results, the first molar appears to be susceptible to distal inclination during single traction. To prevent this, the simultaneous traction of the first and second molars might be preferable.

The force direction from the anchor plate is subject to some restriction because traction hooks of the plate must be positioned to avoid contact with the maxillary teeth and the gingivae as well as the archwires, and to prevent injury to the cheek or the gingivae. Thus, the traction direction for distal movement of the mandibular molar is likely to be downward to the occlusal plane, exerting some intrusive force on the molars. This seems to be advantageous in the treatment of skeletal Class III open-bite patients requiring distal movement and intrusion of the mandibular molars. However, in the treatment of skeletal Class III deepbite patients, we must consider the intrusive forces generated from the downward traction to the occlusal plane. In such cases, the parallel traction applied to the occlusal plane must be attempted by adjusting the position and the figure of the anchor plate hooks or the sliding hooks on the archwire.

**CONCLUSIONS**

Quasi 3-dimensional photoelastic stress analysis was performed for the simulated distal movement of the mandibular molar with the SAS. First- and second-molar simultaneous traction might be preferable to the sequential traction of each molar to prevent the unfavorable distal tipping of the first molar. Regardless of whether simultaneous or sequential traction is used, downward traction to the occlusal plane seems to induce intrusion of the molars and their distal movement.

**REFERENCES**
