Basic mechanisms in craniofacial growth

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Bone growth is controlled by growth areas, not active growth centers as stated earlier. Conversion of cartilage, sutural deposition, and periosteal remodeling are the basic phenomena involved in growth mechanisms. The principles of bone growth will result in changes in the size and shape of the mandible and the nasomaxillary complex in the three dimensions. The growth rate varies at different times during the development of the child. The processes of facial growth and changes in the dental arches continue to a much later age than had previously been realized. Although our knowledge of craniofacial growth has increased during recent times, it is still incomplete with regard to the explanation for the regulation of craniofacial growth. □ *Growth mechanisms; growth pattern; mandibular growth; nasomaxillary growth*

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The fully developed cranium represents the sum of its separate parts, in which growth is highly differentiated and occurs at different rates and in different directions, and is thus a complex concept. By birth the craniofacial skeleton has undergone between 30% and 60% of its total growth. Although this reflects the early development of the skull, the remaining increase in size is not equal in all parts of the cranium. Whereas the size of the neuro-cranium will increase by about 50% after birth, the facial skeleton will grow to more than twice the size, the increase in height being the greatest (approximately 200%), that in depth somewhat smaller, and that in the width the smallest (approximately 75%).

The growth of the soft tissues is also of importance. Changes in the soft-tissue profile with age follow the growth in the underlying hard tissues but are not directly correlated with those in bones. The convexity of the face increases with age, as nasal growth mainly occurs in the anteroinferior direction. The lip profile also changes during childhood, due partly to growth and partly to changes in the dentition.

The old theory on facial growth, introduced by Brodie (1), that the skull increases in size by direct symmetric expansion of all surfaces and contours is an antiquated statement. By the use of cephalometric radiography the Bolton standards (2) will give the impression of a smooth downward and forward pattern of facial growth. This is, however, also misleading. We have learned from years of research that the fully grown skull is not simply a larger version of the infant form and that the adult skull differs not only in size but also in shape from that of the child, depending on a process of differential growth in various parts of the cranium. This can be illustrated by superimposed tracings from boys and girls with normal ('ideal') occlusion, followed from 7 years up to 30 years of age (3) (Fig. 1). As can be seen, there are obvious changes also in the period between 16 and 30 years of age.

The development, growth, and maturation of the skull comprise phenomena falling within the scope of several disciplines and occurring at several levels, including the molecular, cellular tissue, and organ levels. No specific method can therefore be assigned to the study of these events. The commonly used methods are embryologic research, use of tissue and organ cultures, experiments on laboratory animals, twin studies, pathologic conditions (malformations or acquired defects). Biometric and cephalometric data on craniofacial growth usually serve to describe dimensional changes between different bones and growth mechanisms. All these different methods are the basis for modern basic knowledge on craniofacial growth (4).

From experiences of all those studies we can state today that craniofacial growth may be divided into four components: growth mechanism (how new bone is formed), growth pattern (change in size and shape of the bone), growth rate (speed at which the bone is formed), and the regulation mechanism, which initiates and directs those three factors.

Growth mechanisms

Growth and ossification of the cranium occurs in two ways: by growth and ossification of a cartilage model, endochondral ossification, and by a transformation of mesenchymal connective tissue and deposition of bone on existing bone surfaces, intramembranous ossification. Whereas the bone of the skull base is mainly of endochondral origin, the vault of the cranium and facial skeleton are mainly developed by intramembranous ossification.

Although several ossified areas fuse into large morphologic units, remnants of the chondrocranium persist as cartilaginous joints, synchondroses, between bones in the cranial base. When intramembranously formed

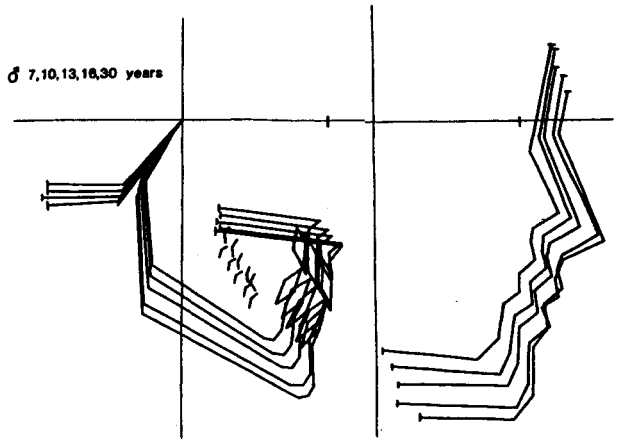

Fig. 1. Templates from boys 7, 10, 13, 16, and 30 years of age (3), illustrating skeletal and soft-tissue changes.

bones meet, sutures develop. Bone growth and adaption can thus proceed as a result of continued separation of bones in the synchondroses and suture areas. Premature fusion or hindrance of separation for any other reason will result in an abnormal growth pattern for the bones in question, with a risk of cranial deformity.

Bone growth is controlled by growth areas, not active growth centers as stated earlier. The following basic phenomena are involved in the growth mechanisms: conversion of cartilage (synchondroses, nasal septal cartilage, condylar cartilage), sutural deposition, and periosteal remodeling.

Synchondroses

Displacement growth in the cranial base is made possible mainly by the synchondroses. Only a few persist postnatally in the region of the cranial midbase, the spheno-occipital synchondrosis being the most important one (5, 6).

The young human synchondrosis consists of a bipolar 'epiphyseal' plate with endochondral ossification (Fig. 2), and its structural organization changes with age. The hyaline cartilage is partly replaced by fibrocartilage in the superior part, which becomes narrower through ossification from both sides, and is completely covered with bone by the age of 12–13 years in girls and some years later in boys. The synchondroses of the cranial base may be regarded as special joints enabling growth to take place at younger ages. The postnatal importance of the spheno-occipital synchondrosis, sometimes considered the driving force for skull base growth, has been questioned. It is more likely that this cartilage plays a relatively greater role in the adjustment changes in cranial base flexure than in its linear growth (7).

Nasal septal cartilage

During the fetal period the midsagittal part of the middle face consists entirely of a cartilage plate (nasal septum), which is a part of the nasal capsule of the chondrocranium (Fig. 3). In connection with ossification of the cranial base, parts of this cartilage septum are also ossified to form the ethmoid and vomer bones. Thus only a small, anterior part of the original cartilage persists postnatally. The nasal septum is thought to play an important part in the prenatal and very early postnatal growth of the middle face. Opinions differ, however, as to its role in postnatal growth (8).

According to Scott (9), the septal cartilage occupies a unique location for pushing the whole maxilla forward–downward, and his famous nasal septal theory was born. The opposing view, commonly termed the functional matrix by Moss (10), suggests that the nasal septal cartilage is a locus of secondary, compensatory, and mechanical growth.

Many experimental studies have been performed to find evidence favoring the septal hypothesis or the functional matrix hypothesis (11). The growth potential of the nasal septum has been investigated by transplanting the whole septum, or parts of it, in 'neutral' environments (subcutaneously, intracerebrally) or in organ cultures. Autoradiographic methods (tritiated thymidine or ^{35}S-sulfate) have shown labeling throughout the whole septum. However, changes in site of growth activity were observed, as were age-specific differences in this activity. Experiments involving partial or total removal of the septum have given different results. Sarnat (12) found a significant decrease in growth of the nasal complex when such a procedure was carried out in the young rabbit. Stenström & Thilander (13), however, found no or only little change in the dimension of the snout of growing guinea pigs after such surgical extirpations, results in agreement with those of Moss et al. (14) in growing rats.

A review of the pertinent literature on the role of the nasal septal cartilage in postnatal midfacial growth will conclude that its growth is secondary to and compensatory for a prior passive displacement of the midfacial bones but plays a significant biomechanical role in maintaining normal midfacial form (11, 14).

Condylar cartilage

This is a secondary type of cartilage and thus differs morphologically from epiphyseal and synchondrosal cartilage. It participates in growth early in human life and absorbs pressure forces later in life. Its histomorphologic picture varies from birth to adulthood (15) (Fig. 4).

The role of the condylar cartilage in mandibular growth is a subject of controversy (7). It has previously been claimed that it was expansive, similar to the epiphyseal cartilage, thereby pushing the mandible forward. The information at hand indicates that the condyle and its cartilage participate only in regional adaptive growth and are thus not a major growth center

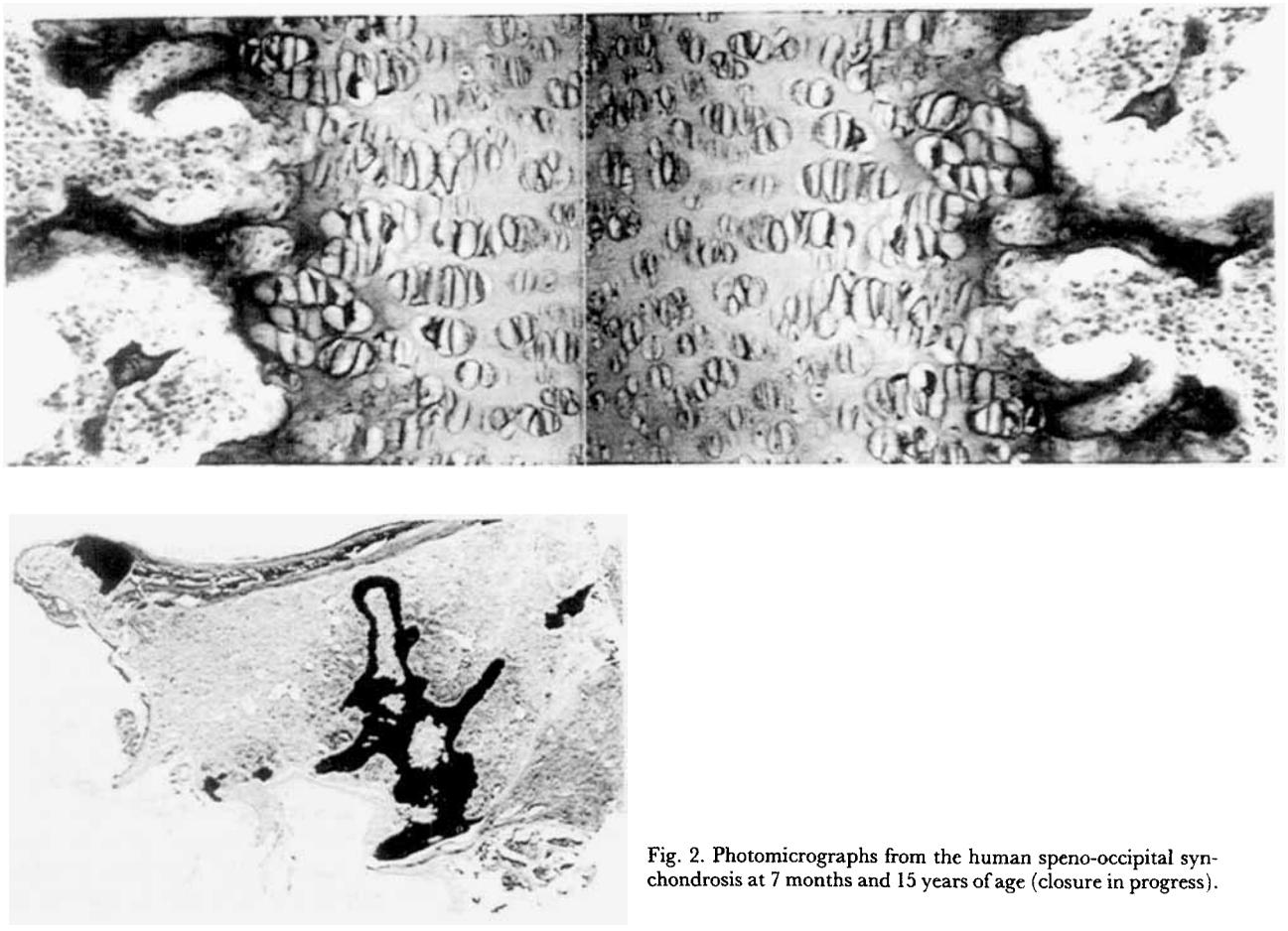

Fig. 2. Photomicrographs from the human speno-occipital synchondrosis at 7 months and 15 years of age (closure in progress).

for the whole mandible. The condyle has a great capacity to adapt to mandibular displacement during growth. As the condyle is also a part of the ramus, the fibrous layers of condylar cartilage are continuous with the periosteum of the ramus, and remodeling processes are seen in all components of the joint. The term 'condylar growth' is therefore misleading. 'Ramus and condylar growth' is more correct (16).

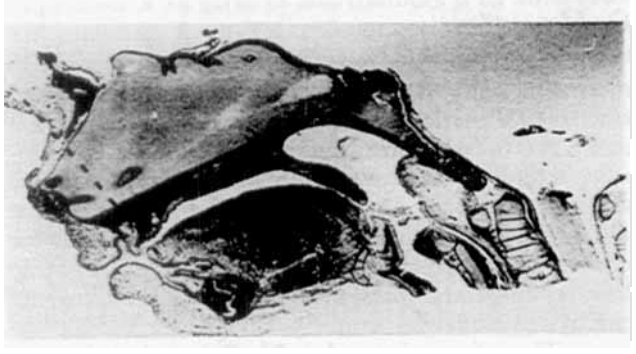

Fig. 3. The human nasal cartilage from a 5-month-old fetus. A small part of the original cartilage, anterior to the dotted line, persists postnatally.

Sutures

Displacement growth is made possible by the craniofacial sutures, which have a dual function of permitting growth movement and uniting the bones of the cranium (Fig. 5). The fibrous component of the suture increases with age, and bundles of fibers can be seen running transversally across the suture and further increasing the mechanical strength of the joint (17). When cranial growth ceases, most sutures ossify. Animal studies indicate that the bone movements resulting from growth also regulate the development of the sutures.

Periosteum

A periosteal cell layer, the inner cambium layer, is established with the initiation of the intramembranous ossification of bone, and the surrounding mesenchymal cells acquire the character of osteoblasts (Fig. 6).

Bone growth presupposes a continuous replacement of matrix-producing cells via cell division in the cam-

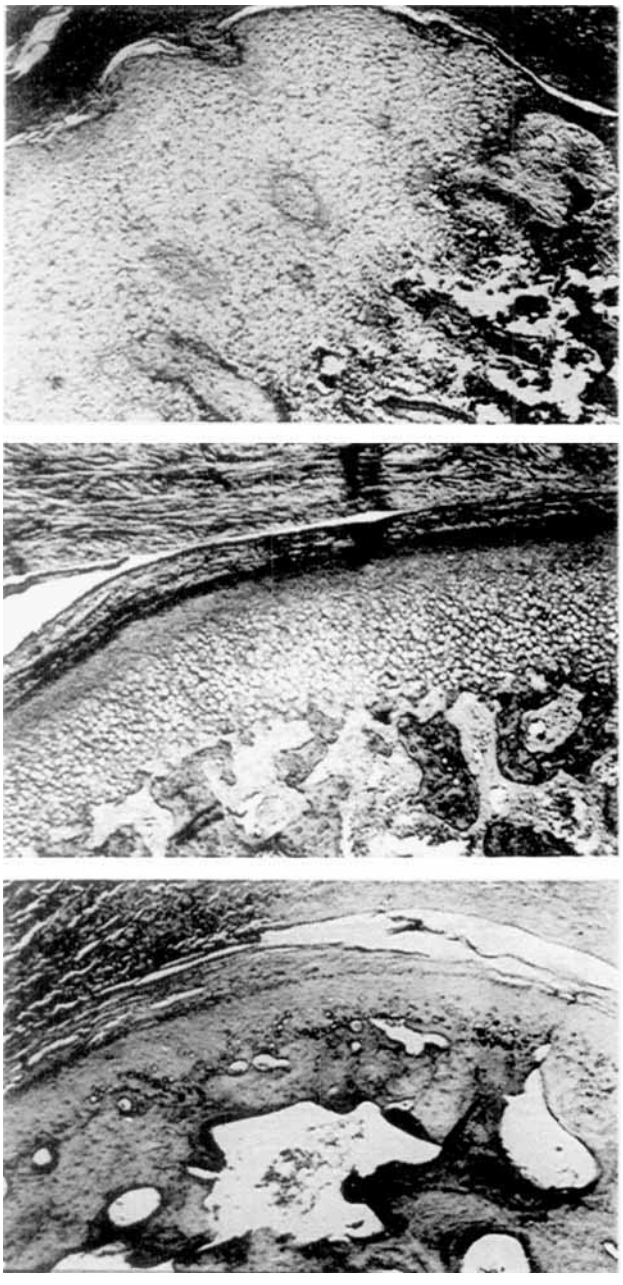

Fig. 4. Photomicrographs from the human condylar cartilage at different ages (newborn, 6 years, and 20 years).

bium layer. Owing to their location, both matrix-producing and proliferating cells are subject to mechanical influence. If the pressure exceeds a certain threshold level, so that the blood supply to these cells is reduced, osteogenesis ceases and osteoclasts appear until a biochemical equilibrium is restored. If, on the other hand, the periosteum is exposed to tension, it responds with bone deposition. The periosteum continues to function as an osteogenic zone throughout life, but its regenerative capacity is extremely high in the young child. The influence of the periosteum is of greatest significance for the change in size and shape of the bones (the growth pattern).

Growth pattern

Bone grows by two fundamental physiologic processes, modeling and remodeling. Modeling is a surface-specific activity (apposition and resorption) that produces a change in the size and shape of the bone. Remodeling, however, occurs in the bone tissues as reconstruction of bone by turnover of previously existing osseous tissue (Haversian system) and rebuilding at the molecular level (biochemical remodeling). The process we are dealing with in facial morphogenesis is growth remodeling—that is, both modeling and remodeling are included in this term. In the present paper the term 'remodeling' in its wide concept will be used.

Most articles and textbooks dealing with growth principles refer to Enlow's theories (16). According to him, the change in size and shape of the bone takes place on the basis of several basic principles: remodeling, cortical drift, relocation, displacement, and 'V-principle'. His original studies were based on 25 human mandibles, obtained from cadaver material or from commercial supply houses (18). Information on race and sex was uncertain in most cases. The two halves of the mandibles were sawed into transversal sections and studied microscopically. In adult specimens extensive structural changes had taken place in the compact bone tissue. Therefore, only mandibles having primary and mixed dentitions were studied; the number is not given.

The continuous remodeling serves to maintain the shape and proportions of the bone throughout the growth period. As bone deposition occurs during a coincident breakdown of opposing bone surfaces, the bone will migrate in relation to a fixed structure. This migration through remodeling is known as drift. As a general rule, the surface towards which growth occurs is appositional, whereas the surface facing away from the direction of growth is resorptive. The two processes need not occur with the same intensity, but, rather, appositional activity normally exceeds resorption during the growth period.

Due to new bone deposition on one surface, all other parts of the structure will undergo shifts in relative position, a movement that is termed relocation. As a result of this process, further adaptive bone remodeling has to take place, to adjust shape and size of the bone to its new position. An example of such passive drift in the facial region is the hard palate, which subsides in relation to the overlying structures, due to resorption of the nasal floor and concomitant deposition on the roof of the palate. Relocation and structural remodeling thus are closely related to each other.

At the same time as the nasal floor subsides owing to

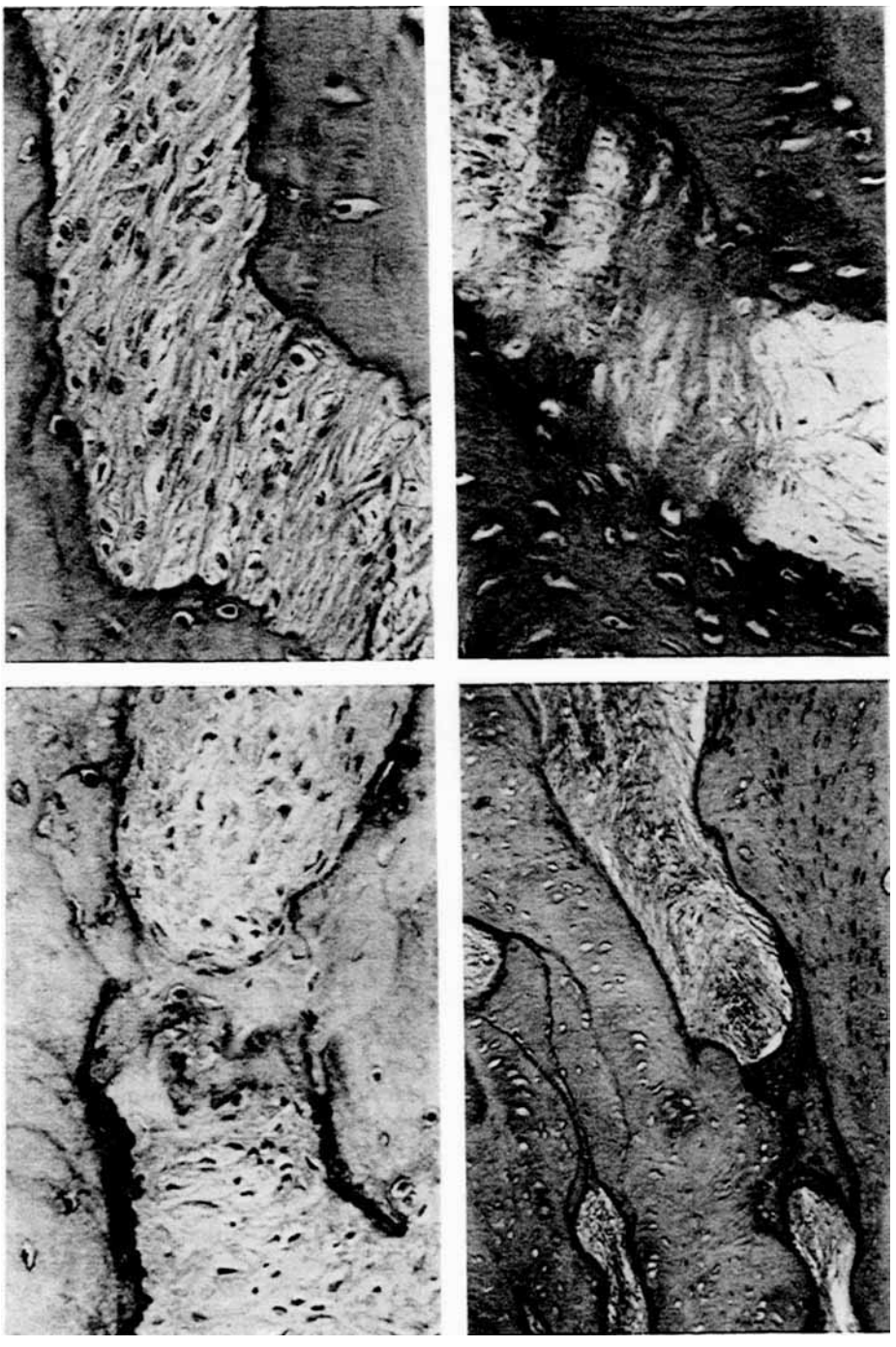

Fig. 5. Photomicrographs from the human intermaxillary suture at different ages (14 to 25 years), showing various stages of fusion.

remodeling, the whole maxilla also subsides in relation to the base of the cranium. This more active movement of a whole bone is called translation or displacement, which is both primary and secondary. The primary displacement is associated with a bone's own enlargement, and it always takes place in the direction opposite to the vector of bone growth. The secondary displacement is not associated with growth of the bone itself but initiated by enlargement of adjacent bones and soft structures and transferred to adjacent bones.

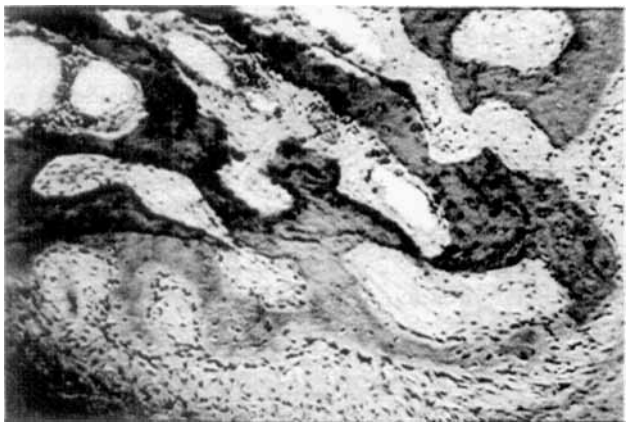

Fig. 6. Intramembranous bone covered with periosteum.

The significance of the interplay between deposition and resorption for the shape of the various bones may be difficult to perceive in the case of complex structures. Enlow (16) has shown, however, that many of these structures are V-shaped and that the same basic rules can be applied to all of them. Deposition on the inside of the V in the direction of growth and resorption on the outside enables the bone to retain its characteristic shape during growth, the V-principle.

These principles of bone growth will result in the following changes in size and shape of the nasomaxillary complex and mandible.

Growth of the nasomaxillary complex

The anterior growth is mainly the result of displacement of the two maxillary bodies. The dimensional increase occurs mainly in the opposite direction, by bone deposition on the tuberosity. This upward-backward relocation will result in a primary forward-downward displacement of the maxillary bones, together with a secondary displacement of the adjacent bones (nasal, orbital). These tensile forces initiate adaptive sutural growth. The alveolar base is thereby elongated, creating space for posterior and late-erupting teeth. The anterior surface, on the other hand, is fairly stable from a growth point of view.

The vertical growth is the combined result of lowering of the maxilla as a whole and a remodeling at the bone surfaces, as shown by Björk & Skieller (19) in a sample of boys 4 to 20 years old. The displacement of the maxilla, classified as sutural lowering of the bone, creates space for an expansion of the nasal cavity and orbits of the eyes. Lowering of the orbital floor is limited by a certain bone deposition towards the orbits, but the floor of the nasal cavity continues to be lowered owing to resorption nasally, with simultaneous deposition of bone orally on the palate. The movement of the nasal floor in relation to overlying structures during growth is therefore the result of two separate growth processes: drift, owing to remodeling growth, and displacement, owing to movement of the maxilla as a whole. Any attempt to study the separate roles of these processes would require access to fixed points in the bone tissue (for example, metal indicators), or else the use of histologic methods such as bone labeling. A knowledge of these separate processes in bone tissue movement is essential for a proper understanding of growth events and the effects of various forms of treatment. An orthopedic force or pathologic fusion of sutures, for example, may prevent normal growth through displacement but need not necessarily prevent drift from continuing or even increasing, to compensate for this absence of displacement growth.

It is important to note that the vertical growth of the alveolar process is rapid during tooth eruption and exceeds the lowering of the roof of the palate threefold.

The transversal growth occurs by separation of the two maxillary bodies in the median suture, i.e. lateral displacement, and bone resorption on the lateral walls of the nasal cavity. During tooth eruption the alveolar process increases in transversal dimension due to the buccal eruption path of the premolars and molars.

Growth of the mandible

Like the nasomaxillary complex, the mandible grows forward and downward mainly as a result of displacement (both primary and secondary) of the whole bone. This creates the conditions for a simultaneous growth in the size of the bone in the opposite direction, including a lengthening of the basal arch at the condyle. Deposition thus occurs on the posterior margin of the ramus, with simultaneous bone resorption along its anterior contours.

Because of its early fusion, the mandibular symphysis plays little part in the postnatal growth in the width. As the two rami have a diverging V-shape, the growth in width will occur, due to the V-principle. A complex sequence of remodeling changes takes place during the growth of the mandibular body (18). A buccal drift of the mandibular body is seen as bone is added on the buccal side, with corresponding resorption and endosteal bone formation on the lingual side. Our own studies, placing fixtures in jaws of growing pigs, are clearly in agreement with these principles (20).

Displacement of the mandible is associated with a rotation, depending on the direction of the condylar growth. Anterior (forward) rotation will take place in subjects with an upward and forward direction of condylar growth, whereas in subjects with predominantly backward direction of the condylar growth the mandible will rotate in a posterior (backward) direction (21). Coincident remodeling along the inferior margin of the mandible reduces the apparent effect of this rotation on the facial morphology. This is especially true in subjects

with an anterior rotation pattern, in whom about half of the mandibular rotation is masked in this manner.

The mechanism underlying the rotation of the jaws is obscure. It was previously believed that growth of the condylar cartilage was the cause of mandibular displacement, on the basis of the assumption that the condyles govern the growth of the entire mandile ('push' theory). However, they are not a type of 'control center' with direct control over the growth fields but function only locally. According to these growth theories, mandibular displacement is the primary process and results from enlargement of the soft tissues (22). The type of rotation (upward or downward) is determined by those structures that start the displacement of the mandible, and the direction of condylar growth thus is a secondary phenomenon to adapt for the space in the temporomandibular joint region ('pull' theory).

Growth rate

The basic pattern of growth is further complicated in that the rate at which adult size is achieved is not constant. The speed varies at different times during the development of the child. Recent studies suggest that the process of facial growth and changes in the dental arches continue to a much later age than had previously been realized (23). The changes observed are small, affecting both the size and the shape of the face and the dentition.

Regulation mechanisms

Postnatal growth processes occur within their individual structures to various extents at different intervals and in various directions. The control of such a complex morphogenesis requires a precise biologic regulator mechanism for initiating and directing the growth mechanisms, growth pattern, and growth rate.

The regularity with which the child's face grows, with maintenance of the general morphology and resemblance to relatives, suggests that genetic factors have a strong influence on craniofacial growth. Craniofacial morphology is now considered to be multifactorial; that is, facial development is influenced by several genes together with various environmental factors.

Even in the 1940s, Sicher (24), among others, was still claiming that craniofacial growth as a whole was the result of innate genetic formation in the skeletal tissues. The importance of environmental factors, such as pressure from adjacent organs, was reduced to a certain influence on the shape of the bone during development.

As this view was incompatible with several clinical observations, Scott (9) limited the heredity and expansive growth of the osteogenic tissues to the periosteum and chondral structures. In contrast to Sicher, he considered suture growth to be a response to growth in adjacent structures, which carried the genetic information (epigenetic regulation). The displacement of the bones of the cerebral cranium was now considered to be secondary to the morphogenetic requirements of the brain mass, whereas the growth of the middle face was mainly the result of growth of the chondrocranium—above all the nasal septum—which pushed the bones away from the structures in the cranial base. Similarly, the growth of the mandible was considered to be the result of the autonomic expansive growth of the condylar cartilage.

On the basis of new information concerning the physiology of bone, Moss (10) launched a completely new theory on the control of craniofacial growth. The osteogenic tissue was deprived of all innate genetic control ('bone has no genes'), and the theory of the functional matrix was formulated instead. The craniofacial complex is regarded as a structure with certain functions, classified as functional cranial components. These consist of a functional matrix, comprising the tissues and cavities that carry out the function as such, and a skeletal unit, consisting of bone, cartilage, and tendons, which protects and supports this matrix. Parts of the functional matrix can be shown to have direct influence on the bone through the periosteum—for example, muscle function in muscle insertions and the teeth in the alveolar process—and are therefore referred to as the periosteal matrix. This control of osteogenesis is a local process comprising remodeling and drift and is limited to changes in the size and shape of small skeletal units. A broader effect is achieved by the tissues and functional cavities surrounded by capsules, summarized by the term capsular matrix—for example, the brain mass and respiratory function—which produce the movement of the whole bone classified as displacement.

Other hypotheses assume that postnatal facial growth is controlled by a multifactorial system that is influenced by intrinsic, genetic, and local factors. According to van Limborgh (25), craniofacial morphogenesis is controlled by five different factors: intrinsic genetic factors, local and general epigenetic factors, and local and general environmental factors. According to this theory, both local and general factors can cause anomalies.

The intrinsic genetic factors exert their influence within the cells in which they are contained and determine the characteristics of cells and tissues (cranial differentiation). Epigenetic factors are those that are determined genetically but are effective outside the cells and tissues in which they are produced. According to van Limborgh, these factors can have an effect on the adjacent structures such as local epigenetic factors (for example, embryonic induction influences) or have a distant influence such as general epigenetic factors (for example, sex and growth hormones). The local environmental factors (such as muscular force) are of much greater relevance to the postnatal craniofacial growth

control than the general factors (for example, food, oxygen supply).

On the basis of studies on growth in the rat, Petrovic et al. (26) have developed a cybernetic model (direction and control of a course of events), illustrating the complexities of multifactorial relationships involved in the growth process. In sum, the physiologic effect of factors controlling the facial growth is not limited to simple commands but includes relays, implying interactions and feedback loops as follows: 1) all of them form a structured system, a servosystem, in which the position of occlusal adjustment plays the role of the peripheral 'comparator'; 2) the sagittal position of the upper dental arch is the 'constant changing reference input', controlled by somatotrophin and somatomedin and by septal cartilage growth and by tongue growth; 3) the sagittal position of the lower dental arch is, cybernetically, the controlled variable; and 4) signals originating from the 'peripheral comparator' of the servosystem produce an increased postural activity of the lateral pterygoid muscle and of some other masticatory muscles, enabling the lower dental arch to adjust to the optimal occlusal position. The increased muscle activity hence induces a posterior growth rotation of the mandible and, secondly, a supplementary growth rate of the condyle.

Conclusion

It can be stated that, although our knowledge of craniofacial growth and development under normal and pathologic conditions has greatly increased during recent times, it is still incomplete and often consists of disconnected islands of information. An example of this is the absence of an explanation for the regulation of craniofacial growth. We should also remember that the mechanism underlying tooth eruption is still obscure.

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