European Journal of Orthodontics 24 (2002) 69–79

Mandibular skeletal growth and modelling between 10 and 15 years of age

Peter H. Buschang* and Luiz G. Gandini Jr**
*Department of Orthodontics and Center for Craniofacial Growth and Research, Baylor College of Dentistry, Texas A&M University System Health Science Center, Dallas, Texas, USA, and
**Department of Orthodontics, Araraquara School of Dentistry—UNESP, Araraquara, SP—Brazil

SUMMARY This study pertains to a random sample of untreated French-Canadian adolescents (79 females and 107 males) evaluated at 10 and again at 15 years of age. Superimpositions on natural reference structures were performed to describe condylar growth and modelling of 11 mandibular landmarks. Superimpositions on natural cranial/cranial base reference structures were performed to describe mandibular displacement and true rotation.

The results showed significant superior and posterior growth/modelling of the condyle and ramus. Males underwent significantly ($P < 0.01$) greater condylar growth and ramus modelling than females. With the exception of point B, which showed significant superior drift, modelling changes for the corpus landmarks were small and variable. The mandible rotated forward 2–3.3 degrees and was displaced 9.6–12.7 mm inferiorly and 1.9–2.7 mm anteriorly. Individual differences in ramus growth and modelling, both amount and direction, can be explained by mandibular rotation and displacements. Multivariate assessments revealed that superior condylar growth and ramus modelling were most closely associated with forward rotation and inferior mandibular displacement. Posterior growth and modelling were most closely correlated with anterior mandibular displacement and forward rotation. Modelling of the lower anterior border was independent of rotation and displacement.

Introduction

Implant and histological studies have established that growth in mandibular length occurs primarily at the condyle (Björk, 1963; Enlow and Harris, 1964; Mathews and Ware, 1978). The condyle grows superiorly and slightly posteriorly or even anteriorly, depending on the orientation and individual growth patterns (Björk and Skieller, 1983; Baumrind *et al*., 1992; Buschang and Santos Pinto, 1998). Relative to the Frankfort horizontal, Baumrind and co-workers (1992) reported a superior to posterior ratio of 10:1 for a mixed sample of 19 subjects 8.5–15.5 years of age. Using an orientation 7 degrees from the sella–nasion plane, Buschang and Santos Pinto (1998) showed approximately eight times more superior than posterior condylar growth for large samples of children and adolescents.

The modelling patterns of the ramus and corpus are also well established. Bone is typically added along the posterior ramus border and resorbed along the anterior border (Hunter, 1771; Humphry, 1863; Brash, 1924). The gonial process shows large, almost equal, amounts of posterior and superior modelling drift (Enlow and Harris, 1964; Baumrind *et al*., 1992). With respect to the lower border, bone is removed posteriorly and added anteriorly (Björk, 1963; Enlow and Harris, 1964). The symphysis enlarges by posterior, superior, and inferior apposition (Björk, 1963; Buschang *et al*., 1992). Menton models downward and backward, whereas point B drifts superiorly and posteriorly (Björk, 1963;

Enlow and Harris, 1964; Björk and Skieller, 1983; Baumrind *et al*., 1992; Buschang *et al*., 1992).

While general mandibular modelling and growth patterns are well qualified, they remain inadequately quantified. Quantification is necessary for estimating sampling distributions, comparing and evaluating changes, and estimating variation. To understand relative mandibular growth and possibly make inferences about its control, simultaneous comparisons of multiple mandibular sites are necessary. Baumrind *et al*. (1992) quantified changes of landmarks based on a mixed longitudinal sample of treated and untreated males and females. Larger samples are needed to reliably estimate multivariate patterns of variation and covariation.

Because mandibular growth and modelling changes are often, if not predominantly, biomechanical in nature, it is also important to understand how the changes relate to mandibular displacement and rotation. Growing mandibles are normally displaced inferiorly and anteriorly (Lundström and Woodside, 1980; Buschang *et al*., 1988a,b) and rotate forward between 0.5 and 1.0 degree per year (Ödegaard, 1970a; Björk and Skieller, 1972; Lavergne and Gasson, 1977b; Spady *et al*., 1992). Forward rotators display greater amounts of condylar growth, directed more anteriorly, than backward rotators (Björk, 1969; Ödegaard, 1970a; Lavergne and Gasson, 1977a). The gonial angles also tend to be smaller and show greater decreases in forward than backward rotators (Ödegaard, 1970b; Lavergne and Gasson, 1977a; Björk and Skieller, 1983). Because Ari-Viro and Wisth (1983) found no association between mandibular growth rotation and the size of gonial angle, the shape of the lower mandibular border, and inclination of the symphysis or condyle, further investigations may be warranted.

Based on a large sample of untreated males and females 10–15 years of age, this study evaluated multiple landmarks to (i) describe the mandibular growth modelling changes that normally occur, (ii) assess patterns of association between mandibular growth and modelling changes, and (iii) evaluate associations between mandibular modelling changes and mandibular displacement/rotation.

Subjec[redacted]and methods

Th[redacted]gitudinal sample included 186 subjects (79 fem[redacted]les and 107 males) evaluated at 10 and 15 years of age (all subjects were seen within [redacted]f their birth dates). The sample included untreated subjects with normal occlusion and malocclusion (48 per cent Class I, 39 per cent Class II division 1, and 12 per cent Class II division 2). The subjects were French-Canadians, randomly drawn from three school districts representing the different socio-economic strata of the larger population (Demirjian *et al*., 1971).

The analyses describe the growth and modelling of 11 mandibular landmarks (Figure 1) defined using operational definitions (Table 1). All cephalograms were traced (the right and left sides were averaged) and digitized by the same technician. Technical reliability, defined as the proportion of error variance to error plus true variance (Buschang *et al*., 1987), ranged between 88 and 99 per cent. All values were adjusted for radiographic enlargement (11.08 per cent).

To describe condylar growth and mandibular modelling, each subject's radiographs were

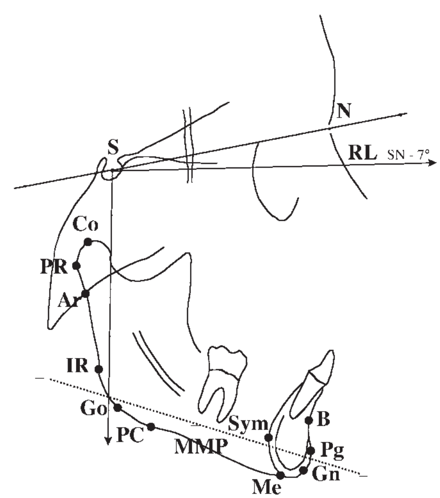

Figure 1 Schematic representation of the 11 landmarks studied, with the coordinate frame of reference orientated parallel and perpendicular to SN minus 7 degrees. The anterior and posterior stable structures reference points and their midpoint (MMP) were used to measure mandibular rotation and displacement, respectively.

Table 1 Landmarks, abbreviations, definitions, and percentage of horizontal/vertical reliability.

Landmark	Abbrev.	Definition	% Reliability horizontal/vertical
Condylion	Co	Superior tangent on the mandibular condyle determined from a perpendicular from the ramal plane	89.9/92.0
Posterior ramus	PR	Point on the posterior contour of the condyle defined by the superior tangent of the ramal plane	93.7/88.2
Articulare	Ar	Intersection point of the inferior cranial base surface and the averaged posterior surfaces of the mandibular condyles	97.1/94.7
Inferior ramus	IR	Intersection point between the posterior contour of the mandibular ramus and its inferior tangent	97.9/94.3
Gonion	Go	Point on the contour of the mandible determined by bisecting the angle formed by the mandibular and ramal planes	98.0/98.9
Posterior corpus	PC	Intersection point between the inferior contour of the mandible corpus and its posterior tangent	97.1/98.0
Symphysis	Sym	Most posterior point on the symphysis determined by the perpendicular tangent to the mandibular plane	98.4/99.1
Menton	Me	Intersection point of the posterior symphysis contour and the inferior contour of the corpus	98.5/98.2
Gnathion	Gn	Point between menton and pogonion, determined by bisecting the angle formed by the mandibular plane and its perpendicular tangent to pogonion	98.8/98.4
Pogonion	Pg	Most anterior point on the contour of the chin, determined by the perpendicular tangent to the mandibular plane	98.8/99.1
Point B	B	The most posterior point on the anterior surface of the symphyseal outline, as determined by a line from infradentale to pogonion	98.6/97.7

superimposed using natural reference structures (Björk and Skieller, 1983). The superimposition orientated the radiographic tracing on:

(1) anterior contour of the chin;
(2) inner contour of the cortical plate at the lower border of the symphysis;
(3) distinct trabecular structures in the symphysis;
(4) contour of the mandibular canal.

As described by Björk and Skieller (1983), anterior and posterior stable structure reference landmarks were marked on the first tracing and transferred to the second, superimposed tracing. Reliability of the mandibular superimpositions ranged between 94 and 99 per cent (Buschang *et al*., 1986).

Rectangular (X,Y) coordinates were used to describe the landmarks' horizontal and vertical positions. Changes were evaluated relative to the original sella and orientated along the stable structure reference line (RL), constructed from the original S–N minus 7 degrees (Figure 1). For example, the horizontal change in the position of gonion was measured parallel with RL (Goh) and the vertical change perpendicular to RL (Gov).

Mandibular displacement and true rotation were evaluated using the same reference frame. True rotation (Solow and Houston, 1988) was the angular change of the mandibular reference line, defined by the anterior and posterior stable structure reference landmarks described above, relative to RL. Horizontal and vertical mandibular displacements were orientated relative to RL, and defined by positional changes of MMP, the midpoint of the anterior and posterior stable reference landmarks (Figure 1).

Statistical analyses

Analyses of skewness and kurtosis showed normal distributions for all of the variables. Sex differences in mandibular modelling, displacement, and rotation were evaluated with *t*-tests. Mandibular growth and modelling were related to mandibular rotation and displacement using Pearson product–moment correlations. Principle components analysis, with varimax rotation, was used to identify multivariate composites of variation between the 22 modelling measurements. Multivariate analyses produce composite variables with greater validity than any single component measure. Using factor loadings, multivariate factor scores were computed for each subject. Multiple stepwise regression, with the factor scores as dependent variables, was used to assess the multivariate contribution of mandibular rotation, horizontal displacement, and vertical displacement to condylar growth and mandibular modelling changes.

Results

Table 2 and Figure 2 show the vertical changes between 10 and 15 years of age. Condylion (Co) showed the greatest superior growth changes; magnitudes of change decreased from Co to posterior corpus. Point B and symphysis modelled superiorly; menton, gnathion, and pogonion showed small, but significant inferior modelling. Sex differences also decreased from Co (3.4 mm) to posterior ramus (1.3 mm). Anterior corpus showed no significant vertical modelling differences between males and females.

The gonial region showed approximately twice as much posterior modelling as the condylar region (Table 3, Figure 2). Landmarks on the anterior corpus showed limited amounts of modelling, all except menton, which modelled posteriorly. With the exception of Co, males showed greater posterior modelling of the ramus than females. Point B showed greater posterior modelling in females than males. None of the other landmarks on the corpus showed sex differences.

The mandible underwent 2–3.3 degrees of forward true rotation between 10 and 15 years; variation among subjects ranged more than [illegible] degrees (Table 4). The mandible was displaced 9.6–12.7 mm inferiorly and 1.9–2.7 mm anteriorly. Males showed significantly more forward mandibular rotation than females. Males also displayed approximately 3.3 mm more inferior growth displacement than females. There was no sex difference in the anterior growth displacement of the mandible.

Most growth and modelling changes, especially those on the ramus, were correlated with mandibular rotation and growth displacements (Table 5). Mandibles that underwent the

Table 2 Sex differences in vertical growth and modelling changes (10–15 years).

Point	Males			Females			Differences *P*
	Mean	SE	SD	Mean	SE	SD	
Co	14.26	0.33	3.47	10.91	0.32	2.79	<0.001
PR	14.16	0.33	3.45	10.77	0.32	2.76	<0.001
Ar	12.62	0.33	3.44	9.51	0.31	2.71	<0.001
IR	7.86	0.28	2.88	5.49	0.30	2.62	<0.001
Go	6.26	0.21	2.16	4.57	0.24	2.07	<0.001
PC	5.29	0.21	2.15	3.95	0.22	1.95	<0.001
Sym	0.54	0.11	1.15	0.29	0.10	0.93	0.123
Me	–0.50	0.07	0.78	–0.42	0.06	0.54	0.418
Gn	–0.32	0.05	0.50	–0.29	0.05	0.39	0.730
Pg	–0.28	0.08	0.89	–0.27	0.08	0.73	0.992
B	2.37	0.14	1.49	2.15	0.15	1.32	0.310

Positive, superior; negative, inferior.

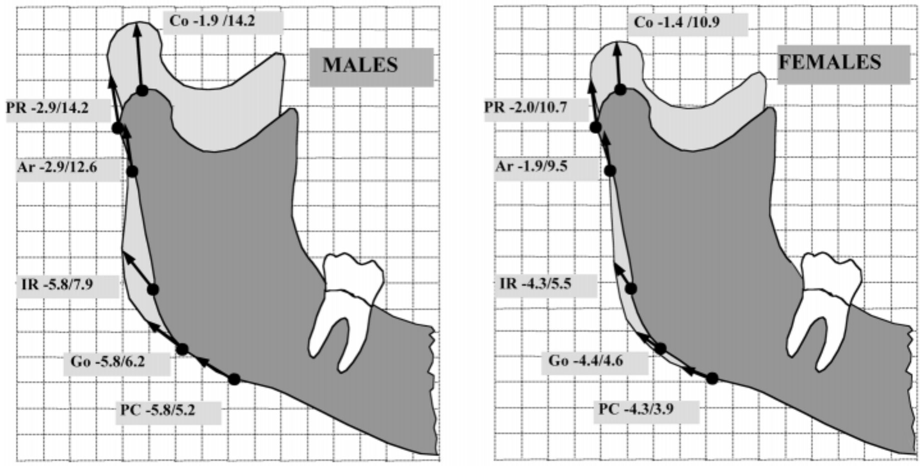

Figure 2 Condylar growth and mandibular modelling between 10 and 15 years of age. The horizontal/vertical components of each landmark's growth vector were proportionately scaled (1 grid = 5 mm).

Table 3 Sex differences in horizontal growth and modelling changes (10–15 years).

Point	Males			Females			Differences
	Mean	SE	SD	Mean	SE	SD	*P*
Co	–1.85	0.24	2.52	–1.35	0.28	2.41	0.184
PR	–2.92	0.22	2.23	–2.03	0.25	2.19	0.008
Ar	–2.91	0.21	2.15	–1.86	0.22	1.96	0.001
IR	–5.80	0.17	1.78	–4.29	0.16	1.36	<0.001
Go	–5.76	0.16	1.63	–4.37	0.14	1.27	<0.001
PC	–5.80	0.17	1.78	–4.29	0.16	1.35	<0.001
Sym	–0.51	0.05	0.53	–0.33	0.06	0.57	0.029
Me	0.27	0.11	1.19	0.13*	0.10	0.89	0.366
Gn	–0.41	0.05	0.55	–0.38	0.05	0.49	0.676
Pg	–0.11	0.04	0.51	–0.19	0.06	0.52	0.307
B	–0.04*	0.07	0.82	–0.38	0.10	0.93	0.011

*No significant change. Positive, anterior; negative, posterior.

Table 4 True mandibular rotation and displacement.

Factor	Males			Females			Differences
	Mean	SE	SD	Mean	SE	SD	*P*
Rotation	–3.34	0.28	2.88	–1.97	0.34	3.00	0.002
Displacement							
Vertical	–12.74	0.27	2.85	–9.58	0.24	2.06	<0.001
Horizontal	2.68	0.37	3.00	1.88	0.43	3.79	0.16

Negative, anterior rotation; positive, inferior and anterior displacement.

Table 5 Bivariate correlations of mandibular growth and modelling in vertical and horizontal directions with rotation (Rot), vertical displacement (VD), and horizontal displacement (HD).

	Vertical			Horizontal		
	Rot	VD	HD	Rot	VD	HD
Co	–0.58***	–0.74***	–0.17*	–0.32***	–0.09	–0.58***
PR	–0.56***	–0.74***	–0.17*	–0.26***	0.01	–0.57***
Ar	–0.61***	–0.75***	–0.16*	–0.21**	0.08	–0.56***
IR	–0.53***	–0.57***	–0.24***	0.14	0.40***	–0.26***
Go	–0.56***	–0.60***	–0.28***	0.17*	0.43**	–0.22*
PC	–0.50***	–0.54***	–0.27***	0.12	0.37***	–0.20
Sym	–0.31***	–0.18*	–0.19**	0.15	0.13	–0.04
Me	–0.04	0.12	–0.05	0.12	0.02	0.15*
Gn	0.06	0.14	0.07	0.16*	0.20*	0.15*
Pg	–0.05	0.05	–0.02	–0.05	–0.02	0.01
B	0.09	–0.28**	0.28***	–0.21**	–0.16*	–0.23**

*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

greatest forward rotation, and most inferior mandibular displacement showed the greatest amount of superior growth and modelling. Superior growth and modelling, especially in the gonial region, was negatively related with anterior mandibular displacement. The ramus displayed the greatest posterior modelling in adolescents who had the most anterior mandibular displacement. The condylar region showed greater posterior growth for individuals with less forward or backward rotation. The gonial region displayed greater posterior drift associated with more inferior mandibular displacement. Associations for the landmarks on the anterior corpus were low and showed no consistent patterns of association.

Principal component analysis identified six independent factors explaining approximately 81 per cent of the total variation (Table 6). The first, vertical ramus (VR) factor explained 25.5 per cent of the variation and isolated six landmarks describing vertical modelling of the ramus. The second horizontal ramus (HR) factor explained 21.6 per cent of the variation and described the horizontal modelling of the ramus. The third factor, explaining 11.4 per cent of the variation, pertained to vertical modelling of the mid-symphysis (VMS) as defined by pogonion and the symphyseal landmark; horizontal modelling of pogonion contributed to a lesser extent. The fourth (HIS) and fifth (VIS) factors explained 17 per cent of the variation, and pertained to the horizontal and vertical modelling of the inferior symphysis, as defined by gnathion and menton. The last alveolar (ALV) factor explained only 5.9 per cent of the variation, and isolated the horizontal and vertical modelling at point B.

The multiple regression analyses (Table 7) showed that mandibular rotation and displacement were associated with four of the six multivariate components. Based on standardized loading, approximately 71 per cent of the variation in VR modelling was explained by rotation, vertical growth displacement, and to a lesser extent, horizontal growth displacements. Subjects with the most vertical growth and modelling had (1) more forward rotation, (2) more inferior displacement, and (3) more anterior displacement. Horizontal growth and modelling of the ramus was primarily related to horizontal mandibular displacement. Subjects with the greatest posterior modelling of the ramus showed (1) more anterior mandibular displacement and (2) greater forward rotation. The third, VMS factor, indicated greater vertical modelling of the mid-symphyseal landmarks in the individuals who displayed the greatest forward rotation. The last ALV factor was negatively associated with vertical mandibular displacement, indicating that the greater the

Table 6 Factor scores for the six principal components identified, with variables contributing substantially in bold.

Variable	VR	HR	VMS	HIS	VIS	ALV	Communalities
	25.5%	21.6%	11.4%	9.3%	7.7%	5.9%	%
Co (v)	**0.92**	–0.19	–0.03	–0.02	–0.07	0.05	0.89
Co (h)	0.37	**0.81**	0.02	–0.12	–0.01	0.05	0.81
PR (v)	**0.93**	–0.17	–0.03	–0.02	–0.07	0.07	0.90
PR (h)	0.26	**0.88**	0.03	–0.09	0.01	0.03	0.85
Ar (v)	**0.92**	–0.15	0.02	–0.06	–0.07	0.04	0.89
Ar (h)	0.19	**0.90**	0.01	–0.09	0.03	0.06	0.86
IR (v)	**0.86**	0.07	0.07	–0.10	–0.03	0.02	0.75
IR (h)	–0.34	**0.85**	–0.04	0.03	0.11	–0.03	0.85
Go (v)	**0.91**	0.19	0.04	–0.16	0.01	0.08	0.90
Go (h)	–0.34	**0.84**	0.01	0.10	0.10	–0.08	0.85
PC (v)	**0.83**	0.19	0.07	0.21	0.05	0.15	0.80
PC (h)	–0.27	**0.76**	–0.06	0.18	0.05	–0.14	0.71
Sym (v)	0.28	0.07	**0.91**	–0.17	0.10	0.04	0.96
Sym (h)	–0.18	0.31	0.02	0.47	–0.01	0.17	0.39
Me (v)	–0.02	0.13	0.09	–0.19	**0.92**	0.02	0.92
Me (h)	–0.05	–0.07	0.11	**0.80**	–0.33	0.01	0.77
Gn (v)	–0.12	0.07	0.37	0.24	**0.71**	–0.01	0.72
Gn (h)	–0.21	–0.11	0.02	**0.82**	0.32	0.02	0.84
Pg (v)	–0.11	–0.05	**0.93**	0.03	0.22	0.04	0.93
Pg (h)	–0.05	–0.05	**0.77**	0.45	0.02	0.05	0.84
B (v)	0.10	–0.31	–0.02	0.01	0.11	**0.83**	0.80
B (h)	0.21	0.32	0.17	0.17	–0.12	**0.71**	0.72

VR, vertical ramus; HR, horizontal ramus; VMS, vertical modelling of the mid-symphysis; HIS, horizontal modelling of the inferior symphysis; VIS, vertical modelling of the inferior symphysis; ALV, alveolar.

Table 7 Stepwise multiple regression analyses of the six components as dependent variables.

Standardized coefficients					
Y	Rot	VD	HD	R	*P*
VR	–0.587	–0.532	0.168	0.84	<0.001
HR	0.532	NS	–0.846	0.59	<0.001
VMS	–0.185	NS	NS	0.19	0.018
HIS	NS	NS	NS	–	–
VIS	NS	NS	NS	–	–
ALV	NS	–0.171	NS	0.17	0.029

Y = Rot + VD + HD.
Rot, rotation; VD, vertical displacement; HD, horizontal displacement; R, multiple correlation.

inferior displacement, the more superior and less posterior point B remodelled.

Discussion

The relative amounts and directions of growth observed compare well with those reported by Baumrind *et al.* (1992). Both studies show the greatest vertical and horizontal changes for the condylar and gonial regions, respectively. While in the present investigation slight anterior modelling of menton was shown for males, Baumrind *et al.* (1992) reported slight posterior movements for their combined sample of males and females. The differences between the two studies may be attributed to the lengths of the observation periods, sample composition, magnification, and their use of implant superimpositions.

The results showed approximately five times more inferior than anterior mandibular displacement between 10 and 15 years of age. It must be emphasized that these ratios pertain to the displacement of MMP, a point located approximately in the middle of the corpus. Because the mandible is simultaneously rotating forward, less anterior and more inferior displacement might be anticipated for MMP than for the chin. The least anterior displacement of MMP might be expected for Björk's (1969) type II forward rotators, who display forward rotation about a centre at the incisal edges and, based on the findings, appear to the most prevalent type of rotators in the present sample. Also, a large proportion of the sample had Class II malocclusions (39 per cent), which may be expected to show less anterior growth potential, especially for those with vertical tendencies.

Sex differences were largely confined to the ascending ramus. With the exception of the mid-symphyseal and B points, there were no differences for the landmarks located on the mandibular corpus. This distinction refines previous reports of mandibular dimorphism in mandibular size favouring males over females (Coben, 1955; Maj and Luzi, 1964; Hunter and Garn, 1972; Riolo *et al.*, 1974; Bishara *et al.*, 1981; Buschang *et al.*, 1986). The landmarks showing the largest sex differences had the most mandibular growth potential. Males have greater growth potential than females between 10 and 15 years due to:

(1) a more intense adolescent growth spurt of males than females;
(2) and approximately two additional years of growth due to maturational differences (Tanner, 1962).

As expected, the larger sample size in this research provided more efficient growth estimates than previously published (Figures 3 and 4). At the 95 per cent confidence level, the estimates of condylar growth were within ± 0.6 mm of the true value. The standard errors of the five-year estimates are consistently lower than the seven and four year estimates reported by Baumrind *et al.* (1992). Accurate estimates of variation are important because individuals at the extremes of the distributions are, by definition, most unlike the others, which commonly translates

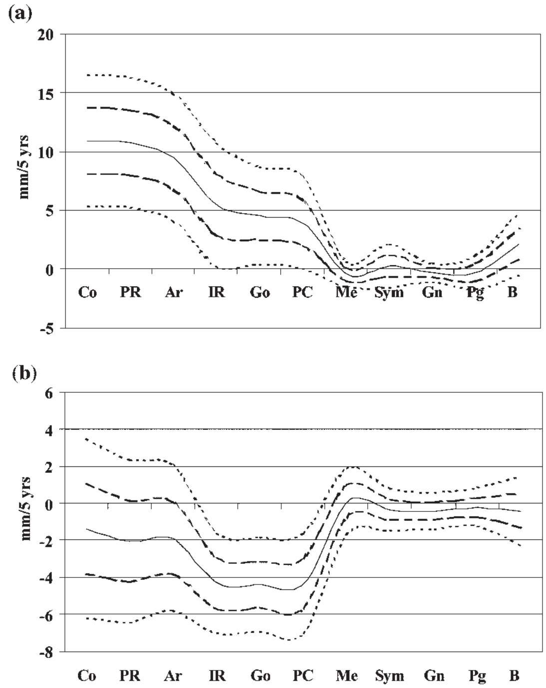

Figure 3 (a) Vertical and (b) horizontal growth and modelling changes between 10 and 15 years of age for males (mean ± 1 SD, ± 2 SD).

into the greatest need for therapy. These estimates suggest that it would be unlikely (at or below the 5 per cent level) for males to show more than 21 mm or less than 7 mm of vertical condylar growth between 10 and 15 years (Figure 3a).

It is also important to consider variation among landmarks, which was greatest for the condyle and decreased progressively through the more inferior landmarks on the ramus. The coefficients of variation showed the greatest relative variability for horizontal changes in the condylar region. For example, horizontal growth of Co was five times more variable than its vertical growth. Vertical changes in the gonial region were also relatively more variable than those in the condylar region. Such comparisons suggest that certain anatomical regions are more susceptible than others to modification by local epigenetic and environmental factors. It is suggested that the observed changes represent adaptive developmental responses, and that the

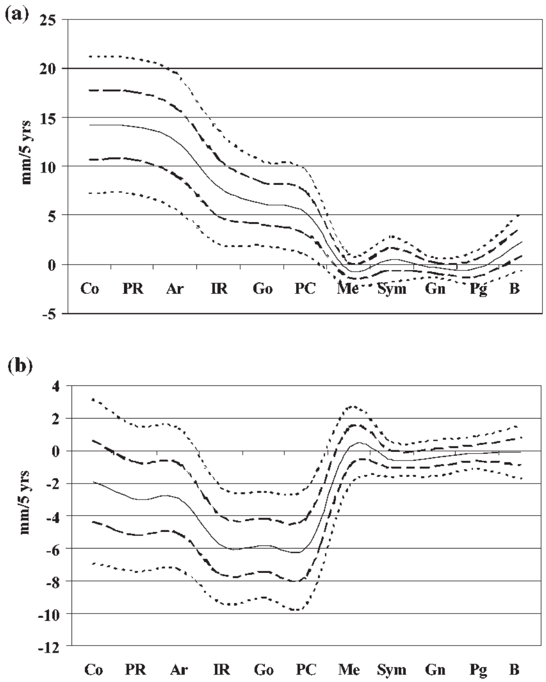

Figure 4 (a) Vertical and (b) horizontal growth and modelling changes between 10 and 15 years of age for females (mean ± 1 SD, ± 2 SD).

regions showing the greatest variation are either most susceptible to respond to a given stimulus or under the greatest biomechanical stimulus. On this basis, a greater response potential to clinical interventions might be expected for horizontal than vertical condylar growth.

Theoretically, the multivariate associations identified the underlying structure of the data. In other words, based on the correlations between the 22 variables, six independent composites were extracted that might be expected to more reliably reflect patterns of change. For example, variation for the 12 variables representing the ramus was explained by two factors—one for horizontal movements and the other for vertical movements. This argues against any localized control of condylar growth; it suggests common control mechanisms for vertical ramus growth.

The results demonstrate that condylar growth and ramus modelling are related to mandibular displacement. Condylar growth changes (amount and direction) may be related to the condyles' intrinsic growth ability (Yozwiak, 1979; Copray *et al.*, 1985) and modulated by functional loads (Whetten and Johnston, 1985). Experimental evidence shows that the condyle adapts to protrusive function (McNamara and Carlson, 1979; Petrovic *et al.*, 1981) by growing posteriorly. Clinical studies have also demonstrated that growth of the condyle is responsive to changes in mandibular position (Folke and Stallard, 1966; McNamara, 1972; McNamara and Carlson, 1979; Petrovic *et al.*, 1981; Pirttiniemi *et al.*, 1993). Marked bone resorption in the gonial region and apposition at the symphysis have been reported for animals forced to lower mandibular posture (Harvold *et al.*, 1973).

True mandibular rotation has been previously associated with ramus growth and modelling. The results of this study show that forward rotators tend to have greater superior and more anteriorly directed condylar growth, as previously demonstrated (Björk, 1969; Ödegaard, 1970a; Lavergne and Gasson, 1977a). Moreover, forward rotators show greater superior–posterior modelling of the gonial region than backward rotators. These changes in the condylar and gonial regions explain why forward rotators are characterized by smaller gonial angles that decrease more during growth (Ödegaard, 1970b; Lavergne and Gasson, 1977a; Björk and Skieller, 1983).

The associations between rotation and mandibular modelling also argue against the notion that remodelling rotation is due to rotation of the corpus inside its matrix, as suggested by Björk (1963). Rather, it supports the contention of Lavergne and Gasson (1976) that modelling occurs principally at the mandibular ramus. For example, an individual with more forward rotation around a centre near the incisors might be expected to respond by showing more superior–anterior condylar growth, greater apposition at the posterior aspect of the ramus, greater resorption at the lower aspect of the ramus, and a greater decrease in gonial angulation. In combination, these would have the effect of decreasing the counterbalancing proportion (Dibbets, 1990) and increasing remodelling rotation.

Interestingly, mandibular displacement and rotation explained little or no variation in the modelling changes of the inferior symphysis (i.e. menton and gnathion). It has been suggested that anterior rotation results in apposition of bone along the lower anterior border of the mandible and resorption along the posterior border (Björk and Skieller, 1983). While anterior rotation was associated with posterior resorption, it was not related to anterior apposition. This suggests that, under normal circumstances, modelling of the anterior border is an adaptive response to mechanisms other than mandibular rotations and displacement. Modelling changes in the inferior symphyseal region are probably more closely associated with the supra-hyoid muscles (Enlow and Harris, 1964).

Conclusions

1. The ramus showed the most growth and modelling (posterior and superior) and the greatest variation. Modelling changes for the corpus were smaller. The symphyseal region enlarged by inferior, posterior, and superior apposition of bone.
2. Sex differences—the ramus showed significantly greater growth and modelling changes for males than for females. For the corpus, apposition at the symphyseal point was greater for males, while resorption at point B was greater for females.
3. Associations—independence was observed within and between growth fields. Growth and modelling changes for the ramus and corpus were relatively independent. The horizontal and vertical changes observed in the ramus were also relatively independent. Within the corpus, the superior, middle, and inferior aspects of the symphysis were independent.
4. Relationships with rotation and displacement —superior growth and modelling changes of the ramus were related to forward rotation and inferior mandibular displacement; posterior changes were associated with anterior displacement and forward rotation. The superior and posterior modelling changes of point B were related to inferior displacement. Modelling changes of the lower anterior border of the mandible were not related to rotation.

Address for correspondence

Dr P. H. Buschang
Department of Orthodontics
Baylor College of Dentistry
The Texas A&M University Health Science Center
3302 Gaston Avenue
Dallas
Texas 75246, USA

Acknowledgement

This research was partially funded by MRC grant MA-8097.

References

Ari-Viro A, Wisth P J 1983 An evaluation of the method of structural growth prediction. European Journal of Orthodontics 5: 199–207

Baumrind S, Ben-Bassat Y, Korn E L, Bravo L A, Curry S 1992 Mandibular remodeling measured on cephalograms. 1. Osseous changes relative to superimposition on metallic implants. American Journal of Orthodontics and Dentofacial Orthopedics 102: 134–142

Bishara S E, Jamison J E, Peterson L C, DeKock W H 1981 Longitudinal changes in standing height and mandibular parameters between the ages of 8 and 17 years. American Journal of Orthodontics 80: 115–134

Björk A 1963 Variations in the growth pattern of the human mandible; longitudinal radiographic study by the implant method. Journal of Dental Research 42: 400–411

Björk A 1969 Prediction of mandibular growth rotation. American Journal of Orthodontics 55: 585–599

Björk A, Skieller V 1972 Facial development and tooth eruption. An implant study at the age of puberty. American Journal of Orthodontics 62: 339–383

Björk A, Skieller V 1983 Normal and abnormal growth of the mandible. A synthesis of longitudinal cephalometric implant studies over a period of 25 years. European Journal of Orthodontics 5: 1–46

Brash J C 1924 The growth of the jaws and palate. Dental Board of the United Kingdom, London

Buschang P H, Santos-Pinto A 1998 Condylar growth and glenoid fossa displacement during childhood and adolescence. American Journal of Orthodontics Dentofacial Orthopedics 113: 437–442

Buschang P H, Tanguay R, Demirjian A, LaPalme L, Goldstein H 1986 Sexual dimorphism in mandibular growth of French-Canadian children 6–10 years of age. American Journal of Physical Anthropology 71: 33–37

Buschang P H, Tanguay R, Demirjian A 1987 Cephalometric reliability. A full ANOVA model for the estimation of true and error variance. Angle Orthodontist 57: 168–175

Buschang P H, Tanguay R, Demirjian A, LaPalme L, Turkewicz J 1988a Mathematical models of longitudinal mandibular growth for children with normal and untreated Class II, division 1 malocclusion. European Journal of Orthodontics 10: 227–234

Buschang P H, Tanguay R, Demirjian A, LaPalme L, Goldstein H 1988b Pubertal growth of the cephalometric point gnathion: multilevel models for boys and girls. American Journal of Physical Anthropology 77: 347–354

Buschang P H, Julien K, Sachdeva R, Demirjian A 1992 Childhood and pubertal growth changes of the human symphysis. Angle Orthodontist 62: 203–210

Coben S E 1955 The integration of facial skeletal variants. American Journal of Orthodontics 41: 407–434

Copray J C V M, Jansen H W B, Duterloo H S 1985 The role of biomechanical factors in mandibular condylar cartilage growth and remodelling *in vitro*. In: Carlson D S, McNamara J A Jr, Ribbens K A (eds) Developmental aspects of temporomandibular joint disorders, Monograph No. 16, Craniofacial Growth Series. Center for Human Growth and Development, University of Michigan, Ann Arbor

Demirjian A, Brault Dubuc M, Jenicek M 1971 Étude comparative de la croissance de l'enfant canadien d'origine français à Montréal. Canadian Journal of Public Health 62: 11–19

Dibbets J M H 1990 Mandibular rotation and enlargement. American Journal of Orthodontics and Dentofacial Orthopedics 98: 29–32

Enlow D H, Harris D B 1964 A study of postnatal growth of the human mandible. American Journal of Orthodontics 50: 25–50

Folke L E A, Stallard R E 1966 Condylar adaptation to a change in intermaxillary relationship. Periodontal Research 1: 79–89

Harvold E P, Vargevik K, Chierici G 1973 Primate experiments on oral sensation and dental malocclusion. American Journal of Orthodontics 63: 494–508

Humphry G M 1863 Results of experiments on the growth of the jaws. British Journal of Dental Science 6: 548–550

Hunter J 1771 The natural history of the human teeth, explaining their structure, use, formation, growth, and disease. J. Johnson, London

Hunter S W, Garn S M 1972 Disproportionate sexual dimorphism in the human face. American Journal of Physical Anthropology 36: 133–138

Lavergne J, Gasson N 1976 A metal implant study of mandibular rotation. Angle Orthodontist 46: 144–150

Lavergne J, Gasson N 1977a Operational definitions of mandibular morphogenetic and positional rotations. Scandinavian Journal of Dental Research 85: 185–192

Lavergne J, Gasson N 1977b Direction and intensity of mandibular rotation in the sagittal adjustment during growth of the jaws. Scandinavian Journal of Dental Research 85: 192–199

Lundström A, Woodside D G 1980 Individual variation in growth directions expressed at the chin and the midface. European Journal of Orthodontics 2: 65–79

Maj G, Luzi C 1964 Longitudinal study of mandibular growth between nine and thirteen years as a basis of an attempt of its prediction. Angle Orthodontist 3: 220–230

Mathews J R, Ware W H 1978 Longitudinal mandibular growth in children with tantalum implants. American Journal of Orthodontics 74: 633–655

McNamara J A Jr 1972 Neuromuscular and skeletal adaptations to altered orofacial function, Monograph No. 1, Craniofacial Growth Series. Center for Human Growth and Development, University of Michigan, Ann Arbor

McNamara J A Jr, Carlson D S 1979 Quantitative analysis of temporomandibular joint adaptations to protrusive function. American Journal of Orthodontics 76: 593–611

Ödegaard J 1970a Growth of the mandible studied with the aid of metal implants. American Journal of Orthodontics 57: 145–157

Ödegaard J 1970b Mandibular rotation studied with the aid of metal implants. American Journal of Orthodontics 58: 448–454

Petrovic A, Stutzmann J, Gasson N 1981 The final length of the mandible: is it genetically determined. In: Carlson D S (ed.) Craniofacial biology, Monograph No. 10, Craniofacial Growth Series. Center for Human Growth and Development, University of Michigan, Ann Arbor

Pirttiniemi P, Kantomaa T, Tuominen M 1993 Increased condylar growth after experimental relocation of the glenoid fossa. Journal of Dental Research 72: 1356–1359

Riolo M L, Moyers R E, McNamara J A, Hunter W S (eds) 1974 An atlas of craniofacial growth, Monograph No. 2, Craniofacial Growth Series. Center for Human Growth and Development, University of Michigan, Ann Arbor

Solow B, Houston W J B 1988 Mandibular rotations: concepts and terminology. European Journal of Orthodontics 10: 177–179

Spady M, Buschang P H, Demirjian A, LaPalme L 1992 Mandibular rotation and angular remodeling during childhood and adolescence. American Journal of Human Biology 4: 683–689

Tanner J M 1962 Growth at adolescence. Blackwell Scientific Press, Oxford

Whetten L L, Johnston L E Jr 1985 The control of condylar growth: an experimental evaluation of the role of the lateral pterygoid muscle. American Journal of Orthodontics 88: 181–190

Yozwiak R A 1979 An experimental investigation of the mechanical properties of condylar growth in young guinea pigs. Master's thesis, St Louis University, Missouri