Initial tooth movement under extraoral force and considerations for controlled molar movement

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When distal molar movement is required, headgear is a very efficient appliance. Its reciprocal force is not transmitted to other teeth, and it can be used at earlier stages of the mixed dentition. However, molar movement can vary considerably according to the various loading conditions of the headgear. For example, molar movements depend on the direction of force in relation to the center of resistance of the molar and the magnitude of force.

Since control of the molar is of the utmost importance in orthodontic treatment, an understanding of the relationship between various force vectors and resultant molar movements produced by each type of headgear is clinically essential. Although many studies on the effect of headgear therapy have been carried out, most of them were in-vitro experiments,[1] mathematical approaches,[2-5] or computer simulations.[6] There are few studies of how molars move in vivo under the application of headgear forces.[7,8]

Previous studies had a number of disadvantages due to certain assumptions which were made. For example, flexibility of the facebow was not taken into consideration in statical or mathematical approaches. That is, the facebow was assumed to be a rigid body and the molar movements were analyzed without respect to deflection of the facebow under an increase in the magnitude of force.[2-5] Lindgren and Lagerström[9] reported that elastic deformation of the facebow generates different effects with increasing forces.

The purpose of the present study was to analyze the influence of changes in the direction of headgear traction in relation to the maxillary first molars accompanied by increasing force lev-

Abstract
Initial movement of the maxillary first molars under the application of straight-pull, cervical-pull, and high-pull headgear was measured in human subjects.
Facebow deflection can influence molar movement as the relationship of the force vector to the molar's center of resistance changes with an increase of force. The present study proposes using headgear with a combination of variable-pull headcap and short outer bow. A variable-pull headcap allows a great range in force direction. The direction of the headgear force system can be accurately determined using a short outer bow.

Key Words
Headgear • Tooth movement • Magnetic sensor • Extraoral traction • Face bow

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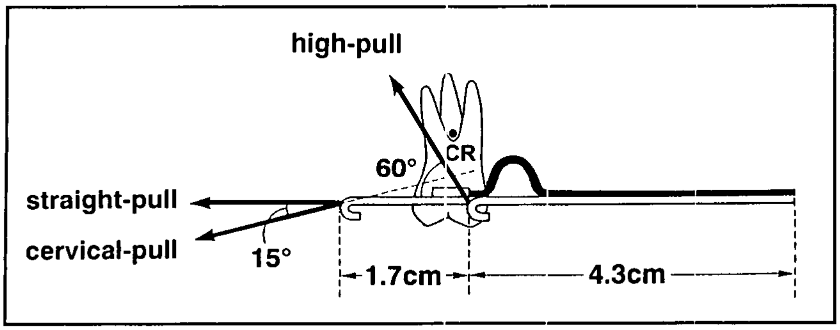

Figure 1

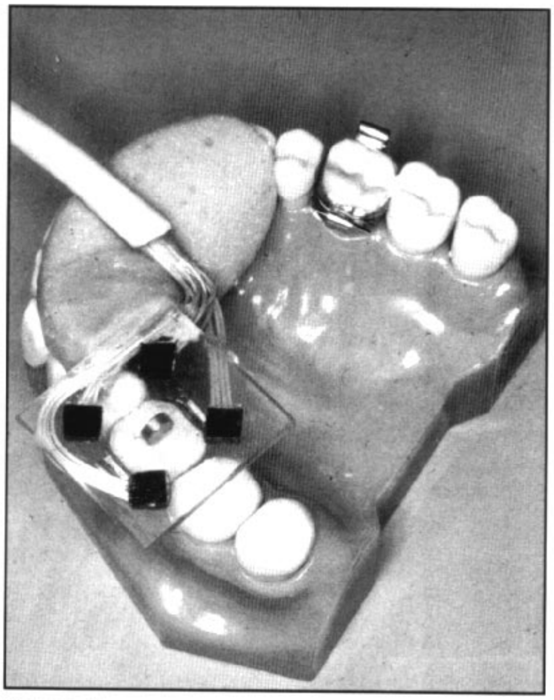

Figure 2

Figure 1
The attachment of the high-pull loading is a point corresponding to the anterior end of buccal tubes; that of both straight-pull and cervical-pull loading is the end of the outer bow whose length is 1.7cm longer than the short outer bow used with high-pull loading. The center of resistance of a periodontally healthy molar is indicated by a letter CR. Its approximate location is 1-2 mm apical to the trifurcation.[11]

Figure 2
The measuring unit is mounted on a model. The magnet is bonded to the center of the occlusal surface of the molar. The plastic sheet with four magnetic sensors is positioned parallel to the occlusal plane and fixed to the anterior teeth by a resin splint.

els on initial molar movement in human subjects. Optimal headgear application and adjustment will be discussed.

Materials and methods

Subjects consisted of three university students, 23 to 27 years of age, who had normal occlusion and were not undergoing orthodontic treatment. Subjects A and B had normal periodontal conditions while subject C showed slight interdental bone loss visible on radiographs and increased tooth mobility (Miller´s abnormal Class 2).[10]

Buccal tubes were attached to the molars directly with 4-META resin (Super-Bond, Sun medical Co., Kyoto, Japan).

The load was applied in three directions, straight-pull, cervical-pull and high-pull through a facebow with U-shaped loops at the end of the inner bow (Figure 1). With high-pull headgear, the load was applied 60° upward to the occlusal plane at a point corresponding to the anterior end of buccal tubes. With straight and cervical-pull headgear, the load was applied in a respective parallel direction 15° below the occlusal plane using an outer bow that was 1.7 cm longer than the short outer bow employed with the high-pull headgear. Loads of 0, 0.25, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, and 5N were manually exerted on the maxillary first molars for 5 seconds each by pulling both sides of the outer bow hooks with two tension gauges (YS-31, Yamaura Inc., Tokyo, Japan), graduated in 0.25 N increments.

Since tooth mobility varies over daytime,[12,13] each measurement was started at the same time of the day to improve the reproducibility of the experimental data.

A two-dimensional measurement system for molar displacement had been designed and tested previously.[14,15] The main part of this system consists of four magnetic sensors (DM-209, Sony Co., Tokyo, Japan) and a samarium cobalt magnet (Hicorex H-30CH, Hitachi Metals Ltd., Tokyo, Japan).

The four magnetic sensors were arranged at the corners of a rectangle on a plastic sheet (Figure 2). They were then fixed with dental cement to the maxillary anterior teeth by a resin splint so that they could not move. The plastic sheet was positioned parallel to the occlusal plane in order to measure displacement of the molar crown in that plane. The magnet was bonded to the center of the occlusal surface of the molar which was the movable target loaded with the various types of headgears. The molar and magnet could then move freely relative to the four sensors. Thus, movements of the molar were detected by sensors.

The measurement system was calibrated extraorally. A plastic sheet with four sensors was set on a rigid table. A samarium cobalt magnet was fixed to a micromanipulator and positioned in the center of four sensors. The displacement of the magnet was measured by a set of two digital microgauges (LF20, Sony Magnescale Inc., Tokyo, Japan) while the magnet was moved in a 500 μm square in 25 μm steps in the given plane.

When the measuring unit was applied to the oral cavity, the magnet and sensors were set at the same relative position as determined during extraoral calibration. This procedure was carried out as follows. At first the magnet was temporarily attached to the plastic sheet at the center of the calibrated square using sticky wax. The plastic sheet with the magnet was fixed in the oral cavity of the subject. The magnet was then firmly attached to the target tooth with 4-META

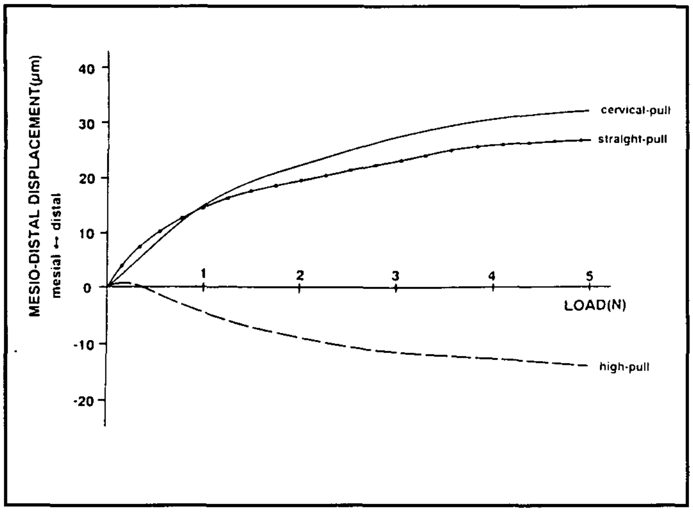

Figure 3A

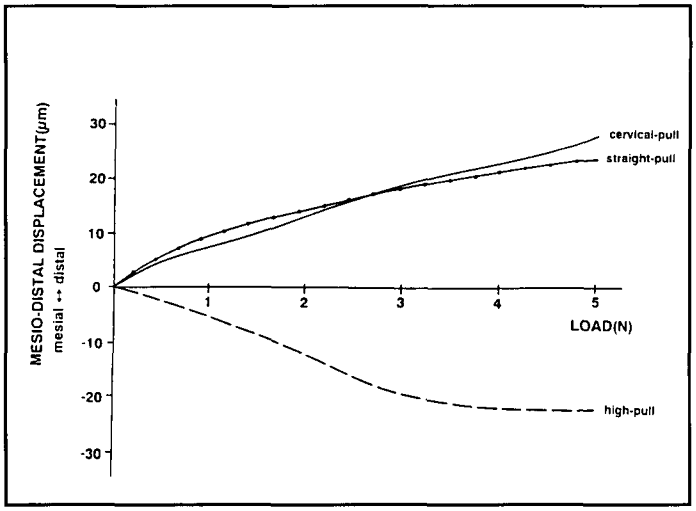

Figure 3B

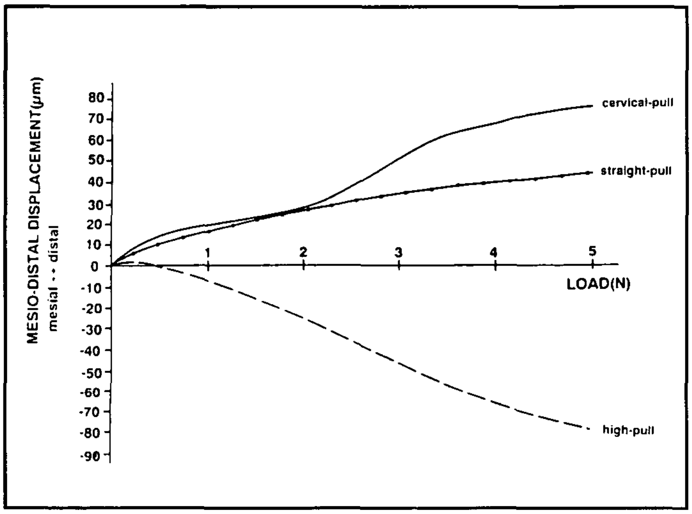

Figure 3C

Table 1
Displacement in mesiodistal direction under load of 5 N (µm)

Loading	Subject A	Subject B	Subject C
Straight-pull	+27	+24	+43
Cervical-pull	+32	+28	+77
High-pull	-14	-22	-80

(+) distal
(-) mesial

resin (Super-Bond). Finally, the sticky wax was removed so that the magnet was free from the plastic sheet.

In a previous study,[8] the initial displacement of the maxillary first molars was measured in two dimensions under the application of a headgear in three planes, i.e. sagittal, frontal and horizontal planes, respectively, and analyzed both the rectilinear and rotational displacements that took place at the approximate point of the center of resistance of the molar. This time crown movements were analyzed so that the space-gaining effect of various headgear types at crown level could be detected.

Results

Mesiodistal displacement

The crowns of the molars moved distally with straight-pull and cervical-pull loading (Figure 3A-C).

When straight-pull loading was applied to the molars, load-displacement curves had approxi-

Figure 3A-C
A: Load-displacement curve in the mesiodistal direction for the right molar of subject A. The crown of the molar moved distally with straight-pull and cervical-pull loading, and the relationship of displacement to load was logarithmic. Cervical-pull loading exceeded straight-pull loading in the amount of distal displacement at a load of 1 N. With high-pull loading, the crown changed its direction of displacement from distal to mesial at a load of 0.25 N.

B: Load-displacement curve in the mesiodistal direction for the right molar of subject B. Cervical-pull loading exceeded straight-pull loading in the amount of distal displacement at a load of 2.5 N. With high-pull loading, the crown displaced mesially irrespective of force level.

C: Load-displacement curve in the mesiodistal direction for the right molar of subject C. The amount of distal displacement with cervical-pull loading is larger than that with straight-pull loading irrespective of force level. With high-pull loading, the crown turned its direction of displacement from distal to mesial at a load of 0.25 N as was observed for subject A (Fig.3A).

Table 2
Displacement in buccolingual direction under load of 5 N (μm)

Loading	Subject A	B	C
Straight-pull	36	25	89
Cervical-pull	26	14	55
High-pull	43	58	272

All values are in the buccal direction.

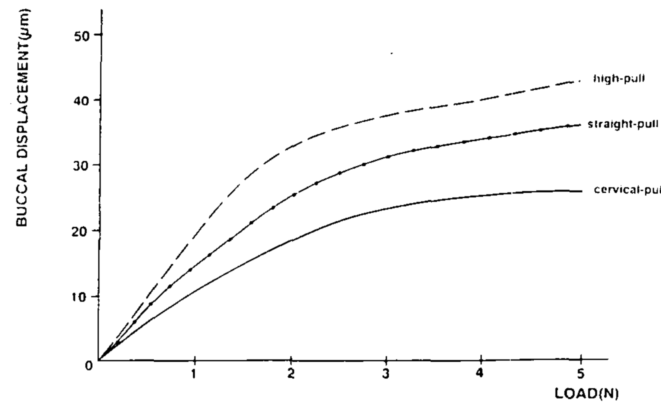

Figure 4

Figure 4
Load-displacement curve in the buccolingual direction for the right molar of subject A. The crown displaced buccally with each loading and each load-displacement curve was logarithmic. The largest amount of buccal displacement was found with high-pull loading followed by straight-pull loading, and the smallest displacement was observed with cervical-pull loading.

mately the same tendency among all subjects. The relationship of displacement to load was logarithmic, namely, big effects with small force increments at low load levels and rather small effects at high load levels on the amount of molar movement.

With cervical-pull loading, load-displacement curves differed among the various subjects. When a small load, up to 1 N, was exerted on the molars of subject A, the crowns of the molars displaced less distally than with straight-pull loading (Figure 3A). With loads of more than 1 N the amount of distal displacement exceeded straight-pull loading. This change was found to also apply to subject B with more than 2.5 N load (Figure 3B). The load-displacement curve of subject C was sigmoid rather than logarithmic with rapid distal displacement within the range of 2 to 3 N load (Figure 3C).

Distal displacement at the maximum load of 5 N with straight-pull loading was smaller than cervical-pull loading for each subject (Table 1).

Application of high-pull loading resulted in a slight distal displacement in the range of 0 to 0.25 N load for subjects A and C. However, when the load exceeded 0.25 N, the crown turned its direction of displacement from distal to mesial (Figure 3A and C). The crown of subject B showed mesial displacement irrespective of force level (Figure 3B).

Buccolingual displacement

There was almost the same tendency among load-displacement curves in the buccolingual direction of subjects A, B and C. A load-displacement curve of subject A is shown in Figure 4. The crown moved buccally with each type of headgear loading, and its displacement followed an almost logarithmic increase with load.

With the maximum load of 5 N, the largest amount of buccal displacement was observed with high-pull loading (43 μm for subject A, 58 μm for subject B, and 272 μm for subject C) followed by straight-pull loading (36 μm for subject A, 25 μm for subject B, and 89 μm for subject C) and cervical-pull loading causing the smallest buccal crown movement (26 μm for subject A, 14 μm for subject B, and 55 μm for subject C [Table 2]).

The displacement that occurred in subject C was evident when compared with other subjects in each loading.

Discussion

Evaluation of the measurement system

When the system was calibrated extraorally, 1.5 μm of resolution was determined. The distortion of the system was found to be less than 6% in a square of 200 μm and 10% in a square of 400 μm. Resolution and accuracy were thought to be high enough to measure molar displacement in comparison to other studies on tooth mobility measurement.[16,17]

Before intraoral measurement, the magnetic sensors were insulated by epoxy resin in order to eliminate the influence of the oral environment with high humidity and temperature. As a result, fluctuation of only 2 to 3 μm was observed. This proved that this system had enough stability for use in the oral cavity.

Each in vivo measurement was repeated twice on two different days. In total, four measurements were made and averaged. Each mean absolute deviation of measured value was within 10% of the average, and the reproducibility was thought to be sufficient.

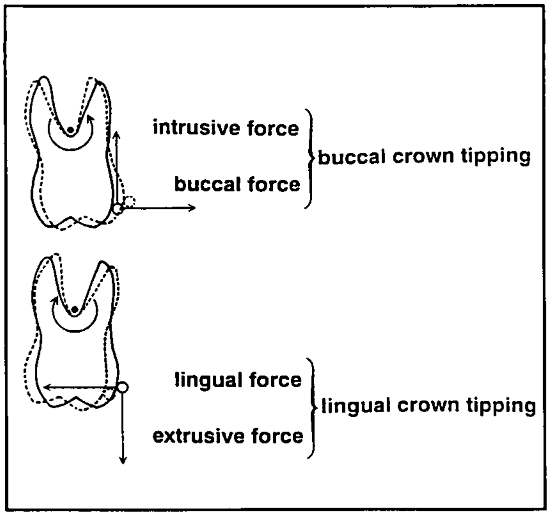

Figure 5

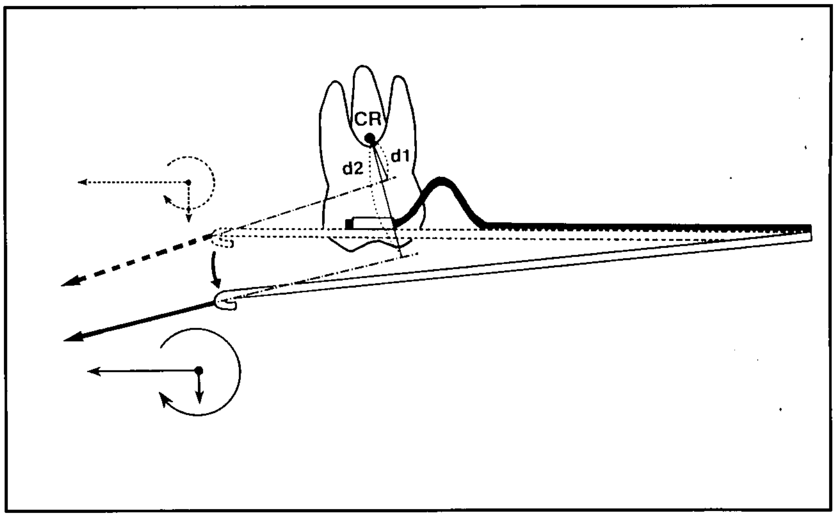

Figure 6

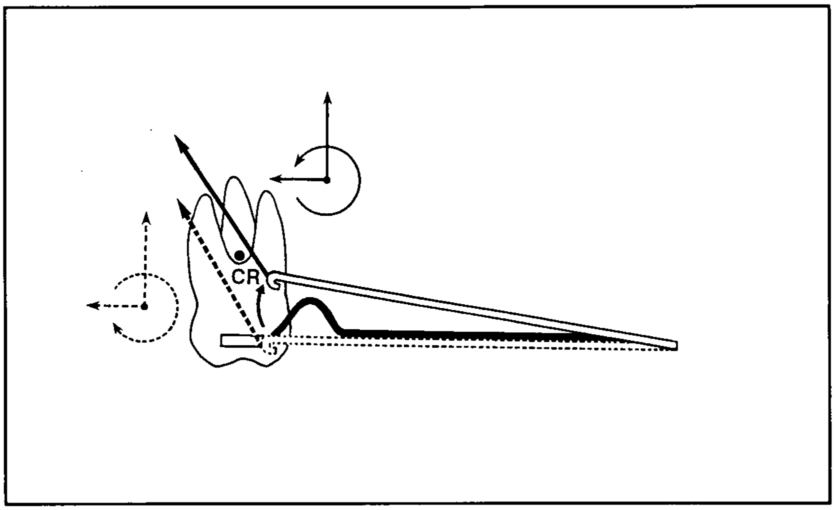

Figure 7

Considerations for methodology

Initial tooth displacement measured in the present experiment is from physical distortion of the periodontium, and is thereby momentary and reversible. On the other hand, orthodontic tooth movement is observed as a result of histologic changes of periodontal tissues adjacent to a tooth. Therefore, it is necessary to draw a distinction between the initial tooth displacement and tooth movement after going through a long-term process of bone remodeling.

Many histologic and biomechanical studies have been performed to clarify biological mechanisms of tooth movement.[18] These studies have shown that (1) orthodontic force initiates bone remodeling sequences, and (2) compressive and tensile forces induce resorption and apposition of the alveolar bone, respectively.

Tanne, Shibaguchi, Terada, Kato and Sakuda[19] have investigated the association between stresses and bone remodeling in living dogs. Their results indicated that the nature of principal stress distributions induced in the periodontal ligament(PDL) was highly coincidental with histologic findings of site-specific tension and compression of the PDL and alveolar bone remodeling. This study emphasized the relationship between principal stresses in the PDL and bone remodeling, and hence, its subsequent tooth movement. Other studies[20,21] have proven that the value and direction of the principal stress in the periodontal membrane are key determinants of tooth movement.

Since distortion of the PDL in the initial phase of tooth movement reflects the stress distributions in the PDL, initial changes may be an indication of expected tooth movement. Physical distortion of the periodontium, after application

Figure 5
The intrusive and/or buccal force cause the crown to tip buccally. The extrusive force and/or lingual force cause the crown to tip lingually.

Figure 6
With increased force, in the case of a cervical-pull headgear, the outer bows are pulled downward (from a broken line to a solid line), which increases the perpendicular distance (from d1 to d2) of the line of force from the center of resistance of the molar (CR). The combination of straight and curved arrows indicates an equivalent force system at CR. The force vector is divided into horizontal and vertical components. The horizontal component of the force is parallel to the occlusal plane. Figures 7-9 are in the same manner.

Figure 7
When a light force is applied to the molar with a high-pull headgear, the line of force passes below the center of resistance of the molar (broken line), and above the center of resistance (CR) with a heavy force (solid line).

Figure 8
When a short outer bow is used with a high-pull headgear, there are two ways to achieve effective distal molar movement. The first is to select the outer bow whose length is extended to the distal end of buccal tubes (Type B). If the outer bow is shorter than Type B, an alternative is to bend the outer bow 5-10° downward (Type C). These procedures cause the line of force to pass below the center of resistance (CR) even after the outer bow is deflected under application of force and avoid mesial crown tipping.

of orthodontic force, is an initial condition which follows on a histologic course of future tooth movement.

Because it is impossible to measure internal stresses in the PDL in vivo, the present experimental system is significant and its results can be directly applied in orthodontic practice. These experimental findings would be more practical if they could be compared with clinical results.

Inoue[22] has reported on the biomechanical property of periodontal tissue changes in the course of orthodontic tooth movement and its effects on tooth trajectories. The present study is based on the assumption that these characteristics of the periodontium and the initial force system is constant throughout tooth movement.

Further study is necessary to elucidate the quantitative relationship between the initial mechanical conditions and the ultimate tooth movement through bone remodeling. That is, long-term histological study should be integrated with biomechanical study in the future.

Molar displacement

All experimental values of subject C were much larger than those of other subjects. This indicates that the molar with periodontal disease can be tipped substantially since the center of resistance moves apically due to bone loss, thereby increasing the length of the tipping cantilever.

Straight-pull headgear

Due to the line of force passing somewhat below the center of resistance of the molar with straight-pull loading (Figure 1), a distal tipping moment was produced. As a result, distal tipping occurred in addition to distal translation. This situation was found in a previous study.[8] Accordingly, a relatively large amount of distal crown displacement took place (Figure 3A-C).

Buccal crown displacement was present in the buccolingual direction (Figure 4). This result was unexpected because there was no vertical component of the load that caused buccolingual crown tipping and thereby buccolingual displacement of the crown. We presumed that a buccal force was produced and, consequently, the molar tipped buccally as shown in Figure 5. Baldini, Haack and Weinstein[23] have also proven theoretically and experimentally that a buccal force to the molar is produced by extraoral traction using a conventional symmetrical facebow.

Initially, buccal forces may act on the molar with cervical-pull and also high-pull headgear. Expansion of the inner bow, done intentionally to keep normal buccal overjet of molars, adds to the buccal force. Therefore, a large expansion should not be done at one time, but little by little,

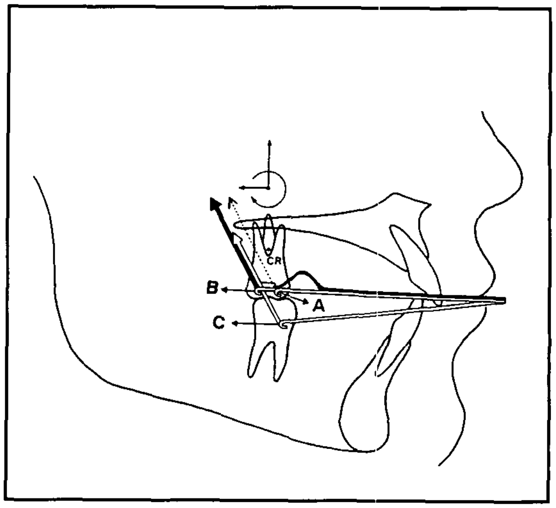

Figure 8

so that excessive buccal crown tipping will not occur.

Cervical-pull headgear

Distal displacement was noted in the mesiodistal direction. Since the line of action of cervical loading is inclined in relation to the occlusal plane, the distal force component and, consequently, the amount of distal translational movement, is thought to be reduced at the expense of the vertical force component, as compared with straight-pull loading. However, load-displacement curves demonstrated that cervical-pull loading exceeded straight-pull loading by the amount of its distal crown displacement at high load levels (Figure 3A-C). This result may be mainly due to a larger amount of distal crown tipping rather than translation. It became evident in a previous study[8] that the molar tipped more distally with cervical-pull loading than straight-pull loading. If the facebow is assumed to be a rigid body, the force vector passes slightly below the center of resistance of the molar when a cervical-pull headgear is applied, as shown in Figure 1. Therefore, a small amount of distal crown tipping is expected. Deflection of the facebow must be taken into consideration in practice, because the facebow is an elastic body. With increased force, the ends of the outer bow are pulled downward because of the extrusive force component, thereby increasing the perpendicular distance of the line of force from the center of resistance (Figure 6). Thus, the distal tipping moment may increase substantially compared with a straight-pull headgear with the increment of force.

Buccal crown movement is correlated with the amount of force (Figure 4). Theoretically the extrusive force should tip the crown lingually

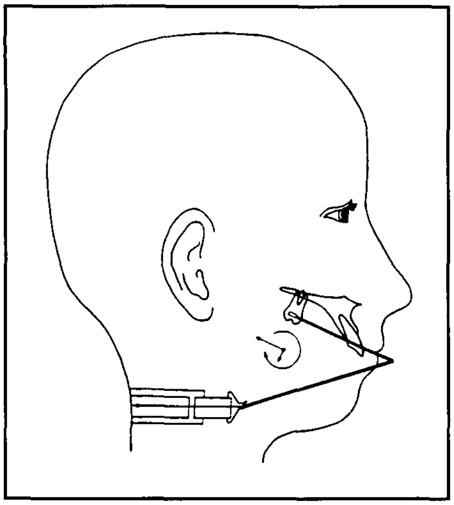

Figure 9A

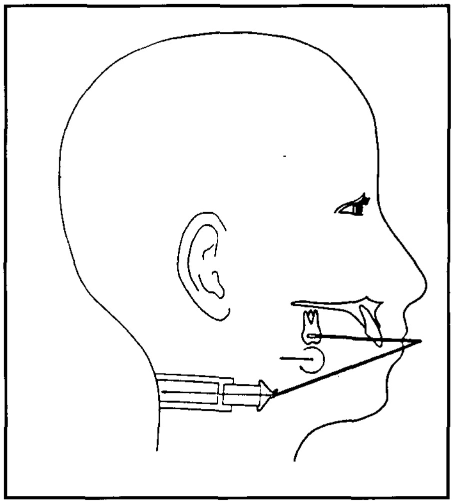

Figure 9B

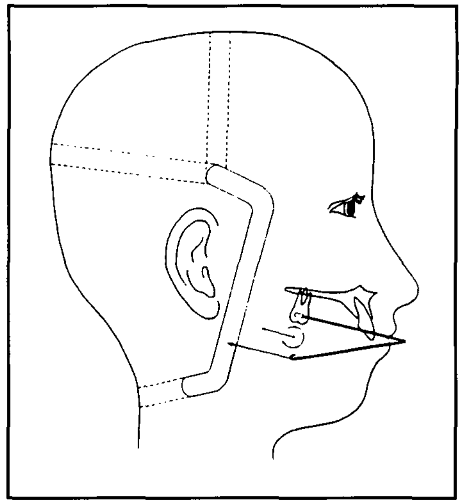

Figure 9C

Figure 9A-C
A: When a cervical headgear is employed with the long outer bow bent downward, effective space regaining can be achieved. However, it is difficult to direct the force vector parallel to the occlusal plane if the occlusal plane is steep. A large amount of downward bend of a long outer bow results in excessive distal crown and mesial root tipping in addition to distal translation because of a large perpendicular distance of line of force from the center of resistance of the molar.

B: When a cervical headgear is used to regain a large amount of space in the case whose occlusal plane is not steep, less downward angulation of the long outer bow is required to direct the force parallel to the occlusal plane.

C: When a variable horizontal-pull headgear with a short outer bow is used, the force vector parallel to the occlusal plane can be easily applied in any patient.

(Figure 5). Therefore, buccal crown movement seen in the experiment is totally unexpected. This indicates that a relatively strong buccal force was produced and the resultant buccal tipping moment exceeded the lingual tipping moment caused by the extrusive force.

The amount of buccal displacement with cervical-pull type headgear at a load of 5 N was smaller than straight-pull type headgear (Table 2), because it was reduced by the extrusive force component which caused the crown to tip lingually.

High-pull headgear

Load-displacement curves in the mesiodistal direction show that the crown changed its direction of movement from distal to mesial in subjects A and C (Figure 3A and C). Mesial crown displacement was found at the maximum load of 5 N in each subject. This is a totally undesirable effect if space regaining or expansion of arch length is the primary aim of the headgear.

Because the molar translated distally due to a distally directed force component, mesial displacement of the crown was likely to be the result of mesial tipping of the molar.[8] The molar showed a slight distal tipping under small forces since the line of action of the force passed somewhat below the center of resistance of the molar (Figure 1). With increased load, outer bow hooks and, consequently, the point of force application, were pulled upward with high-pull loading. This resulted in the line of force passing above the center of resistance and the molar tipped mesially (Figure 7).

When an extraoral force is applied, the facebow distorts, thereby changing the relationship between the line of force and the center of resistance of the molar. The initially planned force system was altered and the direction of the crown's movement was consequently changed in the course of loading. Thus, the deflection of facebow makes it difficult to predict the molar movement. The less a facebow is deflected during activation, the more accurately the force system can be delivered to the molar. In order to minimize facebow deflection during loading, the use of the largest diameter facebow and tubes available was suggested by Worms, Isaacson, and Speidel.[24] The use of a shorter facebow may also be effective for reducing deflection.

Distal crown movement did not occur when a small load was exerted on the molar of subject B. This indicates that the position of the center of resistance, or other factors, vary between individuals and they may affect the molar's movement.

Buccal displacement was the most evident under all loadings (Figure 4, Table 2). The intrusive force, in addition to the buccal force, acted on buccal tubes of the molar, resulting in a great deal of buccal crown tipping (Figure 5).

At least three factors cause buccal crown tipping; 1) buccal force; 2) intrusive force; and 3) expansion of the inner bow, routinely done in order to avoid posterior crossbite. However, only the occlusal forces, usually weak in high mandibular plane angle cases which represent an indication for high-pull headgear, are resistant to buccal crown tipping.

Buccal crown tipping is, therefore, unavoidable with high-pull headgear. When a molar is tipped buccally, the lingual cusp is extruded. This is an unfavorable effect because extrusion of the lingual cusp may induce premature contacts which lead to bite opening. This may be avoided by using a torque headgear[25] with buccal root torque or additional utilization of a palatal bar.

Clinical applications

The line of action of the force in relation to the molar is an important consideration in control of the tipping effect. When the line of force passes through the center of resistance of the molar, the molar is translated without tipping. If the line of force passes above or below the center of resistance, the molar will tip mesially or distally, respectively. The longer the perpendicular distance from the center of resistance to the line of force, the more substantially the molar will tip. These mechanical principles will be a help in understanding the effects of all headgear modifications.

The deflection of the facebow caused by an increase in the magnitude of force moves the direction of force in relation to the molar. As a result, effects opposite to those intended may be produced.

To cite an example, when a high-pull headgear in conjunction with a short outer bow is employed, mesial displacement of the crown, which counteracts space regaining, occurs due to mesial crown tipping.

The line of force is determined by the position of the outer bow hooks in relation to the extraoral anchorage where the force originates. Therefore, molar movements, whether they are mesial or distal inclination, intrusion or extrusion, can be controlled by altering the length of the outer bow or the angle between inner and outer bow with respect to the position of the anchorage as the relationship of the line of force to the center of resistance of the molar is changed.[2-5]

With a high-pull headgear, effective distal displacement of molars can be achieved by bending the short outer bow 5 to 10° downward according to the magnitude of force, or choosing the outer bow whose hooks are located at a point corresponding to the posterior end of the buccal tubes, inasmuch as this procedure would prevent the line of force from passing above the center of resistance during activation. Consequently, mesial molar tipping would thus not occur (Figure 8).

A correct force system can be delivered to the molars according to the individual patient's needs by adjusting the vertical and horizontal position of the outer bow hooks relative to the headgear anchorage. Another example is shown in the following. When a cervical-pull headgear is employed with the long outer bow bent downward, molars can be effectively inclined distally.[26] This type of headgear is efficiently designed to tip molars distally for space regaining. Therefore, it is preferably used for the cases which have lack of space following the premature loss of deciduous molars and the subsequent mesial tipping of first molars. The more the outer bow is bent downward, the less extrusive force is exerted on the molar. In this way, decrease in extrusive force theoretically diminishes extrusion of the molar and resultant clockwise rotation of the mandible. On the other hand, round-tripping is likely to occur since the molar roots tip mesially despite the necessity for molar distalization.

When this type of headgear is prescribed, the patient's skeletal pattern must be considered.

When the occlusal plane is inclined steeply, molar extrusion is generally unfavorable. Therefore, the outer bow needs to be bent considerably downward in order to direct the force vector parallel to the occlusal plane. It is impossible to apply such a direction of force in some cases (Figure 9A). Excessive distal tipping moment may be produced in this situation and, in addition, this facebow does not seem to be comfortable for patients.

On the other hand, a smaller amount of downward bend in the outer bow is necessary if the occlusal plane is not steep (Figure 9B).

The force vector in relation to the occlusal plane varies remarkably from patient to patient due to skeletal variations. Furthermore, a high degree of flexibility of the long outer bow makes prediction of molar movement difficult. It is, therefore, favorable to apply a variable horizontal-pull headgear with the short outer bow bent downward if the occlusal plane is steep and molar extrusion is contraindicated. The direction of force can be altered by using different buttons on the headcap (Figure 9C).

An advantage of a variable-pull headgear is that a constant force system can be applied regardless of the head position, whereas application of the cervical-pull headgear may cause a change in the direction and magnitude of the extraoral force, according to head position.

A cervical-pull headgear is still effective for Angle Class II, Division 2, deep bite patients when molar extrusion or resultant clockwise rotation of the mandible is desired. Application of a high-pull headcap in conjunction with a short outer bow is a proper choice of headgear in Class II open bite cases and more comfortable than a variable-pull headcap for patients because of its simple shape. However, the range of indication and variation of force directions of those types of headgear are relatively limited.

It is suggested that the headgear with a combination of variable-pull headcap and short outer bow, whose ends are located at a point corresponding to the posterior ends of the buccal tubes, can be widely applied to various patients because a variable-pull headcap provides various force directions according to patients′ needs. When using a short outer bow, the force direction can be determined accurately because its deflection is smaller than that of a long outer bow under force application.

Molar movement cannot be predicted from the passive position of the outer bow hooks in relation to the molars because the activating force alters the initial position of the outer bow hooks. Therefore, the final position of the outer bow hooks with the outer bow distorted under force activation should be checked at the beginning of treatment. At this jucture, the optimum direction of a headgear force system can be determined.

Molars tip in the course of treatment with headgear therapy and, consequently, the relative position of the line of force to the center of resistance changes. For this reason, the headgear must be adjusted regularly during treatment.

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