A 3-dimensional analysis of molar movement during headgear treatment

Jennifer L. Ashmore, DDS, MSD,[a] Brenda F. Kurland, MS, EdM,[b] Gregory J. King, DMD, DMSc,[a] Timothy T. Wheeler, DMD, PhD,[d] Joseph Ghafari, DMD,[e] and Douglas S. Ramsay, DMD, PhD, MSD[a,c]

Seattle, Wash, Gainesville, Fla, and Philadelphia, Pa

Superimposition of serial cephalograms provides a limited description of tooth movement that could be complemented by data obtained from serial dental casts. The aim of this study was to develop a mathematical method for superimposing 3-dimensional data obtained from selected landmarks on longitudinally collected dental casts to describe maxillary first molar movement during headgear treatment. The material consisted of dental casts taken bimonthly from 36 children whose Class II Division 1 malocclusion was treated with straight-pull headgear during a 24-month period. Control data were collected from initial and final models of 38 subjects with a similar malocclusion who were not treated during a 24-month observation period. Spatial data from each subject's initial model were oriented similarly in an anatomically derived coordinate system, and a best-fit superimposition of palatal rugae landmarks from subsequent models allowed the measurement of molar movement. On average, headgear treatment resulted in distal movement of the molars, and the fitted net difference between treated and control subjects was 3.00 mm (SE, 0.37 mm; $P < .001$). Also, the headgear caused significantly more molar extrusion (0.56 mm; SE, 0.20 mm; $P < .006$) and buccal expansion (0.58 mm; SE, 0.17 mm; $P < .001$) on average than in the control group. Poor reliability of the method for measuring molar rotations indicated that they could not be determined accurately. Longitudinal description of molar movement for each subject revealed great individual variability in the amount and pattern of tooth movement. Several reasons could account for the wide range of individual variation and warrant exploration. (Am J Orthod Dentofacial Orthop 2002;121:18-30)

In the treatment of Angle Class II malocclusions, headgear is used routinely or occasionally by 9 out of 10 orthodontists.[1] Beginning in the late 1980s, the National Institutes of Health supported 3 separate clinical trials at the Universities of Florida, North Carolina, and Pennsylvania, all of which included evaluations of headgear treatment for Class II malocclusion patients. In growing children, headgear had a significant therapeutic effect when compared with untreated control groups.[2-4] The general consensus is that headgear inhibits the anterior displacement of the maxilla and thus contributes to the correction of the anteroposterior discrepancy between the maxillary and the mandibular dentitions.[3,4] The headgear force, transmitted to the maxilla via the maxillary first molars, can also cause these teeth to move distally.[2,4] All 3 trials documented the wide individual variations in response to headgear treatment,[4,5] underscoring the importance of characterizing the sources of such differences that result from seemingly similar treatments.[5-9]

Understanding the effects of headgear treatment in the anteroposterior and vertical planes is derived primarily from the superimposition of serial lateral head radiographs. Stable anatomic landmarks[10] are used for registering a patient's serial cephalographs to estimate the skeletal and dental change during the time period evaluated.[11] Unfortunately, cephalometric superimpositions have several limitations. Because exposure to ionizing radiation should be minimized, cephalographs are made at relatively long intervals. The observed changes are divided by the number of years between headfilms to yield an annualized measure of change[2,4] that can obscure the true dynamic changes. Furthermore, anatomic landmarks are often difficult to identify reliably because of the overlap of left and right bilateral structures of the head. Variable head positioning in the cephalostat between serial radiographs can affect this overlap, further complicating the superimposition of films. Reliability of cephalometric superimposition is

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[a]Department of Orthodontics, University of Washington.
[b]Department of Biostatistics, University of Washington.
[c]Department of Pediatric Dentistry, University of Washington.
[d]Department of Orthodontics, University of Florida.
[e]Department of Orthodontics, University of Pennsylvania.
Reprint requests to: Dr Douglas S. Ramsay, Department of Orthodontics, University of Washington, Box 357446, Seattle, WA 98195-7446; e-mail, ramsay@u.washington.edu.

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also compromised by the method's susceptibility to unnoticed differences in stable reference structures.[12] The treatment changes of interest are often small relative to the error of the cephalometric method; this makes their precise estimation difficult.[13,14]

An alternative approach to cephalometric analysis to assess dental movement is to measure changes in tooth position with serial maxillary models. Advantages of this approach include (1) 3-dimensional (3D) information is preserved in the model, (2) the impression material provides an accurate spatial reproduction of the original structures of interest, (3) impressions can be taken at frequent intervals, and (4) precise measurement techniques can be used to collect spatial data from the models, including simple linear measuring devices (eg, digital calipers[15]) and more sophisticated devices capable of measuring data in 3 dimensions (eg, reflex metrograph,[16,17] traveling microscope,[18] and laser scanners[19,20]). Although little is known about the stability of identifiable landmarks on dental casts, palatal rugae have been suggested as relatively stable structures for registration of serial maxillary models.[21] The shape of the palatal vault and the medial portions of the palatal rugae are rather stable throughout the development of the dentition.[22] Palatal rugae retain their shape and pattern throughout a person's lifetime;[23] thus, they have been used for identification purposes in forensics.[24] From age 5 to adulthood, the rugae increase in length an average of 2 mm.[25]

Several investigators have studied the potential use of the palatal rugae for the superimposition of serial models.[16,21,26] Almeida et al[16] found that headgear treatment can alter the position of the lateral ends of the rugae. Bailey et al[26] reported that orthodontic treatment involving maxillary premolar extraction resulted in greater spatial change in some areas of the rugae when compared with those of patients treated without extractions. Nevertheless, the authors of both studies concluded that specific parts (eg, medial) of the palatal rugae may be sufficiently stable to serve as an anatomic reference for superimposing serial maxillary models, despite intervening headgear or premolar extraction treatment.

The goal of this study was to describe dental movement of the maxillary first molars during headgear treatment. A retrospective study was conducted with a sample of models taken bimonthly during phase I headgear treatment and a control sample of models obtained from untreated Class II subjects. The specific aims were to (1) develop a mathematical approach for using homologous structures on dental models to orient the initial (T1) models into a common frame of reference, and then to superimpose a patient's subsequent models on the T1 model by registering unique anatomic landmarks selected on the palatal rugae, (2) describe the bimonthly molar movement for each patient during headgear treatment, and (3) compare the molar displacement during headgear treatment to that of an untreated control group.

SUBJECTS AND METHODS

The records were obtained from 2 prospective, longitudinal, randomized clinical trials (RCT) investigating the treatment of children with Angle Class II Division 1 malocclusions. They included dental casts from patients treated with headgear at the University of Pennsylvania[27] and from untreated control subjects at the University of Florida.[2] (The University of Pennsylvania RCT did not include an untreated control sample of subjects.) All subjects were diagnosed with a Class II molar relationship as part of the selection criteria for both RCTs. The minimum criterion for inclusion at the University of Pennsylvania was bilateral molar distoclusion, and those with a unilateral Class I molar relationship were excluded. In the control sample from the University of Florida, the distoclusion was measured in one–fourth-cusp increments with a minimum requirement of either a bilateral one–half-cusp or a unilateral full-cusp Class II molar relationship. To better match the 2 samples, only the untreated control subjects with at least a three–fourths-cusp distoclusion were included in the study. Complete details of these trials have been reported previously.[27,28]

Data for treated subjects were obtained from the dental casts of 36 patients randomized to treatment with straight-pull headgear for a 24-month phase 1 treatment period. No other orthodontic treatment was performed before or during treatment. The inner bow for these subjects was adjusted at each visit to fit passively and to avoid constriction or major expansion of the intermolar distance. On average, each side received 14 to 16 ounces of distalizing force and was measured every 4 weeks. Subjects were instructed to wear the headgear 14 hours a day starting with 10 hours a day the first week. Once neutrocclusion was achieved, the headgear was worn at night only (approximately 10 hours a night) until the patient was ready for fixed appliances. Alginate impressions were taken once every 2 months during headgear treatment, and dental casts were mounted on an articulator.[27]

Data for the control subjects were collected from dental casts of 38 patients randomized to an observation-only condition. These subjects had no orthodontic treatment before or during the observation period. They were seen every 3 months for a clinical evaluation, and impressions were taken at the start and end of a 24-month observation period.

Spatial data from maxillary casts were collected with a desktop mechanical 3D digitizer (Microscribe 3DX, Immersion Corporation, San Jose, Calif), which collects 3D data through a stylus tip connected to a mechanical arm that allows a full range of movements. Data were recorded by pressing a foot pedal when the stylus tip was positioned on the point being captured. The digitizer connects to the computer via a serial port. The data were stored in the computer by using specialized software. A LabVIEW software program (National Instruments, Austin, Tex) read the serial port communications from the digitizer and computed the X, Y, and Z coordinate locations of the stylus tip. In conjunction with the foot pedal control, each entry was added to a data file by means of a specialized user interface, which facilitated annotation of the captured points.

Procedures

The following procedures were used by 1 investigator (J.L.A.) for each subject's series of maxillary models (2 models per control subject and approximately 12 per treatment subject). The T1 model was examined for unique anatomic details in the palatal rugae configuration. A minimum of 8 points (4 on the left side and 4 on the right) was identified that were present on all models in the series. Points were chosen for specificity of detail and reproducibility throughout the series of models. The points were marked with a 0.3-mm graphite pencil, 1 point at a time. An analogous procedure was repeated to identify 4 unique anatomical points on each of the first maxillary molars. Additionally, the initial maxillary and mandibular models were occluded to identify and mark points of posterior dental contact to be digitized to provide an estimate of the occlusal plane. Each maxillary cast was then fixed to the flat desktop work surface with fixturing putty (Tac'N Stick, Taylor, Mich), and the following points were digitized:

MR1: a single point where the median raphe meets the base of the incisive papillae.

MR2-16: 10 to 15 points captured as the stylus tip was traced along the median raphe.

RR1-4: a minimum of 4 unique anatomic rugae points on the right side of the palate.

LR1-4: a minimum of 4 unique anatomic rugae points on the left side of the palate.

RM 1-4: 4 unique anatomic points on the right first permanent molar.

LM 1-4: 4 unique anatomic points on the left first permanent molar.

OP1-3: 3 points of posterior occlusal contact with the mandibular teeth (2 on one side and 1 on the other) used to estimate the occlusal plane.

Lateral cephalometric radiographs were taken of all subjects before treatment or observation. Digitally scanned initial radiographs for the control subjects were measured with the program NIH Image version 1.61 (developed at the U.S. National Institutes of Health and available on the Internet at http://rsb.info.nih.gov/nih-image). Values for SNA, SNB, and SNOP (ie, sella-nasion to occlusal plane) were recorded. These cephalometric values had already been measured at the University of Pennsylvania as part of prior studies on these headgear patients.

Baseline data analysis

Because subjects were not randomly assigned from a common pool to be in either the headgear or the control group, the present study is considered a retrospective analysis of existing orthodontic records. Each group was drawn from a different RCT that took place at different locations and used different inclusion and exclusion criteria. For this reason and to evaluate the similarity of the groups, baseline characteristics for the headgear and the observation groups were compared with *t* tests and a 2-sample test for equality of proportions with continuity correction.

Orientation and superimposition of maxillary casts

The 3D data from all subjects were oriented in a common and interpretable spatial coordinate system to assess molar movement. Each subject's T1 model data were oriented in a uniform coordinate system based on anatomic structures that are homologous to all subjects: the point where the base of the incisive papilla and the median raphe meet (MR1), the median raphe, and the posterior occlusal plane. These structures were oriented with rigid transformations (translations and rotations) that maintained the spatial relationship between all digitized points on each T1 model.

The initial step in this orientation process was to establish a plane through the median raphe points with a principal-components analysis. The first 2 principal components identify the plane that best fits the median raphe data points. The third principal component is a normal vector to the plane and determines the equation for the plane. Next, the data points were rotated to orient the fitted median raphe plane into the X-Z plane. Subsequently, the line created by the intersection of the posterior occlusal plane and the X-Z plane was used to rotate the model points so that this line was parallel to the X-axis. A translation then established the *constructed* MR1 point (the point in the fitted X-Z plane closest to the digitized MR1 point) as the origin (0,0,0) of the coordinate system. These rotations and translations were computed so that, in the final orientation, the median raphe points were in the quadrant with negative X and positive Z values.

The resulting common orientation of the T1 models (Fig 1) provides an interpretable spatial frame of reference so that a movement in the positive direction along the X-axis indicates mesial movement. Movement in the positive Z direction, superior to the occlusal plane, indicates intrusion, and the Y-axis represents the transverse dimension of the digitized models (positive values are to the patient's left, and negative to the right).

Once the T1 models of all subjects were oriented in a similarly defined spatial frame of reference, each patient's subsequent models were superimposed on the T1 model with a least-squares rotational fit (Procrustes) with palatal rugae points as the registration landmarks. Digitized data points from subsequent models were translated and rotated to minimize the sum of squared Euclidean distances between corresponding rugae registration points. The algorithm used to achieve the rigid transformation was adapted from that described by Rohlf.[29] Only rigid transformations (without scaling) were used to achieve the best-fit superimposition.

After all casts in a series had been placed in the same coordinate system via superimposition, it was possible to evaluate how the molar positions changed over time. The 4 points digitized on each molar were averaged to create a centroid, which was used to examine translations (anteroposterior, transverse, and vertical movements) along the X, Y, and Z axes for each molar. Linear mixed-effects models compared the headgear and the control groups with respect to first molar translational movement. Unlike a *t* test, this method accounts for correlations between left and right molars in the same subject. The sign for tooth movement along the Y-axis was reversed for the left molar because symmetrical movement of the molars in the transverse plane results in movement in opposite directions along the Y-axis. The potential association of baseline variables with translational movements was also considered via linear mixed-effects models.

Molar rotations were calculated by Procrustes superimposition of the 4 molar points. After the models had been oriented and superimposed, registration of the T-final (TF) molar points onto the T1 molar points resulted in a 3-vector translation and a 3-×-3 rotation matrix that describes molar movement. The translation vector was the same difference in centroid coordinates as described above. To find angles of tip, torque, and spin, the 3-×-3 matrix was decomposed into 3 separate rotations, each about a single axis. In this study, the rotations were classified relative to the long axis of the tooth as tip (rotation around the Y-axis, or mesiodistal angulation), torque (rotation around the X-axis, or buccolingual angulation), and spin (rotation around the Z-axis, or bodily rotation).

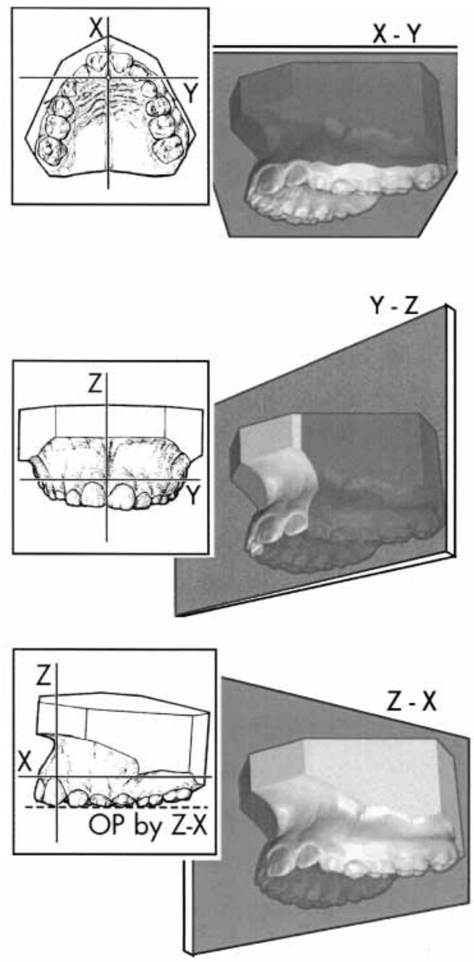

Fig 1. All T1 models for each subject were oriented in this common and interpretable spatial frame of reference. X and Y axes represent anteroposterior direction and buccolingual direction, respectively. X-Y plane is parallel to transverse section through model. Origin of coordinate system is located approximately at junction of incisive papilla and median palatal raphe. Z-axis indicates vertical direction, and Y-Z plane is coronal section through model. Z-X plane is sagittal section through model. Line OP by Z-X refers to intersection of Z-X plane and digitized occlusal plane. OP by Z-X line was positioned parallel to X-axis during orientation of T1 model.

Unlike translations, rotations are generally not commutative: rotation around the X-axis, followed by the Y-axis, then the Z-axis, will not yield the same result as rotation by the same angles in a different order. However, if the angles are small, rotation approaches commutativity. Because rotation of molars does not take place 1 coordinate at a time, but along an unknown body axis, a conservative way to investigate rotation in terms of tip, torque, and spin is to decompose the rota-

Table I. Descriptive statistics at baseline for headgear and control groups

Variable	*Headgear group (Univ of Penn)*	*Control group (Univ of Florida)*	*Statistic (P value)*
Sample size (N)	36	38	
Gender (male, female)	17, 19	29, 9	χ^2 = 5.47*, P < .05
Age (yr) mean (SD, range)	9.65 (1.42, 7.2-13.3)	9.63 (0.87, 8.18-12.56)	t = 0.07, P > .05
Treatment/observation (mo) mean (SD, range)	23.49 (2.27, 18-28)	24.51 (1.55, 20-30)	t = 1.15, P > .05
SNA (°) mean (SD, range)	82.07 (3.02, 76.41-88.63)	80.65 (2.97, 75.56-87.7)	t = –2.03, P < .05
SNB (°) mean (SD, range)	74.51 (2.90, 67.29-81.4)	75.05 (2.86, 67.76-80.45)	t = 0.82, P > .05
ANB (°) mean (SD, range)	7.57 (2.02, 36, 4.46-11.68)	5.60 (2.15, 2.5-10.16)	t = –4.05, P < .001
SNOP (°) mean (SD, range)	16.87 (4.1, 5.85-25.03)	20.41 (3.17, 14.05-28.37)	t = 4.16, P < .001

*2-sample test for equality of proportions, with continuity correction.

tion matrix as if rotations occurred in sequence (XYZ, XZY, YXZ, YZX, ZXY, and ZYX). Each of the 6 orderings is the result of multiplying 3 rotation matrices, 1 about each coordinate axis. The terms of the ordered rotation matrix were equated to terms of the 3-×-3 rotation matrix computed by Procrustes superimposition, with a simple algorithm.[30] If the 6 sets of angles computed are similar, they should accurately describe tip, torque, and spin.

Error of the method

The landmarks identified in pencil on the initial and final models from 26 subjects (14 in the control group and 12 in the headgear group) were digitized a second time for reliability. Preliminary studies with sets of duplicated casts permitted the determination of the variability associated with identifying the same rugae point throughout a series of casts, with (SD = 0.25 mm) and without (SD = 0.56 mm) a pencil mark placed on the rugae point. By using repeated measurements of the same cast, it was possible to calculate molar translations and rotations and thus assess the reliability of the data collection and superimposition methods. The spatial data from the second measurement were superimposed on the initial model measurements in the same way as described for performing serial model analysis to make these calculations. Because the same model was measured twice, any measured movement of the molar could only result from method error.

Stability of palatal rugae points

The Procrustes superimposition used in the rotation step above assumes that the palatal rugae are stable landmarks. This assumption was evaluated by determining whether the measured rugae points changed shape over time. A method of shape comparison that is invariant to changes in translation, rotation, reflection, and scaling is Euclidean distance matrix analysis,[31,32] which describes shape (and form, which is shape for a fixed scale) as the matrix of Euclidean distances between landmarks (rugae points). Comparison of the form of 2 sets of landmarks (such as the digitized rugae points on 2 dental models) is achieved by taking the ratio of each element of the matrix of distances. The form distance matrix of ratios is summarized by the square root of the sum of squared natural logs of each element of the matrix.[33] The form distance matrix divided by the number of distances compared is referred to as the *form dissimilarity index*. For each pair of distances, the form distance matrix entry is 1 if the distances in the 2 forms are the same. Thus, the form dissimilarity index is zero if the models are identical, and values increase for greater form differences between sets of rugae. Form dissimilarity indexes for rugae in the treatment and the control groups were compared by a *t* test.

Another evaluation of rugae stability assessed whether form differences increased over time in the treatment group. Form change was described as lack of fit after superimposition and was measured as lack of fit of the average Euclidean distance between superimposed rugae for the T1 model and a subsequent model. This method overestimates form change because it does not control for measurement error. The lack of fit of rugae between T1 and T2 models (taken approximately 2 months apart) was compared with the lack of fit between the T1 and TF models (taken approximately 2 years apart). This statistical comparison (paired *t* test) could be made only for the treatment group, because no models were taken between the T1 and the TF models for the control group.

RESULTS

Sample description

Demographic and cephalometric characteristics of the sample are presented in Table I. The control and the treated groups were not statistically different with respect to age, treatment/observation time, or SNB angle. The control group had a significantly larger proportion of male subjects (76%) than did the headgear treatment group (47%). On average, the control group had a larger SNOP angle and smaller SNA and ANB angles than did the headgear group. These characteristics (gender, SNA, ANB, and SNOP) were considered as potential confounding variables in analyzing group differences.

Error of the method

Any measured maxillary molar movement obtained from data collected from the same model on 2 occasions could only result from method error. The average translation of the centroid of the 4 molar points between the repeated measurements (Table II) was close to 0 mm, and the standard deviation (0.28-0.41 mm) was only slightly greater than the reported measurement error of the Microscribe 3DX (0.25 mm). In paired and 2-sample *t* tests, the translations were not significantly different from zero, and group differences in degree of measurement error were not detected.

The reliability of the method for computing rotation of maxillary molars was poor. Computed rotations for the repeated digitization of the T1 and the TF models are shown in Table III. The average rotation ranged from –2.48° to 1.31°. Although the true rotation of 0° is certainly within a 95% confidence interval for the mean rotation, the large standard deviations for rotations (7°-11°) indicate an unacceptably large measurement error.

Measurement error in digitization may have a larger role in reliability of rotations (which rely on the positions of the 4 molar points separately) than for translations (computed with the measured centroid). The 4 measured molar points show only small variability in Z-axis coordinates; therefore, small errors in measurement may have a large impact on calculated rotations. For example, adding small changes to the Z-axis coordinates of molars caused aberrant (large, inconsistent between orderings) measured rotations appear sensible. Conversely, adding small changes to the Z-axis coordinates made seemingly reasonable measured rotations become aberrant. Most calculated rotations were small and consistent between the 6 orderings. However, because of this lack of robustness in measuring rotations, neither descriptions of average rotation from T1 to TF nor analysis of group differences in rotation is presented.

Translation

The average translational movement of the molars in the headgear group was significantly larger ($P < .001$) in the anteroposterior direction than that observed for the control group. A mean distal movement of 2.20 mm for the headgear group and a mean mesial movement of 0.76 mm for the observation group were seen, for an overall mean difference of 2.96 mm. With linear mixed-effects regression to model distal movement for the 2 groups, the fitted mean difference was 3.00 mm (Table IV). The fitted mean differences between the groups in the transverse direction (0.58 mm) and the vertical direction (0.56 mm) were also statistically significant (Table IV). Main effects of demographic and cephalometric characteristics were considered through linear mixed-effects models, as well as interactions of these variables with the treatment group effect. None was statistically significant. Inclusion of ANB somewhat mitigated the treatment group difference, but the group difference remained statistically significant. A sensitivity analysis that involved removing influential data points also did not greatly affect the estimated group differences or their statistical significance.

Frequently taken serial models provided a descriptive analysis of the molar movement that occurred during headgear treatment for each patient. Each headgear subject's translational molar movements in the mesiodistal, vertical, and transverse directions are displayed in Figs 2, 3, and 4, respectively. Large individual differences in molar movement are apparent; while some subjects experienced significant distal molar movement throughout treatment (eg, P111, P123), others had little or no tooth movement (eg, P105, P119). Interestingly, some patients had a change in direction in mesiodistal tooth movement midway through treatment (eg, P113, P132).

Table II. Method error for measuring translation of the calculated molar centroid

Direction of translation (axis)	*Mean (mm)*	*Standard deviation*	*Range*
X (anteroposterior)	0.03	0.41	–1.78-1.70
Y (transverse)	–0.02	0.28	–1.22-0.88
Z (vertical)	–0.05	0.28	–0.66-0.97

Models from 26 (12 headgear, 14 control) subjects were measured twice to determine method error. Right and left molars were measured for T1 and TF models. Five molars were not included in analysis because of missing data.

Stability of palatal rugae points

The average percentage of form dissimilarity between rugae at T1 and TF was 1.18% (SD, 0.98; range, 0.28-6.76) for the control group and 2.29% (SD, 0.85; range, 0.92-4.14) for the headgear group. In other words, on average, each Euclidean distance between landmarks at TF was about 1% different from that at T1 for the control group and 2% different for the treatment group. Translating the form dissimilarity index into millimeters is not possible, because the form dissimilarity

Table III. Method error for measuring molar rotation (in degrees)

Order of rotation	*Torque* *Angle of rotation around X-axis, Mean (SD, range)*	*Tip* *Angle of rotation around Y-axis, Mean (SD, range)*	*Spin* *Angle of rotation around Z-axis, Mean (SD, range)*
XYZ	–2.48 (8.02, –40.52-14.55)	1.13 (6.83, –25.32-35.10)	–1.83 (9.94, –89.16-3.93)
XZY	–1.55 (10.83, –39.10-73.80)	0.15 (11.06, –85.96-35.11)	–0.12 (9.11, –31.53-78.25)
YXZ	1.27 (–8.07, –18.96-38.94)	–1.42 (7.06, –35.11-26.05)	–1.31 (9.71, –86.67-6.67)
YZX	0.43 (11.08, –74.49-39.13)	–2.12 (10.97, –86.13-26.71)	0.34 (8.94, –29.18-77.73)
ZXY	–2.39 (7.68, –38.90-10.44)	1.04 (7.27, –27.16-35.12)	–1.82 (9.72, –86.68-3.93)
ZYX	1.31 (8.17, –18.97-40.50)	–1.10 (6.98, –35.11-26.68)	–1.35 (9.92, –89.16-6.15)

Models from 26 (12 headgear, 14 control) subjects were measured twice to determine method error. Right and left molars were measured for T1 and TF models. Five molars were not included in analysis because of missing data.

Table IV. Translation (mm) of calculated molar centroid for headgear treatment group (n = 36) and control group (n = 38)

Direction of translation (axis)	*Headgear group Mean (SD, range)*	*Control group Mean (SD, range)*	*Fitted group difference* Mean (SE)*	*Adjusted* t *statistic*, df=72*
X (negative is distal)	–2.20 (2.22, –8.58-1.29)	0.76 (0.92, –1.33-2.79)	3.00 (0.37)	8.13 (*P* < .001)
Y (negative is buccal)	–0.90 (1.25, –4.57-2.36)	–0.31 (0.66, –2.14-1.99)	0.58 (0.17)	3.50 (*P* < .001)
Z (negative is occlusal)	–1.40 (1.19, –4.53-2.12)	–0.86 (0.94, –3.10-2.28)	0.56 (0.20)	2.83 (*P* < .006)

*Linear mixed-effects model with random intercept to account for repeated measures (left and right molars).

matrix is composed of ratios. A *t* test showed a statistically significant group difference (t = 7.54; P < .001), indicating group differences in form change in rugae over the duration of the study.

To determine if the form difference was greater for comparisons over a longer time, we examined T1 to T2 and T1 to TF form differences for the treatment group. The average Euclidean distance between corresponding rugae points for T1 compared with T2 was 0.31 mm (SD, 0.12; range, 0.16-0.81), and the average distance for T1 compared with TF was 0.72 mm (SD, 0.24; range, 0.29-1.14). The T1 to TF average distance was significantly higher than the T1 to T2 average distance (mean difference, 0.42 mm; SD, 0.22; range, -0.05-0.86; paired t = -11.43; P < .001). Although we could not calculate change in form differences over time for the control group, the average Euclidean distance between corresponding rugae points from T1 to TF was 0.44 mm, verifying differences in rugae form change between groups over a 24-month period. Whether these form changes were large enough to alter the interpretation of molar movement was unclear.

DISCUSSION

Based on the translational movement of the centroid of the digitized molar points, a maxillary molar moved an average of 2.20 mm distally in the headgear group. This posterior movement was significantly different from the average 0.76 mm of mesial molar movement observed in the control group during the 24-month period. The fitted mean difference (3.00 mm) in molar movement during treatment is comparable with previous cephalometric research. Ucem and Yuksel[34] reported 1 of the largest amounts of distal molar movement, an average of 3.6 to 4 mm, for patients instructed to wear a combination headgear for 20 hours a day. A more modest amount of distal movement (0.75 mm a year) was reported by Keeling et al[2] in patients instructed to wear both a headgear and a biteplane for 14 hours each day during a 24-month treatment period. The mesial molar movement in the control group also was comparable with that reported in previous studies of persons with untreated Class II malocclusions.[2,11] On average, headgear treatment caused significantly more molar extrusion (0.56 mm) and buccal expansion (0.58 mm) than was observed in the untreated control group (Table IV). These effects were small, reflecting achievement of the clinical objective of the straight-pull headgear treatment, which was to deliver a distalizing force to the molars while minimizing vertical changes in molar position. The lack of further increase in transverse movement was related to the fact that the inner bow was not overly expanded to maintain a consistent protocol of adjustment across patients.[27]

An important contribution of this study is the development of a serial maxillary model superimposition method that permitted a detailed examination of how each person's molars moved during headgear treatment

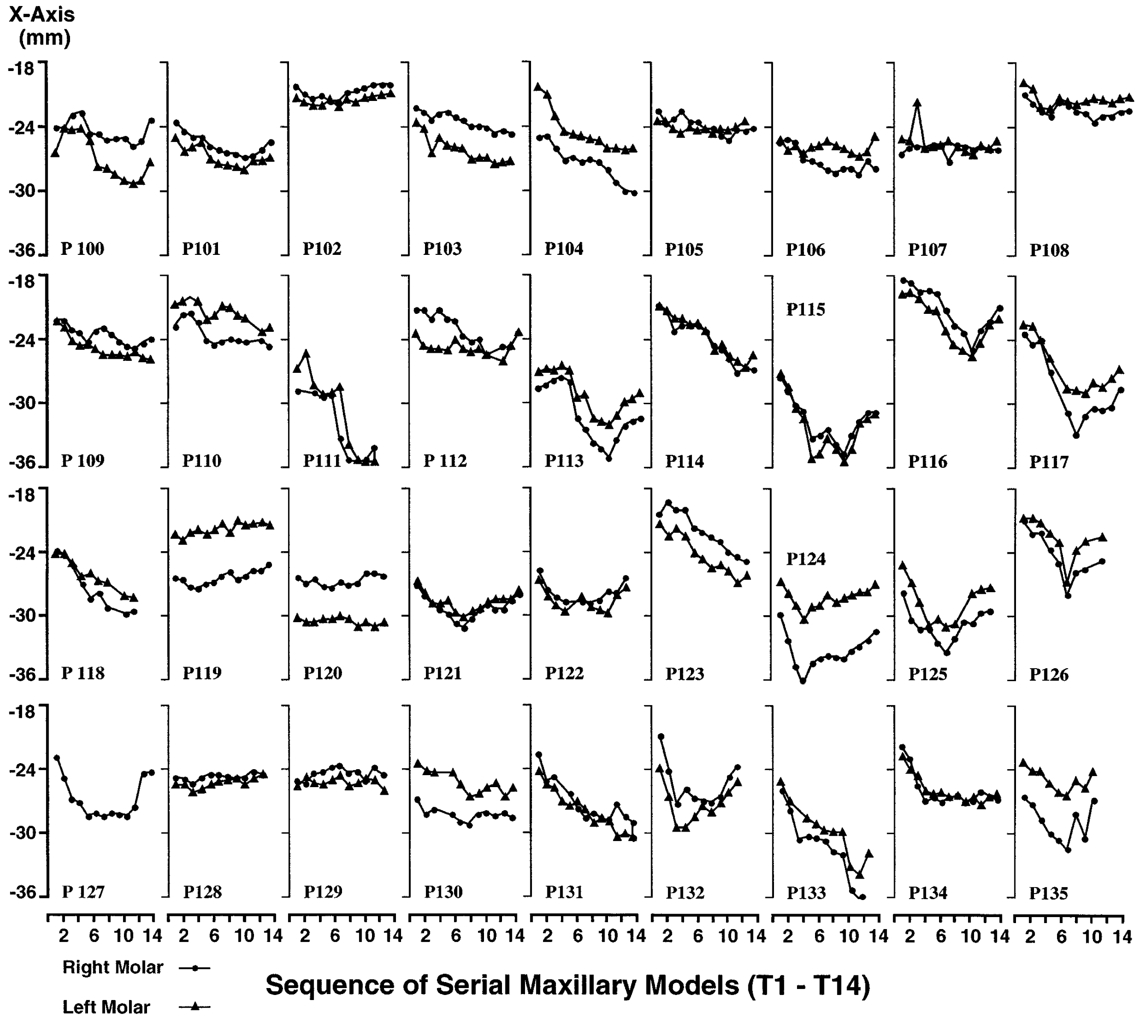

Fig 2. X-axis translational movement of calculated centroid for each maxillary molar over time represents movement in mesiodistal direction. Decreasing values indicate distalization.

(Figs 2-5). Accordingly, the method revealed substantial between-subject variation not only in the magnitude of tooth movement, but also in the pattern of movement over time. Explaining the origin of the individual differences that result from a uniform treatment modality has been recognized as a major goal in orthodontic treatment research.[4,6,9]

The strategy Baumrind[7] recommends to investigate individual variation has 2 major components. The first is that the dependent variable should be measured frequently and precisely. The results of the present study demonstrate that models can be taken often during orthodontic treatment and that the serial model-superimposition methodology is sufficiently precise to provide a detailed description of individual differences in molar translational movement during headgear treatment (Figs 2-5). The second component is that additional measures should be taken during treatment that may account for the individual variations in outcome. This task is difficult because it requires knowledge of the critical sources of variability that result from headgear treatment.[9] No clear agreement exists among orthodontists about specifics of headgear use, such as ideal force levels and amount of time to wear the appliance or the dental and skeletal consequences of varying these parameters. The variation displayed in Figure 2 would support testing the hypothesis that subjects who had considerable distal molar movement might have worn the headgear for more hours each day or had more force exerted on the molars when compared with subjects who displayed little tooth movement. Recent work[35,36] in the development of sophisticated micro-

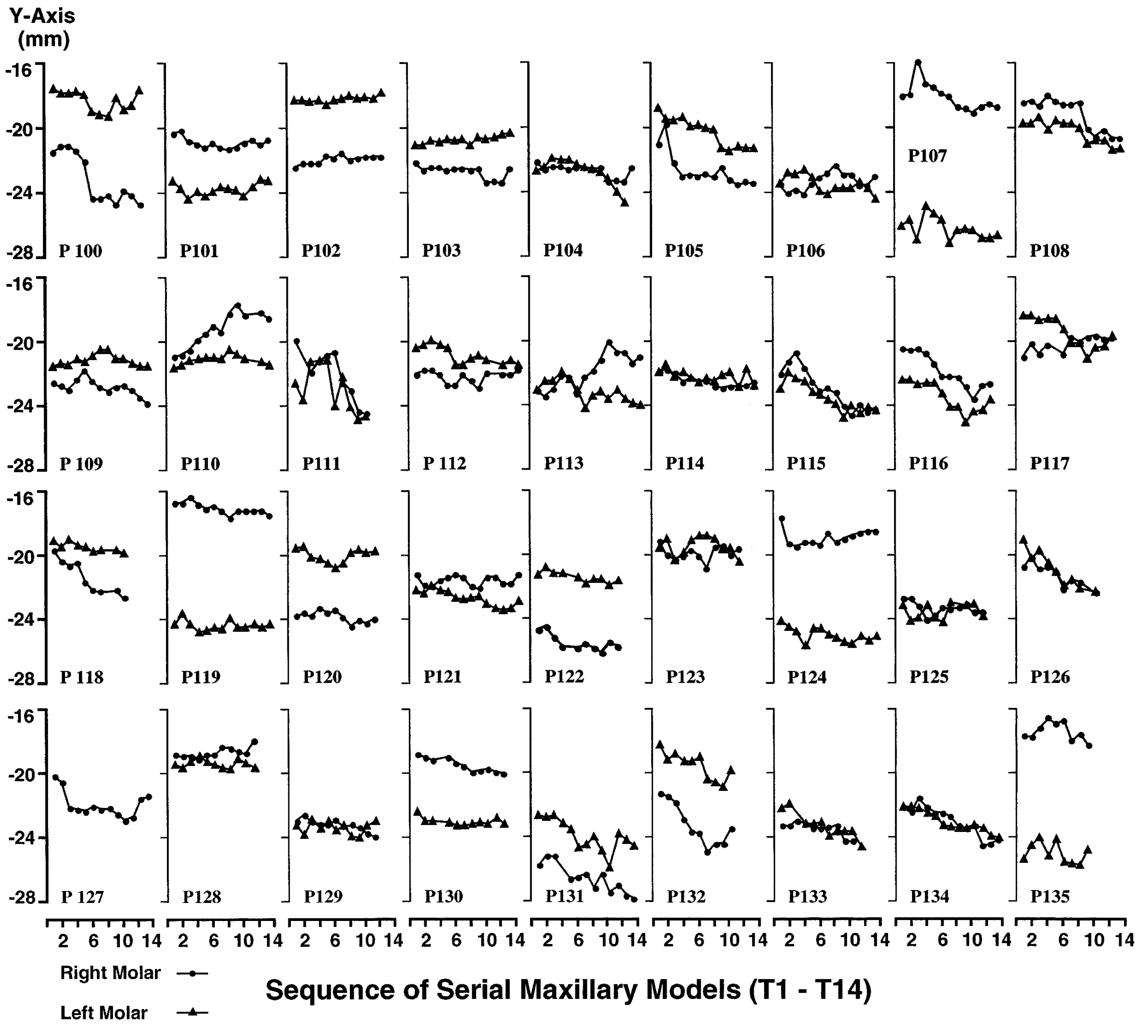

Fig 3. Y-axis translational movement of calculated centroid for each maxillary molar over time represents movement in buccolingual direction. Sign for left molar values was reversed; therefore, decreasing values indicate movement in buccal direction.

electronic devices to measure characteristics of headgear use (eg, amount of force, circadian timing of force, duration of force) or the development of biological indicators of periodontal response to treatment may provide insight into the etiology of individual variation. The development of new methods such as those described in this study may help determine the dose-effect relationship between headgear wear and therapeutic effect.[36] Of course, for a more complete assessment of treatment outcome, information gathered from other records, including cephalometric data, must be considered to appraise the contribution of skeletal growth on treatment of distoclusion.

To track 3D tooth movement from serial models, investigators have relied on the physical superimposition of palatal rugae using impression materials (eg, acrylic or elastomeric material) to construct a template of the rugae that would be transferred over serial models.[37,38] However, any inconsistencies in the dental cast could reduce the stability of the template and thus the accuracy of the superimposition. Also, changes in the rugae[16,26] may require the fabrication of another template that would better fit in a given sequence of the model series. With the mathematical approach introduced in this study, the best fit of the digitized rugae points can be determined despite minor variations in the spatial configuration of the rugae caused by measurement error, growth, or treatment effects.[16,26] The mathematical approach can also help quantify the accuracy of the superimposition of the rugae points.

We used a best fit of rugae to register a series of longitudinal casts, similar to the way a best anatomic fit of

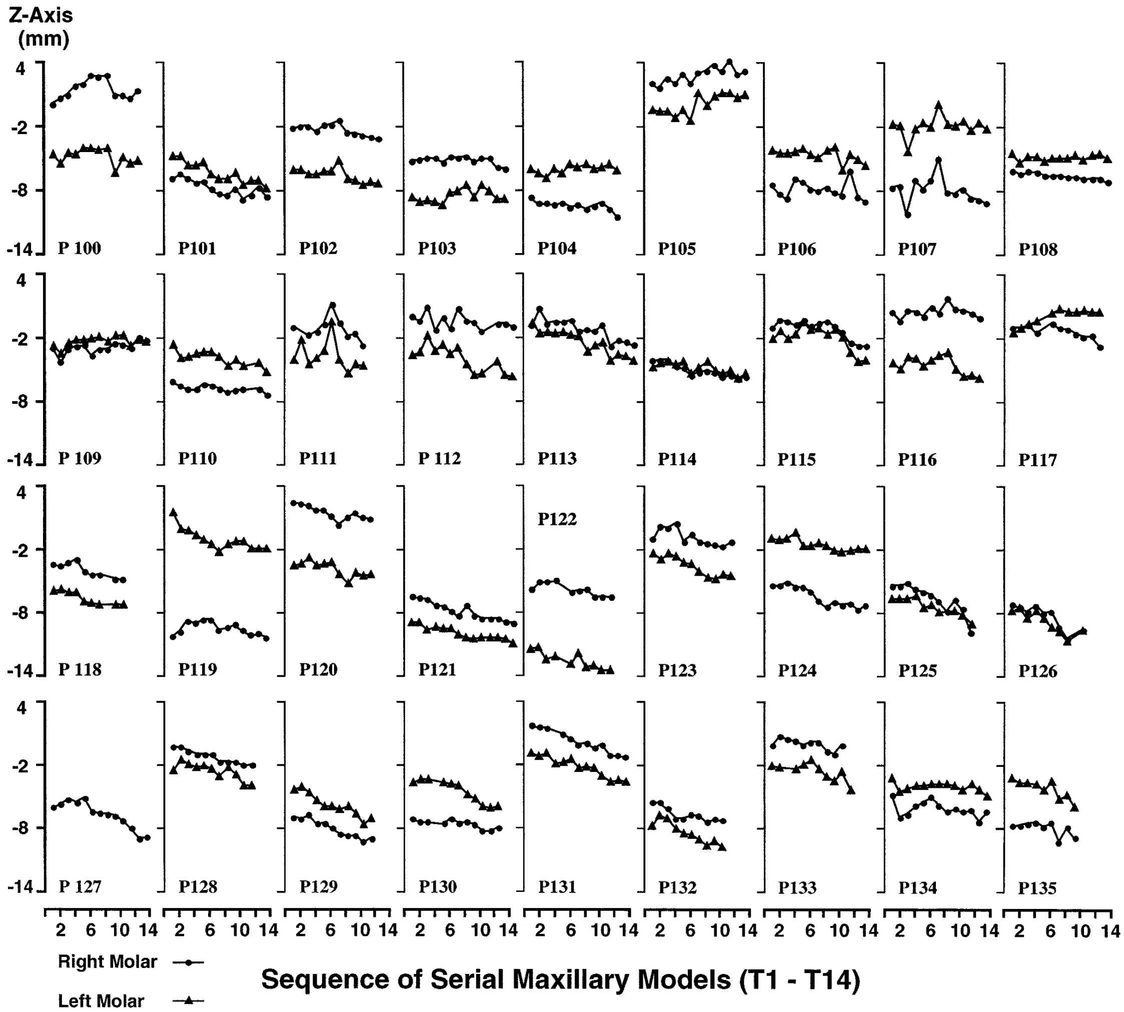

Fig 4. Z-axis translational movement of calculated centroid for each maxillary molar over time represents movement in vertical direction. Decreasing values indicate extrusion.

anterior cranial base structures is used to superimpose serial cephalometric headfilms. After cephalometric superimposition, spatial changes in orofacial structures are usually described in relation to a coordinate system derived from homologous structures across individuals (eg, pretreatment Frankfort horizontal). In this study, a standardized coordinate system was defined for all subjects, using homologous structures (median raphe, incisive papillae, and pretreatment occlusal plane) apparent on each subject's T1 model. If a coordinate system is established on references selected arbitrarily within the cranial base, the palatal rugae, or the physical templates over the rugae, the variation inherent to the method of orientation can mask, and induce errors of interpretation of, the examined changes. Given the technological advances in scanning dental casts and the emerging trends to use 3D scanning to store models as well as diagnostic and therapeutic modalities,[39] the present mathematical approach should serve as a model for orientation, superimposition, and evaluation of serial casts.

In support of previous research,[16,21,26] the present study found statistically detectable changes in the palatal rugae configuration for subjects in both the headgear and the untreated control groups. Euclidean distance matrix analysis indicated that the distance between measured rugae points changed only an average of 2% over the 2-year treatment period in the headgear group. It is unlikely that this change in form is large enough to affect the measured treatment result; however, it should be considered in evaluating the results of studies that use this approach. In future research, investigators may want to consider using a weighted Procrustes superimposition method so that greater statistical emphasis can be placed on rugae points known to be the least susceptible to treatment-induced changes (eg, medial aspects) and less emphasis placed on the areas of the rugae configuration known to change more with treatment (eg, lateral and anterior aspects).

Tracking the movement of a single point (centroid) on the occlusal surface of the molar simply indicates the direction of movement of the tooth, not the type of movement (translation or rotation). The ability to evaluate how headgear treatment may change torque, tip, and spin of the maxillary first molars is important from a clinical point of view and should be the object of a future evaluation. The method proposed to calculate rotations computes a rotation matrix by superimposing 4 landmark points per molar. This is a small number of points, and the distance between points is small, especially in the Z (vertical) dimension, because the digitized points on the molar were selected based on unique details in the occlusal anatomy. It is not possible to increase the distance between these points in the vertical dimension beyond what the anatomy of the tooth allows. Given the close spatial proximity of the 4 molar points, minor measurement errors could have a large impact on the calculated rotations. Translations are less sensitive to measurement error because they are computed with the measured centroid that is the average in each coordinate axis for all 4 molar points. Possible ways to improve the ability to measure molar rotation include (1) using more precise methods to measure molar points, (2) collecting more molar points, (3) spreading the molar points over a larger area, (4) determining the axial inclination of the molar by creating a perpendicular to the tooth's occlusal table, and (5) possibly, although with inherent limitations, using a rigid physical template to extend the surface area of the molars for digitization of points over a broader range in all 3 planes of space.

The present investigation has the limitations common to most retrospective research designs. The patients were recruited at different sites to participate in different studies, and the subject inclusion/exclusion criteria were not identical. For example, the RCT at the University of Pennsylvania required a minimum ANB angle of 4.5°, a criterion not required in the Florida RCT. The 2 groups differed significantly in the average ANB angle. To evaluate the potential influence of these possible confounders, we analyzed known demographic and pretreatment factors and determined that none of the initial differences between the 2 groups changed the significance of the results. Subtle unintended differences between groups can influence the findings of retrospective studies in many ways. Nevertheless, the opportunity to examine a set of frequently taken serial models during a well-controlled study of headgear treatment and the availability of a well-defined sample of untreated Class II subjects made it possible to describe molar movement during headgear treatment more thoroughly than has been done previously.

CONCLUSIONS

When compared with an untreated control group, headgear treatment resulted in distal movement of the maxillary first molars. The method developed for superimposing digital configurations of serial dental models allowed accurate measurement of maxillary first-molar translational movement in 3 dimensions for both headgear and untreated groups; this may have broad application in orthodontics. Wide individual differences in molar movement were observed in response to a common headgear treatment regimen. The sources of variation require extensive investigation.

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COMMENTARY

This is a superb study and a valuable contribution to the literature for several reasons. It is a serious and scholarly analysis of an important clinical problem based on the careful measurement of large and appropriately gathered samples. It represents the first rigorous 3D analysis of study cast materials gathered from randomized prospective clinical trials. Its content is of interest to clinicians and academics alike, from both the clinical and methodologic points of view. Perhaps even more important, it represents the successful merging of information from data sets from the investigations of 2 outstanding groups of clinical investigators—I believe the first such intimate sharing of data in the history of orthodontic research in the United States.

The key clinical question in this study is how the maxillary first molar moves in space when straight-pull headgear is used. The authors' main analysis, however, is focused on how a single point on the occlusal surface of the molar moves through time. Most orthodontists do not immediately grasp the distinction between tracking the displacement of a point and tracking the displacement of a rigid body like a tooth. But if the problem is phrased in different terms, they will understand the dif-