SCIENTIFIC SECTION

Comparison of the Bolton Standards to longitudinal cephalograms superimposed on the occipital condyle (I-point)

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Objective: To compare traditional superimposition on sella turcica and the anterior cranial base (SACB) to superimposition referenced at the occipital condyle (I-point) for demonstrating craniofacial growth and development.

Materials and methods: Tracings for ages 8, 10, 12, 15 and 18 were chosen from the Bolton Standards of Dentofacial Developmental Growth to compare superimposition with the traditional longitudinal reference at SACB (anterior curvature of sella turcica and anterior cranial base) to reference at I-point on the antero-inferior contour of the occipital condyles in *norma lateralis*. The serial tracings were superimposed using both the sagittal and postero-anterior (PA) tracings. Incremental growth of landmarks was measured in relation to Cartesian coordinates and compared between the superimposition methods.

Results: Sagittal and PA tracing superimpositions displayed an average 7 mm greater cephalad movement of landmarks, an average 2.4 mm greater ventral movement, and comparable transverse dimension with superimposition referenced at I-point as compared to the SACB reference.

Conclusion: I-point superimposition demonstrates physiologic growth patterns concealed by traditional registration at sella turcica. The evolution of superimposition on SACB was based on convenience and reproducibility. Fundamental principles of bone development are consistent with the occipital condyles as a more biologic reference for *relative* craniofacial growth. Actual vertical growth is believed to be greater than displayed in this study, due to the cross-sectional and blended nature of the sample.

Key words: Cephalometrics, I-point, occipital condyle, superimposition, craniofacial growth

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Introduction

'The problem of biologically correct registration is a primary one in the field today'.[1] Moss illustrated his point with an example of a Down's syndrome patient, observing that tracings superimposed on the endocranial contours of the cranial base displayed a growth pattern more consistent with observed clinical features, compared with a traditional pre-sella registration. Stable landmarks for superimposition are commonly associated with neural structures, e.g. cribriform plate olfactory, PT point foramen rotundum, sella turcica-pituitary hypophysis. Pre-sella superimposition was chosen based on: fusion of the anterior cranial base (ACB) synchondroses, that superimposition was reproducible, and the midline structures of the ACB were easily visualized. It was assumed that the ACB was stable because the brain had finished growing by the age of 8;[2,3] however, MRI technology has demonstrated continuing brain anterior lobe growth up to age 12.[4,5] This late brain growth combined with the knowledge that growth of lateral skull sutures and the ACB is restricted relatively early,[2,6] is a quandary for displacement of the brain with growth.

The separation of the anterior and posterior cranial base (PCB) by the sphenooccipital synchondrosis (SOS) must be considered as most facial structures are located ventral to the SOS while the mandibular condyle is dorsal to the SOS.[7] Incorporation of structures on the PCB have lead to the development of analyses, notably by Broadbent (Bolton point-nasion),[8,9] Coben (basion-ACB analysis)[7,10] and Frankel (O′; occipital point).[11] These structural landmarks are proximate the occipital condyles, in *norma lateralis*. The cephalometric landmark I-point,[12] the most antero-inferior point on the basi-occipital

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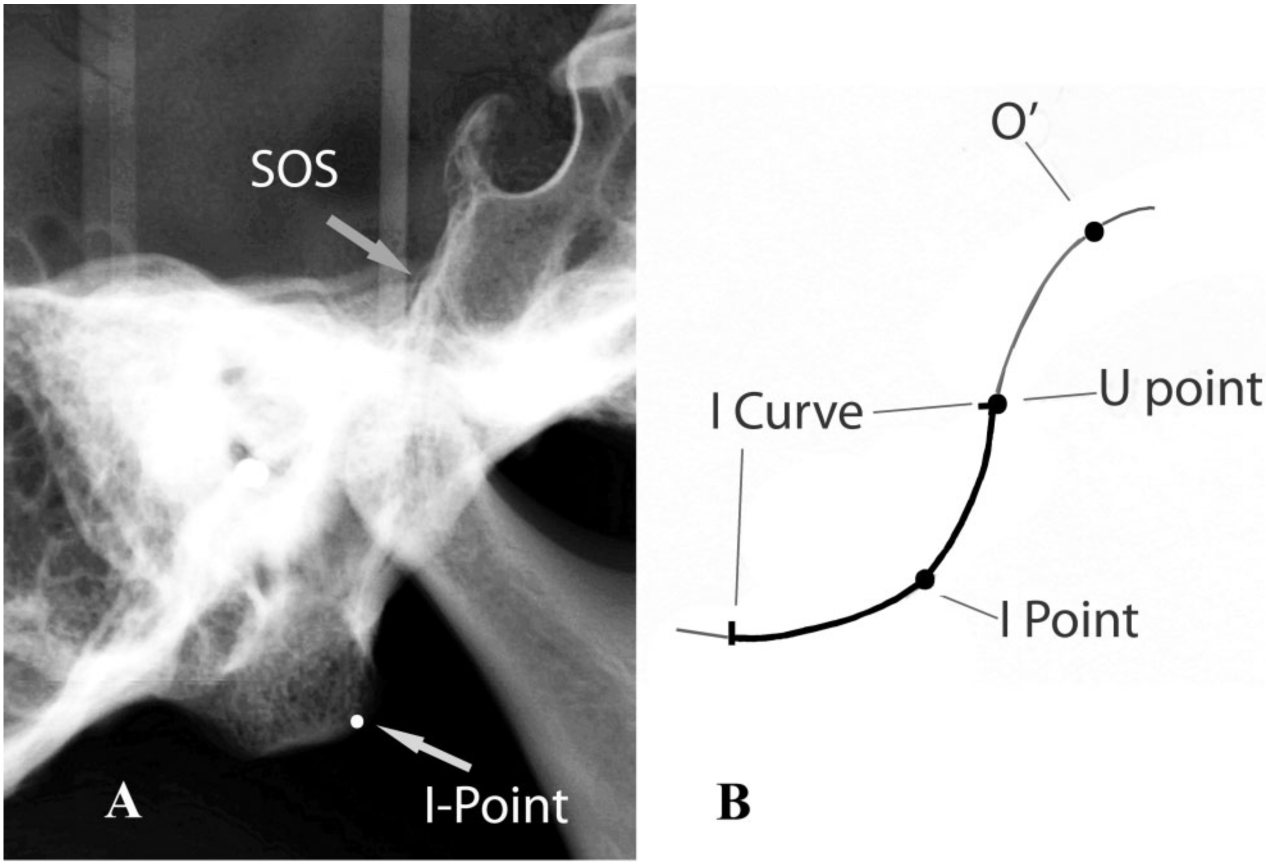


I point: most anterior-inferior point on the condyle; U point: midpoint between O' and I point; I Curve: from U point to the midpoint of the inferior contour (SIA or remnant)

Figure 1 Dry Skull *in norma lateralis* radiograph; arrows pointing to the superimposition of the occipital condyles (bottom arrow) and remnant of the sphenooccipital synchondrosis (top arrow); (B) Tracing of the superimposed occipital condyles as seen on a lateral cephalometric radiograph (Figure from Ref. 12)

portion of the occipital condyles in *norma lateralis* (OC) was utilized for cephalometric superimposition in this study (Figure 1). This method is similar to the Coben analysis (the reference points basion and I-point are both located on the PCB: the ACB orientation is similar to Coben's sella-nasion line which is stable relative to the ethmoid cribriform plate,[5] and both are oriented parallel) and based on the work of Kanomi (K-point). Observed apposition at basion[3] is not large relative to the occipital condyle, however the effect of relative positional change of other landmarks increases with distance from the reference, making the small amounts significant.

I-point is physiologically stable because there is no appositional growth along articulating surfaces due to the high pressure gradient of the head resting on the spinal column and the lack of an interstitial growth mechanism for the bone supporting the joint.[12] Enlow[13] notes that cartilage functions as a growth cartilage in conjunction with certain enlarging bones and specifies that these are synchondrosis, condylar cartilage and the epiphyseal plate cartilage. Furthermore, Enlow's analysis was based on anatomical surface topography of dynamic histomorphometry with intravital labels. Enlow could only determine that bone formation and resorption had occurred at some point in time but he could not determine current activity or rate. This was the departure of Enlow and Frost in the early 1960s.[14] Dixon[15] justifies the growth of certain cartilages by describing them as similar to epiphyseal plates. Also, it must be noted that studies based on surface microscopy patterns are not applicable to the hyaline cartilage on the occipital condyles, and that there is no periosteum, nor muscle attachment compatible with the matrix theory of Moss.[16] I point/ I curve (Figure 1) superimposition reveals a more physiologic growth pattern that is consistent with the Bjork implant studies,[12] airway demands, speech development and microscopic observation of necropsy specimens.[3,12,13,17]

The objective of this study was to determine if the occipital condyle is a more physiologic superimposition reference for demonstrating the modelling and remodelling mechanisms of craniofacial growth.

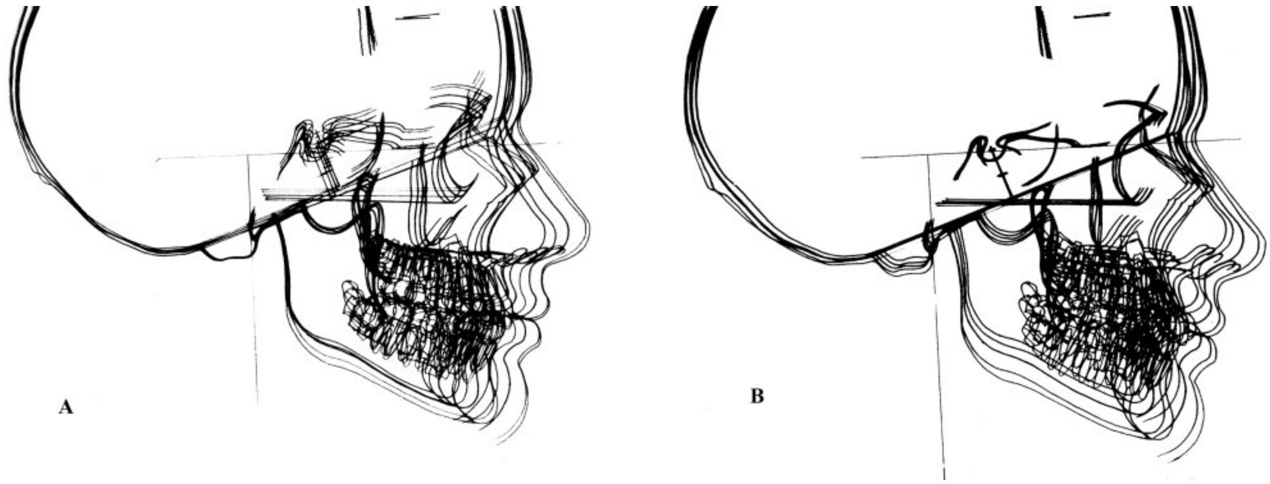


Figure 2 Sagittal Superimposition of 8-, 10-, 12-, 15- and 18-year-old Bolton Standards referenced at (A) I-point oriented to ACB (in parallel) and (B) at the anterior curvature of sella turcica and oriented to anterior cranial base (Tracings from the Bolton Standards of Dentofacial Developmental Growth)[18]

Methods and materials

Tracings from the Bolton Standards of Dentofacial Developmental Growth[18] were chosen to compare the traditional longitudinal reference, the anterior curvature of sella turcica and anterior cranial base (SACB), to reference at I-point; because they are a readily available, high quality resource.[13,19] The Bolton Standards are comprised of cross-sectional data from 32 subjects (16 male and 16 female) chosen from the 93 participants.[18] The 8-, 10-, 12-, 15- and 18-year-old tracings were selected for lateral and frontal superimposition.

The following 31 landmarks were selected for analysis using Cartesian coordinates with the *lateral* cephalometric radiographs:

A-point	ANS	Soft Tissue Pogonion
I-point	PNS	n/a
Bolton point	Antigonion	Soft Tissue Menton
Inion	Ethmoidale	Sella
Ramus point	Supra-orbitale	R-point
Gonion	Articulare	PT-point
Pogonion	Prosthion	Nasion
B-point	Infradentale	Orbitale
Menton	Nose Tip	Porion
Glabella	Upper Lip	Basion
Key Ridge	Lower Lip	

The following 24 landmarks were selected for analysis using Cartesian coordinates with the *frontal* cephalometric radiographs:

Anterior cranial base	Lateral skull surface: external (right and left) internal (right and left)	Supra-orbitale (right and left)
Frontonasal suture	Mastoid process (right and left)	Orbitale (right and left)
Nasal floor	Superior crest of the external sagittal suture	Zygoma (right and left)
Lateral alveolar crest (right and left)	Superior crest of the internal sagittal suture	Menton
Antigonion (right and left)		Jugum (right and left)

The 8-, 10-, 12-, 15- and 18-year-old sagittal tracings were superimposed 3 times by referencing on the anterior curvature of sella and oriented to ACB (SACB), and then, superimposed 3 times referencing at I-point/I-curve while ACB was oriented parallel to subsequent superimposed ACB (Figure 2). Cartesian coordinates where designed for both superimposition methods using transparency graph paper (8.5' × 11' transparency film 0.1 mm, SL5263, Staples Inc., Framingham, MA, USA; which was imprinted with a 1 × 1 cm grid). The x-axis was coincident with a line oriented through the anterior curvature of sella turcica midpoint and ethmoidale (the deepest point on the ACB outline) of the 8-year-old tracing (Figure 3). The y-axis was coincident with a perpendicular line originating from the x-axis and bisecting I-point on the 8-year-old tracing (Figure 3). Overlaying the acetate graph to match the created x-axis and y-axis, points were marked on the graph acetate with a permanent marker (Sharpie® ultra fine point, 0.3 mm, Model 37001). As subsequent tracings were superimposed, the graph acetate was reoriented over the superimpositions, aligned to the x- and y-axis of the 8-year-old tracing, and landmarks plotted for the subsequent tracings. Measurement between points was from the best approximation of the point centres using an electronic digital caliper (Orthopli, #0400-EEP, Philadelphia) recorded to two decimal places.

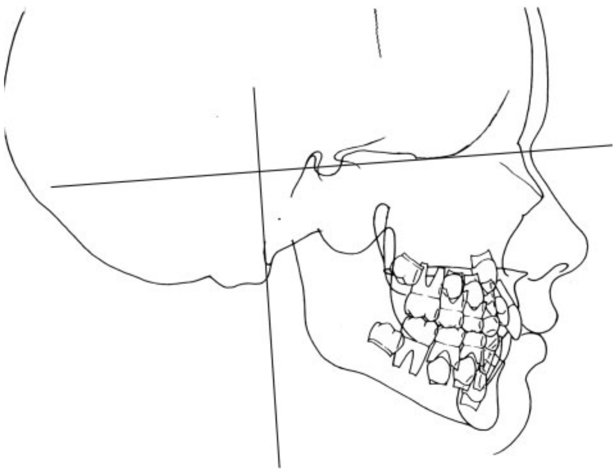


Figure 3 Cartesian co-ordinate system. X-axis formed by a line through the mid-contour of the anterior curvature of sella turcica and the anterior cranial base. The y-axis was formed by a line perpendicular to the x-axis and through I-point (Tracing from the Bolton Standards of Dentofacial Developmental Growth)[18]

The 8-, 10-, 12-, 15- and 18-year-old posterior-anterior tracings were superimposed 3 times on the ACB (to represent the SACB superimposition), and then superimposed 3 times on I-point by orienting the ACB parallel (Figure 4). The vertical distances between ACB on the posterior-anterior tracings were made equal to the vertical distances between ACB as measured from sagittal I-point superimpositions. For example, for the lateral superimposition at I-point, if the distance between the ACB for the 8- and 10-year tracing was 2 mm, the ACB for the PA tracing would be oriented so that the distance between the 8 year and 10 year ACB was also 2 mm, and so on for the age intervals. The Cartesian grid was arranged using the 8-year-old tracing with the origin at crista galli. The x-axis was parallel to the ACB and perpendicular to the y-axis. The y-axis was made perpendicular to the x-axis and through the mid-sagittal structures. For the sagittal tracings, movement in the dorsal or cephalad direction was registered as negative, while movement in the ventral or caudad direction was registered as positive. For the PA superimposition, movement cephalad or to the patient's right

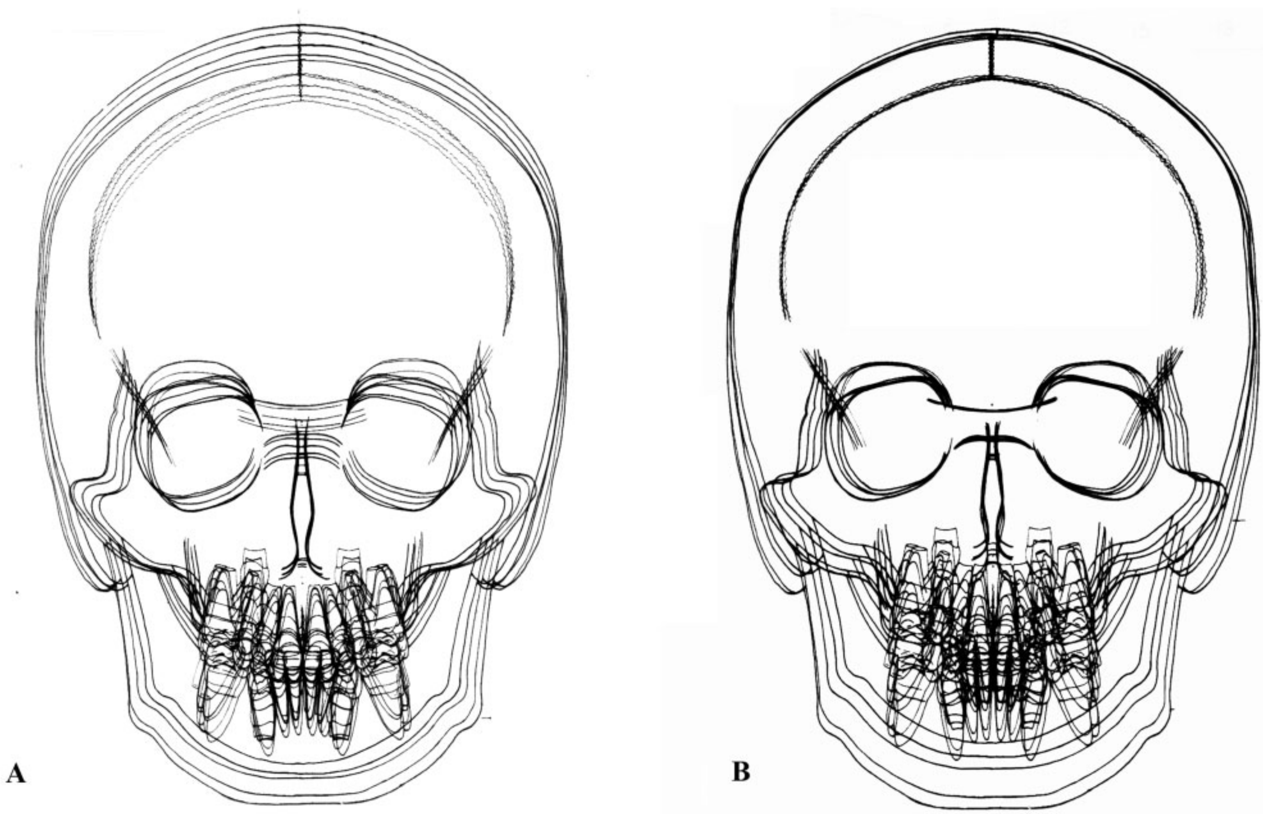


Figure 4 PA superimposition of 8- to 18-year-old Bolton Standards referenced at (A) the I-point/I-curve by orienting ACB parallel, to subsequent superimposed ACB, maintaining ACB distances equal to the distance observed in the sagittal tracings; and (B) the SACB by superimposing on the ACB (Tracings from the Bolton Standards of Dentofacial Developmental Growth)[18]

were registered as negative, while movement caudad or to the patient's left were registered as positive.

Statistical summary

The mean of the distance between the landmarks (x-axis and y-axis) was calculated for the tracings referenced at I-point and SACB for both the sagittal cephalometric tracings and posterior-anterior cephalometric tracings. The standard deviation of the x-axis and y-axis measurements was calculated.

Inter-correlation coefficients (ICCs) were calculated for within-reference repeatability (I point or SACB) for each location, separately for x-axis and y-axis and ICCs for the agreement between measurements using I point and SACB as reference, separately for x-axis and y-axis, again using all of the measurements for that location.

The between-reference difference mean, standard error and *P*-value were calculated, separately for x-axis and y-axis, using I point and SACB as reference again for all of the measurements for that location.

Results

The interval results (between 8 and 10, 10 and 12, etc.) did not reveal an obvious growth pattern, and therefore were excluded. The 8- to 18-year-old observations are shown in Tables 1 and 2. Differences (mean, SE, *P* value) between measurements using I point and SACB as reference revealed large differences between them as shown by the highly significant *P* values; therefore there is not agreement between the references.

Within reference repeatability for ICC was relatively large, but within the range usually observed for cephalometrics. Some data are misleading because the measured distances for specific landmarks were very small resulting in a lower ICC value. The sagittal tracings displayed with-in reference average ICC values for I-point which were nearly identical to SACB; 0.87/0.87 for the x-axis and 0.85/0.86 for the y-axis. The between reference average ICC was 0.58 for the x-axis and 0.26 for the y-axis. The PA tracings displayed similar with-in reference average ICC values for the y-axis, 0.95/I-point and 0.97/SACB; however the x-axis values displayed slight divergence with an I-point value of 0.88 compared to 0.78 for SACB. The between-reference average ICC was 0.74 for the x-axis and 0.23 for the y-axis.

A comparison of landmark movement and the corresponding superimpositions are shown in Figures 2 and 4. For the ages 8 to 18, sagittal tracing superimpositions displayed an average 7 mm greater cephalad movement of landmarks and 2.4 mm greater ventral movement when superimposition was referenced at I-point as compared to the SACB reference. The PA tracings displayed an average 6.7 mm cephalad movement of landmarks and comparable transverse dimension (−0.4 mm) for I-point reference (Table 3).

Differences (mean, SE, *P* value) between measurements using I point and SACB as references, are shown by the highly significant *P* values; these were not an agreement between the references.

Discussion

Consistent with our earlier study which used angular measurements,[12] this study revealed quantitative values for the observed movements. Reference at the occipital condyle demonstrated a more biologically correct modelling pattern of craniofacial growth.

The use of stable internal landmarks (implants) were not available, however within the limitations of this study, the impact of the vertical cranial component of growth was revealed relative to the aponeurotic tension model of craniofacial growth.[12,20]

Also, there is an inability to observe mandibular rotation (Bjork)[21] with the Bolton Standards because the appropriate internal landmarks were not traced: mandibular condyle, internal symphysis and inferior alveolar canal.[12] For future studies using these stable structures, it is recommended that the inferior alveolar canal landmark point be transferred from the initial tracing to subsequent tracings (regional superimposition to locate the same point on the canal) when utilizing internal stable structures for superimposition with I-point.[12,21]

The cross-sectional sample of blended sex mean values used to create the Bolton Standards tracing are a limitation of this study; therefore the vertical component of growth for individuals may be have been underestimated. Additionally, the cross-sectional nature hindered any useful observation from the growth intervals between 8 and 18 years of age, hence they were excluded. The use of digitizing and relative superimposition would have negated superimposition error, but the equipment was unavailable.

Many previous observations were not consistent with ACB superimpositions, which evolved as a convenience because the ACB was easier than PCB to visualize on cephalograms. It is clear that a more biologically valid reference such as I-point is needed, and that it should be more easily located as cephalometrics enters the three-dimensional (3D) age. From a clinical perspective, the anterior rotation of the jaws can be demonstrated

Table 1 Supper imposition Between-Reference Difference: 8 to 18 years of age; Sagittal tracings

Sagittal tracings		8 to 18		8 to 18		Within-reference Repeatability: ICC		Between-reference Agreement: ICC		Between-reference difference					
		x-axis		y-axis						Mean	SE	*P* value	Mean	SE	*P* value
Location	Reference	Mean	SD	Mean	SD	x-axis	y-axis	x-axis	y-axis	x-axis	x-axis	x-axis	y-axis	y-axis	y-axis
Sella	I point	1.99	0.02	−7.14	0.11	0.97	1.00	0.11	0.05	2.04	0.05	0.0007	−6.79	0.17	0.0006
	SACB	−0.05	0.09	−0.35	0.33	0.54	0.27								
Ethmoidale/ACB	I point	4.09	0.42	−6.97	0.35	0.98	0.98	0.51	0.00	2.84	0.67	0.0517	−6.97	0.20	0.0008
	SACB	1.25	1.09	0	0	0.53	0.08								
R point	I point	2.68	0.26	−6.03	0.18	0.96	0.99	0.18	0.00	2.33	0.20	0.0075	−6.47	0.19	0.0008
	SACB	0.36	0.32	0.44	0.4	0.72	0.00								
PT point	I point	3.21	0.12	−5.75	0.24	0.98	0.98	0.20	0.00	2.55	0.21	0.0070	−7.02	0.15	0.0005
	SACB	0.66	0.45	1.27	0.12	0.48	0.79								
Nasion	I point	8.14	0.3	−7.98	0.19	1.00	0.98	0.86	0.14	2.22	0.15	0.0046	−7.02	0.13	0.0003
	SACB	5.92	0.18	−0.96	0.36	0.99	0.72								
Basion	I point	−0.59	0.29	−2.12	0.18	0.45	0.97	0.11	0.00	2.37	0.16	0.0048	−6.76	0.11	0.0003
	SACB	−2.96	0.16	4.64	0.17	0.99	1.00								
Bolton	I point	−0.67	0.68	−2.16	0.18	0.26	0.98	0.00	0.00	0.35	1.88	0.8704	−6.66	0.12	0.0003
	SACB	−1.02	3.83	4.5	0.11	0.00	1.00								
Inion	I point	−5.01	0.07	−1.81	0.29	1.00	0.96	0.78	0.35	2.49	0.35	0.0196	−5.28	0.33	0.0039
	SACB	−7.5	0.67	3.47	0.65	0.97	0.90								
Ramus	I point	−0.66	0.18	0.06	0.1	0.84	0.00	0.00	0.01	2.43	0.20	0.0068	−8.10	0.67	0.0068
	SACB	−3.09	0.3	8.16	1.23	0.98	0.84								
Gonion	I point	0.95	0.85	9.51	1.45	0.69	0.94	0.00	0.74	1.86	1.19	0.2587	−6.57	0.82	0.0152
	SACB	−0.91	2.58	16.07	0.12	0.15	0.98								
Antegonion	I point	4.76	0.39	11.43	0.31	0.83	0.99	0.19	0.82	4.62	0.28	0.0036	−5.91	0.09	0.0002
	SACB	0.14	0.44	17.34	0.36	0.86	1.00								
Articulare	I point	−1.63	0.19	−2.13	0.27	0.95	0.96	0.35	0.00	2.50	0.11	0.0019	−6.87	0.14	0.0004
	SACB	−4.13	0.02	4.74	0.32	0.99	0.98								
Porion	I point	−1.63	0.2	−3.94	0.15	0.93	1.00	0.51	0.00	2.39	0.13	0.0031	−6.82	0.11	0.0003
	SACB	−4.01	0.13	2.88	0.13	0.99	0.98								
Key Ridge	I point	6.63	0.16	−0.05	0.22	0.98	0.93	0.79	0.01	2.13	0.13	0.0038	−7.15	0.01	<0.0001
	SACB	4.5	0.17	7.1	0.23	0.98	1.00								
Pogonion	I point	14.05	0.3	8.38	0.33	1.00	0.96	0.89	0.64	2.63	0.20	0.0059	−8.06	0.48	0.0035
	SACB	11.42	0.19	16.44	1.14	1.00	0.98								
Menton	I point	13.93	0.25	11.04	0.31	0.99	0.98	0.87	0.78	2.99	0.26	0.0073	−6.88	0.21	0.0010
	SACB	10.94	0.37	17.92	0.2	0.99	1.00								
PNS	I point	2.46	2.31	1.37	1.93	0.18	0.16	0.12	0.21	1.16	1.33	0.4770	−5.71	1.11	0.0360
	SACB	1.31	0.07	7.09	0.09	0.99	1.00								

Table 1 Continued

Sagittal tracings		8 to 18		8 to 18		Within-reference Repeatability: ICC		Between-reference Agreement: ICC		Between-reference difference					
		x-axis		y-axis						Mean	SE	*P* value	Mean	SE	*P* value
Location	Reference	Mean	SD	Mean	SD	x-axis	y-axis	x-axis	y-axis	x-axis	x-axis	x-axis	y-axis	y-axis	y-axis
ANS	I point	10.55	0.07	0.6	0.39	1.00	0.88	0.91	0.03	2.19	0.07	0.0009	−7.71	0.29	0.0014
	SACB	8.36	0.09	8.31	0.33	1.00	0.99								
A-point	I point	9.85	0.19	1.12	0.56	1.00	0.91	0.86	0.12	2.44	0.13	0.0029	−6.84	0.74	0.0114
	SACB	7.41	0.12	7.96	1.15	1.00	0.96								
Supra-dentale	I point	10.9	0.63	4.14	0.43	0.99	0.95	0.86	0.37	2.98	0.38	0.0156	−7.07	0.26	0.0013
	SACB	7.92	0.17	11.21	0.11	0.99	1.00								
Infra-dentale	I point	11.56	0.12	4.47	0.4	1.00	0.95	0.87	0.42	2.77	0.12	0.0018	−7.25	0.25	0.0012
	SACB	8.79	0.16	11.72	0.22	1.00	1.00								
B-point	I point	11.37	0.2	6.89	0.67	1.00	0.96	0.85	0.63	2.38	0.06	0.0007	−7.06	0.46	0.0042
	SACB	8.99	0.2	13.95	0.98	0.99	0.98								
Glabella	I point	7.35	0.4	−7.85	2.17	0.98	0.85	0.92	0.42	0.92	0.22	0.0513	−5.46	1.36	0.0572
	SACB	6.43	0.11	−2.39	0.93	0.99	0.73								
Supra-orbitale	I point	6.34	0.16	−7.59	0.15	0.99	0.99	0.84	0.01	1.71	0.11	0.0045	−7.24	0.09	0.0002
	SACB	4.63	0.11	−0.35	0.05	0.99	0.56								
Orbitale	I point	6.81	0.36	−5.49	0.07	0.99	0.99	0.81	0.00	2.32	0.04	0.0004	−7.56	0.08	0.0001
	SACB	4.5	0.39	2.07	0.19	0.97	0.91								
Tip of nose	I point	17.2	0.17	−0.51	0.24	1.00	0.76	0.97	0.00	2.30	0.05	0.0006	−7.94	0.30	0.0014
	SACB	14.91	0.11	7.43	0.46	1.00	0.98								
Upper lip	I point	12.85	0.15	3.52	0.4	1.00	0.92	0.90	0.35	2.84	0.12	0.0018	−8.32	0.12	0.0002
	SACB	10.01	0.15	11.85	0.59	1.00	0.99								
Lower lip	I point	13.7	0.34	4.33	0.44	0.93	0.57	0.88	0.39	2.74	0.19	0.0049	−8.13	0.05	<0.0001
	SACB	10.96	0.03	12.46	0.43	1.00	0.98								
ST Pogonion	I point	14.65	0.12	8.94	0.65	1.00	0.96	0.90	0.70	2.77	0.14	0.0027	−7.42	0.33	0.0020
	SACB	11.88	0.22	16.37	0.54	1.00	0.99								
ST Menton	I point	13.53	0.7	11.55	0.19	0.99	0.99	0.84	0.78	2.93	0.40	0.0180	−7.19	0.22	0.0009
	SACB	10.6	0.41	18.74	0.32	0.97	0.99								
I point	I point	0	0	0	0			0.00	0.00	1.95	0.02	0.0002	−5.82	0.27	0.0022
	SACB	−1.95	0.04	5.82	0.47	0.92	0.95								

Table 2 Supper imposition Between-Reference Difference: 8 to 18 years of age; PA Tracings

PA Tracings		8 to 18		8 to 18		Within-reference		Between-reference		Between-reference difference					
		x-axis		y-axis		Repeatability: ICC		Agreement: ICC		Mean	SE	*P* value	Mean	SE	*P* value
Location	Reference	Mean	SD	Mean	SD	x-axis	y-axis	x-axis	y-axis	x-axis	x-axis	x-axis	y-axis	y-axis	y-axis
Superior crest of the external sagittal suture	I point	0	0	−10.48	0.15		1.00		0.32				−7.59	0.11	0.0002
	SACB	0	0	−2.89	0.14		0.97								
Superior crest of the internal sagittal suture	I point	0	0	−7.78	0.15		1.00		0.08				−7.78	0.08	0.0001
	SACB	0	0	0	0		0.92								
Lateral skull surface (external) Right	I point	−2.66	0.13	0	0	0.98		0.73		−1.17	0.09	0.0064			
	SACB	−1.49	0.3	0	0	0.90									
Lateral skull surface (external) Left	I point	2.28	0.35	0	0	0.93		0.90		−0.38	0.22	0.2279			
	SACB	2.66	0.17	0	0	0.98									
Lateral skull surface (internal) Right	I point	−2.18	0.1	0	0	0.93		0.54		−1.13	0.47	0.1383			
	SACB	−1.05	0.91	0	0	0.52									
Lateral skull surface (internal) Left	I point	1.93	0.34	0	0	0.91		0.83		−0.79	0.19	0.0510			
	SACB	2.72	0.03	0	0	0.96									
Supra-orbitale (Right)	I point	−3.11	1.9	−5.95	1.39	0.55	0.89	0.55	0.00	−1.60	1.10	0.2830	−7.46	0.77	0.0105
	SACB	−1.51	0.09	1.51	0.33	0.77	0.91								
Supra−orbitale (Left)	I point	3.14	2.35	−5.13	3.13	0.37	0.52	0.63	0.00	0.42	1.34	0.7855	−6.72	1.77	0.0629
	SACB	2.72	0.09	1.59	0.4	0.90	0.90								
Orbitale (Right)	I point	−2.91	1.22	−4.61	0.45	0.83	0.98	0.86	0.00	0.46	0.62	0.5402	−7.99	0.19	0.0006
	SACB	−3.37	0.44	3.38	0.33	0.92	0.96								
Orbitale (Left)	I point	3.78	0.34	−5.35	0.37	0.91	0.98	0.89	0.00	0.01	0.16	0.9710	−8.67	0.11	0.0002
	SACB	3.78	0.58	3.32	0.18	0.92	0.96								
ACB	I point	0	0	−7.36	0.33		0.99		0.00				−7.36	0.19	0.0007
	SACB	0	0	0	0										
Frontonasal suture	I point	0	0	−6.9	0.55		0.98		0.00				−8.06	0.32	0.0016
	SACB	0	0	1.16	0.03		0.99								
Nasal floor	I point	0	0	−2.04	0.68		0.89		0.00				−8.22	0.35	0.0018
	SACB	0	0	6.19	0.13		1.00								
Zygoma (Right)	I point	−8.62	0.26	−4.65	0.31	1.00	0.99	0.09	0.00	−5.67	6.02	0.4457	−7.56	0.11	0.0002
	SACB	−2.95	10.42	2.91	0.5	0.00	0.90								
Zygoma (Left)	I point	9.05	0.13	−4.87	0.34	1.00	0.98	1.00	0.00	−0.32	0.07	0.0478	−8.80	0.17	0.0004
	SACB	9.37	0.14	3.93	0.1	1.00	0.97								
Jugum (Right)	I point	−3.6	0.94	1.68	0.22	0.79	0.95	0.05	0.21	−2.79	2.27	0.3434	−8.11	0.13	0.0003
	SACB	−0.81	4.44	9.79	0.15	0.00	0.99								
Jugum (Left)	I point	4.15	0.25	1.21	0.08	0.93	0.98	0.93	0.16	0.29	0.29	0.4259	−8.74	0.15	0.0003
	SACB	3.86	0.43	9.95	0.32	0.91	1.00								

Table 2 Continued

PA Tracings		8 to 18		8 to 18		Within-reference Repeatability: ICC		Between-reference Agreement: ICC		Between-reference difference					
		x-axis		y-axis						Mean	SE	*P* value	Mean	SE	*P* value
Location	Reference	Mean	SD	Mean	SD	x-axis	y-axis	x-axis	y-axis	x-axis	x-axis	x-axis	y-axis	y-axis	y-axis
Mastoid process	I point	−5.39	0.17	1.79	0.3	0.97	0.97	0.96	0.30	0.88	0.11	0.0159	−7.29	0.23	0.0010
(Right)	SACB	−6.27	0.32	9.08	0.25	0.99	0.99								
Mastoid process	I point	5.52	0.1	0.76	0.06	0.98	0.99	0.98	0.21	−0.20	0.06	0.0773	−8.68	0.17	0.0004
(Left)	SACB	5.72	0.2	9.44	0.32	0.99	1.00								
Lateral alveolar crest	I point	−0.56	0.11	7.03	0.09	0.90	1.00	0.57	0.61	−0.07	0.96	0.9486	−8.08	0.21	0.0007
(Right)	SACB	−0.49	1.68	15.11	0.44	0.37	1.00								
Lateral alveolar crest	I point	1.95	0.3	7.32	0.59	0.89	0.98	0.91	0.60	0.01	0.23	0.9583	−8.40	0.23	0.0007
(Left)	SACB	1.94	0.25	15.72	0.27	0.91	1.00								
Antigonion Right (AG)	I point	−7.17	0.05	8.74	0.2	1.00	0.99	0.95	0.71	1.29	0.22	0.0288	−7.22	0.25	0.0012
	SACB	−8.46	0.4	15.96	0.4	0.99	0.99								
Antigonion Left (GA)	I point	9.48	0.14	7.87	0.36	0.99	0.99	0.99	0.61	0.47	0.07	0.0195	−9.03	0.12	0.0002
	SACB	9.01	0.23	16.9	0.16	0.99	1.00								
Menton	I point	0	0	11.46	0.14		1.00		0.76				−7.95	0.06	<0.0001
	SACB	0	0	19.41	0.18		1.00								

directly without the use of implants by way of internal stable structures.[12,22] The Bjork implant method was able to demonstrate jaw rotation during growth by compensating for the biological masking of craniofacial growth, due to ACB superimposition.[23]

Figure 2 displays the disparity of airway growth and speech development associated with ACB superimposition. The expressed dorsal/caudad growth pattern of the mandible would constrict the airway, in conjunction with pharyngeal side bone apposition on the clivus,[3] and compress the hyolaryngeal complex.[17] Therefore, a growth pattern based on ACB superimposition is inconsistent with a physiologic progression of growth and development. Cranial rotation, airorhynchy (posterior and upper portions of the face rotate dorsally relative to the posterior cranial base by extension of the anterior cranial base relative to the posterior cranial base),[17,24] cephalad cranial growth (I-point reference), the expanding V-principal of mandibular growth[13] and forward jaw rotation tend to increase the airway space, cause a relative descent of the hyolaryngeal complex (to allow speech development)[17] and position the genial tubercles of the tongue ventrally. The present results demonstrate that the mandible and maxilla move ventrally to a greater degree with I-point, compared with SACB superimposition. I-point registration demonstrates a more biologically correct growth pattern.

Location of I-point is as reliable as other commonly used landmarks.[12] The I-point reference method is a more biologically correct superimposition method, which demonstrates the jaw rotation observed by the implant reference method of Bjork.[1,25] I-point reference is consistent with the pubertal growth spurt in brain growth, continued enlargement of the occipital lobe up to 20 years of age,[4] airorhynchy[17,24] and brain flexure.[17,20] Previously it was known that the brain temporal lobe grows for several more years following completion of the anterior lobe.[13] This temporal lobe growth was believed to cause secondary displacement of the anterior lobes, driving facial growth. However, middle cranial fossa elongation nearly ceases by 10 years of age[2] and the nasal septum as a conduit of force to the midface has been discounted.[13] Asymmetric separation of the SOS[26] is a problem for any model of 'downward and forward' growth, as the separation rotates the ACB and midface 'up and forward' as observed with the facial block and airorhynchy.[17,20,24] The dural 'slings' which cradle the brain and emerging cranial nerves tend to restrict bone growth that might compromise neurologic function.[20]

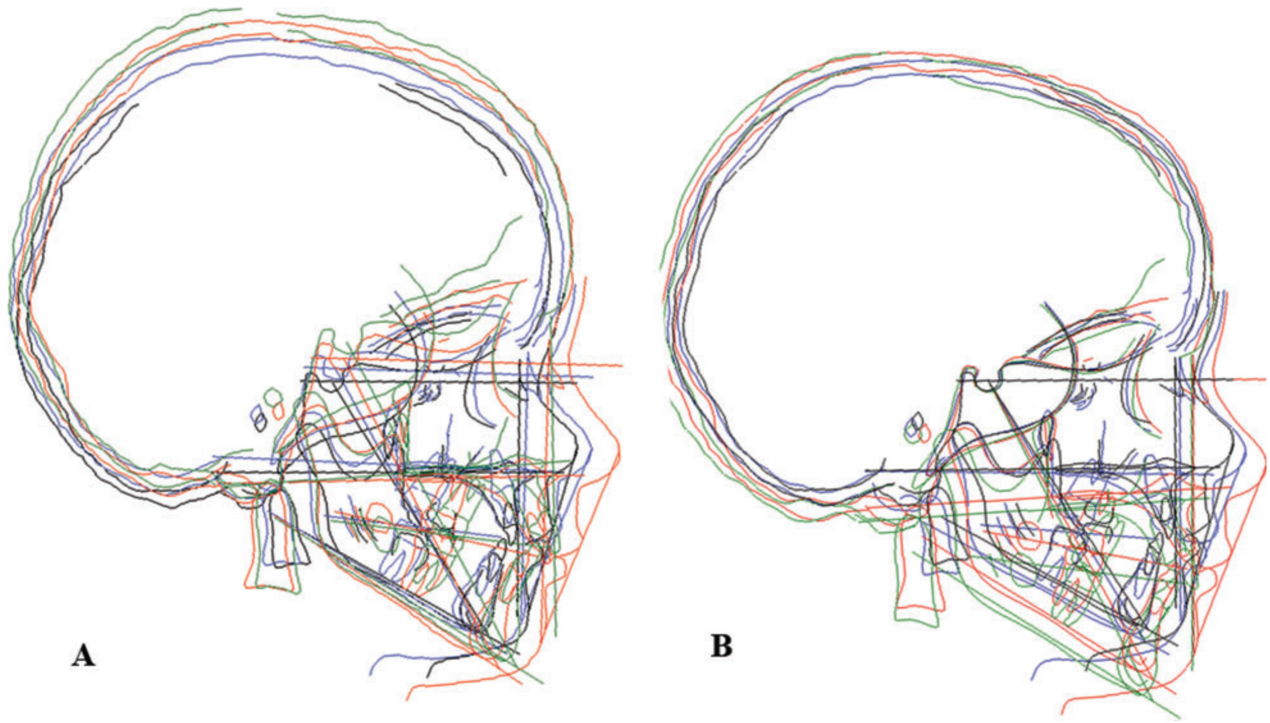
The dura (desmocranial capsule) connective tissue around the brain is anisotropic. At its base, it becomes thick, grows slowly and resists brain enlargement in the developing cranial base in contrast to the thinner less resistant calvarial region.[15] This allows the cerebral hemispheres and to a lesser extent the cerebellar hemispheres, to expand more rapidly.[15] It is this dural attachment that is thought to cause early restriction of lateral cranial expansion,[6,15] necessitating vertical displacement of the brain. The weight of the brain and the dural sling attachment restrict lateral displacement, but the cross-sectional arch form and brain expansion with growth prevent the lateral skull from imploding from tension in the dural slings.

The observed vertical growth complies with the apposition pattern at sella turcica observed by Enlow[13]and the pubertal apposition on the anterior curvature of sella turcica observed by Melsen.[3,20] Significant growth of the head occurs between 5 and 20 years of age, when 2 inches of increased average head circumference is achieved, and between 10 and 20 years, an inch of growth occurs.[27] It can be seen from our sample that the vertical component is probably greater than the circumferential.

Cranial rotation[1,5] and airorhynchy,[17] in a pattern consistent with the fetal head unfolding associated with brain flexure,[17] explains some previously opaque growth observations.[20] For instance, when analyzed with implant radiographic markers the mesial surface of the maxillary first permanent molar in an adult is located ventral to the infrazygomatic crest. In comparison, the distal surface of the deciduous maxillary second molar lies dorsal to the crest in the absence of bone modelling.[28] Also, the distance between the anterior nasal spine and the zygomatic process increases in the absence of pronounced resorption on the anterior zygomatic process (Figures 2 and 4),[28,29] which may be attributable to cranial rotation.

Figure 5 illustrates a typical observation of mandibular rotation when superimposition is referenced at I-point/I-curve, and is more representative of the Bjork implant study observations.[21,22,30] Articulare in Figures 2 and 6 display the patterns seen in Figure 5. Notable is the condylar growth pattern observed with the I-point reference as shown in Figure 5.

These results are directly comparable to those of Trenouth.[19] Trenouth reviewed traditional views of cranial proportions and found, based on the Bolton Standards,[18] the infant to adult cranial-facial ratios were less than traditionally reported; which is better represented by the greater proportionality of growth seen with superimposition at I-point. Campers line was also discussed and illustration displays clear cranial rotation relative to Campers line (porion to nasal spine);[19] although nasal spine is not neural related. The present data conflict with the observation that the cranium



Notice the growth pattern of the cortical contour of the inferior alveolar nerve canal and inferior aspect of the internal symphysis; the stable internal structures as determined by implants[21] Also notice the anterior condylar growth direction[23] displayed in this individual (age 4y9m until 10y6m) with a change to a more superior (and arguably posterior) condylar growth direction (10y6m to 14y0m) assumed to be a result of orthodontic treatment or possibly airway obstruction with development

Figure 5 (A) Growth changes shown by superimposition referenced on the I-point/I-curve and anterior cranial fossa/base in a representative subject; (B) Growth changes shown by superimposition referenced at Sella and anterior cranial fossa/base in the same representative subject in (A). 4y9m (black) 6y6m (blue) 10y6m (red) 14y0m (green) (Figure from Ref. 12)

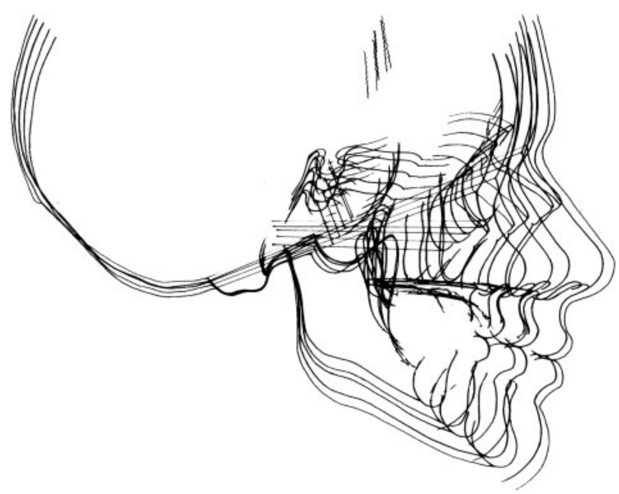


Figure 6 Growth changes in *norma lateralis*, shown by superimposition referenced on I-point/I curve; ages 2, 5, 8, 14 and 18. Notice the cranial contour with growth (Tracings from the Bolton Standards of Dentofacial Developmental Growth)[18]

largely ceases growing by the age of 9.[19] The latter observation is inconsistent with continuing brain growth,[4,31] and probably reflects the difficulty with direct measurement of blended means and sagittal measurement of midline structures.[32] Future study is needed to determine the relationship of cranial morphology to peak height velocity of brain growth and volumetric change.

Therefore, brain temporal lobe growth reflects a vertical component of brain growth, concomitant with asymmetric growth at the SOS,[26] creates tension on the galea aponeurotica, which is transmitted through the craniofacial musculoaponeurotic system (CFMAS). This mechanism drives facial growth and associated rotations and is the essence of the aponeurotic tension model of craniofacial growth.[12,20]

A more biologically correct reference and orientation, based upon the occipital condyle will lead to greater insight into cranial rotation relative to the synergistic development of muscle, connective tissue, airway, and mandibular position. The increased accuracy of landmark definition in 3D will allow craniofacial orientation that will be more consistent with influence of neural structures and development of bone trabecular patterns. In two-dimensional the occipital condyles are viewed in *norma lateralis* as midline structures. CBCT will allow triangulation of the right and left I-points to the superior aspect of the sphenooccipital synchondrosis. It is believed that the basioccipital portion anterior to the inter-occipital synchondrosis is most stable to modelling due to the higher pressure gradient; dorsal to the synchondrosis, the exo-occipital portion anecdotally, seems prone to modelling with age.

Referencing these basilar structures will allow detection of asymmetric growth patterns and the determination of therapeutic responses in all three planes of space. This will be particularly important for realistic assessment of hyperdivergent and hypodivergent rotational growth patterns; sella turcica movement is believed more ventral and less cephalad, relative to I-point, for hypodivergent individuals compared with hyperdivergent. It is believed that the present method will be applicable for accurate description of growth and therapeutic changes prior to the ACB achieving stability at about age 8–12 years (this stability is valid only for the ethmoid portion).[2,5] Thus, superimposition on I-point will be applicable to subjects of all ages. (Figure 6 – Notice the growth superior to inion).

This study displays a quantitative vertical component of brain growth that is consistent with observation in literature not observable with ACB superimposition.

The occipital condyle is a more physiologic superimposition reference for demonstrating the modelling and remodelling mechanisms of craniofacial growth.

Conclusions

- Longitudinal superimposition on occipital condyle is a more physiologic superimposition reference for demonstrating the modelling and remodelling mechanisms of craniofacial growth. Airway and speech development, and vertical cranial growth are better demonstrated.
- Longitudinal superimposition, referenced at I-point and best fit on I-curve, along with parallel orientation of the anterior cranial base, is recommended to replace the traditional superimposition referenced at the anterior curvature of sella and oriented to the anterior cranial base.
- As cone beam computed tomography becomes the standard in clinical radiology, all of the structures of the head can be clearly imaged; therefore it is appropriate to adapt a more biologically correct frame of reference for craniofacial growth: the occipital condyles (I-point).

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