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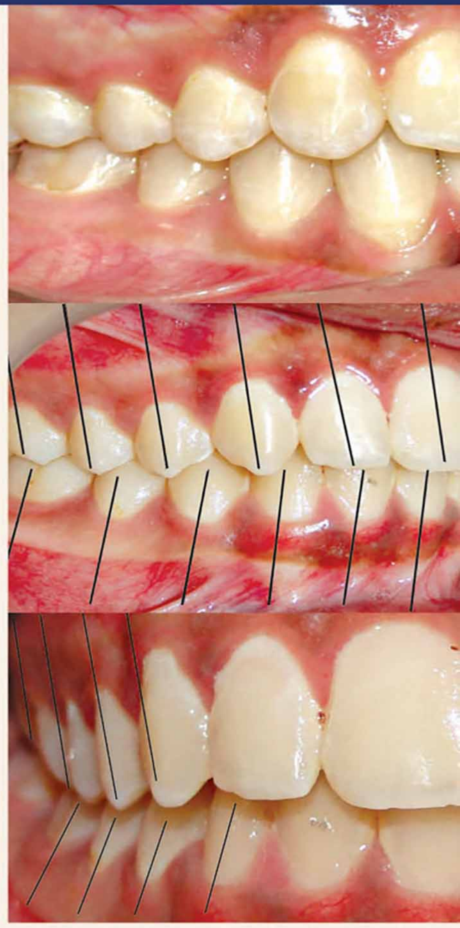
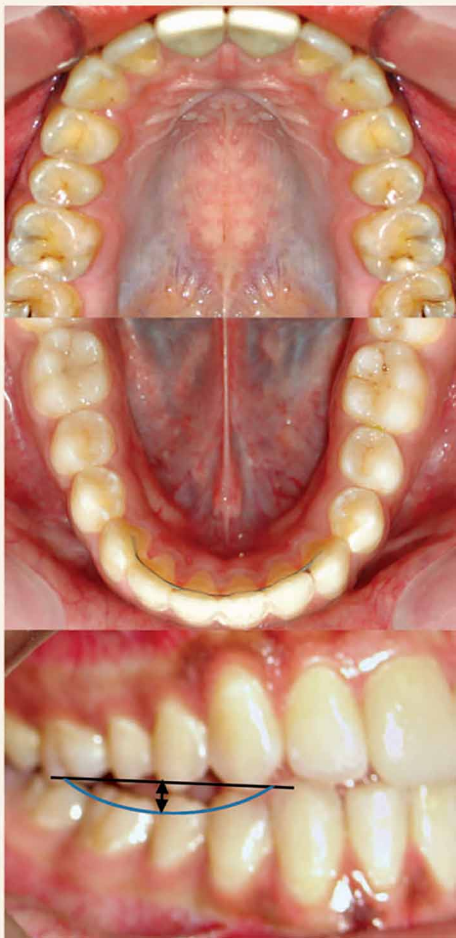


Textbook of ORTHODONTICS



Editor

Gurkeerat Singh

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Basic Principles of Growth

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CHAPTER OUTLINE

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INTRODUCTION AND DEFINITION

The study of head form in humans has always been of considerable interest to anthropologists, anatomists and other students of human growth. In fact, the wide array of students involved in solving the complex phenomenon of growth have been aptly described by **Wilton Marion Krogman** as early as 1943 in these golden words:

"Growth was conceived by an anatomist, born to a biologist, delivered by a physician, left on a chemist's doorstep, and adopted by a physiologist. At an early age—she eloped with a statistician, divorced him for a psychologist, and is now being wooed, alternately and concurrently, by an endocrinologist, a pediatrician, a physical anthropologist, an educationalist, a biochemist, a physicist, a mathematician, an orthodontist, an eugenicist and the children's bureau!"

As an orthodontists we are interested in understanding how the face changes from its embryologic form through childhood, adolescence and adulthood. Of particular interests is an understanding of how and where the growth occurs, how much growth is remaining and in which direction and when the growth will express itself, what role the genetic and environmental factors play in influencing facial growth and in turn how we can influence these factors with our treatment to achieve the optimum results in each individual?

According to **Todd T Wingate** *'growth is an increase in size; development is progress towards maturity.'* But each process relies on the other and under the influence of morphogenetic pattern; the threefold process works its miracles; self-multiplication, differentiation, organization—each according to its own kind! A fourth dimension is time.

Some Definitions Related to Growth

As is the nature of growth, wherein the concepts keep changing with new research findings, there has been no single definition associated with it. Different researchers have defined growth in various ways:

- The self multiplication of living substance— **JX Huxley**.
- Increase in size, change in proportion and progressive complexity—**Wilton Marion Krogman**.
- Entire series of sequential anatomic and physiological changes taking place from the beginning of prenatal life to senility—**Meredith**.
- Quantitative aspect of biologic development per unit of time—**Robert Edison Moyers**.
- Change in any morphological parameter which is measurable—**Melvin L Moss**.

Some Definitions Related to Development

- Development means progress towards maturity—**Todd T Wingate**

- All the naturally occurring unidirectional changes in the life of an individual from its existence as a single cell to its elaboration as a multifunctional unit terminating in death—**Robert Edison Moyers**.

METHODS OF STUDYING PHYSICAL GROWTH

The data collection for the evaluation of physical growth can be done in two ways:

- *Measurement approach:* It is based on the techniques for measuring living animals (including humans), with the implication that measurement itself will do no harm and that the animal will be available for additional measurements at another time.
- *Experimental approach:* This approach uses experiments in which growth is manipulated in some way. This implies that the subject will be available for some detailed study that may be destructive and the animal may be sacrificed. For this reason, such experimental studies are restricted to non-human species.

Measurement Approaches

- Craniometry
- Anthropometry
- Cephalometric radiography.

Craniometry

Craniometry involves measurement of skulls found among human skeletal remains. It has the advantage that precise measurements can be made on dry skulls. The big disadvantage of craniometry is that such a growth study can only be cross sectional.

Anthropometry

Anthropometry is a technique, which involves measuring skeletal dimensions on living individuals. Various landmarks established in the studies of dry skull are measured in living individuals by using soft tissue points overlying these bony landmarks. These measurements can be made on both dry skull as well as living individuals, although in the latter case the thickness of soft tissue will also need to be considered. Despite this shortcoming the most important advantage is that the study can be longitudinal, wherein the growth of an individual can be followed directly over a period of time with repeated measurements without damaging the subject.

Cephalometric Radiography

Cephalometric radiography is a technique that depends on precise placement of the individual in a cephalostat so that the head can be precisely oriented vis a vis the radiograph and precisely controlled magnification can be made. This technique combines the advantages of both craniometry and anthropometry in that direct bony measurements as seen on the radiograph can be made over a period of time for the same individual. However the disadvantage is that it produces a two dimensional representation of a three-dimensional structure making it impossible to make all the measurements.

Experimental Approaches

These include the following:

- Vital staining
- Autoradiography
- Radioisotopes
- Implant radiography.

Vital Staining

Introduced first by John Hunter in the eighteenth century. He studied growth by the pattern of stained mineralized tissues after the injection of dyes into a living animal. These dyes remained in the bones and the teeth, and can be detected later after sacrificing the animal. Alizarin was found to be the active agent and is still used for vital staining studies. Such studies are however not possible in the humans. With the development of radioisotope tracers, it is now possible to replace alizarin. The gamma emitting isotope ^{99m}Tc can be used to detect areas of rapid bone growth in humans but these images are rather more useful in diagnosis of localized growth problems than for studying growth patterns.

Autoradiography

Autoradiography is a technique in which a film emulsion is placed over a thin section of tissue containing radioactive isotope and then is exposed in the dark by radiation. After the film is developed, the location of radiation indicates where growth is occurring.

Radioisotopes

These elements when injected into tissues get incorporated in the developing bone and act as *in vivo* markers and can then be located by means of a Geiger counter, e.g. ^{99m}Tc, Ca-45 labeled component of protein, e.g. proline.

Implant Radiography

Implant radiography, used extensively by Bjork and co-workers, is one of the techniques that can also be used in human subjects. Herein, a biocompatible inert metal pins (generally made of titanium) are inserted some specified places in the bony skeleton including face and jaws alongwith landmarks where the implants are to be inserted in maxillary and mandibular arches. Superimposing radiographs (cephalograms in case of face) on the implants allow precise observation of growth changes in the position of one bone relative to another.

Other methods of studying growth include:
- *Natural markers*—nutrient canals, trabeculae, etc.
- *Comparative anatomy*
- *Genetic studies.*

METHODS OF COLLECTING GROWTH DATA

The data gathered as by above means is then subjected to statistical analysis to arrive at a conclusion. The studies conducted thereof are of two types:
1. Longitudinal studies
2. Cross-sectional studies.

Longitudinal Studies

Longitudinal studies involve gathering data of a given individual or subject over varying periods of time at regular intervals. This represents an example of a study on long-term basis. Although, it has an advantage of studying the developmental pattern of the subject over a period of time giving a good insight into the variations involved, yet the major drawback is that it is very time consuming and runs the risk of loss of subject(s) due to that. Furthermore, it requires elaborate maintenance of records over time, making it an expensive proposition.

Cross-sectional Studies

Cross-sectional studies on the other hand involve gathering data from different samples and are therefore faster. These are less expensive with a possibility of studying larger samples, and can be repeated if required. However, they may not provide conclusive evidence because not all individuals grow in the same way. Also, such a study would obscure individual variations.

Types of Growth Data

1. Opinion
2. Observation
3. Ratings and rankings

Quantitative measurements: include direct, indirect and derived data.

BASIC TENETS OF GROWTH— PATTERN, VARIABILITY, TIMING

The first important feature of growth corresponds to pattern.

Pattern in general terms indicates the proportionality of the given object in relation to its various sizes. However, in the concept of growth, it refers not only to the proportionality at a point of time but also to changes in this proportionality over a period of time. The fourth dimension "time" is of immense importance here. This can be clearly understood in the following illustration (Fig. 1), which depicts the change in overall body proportions over a period of time—from fetus to adulthood.

The Figure 1 illustrates the changes in overall body proportions that occurs during normal growth and

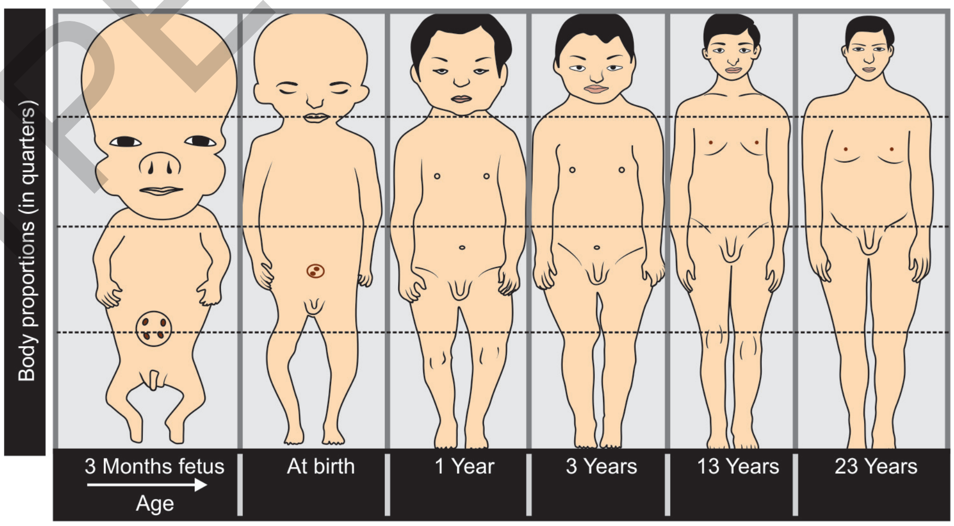


Fig. 1: Cephalocaudal gradient of growth

development. In fetal life, at about the third month of intrauterine development, the head takes up almost 50% of the total body length. At this stage, the cranium is large relative to the face and represents more than half the total head. In contrast, the limbs are still rudimentary and the trunk is underdeveloped. By the time of birth, the trunk and limbs have grown faster than the head and face, so that the proportion of the entire body devoted to the head has decreased to about 30%. The overall pattern of growth thereafter follows this course, with a progressive reduction of the relative size of the head to about 12% in the adult.

All of these changes, which are a part of the normal growth pattern, reflect the *cephalocaudal gradient of growth* (Table 1). This simply means that "there is an axis of increased growth extending from the head toward the feet."

Another aspect of the normal growth pattern is that not all the tissue systems of the body grow at the same rate. After birth, the muscular and skeletal elements grow faster than the brain and central nervous system, as reflected in the relative decrease of head size.

The overall pattern of growth is a reflection of the growth of the various tissues making up the whole organism. Scammon has classically described the growth of various tissues (Table 2) in the following diagram (Fig. 2).

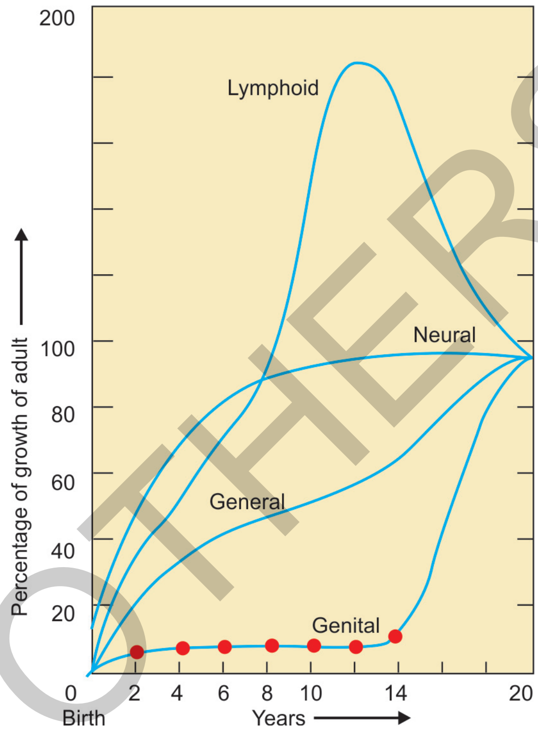


Fig. 2: Scammon's growth curve

Table 1: Cephalocaudal gradient of growth	
Cephalocaudal gradient of growth—Scammon's: There is an axis of increased growth extending from head towards the feet	
•	In fetal life, about the third month of intrauterine development (IUD), head occupies 50% of the total body length and within the head the cranium is large relative to the face. The trunk and limbs are rudimentary
•	*At birth:* head—30% of total body length Legs—1/3rd of total body length
•	*In adults:* head—12% of total body length Legs— ½ of the total body length Therefore, with growth, trunk and limbs grow faster than the head and face

Table 2: Differential growth (Scammon's growth curve)	
Different tissues in the body grow at different times and different rates. Therefore, the amount of growth accomplished at a particular age is variable. Scammon divided the tissues in the body into:	
a.	Neural tissues
b.	Lymphoid tissues
c.	Somatic/general tissues (muscles, bone, viscera).
d.	Genital tissues – Neural tissues complete 90% of their growth by 6 years and 96% by 10 years of age – Lymphoid tissues reach 100% adult size by 7 years: proliferate far beyond the adult size in late childhood (200% by 14 years) and involute around the onset of puberty – Somatic tissues show an S-shape curve with definite slowing of growth rate during childhood and acceleration at puberty going on till age 20 – Growth of the genital tissues accelerate rapidly around the onset of puberty

Patterns are repeated in skeletal proportions over time. A change in growth pattern would indicate an alteration in the expected and predictable sequence of changes in proportions expected for that individual.

The second important concept in the study of growth and development is *variability*. It indicates the degree of difference between two growing individuals in all four planes of space including the all-important time. Since everyone is not alike in the way they grow, it is clinically very difficult to decide and decipher the deviation of growth pattern of an individual from the normal. One way to do this is to compare the growth of a given child relative to person on a standard growth chart (Fig. 3).

Although charts of such nature are commonly used for height and weight, the growth of any part of the body can also be plotted this way. Such charts help us in two ways.

- To evaluate the present growth status of the individual, and
- To follow the child's growth over a period of time using such charts. Probably, the most important concept in the study of growth and development is that of timing. All the individuals do not grow at the same time or in other words possess a biologic clock that is set differently for all individuals. This can be most aptly demonstrated by the variation in timing of menarche (onset of menstruation) in girls. This also indicates the arrival of sexual maturity. Similarly, some children grow rapidly and mature early completing their growth quickly, thereby appearing on the high side of the developmental charts until their growth ceases and their peer group begins to catch up. Others grow and develop slowly and so appear to be behind even though in due course of time they might catch up or even overtake others.

RHYTHM AND GROWTH SPURTS

Human growth is not a steady and uniform process of accretion in which all body parts enlarge at the same rate and same increment per year. The rate of growth is most rapid at the beginning of cellular differentiation, increases until birth and decreases thereafter, e.g. in the prenatal period height increases 5000 times from stage of ovum to birth whereas in the postnatal period increase is only 3 fold. Similarly weight increases 6.5 billion fold from stage of ovum to birth whereas in the postnatal period increase is only 20 fold.

Postnatally growth does not occur in a steady manner. There are periods of sudden rapid increases, which are termed as growth spurts. Mainly 3 spurts are seen:

Name of spurt	*Female*	*Male*
1. Infantile/childhood growth spurt	3 years	3 years
2. Mixed dentition	6–7 years	7–9 years juvenile growth spurt
3. Prepubertal	11–12 yrs	14–15 yrs adolescent growth spurt

Clinical Significance of the Growth Spurts

To differentiate whether growth changes are normal or abnormal.

Treatment of skeletal discrepancies (e.g. Class II) is more advantageous if carried out in the mixed dentition period, especially during the growth spurt.

Pubertal growth spurt offers the best time for majority of cases in terms of predictability, treatment direction, management and treatment time.

Orthognathic surgery should be carried out after growth ceases.

Arch expansion is carried out during the maximum growth period.

FACTORS AFFECTING PHYSICAL GROWTH

The developmental ontogeny of the dentofacial complex is dependent primarily upon the following three elements:

1. *Genetic endowment:* These include:
   - Inherited genotype, like heredity
   - Operation of genetic mechanisms, like race
2. *Environmental factors:* These include:
   - Nutrition and biochemical interactions
   - Physical phenomena like temperature, pressures, hydration, etc.
3. *Functional forces:* These include:
   - Extrinsic and intrinsic forces of muscle actions, like exercise
   - Space occupying organs and cavities
   - Growth expansion.

TERMINOLOGY RELATED TO GROWTH

Growth Fields

The outside and inside surfaces of bone are blanketed by soft tissues, cartilage or osteogenic membranes. Within this, blanket areas known as growth fields, which are spread all along the bone in a mosaic pattern, are responsible for producing an alteration in the growing bone.

Growth Sites

Growth sites are growth fields that have a special significance in the growth of a particular bone, e.g. mandibular condyle in the mandible, maxillary tuberosity in the maxilla. The growth sites may possess some intrinsic potential to grow (debatable).

Growth Centers

Growth centers are special growth sites, which control the overall growth of the bone, e.g. epiphyseal plates of long

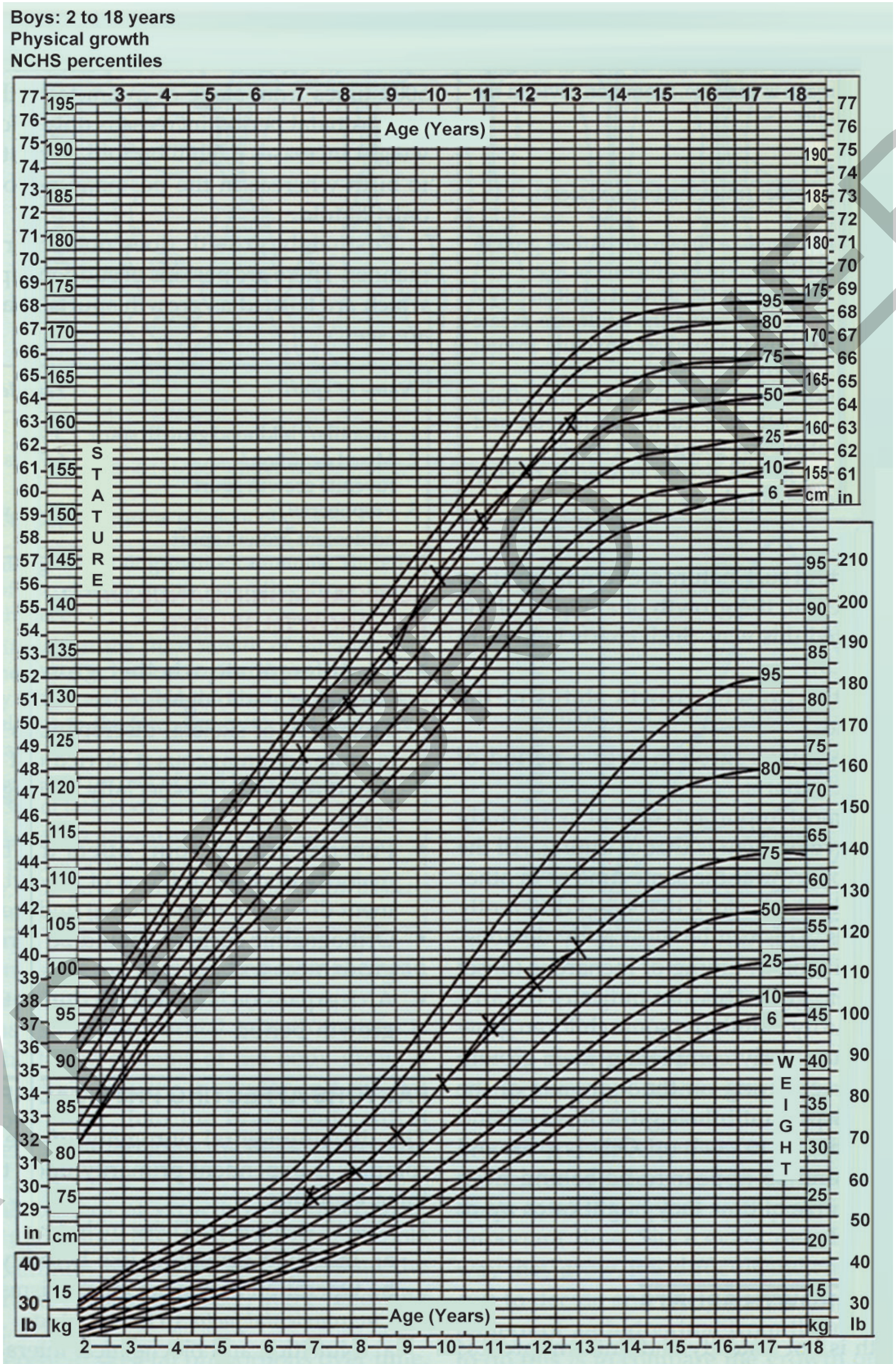


Fig. 3: Growth chart

bones. These are supposed to have an intrinsic growth potential (unlike growth sites).

Remodeling

It is the differential growth activity involving deposition and resorption on the inner and outer surfaces of the bone, e.g. ramus moves posteriorly by a combination of resorption and deposition.

Growth Movements

Growth movements are primarily of 2 types:

Cortical Drift

Cortical drift is a type of growth movement occurring towards the depository surface by a combination of resorption and deposition on the opposing surfaces simultaneously.

Displacement

Displacement is the movement of the whole bone as a unit. Two types are seen.
- *Primary displacement:* Displacement of bone in conjunction with its own growth. It produces space within which the bones continue to grow.
- *Secondary displacement:* Displacement of bone as a result of growth and enlargement of adjacent bone/bones.

Characteristics of Bone Growth

Bone formation occurs by two methods of differentiation of mesenchymal tissue that may be of mesodermal or ectomesenchymal (neural crest) origin. Accordingly two types of bone growth ossification are normally seen.

Intramembranous Ossification

Intramembranous ossification is the transformation of mesenchymal connective tissue, usually in membranous sheets, into osseous tissues.

Endochondral Ossification

Endochondral ossification is the conversion of hyaline cartilage prototype models into bone.

Endochondral bone is three dimensional in its growth pattern, ossifying from one or more deeply seated and slowly expanding centers. The interstitial growth or expansion capability of cartilage, even under pressure leading to its avascularity, precluding ischemia, (cartilage nutrition is provided by perfusing tissue fluids that are not easily obstructed by load pressures), allows for directed prototype cartilage growth. The cartilage 'template' is then replaced by endochondral bone, accounting for indirect bone growth.

Intramembranous bone growth, by contrast, is by direct apposition of osseous tissue in osteogenic (periosteal) membranes creating accretional growth, often with great speed, especially over rapidly growing areas, such as the frontal lobes of the brain, or at fracture sites.

Ossification commences at definable points in either membranes or cartilages, and from these centers of ossification the ossifying process radiates into the precursor membrane or cartilage. Secondary cartilages, not part of the cartilaginous primordium of the embryo, appear in certain membranous bone (mandible, clavicle) after intramembranous ossification begins. Endochondral ossification occurs later in these secondary cartilages of intramembranous bone. The distinction between intramembranous and endochondral bone, while useful at the embryological level of osteogenesis, tends to become insignificant in the postnatal life.

Modes of Bone Growth (Figs 4A to D)

At the cellular level, there are only three possibilities for growth.

Hypertrophy

This refers to the increase in size of individual cells.

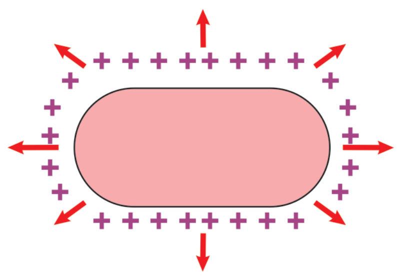


Fig. 4A: Endochondral bone growth

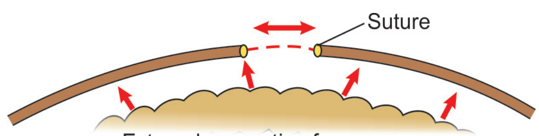


Fig. 4B: Intramembranous bone growth

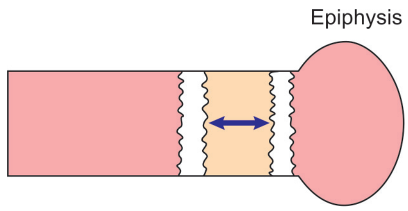


Fig. 4C: Internal expansion of growth cartilage

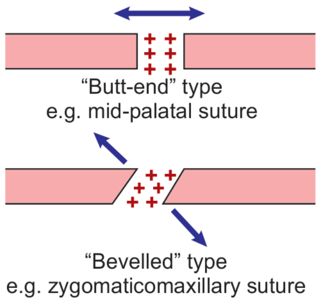


Fig. 4D: Sutural growth

Hyperplasia

This refers to increase in the number of cells.

Extracellular Material

This refers to the cells which secrete extracellular material, thus contributing to an increase in size independent of the number or size of the cells themselves.

In fact, all three processes occur in skeletal growth. Hyperplasia is a prominent feature of all forms of growth. Hypertrophy occurs in a number of special circumstances, but is relatively a less important mechanism. Although tissues throughout the body secrete extracellular material, this phenomenon is particularly important in the growth of the skeletal system where extracellular material later mineralizes.

Growth of the soft tissues occurs by a combination of hyperplasia and hypertrophy. These processes go on everywhere within the tissues, and the end result is what is called interstitial matrix growth, which simply means that it occurs at all points within the tissue.

GROWTH CONTROL

From its earliest days the orthodontic literature has contained reports of investigations into the nature and mechanisms of craniofacial growth.

Mills (1982) notes that orthodontic textbooks invariably commence with a chapter describing the normal development of the face, jaws and dentition. He considers that it is important before understanding the abnormal to have a clear idea of the way the face and its component parts develop. He goes on to say *'although we appear to have a fairly clear idea of how the face grows, and of where it grows, we have little idea of why it grows...we do not fully understand the factors which control the amount and direction of growth.'*

The human growth has a complex growth pattern. Growth of the brain case or calvarium is tied to the growth of the brain itself, while growth of the facial and masticatory bones is relatively independent of the brain growth even though these bones are in actual contact with the cranial super-structure. Obviously in natures' plan, growth of any part of the skull is coordinated with that of other parts. The original pattern of the skeleton is maintained with the stationary biologic center lying in the body of the sphenoid bone.

Limborgh poses three main questions concerning the control of morphogenesis of the skull:

- Are there, in the embryonic phase, any causal relationships between the development of the skull on one hand and the presence of primordium on the other?
- How is the coordination between the endochondral and intramembranous bone growth brought about within the skull once it is formed?
- In which way is the coordination between the skull growth and that of the other structures realized? To answer these questions analysis must be made of the more obvious controlling and modifying factors. These are:
  - **Intrinsic genetic factors** or those inherent in the skull tissues themselves.
  - **Epigenetic factors**, are genetically determined but manifest their influence in an indirect way by means of intermediary actions or structures (i.e. eyes, brain, and so forth)
  - **Local and general environmental factors** are also controlling entities and require a value judgment in the overall picture. To elicit an acceptable answer to these queries, researchers, over a period of time, have postulated various solutions that are collectively termed as theories of growth control.

THEORIES OF SKULL GROWTH CONTROL

Genetic Theory

The **classic approach** attributed control of skull growth largely to intrinsic genetic factors. This approach was questioned by researchers like Scott, Sicher, and Moss. It was van Limborgh in 1970, who analyzed the controlling and modifying factors in the growth of the skull.

Sutural Dominance Theory

Sicher considered that apart from minor remodeling which could be caused by local environmental factors such as muscular forces; bone growth was independent and immutable. The apparent correlation between the growth of the skull and its associated soft tissues was said to be a consequence of genetic harmony and not due to any interdependence. All osteogenic tissues, that is, cartilage sutures and periosteum, were thought to play an equally significant role in the control of the growth of the skull. However, his theory is generally referred to as the **sutural dominance theory**, with proliferation of connective tissue and its replacement by bone in the sutures being a primary consideration.

Sicher's proposition, in which growth of the skull was considered to be highly independent, was soon questioned. There was no reason to believe that the guiding genetic factors were contained in the bones. They may equally well operate indirectly through epigenetic factors. Experimental studies which demonstrated this were:

- Extirpation of facial sutures has no appreciable effect on the dimensional growth of the facial skeleton.
- The shape of the sutures is dependent on functional stimuli
- The closure of sutures is likewise extrinsically determined
- Sutural growth can be halted by mechanical forces, were to provide evidence that the suture does not have an independent growth potential (Koski, 1968).

Furthermore, the findings in spontaneous malformations such as hydrocephaly and microcephaly and the results of experiments carried out on normal embryos, gave strong support to the notion that a close relationship existed between skull growth and the morphology and activity of the associated structures.

Cartilaginous Theory

Scott proposed an alternative view, which is regarded as the second major hypothesis, on the nature of craniofacial growth, in the early 1950's.

He assumed that intrinsic, growth-controlling factors were present only in the cartilage and in the periosteum. He claimed that growth in the sutures was secondary and entirely dependent on the growth of the cartilage and adjacent soft tissues. Scott's hypothesis could explain the coordinated growth that had been observed within the skull, and between the skull and the soft tissues. He introduced the concept of cartilaginous 'growth centers'. The role of these growth centers was explained in a contemporary summary of craniofacial skeletal growth (Scott 1955).

Several of Scott's basic tenets still hold credibility for researchers in the field of growth. Van Limborgh supported the view that synchondroses of cranial base have some degree of intrinsic control. However, he felt that the periosteum should also be considered as a secondary growth site because of its similarity to the suture.

Functional Matrix Hypothesis

Melvin Moss introduced the functional matrix hypothesis to the orthodontic world in 1962. His so called 'method of functional cranial analysis' was a conceptual framework designed to unify the existing concepts and to emphasize the contention that the bones do not 'just grow' (form follow function).

He was inspired by the ideas of Van der Klaauw (1952) that 'bones' were in reality, composed of several 'functional cranial components' the size, shape and position of which were relatively independent of each other. He experimentally verified and expanded on these concepts and incorporated them with his own.

The original version of the functional matrix hypothesis held that, the head is a composite structure, operationally consisting of a number of relatively independent functions; digestion, respiration, vision, olfaction, audition, equilibrium, speech, neural integration, etc. Each function is carried out by a group of soft tissues which are supported and/or protected by related skeletal elements. Taken together, the soft tissues and skeletal elements related to a single function are termed a *functional cranial component*. The totality of all the skeletal elements associated with a single function is termed a *skeletal unit*. The totality of the soft tissues associated with a single function is termed as the *functional matrix*. It may be further demonstrated that the origin, growth and maintenance of the skeletal unit depend almost exclusively upon its functional matrix.

In 1964, Moss presented a unified view of the role of all craniofacial 'growth cartilages'; 'the growth observed both at facial sutures and at cartilaginous areas (nasal cartilages, mandibular condyles, sphenooccipital synchondroses) are all secondary, compensatory events whose net effect is to retain structural and functional continuity between skeletal parts.' An active mechanical role for spaces was suggested explicitly. For example, when considering the nasopharyngeal space, he stated 'this physically empty but physiologically necessary space is the primary biologic object that grows. The growth of nasal septal cartilage is, then, a secondary, mechanically obligatory growth which is totally compensatory in nature.'

In 1968, Moss presented an updated version of his hypothesis. The tissues, organs, spaces, and skeletal parts necessary to carry out a given function were termed collectively, a '*functional cranial component*'. On the basis of their relation to transformative and translative growth, the soft tissues of a functional component were classified as either '*periosteal*' or '*capsular' functional matrices*; on the basis of their relation to functional matrices, skeletal units were classified as either '*microskeletal*' or '*macroskeletal*' units. All translative growth was seen as occurring secondarily to the expansion of central, encapsulated volumes (brains, eyeball, spaces, etc.), while transformative growth was due to the presumably direct action of periosteal functional matrices (muscles, teeth, fat, glands, etc.).

Later, in his quest for the underlying control mechanism for craniofacial growth, Moss (1971) focused his attentions on the phenomenon of neurotrophism. *Neurotrophism is defined as a 'non-impulse transmitting neural function that involves axoplasmic transport and provides for long-term interactions between neurons and innervated tissues that homeostatically regulate the morphologic, compositional, and functional integrity of soft tissues.'* Moss concluded that the nerve influences the gene expression of the cell, and suggested that the genetic control lies not in the functional matrix alone, but reflects constant neurotrophic regulation stemming from a higher neural source.

Taken as a group, these schemes are commonly referred to as the functional matrix hypothesis. It is scientifically parsimonious, emphasizing the need to consider only the form and function in order to understand the basis of growth. It has been applied to explain the observations as diverse as:

- The diminution in size of the coronoid process subsequent to experimental denervation of the temporalis muscle.
- The growth of the calvarium in response to the expanding brain.
- The shrinkage of the alveolar process subsequent to tooth removal.
- Spatial maintenance of the appropriate foramina along a logarithmic spiral path during growth in response to the demand for an unloaded trigeminal neurovascular bundle. These and many other examples were presented by Moss as evidence to support the functional matrix hypothesis.

Servosystem Theory

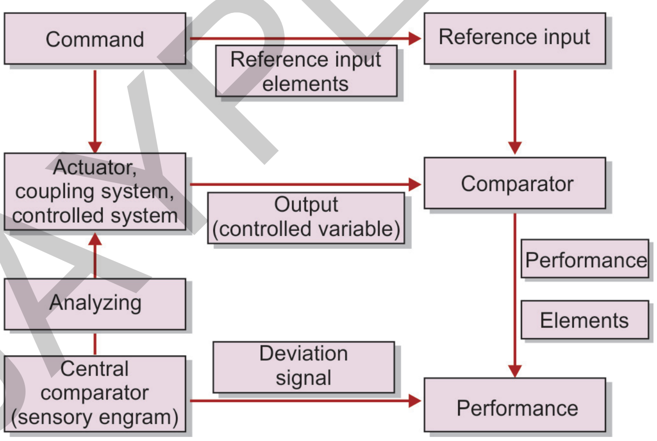
A further step in understanding the mechanisms of craniofacial growth was made when Charlier and Petrovic (1967) and Stutzmann and Petrovic (1970) detected in organ culture, in both transplantation and *in situ* investigations, the basic dissimilarities relative to different growth cartilages.

This led to the servosystem theory of the processes controlling postnatal craniofacial growth (Petrovic and Stutzmann, 1980).

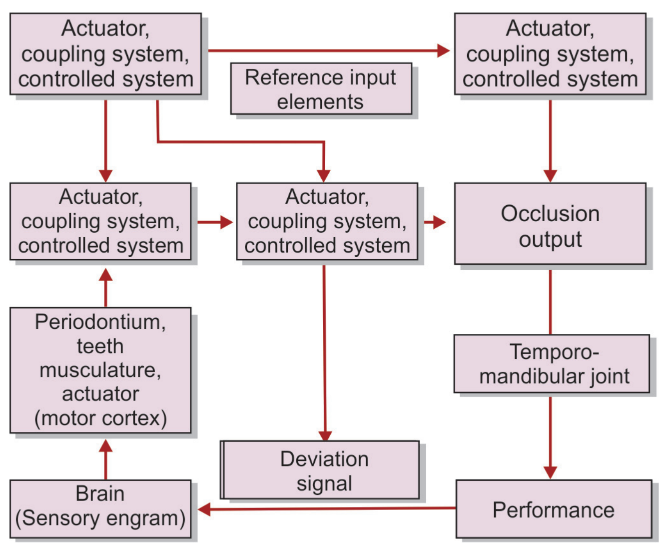
According to this concept, the influence of the STH—somatomedin complex on growth of the ***primary cartilages*** (epiphyseal cartilages of the long bones, cartilages of the nasal septum and sphenooccipital synchondrosis, lateral cartilaginous masses of ethmoid, cartilage between the body and the greater wings of the sphenoid, etc.) has the cybernetic form of a 'command' (i.e., does not include any so far detected local feedback loops) (Flow charts 1 and 2).

Quite the contrary, the influence of the STH-somatomedin complex on the growth of the ***secondary cartilages*** [condylar, coronoid, and angular cartilages of the mandible, cartilages of the mid palatal suture, some other craniofacial sutures, and the provisional callus during bone fracture repair, and (to

Flow chart 1: Components of a servosystem



Flow chart 2: The face as a servosystem



some extent) rib growth cartilages] comprise not only direct but also some indirect effects on the cell multiplication. With condylar, coronoid and angular cartilages these indirect effects correspond to *regional* and *local* factors involving primarily neuromuscular mechanisms relative to postural adjustment.

ARCHITECTURAL ANALYSIS OF THE SKULL

General Plan

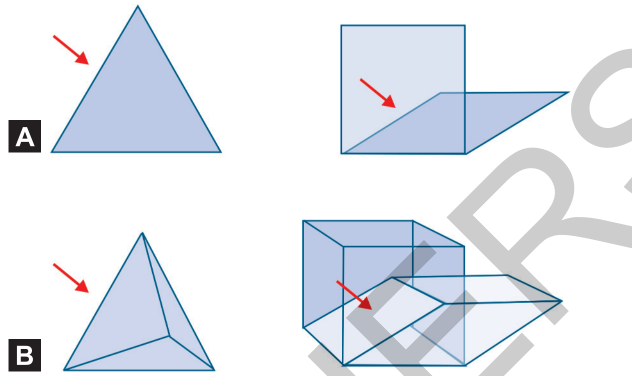
The skull is a stress-bearing structure and has to withstand significant and complicated forces when an individual punctures, shears, or chews its food.

The common engineering solution to the resistance of force is manifest in the design of, "frames and trusses." The basic frame is a triangle, a form in two dimensions. Three members (bars) with joints at their angles resist distortion of the triangle from forces applied in any direction in the same two-dimensional plane. Increase in the number of members weakens the frame, e.g. say a rectangle so jointed collapses when similar angular force is applied (Figs 5A and B).

The basic truss is a tetrahedron (three-sided pyramid), which is simply four triangles (base included), a form in three dimensions. It resists distortion from forces applied in any direction in three planes of space. Increase in number of members weakens the truss, e.g. a cube collapses when similar angular force is applied.

The structural strategy of the skull is a biologic compromise that accommodates multiple competing functional demands. Most evident are the protective housings for the brain and each of the functionally oriented special sense organs, the separate corridors for the airway and food, and the variety of entrances and exits for arteries, veins, and nerves. In addition, the masticatory system is deeply rooted within this assemblage. Though its force-resisting triangles and tetrahedrons may be somewhat wrapped to bypass obstructing organs, the truss-work can be readily traced throughout the skull as pillars of reinforced bone (Fig. 6).

In frontal view several frames can be clearly outlined (Fig. 7). A central triangle dominates the facial skeleton. Its sides are formed by canine buttresses, which begin at the anterior corners of the dentition and run up between nasal and orbital spaces to meet at the glabella, bulging in the midline of the frontal bone. This, in turn, is backed by the vertical temporal squama. The base of the central triangle is formed by the thickened anterior strip across the palate between the canines. A large inverted triangle can be traced on each side of this central frame. Its medial side is the canine buttress in common with the central frame. Its lateral side diverges as the zygomatic process of the maxilla, which is continuous upward through the reinforced middle strip of the zygomatic



Figs 5A and B: Frames and trusses (A) Frame: triangular frame resists distortion from external force, rectangular frame collapses, (B) Truss: tetrahedral truss resists distortion from external force; cubic truss collapses

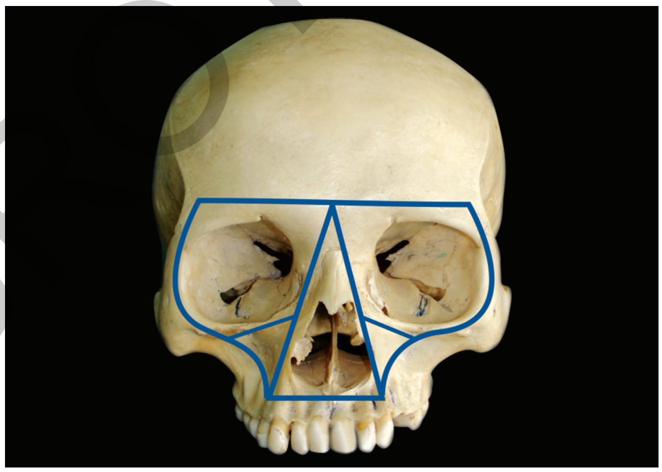


Fig. 6: Frames and trusses of skull, frontal view

bone to meet the frontal bone at its zygomatic process. The base of this inverted triangle is the bulky superciliary bar, which forms the upper margin of the orbit.

A shorter triangle can be seen fitted within the greater frame. Its sides are the same below, but its base cuts it short at the thickened lower margin of the orbit. Now it can be seen that this truss work already meets several of the essential requirements specified previously. It frames nasal, sinus spaces while providing an optimal force-resisting framework for masticatory stress.

In the lateral view this functional plan can be followed in depth (Figs 7 and 8). Canine and zygomatic buttresses can be seen diverging from the dentition. Posteriorly the bulbous maxillary tuberosity can be seen, strongly braced by the pterygoid process, which takes up the force on the posterior

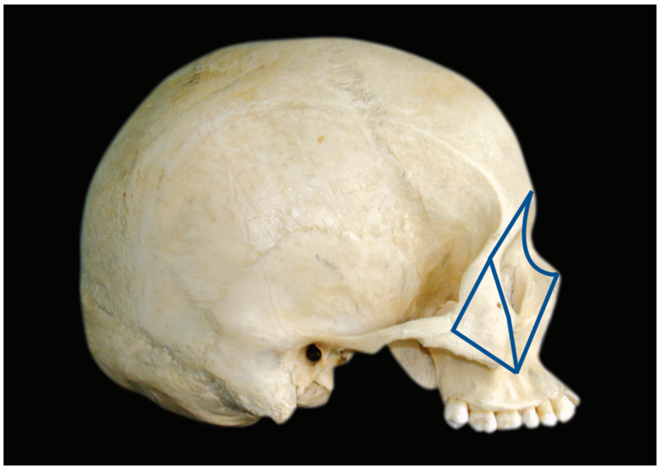


Fig. 7: Frames and trusses of skull; lateral view

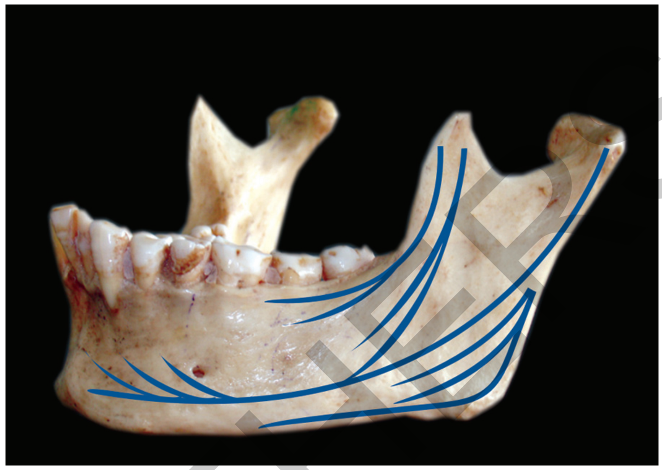


Fig. 9A: Trajectories of the mandible (buccal aspect)

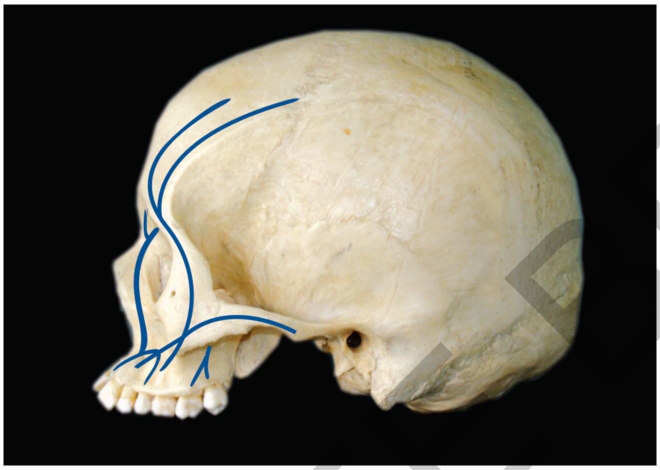


Fig. 8: Supporting pillars of the maxillary skeleton

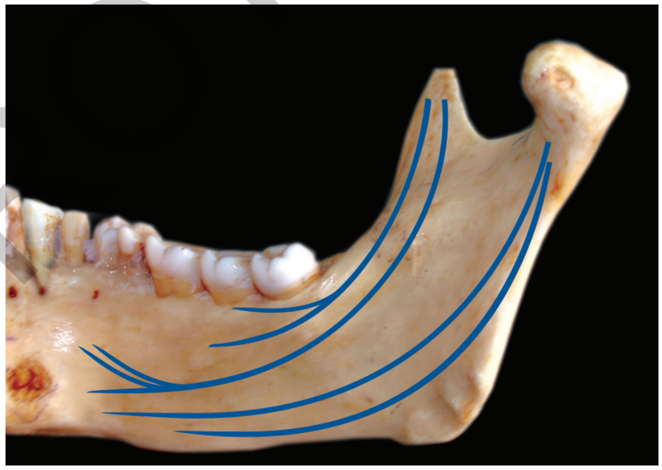


Fig. 9B: Trajectories of the mandible (lingual aspect)

dentition like a flying buttress diverging upward to the cranial base.

The plan of this three-dimensional truss work is convincingly demonstrated in a horizontal section of the maxilla. A three-sided pyramid (tetrahedron) cut in half, yields a triangular plane which, in the maxilla, is reinforced as a bony pillar at each angle; these are the canine buttress, the zygomatic buttress, and the maxillary tuberosity, which butts against the pterygoid buttress. Between these buttresses the bone is thin and forms the walls of the various cavities.

The mandible completes the framework of the skull. It contributes the movable part of a complicated lever system. To meet this function it is designed as a strong central bar, like the shaft of a long bone, running forward in a continuous curve from condyle to condyle (Figs 9A and B). The bar is reinforced at its midline symphysis by the bulging chin, which resists the squeezing action of the lateral pterygoids at the condylar ends of the horseshoe-shaped curve. This central bar supports three processes. Thus two thinner plates are pinched off above and below for the attachment of masticatory muscles. The temporalis inserts on the coronoid process, which is reinforced by the narrow temporal crest; the masseter and the medial pterygoids insert on the mandibular angle, which is a slightly thicker plate since it must resist the pull of two muscles. The alveolar process for the attachment of the dental arch is a continuous process pulled up from the bar with the eruption of teeth.

This basic framework of the mandible is unmistakably demonstrated in the senile jaw. With the loss of teeth the alveolar process disappears. Since masticatory function is thus severely reduced, the masticatory muscles atrophy from disuse. This is accompanied by extensive resorption of their mandibular insertions. Coronoid and angular plates recede, and little but the central bar of bone remains.

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