They are largest in the glands and bones, where they are $\frac{1}{3000}$ to $\frac{1}{2000}$ of an inch (8·3 to 12·5 μ) in diameter. These measurements indicate the size of the vessels and not their caliber. Taking out the thickness of their walls, it is only the very largest of them that will allow the passage of a blood-disk without a change in its form. The average length of the capillary vessels is about $\frac{1}{50}$ of an inch (0·5 mm.).

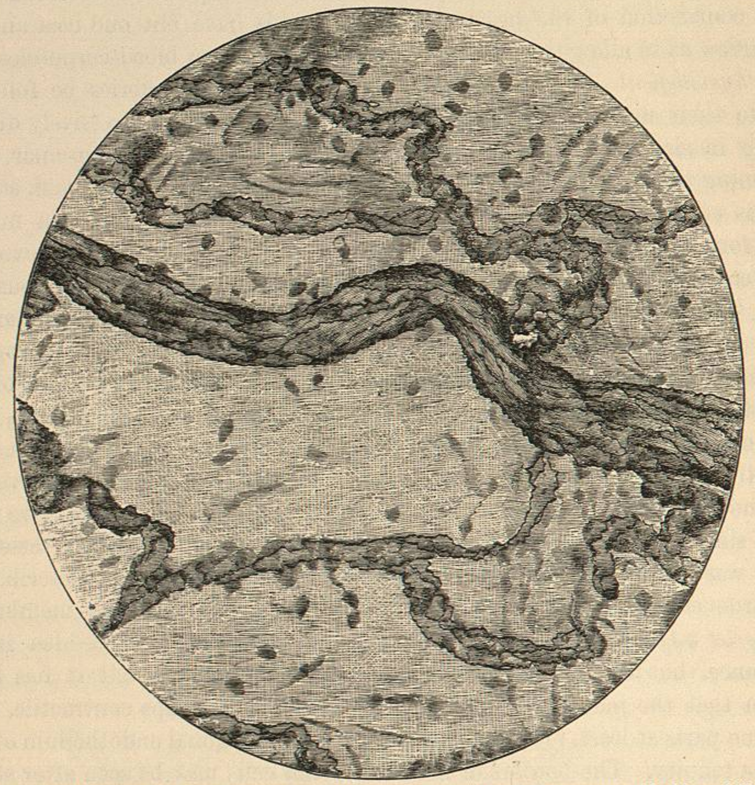

Fig. 32.—*Small artery and capillaries from the muscular coats of the urinary bladder of the frog; magnified* 400 *diameters* (from a photograph taken at the United States Army Medical Museum).
This preparation shows the endothelium of the vessels. It is injected with silver nitrate, stained with carmine and mounted in Canada balsam.

Unlike the arteries, which grow smaller as they branch, and the veins, which become larger, in following the course of the blood, by union with each other, the capillaries form a true plexus of vessels of nearly uniform diameter, branching and inosculating in every direction and distributing blood to the parts as their physiological necessities demand. This mode of inosculation is peculiar to these vessels, and the plexus is rich in the tissues, as a general rule, in proportion to the activity of their nutrition. Although their arrangement presents certain differences in different organs, the capillary vessels have everywhere the same general characteristics, the most prominent of which are the nearly uniform diameter and an absence of any definite direction. The net-work thus formed is very rich in the substance of the glands and in the organs of absorption; but the vessels are distended with

blood only during the physiological activity of these parts. In the lungs the meshes are particularly close. In other parts the vessels are not so abundant, presenting great variations in different tissues. In the muscles and nerves, in which nutrition is very active, the supply is much more abundant than in other parts, like fibro-serous membranes, tendons etc. In none of the tissues do the capillaries penetrate the anatomical elements of the part, as the ultimate muscular or nervous fibres. Some tissues receive no blood, or at least they contain no vessels which are capable of carrying red blood, and are nourished by imbibition of the nutrient plasma of the circulating fluid. Examples of these, which are called extra vascular tissues, are cartilage, nails and hair.

The capacity of the capillary system is very great. It is necessary only to consider the great vascularity of the skin, mucous membranes or muscles, to appreciate this fact. In injections of these parts, it seems, on microscopical examination, as though they contained nothing but capillaries; but in preparations of this kind, the elastic and yielding coats of the capillaries are distended to their utmost limit. Under some conditions, in health, they are largely distended with blood, as in the mucous lining of the alimentary canal during digestion, the whole surface presenting a vivid-red color, indicating the great richness of the capillary plexus. Estimates of the capacity of the capillary system, as compared with the arterial system, have been made, but they are simply approximative. The various estimates given are founded upon calculations from microscopical examinations of the rapidity of the capillary circulation as compared with the circulation in the arteries. In this way, it has been estimated that the capacity of the capillary system is between five hundred and eight hundred times that of the arterial system. These estimates, however, must be regarded as mere suppositions based upon no very accurate data.

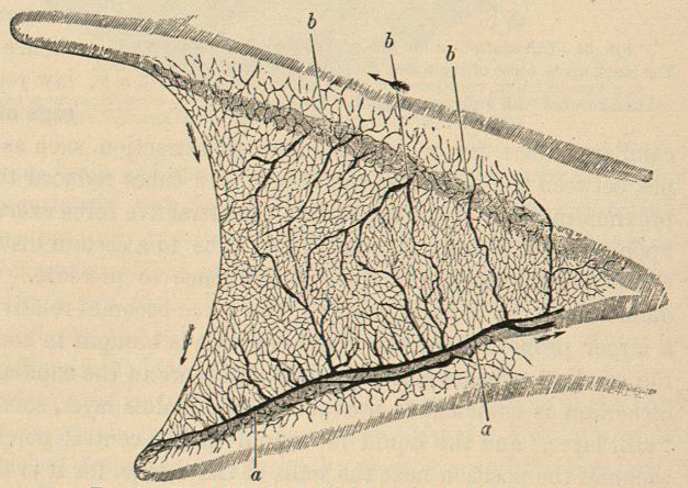

Fig. 33.—*Web of the frog's hind-foot; magnified* (Wagner).
a, *a*, veins; *b*, *b*, *b*, arteries.

Phenomena of the Capillary Circulation.—The most convenient situation for observation of the capillary circulation is the tongue or the web of the frog. Here may be studied, not only the movement of the blood in the true capillaries, but the circulation in the smallest arteries and veins, the variations in caliber of these vessels, especially the arterioles, by the action of their muscular coat, and, indeed, the action of vessels of considerable size. This has been a valuable means of studying the circulation in the capillaries as contrasted with the flow in the small arteries and veins, and the only one, indeed, which could give any definite idea of the action of these vessels.

In studying the circulation under the microscope, the anatomical division of the blood into corpuscles and a clear plasma is observed. This is peculiarly evident in cold-blooded animals, the corpuscles being comparatively large and floating in a plasma which forms a distinct layer next the walls of the vessel. The leucocytes, which are much fewer than the red corpuscles, are generally found in the layer of plasma.

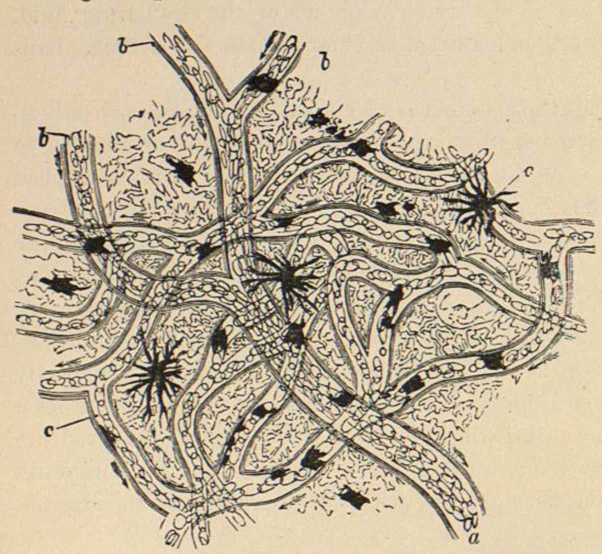

FIG. 34.—*Circulation in the web of the frog's foot* (Wagner). The black spots, some of them star-shaped, are collections of pigment. *a*, a venous trunk, composed of three principal branches (*b*, *b*, *b*), and covered with a plexus of smaller vessels (*c*, *c*).

In vessels of considerable size as well as in some capillaries, the corpuscles, occupying the central portion, move with much greater rapidity than the rest of the blood, leaving a layer of clear plasma at the sides, which is nearly motionless. This phenomenon is in obedience to a physical law regulating the passage of liquids through capillary tubes for which they have an attraction, such as exists, for example, between the blood and the vessels. In tubes reduced to a diameter approximating that of the capillaries, the attractive force exerted by their walls upon a liquid, causing it to enter the tube to a certain distance, becomes an obstacle to the passage of fluid in obedience to pressure. Of course, as the diameter of the tube is reduced, this force becomes relatively increased, for a larger proportion of the liquid contents is brought in contact with it. In the smallest arteries and veins, and still more in the capillaries, the capillary attraction is sufficient to produce the motionless layer, sometimes called the "still layer," and the liquid moves only in the central portion. The plasma occupies the position next the walls of the vessels, for it is this portion of the blood which is capable of "wetting" the tubes. The transparent layer was observed by Malpighi, Haller and all who have described the capillary circulation. Poiseuille recognized its true relation to the blood-current and explained the phenomenon of the still layer by physical laws, which had been previously established with regard to the flow of liquids in tubes of the diameter of one twenty-fifth to one one-eighth of an inch (1 to 3·2 mm.), but which he had succeeded in applying to tubes of the size of the capillaries.

A red corpuscle occasionally becomes involved in the still layer, when it moves slowly, turning over and over, or even remains stationary for a time,

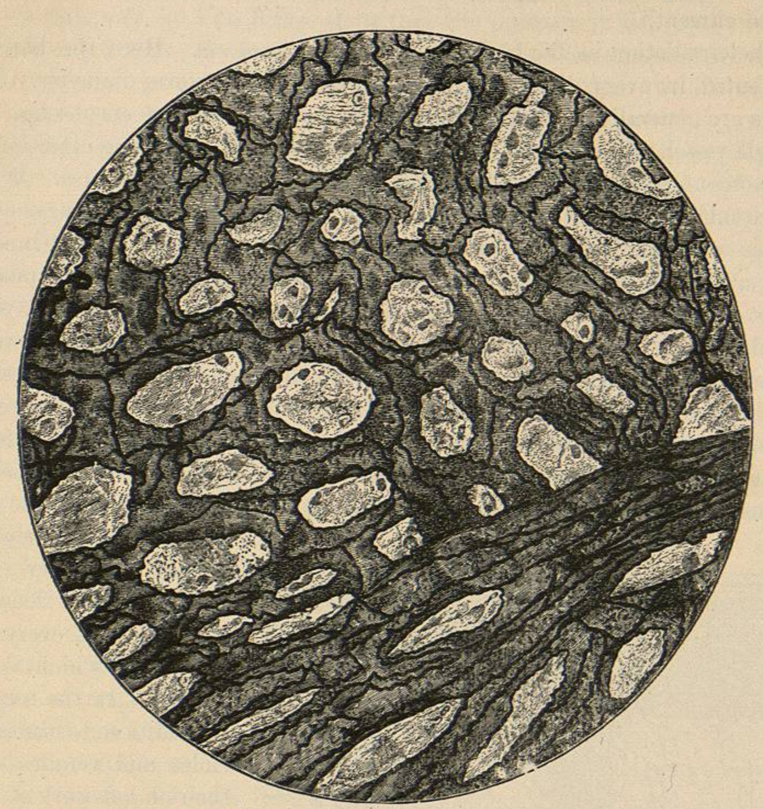

FIG. 35.—*Small artery and capillaries from the lung of a frog; magnified 500 diameters* (from a photograph taken at the United States Army Medical Museum).

until it is taken up again and carried along with the central current. A few leucocytes are constantly seen in this layer. They move along slowly and apparently have a tendency to adhere to the walls of the vessel. This is due to the adhesive character of the surface of the white corpuscles as compared with the red, which can easily be observed in examining a drop of blood between glass surfaces, the red corpuscles moving about freely, while the white corpuscles have a tendency to adhere to the glass.

Great differences exist in the character of the flow of blood in the three varieties of vessels which are under observation. In the arterioles, which may be distinguished from the capillaries by their size and the presence of the muscular and fibrous coats, the movement is distinctly remittent, even in their most minute ramifications. The blood moves in them with much greater rapidity than in either the capillaries or veins. They become smaller as they branch, and carry the blood always in the direction of the capillaries. The veins, which are relatively larger than the arteries, carry the blood more slowly and in a continuous stream from the capillaries toward the heart. In both the arteries and veins the current is frequently so rapid that the form of the corpuscles can not be distinguished. Only a few of the white corpuscles occupy the still layer, the others being carried on in the central current.

The circulation in the true capillaries is *sui generis*. Here the blood is distributed in every direction, in vessels of nearly uniform diameter. The vessels are generally so small as to admit but a single row of corpuscles. In a single vessel, a line of corpuscles may be seen moving in one direction at one moment, a few moments after, taking a directly opposite course. When the circulation is normal, the movement in the capillaries is always quite slow as compared with the movement in the arterioles, and is continuous. Here, at last, the intermittent impulse of the heart is lost. The corpuscles do not necessarily circulate in all the capillaries that are in the field of view. Certain vessels may not receive a corpuscle for some time, but afterward, one or two corpuscles become engaged in them and a current is established. A corpuscle is sometimes seen caught at the angle where a vessel divides into two, remaining fixed for a time, distorted and bent by the force of the current. It soon becomes released, and as it enters the vessel, it regains its original form. In some of the vessels of smallest size, the corpuscles are slightly deformed as they pass through. The scene is changed with every different part which is examined. In the tongue, in addition to the arterioles and venules with the rich net-work of capillaries, dark-bordered nerve-fibres, striated muscular fibres, and epithelium can be distinguished. In the lungs large, polygonal air-cells are observed, bounded by capillary vessels, in which the corpuscles move with great rapidity. It has been observed, also, that the larger vessels in the lungs are crowded to their utmost capacity with corpuscles, leaving no still layer next the walls, such as is seen in the circulation in other situations.

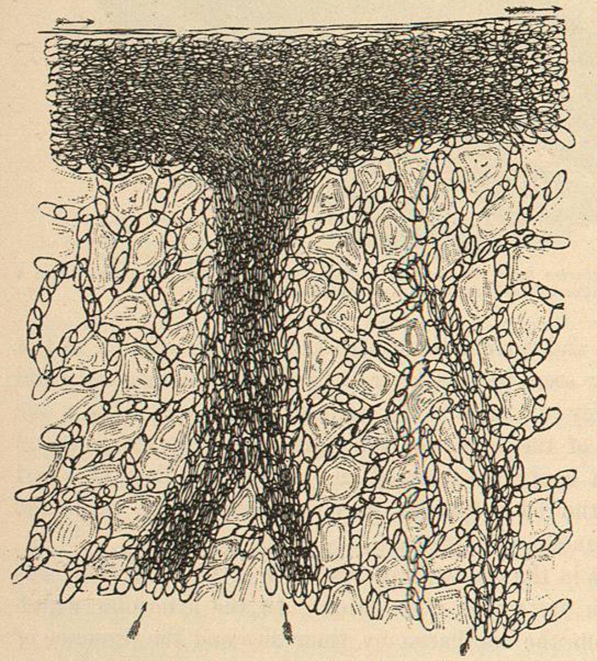

FIG. 36.—*Portion of the lung of a live triton, drawn under the microscope and magnified 150 diameters* (Wagner).

Pressure of Blood in the Capillaries.—There is, apparently, no way of directly estimating the pressure of blood in the capillaries. If, however, a glass plate be placed upon a part in which the capillary circulation is active

and be weighted until the subjacent capillaries are emptied, an approximate idea of the blood-pressure in the vessels may be obtained. Experiments made in this way, by Von Kries, show that the pressure in the capillaries of the hand raised above the head is equal to a little less than one inch (24 mm.) of mercury; in the hand hanging down, a little more than two inches (54 mm.); and in the ear, about 0·8 of an inch (20 mm).

Rapidity of the Capillary Circulation.—The circulation in the capillaries of a part is subject to such great variations and the differences in different situations are so considerable, that it is impossible to give any definite rate which will represent the general rapidity of the capillary circulation. It is for this reason that it has been found impracticable to estimate accurately the capacity of the capillary as compared with the arterial system. In view of the great uncertainty in the methods employed in the estimation of the rapidity of the flow of blood in the capillaries, it seems unnecessary to discuss this question fully. Volkmann calculated the rapidity in the mesentery of the dog and found it to be about one-thirtieth of an inch (0·85 mm.) per second. Vierordt made a number of curious observations upon himself, by which he professed to be able to estimate the rapidity of the circulation in the little vessels of the eye; and by certain calculations, he formed an estimate of its rapidity, putting it at one-fortieth to one-twenty-eighth of an inch (0·63 and 0·9 mm.) per second, which estimate may be provisionally adopted as the probable rate in the human subject.

Relations of the Capillary Circulation to Respiration.—In treating of the influence of respiration upon the action of the heart, the arterial pressure, pulse etc., it has already been stated that non-aërated blood can not circulate freely in the capillaries. Various ideas with regard to the effects of asphyxia upon the circulation have been advanced, which will be again discussed in connection with the physiology of respiration. It is well known that arrest of respiration produces arrest of circulation.

The immediate effects of asphyxia upon the circulation are referable to the general capillary system. In a series of experiments made in 1857, the medulla oblongata was broken up, and the web of the foot was submitted to microscopical examination. This operation does not interfere with the circulation, which may be observed for hours without difficulty. The cutaneous surface was then coated with collodion, care only being taken to avoid the web under observation. The effect on the circulation was immediate. It instantly became less rapid, until, at the expiration of twenty minutes, it had entirely ceased. The entire coating of collodion was then instantly peeled off. Quite a rapid circulation immediately began, but it soon began to decline and in twenty minutes had almost ceased. In another observation, the coating of collodion was applied without destroying the medulla. The circulation was affected in the same manner as before and ceased in twenty-five minutes (Flint). These experiments, taken in connection with observations on the influence of asphyxia upon the arterial pressure, show that non-aërated blood can not circulate freely in the systemic capillaries. Non-aërated blood, however, can be forced through them with a syringe, and even in asphyxia, it passes slowly into the veins. If air be admitted to the lungs before the heart has lost its contractility, the circulation is restored. No differences in the capillary circulation have been noticed accompanying the ordinary acts of inspiration and expiration.

Causes of the Capillary Circulation.—The contractions of the left ventricle are evidently capable of giving an impulse to the blood in the smallest arterioles; for a marked acceleration of the current accompanying each systole can be distinguished in all but the true capillaries. It has also been shown by experiments after death, that blood can be forced through the capillary system and returned by the veins by a force less than that exerted by the left ventricle. This, however, can not rigidly be applied to the natural circulation, as the smallest arteries during life are endowed with contractility, which is capable of modifying the blood-current. Sharpey adapted a syringe, with a hæmadynamometer attached, to the aorta of a dog just killed, and found that fresh defibrinated blood could be made to pass through the double capillary systems of the intestines and liver, by a pressure of three and a half inches (89 mm.) of mercury. It spurted out at the vein in a full jet under a pressure of five inches (127 mm.). In this observation, the aorta was tied just above the renal arteries. The same pressure, the ligature being removed, forced the blood through the capillaries of the inferior extremities.

It is thus seen that the pressure in the arteries which forces the blood toward the capillaries is competent, unless opposed by contraction of the arterioles, not only to cause the blood to circulate in the capillaries, but to return it to the heart by the veins; and the only questions to be considered are first, whether there be any reason why the force of the heart should not operate on the blood in the capillaries, and second, whether there be any force in these vessels which is superadded to the action of the heart. The first of these questions is answered by microscopical observations on the circulation. A distinct impulse, following each ventricular systole, is observed in the smallest arteries; the blood flows from them directly and freely into the capillaries; and there is no ground for the supposition that the force is not propagated to this system of vessels. There is, therefore, a force, the action of the heart, which is capable of producing the capillary circulation; and there is nothing in the phenomena of the circulation in these vessels which is inconsistent with its full operation. When the heart ceases its action, movements in the capillaries are sometimes due to the contractions of the arteries, an action which has already been fully described. Movements which have been observed in membranes detached from the body were undoubtedly due to the mere emptying of the divided vessels or to simple gravitation.

There is a circulation of the blood in the area vasculosa, the first blood-vessels that are developed before the heart is formed; but there are no definite and reliable observations which show that there is any regular movement of the blood, which can be likened to the circulation as it is observed after the development of the heart, anterior to the appearance of a contractile central organ. Another example of what is supposed to be circulation without the intervention of the heart is in cases of acardiac fœtuses. Monsters without a heart, which have undergone considerable development and which present systems of arteries, capillaries and veins, have been described. All of these, however, are accompanied by a twin, in which the development of the circulatory system is quite or nearly perfect.

Influence of Temperature on the Capillary Circulation.—Within moderate limits, a low temperature, produced by local applications, has been found to diminish the quantity of blood sent to the capillaries and retard the circulation, while a high temperature increases the supply of blood and accelerates its current. Poiseuille found that when a piece of ice was applied to the web of a frog's foot, the mesentery of a small warm-blooded animal or to any part in which the capillary circulation can be observed, the number of corpuscles circulating in the arterioles became very much diminished, "those which carried two or three rows of corpuscles giving passage to but a single row." The circulation in the capillaries first became slower and then entirely ceased in parts. On removing the ice, in a very few minutes the circulation regained its former characters. When, on the other hand, the part was covered with water at 104° Fahr. (40° C.), the rapidity of the current in the capillaries was so much increased that the form of the corpuscles could with difficulty be distinguished.

Circulation of the Blood in the Veins.

The blood, distributed to the capillaries of all the tissues and organs by the arteries, is colected from these parts in the veins and carried back to the heart. In studying the anatomy of the capillaries or in observing the passage of the blood from the capillaries to larger vessels in parts of the living organism which can be submitted to microscopical examination, it is seen that the capillaries, vessels of nearly uniform diameter and anastomosing in every direction, empty into a system of vessels, which, by union with others, become larger and larger, and carry the blood away in a uniform current. These are called the venules, or venous radicles. They are the peripheral radicles of the vessels which carry the blood to the heart.

The venous system may be considered, in general terms, as divided into two sets of vessels; one, which is deep-seated and situated in proximity to the arteries, and the other, which is superficial and receives the greatest part of the blood from the cutaneous surface. The entire capacity of these vessels, as compared with that of the arteries, is very great. As a general rule, each vein, when fully distended, is larger than its adjacent artery. Many arteries are accompanied by two veins, as the arteries of the extremities; while certain of them, like the brachial or spermatic, have more than two. Added to these, are the superficial veins which have no corresponding arteries. It is true that some arteries have no corresponding veins, but examples of this kind are not sufficient in number to diminish, in any marked degree, the great preponderance of the veins, both in number and volume. It is impossible to give an accurate estimate of the extreme capacity of the veins as compared with the arteries, but it must be much greater. Borelli estimated that the capacity of the veins was to the capacity of the arteries, as 4 to 1; and Haller, as $2\frac{1}{4}$ to 1. The proportion is very variable in different parts of

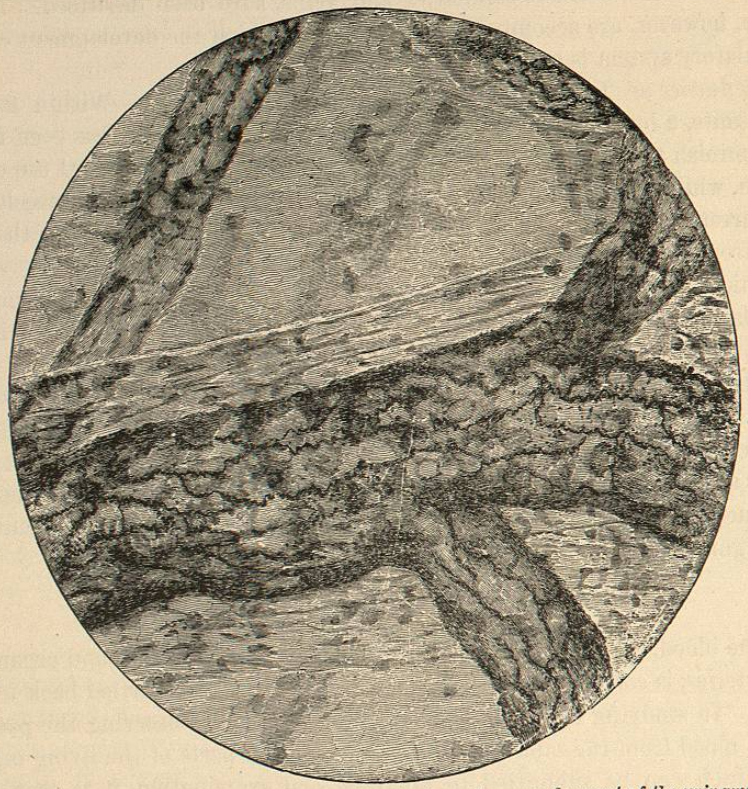

FIG. 37.—*Venous radicles uniting to form a small vein, from the muscular coat of the urinary bladder of the frog; magnified 400 diameters* (from a photograph taken at the United States Army Medical Museum).

This preparation shows the endothelium of the vessels. It is injected with silver nitrate, stained with carmine and mounted in Canada balsam.

the body. In some situations the capacity of the veins and arteries is about equal; while in others, as in the pia mater, the veins will contain, when fully distended, six times as much as the arteries.

In attempting to compare the quantity of blood normally circulating in the veins with that contained in the arteries, such variations are found at different times and in different parts, both in the quantity of blood, rapidity of circulation, pressure etc., that a definite estimate is impossible. It would be unprofitable to attempt even an approximate comparison, as the variations in the venous circulation constitute one of its most important physiological peculiarities, which must be fully appreciated in order to form a just idea of the uses of the veins. The arteries are always full, and their tension is subject to comparatively slight variations. Following the blood into the capillaries, important modifications in the circulation are observed, with varying physiological conditions of the parts. As would naturally be expected, the condition of the veins varies with the changes in the capillaries from which the blood is received. In addition to this, there are independent variations,

as in the erectile tissues, in the veins of the alimentary canal during absorption, in veins subject to pressure, etc.

Following the veins in their course, it is observed that anastomoses with each other form the rule, and not the exception, as in the arteries. There is always a number of channels by which the blood may be returned from a part; and if one vessel be obstructed from any cause, the current is simply diverted into another. The veins do not present a true anastomosing plexus, such as exists in the capillary system, but simply an arrangement by which the blood can readily find its way back to the heart, and by which the vessels may accommodate themselves to the frequent variations in the quantity of their fluid contents. This, with the peculiar valvular arrangement which exists in all but the veins of the cavities, provides against obstruction to the flow of blood through as well as from the capillaries, in which it seems essential to the proper nutrition and action of parts that the quantity and course of the blood should be regulated exclusively through the arterial system.

Collected by the veins from all parts of the body, the blood is returned to the right auricle, from the head and upper extremities by the superior vena cava, from the trunk and lower extremities, by the inferior vena cava, and from the substance of the heart, by the coronary veins.

Structure and Properties of the Veins.—The structure of the veins is more complex than that of the arteries. Their walls, which are always much thinner than the walls of the arteries, may be divided into a number of layers; but for convenience of physiological description, they may be regarded as presenting three distinct coats. These have properties which are somewhat distinctive for each, although not as much so as those of the three coats of the arteries.

The internal coat of the veins is a continuation of the single coat of the capillaries and of the internal coat of the arteries. It is a simple, homogeneous membrane, somewhat thinner than in the arteries, lined by a delicate layer of polygonal endothelium, the cells of which are shorter and broader than the endothelial cells of the arteries.

The middle coat is divided by some anatomists into two layers; an internal layer, which is composed chiefly of longitudinal fibres, and an external layer, in which the fibres have a circular direction. These two layers are intimately adherent and are quite closely attached to the internal coat. The longitudinal fibres are composed of connective-tissue fibres mingled with a large number of the smallest variety of the elastic fibres. This layer contains a large number of capillary vessels (vasa vasorum). The circular fibres are composed of elastic tissue, some of the fibres of the same variety as is found in the longitudinal layer, some of medium size, and some in the form of the "fenestrated membrane." In addition, there are inelastic fibres interlacing in every direction and mingled with capillary blood-vessels, and non-striated muscular fibres. In the human subject, in the veins of the central portion of the nervous system, the dura mater, the pia mater, the bones, the retina, the vena cava descendens, the thoracic portion of the vena cava ascendens, the external and internal jugulars and the subclavian veins, there