Original Article

Partitioning the components of maxillary tooth displacement by the comparison of data from three cephalometric superimpositions

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Local displacements of teeth, which occur within the periodontium, and secondary displacements, which occur as an indirect consequence of sutural or endochondral growth or surface apposition and resorption elsewhere in the skull, may be difficult to differentiate. Our understanding of the biological mechanisms underlying craniofacial growth and response to treatment would be much improved if we could distinguish between these types of displacements. The implant method of Björk and coworkers[1,2] provided orthodontists with an accurate and reliable method for making such distinctions. Data from implant studies have already been used with considerable effect to refine our understanding of jaw rotation[3-5] and modeling/remodeling changes on maxillary and mandibular surfaces.[3-12] However, quantitative data on growth and treatment-associated displacements measured at the loci of the teeth themselves have been scant, despite the fact that specific knowledge concerning displacements of the teeth is important to the understanding of the dimensional changes that occur in the alveolar

Abstract

Using roentgenographic cephalograms from a sample of subjects with metallic implants, appropriately superimposed tracings were used to distinguish developmental and treatment-associated displacements of the maxillary central incisor and first molar associated with "local" changes within the periodontium from "secondary" changes which reflect sutural and appositional growth at more distant osseous loci.

Tracings were superimposed on anterior cranial base (ACB), on the maxillary implants only (IMP_MAX), and according to the best fit of maxillary anatomic structures without reference to the implants (A_MAX). Using the IMP_MAX superimposition, one could measure total local displacement at any landmark taking into consideration the effects of all appositional and resorptive changes on the superior and anterior surfaces of the palate, whereas using the A_MAX superimposition one could measure local displacement without consideration of surface appositional and resorptive changes. If the second of these measurements were subtracted from the first, the result would be a direct measurement of the effects of surface appositional and resorptive changes as they are expressed at that particular landmark.

This strategy has enabled us to quantify and report the amount of accommodation which occurs at the location of each dental landmark in association with the resorptive and appositional changes which occur through time on the superior and anterior surfaces of the hard palate.

Key words

Cephalometrics • Metallic implants • Craniofacial growth • Orthopedic and orthodontic tooth movement.

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bone incident to the delivery of therapeutic forces. This paper develops a method for quantification of tooth displacements at specific dental loci (e.g., the apices and cusps of the maxillary incisor and first molar) by the integration of information from three different types of headfilm superimpositions for subjects with Björk-type implants.

Rationale

The only currently available method which permits distinctions to be made between local/orthodontic and secondary/orthopedic sources of tooth displacement in living subjects is the superimposition of lateral cephalometric images from different time points. De Coster,[13] Broadbent,[14] Brodie,[15] Downs,[16] Krogman and Sassouni,[17,18] Björk and Skieller,[1-8] Koski,[19] Coben,[20] Moorrees,[21] Enlow,[22-24] Ricketts,[25,26] Riedel,[27] Melsen,[28,29] and many others advocated the use of somewhat different rules for optimally relating images from different times, the fundamental conceptions underlying almost all classical descriptions of tooth displacement through time are similar. In almost every case (Björk[3,5] being the exception), total tooth displacement is viewed as the sum of local and secondary displacements and is calculated as the difference between cephalograms from two timepoints when the cephalograms (or tracings of them) are superimposed on some set of relatively stable structures in the cranial base. Local changes in tooth position within either jaw are identified by superimposing images from the two timepoints on relatively stable structures within that jaw. Secondary displacements are then calculated as the difference between total displacement and local displacement. (In clinical use, local displacements in subjects undergoing orthodontic treatment are typically described as orthodontic changes while secondary displacements are typically called orthopedic changes. In subjects not undergoing orthodontic treatment, normal local displacements are 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.)

Although the above-stated rule for partitioning the components of total tooth displacement seems conceptually straightforward, its apparent simplicity masks a problem that has long puzzled craniofacial morphometrists and orthodontic practitioners. All serious investigators have found through experience that the identification of relatively stable structures within the cranial base and the jaws is far from simple because almost all the bones of the craniofacial complex undergo continuous modification during development under the influence of complex biological laws whose application varies from subject to subject. We now realize that, even where the shape of the bones appears to remain relatively constant through time, bone growth occurs not by proportionate expansion in all directions but rather as a result of resorption on some osseous surfaces and apposition on others. With respect to the maxilla, for example, the superior (nasal) surface of the hard palate is a site of net resorption during growth while the inferior (oral) surface of the same bone is a site of net apposition.[6,7,8,22] It is this complexity which has led to the plethora of slightly different superimpositional rules proposed by the expert investigators cited above.

In order to create measurement frames of reference which are stable with respect to these modeling/remodeling changes on the surfaces of the maxilla and mandible, Björk and co-workers pioneered the method of placing inert metal reference markers in the jaws of selected growing subjects.[1,2] To the extent that such markers maintain a constant relationship to each other (without drifting or being lost due to bony resorption), x-ray images of the jaws generated at successive times can be superimposed, thus permitting developmental or treatment changes to be measured without reference to the continuously changing bony surfaces. In an earlier study,[10] we compared the differences in the perceived displacement through time of selected osseous landmarks on the surface of the maxilla referenced alternatively to implants and to the best fit of the maxillary anatomy. In that paper we treated the implant superimposition as the gold standard of true change and the best fit deviations from the implant superimposition as error. In the present paper, after rethinking the meaning of anatomical best fit superimposition, we have found it advantageous to employ information from both anatomical and implant superimpositions in order to further partition the components of tooth displacement through time.

For the purposes of the present study, we reason as follows: Because the image of cranial base on a lateral cephalogram represents the surface along which the face is attached to the cranium, anterior cranial base (ACB) is a reasonable superimpositional framework for measuring overall migration of the teeth with respect to the rest of the head. It therefore seems appropriate to describe tooth displacement relative to ACB as total displacement. The relationship between superimposition on the anatomical best fit of the maxilla (A_MAX) and superimposition on maxillary implants (IMP_MAX) is, however, more complex. First we recall why A_MAX, the simple outline of the hard palate, is not a completely satisfactory superimposition for the evaluation of tooth displacement within the maxilla. The maxilla itself undergoes important surface resorptive and appositional changes during development even when its shape appears substantially unchanged on cephalograms taken at different times. The advantage of the IMP_MAX superimposition is that it reflects all developmental anteroposterior changes in maxillary shape, including those that are substantially immune to detection on conventional cephalograms taken at different times. The A_MAX superimposition, on the other hand, though it does reflect growth at PNS, contains no effective mechanism to account for the resorption on the nasal surface and apposition on the oral surface that have been noted in earlier studies.[6,7,8,22]

Because of the differences, the two types of maxillary superimposition measure overlapping but somewhat different biological phenomena. Both measure local changes within the maxilla. But the IMP_MAX superimposition takes into consideration the effects of surface osseous appositional and resorptive changes while the A_MAX superimposition measures local displacement without taking those osseous changes into consideration. Given the substantial overlap between the two methods, we should not be surprised to find considerable similarities in their outcomes. Indeed, these similarities are what make the A_MAX superimposition a fairly satisfactory surrogate for the IMP_MAX superimposition when no implants are present. On the other hand, precisely because the two procedures overlap but are not identical, the arithmetic differences between them at each landmark (i.e., x2 - x1 and y2 - y1) represent direct quantitative estimates of the dental displacements directly associated with surface osseous remodeling as they are expressed at that particular landmark.

Using this line of reasoning, it is possible to partition total tooth displacement relative to ACB into three interrelated components. These are: (a) secondary displacement as a result of growth at sutures and other developmental interfaces, such as the clivus, which are located between the maxilla and anterior cranial base (i.e., ACB minus IMP_MAX); (b) total local displacement as a consequence of the sum of all changes within the alveolus (i.e., A_MAX per se); and (c) the portion of total local displacement within the alveolus which represents an offset for the growth-associated resorptive and appositional changes on the maxillary surfaces (i.e., A_MAX minus the IMP_MAX standard). Each of these three components of total displacement was quantified in the course of the current study.

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
Case #	Sex				
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	•	•	•	
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

A final caveat is necessary in this statement of experimental design. Not all the local changes in the morphology of the alveolus during growth and treatment can be assumed to take place in the bone. We must bear in mind that the roots of the teeth may also change their conformation during normal growth and orthodontic treatment, both by growth and by resorption. The identification and characterization of the components of change in tooth conformation is, however, not part of this study.

Materials and methods

The data reported in this study were acquired from the same sample and records set from which the data for the preceding articles in this

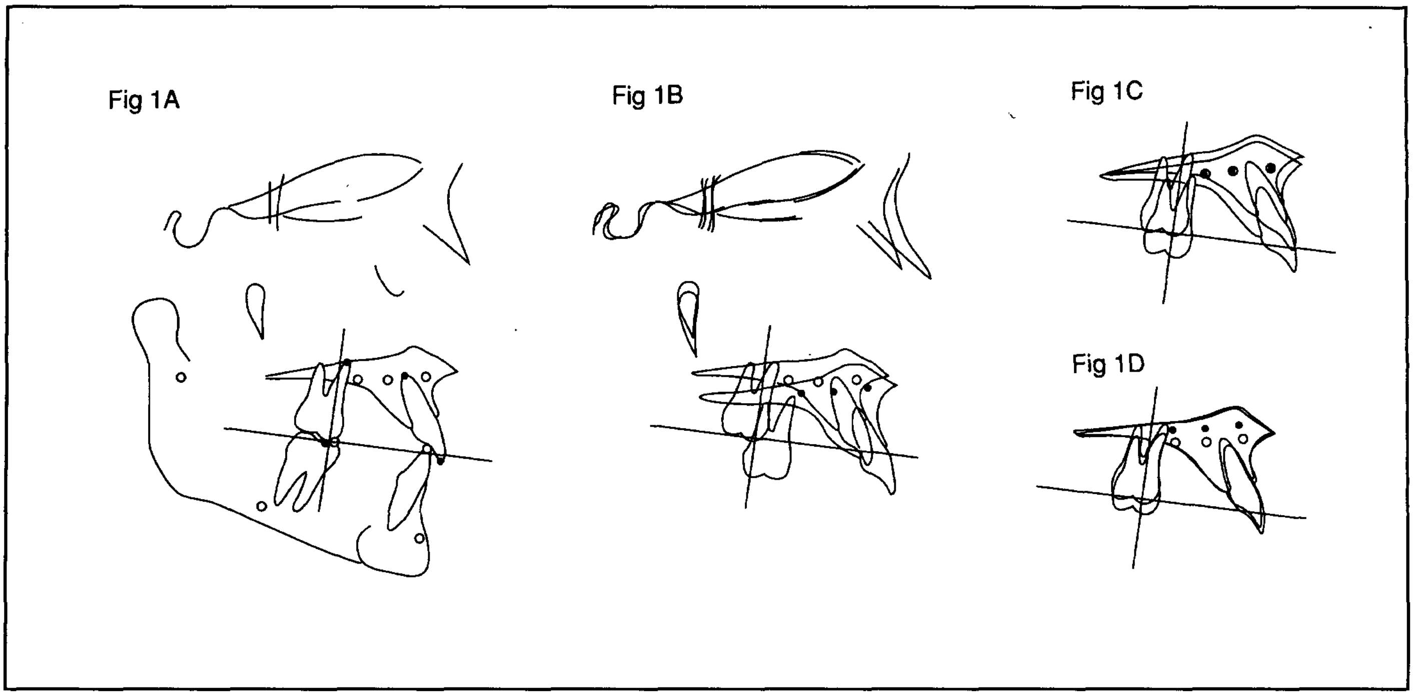

Figure 1

Figure 1A-D
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 maxillary implants (IMP_MAX). Note that the implants from the two timepoints superimpose upon each other almost but not quite perfectly.

D: Local displacement measured relative to superimposition on anatomical best fit of the maxilla (A_MAX). Note that the implants from the two timepoints no longer fit 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 palatal surfaces is calculated as "superimposition on anatomical best fit of the maxilla minus superimposition on maxillary implants."

series[9-12] were drawn. The sample consists of growing subjects with moderately severe Class I or Class II malocclusions in whom maxillary and mandibular implants of the Björk type[1,2] were placed. Longitudinal records were collected under the supervision of Dr. J. Rodney Mathews.[30] For the purposes of the project of which this study is a part, a subset of 31 treated and untreated subjects was selected from an original group of 36 in a manner that has been previously described.[9] The demographics of the final sample are summarized in Table 1. No attempt was made to ensure uniformity among the therapeutic interventions, but all treated subjects had fixed edgewise appliances and most had extra-oral traction. The fact that the sample contained both treated and untreated subjects must be kept in mind when the results of this study are evaluated.

The methods of data acquisition have also been outlined earlier.[9,31] 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 and the greater wings of the sphenoid where primary consideration is given to the region between the anterior clinoid processes and crista galli."

Two maxillary 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_MAX. (See Figure 1C.) For this superimposition, all maxillary 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 maxillary 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.[32,33] If the images of any single implant on successive tracings failed to meet 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 maxillary 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. (Note that this mode of implant superimposition differs from that of Björk's group, which appears to have used only the anteriormost and posteriormost implants for their superimpositions.[4])

The second maxillary superimposition was made using an anatomically defined best fit rule without reference to the implants and is designated A_MAX. (See Figure 1D.) The images of the palatal plane were outlined by each judge on his or her tracing of each cephalogram and the tracings of the films from successive timepoints were best fit. Anatomical best fit of the maxilla was defined as "the best estimate of the optimal fit of the hard palate and anterior maxillary images when primary emphasis is given to concordance of the region between the anterior nasal spine and Point A with the superior surfaces of the hard palate aligned. Reduced attention is given to the fit of the posterior portion of the hard palate."

Landmark location data for four dental landmarks were used. These landmarks, shown on the T1 image in Figure 1A, were (1) U6C, the mesiobuccal cusp of the maxillary first molar, (2) U6A, the apex of the mesial root of the maxillary first molar, (3) UIE, the incisal edge of the maxillary central incisor, and (4) UIA, the apex of the root of the maxillary central incisor. These four dental landmarks had previously been defined as follows:

U6C – the occlusal-most point on the image of the more anteriorly positioned maxillary first molar.

U6A – the point of intersection between the long axis of the mesial root of the more anteriorly positioned maxillary first molar and the contour of the curvature of that root's surface.

UIE – the tip of the incisal edge of the more anteriorly placed maxillary central incisor.

UIA – the point of intersection between the long axis of the more anteriorly positioned maxillary central incisor and the contour of the tooth's root end curvature.

All landmark locations and superimpositions were performed independently by each of two skilled judges and the average of the two estimates was stored in our database. In cases in which the judges did not agree within previously specified limits, an additional tracing was made by a third judge.[31] Data were available for 197 films, with an average of 6.3 timepoints per subject. These previously stored coordinate data were read from the database, and the relationships among them were analyzed in a series of computer-conducted operations using a specialized coordinate geometry program, COGO,[34,35] and the SAS Statistical Package.[36] 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 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 which 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.

For each film, the same landmark location data were used for all superimpositions. For this reason, the errors inherent in landmark location are also common to all superimpositions and cancel out for the purposes of this study.

Results

The basic findings of this study are the outcomes of the landmark location and superimpositional operations just described. The intent of the authors is to analyze, summarize, and comment on the observed data. Of necessity, we have been required to discuss the findings on local and secondary changes sequentially rather than simultaneously. The order of presentation of the findings should not, however, be

Table 2
Displacements of the maxillary first molar cusp and apex
(means ± standard deviations measured relative to the original Downs occlusal plane)

		Total Displacement	Local displacement		Secondary displacement		IABSI Differences Between Sups	Prob.
			Implant	Anatomical	Implant	Anatomical		
Column		1	2	3	4	5	6	7
Superimposition		(ACB)	(IMP_MAX)	(A_MAX)	(ACB)-(IMP_MAX)	(ACB)-(A_MAX)	IA_MAX-IMP_MAXI	
U 6 Cusp								
2 years	X	1.86 ± 1.53	0.68 ± 1.29	1.13 ± 1.22	1.18 ± 1.47	0.73 ± 1.37	0.45 ± 0.79	< 0.005
(n=29)	Y	-3.47 ± 1.15	-2.45 ± 1.37	-1.34 ± 1.18	-1.02 ± 0.91	-2.13 ± 0.64	1.11 ± 0.92	< 0.0001
4 years	X	4.32 ± 2.51	2.39 ± 2.11	3.08 ± 1.63	1.93 ± 2.48	1.25 ± 2.22	0.69 ± 1.01	< 0.003
(n=24)	Y	-7.27 ± 2.50	-4.53 ± 2.34	-2.62 ± 1.99	-2.74 ± 1.41	-4.65 ± 1.43	1.91 ± 1.10	< 0.0001
7 years	X	7.92 ± 3.30	4.98 ± 2.67	5.85 ± 2.53	2.94 ± 3.13	2.10 ± 2.81	0.85 ± 1.73	< 0.05
(n=19)	Y	-10.71 ± 3.02	-7.06 ± 2.30	-4.15 ± 1.73	-3.65 ± 1.96	-6.56 ± 2.02	2.91 ± 1.10	< 0.0001
U 6 Apex								
2 years	X	1.36 ± 1.62	0.01 ± 1.36	0.32 ± 1.30	1.37 ± 0.81	1.04 ± 1.17	0.33 ± 0.79	< 0.04
(n=29)	Y	-2.26 ± 1.18	-1.16 ± 1.28	-0.07 ± 1.13	-1.10 ± 0.90	-2.19 ± 0.68	1.09 ± 0.86	< 0.0001
4 years	X	2.66 ± 2.55	0.23 ± 1.75	0.83 ± 1.70	2.43 ± 1.64	1.83 ± 1.75	0.60 ± 0.94	< 0.005
(n=24)	Y	-5.67 ± 2.43	-2.75 ± 1.39	-0.90 ± 1.27	-2.92 ± 1.38	-4.77 ± 1.50	1.85 ± 0.95	< 0.0001
7 years	X	4.94 ± 2.65	1.23 ± 1.97	2.15 ± 1.89	3.71 ± 1.86	2.80 ± 2.53	0.91 ± 1.26	< 0.006
(n=19)	Y	-9.14 ± 2.69	-5.23 ± 1.96	-2.45 ± 1.50	-3.91 ± 1.94	-6.70 ± 2.10	2.78 ± 1.04	<0.0001

Table 3
Displacements of the maxillary central incisor edge and apex
(means ± standard deviations measured relative to the original Downs occlusal plane)

		Total Displacement	Local displacement		Secondary displacement		IABSI Differences Between Sups	Prob.
			Implant	Anatomical	Implant	Anatomical		
Column		1	2	3	4	5	6	7
Superimposition		(ACB)	(IMP_MAX)	(A_MAX)	(ACB)-(IMP_MAX)	(ACB)-(A_MAX)	IA_MAX-IMP_MAXI	
UI Edge								
2 years	X	2.03 ± 2.33	0.88 ± 2.22	1.32 ± 2.05	1.15 ± 1.52	0.71 ± 1.38	0.44 ± 0.78	< 0.006
(n=29)	Y	-3.69 ± 1.97	-2.33 ± 1.96	-1.04 ± 1.52	-1.36 ± 1.60	-2.65 ± 1.22	1.30 ± 1.04	< 0.0001
4 years	X	3.15 ± 3.71	1.32 ± 3.12	1.95 ± 2.55	1.82 ± 2.59	1.20 ± 2.25	0.62 ± 1.12	< 0.02
(n=24)	Y	-7.36 ± 3.47	-3.76 ± 2.94	-1.71 ± 2.26	-3.59 ± 2.57	-5.65 ± 2.31	2.05 ± 1.73	< 0.0001
7 years	X	3.90 ± 4.62	1.10 ± 4.35	1.86 ± 3.62	2.80 ± 3.27	2.04 ± 2.82	0.76 ± 1.88	< 0.01
(n=19)	Y	-9.79 ± 4.48	-4.82 ± 3.81	-2.04 ± 2.83	-4.97 ± 3.28	-7.74 ± 2.95	2.78 ± 2.61	< 0.0002
UI Apex								
2 years	X	0.84 ± 2.47	0.53 ± 2.17	0.21 ± 1.94	1.37 ± 0.82	1.05 ± 1.19	0.32 ± 0.75	< 0.04
(n=29)	Y	-2.39 ± 2.92	-1.13 ± 2.75	-0.09 ± 2.89	-1.25 ± 1.19	-2.48 ± 0.98	1.23 ± 0.82	< 0.0001
4 years	X	1.91 ± 3.37	0.50 ± 2.50	0.10 ± 2.46	2.41 ± 1.62	1.81 ± 1.77	0.60 ± 0.90	< 0.004
(n=24)	Y	-5.71 ± 4.38	-2.33 ± 3.47	-0.38 ± 3.78	-3.38 ± 1.92	-5.33 ± 1.93	1.95 ± 1.18	< 0.0001
7 years	X	3.77 ± 3.51	0.05 ± 3.01	0.98 ± 2.53	3.72 ± 1.85	2.80 ± 2.51	0.92 ± 1.22	< 0.005
(n=19)	Y	-9.02 ± 4.36	-4.40 ± 3.12	-1.68 ± 3.51	-4.62 ± 2.60	-7.34 ± 2.56	2.71 ± 1.90	<0.0001

taken to indicate a belief on the part of the authors that some of the reported biological changes cause or, alternatively, are consequences of, others. Inferences on causation must be sought from information sources other than headfilm measurements per se.

Tables 2 and 3 list means and standard deviations for the displacements of the incisor molar landmarks at four timepoints (i.e., at the 8.5-year old baseline and at the 2-, 4-, and 7-year intervals thereafter). All points plotted on the remaining figures of this paper represent mean landmark coordinate values abstracted from these two tables.

Figure 2 is designed to facilitate visual comparisons of total molar displacement relative to: (A) superimposition on ACB; (B) local displacement relative to the gold standard IMP_MAX superimposition and; (C) local displacement relative to the A_MAX alternative. Each component fig-

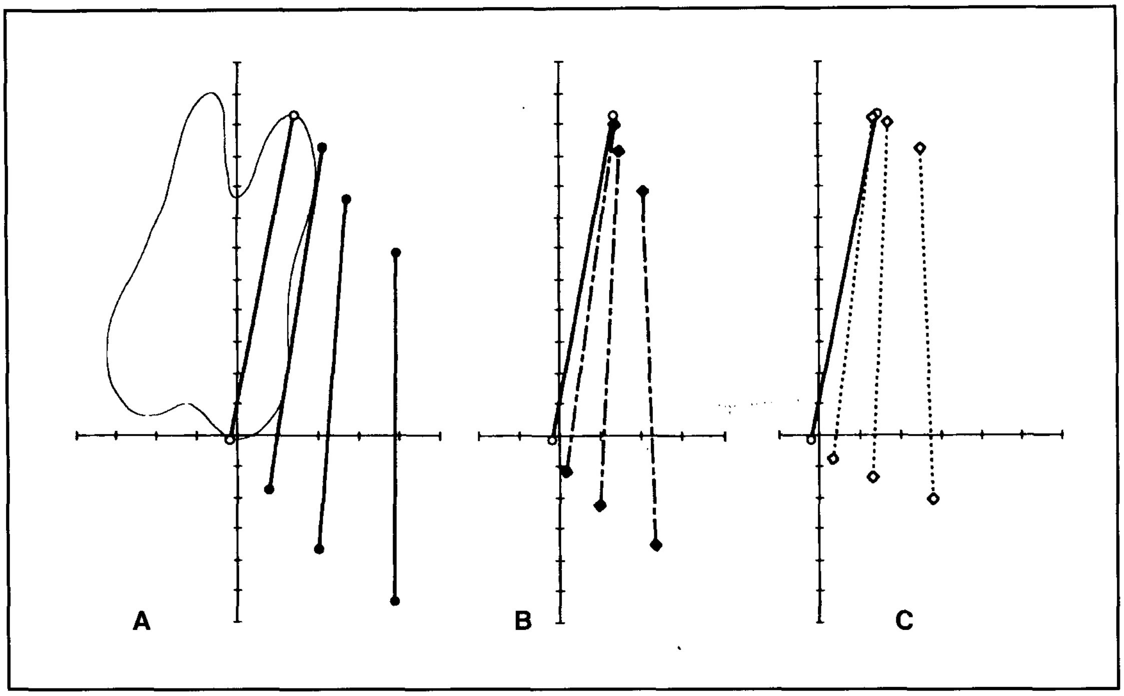

Figure 2

Figure 2
Molar displacement relative to three kinds of superimposition measured at four timepoints: Ages 8.5, 10.5, 12.5, and 15.5. One unit of scale equals 2 mm. (For illustrative simplicity, the occlusal plane frame of reference has been oriented horizontally.)

A: Total displacement measured relative to superimposition on ACB.

B: Local displacement measured relative to Superimposition on IMP_MAX.

C: Local displacement measured relative to superimposition on A_MAX.

Note: A comparison of 2B and 2C shows that local displacement in the downward direction is greater relative to IMP_MAX superimposition and displacement in the forward direction is greater relative to A_MAX superimposition.

ure represents the Table 2 mean positions of the molar cusp and apex at all four timepoints. To facilitate comparisons among them, all three are oriented along a common horizontal line which represents the mean occlusal plane of the baseline 8.5-year film. This arrangement allows one to see the general relationship between local and total displacement. Note the fact that local downward displacement relative to superimposition on the implant gold standard is understated when one superimposes on anatomical structures. To a lesser degree, the anatomical superimposition also seems to overstate the local anterior (i.e., mesial) displacement of the molar as compared with the gold standard implant superimposition.

Another sense of molar displacement through time may be gained by an examination of Figure 3. This figure is designed to facilitate examination of the relationship between total, local, and secondary displacement at each timepoint. Here, each of the four details plots data for all three superimpositions at a single timepoint. The first detail shows the baseline (8.5-year) orientation of the molar with the mean locations of the cusp and apex identified by open circles. In each of the three remaining details (which plot mean values at 10.5, 12.5, and 15.5 years, respectively), filled circles represent displacement relative to ACB superimposition, filled diamonds represent cusp and apex displacement relative to IMP_MAX superimposition, and open diamonds represent displacement relative to A_MAX superimposition. The horizontal axis again represents the timepoint 1 occlusal plane. The mean values of Table 2 quantify the displacements between the symbols in the details of Figure 3 and the standard deviations of the table summarize the distribution of individual case values around those means. For each landmark at each time interval, mean total displacement relative to ACB superimposition (column 1) is represented by the distance between the open circle and the filled circle; mean local displacement relative to the gold standard IMP_MAX superimposition (column 2) is represented by the distance between the open circle and the filled diamond; and mean local displacement relative to the alternative A_MAX superimposition is represented by the distance between the open circle and the open diamond (column 3). Mean secondary displacement relative to the gold standard IMP_MAX superimposition is represented by the distance between the filled diamond and the filled circle with summary statistics in column 4. Finally, mean secondary displacement relative to A_MAX superimposition is represented by the distance between the open diamond and the filled circle and by the statistical values in column 5.

Since total displacement at any timepoint is measured only in terms of the ACB superimposition, its value will be the same for any case and timepoint independent of whether the IMP_MAX or the A_MAX method is used for maxillary superimposition. But since this fixed

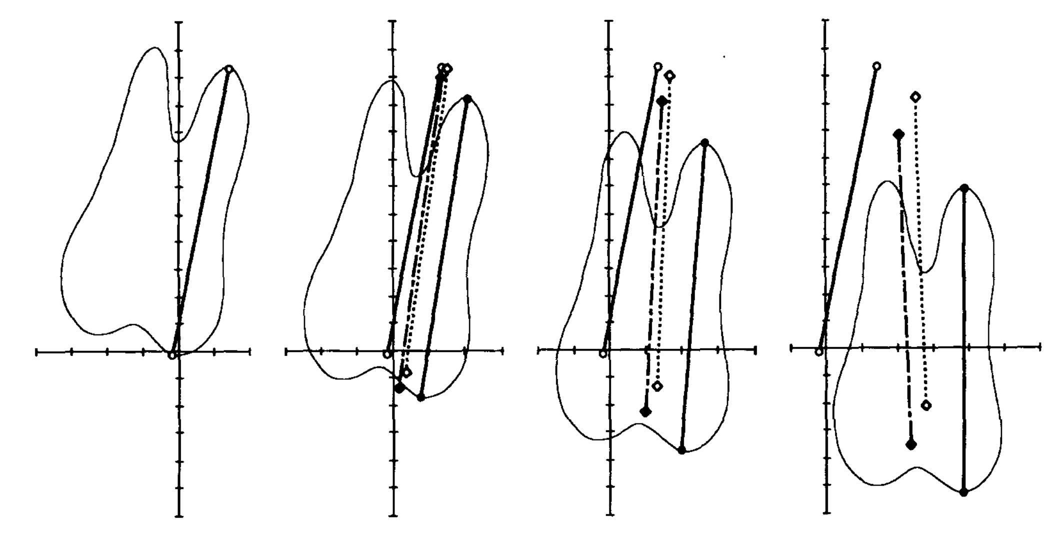

Figure 3

Figure 3A-D
Molar 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.
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_MAX superimposition, and open diamonds represent displacement relative to A_MAX 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 gold standard IMP_MAX superimposition is represented by the distance between the open circle and the filled diamond; and mean local displacement relative to the alternative A_MAX superimposition is represented by the distance between the open circle and the open diamond. Mean secondary displacement relative to the gold standard IMP_MAX superimposition is represented by the distance between the filled diamond and the filled circle and mean secondary displacement relative to A_MAX superimposition is represented by the distance between the open diamond and the filled circle.

At each timepoint beyond the baseline, local displacement relative to IMP_MAX superimposition is seen to carry the molar farther downward and not as far forward as local displacement relative to A_MAX superimposition.

value for total displacement is, by definition, exactly equal to the sum of local displacement and secondary displacement, it follows that if one method of maxillary superimposition yields larger values for local displacement than the other method, it will yield correspondingly smaller values for secondary displacement.

The magnitudes of perceived difference in local effect between the A_MAX and IMP_MAX superimpositions are listed in column 6 and the statistical significances of these differences are listed in column 7. These differences are highly significant in both the horizontal and vertical directions for all landmarks at almost all timepoints. Consistent with the logic of the next to last paragraph of the Rationale, the values of column 6 can be said to represent quantitative estimates of the local adjustments in tooth position at each landmark associated with the modeling changes on the external surfaces of the hard palate during development and treatment.

Figures 4A and 4B combine information from Tables 2 and 3 so as to permit closer examination of the mean displacements of the molar and incisor apices during a single representative time interval (i.e., between the ages of 8.5 and 15.5 years). Figure 4A focuses on secondary changes associated with sutural growth while Figure 4B focuses on local displacements within the alveoli. The line segments of these figures may be considered as vectors representing both the magnitudes and directions of mean displacement.

Considering first the question of absolute mag-

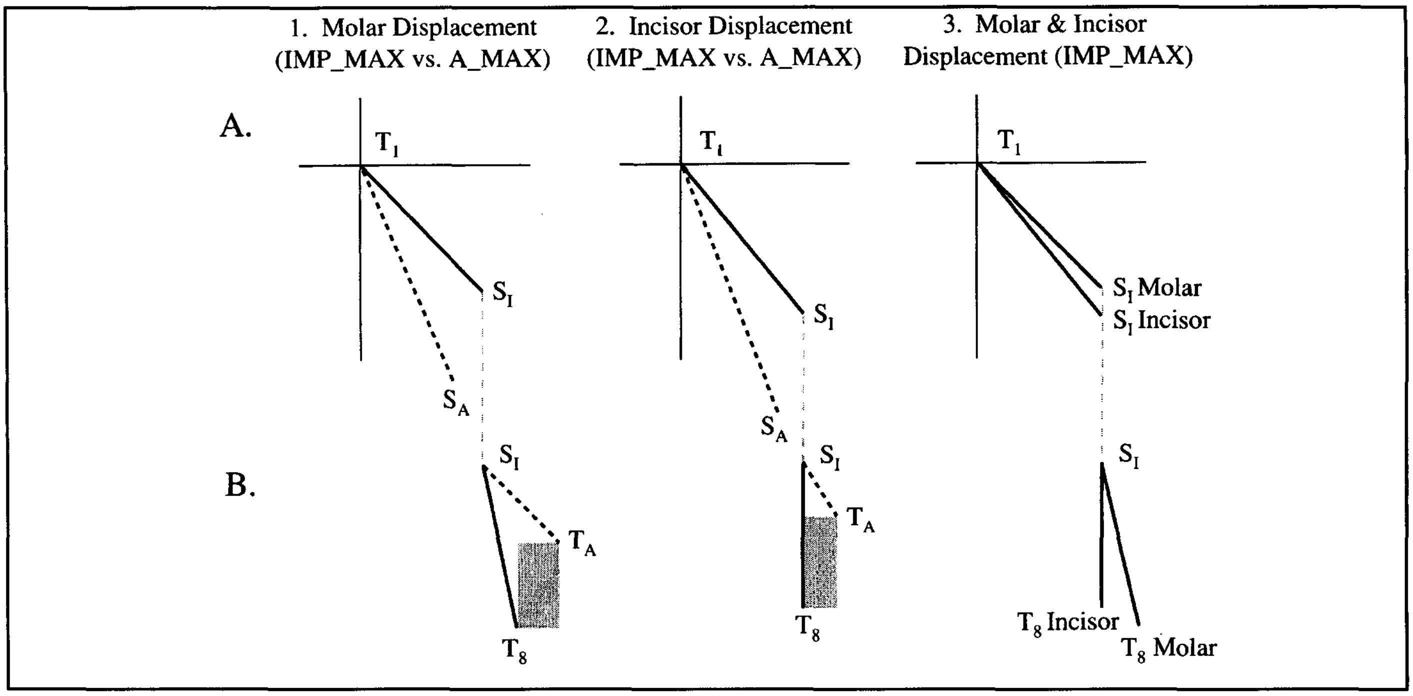

Figure 4

nitude, it may be seen in the first and second details of Figure 4A that the solid vectors representing data from implant superimposition are shorter than the dotted vectors representing anatomical superimposition. This finding is consistent with the inference that, on average, sutural growth changes are smaller overall than they appear to be when the best fit anatomical superimposition is used in lieu of implants. Conversely, it may be seen in the first and second details of Figure 4B that the solid vectors representing implant superimposition data are shorter than the dotted vectors representing anatomical superimposition. This finding is consistent with the inference that on average the local displacements of teeth within their alveoli are larger than they appear to be when the best fit anatomical superimposition is used in lieu of implants. So far as direction is concerned, note that compared with the implant standard, the anatomical superimposition understates forward secondary displacement and downward local displacement while overstating downward secondary positioning and local forward positioning.

The final details of 4A-B compare the displacement of the molar with that of the incisor relative to IMP_MAX superimposition. In Detail 4A3 the two vectors representing the secondary displacement of the apices of both teeth are seen to be fairly similar in both magnitude and direction. This similarity is consistent with the inference that, on average, growth rotation of the maxilla played only a minor role in the observed dis-

Figure 4A-B

Mean vectors of displacement of the molar and incisor apices between 8.5 and 15.5 years. This figure can be thought of as a summary of all three superimpositions performed simultaneously.

A1-3: Secondary displacement associated with sutural and endochondral growth. For each landmark in each detail, T_1 =baseline position, S_I=secondary position when ACB and IMP_MAX are used, and S_A=secondary location when ACB and A_MAX are used.

B1-3: Local displacement associated with changes within the alveoli. In each detail, S_I has been redisplayed as a new starting point directly below its computed location in the corresponding "A" detail. T_8 represents the final position of the landmark relative to ACB. T_A represents the hypothetical final position of the landmark if the local displacement information from A_MAX had been complexed with the secondary displacement information from IMP_MAX. The shaded areas between T_8 and T_A in B1 and B2 represent the local accommodation required in the alveoli to compensate for the modeling/remodeling on the superior and anterior surfaces of the maxilla. These areas are unaccounted for when the A_MAX superimposition is used alone. In A1 and A2, the solid vectors representing data from IMP_MAX are shorter than the dotted vectors representing data from A_MAX (consistent with the inference that, on average, sutural growth changes are smaller than they appear to be when the best fit anatomical superimposition is used in lieu of implants). Conversely, the solid vectors representing IMP_MAX in B1 and B2 are shorter than the dotted vectors representing A_MAX (consistent with the inference that local displacements of teeth are larger on average than they appear to be when the best fit anatomical superimposition is used in lieu of implants).

A3 and B3 compare the displacement of the molar with that of the incisor relative to IMP_MAX superimposition. In A3, the two vectors representing the secondary displacement of the apices of both teeth are seen to be fairly similar in magnitude and direction (consistent with the inference that growth rotation of the maxilla played only a minor role in the observed displacements of the teeth with respect to ACB). B3 shows that, relative to IMP_MAX superimposition, the molar moved slightly further downward and slightly farther forward than did the incisor.

placements of the teeth with respect to ACB. On the other hand, it may be seen in Detail 4B3 that (again relative to IMP_MAX superimposition), the molar moved slightly farther downward and somewhat farther forward than did the incisor. These differences represent a slight loss in arch length expressed at the level of the tooth apices. This effect is not necessarily associated with loss of leeway space or normal mesial drift since several of the subjects in the sample received orthodontic treatment involving extraction.

Discussion

In this discussion, we address several biological and clinical implications of the differences in the perception of tooth displacement measured relative to the three different types of superimposition. Concern here is with the displacement of the maxillary teeth themselves rather than with the changes in the anatomy of the palatal surface that were treated in earlier papers.[9,10] It should be made clear that there is no intention to imply that the tooth movements discussed in this paper are caused by or due to the resorptive and appositional changes on the maxillary surfaces. Rather, this study is a report of temporal associations among changes in different regions of the craniofacial complex, quite aside from considerations of causation. Because the primary focus of the present paper is modal trends, this discussion focuses on mean values and defers for the time being the equally important consideration of individual differences.

On the differences in the perceived magnitudes and directions of local and secondary tooth displacement as a function of the type of maxillary superimposition employed

There has always been considerable debate in the orthodontic specialty as to how much of the tooth repositioning observed during growth and treatment is properly attributable to local displacement (i.e., that associated with intra-alveolar modifications) and how much is attributable to secondary displacement (i.e., that associated with sutural and endochondral growth). In the present sample, when vertical displacement was analyzed relative to the IMP_MAX standard, roughly two-thirds of the observed mean downward positioning of the teeth from ACB appeared to be due to local effects while only one-third appeared to be due to secondary effects. When the same vertical displacement was measured relative to the A_MAX superimposition, this ratio was reversed and only one-third of observed mean downward positioning was thought to be of local origin with two-thirds appearing to be of secondary origin. However, in the anteroposterior (A-P) direction, the average relationship between the two superimpositions was quite different. Compared with the IMP_MAX standard, the A_MAX superimposition tended to overestimate forward local displacement and underestimate forward secondary displacement. Overall, the mean differences between the two superimpositions were considerably smaller in the A-P direction than in the vertical direction.

While between-superimposition differences reported in Tables 2 and 3 may be small in absolute terms, they constituted between 26% and 54% of total vertical displacement and between 11% and 38% of total horizontal displacement for the incisor and molar observed in this sample at different timepoints. Because the A_MAX superimposition underestimated the vertical displacement of both teeth more than it overestimated their anterior displacement, the overall magnitude of local displacement was underestimated in the absence of implants. This phenomenon is represented graphically in Figures 4B1 and 4B2.

On the meaning of the differences

These between-superimposition differences in the relative magnitudes of local and secondary displacement are direct consequences of the fact that the A_MAX superimposition does not take into account the resorptive growth changes on the anterior and nasal surfaces of the hard palate that were first brought to the attention of the specialty by Enlow[22] and Björk.[8]

The currently reported findings for the maxillary teeth themselves have implications for our understanding of developmental and treatment-associated changes both locally in the alveoli and secondarily in other parts of the calvarium. If the developmental osseous changes on the palatal surfaces were unaccompanied by corresponding local displacements of the maxillary teeth within their alveoli, the teeth would have appeared to intrude toward or through the superior surface of the palate and to position labially through time. Such effects are indeed observed when maxillary teeth become ankylosed due to trauma or other causes, and teeth so affected are sometimes said to be "submerged." Under the conditions of normal development, tooth submergence does not occur because net appositional changes within the alveoli reposition the teeth in such a way as to maintain their relative positions within the continuously changing palate. This adjustive phenomenon, a major component of what craniofacial anatomists call passive eruption, is sometimes overlooked by orthodontists in their analyses of tooth displacement during development and treatment. This is probably because, except in the presence of ankylosis, the phenomenon cannot be seen or inferred in the absence of implants. In reporting the precise quantitative differences between the two superimpositions (column 6 of Tables 2 and 3), we believe that we have provided the first quantitative estimates of the amount of interalveolar adjustment required at the locus of each specific dental landmark to compensate for the growth modification of the palatal surface.

Because total tooth displacement relative to ACB is fixed regardless of which maxillary superimposition is used, the underestimation of local tooth displacement which occurs when the A_MAX superimposition is employed in lieu of IMP_MAX is accompanied by a corresponding and reciprocal overestimation of the secondary tooth displacements which occur as a result of sutural and endochondral growth. Examination of Figures 4A1 and 4A2 readily illustrates that tooth displacement at the apices of both the incisor and the molar involves smaller overall contributions from the sutures and the clivus than might have been assumed using the A_MAX superimposition alone. The figures also show that measured relative to IMP_MAX, these contributions are considerably smaller in the vertical direction but slightly greater in the anterior direction than would have been estimated in the absence of implants.

On matrix rotation

Figure 4A3 compares the vectors of displacement of the molar and incisor relative to IMP_MAX superimposition. The two vectors differ only slightly in magnitude and direction. We infer from their similarity that, on average, the contribution of the maxillary matrix growth rotation to maxillary tooth displacement is relatively small. This observation is one of the major surprises among our findings. However, some caution is indicated in the interpretation of this finding because it is highly possible that it is the result of the averaging out of forward and backward rotational effects in different individual cases. This consideration is being examined further in individual case analyses that are now in progress. Note, however, that even within any single case, the detection of rotation always requires the examination of data from more than one landmark, because rotation is a property of structures rather than of individual points. Thus, the common attempt to summarize the displacement of any cranial structure with respect to some anatomical frame of reference with a single pair of coordinate values involves a crucial flaw. (One may read, for example, that the mandible displaced "m" mm downward and "n" mm forward with respect to anterior cranial base. Or alternatively, the maxillary central incisor displaced "p" mm downward and "q" mm backward with respect to superimposition on the palate.) Such summaries would be sufficient if cranial structures moved in a purely translatory manner with respect to each other. (The term translatory is the mathematical and physical equivalent of the orthodontic term bodily.) However, teeth do not undergo purely bodily movements with respect to the jaws in growth and treatment, and the jaws do not undergo purely bodily displacements with respect to the skull. Instead, the incisors and molars rotate somewhat with respect to the maxilla, and the maxilla rotates somewhat with respect to anterior cranial base. And to the extent that rotations occur, each point on each rotating object, (tooth or jaw) displaces in a somewhat different manner from all other points with respect to its frame of reference. For this reason each point within the system moves differently from all others with respect to the same frame of reference, and a full analysis of what is happening at any given point will give a different answer from that for any other point in the system. It is for this reason that we supply the reader with data on the displacement of a number of points within the same jaw or other bony structure.

On the search for an ideal anatomical superimposition

The search for improved and specialized methods for superimposition on the regional anatomy of the palate has a long and honorable history in craniofacial biology[17-29, 37-39] and continues in our own time.[40,41] In analyses of this sort, it is important that investigators avoid becoming diverted into attempts to prove which one among the many possible methods is the true, correct, or best one. Such attempts are corollaries of the preoccupation of some members of our specialty with the identification of some single crucial or ideal criterion upon which all treatment plans should be based. In these endeavors, it is typical to find differences of opinion expressed in terms of what are seen as mutually exclusive dichotomies. Examples include ANB angle vs. Wits appraisal, the SN frame of reference vs. Frankfort, Downs occlusal plane vs. functional occlusal plane, sectional retraction vs. *en masse* retraction, .018 slot vs. .022, 17 degree torque brackets vs. 25, etc. It is in the context of disputes of this sort that the quest for the correct anatomical superimposition of headfilms should be considered. From the time when Broadbent,[14] Brodie,[15] Krogman,[17] Sassouni,[17,18] and Downs[42] first superimposed lateral cephalo-grams, our more sophisticated investigators recognized that there was no single perspective from which all the useful information on the relationship between cephalograms from two or more timepoints could be visualized. Instead, there were several useful ways of superimposing films, each facilitating the identification of a different subset of the total information in them. Salzmann,[43] in his report on the proceedings of the Second Research Workshop on Roentgenographic Cephalometrics (held in 1959) quoted a statement by Garn which makes this point in a way that, even today, can scarcely be improved upon:

> In the growing organism, there is no such thing as a "fixed point" except that the origin for a given measurement is arbitrarily defined as zero. While there may be less change in structures nearer the base of the brain, and while these structures may be useful for measuring the movement of other points, they do also change. The stability of lines of reference is extraordinarily difficult to prov(ide) in a growing system, but it is possible to measure change of one line in reference to another. No reference to a change is acceptable without a definition of the base from which the measurements are made. It must be recognized that this base of reference may also undergo changes...**There is no *a priori* reason why one definable and anatomically meaningful superimposition or point is better than another except by demonstration in a given diagnostic situation. Of paramount importance is the usefulness of the criterion.** (Present authors' emphasis.)

Literally as well as figuratively, almost any piece of data can be examined from several perspectives. Under the best of conditions, data examined from different perspectives yield different and complementary insights. Different superimpositions allow us to view the data from pairs of headfilms in a number of such complementary ways. The appropriate question about the use of different methods of headfilm superimposition is not which way of looking at the data is true and which is false, but rather, whether we can gain additional insights by examining the available data in different ways.

We believe that in this paper we have demonstrated a method for relating information gleaned from three different types of superimposition in such a way as to identify the nature of the changes occurring at the loci of specific dental landmarks with greater clarity than was previously possible. We believe that the value A_MAX minus IMP_MAX is one valid quantitative measurement of the amount of biological activity that occurs at any point in the alveolus in direct association with developmental and treatment-associated resorption and apposition on the surfaces of the bony maxilla. Note that we are not saying that the maxillary osseous changes *cause* the alveolar changes but rather that the two phenomena occur contemporaneously and in direct association with each other. Note further that these changes cannot be quantified using either IMP_MAX or A_MAX taken alone but only by examining the relationship between the two superimpositions. For this reason (as well as for its intuitive simplicity and fairly universal applicability) we consider the A_MAX superimposition to be one tool among many for the quantitative measurement of some aspects of the biological activity associated with craniofacial growth and development.

Some clinical implications

How can the findings of this study be used to improve our understanding of the dynamics of tooth movement in growth and treatment? In the absence of implants, the division of total tooth displacement into three components rather than two cannot be measured but can only be inferred. The question necessarily arises under such conditions: How can one best approximate the magnitude and direction of the error of estimation at each landmark when an anatomical superimposition of the A_MAX type is used in lieu of implants? The general qualitative rule governing estimates made by superimposing on bony outlines when implants are not available may be stated as follows: When a tooth is displacing away from an osseous resorptive front, local effects will tend to be underestimated and secondary effects will tend to be overestimated. Conversely, when a tooth is displacing toward a resorptive front, local effects will tend to be overestimated and secondary effects will tend to be underestimated. In the bony hard palate, the main resorptive fronts are on the superior surface and (to a lesser extent) on the anterior surface. (See Figure 4B.) This means that in the maxilla, local downward displacement will tend to be underestimated and local forward displacement will tend to be overestimated with equal and opposite effects for secondary displacement. Hence in treated subjects, local (orthodontic) displacement will tend to be underestimated in the downward direction and overestimated in the forward direction. Conversely and to an equal degree, secondary (orthopedic) displacement will tend to be overestimated in the downward direction and underestimated in the forward direction. At the quantitative level, the best available estimates of the magnitude of these mis-estimates are the mean values of column 6 in Tables 2 and 3.

As a corollary of the principle just discussed, it is possible to close on a positive note with respect to one major issue which originally impelled orthodontists toward the use of implants in the analysis of treatment effects. This was the concern that treatment-associated loss of upper anchorage (i.e., the mesial displacement of the posterior maxillary teeth within the matrix or basal bone) might have been partially masked by surface modeling/remodeling and hence may actually have been greater than was discernible in the absence of a stable reference frame. The available evidence now strongly implies that this concern was unnecessary. At all three times and for all four landmarks, the anatomical superimposition tends to slightly overstate rather than understate mesial dental migration as compared with the implant standard (at P values ranging from <0.1 to <0.003 for different landmarks and time intervals). These findings imply that, at least on average, loss of maxillary anchorage will tend to be slightly overstated rather than understated in studies in which the A_MAX superimposition is used to analyze records from subjects for whom no implants are available.

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