observations on the arteries of the human subject and the lower animals; and by means of a "*schema*," representing the arterial system by elastic tubes and the left ventricle by an elastic bag provided with valves and acting as a syringe, he established the conditions of tension etc., necessary to their production. In this *schema*, the registering apparatus, simpler in construction than the sphygmograph, could be applied to the tubes with more accuracy and ease. He demonstrated by experiments with this system of tubes, that the amplitude of the pulsations, the force of the central organ being the same, is greatest when the tubes are moderately distended, or when the tension of fluid is low, and *vice versâ*. He demonstrated, also, that a low tension favors dicrotism. In this latter observation, he diminished the tension by enlarging the orifices by which the fluid was discharged from the tubes, imitating the dilatation of the small vessels, by which the tension is diminished in the arterial system. He also demonstrated that an important and essential element in the production of dicrotism is the tendency to oscillation of the fluid in the vessels during the intervals between the contractions of the heart. This can only occur in a fluid which has a certain weight and acquires a velocity from the impulse; for when air was introduced into the apparatus, dicrotism could not be produced under any conditions, as the fluid did not possess weight enough to oscillate between the impulses. Water produced a well marked dicrotic impulse under favorable conditions; and with mercury, the oscillations made two, three or more distinct impulses. By these experiments, he proved that the blood oscillates in the vessels, if this movement be not suppressed by too great pressure or tension. This oscillation gives the successive rebounds that are marked in the descending line of the pulse, and is capable, in some rare instances when the arterial tension is very slight, of producing a second rebound of sufficient force to be appreciated by the finger.

Without treating of the variations in the character of the pulse in disease, due to the action of the muscular coat of the arteries, it will be useful to consider some of the external modifying influences which come within the range of physiology. The smallest vessels and those of medium size possess to an eminent degree what is called tonicity, or the property of maintaining a certain continued degree of contraction. This contraction is antagonistic to the distending force of the blood, as is shown by opening a portion of an artery included between two ligatures in a living animal, when the contents will be forcibly discharged and the caliber of that portion of the vessel be very much diminished. Too great distention of the vessels by the pressure of blood seems to be prevented by this constant action of the muscular coat; and thus the conditions are maintained which give to the pulse the characters just described.

By excessive and continued heat, the muscular tissue of the arteries may be dilated so as to offer less resistance to the distending force of the heart. Under these conditions, the pulse, as felt by the finger, will be found to be larger and softer than normal. Cold, either general or local, has an opposite effect; the arteries become contracted, and the pulse assumes a harder and more wiry character. As a rule, prolonged contraction of the arteries is followed by relaxation, as is seen in the full pulse and glow of the surface which accompany reaction after exposure to cold. It has been found, also, that there is a considerable difference in the caliber of the arteries at different periods of the day. The diameter of the radial has been found very much greater in the evening than in the morning, producing, naturally, a variation in the character of the pulse.

Pressure of Blood in the Arteries.

The reaction of the elastic walls of the arteries during the intervals of the heart's action gives rise to a certain degree of pressure, by which the blood is continually forced toward the capillaries. The discharge of blood into the capillaries has a constant tendency to diminish this pressure; but the contractions of the left ventricle, by forcing repeated charges of blood into the arteries, have a compensating action. By the equilibrium between these two agencies, a certain tension is maintained in the arteries, which is called the arterial pressure.

The first experiments with regard to the extent of the arterial pressure were made by Hales, an English physiologist, more than a hundred years ago. This observer, adapting a long glass tube to the artery of a living animal, ascertained the height of the column of blood which could be sustained by the arterial pressure. In some experiments on the carotid of the horse, the blood mounted to the height of eight to ten feet (243 to 304 centimetres).

If a large artery, like the carotid, be exposed in a living animal, and a metallic point, connected with a vertical tube of smaller caliber and seven or eight feet (213 or 243 centimetres) long by a bit of elastic tubing, be secured in the vessel, the blood will rise to the height of about six feet (183 centimetres) and remain at this point almost stationary, indicating, by a slight pulsatile movement, the action of the heart. On carefully watching the level in the tube, in addition to the rapid oscillation coincident with the pulse, another oscillation will be observed, which is less frequent and which corresponds with the movements of respiration. The pressure, as indicated by an elevation of the fluid, is slightly increased during expiration and diminished during inspiration. In such experiments, it is necessary to fill part of the tube, or whatever apparatus be used, with a solution of sodium carbonate, in order to prevent coagulation of the blood as it passes out of the vessels.

The experiment with the long tube gives, perhaps, the best general idea of the arterial pressure, which will be found to vary between five and a half and six feet of blood (170 and 183 centimetres), or a few inches more of water. The oscillations produced by the contractions of the heart are not very marked, on account of the great friction in so long a tube; but this is favorable to the study of the constant pressure. It has been found that the estimates above given do not vary very much in animals of different sizes. Bernard found the pressure in the carotid of a horse but little more than in the dog or rabbit. In the larger animals, it is the force of the heart which is increased, and not, to any considerable extent, the constant pressure in the vessels.

The experiments of Hales were made with a view of calculating the force of the heart, and were not directed particularly to the modifications and variations of the arterial pressure. It is only since the experiments performed by Poiseuille with the hæmadynamometer, in 1828, that physiologists have had any reliable data on this latter point. Poiseuille's instrument for measuring the force of the blood is a simple, graduated U-tube, half filled with mercury, with one arm bent at a right angle, so that it can easily be connected with the artery. The pressure of the blood is indicated by a depression in the level of the mercury on one side and a corresponding elevation on the other. This instrument is generally considered as possessing great advantages over the long glass tube; but for estimating simply the arterial pressure, it is much less useful, as it is more sensitive to the impulse of the heart. For the study of the cardiac pressure, it has the disadvantage, in the first place, of considerable friction, and again, the weight of the column of mercury produces an extent of oscillation by its mere impetus, greater than that which would actually represent the alternation of systole and diastole of the heart.

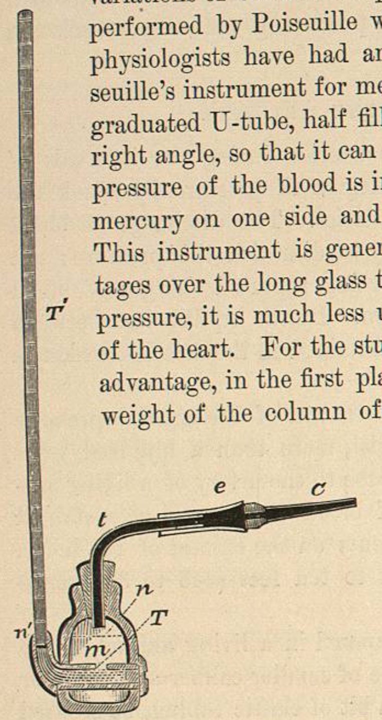

FIG. 28.—*Section of the cardiometer of Magendie, as modified by Bernard.*

A strong glass bottle is perforated at each side and fitted with an iron tube, with an opening, T, by which the mercury enters. One end of the iron tube is closed, and the other is bent upward and connected with the graudated glass tube T′, which has a caliber of $\frac{1}{12}$ to $\frac{1}{8}$ of an inch (2·1 to 3·2 mm.). The bottle is filled with mercury *m*, until it rises to *n′* in the tube, which is marked zero. The cork is perforated by the tube *t*, which is connected by a rubber tube *e* with the point C, which is introduced into the vessel.

An important improvement in the hæmadynamometer was made by Magendie. This apparatus, the cardiometer, in which Bernard made some important modifications, is the one now generally used. It consists of a small but thick glass bottle, with a fine, graduated glass tube about twelve inches (30·5 centimetres) in length, communicating with it, either through the stopper or by an orifice in the side. The stopper is pierced by a bent tube which is to be connected with the blood-vessel. The bottle is filled with mercury so that it will rise in the tube to a point which is marked zero. It is evident that the pressure on the mercury in the bottle will be indicated by an elevation in the graduated tube; and, moreover, from the fineness of the column in the tube, some of the inconveniences which are due to the weight of mercury in the hæmadynamometer are avoided, and there is, also, less friction. This instrument is appropriately called the cardiometer, as it indicates most accurately, by the extreme elevation of the mercury, the force of the heart; but it is not as perfect in its indications of the mean arterial pressure, for in the abrupt descent of the mercury during the diastole of the heart, the impetus causes the level to fall below the real standard of the constant pressure. Marey has corrected this difficulty in the "compensating" instrument, which

is constructed on the following principle: Instead of a simple glass tube which communicates with the mercury in the bottle, as in Magendie's cardiometer, there are two tubes, one of which is like the one already described and represents oscillations produced by the heart, while the other is larger, and has, at the lower part, a constriction of its caliber, which is here reduced to capillary fineness. The latter tube is designed to give the mean arterial pressure; the constricted portion offering such an obstacle to the rise of the mercury that the intermittent action of the heart is not felt, the mercury rising slowly to a certain level, which is constant and varies only with the constant pressure in the vessels.

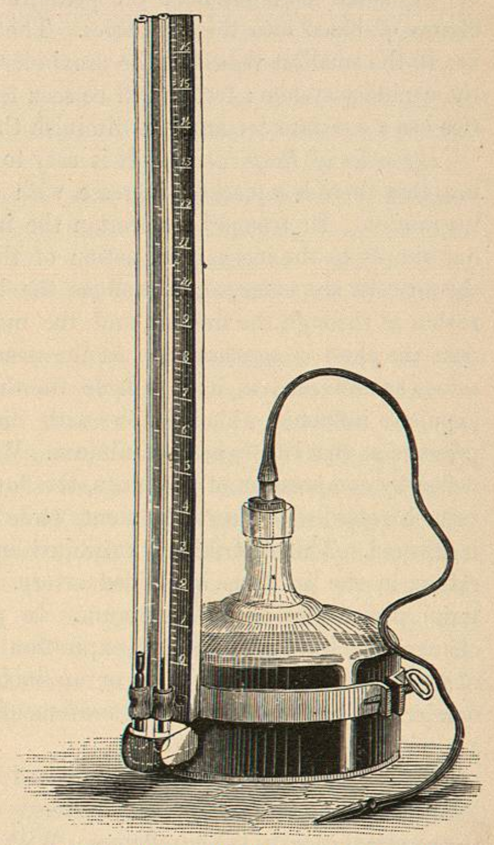

FIG. 29.—*Compensating instrument of Marey.*

Physiologists have only an approximate idea of the arterial pressure in the human subject, derived from experiments on the inferior animals. It has already been stated to be equal to about six feet (183 centimetres) of water or six inches (150 mm.) of mercury.

Pressure in Different Arteries.—The experiments of Hales, Poiseuille, Bernard and others, seem to show that the constant arterial pressure does not vary much in arteries of different sizes. These physiologists experimented particularly on the carotid and crural, and found the pressure in these two vessels about the same. From their experiments they concluded that the force is equal in all parts of the arterial system. The experiments of Volkmann, however, have shown that this conclusion is not correct. With the registering apparatus of Ludwig, he took the pressure in the carotid and the metatarsal arteries and always found a considerable difference in favor of the former. In an experiment on a dog, he found the pressure equal to about seven inches (172 mm.) in the carotid, and 6·6 inches (165 mm.) in the metatarsal. In an experiment on a calf, the pressure was 4·64 inches (116 mm.) in the carotid, and 3·56 inches (89 mm.) in the metatarsal; and in a rabbit, 3·64 inches (91 mm.) in the carotid, and 3·44 inches (86 mm.) in the crural. These experiments show that the pressure is not absolutely the same in all parts of the arterial system, that it is greatest in the arteries nearest the heart, and that it gradually diminishes toward the capillaries. The difference is very slight, almost inappreciable, except in vessels of very small size; but here the pressure is directly influenced by the discharge of blood into the capillaries. The cause of this diminution of pressure in the smallest vessels is the proximity of the great outlet of the arteries, the capillary system; for, as will be seen farther on, the flow into the capillaries has a constant tendency to diminish the pressure in the arteries.

Influence of Respiration.—It is easy to see in studying the arterial pressure, that there is a marked increase with expiration and a diminution with inspiration. In tranquil respiration the influence upon the flow of blood is due simply to the mechanical action of the thorax. With every inspiration the air-cells are enlarged, as well as the blood-vessels of the lungs, the air rushes in through the trachea, and the movement of the blood in the veins near the chest is accelerated. At the same time the blood in the arteries is somewhat retarded in its flow from the thorax, or at least does not feel the expulsive influence which follows with the act of expiration. The arterial pressure at that time is at its minimum. With the expiratory act the air is expelled by compression of the lungs, the flow of blood into the thorax by the veins is retarded to a certain extent, while the flow of blood into the arteries is favored. This is strikingly exhibited in the augmented force, with expiration, in the jet from a divided artery. Under these conditions the arterial pressure is at its maximum. In perfectly tranquil respiration, the changes due to inspiration and expiration are slight, presenting a difference of not more than half an inch or an inch (12·7 or 25·4 mm.) in the cardiometer. When the respiratory movements are exaggerated, the oscillations are very much more marked.

Interruption of respiration is followed by a very great increase in the arterial pressure. This is due, not to causes within the chest, but to obstruction to the circulation in the capillaries. With an interruption of the respiratory movements, the non-aërated blood passes into the arteries but can not flow readily through the capillaries, and as a consequence, the arteries are abnormally distended and the pressure is greatly increased. If respiration be permanently arrested, the arterial pressure becomes, after a time, diminished below the normal standard, and is finally abolished on account of the stoppage of the action of the heart. If respiration be resumed before the action of the heart has become arrested, the pressure soon returns to its normal standard.

Influence of Muscular Action etc.—Muscular effort considerably increases the arterial pressure. This is due to two causes. In the first place, the chest is generally compressed, and this favors the flow of blood into the great vessels. In the second place, muscular exertion produces a certain degree of obstruction to the discharge of blood from the arteries into the capillaries. Experiments upon the inferior animals show a great increase in pressure in the struggles which occur during severe operations. It has been shown that stimulation of the sympathetic in the neck and of certain of the cerebro-spinal nerves increases the arterial pressure, probably from an influence on the

muscular coats of some of the arteries, causing them to contract and thereby diminishing the total capacity of the arterial system.

Effects of Hæmorrhage etc.—Diminution in the quantity of blood has a remarkable effect upon the arterial pressure. If, in connecting the instrument with the arteries, even one or two jets of blood be allowed to escape, the pressure will be found diminished perhaps one-half or even more. It is hardly necessary to discuss the mechanism of the effect of the loss of blood on the tension of the vessels, but it is remarkable how soon the pressure in the arteries regains its normal standard after it has been lowered by hæmorrhage. As the pressure depends largely upon the quantity of blood, as soon as the vessels absorb the serosities in sufficient quantity to repair the loss, the pressure is increased. This takes place in a very short time, if the loss of blood be not too great.

Experiments on the arterial pressure, with the cardiometer, have verified the fact stated in treating of the form of the pulse; namely, that the pressure in the vessels bears an inverse ratio to the distention produced by the contractions of the heart. In the cardiometer, the mean height of the mercury indicates the constant, or arterial pressure; and the oscillations, the distention produced by the heart. It is found that when the pressure is great, the extent of oscillation is small, and *vice versâ*. It will be remembered that the researches of Marey demonstrated that an increase of the arterial pressure diminishes the amplitude of the pulsations, as indicated by the sphygmograph, and that the amplitude is very great when the pressure is slight. It is also true, as a general rule, that the force of the heart, as indicated by the cardiometer, bears an inverse ratio to the frequency of its pulsations.

Depressor Nerve of the Circulation.—Cyon and Ludwig have described a nerve arising in the rabbit, by two roots, one from the main trunk of the pneumogastric and the other from the superior laryngeal nerve, which joins the sympathetic filaments in the chest and passes to the heart. In man the depressor nerve is not isolated, but its fibres are contained in the sheath of the pneumogastric. This nerve has a reflex action, as was shown by the experiments of Cyon, its Faradization reducing the arterial pressure by one-third or one-half. This action is known to be reflex, for when the nerve is divided, stimulation of the central end affects the arterial pressure, while no such result follows stimulation of the peripheral extremity; and the effect is manifested when the pneumogastrics have been divided and no direct nervous influence is exerted over the heart. It is thought that the reduction in the arterial pressure following stimulation of the so-called depressor nerves is due mainly to the action of the splanchnic nerves, by which the abdominal vessels become largely dilated. If the abdomen be opened and one or more of the splanchnic nerves be divided, the arterial pressure is immediately diminished, and the pressure is restored if the divided ends of the nerves be stimulated. If, after division of the splanchnic nerves and the consequent diminution of the arterial pressure, the depressor nerves be stimulated, the pressure still undergoes some additional diminution, but this is much less than the diminution which follows stimulation of the depressor nerves with-without section of the splanchnics.

Rapidity of the Current of Blood in the Arteries.—The question of the rapidity of the arterial circulation has long engaged the attention of physiologists; but the experiments of Volkmann, with his hæmadrometer, and of Vierordt, with a peculiar instrument which he devised for the purpose, did not lead to results that were entirely reliable. The apparatus devised by Chauveau, however, is much more satisfactory. This will give, by calculation, the actual rapidity of the circulation, and it also indicates the variations in velocity which occur at different periods of the heart's action.

The instrument to be applied to the carotid of the horse consists of a thin brass tube, about an inch and a half (38·1 mm.) in length and of the diameter of the artery (about three-eighths of an inch, or 9·5 mm.), which is provided with an oblong, longitudinal opening, or window, near the middle, about two lines (4·2 mm.) long and one line (2·1 mm.) wide. A piece of thin, vulcanized rubber is wound around the tube and firmly tied so as to cover this opening. Through a transverse slit in the rubber, is introduced a very light, metallic needle, an inch and a half (38·1 mm.) in length and flattened at its lower part. This is made to project about half-way into the caliber of the tube. A flat, semicircular piece of metal, divided into an arbitrary scale, is attached to the tube, to indicate the deviations of the point of the needle.

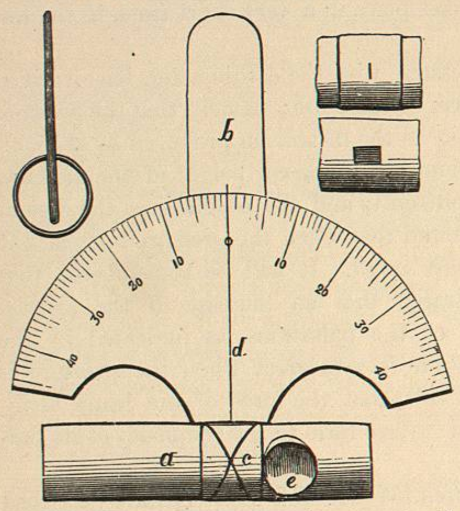

FIG. 30.—*Chauveau's instrument for measuring the rapidity of the flow of blood in the arteries.*
The instrument viewed in face—*a*, the tube to be fixed in the vessel; *b*, the dial which marks the extent of movement of the needle *d*; *e*, a lateral tube for the attachment of a cardiometer, if desired.

The apparatus is introduced into the carotid of a horse, by making a slit in the vessel, introducing first one end of the tube directed toward the heart, then allowing a little blood to enter the instrument, so as to expel the air, and, when full, introducing the other end, securing the whole by ligatures above and below.

When the circulation is arrested, the needle should be vertical, or mark zero on the scale. When the flow is established, a deviation of the needle occurs, which varies in extent with the rapidity of the current. Having removed all pressure from the vessel so as to allow the current to resume its normal character, the deviations of the needle are carefully noted, as they occur with the systole of the heart, with the diastole etc. After withdrawing the instrument, it is applied to a tube of the size of the artery, in which a current of water is made to pass with a rapidity which will produce the same deviations as occurred when the instrument was connected with the blood-vessel. The rapidity of the current in this tube may be easily calculated by receiving the fluid in a graduated vessel and noting the time occupied in discharging a given quantity. By this means the rapidity of the current of blood is ascertained. This instrument is made on the same principle as the one constructed by Vierordt, but in sensitiveness and accuracy it is much superior.

Rapidity of the Current in the Carotid.—It has been found that three currents, with different degrees of rapidity, may be distinguished in the carotid:

1. At each ventricular systole, as the average of the experiments of Chauveau, the blood moves in the carotids at the rate of about 20·4 inches (510 mm.) per second. After this, the rapidity quickly diminishes and the needle returns quite or nearly to zero, which would indicate complete arrest.

2. Immediately succeeding the ventricular systole, a second impulse is given to the blood, which is synchronous with the closure of the semilunar valves, the blood moving at the rate of about 8·6 inches (215 mm.) per second. This is the dicrotic impulse.

3. After the dicrotic impulse, the rapidity of the current gradually diminishes until just before the systole of the heart, when the needle is nearly at zero. The average rate, after the dicrotic impulse, is about 5·9 inches (147·5 mm.) per second.

The experiments of Chauveau correspond with the experiments of Marey on the form of the pulse. Marey showed that there is a marked oscillation of the blood in the vessels, due to a reaction of their elastic walls, following the first violent distention by the heart; that at the time of closure of the semilunar valves, the arteries present a second, or dicrotic distention, much less than the first; and following this, there is a gradual decline in the distention until the minimum is reached. According to the observations of Chauveau, corresponding to the first dilatation of the vessels, the blood moves with great rapidity; following this, the current suddenly becomes nearly arrested; this is followed by a second acceleration in the current, less than the first; and following this, there is a gradual decline in the rapidity, to the time of the next pulsation.

Rapidity in Different Parts of the Arterial System.—From the fact that the arterial system progressively increases in capacity, there should be found a corresponding diminution in the rapidity of the flow of blood. There are, however, many conditions, aside from simple increase in the capacity of the vessels, which modify the blood-current and render inexact any calculations made upon purely physical principles. There are the tension of the blood, the conditions of contraction or relaxation of the smallest arteries, etc. It is necessary, therefore, to have recourse to actual experiments to arrive at any definite results on this point. Volkmann found a great difference in the rapidity of the current in the carotid and metatarsal arteries, the averages being about 10 inches (254 mm.) per second in the carotid, and about 2·2 inches (56 mm.) in the metatarsal. The same difference, although not quite so marked, was found by Chauveau, between the carotid and the facial. The last-named observer also noted an important modification in the character of the current in the smaller vessels. As the vessels are farther and farther removed from the heart, the systolic impulse becomes rapidly diminished, being reduced in one experiment about two-thirds; the dicrotic impulse becomes feeble or may even be abolished; but the constant flow is much increased in rapidity. This fact coincides with the ideas already advanced with regard to the gradual conversion, by reason of the elasticity of the vessels, of the impulse of the heart into first, a remittent, and in the very smallest arteries, a nearly constant current.

The rapidity of the flow in any artery must be subject to constant modifications due to the condition of the arterioles which are supplied by it. When these little vessels are dilated, the artery of course empties itself with greater facility and the rapidity is increased. Thus the rapidity bears a relation to the arterial pressure; as variations in the pressure depend chiefly on causes which facilitate or retard the flow of blood into the capillaries. A good example of enlargement of the capillaries of a particular part is in mastication, when the salivary glands are brought into activity and the quantity of blood which they receive is greatly increased. Chauveau found a great increase in the rapidity of the flow in the carotid of a horse during mastication. It must be remembered that in all parts of the arterial system, the rapidity of the current of blood is constantly liable to increase from dilatation of the small vessels and to diminution from their contraction.

Circulation of the Blood in the Capillaries.

Before entering upon the study of the capillary circulation, it should be distinctly stated what is meant by capillary vessels as distinguished from the smallest arteries and veins. From a strictly physiological point of view, the capillaries are to be regarded as beginning at the situation where the blood is brought near enough to the tissues to enable them to separate the matters necessary for their regeneration and to give up the products of their physiological wear; but at present it is impossible to assign any limit where the vessels cease to be simple carriers of blood, and it is not known to what part of the vascular system the processes of nutrition are exclusively confined. The divisions of the blood-vessels must be, to a certain extent, arbitrarily defined. The most simple, and

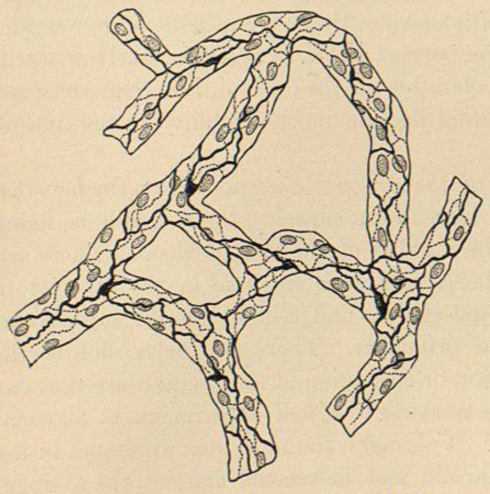

Fig. 31.—*Capillary blood-vessels* (Landois).
The boundaries of the cells (cement-substance between the endothelium) is blackened with silver nitrate. The nuclei of the endothelium are brought out by staining.

what seems to be the most physiological view, is to regard as capillaries those vessels which have but a single coat; for in these, the blood is brought in closest proximity to the tissues. Vessels which are provided, in addition, with a muscular or with muscular and fibrous coats are to be regarded either as small arteries or as venous radicles. This view is favored by the character of the currents of blood as seen in microscopical observation of the circulation in transparent parts. Here an impulse is observed with each contraction of the heart, until the vessels have but one coat and are so narrow as to allow the passage of but a single line of blood-corpuscles.

Physiological Anatomy of the Capillaries.—If the arteries be followed out to their minutest ramifications, they will be found progressively diminishing in size as they branch, and their coats, especially the muscular coat, becoming thinner and thinner, until at last they present an internal, structureless coat lined by endothelium with oval, longitudinal nuclei, a middle coat formed of but a single layer of circular muscular fibres, and an external coat composed of a very thin layer of longitudinal bundles of fibrous tissue. These vessels are $\frac{1}{400}$ to $\frac{1}{200}$ of an inch (62·5 to 125 μ) in diameter. They become smaller as they branch, and undoubtedly possess the property of contractility, which is particularly marked in the arterial system. Following the course of the vessels, when they are reduced in size to about $\frac{1}{800}$ of an inch (31 μ), the external, fibrous coat is lost, and the vessel then presents only the internal coat and a single layer of muscular fibres. The vessels become smaller as they branch, finally lose the muscular fibres, and have then but a single coat. These last will be regarded as the true capillary vessels.

It was formerly thought that the smallest vessels, which are described as the true capillaries, were composed of a single, homogeneous membrane, $\frac{1}{25000}$ to $\frac{1}{2500}$ of an inch (1 to 10 μ) thick, with nuclei embedded in its substance, but not provided with an endothelial lining; but it has been shown that the membrane is homogeneous, elastic, perhaps contractile, and, in some parts at least, provided with fusiform or polygonal endothelium of excessive tenuity. The borders of the endothelial cells may be seen after staining the vessels with silver nitrate. In the smallest capillaries the cells are narrow and elongated or fusiform; and in the larger vessels they are more polygonal, with very irregular borders. The nuclei in the walls of the vessels belong to this layer of endothelium. By the same process of staining with silver nitrate, irregular, non-nucleated areas are frequently brought into view; and it has been supposed by some that these indicate the presence of stomata, or orifices in the walls of the vessels.

The diameter of the capillaries is generally as small as that of the blood-corpuscles, or it may be smaller; so that these bodies always move in a single line and must become deformed in passing through the smallest vessels, recovering their normal shape, however, when they pass into vessels of larger size. The capillaries are smallest in the nervous and muscular tissue, retina and patches of Peyer, where they have a diameter of $\frac{1}{6000}$ to $\frac{1}{4000}$ of an inch (4·25 to 6·25 μ). In the papillary layer of the skin and in the mucous membranes, they are $\frac{1}{4000}$ to $\frac{1}{2400}$ of an inch (6·25 to 10 μ) in diameter.