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Methods of Studying Growth in Orthodontics – A Review

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Abstract : *The growth of the craniofacial skeleton is a complex, dynamic process involving bone deposition, resorption, sutural activity, and soft tissue adaptation, all influenced by genetic and environmental factors. For orthodontists, this variability directly impacts diagnosis, treatment timing, and long-term stability. Over the last century, researchers have used diverse methods to study growth. Early craniometry on skeletal remains provided foundational but cross-sectional insights, while cephalometric radiography revolutionized longitudinal assessment in living individuals. Experimental approaches, such as implant radiography and vital staining, clarified bone remodeling, whereas recent advances like CBCT, MRI, and 3D surface scanning have enabled precise virtual reconstructions. Each method, however, has its limitations: measurement techniques may oversimplify biology, experimental approaches are invasive and often restricted to animals, and modern imaging raises concerns of cost and radiation. This review consolidates classical and contemporary methods—from craniometry and anthropometry to 3D imaging—highlighting their principles, advantages and limitations.*

Keywords – *Anthropometry, Cephalometry, Craniometry, Growth Data, Growth Studies*

I. INTRODUCTION

The growth of the craniofacial skeleton is a complex, dynamic process involving bone deposition, resorption, sutural activity, and soft tissue adaptation, all influenced by genetic and environmental factors. For orthodontists, this variability directly impacts diagnosis, treatment timing, and long-term stability. Over the last century, researchers have used diverse methods to study growth. Early craniometry on skeletal remains provided foundational but cross-sectional insights, while cephalometric radiography revolutionized longitudinal assessment in living individuals. Experimental approaches, such as implant radiography and vital staining, clarified bone remodeling, whereas recent advances like CBCT, MRI, and 3D surface scanning have enabled precise virtual reconstructions. Each method, however, has its limitations: measurement techniques may oversimplify biology, experimental approaches are invasive and often restricted to animals, and modern imaging raises concerns of cost and radiation. This review consolidates classical and contemporary methods—from craniometry and anthropometry to 3D imaging—highlighting their principles, advantages and limitations.

II. WHY ASSESS GROWTH?

Growth assessment plays a crucial role in orthodontics as it establishes a dynamic framework for accurate diagnosis, optimal treatment timing, and reliable evaluation of outcomes. It enables early identification of pathologic growth patterns such as hemimandibular hyperplasia and syndromic asymmetries, allowing timely intervention. Beyond pathology, it also helps recognize developmental deviations like Class II mandibular retrusion or vertical maxillary excess, which are common non-pathologic variations influencing treatment planning. By assessing growth status, orthodontists can determine the most appropriate time to initiate functional appliance therapy, camouflage strategies, or surgical correction, thereby enhancing treatment efficiency and stability. Furthermore, growth evaluation is essential in outcome analysis, as it helps differentiate natural growth-related changes from those induced by orthodontic or surgical treatment, ensuring a more accurate assessment of therapeutic effectiveness.

III. METHODS OF GATHERING GROWTH DATA

Reliable data collection is essential for understanding the dynamics of craniofacial growth. Over the years, researchers have relied on different study designs to document growth patterns and their variations across individuals and populations. The three principal approaches are **longitudinal studies, cross-sectional studies,** and **overlapping (or semi-longitudinal) studies**.[1] Each of these methods offers unique strengths and faces specific limitations (Table 1).

IV. CLASSIFICATION OF METHODS OF STUDYING GROWTH

Different authors have proposed ways to classify methods of studying craniofacial growth, reflecting whether the emphasis is on biological insight or clinical measurement. Two of the most cited classifications are those by Proffit and Sarnat.

Proffit's Classification[2]: Proffit grouped growth study methods into experimental and measurement approaches.

- Experimental approaches are invasive, performed mainly on animals, and include techniques such as vital staining, implant studies, and the use of radioactive tracers. These provide valuable biological information but are not suitable for human subjects.
- Measurement approaches are non-invasive, applicable to humans, and include anthropometry, cephalometry, and modern imaging. Because they can be repeated safely, they are most useful in longitudinal studies.

Sarnat's Classification[3]: Sarnat divided methods into direct and indirect.

- Direct methods include anthropometry, vital staining, histology, histochemistry, and implants. These examine tissues or dimensions directly and are useful in both research and clinical contexts.
- Indirect methods include photography, impressions and casts, radioautography, and radiography. These techniques evaluate growth changes without interfering with tissues, making them especially important for routine clinical use.

V. MEASUREMENT APPROACHES

5.1 Craniometry

Craniometry was the earliest measurement approach for studying craniofacial growth and also marked the beginning of physical anthropology. It is based on direct measurements made on human skulls obtained from skeletal remains. Historically, this method was used to analyze the skulls of Neanderthal and Cro-Magnon populations discovered in European caves during the 18th and 19th centuries. By examining skeletal material, researchers were able to reconstruct information about extinct populations and gain insights into their growth patterns through comparative analysis of skulls of different ages. An important strength of craniometry is the ability to obtain precise linear and angular measurements on dry skulls. Its major drawback, however, is that it can only provide cross-sectional data. Since each skull represents a single point in time, longitudinal changes within the same individual cannot be observed.[2] (Fig 1,Table 2)

Craniometric indices

Cephalic Index (Table 3) - Ratio of the maximum width of the head to its maximum length.
Maximum cranial width is measured between eurion to eurion and maximum
cranial length is measured between nasion and opisthocranion.
Facial Index - Facial index characterizes the proportions of the face. (Table 4, Fig 2)
Palatine Index[4]:
Palatine index is calculated using the formula:

$$\frac{\text{Palate breadth} \times 100}{\text{Palate length}}$$

This index enables the identification of skulls with narrow palate (leptostaphyline) and those with wide palate (brachystaphyline). (Fig 3)

5.2 Anthropometry

The term *anthropometry* is derived from the Greek words *ánthrōpos* ("human") and *métron* ("measure"), and refers to the systematic measurement of human body dimensions, especially size, shape, and proportion. In craniofacial research, anthropometric landmarks established on dry skulls are transferred to living individuals by using corresponding soft tissue points. Although the presence of soft tissues introduces variability, repeated measurements at different ages make it possible to follow growth longitudinally. Among the most influential works are those of Farkas (1994), who described 47 standard craniofacial landmarks and provided normative data for facial growth across childhood, adolescence, and adulthood. These landmarks are usually identified visually, with the head positioned in the standard Frankfurt Horizontal plane, or by palpation over underlying bony structures.[5]

Direct anthropometry refers to the process of recording craniofacial measurements directly on the subject. A comprehensive system includes approximately 132 variables—103 linear and 29 angular—providing a detailed description of facial proportions. The accuracy of this method depends heavily on the examiner's ability to correctly identify landmarks, maintain the appropriate craniofacial orientation, and ensure both technical precision and patient cooperation. The strengths of direct anthropometry include access to regions otherwise obscured by hair, the ability to measure areas that may be distorted when assessed indirectly, and the capacity to record dimensions requiring special head positions. However, it also has notable drawbacks: the process is time-consuming, requires considerable operator skill, and is dependent on the compliance of the subject as well as the precision of the examiner.[5]

In contrast, indirect anthropometry involves obtaining measurements through techniques such as photogrammetry, facial-profile cephalometry, and three-dimensional (3D) surface scanning. These approaches are less demanding in terms of patient cooperation and allow examinations to be completed more quickly.

Accuracy may be further enhanced if landmarks are marked on the subject prior to imaging. Nevertheless, indirect anthropometry has its limitations. The number of reliable linear measurements that can be obtained is reduced compared to direct methods, and distortions are often introduced in two-dimensional photographs or radiographs. Although 3D surface scans offer significant potential, their reliability must still be validated against direct measurements. Furthermore, the equipment required for these methods is costly and may not be readily available in all clinical or research settings.[5]

5.3 Cephalometry

Cephalometric radiography is a cornerstone in orthodontics as it enables direct measurement of craniofacial structures in living subjects while also allowing longitudinal assessment through repeated records. It is widely applied in both research and clinical practice for diagnosis and treatment planning. Despite these advantages, cephalometry relies on two-dimensional radiographs to represent a three-dimensional structure, which inevitably introduces distortion and loss of detail.

Reference Planes -

Accurate orientation is essential for cephalometric analysis. The Frankfort Horizontal Plane, introduced in 1882, was adopted as a standard reference since it often coincides with the natural head posture. However, identifying porion on radiographs is challenging, leading to variations in FH orientation. To overcome this, clinicians increasingly rely on Natural Head Position, a physiologic and reproducible method that better reflects the individual's natural posture.

Superimposition in Growth Studies -

Superimposition of serial cephalograms is a key method for studying growth. The cranial base, due to its early completion of growth, serves as the most reliable reference area. Various techniques such as the anterior cranial base best-fit method, the Sella–Nasion line, and the Basion–Nasion plane have been proposed for this purpose. Maxillary superimposition is typically carried out along the palatal plane using the anterior nasal spine as the registration point, while mandibular assessments rely on the inner symphysis, mandibular canal, and unerupted third molar crypts, though remodeling reduces accuracy.[6]

5.4 Three-Dimensional Imaging

The advent of three-dimensional imaging has expanded possibilities for growth studies. Initially, computed tomography provided detailed reconstructions but was restricted by high cost and radiation exposure. The introduction of cone beam computed tomography marked a major advancement, as it delivers high-quality volumetric images with reduced radiation comparable to conventional cephalograms, making it more suitable for routine orthodontic use.[2]

Three-Dimensional Superimposition -

Unlike two-dimensional cephalometry, superimposition in three dimensions is technically complex but standardized approaches have been developed. These include voxel-based, landmark-based, and surface-based superimpositions. In all methods, the anterior cranial base is regarded as the most reliable reference, since it remains stable beyond early growth, thereby ensuring accurate longitudinal comparisons.[7]

VI. EXPERIMENTAL APPROACHES

6.1 Implant Radiography

Implant radiography is one of the most influential experimental techniques developed to study craniofacial growth. This method involves placing small metallic implants, often tantalum pins, into specific regions of the jaws. Once integrated into the bone, these implants act as stable reference markers. Serial cephalometric radiographs taken over time allow accurate superimposition on these fixed points, enabling precise evaluation of bone deposition, resorption, and overall growth patterns.

The technique was pioneered by Arne Björk, who conducted a landmark longitudinal study on nearly 100 children aged 4 to 24 years. His findings revealed that craniofacial growth is not simply a matter of bone addition but results from a complex interplay of apposition and resorption.[8,9] In the mandible, implants placed in the symphysis, beneath premolars and molars, and along the ramus demonstrated that lengthening occurs mainly

at the condyles, while the chin exhibits minimal forward growth. Thickening of the symphysis was attributed to apposition on its posterior surface, while deposition along the lower border contributed to subtle lengthening.[10]
In the maxilla, implants placed beneath the anterior nasal spine and in the zygomatic process revealed that growth occurs through sutural displacement toward the palatine bone, with additional apposition at the maxillary tuberosity. Sutural activity at the frontal and zygomatic processes drives vertical development, while resorption of the nasal floor and deposition on the palate contribute to downward displacement. Remodeling further modifies the anterior nasal spine and orbital floor. Björk's implant studies provided dynamic, visual confirmation of the remodeling concept of growth and reshaped orthodontic understanding of craniofacial development.[10]

6.2 Radioactive Tracer Studies
The use of radioactive tracers added a novel dimension to growth research by allowing visualization of dynamic metabolic processes in mineralizing tissues. Labelled metabolites incorporated into bone act as vital stains, emitting radiation that can be detected externally. Among these, technetium-99m (99mTc), a gamma-emitting isotope, has been particularly useful in humans. It highlights active sites of bone formation and has clinical utility in identifying localized growth abnormalities such as condylar hyperplasia. However, because tracer images primarily show areas of metabolic activity rather than long-term structural changes, their role in documenting general craniofacial growth patterns remains limited.[2]

6.3 Autoradiography
Autoradiography complements tracer studies by providing microscopic localization of radioactive substances within tissues. Thin sections of bone are placed beneath photographic emulsion film, which is exposed by the radiation emitted from incorporated isotopes. After development, the film reveals precise sites of mineral deposition. This technique has been extensively applied in animal models, offering insights into the micro-level processes of calcification and growth. It has been especially valuable for understanding tissue-level dynamics such as remodeling fronts and mineralization sites, bridging the gap between biochemical labeling and structural visualization.[2]

6.4 Vital Staining
Vital staining, one of the oldest experimental approaches, uses dyes that bind to calcium at sites of mineralization. The method originated in the 18th century when John Hunter noted unusual coloration in pig bones fed with textile waste containing alizarin dye. Later, alizarin and other agents such as tetracycline, fluorochromes, procion, and sodium fluoride were administered in vivo to produce distinct color bands at mineralizing sites.
After animal sacrifice, thin ground sections reveal linear stain deposits that correspond to areas of new bone formation. This technique not only identifies deposition but also indirectly indicates resorption, as stained material disappears from remodeled regions. While ethical constraints prevent its use in humans, inadvertent examples occurred when tetracycline therapy in children during the mid-20th century caused permanent tooth discoloration by binding to mineralizing enamel and dentin. Despite its limitations, vital staining remains a cornerstone for mapping growth patterns in experimental animals.[11]

6.5 Histological Methods
Histology has long provided qualitative evidence of craniofacial growth by enabling visualization of deposition and resorption at the cellular level. Osteoblasts, responsible for apposition, and osteoclasts, mediators of resorption, act simultaneously to produce drift and reorientation of bone segments. Donald Enlow's contributions were especially significant, as he demonstrated through decalcified and ground sections how remodeling sculpts cortical and trabecular bone. His schematic models illustrated how opposing deposition and resorption lead to directional changes in bone form, an essential concept for orthodontics.[12,13]

6.6 Histochemical Methods

Histochemistry enhances histology by localizing specific biochemical activities within cells and tissues, offering insights into the metabolic underpinnings of growth. Enzyme histochemistry has been particularly influential in studying bone and dentin remodeling:

Alkaline phosphatase (ALP): Highly active in osteoblasts, odontoblasts, and newly embedded osteocytes, reflecting its essential role in mineralization. Increased activity is observed during intramembranous ossification and in the hypertrophic zone of cartilage during endochondral ossification. Clinical associations, such as increased ALP activity following vitamin D therapy in rickets, reinforce its significance.

Acid phosphatase (ACP): Concentrated in osteoclasts and odontoclasts, particularly along resorbing surfaces, signifying its function in bone and dentin breakdown.

Esterases: Among them, naphthol acetate esterase demonstrates strong activity in calcifying matrices, indicating involvement in mineral deposition.

Cytochrome oxidase and succinate dehydrogenase: Both are active in osteoblasts and osteoclasts, though activity is higher in osteoclasts, highlighting the high metabolic demand of resorption.

These findings provided a biochemical framework for understanding the cellular mechanisms that regulate skeletal remodeling and mineralization.

6.7 Natural Markers

To avoid the invasiveness of implant techniques, natural anatomical structures have been utilized as reference markers in growth studies. Björk identified several reliable internal features that could serve this purpose, including the inner contour and trabecular pattern of the mandibular symphysis, the outline of the mandibular canal, the contour of unerupted molar germs, and the anterior surface of the chin. Later, a fifth marker was added by Björk and Skieller in 1983. By relying on these stable internal features rather than external outlines, researchers could achieve more reliable assessment of mandibular growth through serial radiographs. Natural markers thus provided a valuable alternative to experimental implants.[14]

VII. MAJOR GROWTH STUDIES

The foundation of orthodontic growth research rests on large-scale longitudinal investigations initiated in the early 20th century. Pioneers such as Todd, Broadbent, Humphries, Waldo, and Lewis spearheaded systematic data collection that continues to inform orthodontics today.[15]

Bolton-Brush Growth Study: Initiated in the 1920s by Todd and Broadbent, this study amassed over 200,000 radiographs, making it one of the most comprehensive datasets on craniofacial and dental development. The collection remains archived at Case Western Reserve University.[16]

Burlington Growth Study: Established in 1952 at the University of Toronto under Moyers and later Popovich, it compiled extensive cephalometric, dental, and medical records. Its contributions extended beyond orthodontics, influencing broader medical research.[17]

Denver Child Growth Study: This project followed 100 boys and 100 girls of Caucasian origin, aged 2–20 years. Nanda and colleagues later analyzed its records to detail nasal changes with age.[18]

Iowa Child Welfare Study: Led by Samir Bishara, this study tracked Caucasian children aged 4–17 years, documenting untreated facial growth and dental changes.[19]

Forsyth Twin Study: Conducted by C.F.A. Moorrees, this study followed 414 twins, uniquely evaluating the relative roles of genetics and environment in craniofacial growth and dental development.[20]

Together, these longitudinal studies provided a robust evidence base, shaping contemporary orthodontic concepts of growth, development, and treatment timing.

VIII. FIGURES AND TABLES

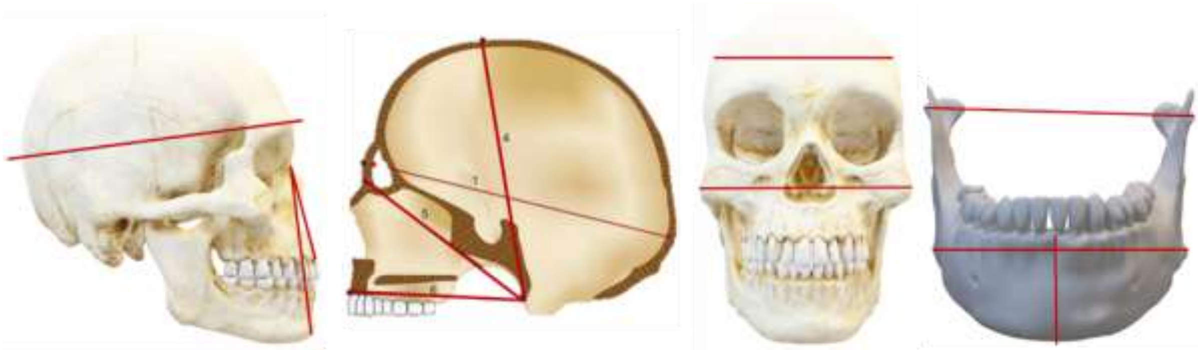

Fig 1 – Craniometric measurements in the Norma Lateralis, Frontalis view and the Mandible

$$\text{Facial index} \quad \frac{\text{Morphological facial height (N-Gn)} \times 100}{\text{Bizygomatic width (Zyr – Zyl)}}$$

Fig 2 – Facial Index

$$\text{Facial index} \quad \frac{\text{Morphological facial height (N-Gn)} \times 100}{\text{Bizygomatic width (Zyr – Zyl)}}$$

Fig 3 – Palatal Index

Study Design	Description	Advantages	Disadvantages	Example/Use
Longitudinal	Same individuals measured repeatedly over long periods (childhood to adulthood).	Captures individual variability Tracks true growth trajectories Detects errors/unusual growth events	Very time-consuming Expensive High attrition (up to 50% over 15 years)	Bolton-Brush Study, Burlington Growth Study
Cross-Sectional	Different individuals of varying ages measured at a single point in time.	Quick and inexpensive Easier to obtain large samples Simple and repeatable	Assumes age groups are comparable Cannot observe individual growth Only group averages seen	Establishing normative standards, population data

Semi-Longitudinal	Overlapping cohorts studied for shorter spans, covering full growth period.	Shorter study duration Lower attrition Continuous coverage of development	Less detailed than full longitudinal Requires multiple cohorts	Pragmatic compromise approach in growth studies

Table 1 – Methods of Gathering Growth Data

View / Region	Measurement	Landmarks (Abbreviation)	Description
Norma Lateralis	Upper Facial Height	n – pr (Nasion – Prosthion)	Straight distance between nasion and prosthion.
	Maximum Cranial Length	g – op (Glabella – Opisthocranion)	Distance between glabella and opisthocranion in midsagittal plane.
	Morphological Facial Height	n – gn (Nasion – Gnathion)	Straight distance between nasion and gnathion.
	Basion–Bregma Height	ba – b (Basion – Bregma)	Direct distance from basion to bregma.
	Cranial Base Length	ba – n (Basion – Nasion)	Direct distance from nasion to basion.
	Facial Length / Depth	ba – pr (Basion – Prosthion)	Direct distance from basion to prosthion.
Norma Frontalis	Maximum Cranial Breadth	eu – eu (Euryon – Euryon)	Distance between the two most lateral points of the skull.
	Bizygomatic Diameter	zy – zy (Zygion – Zygion)	Direct distance between the most lateral points on the zygomatic arches.
Mandible	Chin Height	id – gn (Infradentale – Gnathion)	Direct distance from infradentale to gnathion.
	Bicondylar Breadth	cdl – cdl (Condylion – Condylion)	Direct distance between the two most lateral points on the mandibular condyles.
	Bigonial Width	go – go (Gonion – Gonion)	Direct distance between right and left gonion.

Table 2 – Craniometric Measurements

Females	Males	Scientific term	Meaning
< 75%	< 65%	dolichocephalic	long-headed
75–80%	65–75%	mesocephalic	medium-headed
> 80%	> 75%	brachycephalic	short-headed

Table 3 – Cephalic Index

Type of face	Facial index
Hypereuryprosopic	< 79.9
Euryprosopic	80.0–84.9
Mesoprosopic	85.0–89.9
Leptoprosopic	90.0–94.9
Hyperleptoprosopic	95.0–>95

Table 4 – Facial Index

IX. Conclusion

Methods of studying craniofacial growth have progressed from simple craniometry to advanced 3D imaging and experimental techniques. Each method has strengths and limitations, but together they provide valuable insights into growth patterns, treatment timing, and long-term stability. A combined approach using classical studies and modern technology offers the most accurate understanding for orthodontic diagnosis and planning.

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