Lower molar and incisor displacement associated with mandibular remodeling

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Superimposition of lateral cephalograms generated at different timepoints is a method widely used by craniofacial investigators and orthodontic clinicians for the analysis of developmental and treatment-associated changes. The operation of registering cephalometric images from different timepoints is, however, not as straightforward as would be desired, because growth changes and technical inaccuracies confound the detection of one-to-one correspondences between regions of interest on different films. Although some areas of relative stability in cranial base and the mandible have been reported by a number of authors,[1-8] it is now generally accepted that no truly stable reference planes exist in the jaws—at least in growing subjects. The best approximations of such stable references are considered to be those obtained by the placement of artificial metal marker-implants of the type pioneered by Bjørk.[9-14]

Using records from a sample of subjects in whom metallic markers of the Bjørk type had been implanted, the present investigators have

Abstract

The purpose of this study was to quantify the amount of alveolar modeling at the apices of the mandibular incisor and first molar specifically associated with appositional and resorptive changes on the lower border of the mandible during growth and treatment. Cephalometric data from superimpositions on anterior cranial base, mandibular implants of the Björk type, and anatomical "best fit" of mandibular border structures were integrated using a recently developed strategy, which is described. Data were available at annual intervals between 8.5 and 15.5 years for a previously described sample of approximately 30 children with implants. The average magnitudes of the changes at the root apices of the mandibular first molar and central incisor associated with modeling/remodeling of the mandibular border and symphysis were unexpectedly small. At the molar apex, mean values approximated zero in both anteroposterior and vertical directions. At the incisor apex, mean values approximated zero in the anteroposterior direction and averaged less than 0.15 mm/year in the vertical direction. Standard deviations were roughly equal for the molar and the incisor in both the anteroposterior and vertical directions. Dental displacement associated with surface modeling plays a smaller role in final tooth position in the mandible than in the maxilla. It may also be reasonably inferred that anatomical best-fit superimpositions made in the absence of implants give a more complete picture of hard tissue turnover in the mandible than they do in the maxilla.

Key Words

Cephalometrics • Metallic implants • Mandibular modeling/remodeling • Alveolar modeling/remodeling • Craniofacial growth

Submitted: February 1996 **Revised and accepted:** July 1996 Angle Orthod 1997; 67(2):93-102.

Table 1
Summary demographics

	TP-1	TP-3	TP-5	TP-8
Nominal Age	8.5	10.5	12.5	15.5
N at Timepoint	30	28	24	19
Age (Mean)	8.50	10.51	12.50	15.53
Std ERROR	0.05	0.05	0.06	0.06
M/F Ratio	11/19	10/18	8/16	8/11

Case #	Sex	TP-1	TP-3	TP-5	TP-8
1	M	•	•	•	
2	M	•	•	•	•
3	M	•	•	•	•
4	M	•	•	•	•
5	F	•		•	
6	M	•	•	•	•
7	F	•	•	•	
8	F	•	•	•	
9	F	•	•	•	•
10	M	•		•	•
12	F	•	•	•	•
14	F	•	•	•	•
15	M	•	•		•
17	F	•	•	•	
19	F	•	•	•	•
20	F	•	•	•	•
21	F	•	•	•	•
22	F	•	•		
24	F	•	•	•	•
25	F	•	•	•	
26	F	•	•	•	•
27	F	•	•	•	•
28	F	•	•	•	•
29	M	•	•		•
30	M	•	•	•	
31	M	•	•	•	
32	M	•	•		•
33	F	•	•		•
35	F	•	•	•	
36	F	•	•		
N at timepoint		30	28	24	19

previously attempted to quantify the magnitude, location and variability of bony remodeling on the surfaces of the maxilla[15] and mandible[16] through time; to assess the biases of common methods for making anatomical superimpositions in the absence of implants;[17,18] and to monitor transverse development of the mandible in three dimensions.[19,20] More recently, we have used information from three kinds of cephalometric superimpositions to quantify the displacements of specific maxillary dental landmarks that occur in association with appositional and resorptive changes on the superior and anterior surfaces of the hard palate during growth and treatment.[21] In the present paper we present a parallel investigation of tooth displacements within the mandible and we compare the displacements of teeth in the mandible with those in the maxilla.

Rationale

Quantitative measurement of the displacement of the jaws and teeth within the skull is crucial to improving our understanding of the processes of growth and treatment. The main modality available for making such measurements is the superimposition of standardized lateral skull X-ray images generated at different timepoints. Superimposition of images on selected areas of interest, (e.g., anterior cranial base or the bony maxilla or mandible) has a considerable advantage over generalized angular and linear measurements of the whole skull because superimpositions allow us to differentiate displacements due to local growth and treatment effects from those which occur as secondary consequences of morphological changes at more distant sites.

Yet since the early work of Broadbent[22] and Krogman,[23] investigators and clinicians have been confronted by a fundamentally insoluble problem: precisely what structures should one superimpose on? The early answer was simply "on the center of growth," but morphological investigations and a consideration of geometrical first principals have taught us the impossibility of such an approach. We have learned to our chagrin that what appear to be centers of growth change continuously through time because the major osseous structures of the growing skull change continuously in size and shape, with each structure changing at a different rate even within the same individual. Thus, while one certainly can calculate mathematically the instantaneous center of rotation of either jaw for any single pair of lateral cephalograms,[24,25] the centers thus calculated for any series of cephalograms generated within the subject at several different timepoints will not superimpose. Rather, a series of centers will be generated that may be randomly distributed or displaced in an irregular path (such as that which Bennett,[26] in a somewhat similar context, called a *centrode*); in either case, their biological meaning is usually unclear.

With the realization that the quest for a single superimpositional growth center was, at best, ephemeral, the search for alternatives was on. Time has shown that the best approximations of constancy, at least for the purposes of reference, are those obtained using the implant method of Bjørk and associates, but the biological underpinnings of this method are worth a brief restatement. Studies of osseous modeling and remodeling had established by the mid-1800s that, at least at the gross morphological level, changes in the size and shape of bones occurred only at surfaces.[27] Shape and size change mechanisms on osseous surfaces can be either periosteal, sutural, or endochondral (where endochondral changes include epiphyseal, synchondrotic, and condylar).

The developmental and treatment-associated displacements of the teeth within their alveoli are no exception to this general rule. Since teeth are positioned at the surfaces of the bony jaws, the periodontal ligament can for the present purposes be considered a slightly modified extension of the periosteum. Within the depth of the bone, structural reorganization of the Haversian canal systems can and does take place, but this reorganization (i.e., remodeling) does not involve macroscopic changes in size or shape. That is why the distances between well-placed implants of the Bjørk type in a single bone do not change their dimensional relationships to each other through time and why we say that there is no interstitial growth of bone.

Materials and methods

The data reported in this study were acquired from the same sample, records set, and data set from which the data for the preceding articles in this series[15-18,21] were drawn. The sample consists of growing subjects with moderately severe Class I and Class II malocclusions in whom maxillary and mandibular implants of the Bjørk type were placed. Longitudinal records were collected under the supervision of Dr. J. Rodney Mathews.[28] For the purposes of the present project, a subset of 30 treated and untreated subjects was selected from an original group of 36 in a manner that has been previously described.[15] The cases and timepoints are identical with those in our recent report on the displacements of maxillary teeth,[21] with the exception of the fact that mandibular data for Case 05 are missing at the 10.5-year timepoint. The demographics of the subset are summarized in Table 1.

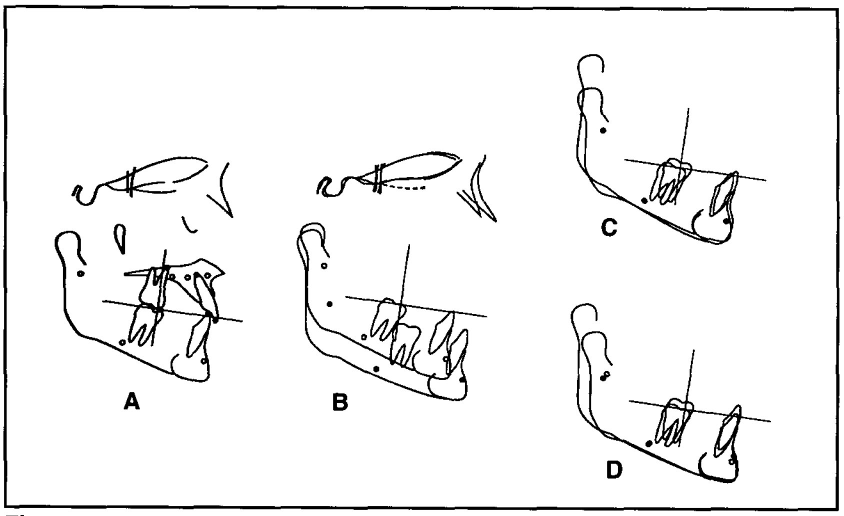

Figure 1

Figure 1
Semischematic representation of the measurement rationale for a single representative case.
A. Baseline tracing illustrating the location of the incisor and molar landmarks and the establishment of a coordinate frame of reference in which the x-axis is the Downs occlusal plane. The three remaining details of this figure represent superimposition of tracings from different timepoints. Note that for all superimpositions measurements are made relative to the transferred baseline frame of reference.
B. Total displacement measured relative to superimposition on anterior cranial base (ACB).
C. Local displacement measured relative to superimposition on mandibular implants (IMP_MAND). Note that the implants from the two timepoints superimpose upon each other almost perfectly.
D. Local displacement measured relative to superimposition on anatomical best fit of the mandible (A_MAND). Note that the implants from the two timepoints no longer fit as well in this case and that the implants from the later timepoint are systematically displaced upward. After physical data from these three superimpositions have been obtained, secondary displacement is calculated as total displacement minus local displacement. The amount of local adjustment required at each landmark to compensate for modeling/remodeling on the mandibular surface is calculated as superimposition on anatomical best fit of the mandible minus superimposition on mandibular implants.

The methods of data acquisition have also been outlined earlier.[29,30] Figure 1 summarizes the physical operations used to make the measurements. First, in order to estimate total tooth displacement with respect to the cranium between timepoints, tracings from two timepoints were superimposed on anterior cranial base. For this purpose, the image of anterior cranial base on each cephalogram was outlined by each judge on a separate acetate overlay (tracing) and the tracings of the films from successive timepoints were best fit (Figure 1B). "Best fit of anterior cranial base" (ACB) was defined as the judge's best estimate of the optimal fit of the two films' images of the anatomical structures of the floor of the anterior cranial fossa

Table 2
Method errors for double-determined mandibular superimpositions (standard deviations for double determinations for each type of superimposition for 60 representative film pairs taken 1 year apart)

		A_MAND	IMP_MAND
Measured at pogonion	X	0.40	0.32
	Y	0.68	0.24
Measured at gonion	X	0.51	0.25
	Y	1.19	0.68

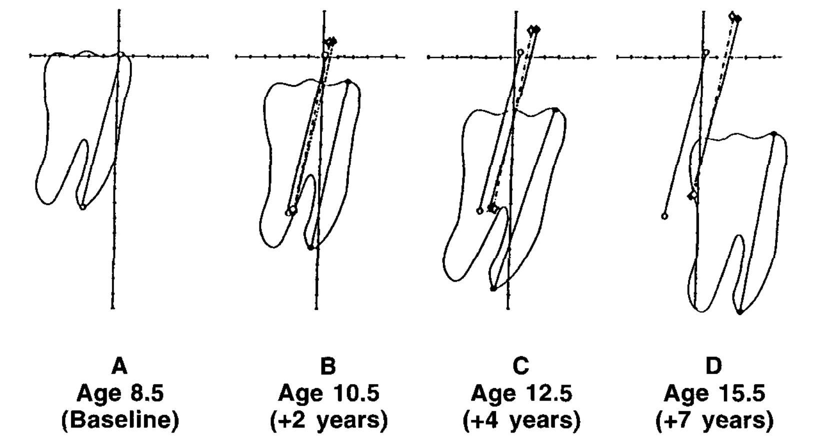

Figure 2
Lower molar displacement at four timepoints showing the effects of three kinds of superimposition at each timepoint. (One unit of scale equals 2 mm. The occlusal plane frame of reference has been oriented horizontally.)
A. The 8.5-year-old baseline.
B. Local and total displacements from baseline at age 10.5.
C. Local and total displacements from baseline at age 12.5.
D. Local and total displacements from baseline at age 15.5.
The baseline positions of the molar cusp and apex are represented by open circles. At each age beyond the baseline, filled circles represent displacement relative to ACB superimposition, filled diamonds represent cusp and apex displacement relative to IMP_MAND superimposition, and open diamonds represent displacement relative to A_MAND superimposition. The horizontal axis represents the baseline occlusal plane and characteristic solid or broken lines connect the symbols representing the cusp and apex for each superimposition at each timepoint. For each landmark at each time interval, mean total displacement relative to ACB superimposition is represented by the distance between the open circle and the filled circle; mean local displacement relative to the IMP_MAND superimposition is represented by the distance between the open circle and the filled diamond; and mean local displacement relative to the A_MAND superimposition is represented by the distance between the open circle and the open diamond. Mean secondary displacement relative to the IMP_MAND superimposition is represented by the distance between the filled diamond and the filled circle and mean secondary displacement relative to A_MAND superimposition is represented by the distance between the open diamond and the filled circle. At each timepoint beyond the baseline, displacement relative to ACB was in a generally downward and forward direction with a minimum of rotation. Local displacement relative to IMP_MAND superimposition is seen to be very similar to that relative to A_MAND superimposition. Data points represent mean values from columns 1, 2, and 3 of Table 3. Tooth outlines have been generated freehand and are not necessarily to scale.

and the greater wings of the sphenoid where primary consideration is given to the region between the anterior clinoid processes and crista galli.

Then, two mandibular superimpositions were made by each judge for each film pair. The first of these was based entirely on the metallic implants and hence is designated IMP_MAND. (See Figure 1C.) For this superimposition, all mandibular implants on each image were identified and traced on an acetate overlay of each cephalogram. The tracings from each successive pair of timepoints were then superimposed with the images of the mandibular implants best fit by eye. Drifting or loss of individual implants could then be detected by failure of their images to superimpose on tracings from successive timepoints.[20] If the images of any single implant on successive tracings failed to contact when the entire group of implants was best fit, then that implant was considered to be unreliable and was dropped from consideration in computing the mandibular best fit for that pair of images. Any implant deemed unreliable was also excluded from consideration in best fitting the tracings for all subsequent timepoints for that subject.

The second mandibular superimposition was made using an anatomically defined best fit rule without reference to the implants and is designated A_MAND. (See Figure 1D.) The images of the mandibular border were outlined by each judge on his/her tracing of each cephalogram and the tracings of the films from successive timepoints were best fit. "Anatomical best fit of the mandible" was defined as the judges' best estimate of the optimal fit of the two images of the mandible where primary consideration is given to the inner table of the symphysis and the average between the bilateral images representing the lower borders of the mandible while the relationship between the images of the ascending rami is ignored.

For any landmark within the mandible, displacement relative to superimposition on ACB constitutes a reasonable measurement of total displacement, while displacement relative to each of the two mandibular superimpositions yields a slightly different measurement of local displacement. Subtracting either estimate of local displacement from total displacement (i.e., ACB minus IMP_MAND, or ACB minus A_MAND) yields a residuum, which we have called secondary displacement.[21] From the general perspective of biological growth and development, local displacements of teeth are those that occur within the periodontium, while secondary displacements are indirect consequences of changes that occur elsewhere in the skull, including sutural growth, endochondral growth, and surface apposition and resorption. In common clinical usage, local displacements of teeth in subjects undergoing orthodontic treatment are typically described as orthodontic changes, while secondary displacements are typically called orthopedic. In subjects not undergoing orthodontic treatment, normal local displacements are typically designated by terms such as eruption, mesial drift, and dental compensation, while abnormal local displacements are described by terms such as migration, extrusion, and proclination.

Data for four dental landmarks were examined. (See Figure 1A.) These landmarks were (1) L6C, the mesiobuccal cusp of the lower first molar; (2) L6A, the apex of the mesial root of the lower first molar; (3) LIE, the incisal edge of the lower central incisor; and (4) LIA, the apex of the root of the lower central incisor. Earlier, at the time of data acquisition, the four had been operationally defined as follows:

L6C — the occlusal-most point on the image of the more anteriorly positioned lower first molar.

L6A — the point of intersection between the long axis of the mesial root of the more anteriorly positioned lower first molar and the contour of the curvature of that root's surface.

LIE — the tip of the incisal edge of the more anteriorly placed lower central incisor.

LIA —the point of intersection between the long axis of the more anteriorly positioned lower central incisor and the contour of the tooth's root end curvature.

All landmark locations and superimpositions were performed independently by two skilled judges and the averages were stored in our numerical database.[29,30] In cases in which the two judges did not agree within previously specified limits, an additional tracing was made by a third judge. The relationships among the landmarks and superimpositions were analyzed in a series of computer-conducted operations using a specialized coordinate geometry program, COGO,[30,31] and the SAS Statistical Package.[32] All measurements for each landmark are reported as displacements from that landmark's original position on the 8.5-year film. Measurements for each landmark are reported in terms of a coordinate system oriented parallel (x) and perpendicular (y) to the occlusal plane of the reference film (See Figure 1A). For this purpose, occlusal plane is defined (after Downs) as the line that passes through the midpoint between the mesiobuccal cusps of the maxillary and mandibular first molars, and the midpoint between the incisal edges of the maxillary and mandibular central incisors.

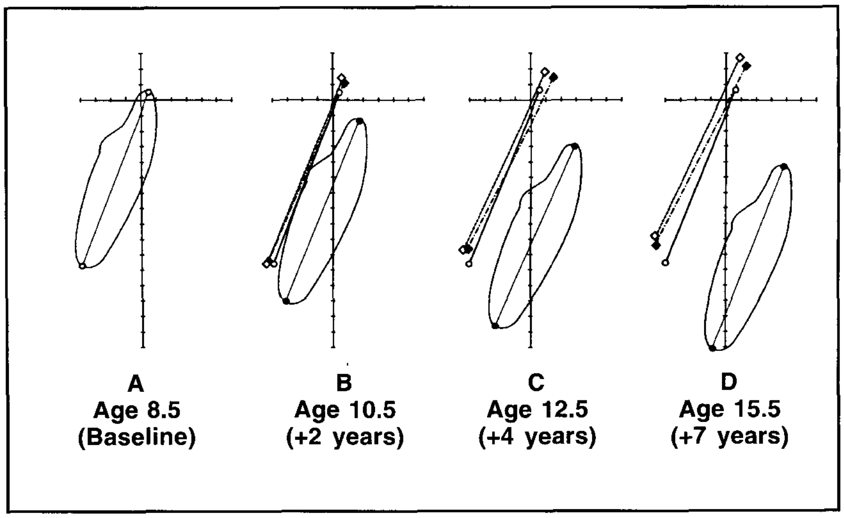

Figure 3
Lower incisor displacement at four timepoints showing the effects of three kinds of superimposition at each timepoint. (One unit of scale equals 2 mm. For illustrative simplicity, the occlusal plane frame of reference has been oriented horizontally.)
A. The 8.5-year-old baseline.
B. Local and total displacements from baseline at age 10.5.
C. Local and total displacements from baseline at age 12.5.
D. Local and total displacements from baseline at age 15.5.
This figure plots mean values from Table 4 and is precisely analogous to Figure 2.

Method errors

The data acquisition errors relevant to the present study accrue from landmark location and image superimposition. Because the two mandibular superimpositions for each case and timepoint use the same set of landmark locations, the errors in landmark location are common to the two superimpositions and therefore cancel out for the purposes of this study. Method errors for within-film double determinations for the two superimpositional rules are supplied in Table 2.

Results

As in our previous study of maxillary dental displacements,[21] the basic findings of this study are the outcomes of the landmark location and superimpositional operations just described. Figure 2 illustrates graphically and to scale the components of mean mandibular molar displacement as accounted for by all three superimpositions (ACB, IMP_MAND, and

Table 3
Displacements of the lower first molar cusp and apex
(means ± standard deviations measured relative to the original Downs occlusal plane)

		Total Displacement Col. 1 ACB	Local displacement Implant Col. 2 IMP_MAND	Local displacement Anatomical Col. 3 A_MAND	Secondary displacement Implant Col. 4 ACB-IMP_MAND	Secondary displacement Anatomical Col. 5 ACB-A_MAND	Between-sup Differences Col. 6 A_MAND-IMP_MAND	Prob. Col. 7
L 6 Cusp								
Two years	X	2.94 ± 2.08	1.01 ± 1.66	0.71 ± 1.49	1.94 ± 1.59	2.23 ± 1.64	-0.30 ± 0.85	NS
(n=28)	Y	-3.44 ± 1.18	1.73 ± 1.21	1.65 ± 1.10	-5.17 ± 1.92	-5.09 ± 1.89	-0.08 ± 0.82	NS
Four years	X	5.26 ± 2.81	2.39 ± 2.48	1.62 ± 2.20	2.87 ± 2.06	3.64 ± 2.30	-0.77 ± 1.34	< 0.01
(n=24)	Y	-7.17 ± 2.29	3.06 ± 1.93	2.96 ± 1.77	-10.22 ± 3.49	-10.13 ± 3.44	-0.10 ± 0.90	NS
Seven years	X	9.63 ± 3.61	4.83 ± 2.59	4.05 ± 2.42	4.80 ± 2.73	5.58 ± 3.08	-0.78 ± 1.51	< 0.04
(n=19)	Y	-10.40 ± 3.08	4.43 ± 1.80	4.65 ± 1.71	-14.83 ± 4.33	-15.04 ± 4.27	0.21 ± 1.15	NS
L 6 Apex								
Two years	X	2.99 ± 2.31	0.53 ± 1.70	0.59 ± 1.50	2.46 ± 1.73	2.40 ± 1.84	0.06 ± 0.75	NS
(n=28)	Y	-5.39 ± 2.13	-0 11 ± 1.69	-0.27 ± 1.45	-5.28 ± 1.88	-5.12 ± 1.83	-0.16 ± 0.86	NS
Four years	X	5.90 ± 3.54	1.79 ± 2.68	1.93 ± 2.54	4.11 ± 2.57	3.97 ± 2.71	0.15 ± 1.03	NS
(n=24)	Y	-9.79 ± 3.42	0.65 ± 2.58	0.39 ± 2.20	-10.44 ± 3.48	-10.18 ± 3.36	-0.26 ± 0.95	NS
Seven years	X	9.94 ± 4.43	3.11 ± 2.70	3.23 ± 2.37	6.83 ± 3.74	6.71 ± 3.84	0.12 ± 1.16	NS
(n=19)	Y	-13.35 ± 3.93	1.85 ± 2.32	1.86 ± 2.52	-15.19 ± 4.28	-15.21 ± 4.16	0.01 ± 1.21	NS

A_MAND) at each of the four timepoints under study. Figure 3 supplies similar graphical information for the mandibular central incisor. In each of these two figures, the occlusal plane has been rotated so that the details for all four timepoints can be represented along a single horizontal x-axis. The effect of this modification in orientation is to upright the graphics for the molar and incisor just as the teeth on a lower study cast are uprighted when the cast is examined with its occlusal plane oriented horizontally.

Tables 3 and 4 supply numerical statistics concerning the displacements of the molar and incisor, respectively. Means and standard deviations for total displacement relative to ACB, local displacement relative to IMP_MAND, and local displacement relative to A_MAND are listed in columns 1, 2, and 3 of each of these two tables. The findings for the displacement of the two teeth differ slightly, so we will consider them separately. Data for both the occlusal and apical landmarks are supplied for both teeth, but this presentation will focus on the apical landmarks because they are more interesting in terms of the interactions between alveolar changes and surface remodeling.

As far as the molar is concerned, average total displacement relative to ACB involved downward and forward translation with a barely perceptible tendency to upright. Comparison of local displacement relative to IMP_MAND with local displacement relative to A_MAND revealed smaller mean differences than we had expected. Examination of columns 6 and 7 of Table 3 indicates (1) that there were no statistically significant differences in the vertical direction for either the molar cusp or apex at any timepoint; (2) that the only statistically significant differences in the horizontal direction occurred at the cusp over the 4- and 7-year time intervals; and (3) that at the two timepoints in which statistically significant differences were found, the best estimates of the mean differences were between 0.11 and 0.15 mm per year. These values are far smaller than the measurement errors associated with locating the mandibular molar cusp in individual cases.[33]

Statistics for secondary displacement of the molar may be found in columns 4 and 5 of Table 3. Secondary tooth displacement in the mandible measures the sum of all growth changes in the cranium plus the sum of all dental and osseous changes in the maxilla. Figure 2 and the data of Table 3 demonstrate in graphic and numerical form the fact that local and secondary growth of the mandible, unlike the case in the maxilla, carries the tooth in opposite directions. (Relative to cranial base, the jaw itself moves downward while the teeth within the jaw move upward.)

Figure 3 and Table 4 provide analogous information for the displacements of the mandibular central incisor. As was the case for the molar, total displacement relative to ACB in-

Table 4
Displacements of the lower incisor edge and apex
(means ± standard deviations measured relative to the original Downs occlusal plane)

		Total Displacement Col. 1 ACB	Local displacement Implant Col. 2 IMP_MAND	Anatomical Col. 3 A_MAND	Secondary displacement Implant Col. 4 ACB-IMP_MAND	Anatomical Col. 5 ACB-A_MAND	Between-sup Differences Col. 6 A_MAND-IMP_MAND	Prob. Col. 7
L I Edge								
Two years	X	2.71 ± 1.83	0.80 ± 1.40	0.49 ± 1.08	1.91 ± 1.58	2.22 ± 1.64	-0.31 ± 0.86	NS
(n=28)	Y	-3.32 ± 2.09	1.19 ± 0.98	1.56 ± 0.95	-4.51 ± 2.27	-4.88 ± 2.39	0.37 ± 0.71	< 0.01
Four years	X	4.59 ± 3.08	1.76 ± 1.93	0.99 ± 1.74	2.83 ± 1.98	3.60 ± 2.27	-0.77 ± 1.34	< 0.01
(n=24)	Y	-6.71 ± 3.09	2.01 ± 1.98	3.01 ± 2.05	-8.73 ± 3.86	-9.72 ± 4.05	1.00 ± 1.03	< 0.001
Seven years	X	6.10 ± 2.63	1.40 ± 2.60	0.61 ± 2.44	4.70 ± 2.69	5.49 ± 3.04	-0.79 ± 1.49	< 0.04
(n=19)	Y	-9.44 ± 4.14	3.28 ± 1.77	4.42 ± 1.79	-12.72 ± 5.00	-13.87 ± 5.10	1.14 ± 1.23	< 0.001
L I Apex								
Two years	X	1.54 ± 2.52	-0.90 ± 1.79	-0.84 ± 1.46	2.44 ±1.71	2.38 ± 1.82	0.06 ± 0.76	NS
(n=28)	Y	-4.70 ± 3.51	0.06 ±2.70	0.26 ± 2.74	-4.76 ± 2.11	-4.97 ± 2.20	0.21 ± 0.70	NS
Four years	X	3.45 ± 3.57	-0.59 ± 2.14	-0.48 ± 1.57	4.04 ± 2.47	3.93 ± 2.66	0.11 ± 1.04	NS
(n=24)	Y	-7.96 ± 3.65	1.34 ± 3.03	1.92 ± 3.15	-9.29 ± 3.67	-9.88 ± 3.80	0.58 ± 0.92	< 0.005
Seven years	X	5.78 ± 4.03	-0.92 ± 2.69	-0.85 ± 2.09	6.70 ± 3.67	6.62 ± 3.77	0.07 ± 1.14	NS
(n=19)	Y	-10.82 ± 4.02	2.73 ± 2.53	3.51 ± 2.35	-13.55 ± 4.70	-14.33 ± 4.76	0.78 ± 1.15	< 0.01

Table 5
Comparison of perceived differences in local displacement as a function of superimposition
(means and standard deviations; absolute values in mm)

		Lower first molar Between-Sup Differences I A_MAND - IMP_MAND I	Prob.	Upper first molar Between-Sup Differences I A_MAX - IMP_MAX I	Prob.	Lower central incisor Between-Sup Differences I A_MAND - IMP_MAND I	Prob.	Upper central incisor Between-Sup Differences I A_MAX - IMP_MAX I	Prob.
Cusp/edge									
Two years	X	0.30 ± 0.85	NS	0.45 ± 0.79	< 0.005	0.31 ± 0.86	NS	0.44 ± 0.78	< 0.006
(n: L=28; U=29)	Y	0.08 ± 0.82	NS	1.11 ± 0.92	< 0.0001	0.37 ± 0.71	< 0.01	1.30 ± 1.04	<0.0001
Four years	X	0.77 ± 1.34	< 0.01	0.69 ± 1.01	< 0.003	0.77 ± 1.34	< 0.01	0.62 ± 1.12	< 0.02
(n=24)	Y	0.10 ± 0.90	NS	1.91 ± 1.10	< 0.0001	1.00 ± 1.03	< 0.001	2.05 ± 1.73	< 0.0001
Seven years	X	0.78 ± 1.51	< 0.04	0.85 ± 1.73	< 0.05	0.79 ± 1.49	< 0.04	0.76 ± 1.88	< 0.1
(n=19)	Y	0.21 ± 1.15	NS	2.91 ± 1.10	< 0.0001	1.14 ± 1.23	< 0.001	2.78 ± 2.61	< 0.0002
Apex									
Two years	X	0.06 ± 0.75	NS	0.33 ± 0.79	< 0.04	0.06 ± 0.76	NS	0.32 ± 0.75	< 0.03
(n:L=28; U=29)	Y	0.16 ± 0.86	NS	1.09 ± 0.86	< 0.0001	0.21 ± 0.70	NS	1.23 ± 0.82	< 0.0001
Four years	X	0.15 ± 1.03	NS	0.60 ± 0.94	< 0.005	0.11 ± 1.04	NS	0.60 ± 0.90	< 0.004
(n=24)	Y	0.26 ± 0.95	NS	1.85 ± 0.95	< 0.0001	0.58 ± 0.92	< 0.005	1.95 ± 1.18	< 0.0001
Seven years	X	0.12 ± 1.16	NS	0.91 ± 1.26	< 0.006	0.07 ± 1.14	NS	0.92 ± 1.25	<0.005
(n=19)	Y	0.01 ± 1.21	NS	2.78 ± 1.04	< 0.0001	0.78 ± 1.15	< 0.01	2.71 ± 1.90	<0.0001

volved downward and forward displacement, but here there was a modest rotation of the incisor, tending, on average, to increase the tooth's proclination slightly. As far as local changes are concerned, again the mean differences between the implant IMP_MAND and A_MAND superimpositions were, though statistically significant, small in absolute terms (i.e., less than 1 mm). These differences are probably related to the fact that the A_MAND superimposition tends systematically to underestimate small appositional changes in the region of menton.[18]

Discussion

In this section, we will consider four subjects: (1) a comparison of the magnitudes of difference in mean local displacement of incisor and molar landmarks for two types of mandibular superimposition (i.e., change relative to

A_MAND versus change relative to IMP_MAND); (2) between-case variability for the same measures; (3) the biological meaning of the differences observed for the two mandibular superimpositions, and (4) a comparison of the differences between the two mandibular superimpositions and the previously reported differences between the two analogous maxillary superimpositions.

(1) The most striking and least expected finding of this study is that the mean differences in local tooth displacement differ so little between the implant and the anatomical superimpositions. The data from Tables 3 and 4 clearly demonstrate that mean between-superimposition differences do not exceed 0.2 mm per year in either the x or y direction for any of the four dental landmarks under consideration. For all landmarks, the differences observed between the anatomical and implant superimpositions were smaller than had been anticipated. This was true even though the investigators chose to use an anatomical superimpositional rule that some have considered to be relatively unsophisticated.

(2) Examination of the standard deviations in Table 3 showed that between-case variability in landmark displacement relative to all three superimpositions was quite consequential compared with the values of the means. Such variability tends to compound the problem of predicting changes in individual cases. The standard deviations for local displacement relative to both the A_MAND and IMP_MAND superimpositions approached or exceeded mean displacement values at both cusp and apex, particularly at the 2- and 4-year time intervals. Between-case variability measured relative to superimposition on implants was generally at least equal to that measured relative to best fit superimposition on anatomical structures. Variability tended to become greater as the time interval from the 8.5-year baseline increased. These observations are consistent with the idea that patterns of apposition and resorption on the mandibular surface differ among individuals.

(3) In order to evaluate the meaning of the fact that the between-superimposition differences were so small, we re-examined our theory concerning the relationship between the A_MAND and IMP_MAND superimpositions. At the outset of this general study in the mid-1980s, we believed that the implant superimposition was the only completely valid one, and that all anatomical superimpositions were merely alternative approximations to be used with regret in that vast majority of subjects for whom implants were not available. In the course of our recent attempts to partition more precisely the components of tooth displacement within the maxilla,[21] we have come to realize that such a view disregards valuable information uniquely encoded in the anatomical superimpositions themselves.

Our present view starts with an analysis of the special properties of each type of superimposition. What follows is an extension of the line of thinking developed earlier for partitioning the components of maxillary tooth displacement,[21] now applied to the slightly different conditions of the mandible: The advantage and special property of implant superimposition is that it reflects all developmental changes in mandibular size and shape between timepoints including changes on the various mandibular surfaces. The anatomical superimposition, on the other hand, is insensitive to appositional and resorptive changes on the mandibular surfaces, particularly those on the inferior border. Thus, the two types of superimposition measure overlapping but somewhat different biological phenomena. Both measure local changes within the mandible. But while the IMP_MAND superimposition takes into consideration the effects of surface osseous apposition and resorptive changes, the A_MAND superimposition measures local displacement (e.g., of the teeth) without taking those surface osseous changes into consideration.

Because the two methods overlap considerably, we should not be surprised to find considerable similarities in their outcomes. Indeed, those similarities are precisely the reason why the A_MAND superimposition has long been considered a fairly satisfactory surrogate for the IMP_MAND superimposition in cases where no implants are present. On the other hand, precisely because the definitions and procedures of the two types of superimposition are not identical, we should not be surprised to find some differences between them at each landmark. The question is how large those differences are and what they mean. We suggest that these differences (measured in x and y) represent valuable quantitative estimates of displacement directly associated with surface osseous changes as expressed at each particular landmark.

From a conceptual point of view, this operation is analogous to the way we customarily measure treatment-associated orthopedic change in either jaw by subtracting orthodontic change relative to superimposition on the maxilla or mandible from total change relative to superimposition on ACB. Note that none of these operations, taken by itself, tells us anything about cause. Just as total change does not cause orthodontic or orthopedic change, so change on the mandibular surface does not cause change at the molar and incisor apices. However, in each case knowledge of the relative magnitudes of the associations between changes can help us toward an understanding of the biological processes involved.

(4) Finally, we may ask how apical alveolar accommodations for surface remodeling in the mandible compare in magnitude with the analogous accommodations in the maxilla. For this purpose, we compare the values for A_MAND minus IMP_MAND with the previously reported values for A_MAX minus IMP_MAX. Table 5 supplies comparative data for these relationships. Again our focus is on the apical regions in which actual bone turnover is occurring; statistics for this can be found in the lower half of the table. It can be seen that statistically significant tooth displacements associated with surface remodeling were observed in the maxilla at all timepoints, whereas significant differences in the mandible were observed only in the vertical direction at the incisor at the 4- and 7-year time intervals. It can also be seen that mean differences in landmark location between the implant and anatomical superimpositions were less than a quarter as large in the mandible as they were in the maxilla. We also see that the dispersions of the differences between the two types of superimposition (as reflected by their standard deviations) are roughly equivalent in both jaws. When one recalls that implant superimpositions account for developmental changes on the jaw surfaces, while anatomical superimpositions do not, these findings support the conclusion that dental accommodations to surface remodeling are much smaller in the mandible than they are in the maxilla.

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This study was supported by NIH-NIDR Grants #DE07332 and DE08713.

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