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With Six Plates

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INTRODUCTION

This article on the circulatory system in bone is the result of a continued study of the comparative histology of bone published in a monograph entitled " A Contribution to the Comparative Histology of the Femur," Smithsonian Contributions to Knowledge, Vol. 35, No. 3, 1916.

In that monograph were described the structural bone types and the type combinations as they were observed in cross sections of the femora of various animals from amphibians to and including man.[1] The circulation within the bone substance was not seen at that time, as cross sections do not show it properly.

In 1919 a casual preparation of a tangential section of the femur of a domestic turkey disclosed a very remarkable circulation in the bone substance and it was this disclosure that led to further examination of tangential sections of the bones of different animals, the drawings and descriptions of which are here presented.

Later (1919-20) the structure of and circulation in the bone of the fish, as seen in the Mascalonge, Esox, were studied, compared with the bone types of later vertebrate animals and added to the list of bones examined.

THE CIRCULATORY SYSTEM IN BONE

The circulatory system in bone, as usually described, is limited to the blood vessels of periosteal membranes, medullary canals and diplöe of long and cranial bones respectively, little being known about the circulation within the bone substance itself.

The circulation described in this article is situated in the bone substance of the mandible and cranial bones of the fish, Mascalonge, Esox, in the walls of the long bones of the amphibian, reptile, bird,

[1] Number of sections of femora described and drawn in the monograph, 440.

bat, other mammals and man, in the cranial bones of man, in the inner wall of the 9th rib and in the infra- and supra-spinous fossae of the scapula of man. The blood supply of the lower jaw and cranial bones of the fish is derived from the dermal vessels which enter the bone at various points and assume parallel positions in the bone substance, while the blood supply of the long bones of the higher vertebrates comes from two sources, viz. the periosteal vessels which send off many small branches into the bone through entering canals (canals of Volkmann and other canals), and the medullary arteries which pass obliquely through the walls of the shafts into the medullary canals where they divide into ascending and descending branches from which small vessels are sent off into the walls of the bones and here become continuous with the vessels from the periosteum.

The blood supply of the flat bones, such as the cranial, is derived from the vessels of the pericranial and endocranial membranes which send off branches into the outer and inner tables of these bones communicating by way of the central medullary diplöe.

From a study of a large number of bone sections [2] there are found to be three structural types and various type combinations [3] which enter into the formation of bone: these are the first, composed of lamellae; the second, composed of laminae; and the third, composed of Haversian systems. These three types are combined in various proportions in the bones of different animals. The circulations which are found to be present in the different types of bone also present variations which are sufficiently distinctive in character to form two circulatory types, viz., the branching, and the plexiform. The branching type, composed of tree-like branches, is found in the first type bones, the plexiform, composed of small, large and irregularly shaped meshes enclosed by small vessels, is found in the second and third type bones, while combinations of the branching and plexiform circulations are present in structural type combinations.

In the demonstration of the circulations some difficulty arises in the preparation of the bone slides. In small animals like the frogs or other animals of the same size it is practically impossible since the long bones are almost always round and tangential sections of them are necessarily flat. In large animals the long bones have flat areas of sufficient extent to make satisfactory slides.

In the preparation of bone sections for the purpose of showing the circulation, a flat surface of bone is selected and as large a piece as

[2] Number of sections of bones examined up to the present, 1000.

[3] A Contribution to the Comparative Histology of the Femur, by J. S. Foote, M. D., Smithsonian Contr. to Knowl., Vol. 35, No. 3, 1916.

possible is sawed out, tangential to the diameter of the bone, and ground down to a suitable thinness which is determined by the appearance of the circulation.

It is not the thinnest possible section, measured in microns, that is most desirable, but one of sufficient clearness to show the circulation. During the grinding process it is necessary to examine the section at short intervals in order to ascertain just when to terminate the process.

The following sections taken from the bone of fish, amphibian, reptile, bird, mammal, and man have been studied, described, and drawn for the purpose of showing the structure and the circulation which belongs to it.

CROSS AND TANGENTIAL SECTIONS OF THE LOWER JAW AND TANGENTIAL SECTION OF THE CRANIAL BONE OF THE MASCALONGE, ESOX, A FISH OF WISCONSIN WATERS

CROSS SECTION OF A PORTION OF THE LOWER JAW

PL. 1, FIG. 1A

The section is composed of parallel disks of bone substance situated between vascular channels or clefts. The bone substance does not show the presence of lacunae with their canaliculi. Very minute parallel canaliculi extend across the disks from one channel or cleft to another. A wave effect is given to the section by the undulating forms of the clefts. This arrangement of channels in the bone substance produces a very fine channel circulation. At short intervals within the clefts, as at C, figure 1, plate 1, may be seen small objects from which radiate minute canaliculi presenting the appearance of the canaliculi radiating from their lacunae, but these are in the vascular clefts and not in the bone substance.

TANGENTIAL SECTION OF A CRANIAL BONE OF THE MASCALONGE

PL. 1, FIG. 1B

In this section are seen parallel rows of objects of various shapes situated in the bone substance. Some of them are circular with dark crescents on one side, while others are very irregular in shape. No canaliculi extending outward from them can be seen. For this reason they cannot be lacunae in the bone substance, as osteoblasts occupying such lacunae would be without a blood supply. On account of their general circular character these objects appear to be different sections of the vascular clefts of the bone and if any bone-producing cells are present they must be within the vascular clefts.

CROSS SECTION OF ANOTHER PORTION OF THE LOWER JAW OF THE MASCALONGE SHOWING THE EARLY DIFFERENTIATIONS OF HAVERSIAN SYSTEMS

Pl. 1, Fig. 2

These are small vascular canals surrounded by clear areas—in some instances lamellated, in others, homogeneous. Between the vascular canals is the bone substance with very fine channels. The vascular canals with surrounding clear areas become Haversian systems as vascular differentiation progresses. This early form of Haversian differentiation has a wide distribution since it is found in bone sections from fish to and including man. It is much more prominent in the lower orders of vertebrates than in the higher. Thus two early phases of the circulation are found in the bone of the mascalonge, viz., the channeled and early Haversian differentiation.

TANGENTIAL SECTION OF THE INNER RIDGE OF THE LOWER JAW OF THE MASCALONGE SHOWING THE BLOOD VESSELS

Pl. 1, Fig. 3

The blood vessels vary in size. They are parallel with each other. Some are branching. Around the outside of their delicate connective tissue walls are seen fine plexuses of nerves. Between the vessels is seen a fine channeled bone substance without lacunae.

CROSS AND LONGITUDINAL SECTIONS OF THE FEMUR OF A MEDIUM SIZED BULLFROG, RANA CATESBEIANA

(The large, medium sized and small bullfrogs have different degrees of bone differentiation.) [4]

CROSS SECTION SHOWING THE STRUCTURE

Pl. 1, Fig. 4

The type of bone is an early first. The inner wall is composed of bone substance in which are radiating, vascular, bush-like channels extending from the external to the internal circumferential lamellae and between which are round or oval lacunae with short branching canaliculi embedded in the bone substance and communicating with the bush-like radiations by means of their canaliculi. The bush-like vascular radiations appear to be segmented in some instances due to their oblique positions and the plane of the cross section. In the outer wall these radiating channels are absent and the bone is composed of lamellae with oval lacunae and radiating canaliculi.

[4] *Idem.*

LONGITUDINAL SECTION OF THE SAME FEMUR SHOWING THE CIRCULATION

Pl. 1, Fig. 5

The oblique entering canals in the shafts of the femora of bull frogs, for the passage of the medullary arteries, are found in the bone of the large and medium sized but not in the small animals. As the femur of the frog is small and round the circulation in a tangential section could not be seen. The general plan, however, is shown in a longitudinal section of the inner wall as represented in figure 5, plate 1. The letter C is placed at the center of the shaft. In this wall are two sets of six or seven oblique vascular canals entering the shaft from the periosteal surface and united in such a manner as to form slanting m-shaped converging loops. These loops, beginning near the extremities of the shaft, converge toward the lineal center and medullary surface. From these loops and their stems minute canaliculi are sent off into the bone substance where they communicate with the lacunae. Between the two sets of converging loops are short segments of loops extending across the wall transversely. In the outer wall the loops are not seen in longitudinal section nor are the radiating vascular channels seen in the cross section of this wall.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF THE REPTILE, ALLIGATOR MISSISSIPPIENSIS

CROSS SECTION SHOWING THE STRUCTURE

Pl. 1, Fig. 6

This section is composed of three wide, concentric rings of incompletely differentiated Haversian systems alternating with two narrow, concentric laminae. The vascular canals surrounded by clear areas similar to those seen in the bone of the fish are early forms of Haversian systems. The laminae are more advanced in differentiation than the Haversian systems. The bone, as a whole, shows an early second and third type structure.

TANGENTIAL SECTION OF THE SAME FEMUR, SHOWING THE CIRCULATION

Pl. 1, Fig. 7

The circulation is in the form of a vascular plexus. The section is situated below the periosteal surface near the posterior ridge. Several entering canals, without surrounding lamellae, are seen in cross section in the bone substance through which periosteal vessels pass into the bone. The vascular plexus is very extensive and has a general longitudinal direction. The meshes are irregular in size and shape. In some portions of the section vascular expansions are found. The blood vessels are round and occupy similarly shaped channels in the bone substance. They are composed of very thin connective tissue walls, without smooth muscle, and are striated spirally and longitudinally. The exact purpose of the vascular expansions is not clearly understood. They are found too frequently to be accidental, and, as will be noted later, are more prominent in the branching than in the plexiform types of circulation. They may have an important physical value.

CROSS AND TANGENTIAL SECTIONS OF A SECOND TYPE BONE OF BIRDS AS SEEN IN THE FEMUR OF A DOMESTIC TURKEY, MELEAGRIS GALLOPAVO

CROSS SECTION SHOWING THE STRUCTURE

Pl. 1, Fig. 8

The section is composed of concentric laminae separated and crossed by vascular canals. The wall of the bone is divided into nearly equal segments by large radiating canals extending from the medullary canal to the periosteal surface. From these canals are sent off lateral, small, parallel canals which divide the wall of the bone into laminae. The laminae are interrupted in the anterior wall and posterior ridge by incompletely differentiated Haversian systems. It was the femur of the turkey which first called attention to the variations in structure and circulation.

TANGENTIAL SECTION OF A FEMUR OF THE TURKEY, SHOWING CIRCULATION

Pl. 1, Fig. 9

This section consists of a very rich, small-meshed plexus of vessels situated between the laminae and having a general longitudinal direction. In the central portion of the section two plexuses can be seen, one above the other, with a lamina of bone between them. This is one of the most extensive circulations observed in long bones and with such a blood supply as is here shown, this becomes a vascular organ of great importance.

RECONSTRUCTION OF A SECOND TYPE BONE WITH ITS INTERLAMINAR CIRCULATION

Pl. 2, Fig. 10

This figure shows a reconstruction of a second type bone with its circulation. The drawing represents three concentric laminae with two interlaminar plexuses of blood vessels. The vessels are uniform in size, composed of thin connective tissue walls and the vascular expansions are not at all prominent. It is difficult to understand why such a rich blood supply should be required in bone for its nutrition.

CROSS AND TANGENTIAL SECTIONS OF AN EARLY DIFFERENTIATION OF A THIRD TYPE BONE IN BIRDS AS SEEN IN THE FEMUR OF A TURKEY BUZZARD, CATHARTES AURA SEPTENTRIONALIS

CROSS SECTION SHOWING THE STRUCTURE

Pl. 2, Fig. 11

This bone is more advanced in differentiation than that of the domestic turkey since it is composed of third type structural bone units instead of the second. These units are enclosed between the external and internal circumferential lamellae and form nearly the whole bone structure.

TANGENTIAL SECTION OF THE FEMUR OF THE SAME ANIMAL SHOWING THE CIRCULATION

Pl. 2, Fig. 12

The meshes of the circulatory plexus are longer and enclose larger bone areas than those seen in the femur of the turkey. The vascular expansions are not as prominent as they are in some of the other bones, but may be seen here and there. A general plexiform plan of circulation is evident, but an elongation of the meshes in the central portion shows a slight variation in the circulatory distribution.

TANGENTIAL SECTION OF THE FEMUR OF A DOMESTIC CHICKEN, GALLUS

Pl. 2, Fig. 13

The type of structure is a first and early third. Several entering canals without surrounding lamellae are present. The circulation appears as a rich plexus of small blood vessels coming off from a central vessel which extends lengthwise of the section. The meshes of the plexus are small, round, oval or irregular in shape and the lacunae of the bone substance are round or oval with short, branching canaliculi.

TANGENTIAL SECTION OF THE FEMUR OF A PRAIRIE CHICKEN, TYMPANUCHUS AMERICANUS, SHOWING THE CIRCULATION

Pl. 2, Fig. 14

The type of bone is first. A few entering vascular canals, without surrounding lamellae, are seen in the bone substance. The circulation is a rich plexus of blood vessels with small, round and irregularly shaped meshes. It is situated nearer the periosteal than the medullary surface. The lacunae of the bone substance are round or oval and have short bushy canaliculi.

TANGENTIAL SECTION OF THE FEMUR OF A DOMESTIC DUCK, ANAS DOMESTICA, SHOWING THE CIRCULATION

Pl. 2, Fig. 15

The type of bone is an early second. The section has two rich plexuses of blood vessels, one above the other, with bone substance between them. The meshes are quite regular in form and somewhat larger than those found in the other birds examined. Here and there are seen entering vascular canals without surrounding lamellae. The lacunae of the bone substance are round or oval with short bushy canaliculi.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF A FRUIT BAT, PTEROPUS (CELEBES)

CROSS SECTION SHOWING THE STRUCTURE

Pl. 2, Fig. 16

The section is composed of a wide central ring of lamellae perforated in the inner wall by a few vascular canals extending lengthwise of the bone. Internal circumferential lamellae surround the medullary canal and poorly differentiated external lamellae surround the section. The lacunae are oval with straight canaliculi.

TANGENTIAL SECTION OF THE SAME FEMUR SHOWING THE CIRCULATION

Pl. 2, Fig. 17

In this section are seen the vascular canals of the inner wall extending from above downward and inward. The canals are parallel with each other and some of them are branched. They were absent in the outer wall.

CROSS AND TANGENTIAL SECTIONS OF A SECOND TYPE BONE IN MAMMALS AS SEEN IN THE FEMUR OF A LAMB, OVIS

CROSS SECTION SHOWING THE STRUCTURE

Pl. 2, Fig. 18

The section is composed of concentric laminae which are more completely differentiated than they are in birds. Here and there the laminae are interrupted by Haversian systems of a late differentiation and the concentric canals between the laminae are widened at intervals and around them are incompletely differentiated lamellae forming an early aberrant type of Haversian system. The posterior ridge is composed of Haversian systems of a late differentiation.

TANGENTIAL SECTION OF THE FEMUR OF THE SAME ANIMAL SHOWING THE CIRCULATION

Pl. 2, Fig. 19

The circulatory plan of arrangement in this bone is not precisely like that observed in the second type bone in birds. While it is plexiform in character there is about it more or less irregularity in distribution approaching the branching type of circulation. Near the sides of the drawing the plexus has a long mesh; while in the central portion it has more of a branching character. The vascular expansion seen in the center of the drawing gives the impression of a distributing point in the circulation. A few entering vascular canals are seen.

CROSS AND TANGENTIAL SECTIONS OF ANOTHER SECOND TYPE BONE IN MAMMALS AS SEEN IN THE FEMUR OF THE MEXICAN BURRO

CROSS SECTION SHOWING STRUCTURE

Pl. 2, Fig. 20

The section is composed of concentric laminae interrupted by Haversian systems of different degrees of differentiation. The structure is similar to that seen in the femur of the lamb and a large number of other mammals which have the same type bone.

TANGENTIAL SECTION OF THE FEMUR OF THE SAME ANIMAL, SHOWING THE CIRCULATION

Pl. 2, Fig. 21

The type is plexiform and the meshes of the plexus are much more regular in shape than those seen in the femur of the lamb. There is no evidence of a branching character. The vascular expansions are not as prominent as they were in the femur of the lamb.

TANGENTIAL SECTION OF THE FEMUR OF AN ELK, ALCES AMERICANUS, SHOWING THE CIRCULATION

Pl. 3, Fig. 22

The type of bone is second. Several perforations in the bone substance for the passage of blood vessels are present. Some of them are surrounded by enclosing lamellae and some are not (Volkmann's canals). The circulation is an extensive plexus of blood vessels with round and irregularly shaped meshes. It has a general direction lengthwise of the bone.

TANGENTIAL SECTION OF THE FEMUR OF A BELGIAN HARE, LEPUS, SHOWING THE CIRCULATION

Pl. 3, Fig. 23

The type of bone is an early second and third. Entering vascular canals through which blood vessels are seen to pass and ramify in the bone substance are present in the central portion of the section. The canals are not surrounded by lamellae. The circulation is a combination of a branching and plexiform distribution. The vascular expansions are prominent. One is seen in a vessel shortly after entering the bone. It is a matter of observation in bone circulations that the type of circulation varies with the type of structure.

TANGENTIAL SECTION OF THE FEMUR OF A BULLDOG, SHOWING THE CIRCULATION

Pl. 3, Fig. 24

The type of bone is second and third. Entering vascular canals, without enclosing lamellae, are seen in the bone substance through which blood vessels are passing. The circulation is a dense branching and plexiform combination. The vessels are small in diameter, frequently branching, the union of their branches producing a plexiform effect.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF A MONKEY, MACACA RHESUS

CROSS SECTION SHOWING THE STRUCTURE

Pl. 3, Fig. 25

The type of bone is first and third. The section is composed of lamellae interrupted by Haversian systems of early and late differentiations. Crescents of late Haversian differentiation are found bordering upon the medullary canal in the anterior inner and posterior outer wall. The lacunae of the bone are long with straight canaliculi. The principal structure is lamellar and the type is much more first than third.

TANGENTIAL SECTION OF THE SAME FEMUR, SHOWING THE CIRCULATION

Pl. 3, Fig. 26

A few entering vascular canals without surrounding lamellae are present. The circulation is a dense branching type which, here and there, presents a slight appearance of the plexiform distribution. The blood vessels are large and trunk-like in places and a very few vascular expansions are present.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF A 9 MONTHS' HUMAN WHITE FETUS

CROSS SECTION SHOWING THE STRUCTURE

Pl. 3, Fig. 27

The section is composed of short laminae with central canals widening and shortening until they are transformed into Haversian systems. External circumferential lamellae surround the section (posterior wall excepted) and directly underneath the lamellae is a row of advanced differentiations of Haversian systems. The medullary canal is small, irregular in shape and situated in the anterior half of the section. The posterior wall is composed of Haversian systems of advanced differentiations and in the mid line where the walls of the bone unite is a narrow radiating layer of bone substance which disappears as complete union takes place.

TANGENTIAL SECTION OF THE SAME FEMUR SHOWING THE CIRCULATION

Pl. 3, Fig. 28

The circulation is plexiform in type, the general direction of which is longitudinal and slightly oblique. The vessels forming the plexus have short branches which seem to disappear in the bone substance within the meshes. Vascular expansions are present, one being shown in the left central portion of the figure.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF A WHITE CHILD 9 YEARS OLD

CROSS SECTION SHOWING THE STRUCTURE

Pl. 3, Fig. 29

The type of bone is first and third. Around the periphery of the section is a wide crescent shaped band of lamellae enclosing numerous vascular canals of the earliest Haversian differentiation, such as were observed in the bone of the fish, plate 1, figure 2. Around the medullary canal are the internal circumferential lamellae forming an enclosing ring of irregular widths. Within this ring are also found vascular canals of early Haversian differentiation extending longitudinally. Between the external and internal lamellae above described, is a ring of Haversian systems of late differentiation, deficient in the anterior wall and increasing in width in the outer lateral wall as it reaches the posterior ridge. The lacunae are long and narrow with straight canaliculi.

TANGENTIAL SECTION OF THE SAME FEMUR SHOWING THE CIRCULATION

Pl. 3, Fig. 30

Entering canals with and without enclosing lamellae are of frequent occurrence. The circulation is a combination of the branching and plexiform types. The central portion is branching and the lateral, plexiform, vascular expansions are not as prominent as they are in many other sections. The section shows the circulatory combination of type conforming to the structural type combination.

CROSS AND TANGENTIAL SECTIONS OF THE FEMUR OF ADULT MAN, A WHITE MALE

CROSS SECTION SHOWING THE STRUCTURE

Pl. 4, Fig. 31

The bone is third type in differentiation with the exception of a portion of the anterior wall where the remains of first type bone are found. The section is composed of completely differentiated Haversian systems, some of which are senile. The external circumferential lamellae are fragmentary, while the internal are complete.

TANGENTIAL SECTION OF THE SAME FEMUR, SHOWING THE CIRCULATION

Pl. 4, Fig. 32

The type of circulation is plexiform with wide, irregularly shaped meshes. Entering vascular canals surrounded by lamellae are seen here and there in the section. Vascular expansions are prominent. This section is taken from the bone represented in plate 4, figure 31, near the periosteal surface of the left side of the drawing and near the posterior ridge. It is difficult to think of the circulation as shown in plate 4, figure 32, as belonging to that locality.

TANGENTIAL SECTION OF THE FEMUR OF MAN, A WHITE MALE, SHOWING CIRCULATION

Pl. 4, Fig. 33

The type of bone is first and third. Numerous entering vascular canals with and without enclosing lamellae are present. The circulation is a dense branching and plexiform distribution of blood vessels with small meshes of various shapes. Vascular expansions are numerous and large. The lacunae of the bone substance are round, oval, and long and narrow with the canaliculi which belongs to each degree of differentiation. The density of the circulation varies in different bones of the same structural type and also in bones of different type combinations.

TANGENTIAL SECTION OF THE FEMUR OF MAN, A WHITE MALE, SHOWING THE CIRCULATION

Pl. 4, Fig. 34

The type of bone is first and third. The type of circulation is branching, changing to plexiform. Entering canals, for the most part without enclosing lamellae, are few in number in this section. The circulation shown in the drawing is situated in the external lamellae which encloses the internal third type differentiation. It is a large branch dividing into many small ones which, by uniting, form a plexiform distribution.

TANGENTIAL SECTION OF THE FEMUR OF MAN, A WHITE MALE, AGE 50, WHO DIED OF PULMONARY TUBERCULOSIS

Pl. 4, Fig. 35

The type of bone is third. The type of circulation is essentially branching although a coarsely plexiform arrangement can be distinguished. Entering canals with and without enclosing lamellae are seen in the bone substance. The blood vessels are irregular in size and shape and show varicose enlargements very frequently. Whether or not this varicose condition and irregularity in the circulation in bone are indices of similar changes in the general circulation cannot be told; but they may be thought of in connection with the pathological condition present in this individual.

THE CIRCULATION IN FLAT BONES

CROSS, LONGITUDINAL, AND TANGENTIAL SECTIONS OF A HUMAN FRONTAL BONE

CROSS SECTION SHOWING THE STRUCTURE

Pl. 4, Fig. 36

The bone is composed of outer and inner tables united by a central cancellous diplöe. The two tables are composed of first type bone enclosing a few Haversian systems in cross section and a few short segments of blood vessels. The diplöe is a coarse, cancellous bone with large, small, and irregularly shaped cavities enclosed by first type bone walls. The walls are composed of lamellae in which Haversian systems are seen in cross section. This section was taken from the vertical portion of the frontal bone.

LONGITUDINAL SECTION OF THE SAME FRONTAL BONE, SHOWING THE STRUCTURE

Pl. 4, Fig. 37

This section has practically the same structure as the cross section, as may be seen by comparing the drawings. This section is cut at right angles to that seen in plate 4, figure 36. It is taken from the same region, and Haversian systems, in cross section, are found in both situations. The Haversian systems therefore run at right angles to each other, which can hardly be accounted for on mechanical grounds.

TANGENTIAL SECTION OF THE OUTER TABLE OF THE SAME FRONTAL BONE TAKEN FROM THE SAME REGION AS FIGURE 36, PLATE 4, SHOWING THE CIRCULATION

Pl. 4, Fig. 38

The section is situated nearer the external surface of the bone than the diplöe. Numerous entering canals with and without enclosing lamellae are found in the bone substance. The circulation is branching in type. The vascular expansions are large and numerous and appear to form physical centers of distribution. The blood vessels are relatively large and frequently branch.

ENTERING VASCULAR CANALS OF THE OUTER TABLE OF THE FRONTAL BONE

Pl. 5, Fig. 39

There are two forms, the one at the left in the drawing without enclosing lamellae (Volkmann's canals), and the one at the right with enclosing lamellae. The Volkmann's canals are smaller than the others. As soon as the blood vessels pass through the external surface of the bone they send off branches into the planes of their divisions and form the branching distributions there.

TANGENTIAL SECTION OF THE INNER TABLE OF THE SAME FRONTAL BONE, SHOWING THE CIRCULATION

Pl. 5, Fig. 40

In this section the bone is perforated by numerous entering canals with and without enclosing lamellae. The blood vessels from the cerebral surface enter the bone by these canals and find their way to the diplöe. The circulation within the bone is branching in type and situated nearer the cerebral surface than the diplöe. Many vascular expansions are present with their incoming and outgoing vessels.

TANGENTIAL SECTION OF THE OUTER TABLE OF A HUMAN PARIETAL BONE, SHOWING THE CIRCULATION

Pl. 5, Fig. 41

The section is taken from the central portion of the bone. The type of bone is first. Entering vascular canals surrounded by lamellae are numerous. The circulation is branching in type. Vascular expansions are large and numerous. Those in the center give the impression of distributing points in the circulation.

TANGENTIAL SECTION OF THE INNER TABLE OF THE SAME PARIETAL BONE SHOWING THE CIRCULATION

Pl. 5, Fig. 42

The section is situated nearer the cerebral surface than the diplöe. Entering vascular canals with enclosing lamellae are numerous. The circulation is branching in type and not as dense as that of the outer table. The vascular expansions are many and large. The type of bone is first.

TANGENTIAL SECTION OF THE SQUAMOUS PORTION OF THE TEMPORAL BONE OF MAN, SHOWING THE CIRCULATION

Pl. 5, Fig. 43

The type of bone is first. Entering canals with and without enclosing lamellae are present. The circulation is branching in type and the vascular expansions are large and very numerous. The expansions vary in size and frequency of occurrence in different sections. In some instances they are very small and few in number, in others, large and numerous, and they are much more prominent in the branching than in the plexiform type of circulation. They are especially prominent in this section.

TANGENTIAL SECTION OF THE OUTER TABLE OF A HUMAN OCCIPITAL BONE, SHOWING THE CIRCULATION

Pl. 5, Fig. 44

The section is taken a short distance above the foramen magnum. The circulation is a dense branching type situated near the external surface of the bone. There are many vascular expansions from which branching vessels take their departure. Entering canals with and without surrounding lamellae are present in the first type bone substance.

TANGENTIAL SECTION OF THE INNER TABLE OF THE SAME OCCIPITAL BONE, SHOWING THE CIRCULATION

Pl. 5, Fig. 45

The type of bone is first. Entering canals with and without surrounding lamellae are numerous. The section is situated near the cerebral surface. The circulation is branching in type and very dense in character. Large branches extend in different directions and from these, small branches are sent off into the bone substance. The vascular expansions are not as numerous as those in the outer table, figure 44.

TWO VASCULAR EXPANSIONS AS THEY WERE SEEN IN THE OUTER TABLE OF THE OCCIPITAL BONE

Pl. 5, Fig. 46

The vascular expansions are observed in all branching and in many sections of the plexiform type of circulation. They are nearly always filled with fat globules with dark, wide contours which are so closely faceted together that they completely occupy the expansion cavities. This would, of course, block the circulation if it existed in the living bone. The condition was misleading in significance until it was noticed that the fat globules were found in ground sections and not in thin unground bone plates; so that they are probably produced by the melting heat of friction during the grinding process and fill the expansions. The expansions probably have a physical value as distributing centers in the circulation or they may be for the purpose of establishing and maintaining a circulatory equilibrium in bone.

TANGENTIAL SECTION OF A HUMAN INFERIOR MAXILLA, SHOWING THE CIRCULATION

Pl. 5, Fig. 47

The section is taken from the bone just in front of and below the left central incisor tooth. The type of bone is first. Entering canals with and without lamellae are present. The circulation is a branching plexiform type having a slanting direction from above downward and forward. The meshes are long and irregular in shape. Vascular expansions are numerous.

TANGENTIAL SECTION OF THE INFRA-SPINOUS FOSSA OF A HUMAN SCAPULA, SHOWING THE CIRCULATION

Pl. 6, Fig. 48

The type of bone is first with here and there an Haversian system. A few entering canals with enclosing lamellae are seen in the section. The circulation is a branching and plexiform type, the former predominating. Vascular expansions are prominent. The one in the center of the drawing suggests a distributing center.

TANGENTIAL SECTION OF THE SUPRA-SPINOUS FOSSA OF THE SAME SCAPULA, SHOWING THE CIRCULATION

Pl. 6, Fig. 49

The type of bone is first. A few entering canals with and without surrounding lamellae are present. The circulation is branching in type with a few vascular expansions. It takes an oblique direction from above downwards and toward the vertebral border.

CROSS AND TANGENTIAL SECTIONS OF THE 9TH RIB OF ADULT MAN, MALE WHITE

CROSS SECTION SHOWING THE STRUCTURE

Pl. 6, Fig. 50

This is a third type bone composed of Haversian systems of a late degree of differentiation. The systems extend lengthwise of the rib and enclose a cancellous center.

TANGENTIAL SECTION OF THE INNER WALL OF THE SAME RIB, SHOWING THE CIRCULATION

Pl. 6, Fig. 51

The section is taken from the posterior third of the bone. The circulation is an elongated plexus. In the center of the section is a vascular expansion which suggests a center of distribution for the blood vessels.

DEVELOPMENTAL ADVANCES IN THE CIRCULATION DETERMINE THE STRUCTURAL TYPES OF BONE

It is generally supposed that bone is preeminently mechanical in function on account of its position in the body and its rigid character. It forms the skeleton of the animal body, supports its weight, gives attachment to muscles by means of which locomotion is possible, serves as a framework upon which the viscera are hung, affords protection and gives efficiency to the laboratory of chemical activities constantly in operation during life. It is chiefly for these reasons that we attribute a mechanical function to bone. This thought is further strengthened by the microscopic structure so familiar to us either from personal observation or from text books of histology, in both of which bone is represented, usually, as composed of Haversian systems.

There are however, as shown before, three structural types of bone, the first, second, and third.

The first type is composed of bone substance or lamellae, the second of laminae which are produced by a vascular separation of lamellae into parallel divisions, and the third, of Haversian systems which are produced by arranging lamellae around small central vascular canals called Haversian canals. The Haversian system, therefore, is the most complex and highly organized bone unit. The types of structure follow the advancing changes in the circulation, since the second type bone is not recognizable until the first has been separated into laminae by parallel vascular canals. There are two general types of circulation, the branching and the plexiform, each one giving an individual character to the type of bone it produces. Bone derived from connective tissue membranes retains the branching circulation of those membranes, while bone derived from cartilage has the plexiform circulation.

In going from a branching to a plexiform type of circulation, the type of bone advances from the first to the second or third. The blood supply in a plexiform circulation is greater in volume than it is in a branching circulation, for the reason that there are more blood vessels in a given area in the former than in the latter. This increased blood supply adds an increased physiological value to the bone units of structure and is the foundation of advancement in tissue values: so that blood supply is determined by the extent, plan of distribution, or type of circulation and the type of tissue, physiologically considered, by the blood supply, or in this particular instance, the type of bone is determined by the type of circulation.

THE STRUCTURAL UNITS OF BONE—FIRST, SECOND, AND THIRD, OR LAMELLAE, LAMINAE, AND HAVERSIAN SYSTEMS—ARE NOT ESSENTIALLY MECHANICAL

If all bones were Haversian system bones, or, if there was any one bone which always has Haversian systems as the predominating structural units, no matter in what individual it was found, we might be convinced that their constant presence was sufficient evidence of a mechanical function. But when we know that there are three bone units of structure and that no one of them is constantly present in bones of different animals as the only unit, and not even in bones of individuals of the same birth,[5] the idea of a purely mechanical function of bone is severely shaken if not abandoned. The three units, the lamella, lamina, and Haversian system, are found in bones of various animals in such great proportional and locational confusion that their mechanical purposes disappear and we are obliged to look further for an explanation of their strange and unexpected occurrences.

Again, if we examine these units from a mechanical viewpoint and then observe their locations in the bones of different animals we will find that they are *not* always found where the same mechanical conditions would require them and are very often found where they could serve no mechanical function of any importance. Lamellae are layers of bone substance, laminae are strata composed of lamellae, and Haversian systems are hollow cylinders composed of a variable number of lamellae enclosing a central canal. Of the three units, therefore, the Haversian systems offer the most mechanical service by construction and are the best adapted to support weight, withstand muscular stress, and serve the general requirements of a skeleton. We would, then, naturally expect to find them constantly present in such long bones as the femur, tibia and fibula of quadrupeds and bipeds and generally absent from the flat bones of the head and face. But in these respects we are disappointed. They are found, as a pure type, in the long bones of only a few mammals and are absent as predominating units in the long bones of a large number of mammals including the three races of man, black, yellow-brown and white.[6] Haversian systems in their later degrees of differentiation are not found at all in amphibians, reptiles, birds, bats, monotremes, marsupials and many of the edentates, although the same mechanical functions are demanded by their vocational habits. In the femur, tibia, fibula, humerus, radius, ulna, clavicle, metacarpal and metatarsal bones of man, they are present as predominating

[5] *Idem.*

[6] *Idem.*

units in some and occur very infrequently in other individuals. In the flat bones of the cranium and in the irregular bones like those of the pelvis a few are found where it is difficult, if not impossible, to understand how they could perform any mechanical function of any value.

In the human frontal, parietal and occipital bones, a few Haversian systems may be found at right angles to each other; in the squamous portion of the temporal bone they extend vertically; in the hard palate, antero-posteriorly; in the superior and inferior maxillae, horizontally; in the spine of the scapula, horizontally; in the crest of the ilium horizontally; and in the ribs horizontally. In these different situations the mechanical functions of the Haversian systems do not seem to answer any requirement which is common to them all. Furthermore, they are not invariably found in these situations and even may not be present at all. Their presence or absence or situation within the bone is more satisfactorily explained if we assume that developmental advances in the circulation determine the types of bone.

CONCLUSIONS

A study of the circulations as they were observed in the foregoing slides leads one to the following conclusions:

1. That a cross section of bone gives no idea of the plan of circulation.

2. That there are two types of circulation, the branching and the plexiform, and these are seen only in tangential sections.

3. That the plan of circulation in bone derived from connective tissue is branching; derived from cartilage, plexiform.

4. That the circulation in a first type bone is branching, in the second and third, plexiform.

5. That the plexiform is a more advanced type of circulation than the branching and represents a later plan of vascular distribution and a more advanced degree of bone differentiation.

6. That bone is a very vascular organ.

7. That blood vessels are composed of extremely thin and finely striated connective tissue walls, without smooth muscle, occupying canals in the bone substance.

8. That vascular expansions occur in bone circulations and, by their positions, suggest equalizing blood pressures and uniformity in the circulation.

9. That developmental advances in the circulation determine types of bone.

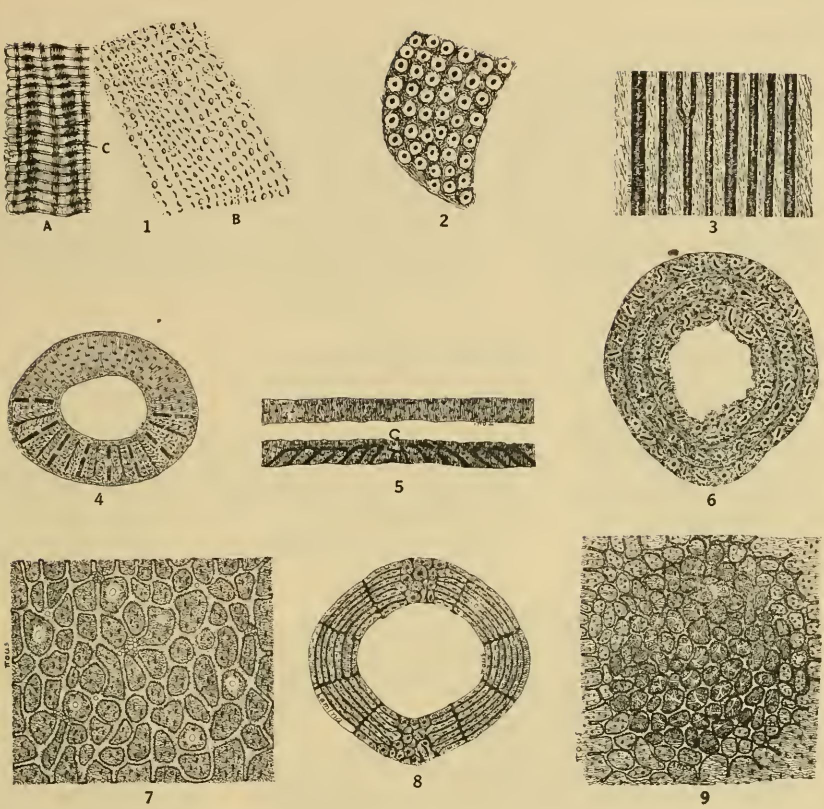

FIG. 1. A. Cross section of the bone substance of the lower jaw of a Mascalonge, Esox, showing vascular channels.

1. B. Tangential section of a cranial bone of the Mascalonge, showing parallel rows of small objects in the bone substance.

2. Cross section of the lower jaw of the Mascalonge, showing the early differentiation of Haversian systems.

3. Tangential section of the inner ridge of the lower jaw of Mascalonge, showing the circulation.

4. Cross section of the femur of a medium sized bullfrog, Rana catesbeiana, showing the structure.

5. Longitudinal section of the femur of a medium sized bullfrog, Rana catesbeiana, showing the looped vascular canals of the inner wall. C, center of the shaft.

6. Cross section of the femur of an alligator, Alligator mississippiensis, showing the structure.

7. Tangential section of the same, showing the circulation.

8. Cross section of the femur of a domestic turkey, Meleagris gallopavo, showing the structure.

9. Tangential section of the same, showing the circulation.

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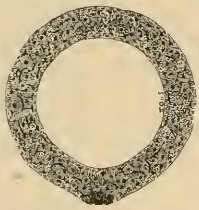

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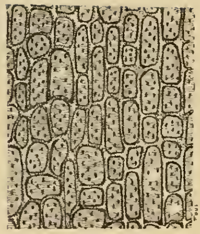

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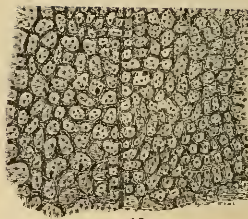

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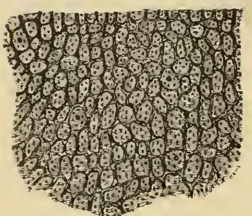

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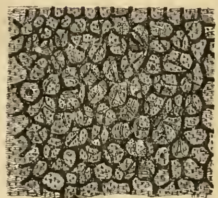

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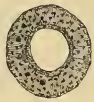

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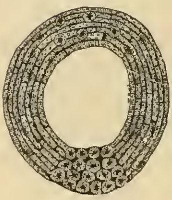

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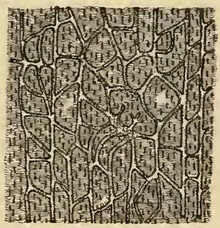

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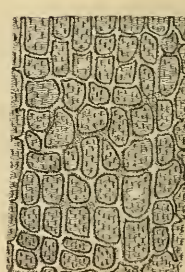

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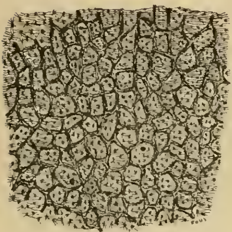
FIG. 10. Reconstruction of a second type bone with its circulation.
11. Cross section of the femur of a turkey buzzard, Cathartes aura septentrionalis, showing the structure.
12. Tangential section of the same, showing the circulation.
13. Tangential section of the femur of a domestic chicken, Gallus, showing the circulation.
14. Tangential section of the femur of a prairie chicken, Tympanuchus americanus, showing the circulation.
15. Tangential section of the femur of a domestic duck, Anas domestica, showing the circulation.
16. Cross section of the femur of a fruit bat, Pteropus (Celebes), showing the structure.
17. Tangential section of the same, showing the circulation.
18. Cross section of the femur of a lamb, Ovis, showing the structure.
19. Tangential section of the same, showing the circulation.
20. Cross section of the femur of a Mexican burro, showing the structure.
21. Tangential section of the same, showing the circulation.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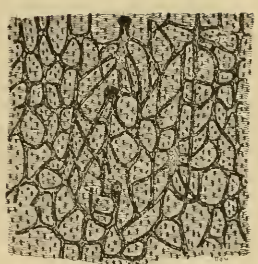
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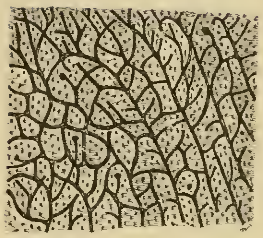
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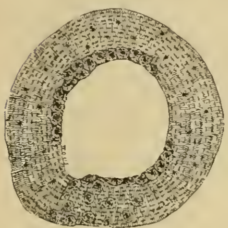
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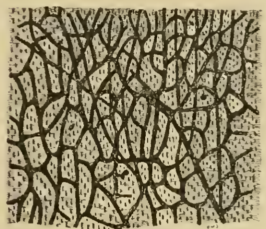
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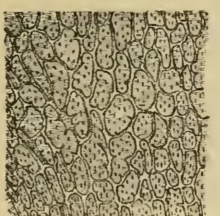
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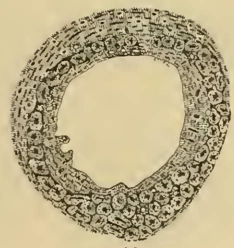
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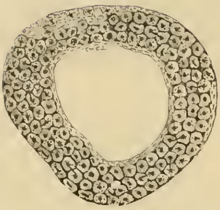
FIG. 22. Tangential section of the femur of an elk, Alces americanus, showing the circulation.
23. Tangential section of the femur of a Belgian hare, Lepus, showing the circulation.
24. Tangential section of the femur of a bulldog, showing the circulation.
25. Cross section of the femur of a monkey, Macaca rhesus, showing the structure.
26. Tangential section of the same, showing the circulation.
27. Cross section of the femur of a 9 months fetus (human), showing the structure.
28. Tangential section of the same, showing the circulation.
29. Cross section of the femur of a white child 9 years old, showing the structure.
30. Tangential section of the same, showing the circulation.



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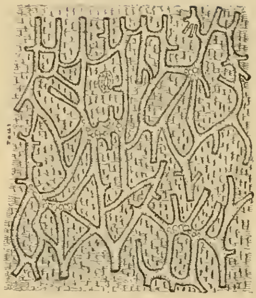

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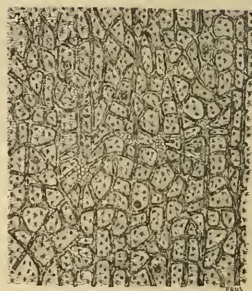

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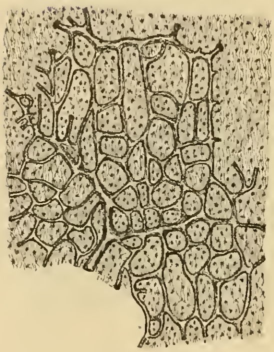

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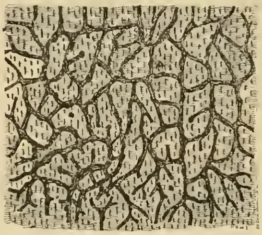

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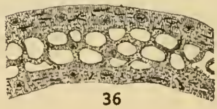

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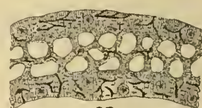

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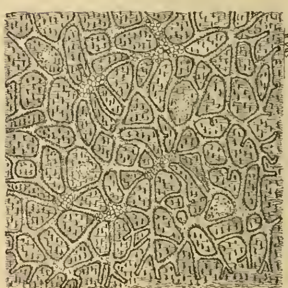

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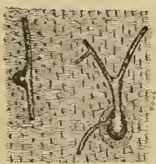
FIG. 31. Cross section of the femur of an adult white male, showing the structure.
32. Tangential section of the same, showing the circulation.
33. Tangential section of the femur of an adult white male, showing the circulation.
34. Tangential section of the femur of an adult white male, showing the circulation.
35. Tangential section of the femur of an adult white male, age 50, who died of pulmonary tuberculosis, showing the circulation.
36. Cross section of a human frontal bone, showing the structure.
37. Longitudinal section of the same, showing the structure.
38. Tangential section of the outer table of the same bone, showing the circulation.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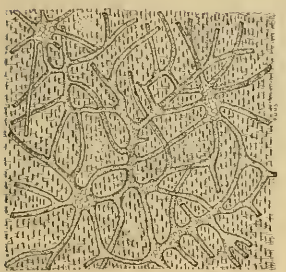
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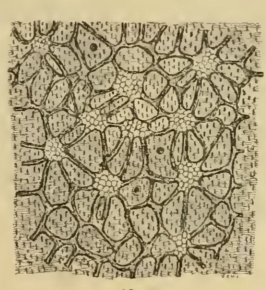
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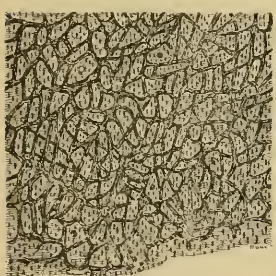
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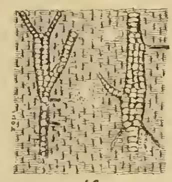
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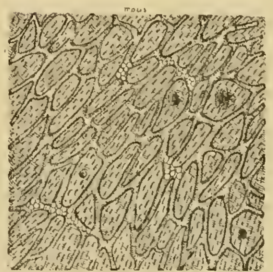
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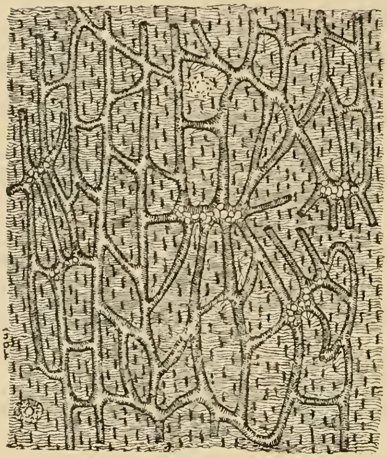
FIG. 39. Entering vascular canals of outer table of a human frontal bone.
40. Tangential section of the inner table of the same bone, showing the circulation.
41. Tangential section of the outer table of a human parietal bone, showing the circulation.
42. Tangential section of the inner table of the same bone, showing the circulation.
43. Tangential section of the squamous portion of a human temporal bone, showing the circulation.
44. Tangential section of the outer table of a human occipital bone, showing the circulation.
45. Tangential section of the inner table of the same bone, showing the circulation.
46. Vascular expansions filled with fat globules as seen in outer table of occipital bones.
47. Tangential section of human inferior maxilla in front of and just below left central incisor tooth, showing the circulation.



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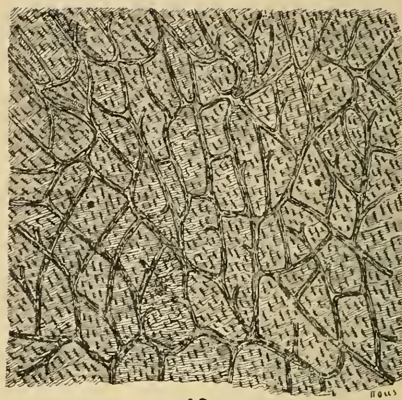

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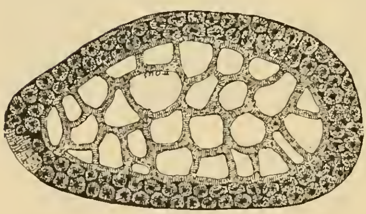

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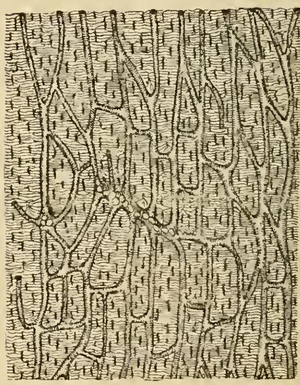

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FIG. 48. Tangential section of the infra-spinous fossa of a human scapula, showing the circulation.

49. Tangential section of the supra-spinous fossa of the same bone, showing the circulation.

50. Cross section of the 9th rib of an adult white male, showing the structure.

51. Tangential section of the same bone, inner wall, showing the circulation.