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Longitudinal eruptive and posteruptive tooth movements, studied on oblique and lateral cephalograms with implants

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Introduction: The purpose of this study was to investigate the eruptive and posteruptive tooth displacements of untreated growing subjects longitudinally and the potential connections between posteruptive displacement of the maxillary and mandibular first molars and skeletal facial growth. **Methods:** The sample comprised 11 series of right 45° oblique cephalograms and lateral cephalograms of untreated children with metallic implants of the Björk type obtained from the archives of a growth study. Cephalograms generated at approximately 2-year intervals between the ages of 8.5 and 16 years were selected and traced. Superimpositions of serial tracings of oblique cephalograms on stable intraosseous implants were made to determine the displacements of buccal segment teeth in both arches, and superimpositions of serial tracings of lateral cephalograms were used to evaluate growth of the jaws. **Results:** Continuous mesial tipping of the maxillary molars was observed from 8.5 to 16 years of age, averaging 8.2° ± 5.5° for the first molars and 18.3° ± 8.5° for the second molars. Compared with the maxillary molars, the mandibular first molars showed less change in angulation except in the later mixed dentition when more than half of the subjects had accelerated forward tipping of the first molar in the late mixed dentition associated with migration into the leeway space. Average amounts of cumulative eruption from 8.5 to 16 years of age were 12.1 ± 2.1 mm downward and 3.8 ± 1.7 mm forward for the maxillary first molar. The mandibular first molar showed 8.6 ± 2.3 mm of eruption and 4.4 ± 1.9 mm of mesial migration. Peak velocity of vertical eruption of the maxillary and mandibular first molars corresponded to the skeletal vertical growth spurt. The maxillary canines and first premolars showed remarkable and continuous uprighting migration during eruption, averaging 9.5° ± 5.0° and 10.5° ± 6.7°, respectively. However, when they erupted into the occlusion, their changes in angulation reverted to forward tipping. The same tendency was also found in the mandibular canines and first premolars. **Conclusions:** Remarkable eruption and migration occur to the teeth of both arches during childhood and adolescence. Rates of first molar eruption during adolescence follow the general pattern of somatic growth. We infer that maintaining the original distal crown angulation of the maxillary molars may be an effective protocol for preservation of anchorage. (Am J Orthod Dentofacial Orthop 2018;153:673-84)

Knowledge of craniofacial growth and development of the dentition is an essential part of orthodontics. Longitudinal craniofacial growth studies with intraosseous implants, a method developed by Björk et al[1-5] at the Royal Dental College in Copenhagen, Denmark, considerably increased the accuracy of longitudinal cephalometric analysis of growth patterns and provided important information about the growth patterns of the jaws.[1-9] Superimposing cephalometric radiographs on metal implants allows precise observation of changes in the position of 1 bone relative to another, changes in the external contours of individual bones, and displacements of the teeth within the bones, such as tooth eruption.

Using this method, Björk and Skieller[3] found the connection between the differential vertical eruption of the molars and the incisors, and drew the conclusion that the rotation of the face necessitates compensatory adaptation of the paths of eruption of the teeth. They pointed out that malocclusions are due to incomplete

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Table I. Sample demographics at each time point

	Time point				
	1	*2*	*3*	*4*	*5*
Sample size (n)	10	11	11	11	8
Nominal age at film (y)	8.5	10.5	12.5	14.5	16
Actual age (y)	8.5 ± 0.4	10.5 ± 0.3	12.5 ± 0.5	14.5 ± 0.4	16.2 ± 0.5
Boys/girls (n)	6/4	7/4	7/4	7/4	6/2

compensatory guidance of eruption to a greater extent than to dysplastic deformation of the dental arches. But in the literature, few longitudinal data are available to guide dental professionals concerning tooth migration and eruption during growth. Siersboek-Nielsen[10], using the method of Björk and Skieller, reported the rates of eruption of the central incisors in 8 boys during the years around puberty. Iseri and Solow[11] described the average and individual patterns of continued eruption of the maxillary incisors and first molars in a longitudinal sample of girls, which comprised 14 series of lateral cephalometric films of girls from 9 to 25 years of age obtained from the archives of the implant study of Björk.[1]

Because of jaw rotation and modeling and remodeling changes on the maxillary and mandibular surfaces, strictly speaking, the path and the degree of eruption of the maxillary teeth cannot be analyzed without the use of implants. Thus far, the longitudinal growth sample with implants is the best available material for the study of tooth eruption. But with conventional lateral cephalograms, superimposition of bilateral tooth structures makes it difficult to trace the contours of the teeth precisely. Starting in 1967, Dr J. Rodney Mathews in the Section on Orthodontics, School of Dentistry, University of California San Francisco, conducted the first long-term study in the United States of growing children with metallic implants of the Björk type. In that sample, left and right 45° oblique cephalograms and lateral and posteroanterior cephalograms were collected at each time point, which provided the perfect materials for the tooth eruption study, because using 45° oblique cephalograms, superimposition of the contralateral teeth was eliminated, and visualization of 1 side of the buccal segment of the teeth (from canine to third molar) was enhanced.

The oblique cephalometric radiograph was introduced by Cartwright and Harvold.[12] It is taken in the same cephalostat as the one used for lateral cephalograms, but the patient is rotated 45° toward the film so that only 1 side of the face is in focus. Barber et al[13] studied the image distortion of the 45° exposure and found that magnifications varied from 0.64% to 5.15% in the mandible and from 0.5% to 7.93% in the maxilla, depending on which part of these structures was studied. They concluded that the degree of distortion for oblique film was less severe than that encountered with the standard lateral head film, and confirmed the reliability of using oblique film as a valid means for studying the rate of tooth eruption. Wyatt et al[14] preferred oblique radiographs when greater clinical accuracy was needed.

The series of 45° oblique cephalograms collected by Mathews which might be the first and last radiographies of longitudinal oblique cephalograms with metallic implants of the Björk type, was used to investigate the eruptive and posteruptive tooth displacements of untreated growing subjects in this study. The correlation between posteruptive displacement of the maxillary and mandibular first molars and the differential growth of the maxilla and the mandible were also explored.

MATERIAL AND METHODS

The primary record set from which the data used in this study consists of lateral, frontal, and 45° cephalograms taken at approximately annual intervals for 36 growing subjects, who were the same sample used in a series of growth studies described previously.[6-9] Before the acquisition of the first cephalograms for each subject, maxillary and mandibular implants of the Björk type were placed using open surgical methods. The subjects were recalled at annual intervals between the ages of 7 and 18 years, although few have records at more than 8 time points. A subset of 11 subjects, including 4 girls and 7 boys, was selected from the total group of 36 based on the following criteria: no orthodontic intervention including serial extraction and space maintaining (except for 1 subject treated after the observed period) and no missing teeth except third molars. They were growing children with a moderately severe Class I or Class II malocclusion, 3 of which were skeletal Class II with ANB angles initially greater than 5.0°; the rest of them were skeletal Class I with ANB angles initially between 0° and 5.0°. Cephalograms at approximately 2-year intervals between the ages of 8.5 and 16 years were chosen for

Table II. Dental stage of each patient at each time point

Patient		*8.5 y*	*10.5 y*	*12.5 y*	*14.5 y*	*16 y*
1	M	Mixed	Mixed	Mixed	Permanent	Permanent
2	M	Mixed	Mixed	Permanent	Permanent	Permanent
3	M	Mixed	Permanent	Permanent	Permanent	Permanent
4	F	Mixed	Mixed	Permanent	Permanent	
5	M	Mixed	Mixed	Mixed	Permanent	Permanent
6	M	Mixed	Permanent	Permanent	Permanent	Permanent
7	M	Mixed	Mixed	Mixed	Permanent	
8	F	Mixed	Mixed	Mixed	Permanent	Permanent
9	M		Mixed	Mixed	Permanent	Permanent
10	F	Mixed	Mixed	Mixed	Permanent	Permanent
11	F	Mixed	Mixed	Mixed	Permanent	

M, Male; *F*, female.

this study. The demographics of the final sample are summarized in Table I. The dental stage of each subject at each time point is given in Table II.

Oblique and lateral cephalograms were traced using the pressure-sensitive digital LCD pen-tablet system (Cintiq DTK-1300; Wacom, Saitama, Japan) by an experienced examiner (X.Z.). In Adobe Photoshop CS (version 8.0.1; Adobe Systems, San Jose, Calif), superimpositions of serial tracings on maxillary and mandibular stable intraosseous implants were performed; the inclination changes of the canines, premolars, and molars in both arches were measured (Fig 1). Different frames of reference were used to evaluate the displacements of the buccal segment teeth. As illustrated in Figure 2, the palatal plane at the initial time point was used as the reference plane to evaluate the eruption of the maxillary buccal segment teeth, and the mandibular plane at the initial time point was used to measure the eruption of the mandibular buccal segment teeth. The functional occlusal plane at 14.5 years of age, when most of the subjects' permanent dentitions were complete, was used as a frame of reference to assess the sagittal displacements of the maxillary and mandibular first molars (Fig 3).

Lateral cephalograms were also traced and superimposed to evaluate the growth of the jaws and the rotation of the mandible. Length increments of both jaws were measured by incremental changes of condylion to pogonion and condylion to A-point. Anterior cranial base superimposition was performed on serial tracings of lateral cephalograms; sagittal and vertical displacements of the maxillary implants relative to the cranial base were measured to assess the growth displacement of the maxilla. Rotation of the mandibular core relative to the cranial base was measured by the angle formed between the line connecting the 2 implants in the mandibular body and the Frankfort horizontal plane at the initial time point (Fig 4).

Statistical analysis

Descriptive and analytic statistical analyses were performed using the Statistical Package for the Social Science (version 16.0; SPSS, Chicago, Ill).

To assess intraexaminer reliability, 10 oblique radiographs and 10 lateral radiographs were retraced and remeasured by the same examiner after 2 weeks. The results of the analysis indicated no statistically significant differences between the original and repeated measurements at the 0.05 level.

To evaluate the random error of the study method, 3 series of oblique cephalograms and 3 series of lateral cephalograms were chosen at random, and the tracings, superimpositions, and measurements of change were redone. The error standard deviations[15] and the indexes of reliability[16] were calculated for the 15 double determinations of all increments of change. The results are summarized in Table III.

RESULTS

Superimposed on the maxillary and mandibular implants, angulation changes of the canines, premolars, and molars in both arches were measured and are shown in Table IV.

From 8.5 to 10.5 years of age, the variability in amount and direction of maxillary canine tipping was large, ranging from −8.8° to 10.0°. Thereafter, in all subjects except one, continuous uprighting of the maxillary canines occurred. The peak amount of canine distal tipping occurred between 10.5 and 12.5 years of age, averaging 6.9° ± 4.6°. The average distal tipping of the maxillary first premolars between 8.5 and 16.5 years of age was 9.9° ± 6.7°, of which 5.8° ± 9.4° took place between 8.5 and 10.5 years of age. Angulation changes of the maxillary second premolars showed great variability between subjects. The forward tipping of maxillary second premolars ranged from −14° to +13°. Forward tipping of the maxillary molars was observed from 8.5 to 16 years of age, averaging 8.2° ± 5.5° for the first molar and 18.3° ± 8.5° for the second molar. Tipping peaked at 12.5 to 14.5 years for maxillary first molars and at 8.5 to 10.5 years for maxillary second molars.

Angulation changes of mandibular teeth were generally much smaller than the maxillary ones. Compared with the maxillary canines, the mandibular canines showed less uprighting but large variability in inclination changes. For most subjects, uprighting of the mandibular

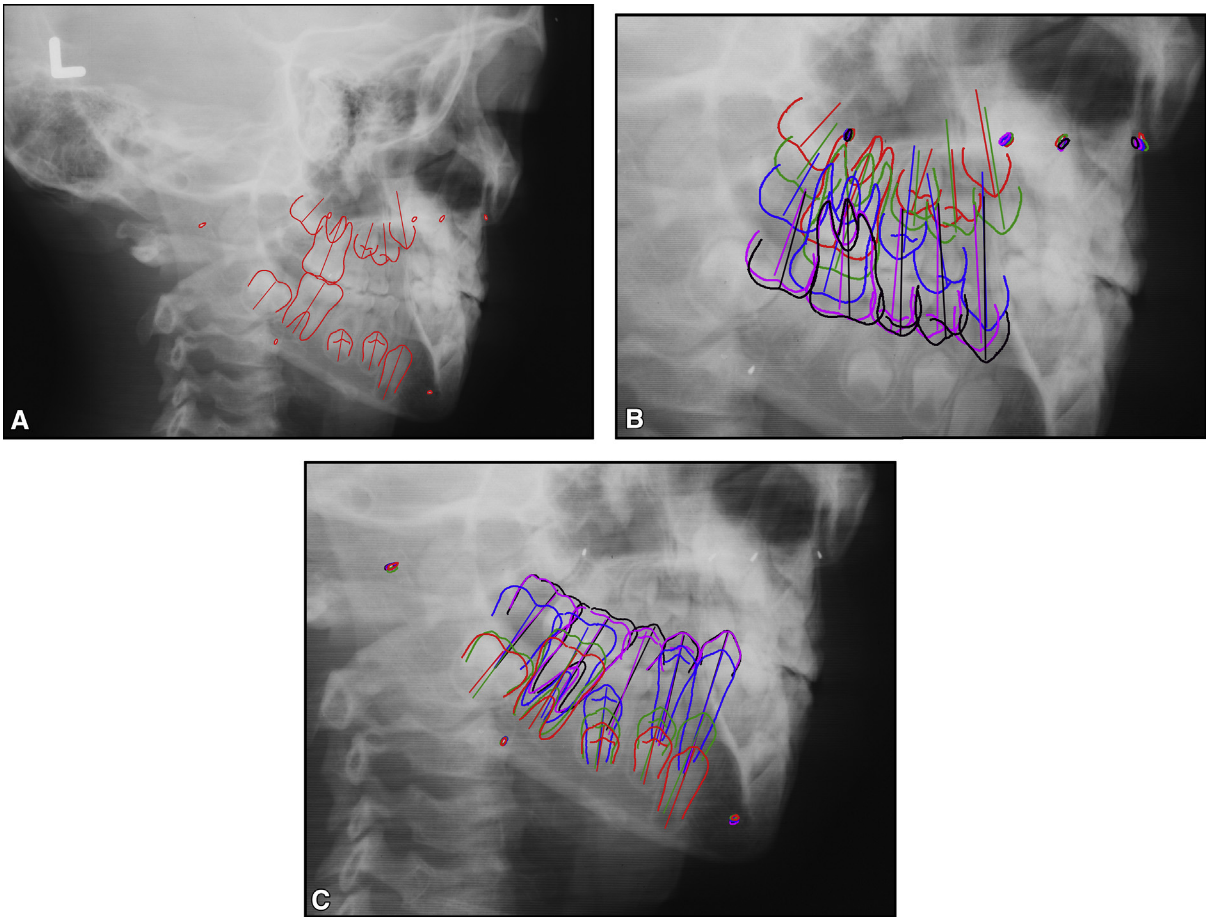

Fig 1. **A,** An oblique cephalogram traced using the pressure-sensitive digital LCD pen-tablet system; **B,** superimposition of serial tracings from successive time points on maxillary stable intraosseous implants; **C,** superimposition of serial tracings from successive time points on mandibular stable intraosseous implants.

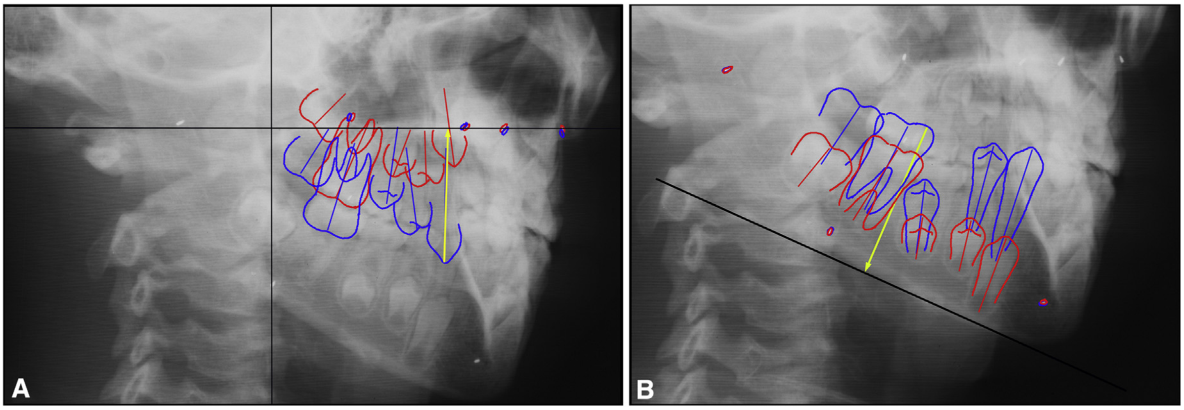

Fig 2. **A,** The palatal plane at the initial time point was used as the reference plane to evaluate the eruption of the maxillary buccal segment teeth; **B,** the mandibular plane at the initial time point was used as the reference plane to measure the eruption of the mandibular buccal segment teeth.

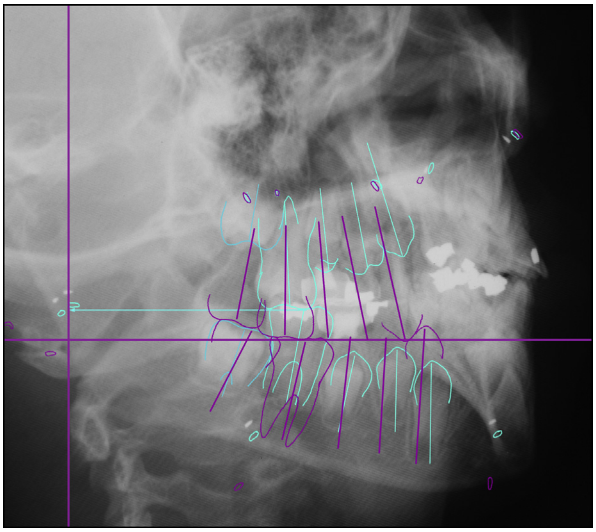

Fig 3. Superimposed on maxillary implants, sagittal displacements of the maxillary first molar were measured using the functional occlusal plane at time point 4 (14.5 years of age, traced in *purple*) as the frame of reference. The background cephalogram is time point 1; the *green* trace is time point 2.

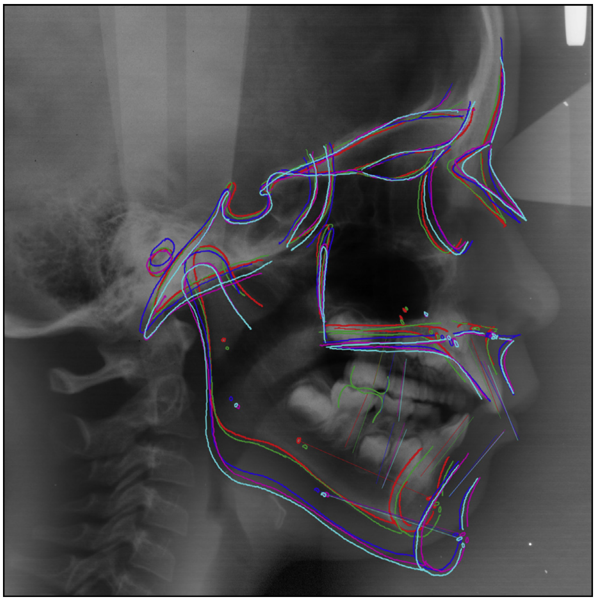

Fig 4. Anterior cranial base superimposition of serial tracings of lateral cephalograms was used to evaluate the rotation of the mandibular core and the displacement of the anterior maxillary implants.

canines took place before the tooth came into occlusion, averaging 3.6° (range, −7.6°−20.3°). Uprighting occurred between 10.5 and 14.5 years of age. Thereafter, a small amount of mesial tipping was detected. Large variabilities in inclination changes of the mandibular second molars and premolars were also found. More than half of the subjects showed accelerated forward tipping and mesial drift of the mandibular first molars when shedding the deciduous second molars.

Since large differences existed between chronologic and dental ages, investigations of the eruptive (before the tooth erupted into theocclusion) and posteruptive tooth inclination changes of canines and premolars were performed. Results in Table V confirmed that the canines and first premolars in both arches tended to upright during eruption, whereas the maxillary and mandibular second premolars showed great variability in angulation changes. But after eruption to the occlusion, all teeth showed forward tipping tendencies.

Vertically, the teeth kept erupting during the entire growth period. Table VI reports the vertical displacements of the maxillary teeth relative to the initial palatal plane and the eruption of the mandibular teeth relative to the initial mandibular plane. Table VII reports the rates of eruption of the maxillary and mandibular teeth.

Superimposed on maxillary implants, about 32.7 mm of eruption of the maxillary canines was detected from 8.5 to 16 years of age relative to the palatal plane at the initial time point. The peak rate of eruption of the maxillary canines occurred between 10.5 and 12.5 years of age, the same time as the peak rate of canine uprighting. The peak rate of maxillary first premolar eruption also occurred between 10.5 and 12.5 years of age, whereas the rate of eruption of the second premolars remained relatively stable from 8.5 to 14.5 years of age. The maxillary first molars attained their peak rate of eruption between 12.5 and 14.5 years of age, accumulating on average 12.06 mm of eruption from 8.5 to 16 years of age. The rate of maxillary second molar eruption peaked between 12.5 and 14.5 years of age, and cumulative eruption averaged 26.13 mm. When all teeth had erupted into the occlusion (14.5 years of age for most subjects), an obvious deceleration of eruption occurred, although there were 0.54 to 1.98 mm per year of eruption remaining, and the posterior teeth had more posteruptive vertical displacement. The differential eruption of the maxilalry teeth is shown in Figure 5.

The canines showed the greatest amount of eruption among the mandibular teeth, with an average of 28.2 mm of vertical eruption between 8.5 and 16 years of age; the maximum velocity of eruption took place early. Differential eruption of the mandibular teeth was also observed and is shown in Figure 6. The mandibular second premolars and second molars tended to erupt later, and the mandibular canines and first

Table III. Error estimates for increments of change

Measurement	*Error SD*	R
Lateral cephalograms		
Maxillary length (Co-A) (mm)	1.73	0.86
Mandible length (Co-Gn) (mm)	2.02	0.83
Vertical displacement of MxImp (mm)	0.90	0.84
Sagittal displacement of MxImp (mm)	0.44	0.95
Mandible core forward rotation (°)	1.21	0.90
Oblique cephalograms		
U6 mesial migration (mm)	0.67	0.87
L6 mesial migration (mm)	0.56	0.83
U6 vertical eruption (mm)	0.63	0.91
L6 vertical eruption (mm)	0.92	0.95
Angulation changes of U6 (°)	1.50	0.95
Angulation changes of L6 (°)	1.21	0.82
Upper teeth vertical eruption (mm)	0.63-1.77	0.91-0.98
Lower teeth vertical eruption (mm)	0.92-1.49	0.92-0.98
Angulation changes of maxillary teeth (°)	1.50-2.07	0.88-0.96
Angulation changes of mandibular teeth (°)	1.21-1.57	0.82-0.98

Co-A, Condylion to A-point; *Co-Gn*, condylion to gnation; *MxImp*, maxillary implant; *U*, maxillary; *L*, mandibular; *6*, first molar.

Table IV. Angulation changes of buccal segment teeth

	8.5-10.5 y (n = 10)		*10.5-12.5 y (n = 11)*		*12.5-14.5 y (n = 11)*		*14.5-16 y (n = 8)*		*8.5-16 y (n = 8)*	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Maxillary tooth angulation changes during eruption (°)										
U3	0.7	6.7	−6.9	4.6	−0.3	5.1	−0.7	3.2	−9.4	4.2
U4	−5.8	9.4	−2.5	9.4	0.2	7.4	−0.2	3.3	−9.9	6.7
U5	0.7	7.1	−0.6	5.5	−0.4	7.3	2.5	2.9	0.0	9.5
U6	1.6	4.3	1.3	4.0	3.7	4.4	2.0	3.4	8.2	5.5
U7	7.6	4.9	2.5	6.9	3.8	5.2	3.2	3.5	18.3	8.5
Mandibular tooth angulation changes during eruption (°)										
L3	−0.2	3.4	−2.5	5.4	−1.1	3.4	1.2	2.3	−0.1	5.0
L4	−2.0	4.0	−1.3	6.6	−1.0	3.5	1.4	2.3	−2.2	6.8
L5	−2.7	7.1	0.5	6.7	3.6	5.9	2.1	2.4	3.4	12.3
L6	0.3	2.4	−0.6	2.5	1.3	3.1	−0.9	4.2	−0.1	3.4
L7	0.4	5.2	−2.7	7.8	0.3	7.4	0.5	2.5	4.0	4.2

Negative values mean backward tipping of the crown.
U, Maxillary; *L*, mandibular; *3*, canine; *4*, first premolar; *5*, second premolar; *6*, first molar; *7*, second molar.

premolars erupted earlier. Relative to the initial mandibular plane, an average of 8.6 mm posteruption occurred for the mandibular first molars, peaking at 10.5 to 12.5 years of age. Compared with the maxillary teeth, the mandibular teeth displayed less vertical eruption.

As reported in Table VIII, and illustrated in Figure 7, the maxillary first molar showed 3.8 mm of mesial displacement with the functional occlusal plane as the reference plane. The peak rate of migration was synchronized with the forward tipping and vertical eruption occurring between 12.5 and 14.5 years of age. Compared with the maxillary first molars, the mandibular teeth had a little more mesial migration from 8.5 to 16 years of age. But after 12.5 years of age, when the peak mandibular growth took place, mesial movement of the first molars decelerated compared with the maxillary first molars. The peak rate of increment of Co-A and the apparent sagittal displacement of the maxillary implants both occurred between 10.5 and 12.5 years of age, earlier than the peak increment of, which occurred between 12.5 and 14.5 years of age. Differential growth of the maxilla and mandible was detected. The maximum amount of excess growth of the mandible was observed between 12.5 and 14.5 years of age, corresponding to the peak

Table V. Eruptive (before tooth erupted into occlusion) and posteruptive tooth angulation changes of canines and premolars (°)

	Eruptive inclination changes (n = 11)				*Posteruptive inclination changes (n = 10)*			
	Minimum	*Maximum*	*Mean*	*SD*	*Minimum*	*Maximum*	*Mean*	*SD*
U3	0.3	−19.2	−9.5	5.0	7.7	−2.4	2.2	3.3
U4	−2.6	−21.4	−10.5	6.7	11.0	−1.5	2.6	3.9
U5	10.9	−16.7	−2.3	9.2	9.1	−1.6	2.4	3.6
L3	1.1	−19.6	−4.8	6.0	6.6	−3.6	1.7	2.6
L4	2.1	−15.8	−5.8	5.3	11.4	−4.0	4.0	5.0
L5	11.7	−19.3	0.8	9.6	12.4	−0.8	4.2	4.7

Negative values mean backward tipping of the crown.
U, Maxillary; *L*, mandibular; *3*, canine; *4*, first premolar; *5*, second premolar.

Table VI. Vertical eruptive and posteruptive displacement of buccal segment teeth

	8.5-10.5 y (n = 10)		*10.5-12.5 y (n = 11)*		*12.5-14.5 y (n = 11)*		*14.5-16 y (n = 8)*		*8.5-16 y (n = 8)*	
Age at filming	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Maxillary tooth eruption relative to initial palatal plane (mm)										
U3	10.5	6.3	15.3	8.0	6.9	7.2	1.0	1.1	32.7	4.0
U4	6.6	4.7	10.5	5.2	4.8	4.0	1.0	0.9	22.7	3.5
U5	7.2	5.6	7.9	5.8	8.8	6.8	1.9	1.2	25.9	2.3
U6	2.8	1.3	3.5	2.2	3.8	1.8	1.9	0.8	12.1	2.1
U7	4.0	1.8	8.7	5.2	10.0	5.1	2.9	1.4	26.1	3.4
Mandibular tooth eruption relative to initial mandibular plane (mm)										
L3	12.6	6.3	10.8	8.5	4.9	6.4	1.5	0.5	28.2	4.1
L4	7.5	5.8	8.4	7.1	4.1	4.5	1.9	0.9	20.9	7.9
L5	5.8	5.2	8.5	7.8	9.1	8.3	2.6	1.6	25.2	4.8
L6	1.9	1.5	2.7	1.8	2.3	1.3	1.7	1.1	8.6	2.3
L7	4.3	3.7	8.9	4.6	6.1	4.6	1.0	0.8	19.4	2.0

U, Maxillary; *L*, mandibular; *3*, canine; *4*, first premolar; *5*, second premolar; *6*, first molar; *7*, second molar.

Table VII. Rates of vertical eruption of teeth

	8.5-10.5 y (n = 10)		*10.5-12.5 y (n = 11)*		*12.5-14.5 y (n = 11)*		*14.5-16 y (n = 8)*	
Age at filming	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
Maxillary tooth eruption (mm/y)								
U3	5.0	2.7	7.5	3.5	3.4	3.0	0.5	0.6
U4	3.2	1.9	5.4	3.2	2.2	1.7	0.7	0.6
U5	3.6	2.4	4.3	4.0	4.5	3.3	1.2	0.7
U6	1.5	0.8	1.7	0.9	1.8	0.6	1.3	0.6
U7	2.1	1.1	4.2	2.4	4.9	2.2	2.0	1.1
Mandibular tooth eruption (mm/y)								
L3	6.2	2.5	5.2	3.7	2.2	2.0	1.0	0.5
L4	3.7	2.7	4.0	3.2	1.7	1.5	1.3	0.6
L5	2.9	2.4	3.9	3.1	4.1	3.5	1.7	1.0
L6	1.0	0.8	1.3	0.9	1.2	0.6	1.2	0.9
L7	2.1	1.6	4.4	2.1	3.1	2.2	0.6	0.4

U, Maxillary; *L*, mandibular; *3*, canine; *4*, first premolar; *5*, second premolar; *6*, first molar; *7*, second molar.

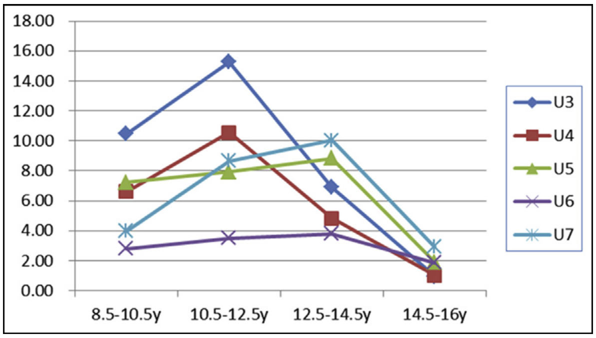

Fig 5. Average rates of vertical eruption of maxillary teeth relative to the initial palatal plane.

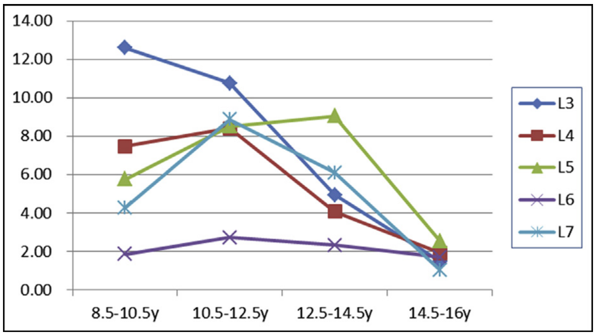

Fig 6. Average rates of vertical eruption of mandibular teeth relative to the initial mandibular plane.

rate of maxillary first molar mesial movement, as illustrated in Figure 8. All subjects in this sample showed forward rotation of the mandible.

DISCUSSION

A significant limitation of this study was the small size of the sample, since only 11 subjects (4 girls, 7 boys) were evaluated. Great values in the standard deviations characterized many measurements presented in the tables, which in part are due to the small sample. Another possible reason for it might be that great variations occurred to the eruptive tooth movements of growing subjects because of different growth potentials and different growth rates.

Although the sample size was limited, this study still gives us a rather clear view of the eruption patterns of the maxillary and mandibular buccal segments. It also allows us to explore the possible mechanism of compensatory posteruptive displacement of the molars with respect to the differential growth of the jaws.

According to the literature, the normal preeruptive position of the maxillary canine is superior to its predecessor, angulated mesially with its crown lying distal and slightly buccal to the lateral incisor.[17] The canine follows a mesial path until it reaches the distal aspect of the lateral incisor root. The erupting canine is gradually uprighted to a more vertical position as if it were guided by the lateral incisor root until fully erupted.[18] Preeruptive changes in maxillary canine and first premolar inclinations have been investigated on panoramic radiographs.[18-22] Fernandez et al[19] found that the canine erupts, increasing its mesial inclination until about 9 years of age, after which it begins to upright progressively. Incerti Parenti et al[20] reported that canine and premolar inclinations and mesiodistal locations varied between 8 and 10 years of age. Nevertheless, we must keep in mind that image magnification and distortion in panoramic radiographs compromise the dimensional accuracy of angular and linear measurements.[23] In our study, instead of panoramic radiographs, 45° oblique cephalograms were used to investigate the changes in inclination of the canines; this is believed to minimize image distortion and improve the accuracy of the measurements.[14] In our study, great variabilities among changes in maxillary canine inclination were found from 8.5 to 10.5 years of age; this might be due to the variability in age at which the canine reached the distal part of the lateral incisor root. Starting about age 10.5 years, continued uprighting of the canine was seen. In total, an average of 9.5°±5.0° of backward tipping occurred to the maxillary canine during eruption. When the canine was fully erupted and came into contact with an antagonist, mesial tipping was detected in some subjects. In addition, an average of 2.2°±3.3° of forward tipping of the maxillary canines was measured posteruptively.

Cumulative amount and peak velocity of vertical posteruptive displacement of the maxillary and mandibular first molars has been investigated in several studies. Different methods and reference planes have been used, and different results have been demonstrated. Using metal implants as stable reference markers, Iseri and Solow[11] showed that the average cumulative continued eruption of maxillary first molars in girls from 9 to 25 years of age approximated 8 mm, with peak velocity occurring about 12 years of age. Kim et al[24] using conventional lateral cephalograms without superimpositions investigated longitudinal cephalometric changes with an age range of 6 to 24 years. Average downward movement of the maxillary first molars with respect to the palatal plane was 16.95 mm. Our study yielded an average vertical eruption of 12.1 ± 2.1 mm between 8.5 and 16 years of age. This value seems a bit large and closer to the results reported by Iseri and Solow. The reason for the similarity between these 2 studies may be that similar systems of

Table VIII. Posteruptive displacements of first molars and growth changes of jaws

	8.5-10.5 y (n = 10)		*10.5-12.5 y (n = 11)*		*12.5-14. y (n = 11)*		*14.5-16 y (n = 8)*		*8.5-16 y (n = 7)*	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
U6 mesial migration (mm)	0.2	1.3	0.1	1.5	2.6	1.5	1.1	0.7	3.8	1.7
L6 mesial migration (mm)	0.8	1.1	1.3	1.5	1.9	1.2	0.5	0.5	4.4	1.9
U6 mesial migration rate (mm/y)	0.2	0.7	0.1	0.8	1.4	0.7	0.8	0.7		
L6 mesial migration rate (mm/y)	0.4	0.5	0.6	0.8	0.8	0.6	0.4	0.4		
Maxillary length (Co-A) (mm)	4.5	2.2	5.5	2.6	4.4	2.8	1.3	1.5	15.6	4.5
Mandible length (Co-Gn) (mm)	6.9	3.2	7.0	3.7	8.5	4.7	3.6	2.3	26.6	6.1
Mandibular excess (mm)	2.4	2.0	1.6	2.4	4.1	3.7	2.3	1.9	11.0	3.6
Vertical displacement of MxImp (mm)	1.5	0.9	2.5	1.4	2.6	2.3	0.9	1.3	7.8	3.5
Sagittal displacement of MxImp (mm)	2.1	1.4	2.6	0.9	2.1	1.5	1.0	1.0	7.5	2.4
Mandible core forward rotation (°)	2.1	1.1	2.0	1.8	2.2	2.1	2.1	5.1	6.2	3.1

U, Maxillary; *L*, mandibular; *6*, first molar; *Co-A*, Condylion to A-point; *Co-Gn*, condylion to gnation; *MxImp*, •••.

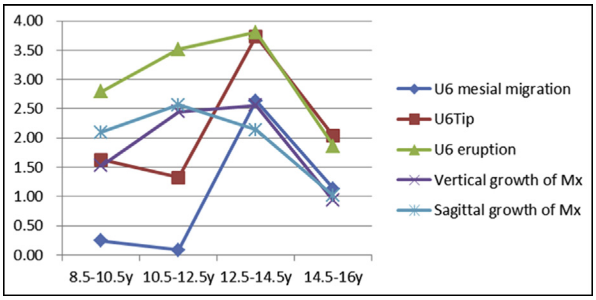

Fig 7. Average posteruptive displacements of maxillary first molars and maxillary growth displacement.

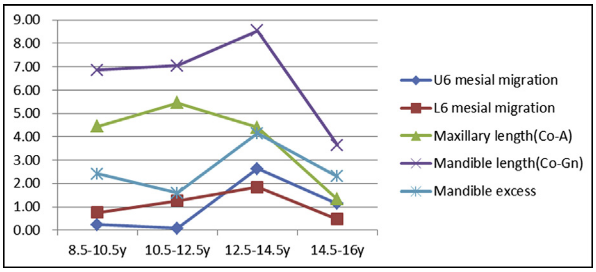

Fig 8. Average mesial migrations of maxillary and mandibular first molars and lengthening of the jaws during different growth stages.

stable reference markers (intraosseous implants) were used for superimpositions. Moreover, most subjects in our study were boys who on average had greater facial growth and tooth eruption. Maximum velocity of vertical eruption of the maxillary first molars was measured at 1.8 ± 0.6 mm per year. It occurred between 12.5 and 14.5 years of age, simultaneously with the peak vertical growth of the maxilla in both samples.

To our knowledge, there are no published longitudinal investigations of mandibular molar eruption using intraosseous implants as stable markers for superimposition. Based on a large sample of untreated Class I and Class II subjects with cephalograms superimposed on stable reference structures, Watanabe et al[25] reported 5.7 mm of mandibular first molar eruption for boys between 8 and 15 years of age. The corresponding value for girls was 4.2 mm. They also reported that the rate of eruption of the mandibular molars in boys steadily increased from 0.6 mm per year between 8 and 10 years to 1.2 mm per year between 13 and 15 years of age. Rates of eruptions for girls were lower in the prepubertal period but increased to 0.8 mm per year between 12 and 14 years of age, after which they again decreased. Liu and Buschang[26] evaluated cephalograms from a mixed longitudinal sample of 124 girls measured annually between 10 and 15 years of age, and found that mandibular molar eruption accelerated from 0.59 mm per year at 10.5 years of age to a peak of 0.76 mm per year at 12.1 years of age, followed by deceleration to 0.42 mm per year at 14.5 years of age. In our study, the average cumulative eruption of the mandibular first molars from 8.5 to 16.5 years of age, relative to the mandibular plane, was 8.6 ± 2.3 mm, and the maximum velocity of mandibular first molar vertical eruption was 1.3 ± 0.9 mm per year, occurring at 10.5 to 12.5 years of age; this is greater than in previous studies. Actually, even after the peak rate of the mandibular molar vertical eruption at 10.5 to 12.5 years of age, a remarkably large velocity of eruption, 1.2 ± 0.6 mm per year still remained from 12.5 to 14.5 years of age. After 14.5 years of age, the mandibular molar eruption decelerated.

Correspondingly, the accelerated growth of the mandible began at 10.5 years of age and was completed by 14.5 years of age.

Based on these observations, it is reasonable to infer that posteruptive movement of first molar adaptation to the skeletal vertical growth followed the general pattern of somatic growth.

Accompanying vertical eruption, mesial migration and forward tipping of the maxillary first molars have been reported in previous studies. The implant studies of Björk and Skieller[3] demonstrated average forward tipping of 5.5° in a sample of 19 subjects with forward rotation of the mandible during growth. Iseri and Solow[11] reported an average cumulative mesial shift of 3 mm in the maxillary first molars of female subjects from 9 to 25 years of age. In a longitudinal study of 39 untreated subjects between 5 and 16 years of age, Tsourakis and Johnston,[27] using regional superimpositions, reported 5.80 to 7.36 mm of mesial movement of the maxillary molars for the different molar relationship groups. Kim et al[24] found, for subjects with more mandibular growth than maxillary growth, 2.41 mm of forward movement and 9.94° of mesial tipping of the maxillary first molars with reference to the palatal plane from the early transitional dentition to the early permanent dentition, and 2.35 mm of forward movement and 7.01° of mesial tipping of the maxillary first molars from the early permanent dentition to the postpubertal growth at 20 to 24 years of age. In our study, the cumulative average mesial migration was 3.8 mm, and the forward tipping of the maxillary first molars was 8.2° from 8.5 to 16 years of age. The largest amount of migration of the maxillary first molars, averaging 2.6 mm, was synchronized with the peak of forward tipping (3.7° on average) between 12.5 and 14.5 years of age, corresponding to peak mandibular growth. These findings support the conclusion that migration and forward tipping are dentoalveolar compensations for excess growth of the mandible.

Usually, mesial migration or mesial tipping of the maxillary molars during orthodontic treatment is considered as anchorage loss. A retrospective cross-sectional study based on 1403 orthodontically treated adolescent patients showed an average of 3.0° of mesial tipping in extraction and nonextraction patients.[28] In our previous randomized clinical trial comparing retraction techniques, average mesial displacement of maxillary first molars was 4.3±2.1 mm.[29] Although no difference was found between techniques, we did find between-sex differences and between-age differences in anchorage loss. Boys had significantly more mesial displacement than did girls. Younger adolescents had significantly more mesial displacement than did older adolescents. McKinney and Harris[30] also reported differences in anchorage loss between boys and girls treated with Begg, edgewise, and straight-wire appliances. Two other studies using retrospective samples of different characters each reported higher mean values for mesial displacement of the maxillary first molar for younger subjects than for more mature subjects.[31,32] In these studies, the reasons for between-sex differences and between-age differences in maxillary molar anchorage loss were not fully discussed. Given our study results, it is reasonable to infer that the mesial drift of maxillary molars as compensation for the excess growth of the mandible, rather than treatment mechanics, plays an important role in anchorage loss. The anchorage loss during orthodontic treatment for growing patients is caused partially by treatment mechanics and partially by natural growth. Hence, we refer to it as "physiological anchorage loss."

Mesial movement of maxillary molars and mandibular growth excess seem to be key determinants of occlusal development. Tsourakis and Johnston[27] recommended a strategy using a holding appliance to prevent maxillary dentoalveolar compensations until the mandible outgrows the maxilla enough to adjust the distal occlusion to Class I. You et al[33] suggested that disarticulating the occlusion to minimize the effects of the adaptive changes of dentoalveolar complexes should greatly facilitate treating growing Class II subjects. Given the magnitude and persistence of maxillary first molar migration and forward tipping documented here, we would argue that holding the original distal crown inclination position of the maxillary molar should be an effective protocol for the preservation of anchorage and arch length, facilitating distal uprighting and eruption of the canines.

Based on a large sample of untreated Class I and Class II subjects with cephalograms superimposed on stable reference structures, Watanabe et al,[25] using planes parallel and perpendicular to the mandibular plane of the first tracing as the frame of reference, reported 1.6 and 2.3 mm of mesial migration between 8 and 15 years of age for boys and girls, respectively. However, using regional superimpositions, Tsourakis and Johnston[27] reported only 0.10 to 1.14 mm of mesial movement of the mandibular molars for subjects with different molar relationship relative to the mean functional occusal plane between 5 and 16 years of age. In our study, from 8.5 to 16 years of age, 4.4 mm of mesial migration of the mandibular first molars was recorded, with the functional occlusal plane used as the frame of reference. For most subjects, the largest amount of mandibular first molar migration took place in the late stage of transition of dentition when the deciduous second molar exfoliated and the second premolar erupted, coinciding with accelerated forward tipping of the first molar.

CONCLUSIONS

Significant eruption and migration occurred to the teeth in both arches during childhood and adolescence.

Maxillary canines and first premolars showed remarkable and continuous uprighting during eruption. However, their changes in angulation reversed to forward tipping when the teeth erupted into the occlusion. The same tendency was also seen in the mandibular canines and first premolars.

Maximum velocity of the vertical eruption of the maxillary first molars occurred simultaneously with the peak vertical growth of maxilla. Speedy vertical eruption of the mandibular first molars corresponded to the accelerated growth of the mandible. It is reasonable to deduce that posteruptive movement of the first molars adapted to skeletal vertical growth and followed the general pattern of somatic growth.

Marked mesial migration and forward tipping of the maxillary molars correlated strongly with the growth spurt of the mandible. This association might be regarded as dentoalveolar compensation for excess growth of the mandible during the pubertal growth spurt and may also be associated with between-sex differences and between-age differences in maxillary molar anchorage loss for orthodontically treated growing subjects. Maintaining the deciduous distal crown inclination of the maxillary molars might be an effective protocol for the preservation of anchorage and maxillary arch length, facilitating the distal uprighting and eruption of the canines.

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