Patterns of Vascular Channels in the Cortex of the Human Mandible[1]

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The plan and organization of vascular channels of cortical bone are best known for the shafts of mammalian long bones where numerous elongate parallel vessels either have cross connections or branch and anastomose to form a complex three-dimensional mesh with a predominant proximo-distal orientation (Petersen, '30; Schumacher, '35; Ruth, '47; Bartoli and Vasciaveo, '57; Cohen and Harris, '58). The pattern is roughly comparable to that seen in carmine-gelatin injected striate muscle; in muscle, the intervascular tissue consists largely of muscle fibers and endomysium; in bone it consists of osseous lamellae and osteocytes. A recent technique (Knapp, Avery and Costich, '58; Avery and Knapp, '59; Avery, Knapp and Dempster, '59) has made it possible to see the cortical vascular channels of whole bones or of large pieces of them. The technique, in its simplest form, requires: (1) deorganifying a large piece of cortical bone (i.e., removing cells, fibers and ground substance) by leaching in ethylenediamine, (2) filling cortical channels with India ink, (3) removing dried surface carbon by a jet of abrasive and (4) clearing in styrene.

In much the way that the orientation of the xylem and xylem fibers in wood results in a linear "grain" pattern, the vascular channels and osteones produce a grain in cortical bone. As in wood the mechanical properties of bone differ in a direction along and across the grain (Dempster and Liddicoat, '52), the grain pattern of various bones has been most clearly demonstrated by the Benninghoff split-line technique. When pointed awls with a circular cross section are pushed into decalcified cortical bone and withdrawn, the holes close to form longitudinal crevices which, when touched with ink, show as blackened lines. When successive puncture marks that are aligned are interconnected, the grain of the bone is revealed. It should be noted, however, that intact skeletal material and decalcified bone have entirely different mechanical properties. Olivo, Maj and Toajari ('37) considered that both the anisotropy exhibited by strength tests on bones and the directions of split lines were correlated with the resultant of the predominantly obliquely longitudinal orientation of the collagenous fibrillae in the lamellae of osteones. Dowgjallo ('32), Benninghoff ('25), and Siepel ('48) have shown split-line patterns for the human mandible. Siepel's study also includes data on anthropoid jaws; additional data on primate bones have been provided by Henckel ('31) and by Tappan ('53, '54).

The overall pattern and arrangement of vascular channels are well shown by our cleared, deorganified and ink infiltrated material. These vascular channels, for adult mandibles, are in turn correlated with the organization of the osseous component of the cylindrical Haversian systems of lamellae or osteones. No other known technique brings out as clearly the regional differences in vascular structure of a whole bone. Details such as channel angulation and diameter, regions of bone resorption, blind-end channels, local discontinuities and Volkmann canals may be seen when preparations are magnified. The method provides a quick means for detecting localized structural peculiarities and should become a valuable adjunct for evaluating experimentally induced changes in bone or alterations due to disease.

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The present paper deals with (1) the organization of the cortex of a complex whole bone—the mandible, (2) the general pattern of the vascular channels found in it, (3) the histology of different regions of the bone, as seen in ground sections, and (4) details of the channels themselves and their anastomoses.

METHOD

Ordinary osteological preparations of adult human mandibles were screened to obtain specimens with complete or nearly complete dentitions; 10 in all were subjected to the technique. In addition two edentulous adult specimens and 7 infant and child mandibles were studied. The teeth were extracted with minimal damage to the alveolar sockets and the bones were sawed at the symphysis; in several instances preparations of only one side of the mandible were made; more commonly both the right and left sides provided material for study. Each half mandible was cut lengthwise with a small circular dental saw through the base, through the dental alveolar arch and through the anterior and posterior margins of the ramus to partially separate an external from an internal cortical plate. In order to protect the bone from fracturing during handling the exterior face of the bone was attached to a block of wood (about 7/8″ × 3″ × 4″) using a mass of plastic wood (Boyle-Midway Co., Chicago). After the plastic wood had hardened a fine jig-saw blade was worked through the bone between the external and internal cortical plates so that the inner plate could be lifted away. The latter was in turn fastened superficial surface face down with plastic wood to a second wooden block. Next, all of the spongiosa was carefully cleaned away from each half with dental burrs. After the plastic wood had been softened by soaking in an alcohol-acetone mixture and removed, the cortical plates were subjected to hot ethylenediamine in a Soxhlet extractor (Avery et al., '59a and b; Knapp et al., '58).

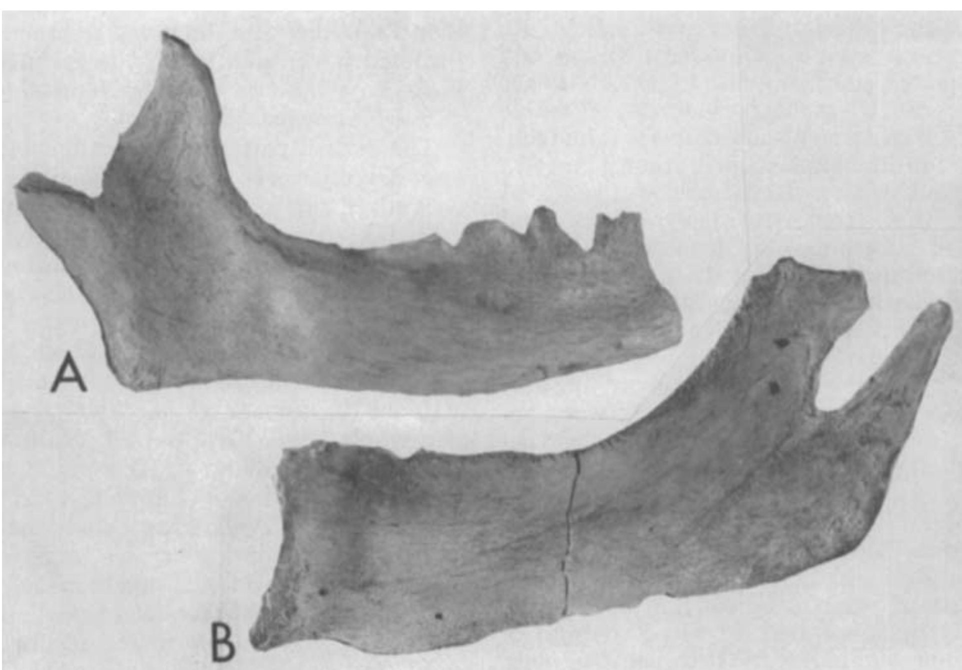


Fig. 1 A and B, External and internal views (respectively) of dry cortical plates of half mandibles after deorganifying and carbon impregnation. Styrene has not been applied. Fine surface pitting identifies Volkmann canals; dark streaks indicate the more superficial vascular channels.

After 72 hours of extraction virtually all of the organic material in the bone (collagenous tissue of the bony matrix, contents of the Haversian channels, etc.) disappeared leaving an ashy white, brittle, calcareous phantom of the cortical plate of the original bone. Since the organic contents of the vascular canals were totally removed, there were no mechanical obstructions to prevent infiltration by a fluid. The bony plates were immersed in dilute (25%) ammoniated India ink which was forced into vascular channels by a vacuum. After drying, the surface of the blackened bone was cleaned by a jet of abrasive dust using an Airdent unit, (produced by S. S. White Co., Philadelphia); the surface was then ash-white except for the blackened markings of the superficial vascular channels and Volkmann canals (fig. 1). At this stage the cortical plates were examined or photographed for surface texture. Most commonly, the specimens were immersed in styrene (or, less satisfactorily, wintergreen oil); as cleared specimens, they were transilluminated and studied directly under the dissecting microscope or were photographed (fig. 2).

An intensive study with a low power, binocular microscope of the dry outer and inner cortical plates of 5 mandibles revealed that Volkmann canals were numerous and widely scattered over the exposed surfaces; figure 3A and C, is representative. Each of our specimens showed localized clusters with a high concentration of these canals (viz., coronoid region, midramus, ramus/body junction, alveolar process, mental region, etc.), but no consistent or dominant pattern of Volkmann canals was recognized in the 5 specimens studied.

When dry cortical plates were examined as opaque specimens with a binocular dissecting microscope and a drop or two of styrene was applied (or the whole bone was briefly immersed and then removed from styrene) vascular channels beyond the surface were made visible for a short time. Figure 3B shows such a specimen;

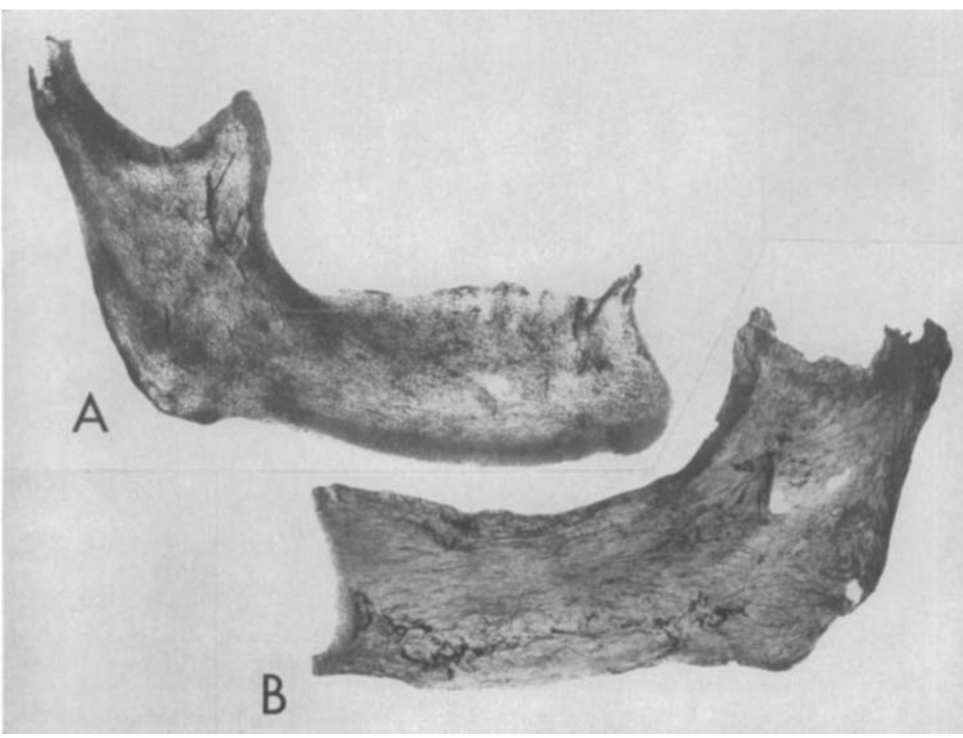


Fig. 2 A and B, Trans-illuminated, cleared specimens of external and internal cortical plates of half mandibles showing ink-filled vascular canals.

certain regions (viz., the upper mental region, the alveolar process, the junction of the body and ramus, below the mandibular notch, and in the coronoid process) show patterns of short irregular lines, appearing like the hairs of a scraggly day-old beard—these were Volkmann canals; we apply the term strictly to cross canals between the surface and the vascular mesh, since, as will be evident shortly, deeper cross connections in the mandibular cortex cannot always be distinguished from branched Haversian canals. (The preparation illustrated is the same as that shown in fig. 1A).

To show different levels through a cortical plate (1) the spongiosa side of the bone was pressed into a mass of dental stone for easier handling, (2) a photographic record of the exposed surface was made, (3) a thin layer of bone was sanded away with an abrasive dental Burlew-Sulci disc and another opaque view photo was made, without or with styrene clearing; next, (4) deeper layers (after evaporation of the styrene) were exposed to view and

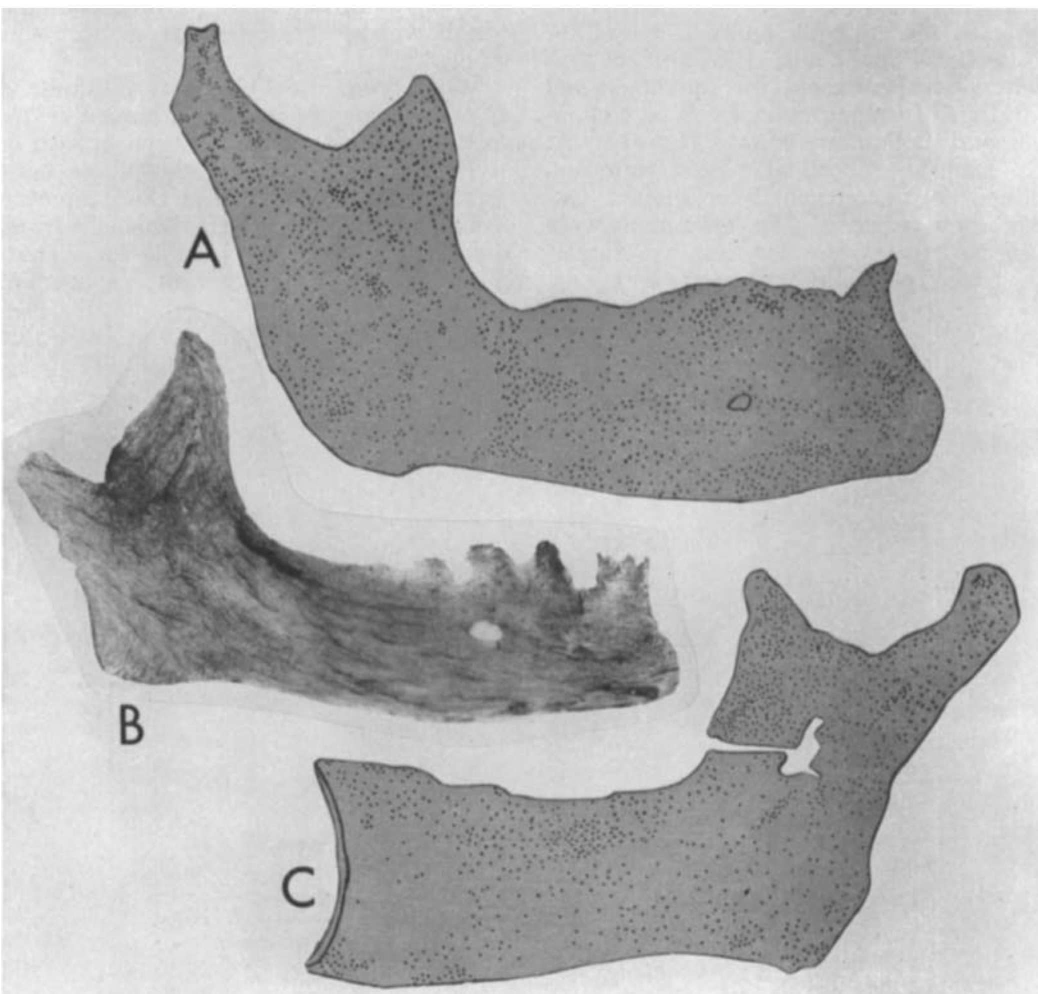


Fig. 3 Sketches A and C show a representative distribution of Volkmann canals on the external and inner cortical plates of a half mandible. At B a specimen slightly cleared with styrene, and photographed with direct illumination shows the more superficial vascular channels and Volkmann canals.

Fig. 4 A cleared, trans-illuminated specimen of the external cortical plate of a half mandible. The specimen shows saw-cut lines where bone sections were removed before deorganifying to provide correlative material.

for photography by additional abrading. Thus, layer by layer, the whole thickness of a cortical plate through to the matrix of dental stone could be examined. Characteristically, in the inner and outer cortical plates of the two half mandibles treated in this manner, the directional pattern of the dominant vascular canals seen at the surface was repeated at every level; it was only rarely in localized areas that one could identify a major change in pattern at different depths.

In addition to inner and outer cortical plates of half mandibles, the basal region of whole mandibles, the front and rear faces of the condyles and the front and rear views of the mental region were prepared for study.

In order to demonstrate the relations of the Haversian systems, the surface lamellae, Volkmann canals and other features, ground microscopic sections were made of representative regions. Since it was extremely difficult to prepare sections of the deorganified bone, small slices of bone for microscopic study were cut out of different regions of mandibles before the specimens were prepared for organic extraction and ink impregnation. Photographs (fig. 4) were made to show the precise location of the sawcuts and microscopic sections. A technique developed earlier (Enlow, '54) was used in the preparation of ground sections. Comparisons were then made between the structure revealed by the sections and the vascular organization of adjacent cleared bone.

The vascular supply

It is presumed that both the periosteum and outer circumferential portions of the osseous mandible are supplied by such adjacent arteries as the facial, the submental, the inferior alveolar, the mylohyoid, the mental, the masseteric, the lateral pterygoid, the medial pterygoid, the temporal, and the sublingual branch of the lingual; to determine precise areas of supply, differently colored injection masses would be necessary.

One or more nutrient foramina, passing through to the marrow space, were evident above the genial tubercle (sublingual A.) and multiple small foramina were usually seen in the small triangular area on the inner face of the ramus below the mandibular (sigmoid) notch and above or on the endocondylar and endocoronoid ridges (of Lenhossek, '20). Other nutrient foramina (as on the temporal ridge or within the areas of attachment of the mentalis, lateral pterygoid, medial pterygoid or anterior digastric muscles) were inconstant —it is difficult from surface examination to distinguish small nutrient foramina (passing from the surface to the marrow space) from large Volkmann canals (surface into cortical bone). Figure 3A and C, and our earlier comments show the type of information on Volkmann canals that may be derived from dry, deorganified, carbon filled bone. We have not been concerned here with the medullary distribution of vessels (Hashimoto, '35). Medullary vessels, however, are continuous with those of the endosteal part of the cortex.

The gross intracortical vascular pattern

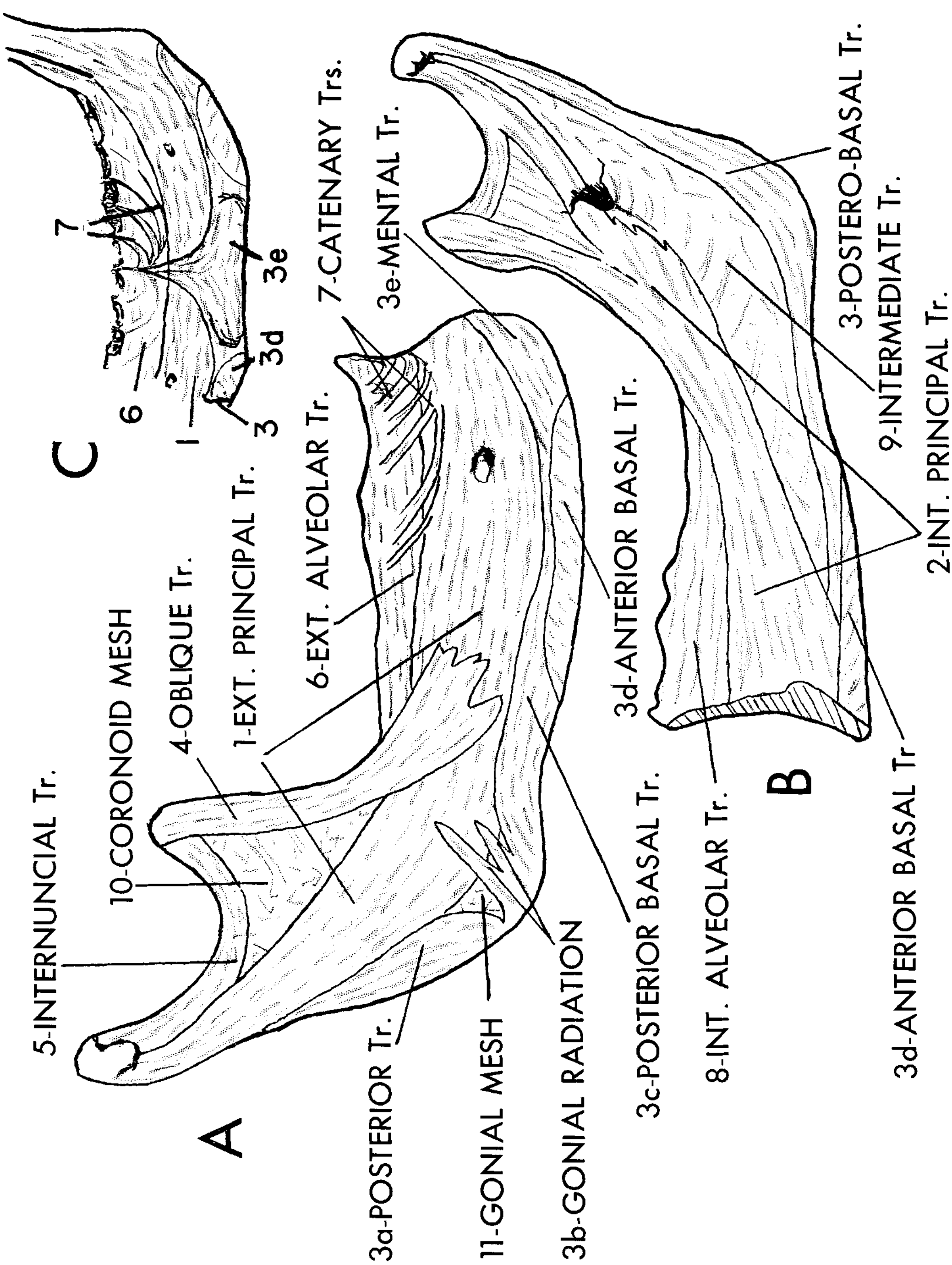
The simplest and most representative classification of the surface of the dentulous mandible into sub-areas, each with a distinct arrangement of vascular channels, is shown in figure 5. Eleven by 14″ photo enlargements of each cleared specimen were repeatedly examined and wax pencil contours on clear plastic overlays were made and corrected till we had a map-like pattern of contours that was reasonably applicable to the various specimens. These patterns are generally similar to those shown by the split-line technique (Siepel, '48), but the present classification is more extensive. Our plan of organization is based on the predominant direction of canals in the Haversian mesh. Throughout most of the bone the Haversian mesh looks like figure 7 or 8, but in localized regions it approached the extreme patterns shown in figures 9, 10 and 11. Although there is but one continuous vascular mesh, several sub-areas may be recognized. The areas of cortical bone may be grouped into 7 major tracts, into several secondary or minor sub-tracts, and into three regions of somewhat random organization. In our system, three of the major tracts extend from condyle to condyle. The other areas are smaller. The subdivisions, designated below by a paragraph number code and by the areas of figure 5A, B and C, are described as follows:

1. *External principal tract* (fig. 5A). This tract arises from the lateral half of the condyle posterior to the lateral condylar tubercle; it broadens as it sweeps obliquely across the mid and lower region of the ramus toward the body; then it continues forward on the lateral side of the body to the symphysis and contralateral part of the bone. In one instance it was thinly developed and interrupted in the region of the mid ramus (fig. 6B); normally in the body region of the bone it merges with or is overlaid by the oblique tract (4, tract code number), the mental tract (3e) and the catenary tracts (7).

2. *Internal principal tract* (fig. 5B). This begins in the region of insertion of the lateral pterygoid muscle on the anterior face of the condyle; it runs obliquely across the upper part of the medial face of the ramus, a broader band than the endocondylar ridge, to the upper part of the mandibular canal, through the root of the lingula and to the temporal crest. In this course it is joined from above by a fan-like convergence of Haversian channels (below the internuncial tract, 5) from the condyle to the tip of the coronoid process. With an additional confluence of osteones from the contiguous oblique tract (4) it sweeps along the temporal crest and mandibular recess to the region between the alveolar margin of the molar region and the mylohyoid ridge and lingual tuberosity (Edwards and Boucher, '42). Then its osteones diverge as they course forward above the mylohyoid line but below the internal alveolar tract (8) to the symphysis and contralateral half of the bone.

3. *Postero-basal tract* (fig. 5A and B). This tract arises in the medial half of the posterior subcondylar region and sweeps along the posterior border of the ramus with considerable overlap on both the internal and external surfaces. On the internal surface, the postero-basal tract ordinarily extends over the mandibular angle without interruption and along the base to the digastric area, the symphysis and the contralateral side; a subtract of strongly oblique osteones (coursing anterosuperiorly), the *anterior basal tract* (3d), was identified in about the anterior half of the basal area (except for one specimen, fig. 6D). Typically, the *postero basal tract* is interrupted on the lateral aspect of the

Fig. 5 The general plan, based upon the organization of vascular canals, of the texture of cortical bone in the adult mandible. A and B respectively are external and internal views of the right side; C shows the anterior aspect of the jaw. The predominant direction of osteones, a terminology for the different regions and a number code consistent with the text and certain later figures are shown.


A
B
C
5-INTERNUNCIAL Tr.
10-CORONOID MESH
4-OBLIQUE Tr.
1-EXT. PRINCIPAL Tr.
6-EXT. ALVEOLAR Tr.
7-CATENARY Trs.
3e-MENTAL Tr.
3d-ANTERIOR BASAL Tr.
3c-POSTERIOR BASAL Tr.
3a-POSTERIOR Tr.
11-GONIAL MESH
3b-GONIAL RADIATION
8-INT. ALVEOLAR Tr.
3-POSTERO-BASAL Tr.
9-INTERMEDIATE Tr.
2-INT. PRINCIPAL Tr.
3d-ANTERIOR BASAL Tr
7
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3d
3e

mandible in the gonial region; in two specimens (fig. 6C and D) it was interrupted on the medial side also; the posterior tract of osteones (3a), along the posterior margin of the ramus, arches and ends in the posterior part of the gonial region. Commonly, two or three oblique *gonial radiations* (3b) arise from the angle of the mandible and extend obliquely across the lower ramal region and the adjacent external principal tract (1). More anteriorly, a *posterior basal tract* (3c) arches from the exterior gonial region and extends forward to the mental region and contralateral side. Its posterior part is parallel to and continuous with the medial surface of the postero-basal tract (3). On the body of the mandible in the region of the insertion of the platysma muscle and nearly as far posterior as the masseter insertion, the *anterior basal tract* (3d) of very oblique osteones is evident. More anteriorly a less oblique fan of osteones that partly overlaps the front part of the lateral principal tract forms the *mental tract* (3e).

4. *Oblique tract* (fig. 5A and B. The oblique tract courses chiefly on the lateral face of the ramus at its anterior border as a narrow band extending from the apex of the coronoid process along the oblique line to the lateral face of the ramus-body junction. In the ramus it is adjacent to and continuous with osteones of the medial principal tract (2); below the oblique line the tract broadens, overlies and merges with the lateral principal tract (1).

5. *Internuncial tract* (fig. 5A and B). Since no spongiosa is present in this region, this single tract within solid cortex is observed on both lateral and medial faces of the ramus (as, also, the ramal part of the oblique tract, 4). It follows the curve of the mandibular (sigmoid) notch from the rear margin of the oblique tract (4) to the neck of the condyle lateral and below the lateral pterygoid insertion.

6. *External alveolar tract* (fig. 5A). This tract of osteones on the exterior face of the alveolar process begins posteriorly at the ectalveolar margin (Lenhossek, '20) of the molar region and buccal shelf (Edwards and Boucher, '42). Its osteones, which are contiguous with the oblique tract (4) and above the lateral principal tract (1), are mostly parallel to the alveolar margin; the tract broadens as it sweeps forward to the symphysis where it continues into the contralateral side. Its borders above and below at the symphysis coincide with anthropometric points: infradentale and supramentale. On its external face are the catenary tracts (7).

7. *Catenary tracts* (fig. 5A and C). These narrow tracts on the exterior surface of the alveolar process loop downward on each side in the span from the second pre-molar tooth to the symphysis; the longest catenaries also overlie the upper part of the lateral principal tract (1). Shorter catenaries loop from the interalveolar septa proximal to the first premolar, the canine and the lateral incisor teeth to the symphysis; small loops in the canine-incisor region often extend between adjacent interalveolar septa across the cortical plate anterior to the tooth sockets. These tracts were scarcely evident in some specimens.

8. *Internal alveolar tract* (fig. 5B). This tract arises at the post-molar region of one side and extends on the inner side of the alveolar process to the same region on the opposite side of the jaw; it broadens anteriorly as it passes along the inner cortical plate on the lingual surface of the alveolar process. At the symphysis it is about one third the depth of the mandible. Its osteones, which are predominantly parallel to the alveolar margin, blend with those of the medial principal tract (1).

In our two edentulous specimens alveolar resorption was not extreme and there was a well marked residual ridge. The patterns of relatively parallel vascular channels (fig. 12) had changed to a short channeled polygonal mesh. The shorter catenary tracts (7) had resorbed entirely and the longer lower ones had broadened and coalesced with the underlying external alveolar (6) and principal (1) tracts so that only a slight obliquity to the vascular channels of the regions was a residual indication of the catenary tracts.

9. *Intermediate tract* (fig. 5B). This tract lies between the medial principal tract (2) and the posterobasal tract (3). It is not a well differentiated tract like the foregoing areas. It extends on the inner cortical plate from the medial condylar tubercle to the forward region of the body

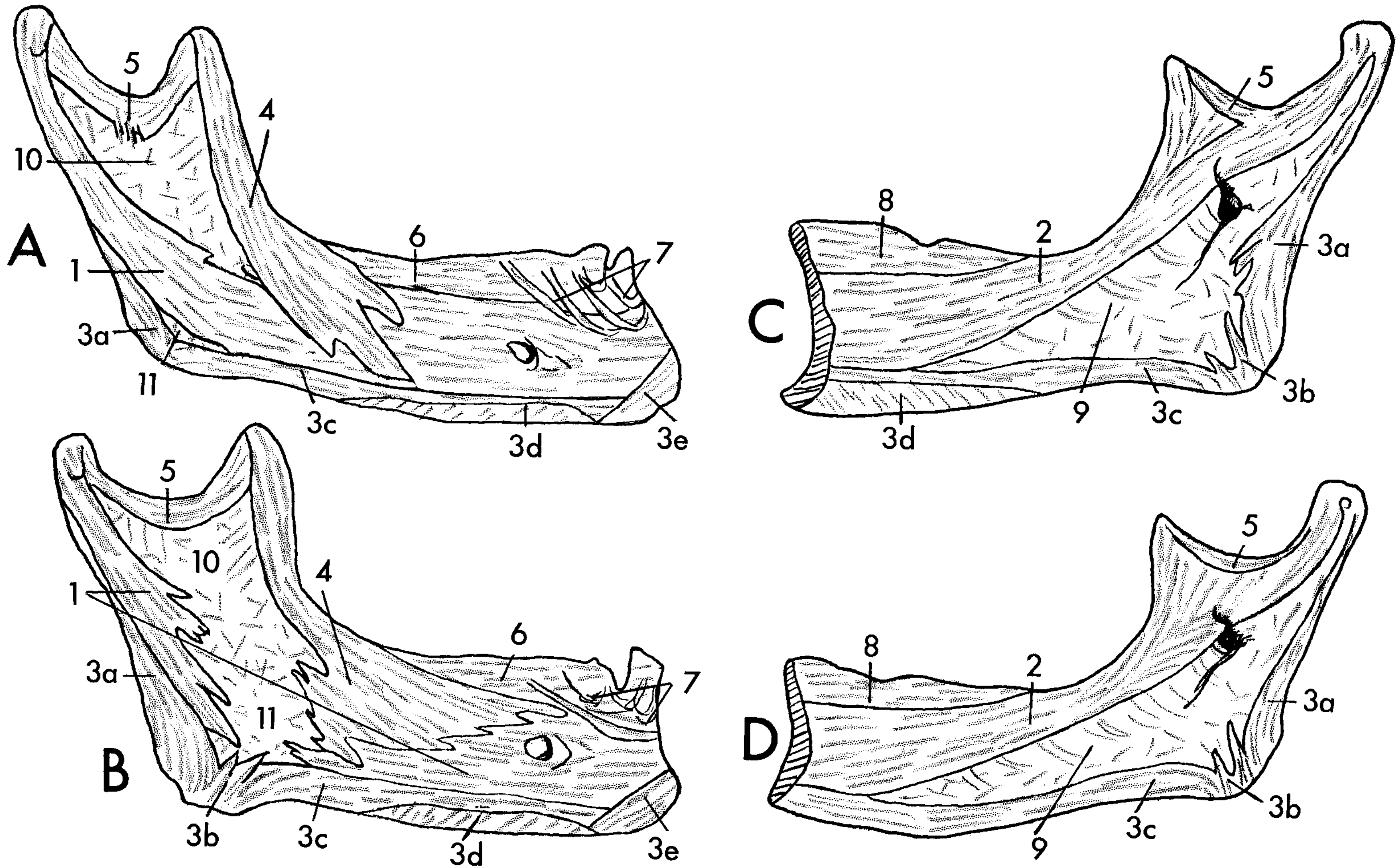


Fig. 6 Extreme variant patterns of cortical texture seen in different half mandibles. A and B are exterior views while C and D are internal. Areas identified by code numbers may be compared with those of the more basic patterns of figure 5.

where it blends with adjacent tracts. Most of the area consists of an indifferently oriented mesh of osteones; the region from the lingula and inferior border of the mandibular foramen and the area below shows a definitely oblique orientation of osteones (e.g., upward and forward) relative to the length of the tract. A lattice of scattered and similarly oblique osteones below the mylohyoid line spans the cortical plate medial to the mandibular canal (i.e., floor of the submandibular fossa).

10. *Coronoid mesh* (fig. 5A). Invariably there is a triangular area with a loose disoriented mesh of osteones on the lateral side of the ramus (surrounded by external principal tract (1), oblique tract (4) and internuncial tract (5). In the rear half or third of this mesh, prominent vertical osteones which also extend into the internuncial tract (5) are often identified. Thrusting backward and downward from the oblique tract (4) a few prominent oblique osteones are usually evident.

11. *Gonial mesh* (fig. 5A). A similar loose mesh of canals is evident between the lateral principal tract (1) and the gonial specializations (3a, 3b and 3c) of the postero-basal tract (3). The coronoid and gonial meshes vary in area and in one instance (fig. 6B) the two meshes (10 and 11) were practically continuous except for thin osteones of the lateral principal tract which intermingled.

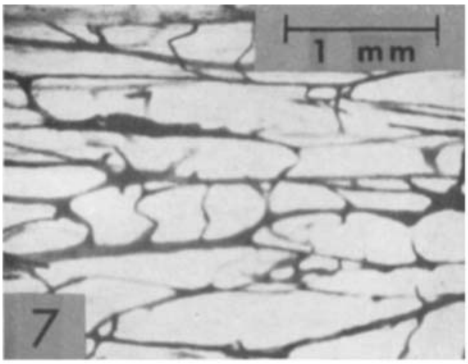
Figure 6 shows representative variant patterns of osteone orientation that were found in the bones studied. In certain regions also, minor specializations were evident. Osteones of the external principal tract (1) posterior to the mental foramen dipped into the rear wall of the mental canal while other osteones swept above and below to form an anterior foraminal margin; still other osteones above and below blended anteriorly and enclosed a small triangular area of irregular osteones anterior to the foramen. At the symphyseal region, catenary-tract osteones (7) united to produce a predominantly vertical orientation; this was joined also by osteones from the upper region of the mental trigone. Much of the surface sculpturing of the bone (such as oblique ridges of the platysma area, the surface of the mental trigone, the ectocondylar ridge, the medial pterygoid tubercles, the sub-sigmoid trigone on the medial surface of the ramus), were not specifically demarcated by patterns of osteone orientation.

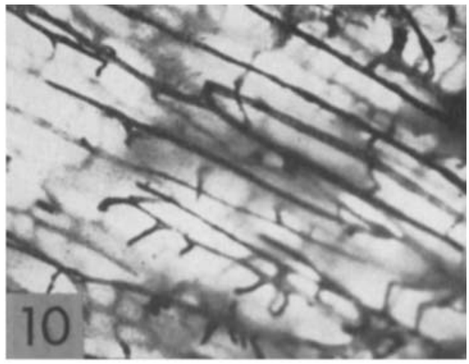
Cleared bone

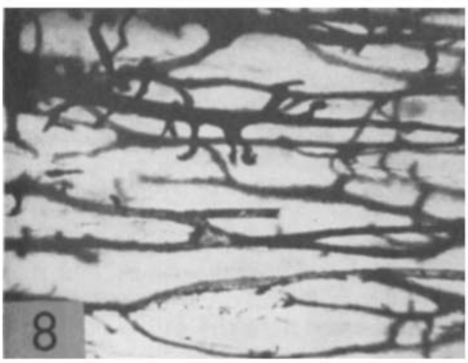
Specimens examined with a binocular microscope show that carbon actually infiltrated into the vascular canals. Carbon-filled cracks were occasionally found, but these were not confusing. Primary and secondary bone could not be distinguished by the appearance of vascular canals in cleared material; supplementary histological sections were required for this.

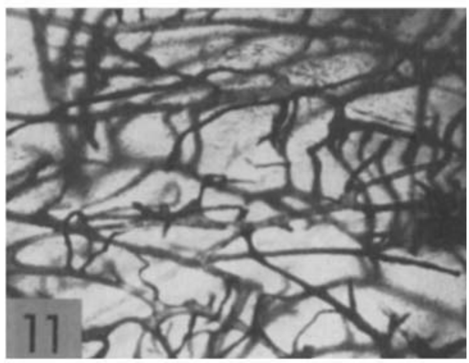
Most of the mandibular cortex consists of distinct tracts with a predominantly parallel osteone arrangement (figs. 7 and 8); the vascular canals had an average unbranched length of about 0.7–0.8 mm with variations that rarely were outside a range of 0.4–1.2 mm. (These measurements which are less than earlier data on osteone lengths in long bones—Filogama, '46a and b; Cohen and Harris, '58—are not strictly comparable since the latter did not measure the distance between cross connections.) A caliber of 30–50 micra was common, but thinner and thicker canals were adjacent to and connected with those of average or above average size. The smallest canals (fig. 7) were 15 microns or less in diameter—about a close-off size for a capillary circulation. The caliber of canals between branchings tended to be constant; beyond a cross connection the caliber often increased or decreased abruptly. There was, of course, no indication of the direction of flow through any of the conduits though the decreasing caliber of a straight canal after each cross connection would suggest a caliber gradient for both the arterioles and venules within. When, as in figures 8, 9, 11 and 12, a thin deposit of carbon was seen in certain canals, the luminal surfaces appeared smooth. There was little evidence in the adult that lacunae and canaliculi received the carbon; in immature bone, however, carbon-filled lacunae could be identified in the matrix adjacent to the canals (fig. 20).

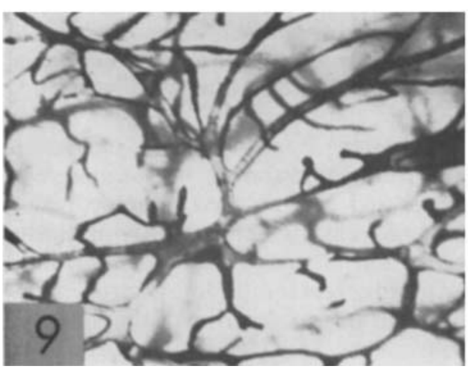
The span between the more parallel canals was normally about 0.3 mm and a spacing of three to 4 osteones per millimeter was the rule; thus, as seen also in figure 13, the thickness of a cortical plate (about 2.5 mm on the average) would usually consist of 7 or 8 layers of osteones. Cross connections averaged about three-fourths the caliber of the predominantly parallel canals. They had a branching angulation of 10° or 20° to 90°; an average branching angle of nearly 60° in certain regions (figs. 7 and 8) may be contrasted with a more infrequent pattern of

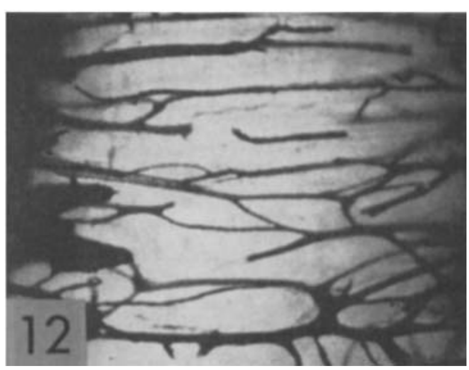












Figures 7–12 were magnified to the same degree; line equals 1 mm.

Fig. 7 Pattern of vascular canals of the external principal tract (1) of the mandible neck.

Fig. 8 Posterior tract (3a)—internal cortical plate—about mid-ramus level.

Fig. 9 Posterior tract (3a)—external cortical plate—near gonion.

Fig. 10 Internal principal tract (2) of the lingula at the anterior margin of the mandibular foramen.

Fig. 11 Intermediate tract (9) just inferior to the mandibular foramen.

Fig. 12 Internal alveolar tract (8); the cortex just medial to the cuspid alveolus.

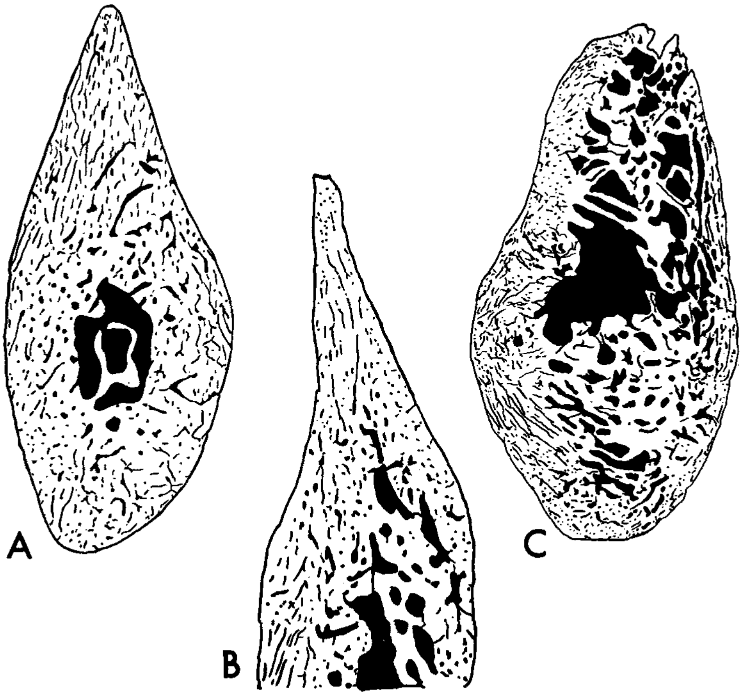


Fig. 13 Inked, bleached-photographs of ground sections of mandibular bone. A, oblique section through the lower part of the neck. B, a vertical section through the border of the mandibular notch and upper part of the ramus. C, parasagittal section near the symphysis.

angulation closer to 40° (fig. 12) or one with numerous right-angle branches (figs. 9 and 10). Side branches were usually larger at the junction with the main channels so that profiles at points of union were curved and arching rather than sharply angular. Junctions of main branches and side channels often represented an enlarged confluence of several radially arranged conduits.

Sometimes, as in figures 8 and 12, carbon-filled canals ended abruptly; the relation of these canals to adjacent parts of the mesh or to thinly impregnated continuations suggest that the infiltration of India ink may be capricious. Nevertheless, in occasional instances, blind-end Haversian systems (Cohen and Harris, '58) were clearly shown by the technique—blind, bulb-ended, enlarged side branches (figs. 8 and 9) were more common. Many photomicrographs and the appearance of actual material while the microscope focus was changed were both confirmatory of blind-end vascular canals and suggestive of the dynamics of remodelling changes.

The intermediate tract (fig. 11), the coronoidal and gonial meshes, and regions of local specialization were not developed into organized patterns with a predominate osteone orientation. The unbranched span of vascular canals decrease to 0.3 or 0.4 mm; the branching patterns become more frequent and more irregular. The spacing between canals, however, shows less change.

Although localized areas of resorption and remodelling may be studied best in decalcified and stained microscopical sections, regions which we have regarded as resorption spaces may be identified in cleared material only in a gross way by the location of enlarged canals and cavitations (figs. 15, 16 and 17). In most of our cleared adult specimens, (figs. 2 and 4) enlarged canals were interspersed here and there in an apparently random way among those of more normal size. The appearance is suggestive of a bone remodelling process that may be continuous during the adult period.

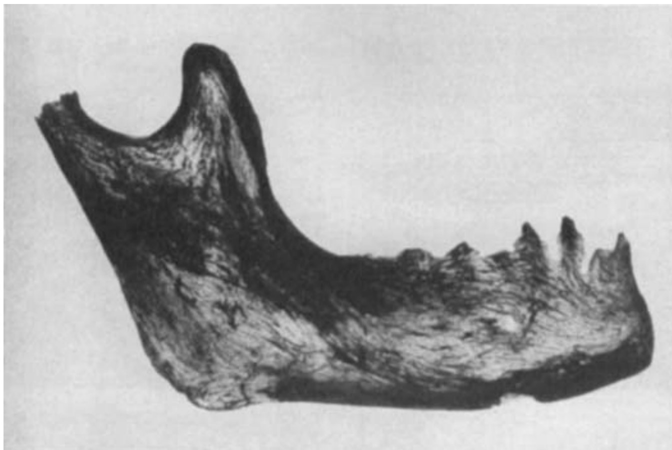
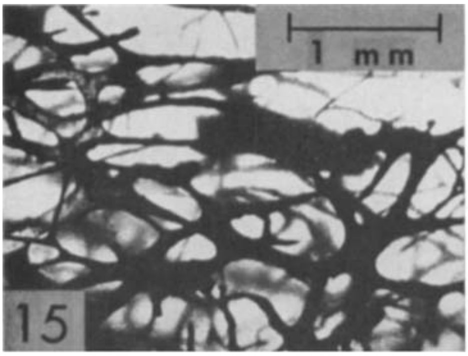


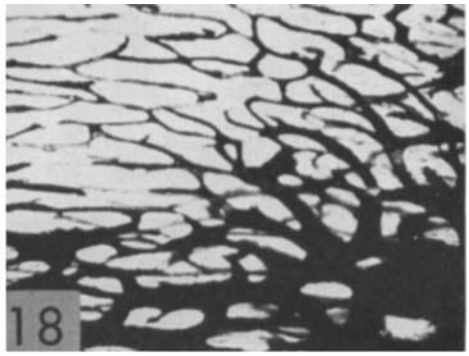
Fig. 14 Vascular channels in a cleared trans-illuminated specimen of the lateral cortical plate. Many of the inked-filled channels are much enlarged in this mandible.

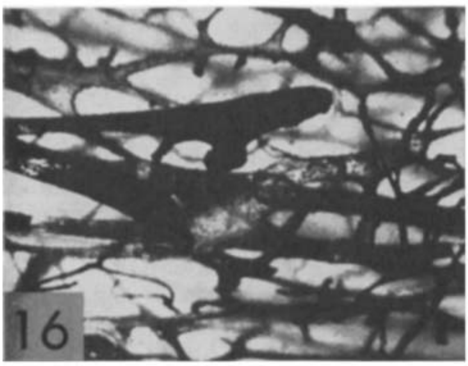
In a group of photographs of various regions from 5 mandibles the caliber of 640 random Haversian canals was measured. Seven per cent were 15 micra or less; 84% (showing an approximately normal distribution) were between 15 and 90 micra and 9% were not only larger but were distributed through a wide range of diameters; of the latter 6.4% were over 100 micra, 1.4% were over 150 micra and 0.4% were over 200 micra. In this material resorptive-remodelling changes reaching the full diameter of a Haversian cylinder (250 ± micra) were either very rare or were of short duration. Several specimens (fig. 14) showed marked evidence of resorption of vascular canals.

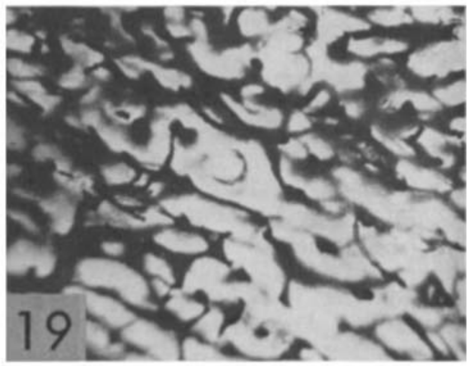
Figures 15, 16 and 17 show the character of change in localized regions. Although canals of normal to small caliber may be seen in each field, many of the canals had increased from two to 4 or more times the usual diameter. The space between these channels was less than usual. The region of junction of side connections to main channels were enlarged; the angulations of junctions were rounded, and where several connections joined close together a sinus-like cavitation was often present. Figure 17 shows especially large sinuses. The enlarged conduits were frequently conical or had dilated and constricted regions. Usually, normal sized and small channels also joined into the mesh of enlarged channels. From the cleared specimens alone it was quite impossible to tell whether reconstructive or resorptive processes were occurring in the walls of the enlarged canals.

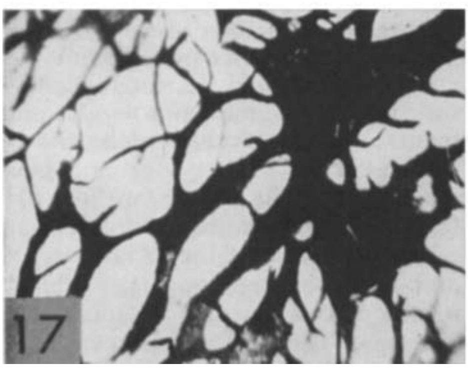
Infant mandibles under one year of age consisted entirely of primary bone rather than of secondary Haversian systems and had canals of a distinctive type. The mean caliber of canals was about half again as large (60 micra) as in the adult (45 micra). The luminal diameter changed erratically with numerous irregular enlargements and constrictions along the length of the canals, but in a given region the canals were quite similar, without the variation in mean caliber size found in the adult. The walls of the canals were pitted and they had free openings which permitted carbon to enter adjacent lacunae. The span between canals was less than in the adult, usually between 0.1 and 0.2 mm. Figures 18, 19 and 20 show that channel size, mesh patterns and angulation of branches varied notably from region to region. A full descriptive treatment, however, is not warranted since the number of available specimens was too limited to permit us to make a topographic study comparable to that made for the adult and since suitable stages between immature and adult mandibles were not available for a developmental study.











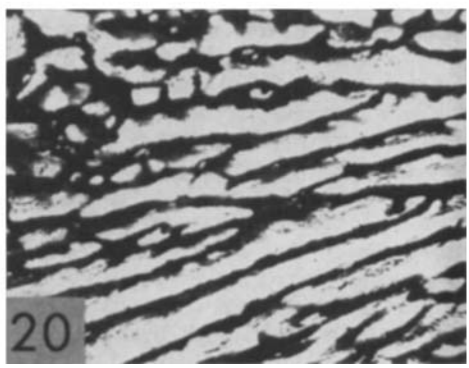


Fig. 15 Internal principal tract (2) at the condylar neck of a specimen showing widely resorbed channels. The magnification is the same for all photographs on the page.

Fig. 16 Internal alveolar tract (8) showing resorption spaces.

Fig. 17 Large resorption spaces.

Fig. 18 Vascular canals in primary bone, lateral to the alveolus of primary first molar; one-year-old infant.

Fig. 19 Vascular canals in primary bone of an 8-months-old infant; external cortical plate of the inferior region of the body of the mandible.

Fig. 20 Vascular canals from a one-year-old infant; anterior lower region of the mandibular body (platysma area).

The evidence of sections

In our sections of the adult mandible, the whole thickness of the bone or a sizeable part of it was transected including the external and internal tables of the cortex and the spongiosa (fig. 13). The cortical plates were composed largely of dense secondary (Haversian) bone. Substantial outer or inner circumferential strata of primary bone, however, were deposited in localized and restricted regions of the surfaces in most sections prepared through the body, ramus or neck regions of the mandibles. These areas, containing only primary lamellae and associated vascular canals (i.e., non-Haversian osteones), were present in both dentulous and edentulous mandibles of adults and on either or both tables. Such primary bone deposition was usually confined to either the periosteal or endosteal surface in any given section, but seldom to both. In occasional areas (e.g., the gonial angle in one specimen), an entire table was primary. Compact and cancellous bone in newborn specimens was composed entirely of primary bone. Areas of remodelling were recognizable, but Haversian replacement of primary osteones had not taken place.

The whole diameter of the compacta of one table as seen in any single transverse section, whether made of primary, secondary or mixed bone, usually showed canals which ran in the same direction. There were, however, restricted areas that had a different arrangement of canals in periosteal and endosteal regions at the same level in the mandible.

The caliber of Haversian canals is generally greater within the endosteal half of both the external and internal cortical plates. Progressively enlarged canals graded, without distinct abrupt transitions, into medullary spaces associated with the cancellous bone of the spongiosa (fig. 13, large dark areas).

Many cortical areas in the specimens studied showed extensive histological remodelling and cumulative secondary reconstruction. In quite a few cortical areas the half of the compacta nearer the marrow cavtiy presented a complex secondary Haversian pattern which implies a much greater degree of actual reconstruction than the periosteal half, but distinct regions were found in a number of subperiosteal regions which showed considerable reconstruction. The functional significance and specific gross anatomical correlations of this observation were not apparent from our observations.

The organization of vascular canals in the mandible differed from that of primate long bones where transverse diaphyseal sections show a regular mosaic-like pattern of cross-cut individual Haversian cylinders; thin sections of the latter bone show only scattered anastomoses. In contrast, the secondary osteones of mandibular sections ran in various directions and there were frequent connections between adjacent systems. These facts correlate nicely with the close meshed lattice of anastomosing vascular channels demonstrated by cleared carbon impregnated bone. Even though the osteones had a multiple orientation, the predominate directions of canal arrangement were to a degree recognizable. Localized areas of the cortex which were distinguished by a characteristic orientation of canals were identified in a general way with named vascular tracts (fig. 5).

Sections through the ramus, coronoid process, condylar neck, mandibular notch, mandibular body, alveoli, and gonial angle were usually prepared so that the section cut a given border transversely. Although a tract parallel to the border was cut transversely, other areas showed obliquely cut tracts of osteones. The apparent canal direction in a single thin section, as seen through a microscope, was often uncertain or misleading. For example, a section perpendicular to the posterior border of the ramus passed obliquely through the neck of the condyle into the mandibular notch; much of the anterior part of the section showed obliquely cut canals which appeared to course apically toward the thin edge of the sigmoid notch (fig. 13A and B). Actually, as seen in the adjacent cleared material, these canals, as the internuncial tract (5), ran parallel to the margin of the notch.

Ground sections must be used to supplement cleared and carbon impregnated preparations in order to recognize and determine the extent and distribution of periosteal apposition or resorption of inner and outer circumferential lamellae. They are also necessary for the identification of intervascular areas involving reconstruction of Haversian and interstitial lamellae. A distinction between primary and secondary osteones can be made only by actual microscopic examination of sections. From thin sections one may measure the diameter of the cylinders of Haversian lamellae and the depth of osteone tracts.

SUMMARY

The inner and outer cortical plates of macerated half mandibles, after leaching in hot ethylenediamine to remove all organic matter, were immersed in dilute India ink under vacuum; the vascular channels within the cortex became filled and on drying and removal of surface carbon, the bone was cleared in styrene. Low power microscopy of different areas of the cortex, when trans-illuminated, shows complex three-dimensional meshes of carbon filled canals. The mesh for most areas has a dominant orientation; the longer canals have a length of about 750 micra with calibers of 40 micra or so down to 15 micra. Cross branches are generally below average size. In certain regions many Volkmann canals joined into the mesh. At random intervals, enlarged canals and resorptive spaces at canal junctions may be found; in some bones these are notably more frequent than in others. From the general orientation of vascular canals the surfaces of the inner and outer cortical plates of the mandible have been subdivided into some 11 tracts of osteones; three of these extend from one condyle across the symphysis to the other. Variant patterns have been described. Ground sections of bone removed prior to deorganifying, preparation and clearing of the mandible were compared with adjacent cleared bone. They show areas of primary (non-Haversian) bone, of secondary bone and of bone remodeling; they also give supplementary data on osteone thickness and the degree of overlapping of osteone tracts.

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