Craniofacial Change and Non-Change After Experimental Surgery in Young and Adult Animals

Bernard G. Sarnat

A review of various animal experiments related to growth of the cranium and face, clarifying basic relationships between both the natural and the extrinsic influences on the processes of growth and remodeling of these structures

KEY WORDS: · GROWTH · SURGICAL EXPERIMENTATION ·

In July, 1963, an article titled *Postnatal growth of the upper face: some experimental considerations* appeared in *the Angle Orthodontist* (SARNAT 1963). The purpose of that report was to review and summarize selected information obtained as a result of animal experimentation on the following subjects in my laboratories:

I. Methods of assessing growth of bones.
II. Growth at several facial sutures in the young monkey.
III. Growth at the frontonasal suture in the young rabbit.
IV. Growth at the frontonasal suture region after extirpation of the frontonasal suture in the young rabbit.
V. Palatal and facial growth after extirpation of the median and transpalatine sutures in the young monkey.
VI. Growth of the young rabbit snout after extirpation of the septovomeral region.
VII. Facial and neurocranial growth after resection of the mandibular condyle in the young monkey.

The methods employed in the above series of animal experiments on postnatal growth of the upper face were gross studies, some using metallic implants and serial roentgenography. An increase in the separation between implants on opposite sides

Author Address:
Dr. Bernard G. Sarnat
Suite 426
9735 Wilshire Boulevard
Beverly Hills, CA 90212-2150

Dr. Sarnat is in the private practice of Plastic Surgery and Senior Research Scientist, Research Institute and Formerly Chief, Division of Plastic Surgery at Cedars-Sinai Medical Center; Adjunct Professor, Section of Oral Biology, School of Dentistry; Adjunct Professor, Division of Plastic Surgery, School of Medicine and Dental Research Institute, University of California at Los Angeles, California (UCLA). He holds an M.D. degree from the University of Chicago and M.S. and D.D.S. degrees from the University of Illinois. He is a Diplomate of the American Board of Plastic Surgery.

of a suture was taken as an indication of sutural bone growth. In attempts to arrest growth, the frontonasal and the median and transpalatine sutures were resected.

Information was obtained about total amount, rate, and direction of bone growth, highlighting periods of maximum and minimum growth activity. Many instances of differential sutural growth were demonstrated.

Differences were observed in growth between five monkey facial sutures, and also the same suture at different times. Growth was greatest at the zygomaticotemporal suture and least at the premaxillomaxillary suture.

The frontonasal suture of the rabbit was a site of rapid growth, with the nasal bone side growing about twice as fast as the frontal bone side. In all of the animals, the rate of sutural growth decreased with increase in age.

No gross regional growth disturbance was noted after resection of the frontonasal, median or transpalatine sutures. The gross size and shape of the snout in the rabbits in which the frontonasal suture had been either bilaterally or unilaterally extirpated were similar to those of the control rabbits. No lateral deviation of the snout was observed in the rabbits with unilateral extirpation. The snout was not less long in the rabbits after bilateral extirpation of the frontonasal suture; rather, it was found that longitudinal growth as measured by increase in separation of implants was essentially the same as in the control animals.

The channel width increased as longitudinal growth proceeded. Thus, a wedging or expansive force between frontal and nasal bones by the frontonasal suture apparently was not necessary for growth to occur in that region. What, then, is the growth impetus at this suture?

After extirpation of the median and transpalatine sutures on monkeys, the median palatine suture reformed in an eccentric position in a number of instances. The operated and unoperated sides of the skulls were compared with each other, and skulls of operated monkeys were compared with unoperated controls.

No significant gross difference was noted in growth and development of the hard palate, maxillary arch, mandibular arch, maxillomandibular relationship (arch size and form, occlusion, and tooth relationships). It was concluded that bone growth which occurred at sutures was secondary or compensatory to some other factor. This was reviewed recently in greater detail (Sarnat 1986b).

Resection of the septovomeral region or the mandibular condyle, however, produced profound facial changes.

Modes of Growth

The three modes of postnatal growth and change of bone(s) may be classified broadly as cartilaginous, sutural, and appositional/resorptive (remodeling). In addition, changes in size and shape of cavities are important in determining bone form, particularly in the skull.

A basic concept of physiology is that bone is in a continuous state of flux, apposition and resorption, throughout life. Consequently, skeletal size and shape are always subject to change. When the skeletal mass increases (positive growth), as in children. apposition is more active than resorption. Cartilaginous and sutural growth are both active. When the skeletal mass is constant (neutral growth), as in the middle years, apposition and resorption are still active in approximate equilibrium. Cartilaginous and sutural growth have ceased. When the skeletal mass decreases (negative growth), as in old age, resorption is more active than apposition.

The concept of negative growth is not new (THOMPSON 1968). Recent publications include more detailed information (DIXON AND SARNAT 1982, 1985).

The purpose of the present report and summary is to update the 1963 report with additional findings in follow-up experiments on both young and adult animals under both normal and abnormal conditions (Table 1).

Table 1

Differential Craniofacial Skeletal Changes after Postnatal Experimental Surgery in Young and Adult Animals

Procedure	Craniofacial Change? Young	Adult
Extirpation of cartilaginous nasal septum	yes	no
Resection of mandibular condyle	yes	yes
Yellow phosphorus added to diet	yes	—
Extirpation of frontonasal, median, and transpalatine sutures	no	—
Decrease in orbital contents	yes	no
Increase in ocular volume	yes	no
Extraction of teeth adjacent to maxillary sinus	—	yes

These studies are new, all directed toward attaining greater knowledge and understanding of some of the complex processes of craniofacial change. The following will be presented:

I. Cartilaginous growth.
  A. The face and jaws after surgical experimentation with the septovomeral region in both young and adult rabbits (SARNAT 1970).
  B. Facial changes after resection of the mandibular condyle in both young and adult monkeys (SARNAT AND MUCHNIC 1971).
  C. Changes in endochondral growth of the base of the skull and long bones in young rats and rabbits with yellow phosphorus added to the diet (ADAMS AND SARNAT 1940).

II. Sutural growth: Sutural growth of the turtle plastron (SARNAT AND MCNABB 1981)

III. Appositional and resorptive bone growth (remodeling) — growth pattern of the rabbit nasal bone region (SARNAT AND SELMAN 1978).

IV. Change in size and shape of cavities.
  A. The orbit and eye: Experiments affecting volume in both young and adult rabbits (SARNAT 1981).
  B. Change of volume of the maxillary sinus in the adult dog after extraction of adjacent teeth (ROSEN AND SARNAT 1955).

I. Cartilaginous Growth

Septovomeral Growth and Resection

To study the effects of different degrees of injury to the septovomeral region in the rabbit snout, varying amounts of the septovomeral joint, nasal septum, vomer, and maxillary process of the premaxilla were extirpated (SARNAT AND WEXLER 1966). Although subsequent experiments were limited to the cartilaginous nasal septum, the suggestion was made to pursue experiments on the role of the vomer in the downward and forward growth of the maxillae with deepening of the nasal fossae.

About four months after resection of the cartilaginous nasal septum and associated mucoperichondrium in young rabbits, the snout was not as long and not as large in the experimental animals (Fig. 1C) as in the controls (Fig. 1A). At the posterior border of the septal defect, there was a strong downward anterior deflection of the nasal bones, in contrast to the smoothly curved dorsum of the control animals.

This raised questions about the role of the nasal septum and its sites of activity in relation to the growth and form of the snout. Was the snout deformity after resection of nasal septum in young rabbits a result of either lack of growth or lack of support?

In a different experiment the nasal septum was resected in adult rabbits (SARNAT AND WEXLER 1967). After a postoperative survival of 16 weeks, study of the dissected skulls showed a large defect but no deformity of the snout (Fig. 1B).

These experiments suggest that: 1) the deformity of the snout after resection of the nasal septum in young rabbits is the result of a lack of growth rather than a lack of support by the nasal septum, and 2) septal growth may be the factor influencing growth at the frontonasal suture.

Autoradiographic studies with tritiated thymidine were undertaken to determine normal levels of proliferative activity in the cartilaginous nasal septum of the young rabbit (LONG, GREULICH, AND SARNAT 1968). A three-week-old Dutch rabbit was given a single intraperitoneal injection of 258μCi of tritiated thymidine and killed one hour later. The head was divided parasagittally and fixed in Hollande's modification of Bouin's fluid. The cartilaginous nasal septum region was embedded in paraffin and parasagittal sections 6μ thick were cut for autoradiographic study.

A complete section approximating the midline was selected for intensive microscopic study. Under oil immersion (1000×) the field of view was subdivided by use of an ocular grid, and all labeled and unlabeled nuclei within successive fields were counted. Regional zones of the specimen were defined arbitrarily, and labeling indexes were determined for each region (Fig. 2). Cell counts in some regions were made on a limited sampling basis but always included 1000 or more nuclei to provide an adequate basis for comparison with other regions. A total sample of 78,125 cells, 1031 of which were labeled, was observed in the specimen.

The posterior aspect of the septum is directly contiguous with the endochondral growth site of the septoethmoidal junction; thus, the increased proliferative activity in zones 2, 3, 6, 8, and 9 may reflect endochondral growth in this region. Endochondral ossification, however, did not occur at the anterior or anteroinferior aspects of the septum (zones 1, 4, 5, 7, and 11), in which comparably elevated proliferative activity was also observed.

In summary, active differential proliferation of the cellular component of the cartilaginous nasal septum was noted in the growing rabbit, and this proliferation was most pronounced in the anteroinferior and posterior zones. The increase in cellular mass presumably contributed to the growth of the cartilaginous nasal septum as a whole.

Comment

Does growth of the nasal septum drive the snout forward, with sutural accommodation of the related bones?

Did resection of a large part of the septum trigger closure or cessation of activity of the suture complex in the growing nasal bone region?

Does normal interaction of the various growth patterns in a bone complex require maintenance of normal spatial relations of the individual units in the complex?

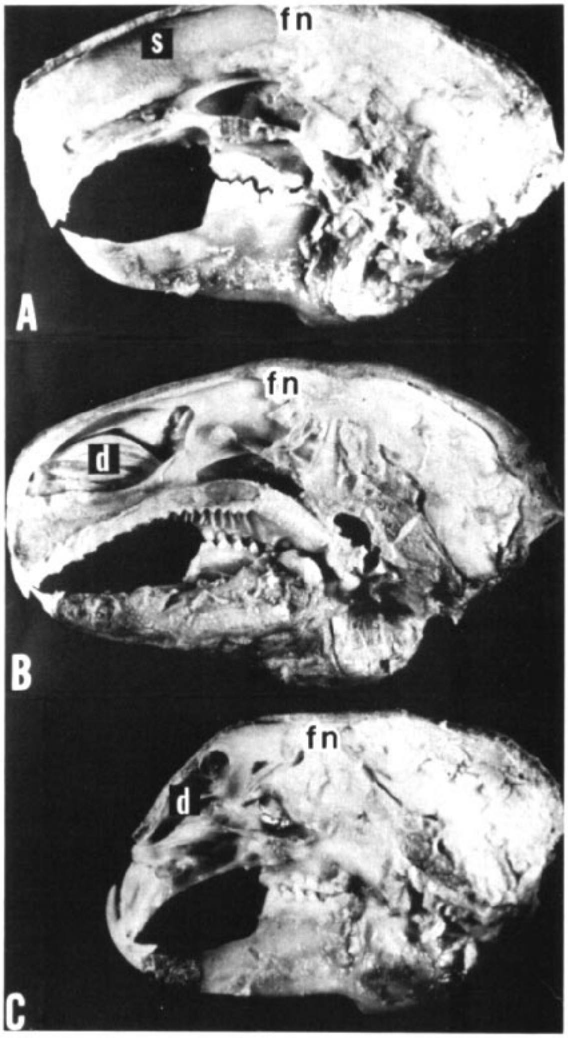


Figure 1

Postmortem photographs of the right halves of left parasagittally sectioned rabbit skulls.
d = surgical defect; s = septum; fn = frontonasal suture.

A **An unoperated control animal. Cartilaginous nasal septum not resected.**

B **Adult animal; cartilaginous nasal septum resected. Compare with A, and note similarities of size, shape, regularity and relationship of upper and lower incisors. Also note that the dorsal curvature is not affected by the underlying septal defect, d.**

C **Young animal; cartilaginous nasal septum resected at 3 weeks of age, killed at about four months of age. Note the shorter snout, with the deficiency beginning at the septal defect d.**

(from Sarnat and Wexler, 1967)

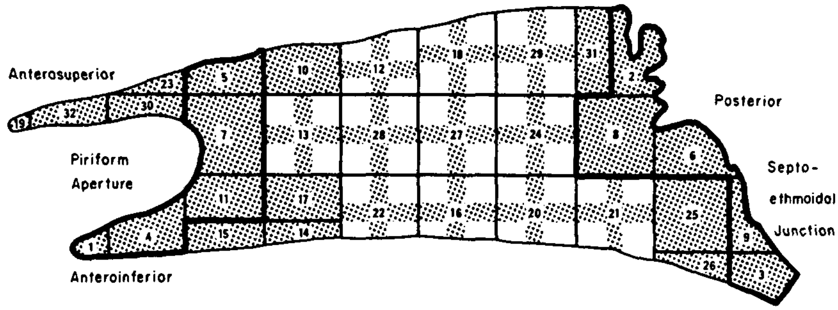


Figure 2

Diagrammatic representation of a longitudinal section of the cartilaginous nasal septum of a three-week-old Dutch rabbit after intraperitoneal injection of tritiated thymidine. The various zones are numbered according to their differential activity (labeling index: zone 1 = 3.36%, zone 32 = 0.35%). Anteroinferior and posterior areas (heavily outlined) were the most active. Cell counts were made in the stippled areas.

(from Long, Gruelich and Sarnat 1968)

Further investigation is indicated, such as a study of frontonasal sutural growth after septal resection.

The rabbit was selected deliberately because of the rapid growth of its snout. Similar experiments of septal resection in primates with principally a horizontal component of growth (baboon) resulted in somewhat comparable findings. Experiments in primates with a more active vertical component of growth (chimpanzee), as in humans, have not resulted in comparable findings (SIEGEL 1978).

It would be advisable, nevertheless, that children who have sustained injuries to the cartilaginous septum and nose be treated and observed not only for immediate effects but also for later septal and nasal deformities.

Condyle Resection

Facial changes after resection of the mandibular condyle were studied in both young and adult monkeys.

The condylar process of the mandible grows by the replacement of cartilage by bone (SARNAT 1986A). Microscopic examination of a growing condyle reveals the presence of three zones: 1) chondrogenic, 2) cartilaginous, and 3) osteogenic. The condyle is capped not by hyaline cartilage but by a thin layer of avasçular fibrous tissue that contains a few cartilage cells. The inner layer of this covering is chrondrogenic, giving rise to the hyaline cartilage cells that constitute the second zone. In the third zone cartilage destruction and formation of bone around the cartilage scaffolding take place.

This cartilage is not a derivative of a cartilaginous model, as are the epiphyseal and articular cartilages in long bones which are derived from the primary cartilaginous skeleton. The condylar cartilage of the mandible can be classified as a secondary cartilage, with appositional and interstitial growth of the cartilaginous portion of the condyle contributing directly to the increase of mandibular height and length.

However, the condylar cartilage is not homologous to an epiphyseal cartilage because it is not interposed between two bony parts, and because the free surface bounding the articular space is covered by fibrous tissue, it is not homologous to articular cartilage. Defects in the articular surface of the condyle are repaired more rapidly and completely than similar injuries in long bones, a difference related to the presence of the fibrous tissue rather than the hyaline cartilage covering.

After unilateral mandibular condylectomy in both young (Fig. 3) and adult (Fig. 4) monkeys, the operated side, showed a lesser total facial height, a shorter ramus, a coronoid process extending above the zygomatic arch, and an occlusal plane about level with (instead of considerably lower than) the zygomatic arch (Sarnat and Muchnic 1971).

Since the facial skeletal changes were similar, but not the same, following condylectomy in both young and adult monkeys, it seems that removal of the condylar growth site in the young monkey is not the principal factor responsible for the changes. Rather, the changes are probably secondary to disruption of normal temporomandibular joint function, including alteration of sensory receptors.

The direction and amount of muscle pull with altered position and motion of the mandible were modified by loss of the anatomical and physiological integrity of the temporomandibular joint. These changes in function include loss of function of the lateral pterygoid muscle, altered function of the medial pterygoid, masseter, temporalis, and suprahyoid muscles, and establishment of a false joint. The remodeling of the ramus and adjacent bony structures, with changes in the bony trabecular pattern, can be expected to follow these functional alterations (Herzberg and Sarnat 1962).

Growth of bone occurs at the superoposterior surfaces of the mandible, including the condyle (Sarnat 1986a). There has been much discussion about whether the mandibular condyle is either a primary or a secondary site of growth.

In this regard, an ingenious experiment was recently reported which tested the thesis of whether bone growth would occur without a functional soft tissue matrix. Rat heads were transplanted to recipient animals and bone growth was observed! (Hirayabashi et al. 1988).

Condylectomy experiments in both the young and adult monkeys have demonstrated extreme loss of bone. However, these experiments do not prove that the condyle is not a growth site.

Comment

The characteristic clinical and radiographic observations after a unilateral arrest of mandibular condyle growth are — a short, wide condylar process and ramus in a more anterior position than its opposite, — a relatively lower, heavier, and posteriorly directed coronoid process, — a shallow mandibular notch — and fullness of the face.

On the opposite, uninjured side, there is elongation of the body of the mandible and a flat appearance of the face and malocclusion of the teeth, with the mandible skewed toward the affected side.

With a bilateral growth arrest, the mandible is usually symmetrically underdeveloped, with the chin at about the level of the hyoid bone.

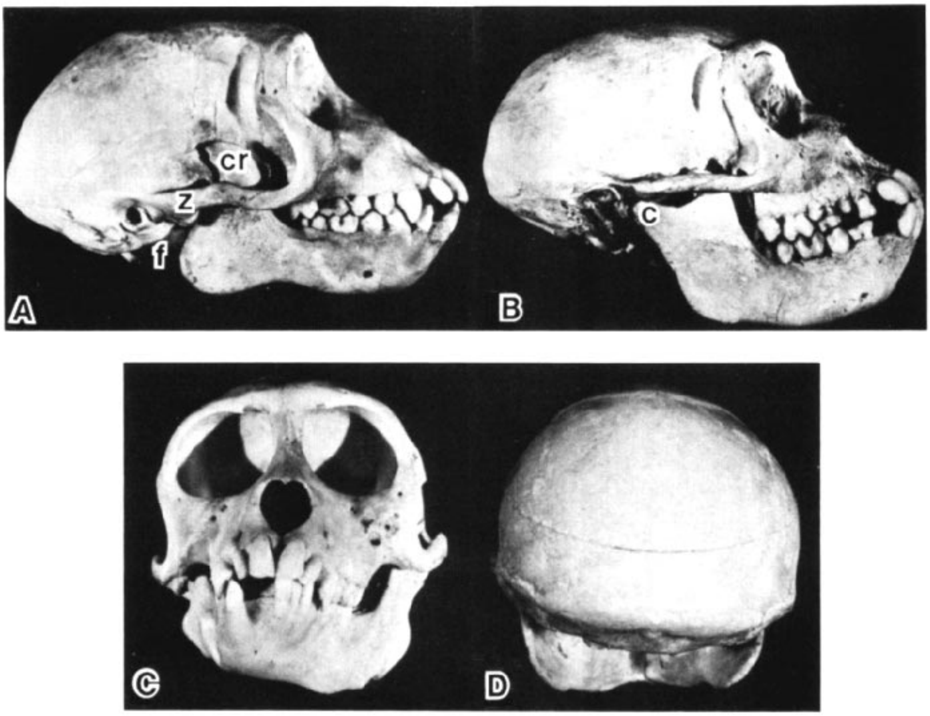


Figure 3

Skulls of two young rhesus monkeys (A, C, D) in which the right mandibular condyle was resected at about eight months of age, and B, an unoperated control.

c = condyle; Cr = coronoid process; f = false articulation; z = zygomatic arch.

A and C   Animal 1, postoperative period 29 months.

B   Control.

D   Animal 2, postoperative period 14months.

Note that the facial height in A and C is less than that of the control, B. No true condyle, fossa, or articular eminence is visible, and the coronoid process is directed more posteriorly and above the zygomatic arch. The anteriorly positioned ramus is shorter and wider, and note the position of the posterior border of the ramus relative to where the true fossa should be. The mandibular angle is less then 90°, the antegonial notch is accentuated, and the mandibular body is shorter. In C, note the lesser facial height on the operated (right) side, the relatively lower level of the zygomatic arch, and the shorter ramus.

In the posterior view of D, note the higher level of the mandible on the operated (right) side. *(from Sarnat 1957)*

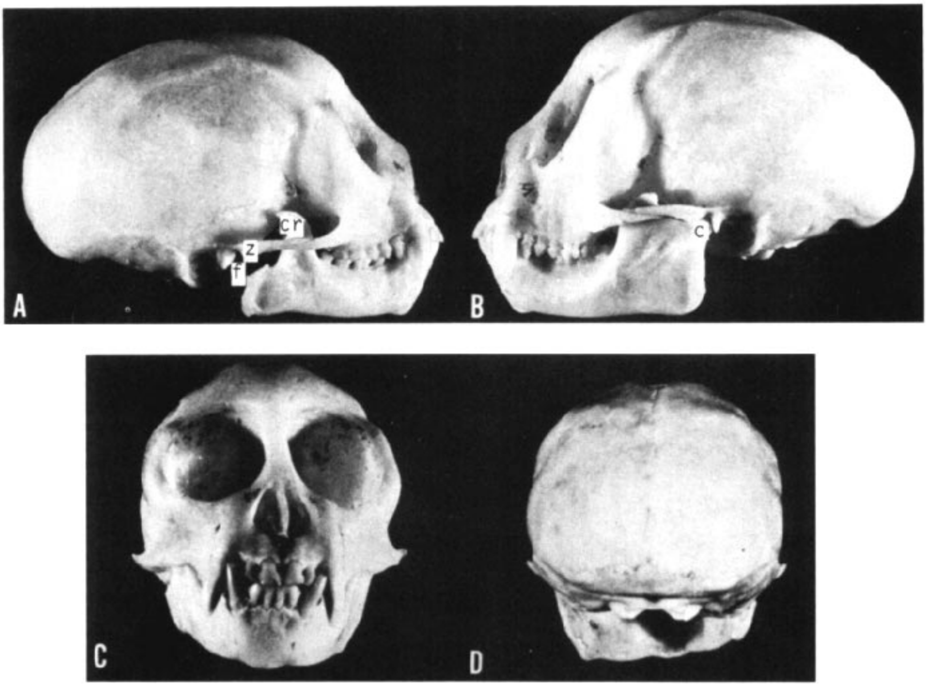


Figure 4
Skull of an adult squirrel monkey in which the right mandibular condyle was resected two years before death.

c = condyle; cr = coroniod process; f = false articulation; z = zygomatic arch.

A *Lateral view of the operated side.*

B, C, D The unoperated left side.

Note the shorter facial height on the operated right side, as well as the absence of the condyle, the shorter posterior ramus, the lack of articulation with the neurocranium, and the relatively more prominent coronoid process extending above the zygomatic arch. The higher level of the mandible on the operated right side may be seen in C and D.

Compare these results with those seen in Figure 3, of two young monkeys in which a mandibular condyle was resected. *(from Sarnat and Muchnic 1971)*

Clinically, patients with retarded mandibular development may have disturbances in the eruption and position of the teeth in the region influenced by the affected ramus. This is true for at least two reasons. First, the mandibular ramus does not increase in height sufficiently to open in harmony with concomitant growth of the alveolar processes, and second, since resorption of the anterior border of the ramus is decreased, the last molars remain within the ramus.

After either a severe fracture dislocation or a condylectomy, restoration of the anatomic, let alone the physiologic, integrity of this region may contribute to a more desirable clinical result (Sarnat and Laskin 1980).

Skull Base

Changes in endochondral growth of the base of the skull and long bones (and teeth) were studied in young rats and rabbits with yellow phosphorus added to their diet (Adams and Sarnat 1940). Thirty-four rabbits and 24 rats, 28-65 days of age, were used for experimental and control purposes. A 0.6mg yellow phosphorus pill was given to the rabbits daily, and 0.01-0.4% yellow phosphorus was added to the cod liver oil of the standard diet for the rats during the first, third, and fifth weeks of the experiment.

In the experimental animals the length of the long bones and skulls were found to be less than in the control animals (Fig. 5). A phosphorus band in the metaphyses of the growing long bones and the basal bones of the skull (synchondroses — bones are joined by cartilage) was visible as a zone of increased density on the radiographs. This same region was observed in the sectioned specimens both grossly and histologically. The effect was believed to be due to a diminution in the resorption of cartilage matrix and bone during endochondral bone formation.

No changes were found on the radiographs of the growing teeth. Histologically, zones of disturbed mineralization were found in the dentin of the rat incisors and molars that corresponded to the period of ingestion of the drug. Yellow phosphorus could be used for radiographic measurement of the rate of growth between the phosphorus bands of selected bones but not of teeth. This difference is attributed to the dual capacity of bone for both deposition and resorption, whereas teeth usually have the capacity for deposition only.

Comment

Endochondral growth of the rat tibia was found to be considerably greater than endochondral growth at the base of the skull (Fig. 5). In addition, the toxic affects of yellow phosphorus on endochondral bone growth were demonstrated, in that the length of both the tibia and skull was less in the experimental animals than in the control animals.

The radiopaque phosphorus bands could be compared with lines of arrested growth.

II. Sutural Growth

The turtle plastron provides a model for the study of sutural growth. Sutures are synarthroses, with the bones joined by connective tissue, and except for the turtle shell, sutural bone growth is found only in the skull.

The periodic increments and total amount of bone growth at the hyohypoplastron (length) and interhyoplastron (width) sutures were investigated in 23 turtles from 233 to 1154 days of age by means of serial radiographic studies of the increase in separation of

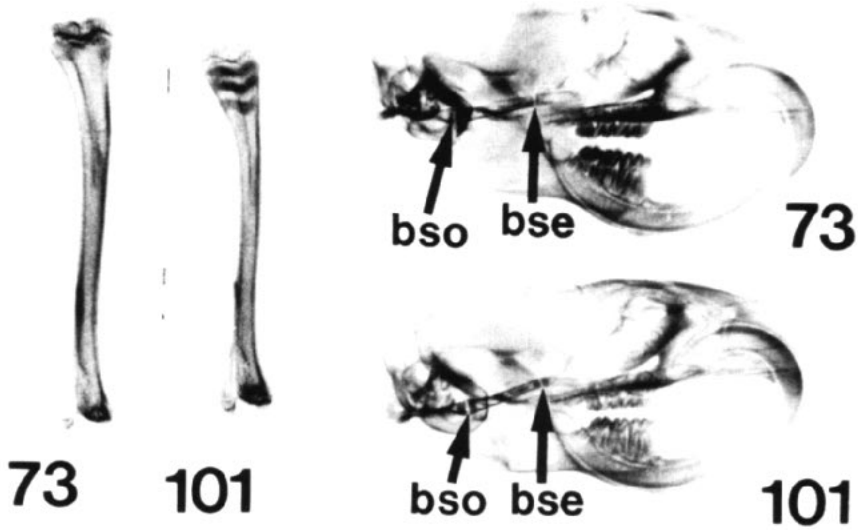


Figure 5
Radiographs of tibiae and midsagittally sectioned skulls of rat No.73 (normal) and rat No. 101, for which 0.01% yellow phosphorus was added to the cod liver oil of the diet during the first, third, and fifth weeks of the experiment. Both animals were killed at the end of the sixth week of the experiment. Three dense metaphyseal bands corresponding to the periods of ingestion of yellow phosphorus are present in the proximal end of the tibia of animal No. 101. Increased density is visible on both sides of the basispheno-occipital (bso) and basispheno-presphenoid (bse) junctions. No radiographic changes are visible in incisors or molars.
Note the following examples of differential growth: the distances between the radiopaque bands in the tibia are different; the tibia of the control animal is longer than that of the experimental animal; the radiopaque regions at the base of the skull appear as one rather than three bands because of the slower rate of growth, about one-sixth that of the tibia; and the skull of the control animal is longer than that of the experimental animal.

(modified from Adams and Sarnat 1940)

radiopaque implants on either side of the selected sutures (Sarnat and McNabb 1981). The turtles were maintained in aquaria under constant laboratory conditions (16 hours of artificial light, 8 hours of darkness; temperature 24°-27°C; relative humidity 30%; feeding twice weekly).

Mean sutural bone growth was greatest in the 233- to 317-day period and decelerated thereafter in each successive period. In the 606- to 786-day period mean bone growth at the hyohypoplastron suture was about 25%-35% of that of the earliest period, and at the interhyoplastron suture mean bone growth was about 40% of that of the earliest period.

Comparison of width (midsagittal) versus length (Hyohypoplastron) sutures showed significantly greater growth in width than in length (Fig. 6). However, more sutures contribute to growth in length of the turtle shell than to width.

No differences were noted between growth in the summer and in winter, when turtles in certain natural environments go into winter dormancy. Increase in the size of the turtle shell may be related to increase in the size of the contents, as increase in size of the neurocranium and orbit are related to increase in size of their contents.

III. Apposition and Resorption

Appositional and resorptive (remodeling) bone growth were studied in the differential growth activity at several borders of the nasal bone region in the rabbit (SARNAT AND SELMAN 1978). Two radiopaque implants were inserted into each left and right nasal bone in five female rabbits. Ventrodorsal cephalometric radiographs were exposed in a specially designed headholder when the rabbits were 6 and 16 weeks of age (Fig. 7). Separate tracings of the images of the left and right nasal bone regions were made on matte acetate film. These tracings included the radiopaque implants (Fig. 8).

Since the implants maintained the same relation to each other in each nasal bone, they served as stable reference sites. The markers of the 16-week tracing were superimposed on the markers of the six-week tracing. The difference in the two established outlines represented the changes in size and shape in two dimensions during the 10-week period.

The mean increase (Fig. 9) was about 6.79mm at the proximal (posterior) border, 6.19mm at the distal (anterior) border, 2.73mm at the lateral border, and 1.22mm at the medial border. Thus, growth at the proximal and distal borders was approximately equal and about twice that of the lateral border and five times that of the medial border.

What factors are active to produce this differential in growth?

IV. Cavities
The Orbit

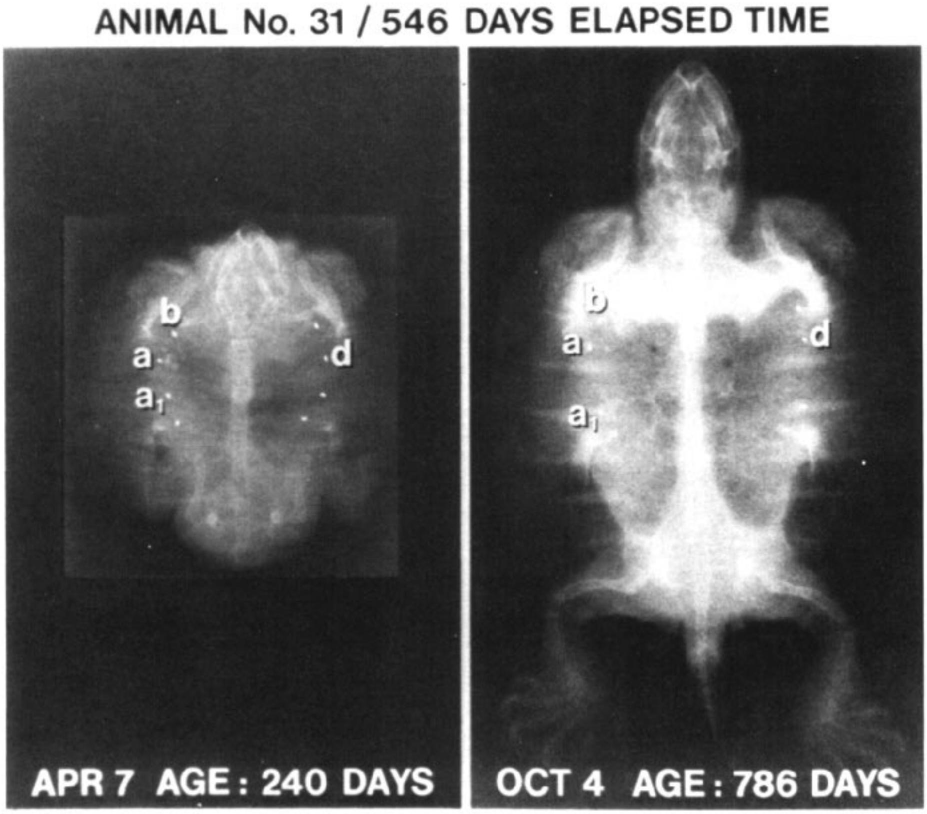
Change in size and shape of the orbit was studied in a series of experiments to determine normal orbital volume and the effects of increase or decrease of volume of the orbital contents on orbital growth in both young and adult rabbits (SARNAT 1978, 1980, 1981; SARNAT AND SHANEDLING 1970, 1972, 1974). These studies suggest that orbital volume in the young rabbit is dependent, at least in part, on the volume of the contents.

Normal orbital volume. One hundred ninety-nine postnatal volumetric determinations were made of orbits from 159 young and adult rabbits (64 New Zealand, 95 Dutch) by means of either linear measurements or removable permanent elastic rubber-base casts (SARNAT 1980). The volumes were calculated from either formulae or from the weight and specific gravity of the orbital casts.

Orbital volume in the New Zealand albino rabbits ranged from 0.7ml at 14 days to 7.8ml at 302 days of age. By about 180 days of age the orbital volume neared its maximum at about 6.5ml, about nine times its size at 14 days of age.

Orbital volume in the Dutch rabbits ranged from 3.6ml at 98 days to 5.8ml at 540 days of age, and was not as large as that of the New Zealand rabbit. By about 100 days, the Dutch rabbit orbital volume reached its maximum of about 5ml, about 25% larger than at 100 days of age.

Acceleration of increase in volume. Orbital volume was increased in this experiment by periodically increasing the volume of the bulb (SARNAT AND SHANEDLING 1974). Eighteen four-week-old 220-420gm Dutch rabbits were separated



Distance Between Implants			Difference
ad	22.1 mm	29.8 mm	7.7 mm
aa_1	4.9 mm	9.2 mm	4.3 mm
ab	4.2 mm	4.2 mm	0

Figure 6

Dorsoventral radiographs of turtle No. 31 at 240 and 786 days of age.

Two radiopaque implants were inserted into each left (a and b) and right hypoplastron, and each left (a_1) and right hyohypoplastron bones at 233 days of age. Note the greater increase in the separation of implants in width (a-d, 7.7mm at the midsagittal suture), than in length (a-a_1, 4.3mm at the hyohypoplastron suture).

More than one suture contributed to the overall increase in length. Note the lack of increase in separation between implants a and b, which were in the same bone during the 546-day period, demonstrating that there was no interstitial growth of bone. *(from Sarnat 1984)*

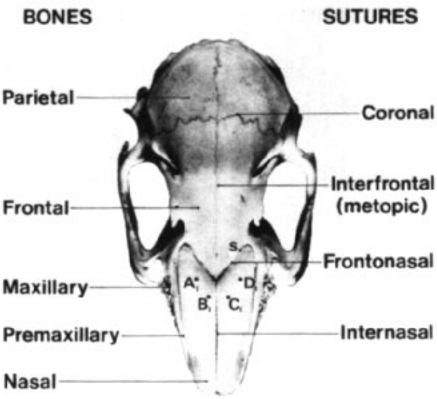


Figure 7
Dorsal view of rabbit skull showing sites of implantation of dental amalgam in right (A_1, B_1) and left (C_1, D_1) nasal bones. S = a point on the frontonasal suture.
(from Sarnat and Selman 1978)

into three groups. Silicone was injected into the right eye in one group, into the left eye in another group, and the third (control) group was not injected. In an 11-week period the total amount of ten silicone injections into each eye ranged from 1.2 to 1.6ml.

After the rabbits were killed, elastic rubber-base casts were made of the cleaned orbits and the volume calculated from the weight and specific gravity of the orbital cast.

In the six control animals the difference between the right and left orbital volumes ranged from 0.1 to 0.2ml (2.4% to 4.7%). When either the left or right eye was injected with silicone the difference in orbital volumes between the injected and non-injected sides ranged from 0.6 to 0ml (14.6% to 0%). The difference of the averages was 0.3ml (8.5%). Thus, periodic intrabulbar injection of silicone in the growing rabbit did result in a significant differential in the increase of orbital volume.

Deceleration of increase in volume. This part of the investigation was conducted to determine whether there was a correlation between orbital volume and decreased intraorbital mass (Sarnat and Shanedling 1970, 1972).

In three groups of rabbits seven to 42 days of age, varying amounts of intraorbital tissue were removed unilaterally. Each rabbit was secured on an operating board with the right side of the face exposed. This was cleansed with an antiseptic solution, and the area draped. After injection of a local anesthetic agent and intravenous pentobarbital sodium, the eyelids were separated manually. The surgical procedure was performed unilaterally, with the opposite unoperated on side used for comparison. In one group (22 rabbits) the intraocular contents, but not the cornea and sclera, were extracted (evisceration); in a second group of 23, the eye was removed (enucleation); and in a third group of 6 rabbits the contents of the orbit were removed (exenteration) (Fig. 10).

Postoperative survival ranged from one to 283 days. A removable permanent elastic rubber-base casting was made of the cleaned orbit. Comparison of the orbital volume data after evisceration, enucleation, and exenteration showed a direct differential relation between the lack of orbital mass and the subsequent deceleration of growth of the orbit (Fig. 11). Repetition in adult rabbits, which bears further investigation, did not produce such gross results (Sarnat 1978, 1980).

Comment

Facial growth is related to orbital growth. The shape and size of the orbit result from the balance of a number of genetic and epigenetic factors which may function on a systemic, regional or local

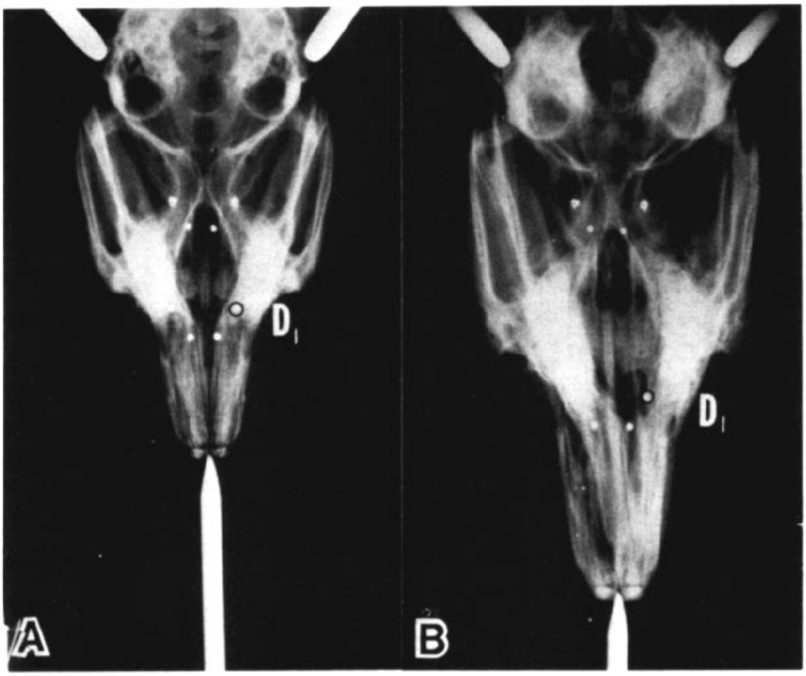


Figure 8

Ventrodorsal cephalometric radiographs of rabbit at 6 (A) and 16 (B) weeks of age. Note the increase in size and change in shape of the skull and snout. The relationship between implants in the same bone did not change during the 10-week period. Earpost tips are in the external auditory canals and anterior pin at incisal edge. D_1 is one of two implants in the left nasal bone.

(from Sarnat and Selman 1978)

basis. Is there one key factor, or are there many factors that influence orbital growth? Is there a correlation between orbital size and intraorbital mass?

Relatively rapid early growth result in diminishing *relative* capacity of the orbit and size of the eye with increase in body weight (Schultz 1940). In fetuses and newborns, the eyeball is so large in relation to the socket that it projects considerably beyond the orbital rim, exhibiting normal fetal exophthalmus. In infants, the relative size of the eyes is larger than in the adult, both in proportion to body weight and in proportion to the size of the orbit.

Scott (1953) states that the growth of the zygoma is related to the growth of the eyeball. He also points out that in humans, orbital height is 55% of its adult size at birth, 79% at three years of age, and 94% at seven years of age. In contrast, facial height is only 80% of its adult size at seven years of age.

Experimentally, orbital size in young rabbits was increased by periodic injections of silicone into the bulb. This procedure has not been used as often to

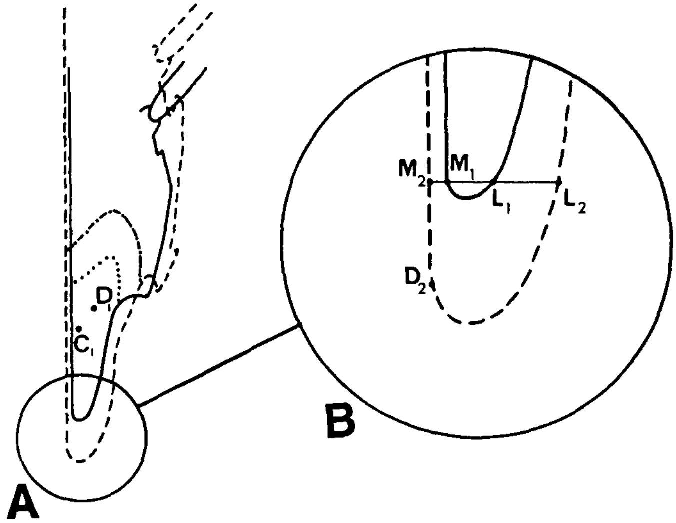


Figure 9

Tracings of the left nasal bone region taken from the ventrodorsal cephalometric radiographs in Figure 8 and superimposed on the implant images in the left nasal bone.

A: Superimposition of nasal bones on implant images, showing the growth pattern of the nasal bone region. Greatest increase in size is proximally and distally, less laterally, and least medially.

B: Enlarged area of A, to demonstrate the reference points for measurement.
M_1, most distal point on medial border at 6 weeks of age.
M_2, most distal point on medial border at 16 weeks of age.
M_2–L_2, line at right angles to medial borders.
D_2, most distal point on medial border at 16 weeks of age.
L_1, point on lateral border at 6 weeks of age.
L_2, point on lateral border at 16 weeks of age.
M_1–M_2, increase in medial dimension.
L_1–L_2, increase in lateral dimension.
M_2–D_2, increase in distal dimension.

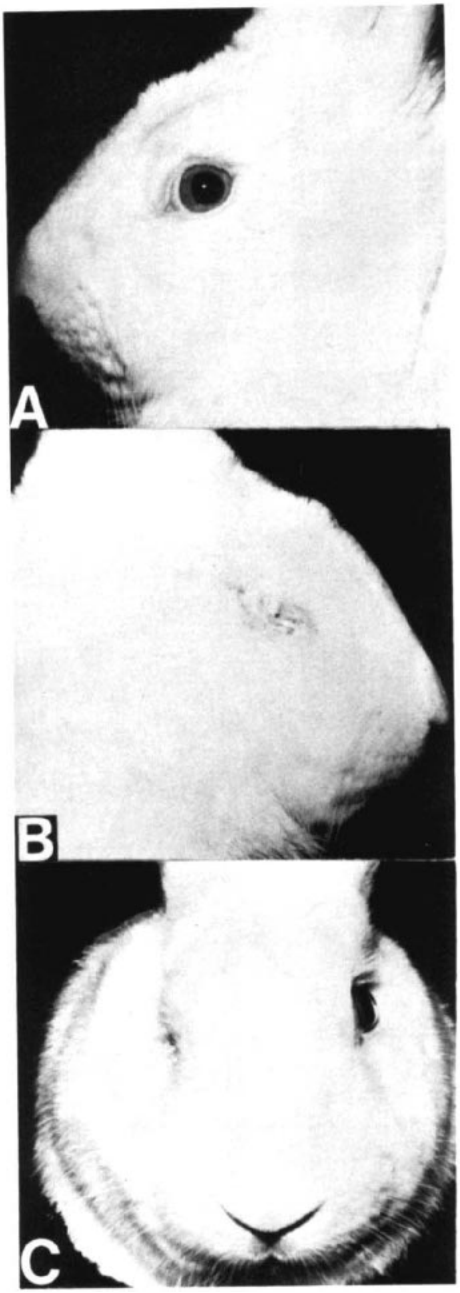
C_1, D_1: Implant images from the left nasal bone.

___ *six weeks of age;* - - - *16 weeks of age*

.... *estimated position and pattern of frontonasal suture at 6 weeks of age*

..._ *estimated position and pattern of frontonasal suture at 16 weeks of age.*

(from Sarnat and Selman 1978)



from Sarnat and Shanedling 1970

expand a bony cavity as it has for soft tissue expansion.

Although a decrease in orbital contents decelerated the increase in orbital size, it nevertheless continued to increase. Early removal of the orbital contents, as may be required because of a retinoblastoma, will result in a deceleration but not an arrest of orbital growth. Thus, placement of successively larger prostheses is probably following, rather than leading, orbital growth.

Radiation therapy could affect growth at the cranial base and lead to additional deformity of the upper face. In instances of Crouzon's and Apert's conditions, disassociation of ocular and orbital volume and growth has been reported. The eyes continue to grow without a corresponding response from the orbit and extraorbital restraints, including encroachment of the great wing of the sphenoid bone, with resultant exorbitism (Tessier 1971).

In the young, increase in size of both the neurocranium and the orbit are related in part to increase in the volume of the contents. In the adult, increase in the orbital

Figure 10
Antemortem photographs of the face of a rabbit which was killed after a postoperative survival of 246 days.

A Left lateral view.
Unoperated left orbit had a postmortem volume of 6.0ml.

B Right lateral view.
The right orbit, exenterated at 42 days of age, had a postmortem volume of 3.9ml.

C Frontal view.
Note the lesser fullness of the right orbital and periorbital regions compared to the unoperated left side.

contents did not result in an increase in orbital volume. In the case of increase in intracranial volume, the result is increased intracranial pressure with no increase in neurocranial size.

Maxillary Sinus

Change of volume of the maxillary sinus in the adult dog was studied by comparing the volumes of left and right maxillary sinuses after extraction of the teeth adjacent to the left maxillary sinus (ROSEN AND SARNAT 1955).

In ten normal adult dogs with complete dentitions, the upper left third and fourth premolars and first and second molars immediately adjacent to the maxillary sinus were extracted. The dogs were killed 6 to 12 months later and their heads immediately fixed and sectioned in the midsagittal plane. A low-fusing-point metal was poured into the maxillary sinus of each half via the ostium and the casts then delivered by removal of the medial wall of the sinus (Figs. 12 and 13). The volumes of the left and right maxillary sinuses were calculated from the weight of the casts and specific gravity of the metal. In two of the experimental animals the volumes of the left and right maxillary sinuses differed by less than 2%. In the other eight dogs the differences ranged from 4.5% to 27%. In seven of these eight animals the maxillary sinus was significantly larger on the side from which the teeth were extracted. It was therefore concluded that there was an increase in maxillary sinus volume in dogs in which maxillary teeth were extracted.

Comment

The maxillary sinus occupies the region between the palatine process of the maxilla, the facial surface, and the base of the alveolar process. Thus, it lies at the crossroads of the pathway of forces transmitted from the teeth to the cranium. Since much of the walls of the antrum, and especially the floor, are devoid of muscle attachment, most of the functional forces on this bone are dental. After the extraction of maxillary teeth, the sinus is bounded by walls in which the functional forces have been reduced. With adaptive remodeling, the bulk of the walls is lessened and the cavity thus enlarged.

— Summary —

After resection of either nasal septum or orbital tissues, increase in size is slowed considerably of both the nasal and orbital cavities. An increase in the volume of the ocular contents resulted in an increase in orbital volume. These prominent gross changes in young rabbits were not noted in adult rabbits after resection of the nasal septum, enucleation of the eye, or intrabulbar injection of silicone.

After unilateral resection of the mandibular condyle in both young and adult monkeys, an extreme unilateral facial skeletal deficiency developed. The important factor apparently was loss of anatomic and physiologic integrity of the temporomandibular joint, rather than loss of a growth site.

Sutures grow differentially. Since no local gross deformity was noted after extirpation of various sutures, it was concluded that sutures are a secondary or accommodating site of growth.

An understanding of normal and abnormal postnatal skeletal changes and nonchanges in both the young and adult animals can aid in the prevention, early recognition, and improved surgical and nonsurgical treatment of craniofacial deformities. Research findings may have important implications and applications in relation not only to the basic problem of change of bone form, but also to the clinical problems of craniofacial procedures.

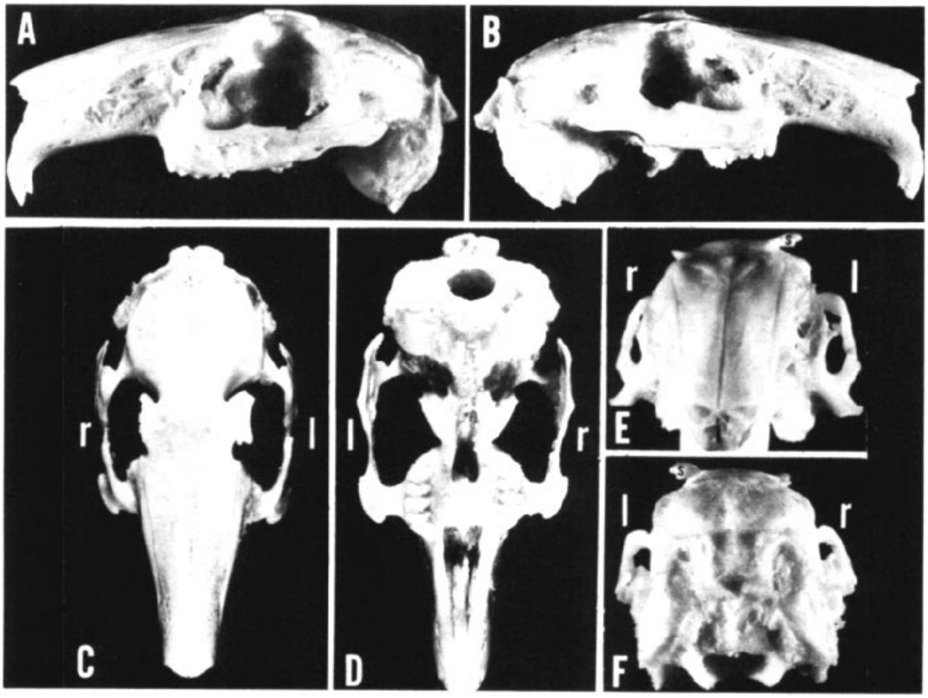


Figure 11

Photographs of the skull of a rabbit whose right eye was enucleated and and an acrylic sphere 6mm in diameter inserted at 15 days of age. The rabbit was killed after 165 days.

A—Left lateral view **B—Right lateral view**
E—Anterior view
C—Superior view **D—Inferior view** **F—Posterior view.**

The unoperated left orbit had a postmortem volume of 5.4ml, the operated right orbit only 3.8ml. The left orbital rim circumference is larger and higher, and the zygomatic arch is larger. Note that s, the supraorbital process of the unoperated left side, is higher and larger.

(from Sarnat and Shanedling 1972)

Precise analogies, however, should not be made between animals and human beings.

Change in form of the craniofacial skeleton, a three-dimensional mosaic of bones and cavities, is a result of the synchronous coordination of the differential activities at various sites at different times. The dynamics of normal and abnormal postnatal growth, change and non-change of the craniofacial skeletal system in both the young and adult is a fascinating, complex, and yet incompletely understood problem in the field of biology.

I am grateful to Lori Goldman and the Word Processing Center for devoted assistance in the preparation of this manuscript, and to Irene Petravicius, Illustration Department, School of Dentistry, UCLA.

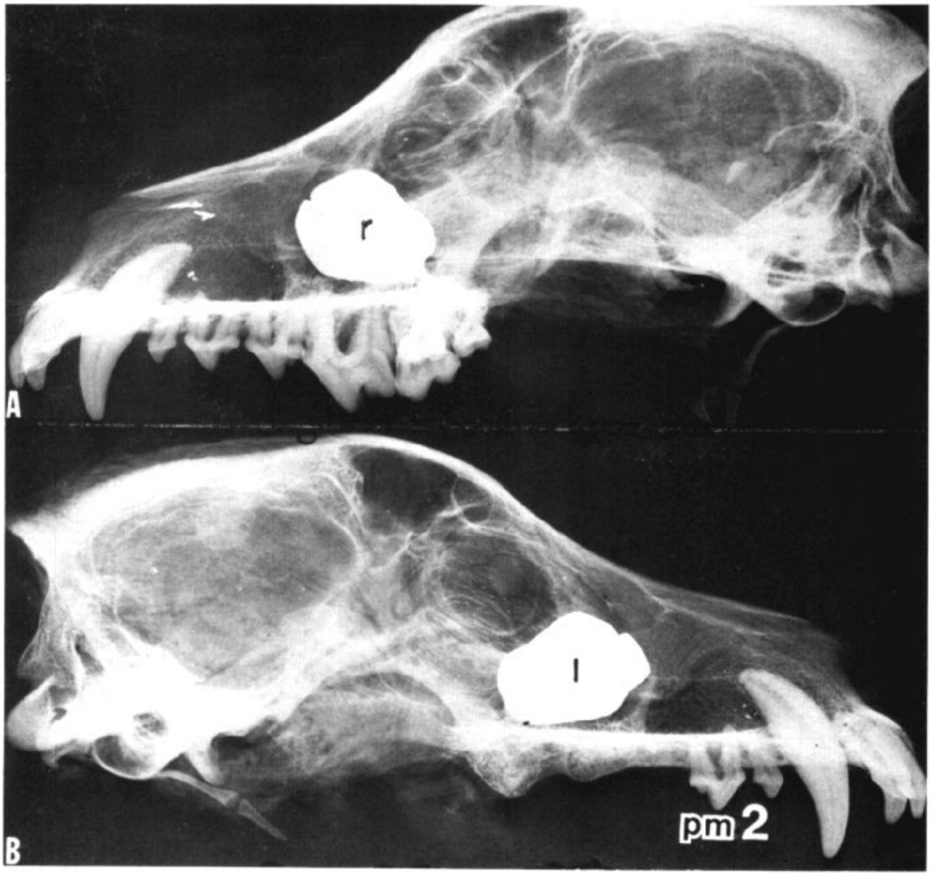


Figure 12
Radiographs of right (A) and left (B) halves of the skull of an operated dog, with metal casts reseated in the maxillary sinuses. The left maxillary third and fourth premolars and first and second molars were extracted 12 months before death. The last tooth on the left side is the second premolar, pm2. At postmortem, the volume of the left maxillary sinus was 1.7ml, and that of the right maxillary sinus was 1.3ml.
(from Rosen and Sarnat, 1955)

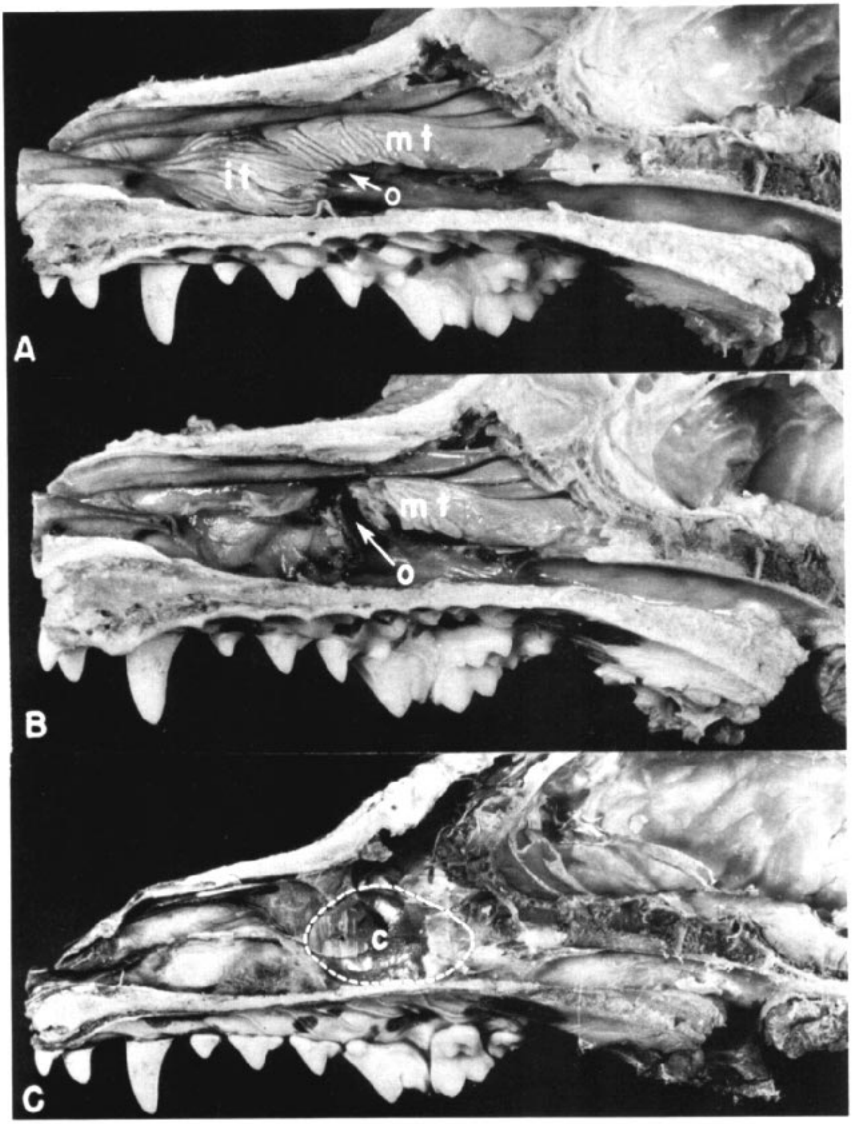


Figure 13

Medial aspect of right half of adult dog head.

A Lateral wall of nasal fossa.
it– inferior turbinate; mt– middle turbinate; o– ostium of maxillary sinus

B Ostium, o, of maxillary sinus exposed after removal of inferior turbinate and sectioning of middle turbinate.

C Trimmed cast, reseated in the maxillary sinus. *(from Rosen and Sarnat 1955)*

REFERENCES

Adams, C. O. and Sarnat, B. G. 1940. Effects of yellow phosphorus and arsenic trioxide on growing bones and growing teeth. *Arch. Pathol.* 30:1192.

Dixon, A. D. and Sarnat, B. G. 1982. *Factors and mechanisms influencing bone growth.* A. R. Liss, New York.

—1985. *Normal and abnormal bone growth: Basic and clinical research.* A. R. Liss, New York.

Herzberg, F. and Sarnat, B. G. 1962. Radiographic changes in the bony trabecular pattern in the mandible of growing Macaca rhesus monkeys following condylar resection. *Anat. Rec.* 144:129.

Hilton, J. 1950. *Rest and pain,* ed. 8, p.XX. Lipincott, Philadalphia.

Hiroyabashi, S., Harii, K., Sakurai, A., Takaki, E., and Fukuda, O. 1988. An experimental study of craniofacial growth in a heterotopic rat head transplant. *Plast. Reconstr. Surg.* 82:236.

Long, R., Greulich, R. C. and Sarnat, B. G. 1968. Regional variations in chondrocyte proliferation in the cartilaginous nasal septum of the growing rabbit. *J. Dent. Res.* 47:505.

Rosen, M. D. and Sarnat, B. G. 1955. Change of volume of the maxillary sinus of the dog after extraction of adjacent teeth. *Oral Surg., Oral Med., Oral Path.* 8:420.

Sarnat, B. G. 1957. Facial and neurocranial growth after removal of the mandibular condyle in the macaca rhesus monkey. *Am. J. Surg.* 94:19.

—1963. Postnatal growth of the upper face: Some experimental considerations. *Angle Orthod.* 33:139.

—1970. The face and jaws after surgical experimentation with the septovomeral region in growing and adult rabbits. *Acta Otolaryng.* 268 (suppl.):1.

—1978. Orbital volume after enucleation and eye volume in the adult rabbit. *Graefes Arch. Ophthalmol.* 208:241.

—1980. Orbital volume in young and adult rabbits. *Anat. and Embryol.* 159:211.

—1981. The orbit and eye: Experiments on volume in young and adult rabbits. *Acta Ophthalmol.* 147 (suppl.):1

—1984. Differential growth and healing of bones and teeth. *Clin. Orthop.* 183:219.

—1986a. Growth pattern of the mandible: some reflections. *Am. J. Orthod.* 90:221.

—1986b. Something of the nature of gross sutural growth. *Ann. Plast. Surg.* 17:339.

Sarnat, B. G. and Laskin, D. M. (eds.) 1980. *The temporomandibular joint: A biological basis for clinical practice,* ed. 3. C C Thomas Springfield, IL.

Sarnat, B. G. and McNabb, E. G. 1981. Sutural bone growth of the turtle Chrysemys scripta plastron: A serial radiographic study by means of radiopaque implants. *Growth.* 45:123.

Sarnat, B. G. and Muchnic, G. 1971. Facial skeletal changes after mandibular condylectomy in growing and adult monkeys. *Am. J. Orthod.* 60:33.

Sarnat, B. G. and Selman, A. J. 1978. Growth pattern of the nasal bone region in the rabbit. *Acta Anat.* 101:193.

Sarnat, B. G. and Shanedling, P. D. 1970. Orbital volume following evisceration, enucleation and exenteration in rabbits. *Am. J. Ophthalmol.* 70:787.

—1972. Orbital growth after evisceration or enucleation without and with implants. *Acta Anat.* 82:497.

—1974. Increased orbital volume after periodic intrabulbar injections of silicone in growing rabbits. *Am. J. Anat.* 140:523.

Sarnat, B. G. and Wexler, M. R. 1966. Growth of the face and jaws after resection of the septal cartilage in the rabbit. *Am. J. Anat.* 118:755.

—1967. The snout after resection of nasal septum in adult rabbits. *Arch. Otolaryng.* 86:463.

Schultz, A. H. 1940. Size of orbit and of eye in primates. *Am. J. Phys. Anthrop.* 26:389.

Scott, J. H. 1953. Growth of human face. *Proc. Roy. Soc. Med.* 47:91.

Siegel, M. I. 1978. Early septal surgery in the chimpanzee animal model. *Cleft Palate J.* 15:77.

Tessier, P. 1971. Relationship of craniostenoses to craniofacial dysostoses, and to faciostenoses. A study with therapeutic implications. *Plast. Reconstr. Surg.* 48:224.

—1971. The definitive plastic surgical treatment of the severe facial deformities of craniofacial dysostosis. *Plast. Reconstr. Surg.* 48:419.

Thompson, D. 1968. *On growth and form.* p. 283. Cambridge University Press, Cambridge, England.