CHAPTER III.

CIRCULATION OF THE BLOOD IN THE VESSELS.

Physiological anatomy of the arteries—Course of blood in the arteries—Locomotion of the arteries and production of the pulse—Pressure of blood in the arteries—Pressure in different parts of the arterial system—Depressor nerve—Influence of respiration on the arterial pressure—Rapidity of the current of blood in the arteries—Rapidity in different parts of the arterial system—Circulation of the blood in the capillaries—Physiological anatomy of the capillaries—Pressure of blood in the capillaries—Relations of the capillary circulation to respiration—Causes of the capillary circulation—Influence of temperature on the capillary circulation—Influence of direct irritation on the capillary circulation—Circulation of the blood in the veins—Physiological anatomy of the veins—Course of the blood in the veins—Pressure of blood in the veins—Rapidity of the venous circulation—Causes of the venous circulation—Air in the veins—Uses of the valves—Conditions which impede the venous circulation—Regurgitant venous pulse—Circulation in the cranial cavity—Circulation in erectile tissues—Derivative circulation—Pulmonary circulation—Circulation in the walls of the heart—Passage of the blood-corpuscles through the walls of the vessels (diapedesis)—Rapidity of the circulation—Phenomena in the circulatory system after death.

IN man and in all animals possessed of a double heart, each cardiac contraction forces a charge of blood from the right ventricle into the pulmonary artery, and from the left ventricle into the aorta; and the valves which guard the orifices of these vessels effectually prevent regurgitation during the intervals of contraction. There is, therefore, but one direction in which the blood can flow in obedience to this intermittent force; and the fact that even in the smallest arteries, there is an acceleration in the current coincident with each contraction of the heart, which disappears when the action of the heart is arrested, shows that the ventricular systole is the cause of the arterial circulation. The arteries have the important office of supplying nutritive matters to all the tissues and furnishing to the glands materials out of which the secretions are formed, and, in short, are the vessels of supply to every part of the organism. The supply of blood regulates, to a considerable extent, the processes of nutrition and has an important bearing on the general and special functions; and the various physiological processes necessarily demand considerable modifications in the quantity of arterial blood which is furnished to parts at different times. The force of the heart, however, varies but little within the limits of health; and the conditions necessary to the proper distribution of blood in the economy are regulated almost exclusively by the arterial system. These vessels are endowed with elasticity, by which the circulation is considerably facilitated, and with contractility, by which the supply to any part may be modified, independently of the action of the heart. Sudden flushes or pallor of the countenance are examples of the facility with which this may be effected. It is evident, therefore, that the properties of the coats of the arteries are of great physiological importance.

PHYSIOLOGICAL ANATOMY OF THE ARTERIES.

The vessels which carry the venous blood to the lungs are branches of a great trunk which takes its origin from the right ventricle. They do not differ in structure from the vessels which carry the blood to the general system, except in the fact that their coats are somewhat thinner and more distensible. The aorta, branches and ramifications of which supply all parts of

the body, is given off from the left ventricle. Just at its origin, behind the semilunar valves, the aorta has three sacculated pouches, called the sinuses of Valsalva. Beyond this point the vessels are cylindrical. The arteries then branch, divide and subdivide, until they are reduced to microscopic size. The branches, with the exception of the intercostal arteries, which make nearly a right angle with the thoracic aorta, are given off at an acute angle. As a rule, the arteries are nearly straight, taking the shortest course to the parts which they supply with blood; and while the branches progressively diminish in size, but few are given off between the great trunk and small vessels which empty into the capillary system. So long as a vessel gives off no branches, its caliber does not progressively diminish; as the common carotids, which are as large at their bifurcation as they are at their origin. There are one or two instances in which vessels, although giving off many branches in their course, do not diminish in size for some distance; as the aorta, which is as large at the point of division into the iliacs as it is in the chest, and the vertebral arteries, which do not diminish in caliber until they enter the foramen magnum. It has long been remarked that the combined caliber of the branches of an arterial trunk is greater than that of the main vessel; so that the arterial system, as it branches, increases in capacity. A single exception to this rule is in the instance of the common iliacs, the combined caliber of which is less than the caliber of the abdominal aorta.

The arrangement of the arteries is such that the requisite supply of blood is sent to all parts of the economy by the shortest course and with the least possible expenditure of force by the heart. Generally the vessels are so situated as not to be exposed to pressure and consequent interruption of the current of blood; but in certain situations, as about some of the joints, there is necessarily some liability to occasional compression. In certain situations, also, as in the vessels going to the brain, particularly in some of the inferior animals, it is necessary to moderate the force of the blood-current, on account of the delicate structure of the organs in which they are distributed. Here there is a provision in the shape of anastomoses, by which, on the one hand, compression of a vessel simply diverts, and does not arrest the current of blood, and on the other hand, the current is rendered more equable and the force of the heart is moderated.

The arteries are provided with fibrous sheaths, of greater or less strength, as the vessels are situated in parts more or less exposed to disturbing influences or accidents.

The arteries have three well defined coats. As these vary very considerably in arteries of different sizes, it will be convenient, in their description, to divide the vessels into three classes:

1. The largest arteries; in which are included all that are larger than the carotids and common iliacs.

2. The arteries of medium size; that is, between the carotids and iliacs and the smallest.

3. The smallest arteries; or those less than $\frac{1}{15}$ to $\frac{1}{12}$ of an inch (1·7 to 2·1 mm.) in diameter.

The largest arteries are very strong and elastic. Their external coat is composed of ordinary fibrous tissue, with a few longitudinal and oblique fasciculi of non-striated muscular fibres. This coat is no thicker in the largest vessels than in some of the vessels of medium size; and in some medium-sized vessels it is actually thicker than in the aorta. This is the only coat that is vascular.

The middle coat, on which the thickness of the walls of the vessel depends, is composed chiefly of yellow elastic tissue. This tissue is disposed in a number of layers. Externally there is a thin layer of ramifying elastic fibres, and then a number of layers of elastic membrane, with oval, longitudinal openings, an arrangement which has given it the name of the "fenestrated membrane." Between the different layers of this membrane are found a few non-striated muscular fibres. These muscular fibres, however, are not abundant and have but little physiological importance. A small portion of the aorta and pulmonary artery near the heart is entirely free from muscular fibres. In the largest arteries the fibres are arranged in fasciculi, with amorphous and fibrous connective tissue running in circular, longitudinal and oblique directions. The longitudinal and oblique fibres exist chiefly in the outer coat.

The internal coat of the largest arteries does not differ materially from the lining membrane of the rest of the arterial system. It is nearly identical in structure with the endocardium and is continued throughout the vascular system. It is a thin, homogeneous, elastic membrane, covered with a layer of elongated cells of endothelium, with oval nuclei, the long diameter of the cells and nuclei following the direction of the vessel. Between the endothelial cells, is an amorphous cement-substance, which is rendered dark by a solution of silver nitrate, so that this reagent clearly defines their borders.

The arteries of medium size possess considerable strength, some elasticity and very great contractility. In the outer and inner coats there is no great difference between these and the largest arteries, even in thickness. The essential difference in the anatomy of these vessels is found in the middle coat. Here there is a continuation of the elastic elements found in the largest vessels, but relatively diminished in thickness and mingled with the fusiform, non-striated muscular fibres arranged nearly always at right angles to the course of the vessel. These fibres are found chiefly in the inner layers of the middle coat and only in arteries smaller than the carotids and primitive iliacs. In arteries of medium size, like the femoral, profunda femoris, radial or ulnar, the muscular fibres exist in several layers. There is no distinct division, as regards the middle coat, between the largest arteries and those of medium size. As the arteries branch, muscular fibres make their appearance between the elastic layers, progressively increasing in quantity, while the elastic elements are diminished in their relative proportion.

In the smallest arteries, the external coat is thin and disappears just before the vessels empty into the capillary system; so that the very smallest arterioles have only the inner coat and a layer of muscular fibres. Although most of the muscular fibres in the middle coat of the arteries are arranged

at right angles to the course of the vessels, nearly all of the arteries in the human subject are provided with longitudinal and oblique muscular fasciculi,
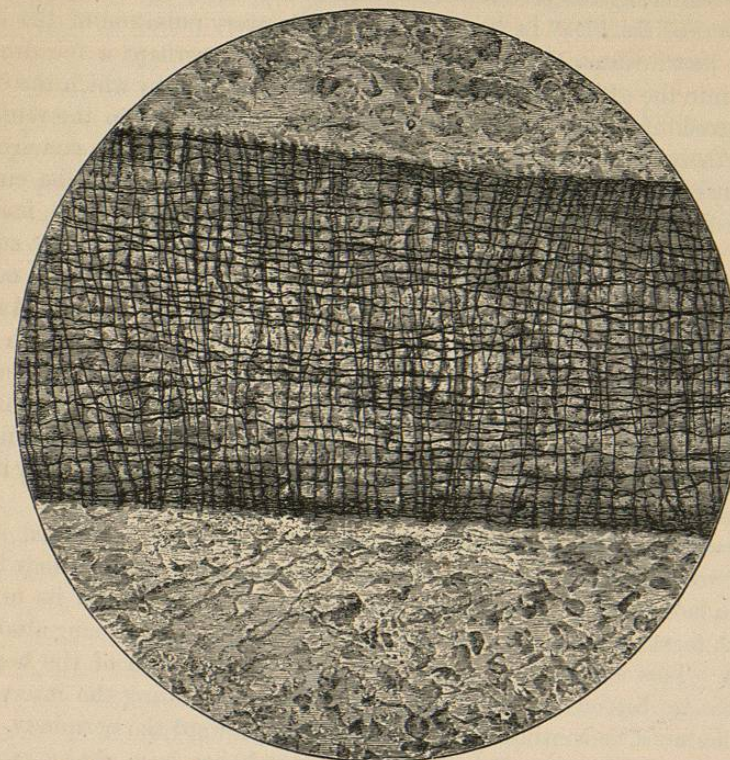

FIG. 23.—*Small artery from the mesentery of the frog, showing endothelium and circular muscular fibres; magnified 500 diameters* (from a photograph taken at the United States Army Medical Museum).

which are sometimes external, sometimes internal and sometimes on both sides of the circular layers.

The middle coat is composed of circular muscular fibres, without any admixture of elastic elements. In vessels $\frac{1}{100}$ of an inch ($254\,\mu$) in diameter, there are two or three layers of fibres; but nearer the capillaries and as the vessels lose the external fibrous coat, these fibres exist in a single layer.

The internal coat presents no essential difference from the coat in other vessels, with the exception that the endothelium is rather less distinctly marked.

A tolerably rich plexus of vessels is found in the external coat of the arteries. These are called vasa vasorum and come from the adjacent arterioles, generally having no direct connection with the vessel on which they are distributed. A few vessels penetrate the external layers of the middle coat, but none are ever found in the internal coat.

Nervous filaments accompany the arteries, in all probability, to their remotest ramifications. These are not distributed in the walls of the large vessels, but follow them in their course, their filaments of distribution being

found in those vessels in which the muscular element of the middle coat predominates. The vaso-motor nerves, as they are called, play an important part in regulating the processes of nutrition.

Course of the Blood in the Arteries.—With every pulsation of the heart, all the blood contained in the ventricles, excepting perhaps a few drops, is forced into the great vessels. The valvular arrangement by which the blood, once forced into these vessels, is prevented from returning into the ventricles during their diastole, has already been described. The foregoing sketch of the anatomy of the arteries indicates a complexity of phenomena in the circulation in these vessels, which would not obtain if they were simple, inelastic tubes. In this case, the intermittent force of the heart would be felt equally in all the vessels, and the arterial circulation would be subject to no modifications which did not come from the action of the central organ. As it is, the blood is received from the heart into vessels endowed, not only with great elasticity, but with contractility. The elasticity, which is the prominent property of the largest arteries, moderates the intermittency of the heart's action, providing a continuous supply to the parts; while the contractility of the smallest arteries is capable of increasing or diminishing the supply in any part, as may be required in the various functions.

Elasticity of the Arteries.—This property is particularly marked in the largest vessels. If the aorta be forcibly distended with water, it may be dilated to more than double its ordinary capacity and will resume its original size and form as soon as the pressure is removed, its elasticity being absolutely perfect. This simple experiment shows that if the force of the heart be sufficient to distend the great vessels, their elasticity during the intervals of its action must be continually forcing the blood toward the periphery. The fact that the arteries are distended at each systole has been shown by direct experiments; although the immense capacity of the arterial system, as compared with the small charge of blood which enters at each pulsation, renders the actual distention of the vessels less than would be expected from the force of the heart's contraction.

Division of an artery in a living animal illustrates one of the important phenomena due to the elastic and yielding character of its walls. It is observed, even in vessels of considerable size, as the carotid or femoral, that the flow of blood is not intermittent but remittent. With each ventricular systole there is a sudden and marked impulse; but during the intervals of contraction, the blood continues to flow with considerable force. In the smaller vessels, the impulse becomes less and less marked; but it is not entirely lost, even in the smallest vessels, the flow becoming constant only in the capillary system. That the force of the heart is absolutely intermittent, is shown by the following experiment: If the heart be exposed in a living animal, and a canula be introduced through the walls into one of the ventricles, there is a powerful jet at each systole, but no blood is discharged during the diastole. The same absolute intermittency of the current is observed in the aorta near the heart. The conversion of the intermittent current in the largest vessels into a nearly constant flow in the smallest arterioles is effected by the physical

property of elasticity; and the intermittent impulse may be said to be progressively absorbed by the elastic walls of the vessels. This modification of the impulse of the heart has great physiological importance; for it is evidently essential that the current of blood, as it flows into the delicate capillary vessels, should not be alternately intermitted and impelled with the full power of the ventricle.

The elasticity of the arteries favors the flow of blood toward the capillaries by a mechanism that is easily understood. The blood discharged from the heart distends the elastic vessel, which reacts, after the distending force ceases to operate, and compresses its fluid contents. This reaction would have the effect of forcing the blood in two directions, were it not for closure of the valves, which renders regurgitation into the heart impossible. The influence, then, can be exerted only in the direction of the periphery. It is evident, therefore, that in vessels removed a sufficient distance from the heart, the force exerted on the blood by the reaction of the elastic walls is competent to produce a very considerable current during the intervals of the heart's action.

Contractility of the Arteries.—The medium-sized and smallest arteries contain non-striated muscular fibres; and it has been shown that as a consequence of the condition of these fibres, the vessels undergo considerable variations in their caliber. These changes in the size of the arteries can be produced by stimulation or section of the vaso-motor nerves. If the sympathetic be divided in the neck of a rabbit, the arteries of the ear on that side soon become dilated. If the divided extremity of the nerve be stimulated, the vessels contract and may become smaller than on the opposite side. These experiments demonstrate the contractile properties of the small arteries and give an idea how the supply of blood to any particular part may be regulated. The contractility of the arteries has great physiological importance. As their office is simply to supply blood to the various tissues and organs, it is evident that when the vessels going to any particular part are dilated, the supply of blood is necessarily increased. This is particularly well marked in the glands, which, during the intervals of secretion, receive a comparatively small quantity of blood. The pallor of parts exposed to cold and the flush produced by heat are due, on the one hand, to contraction, and on the other, to dilatation of the small arteries. Pallor and blushing from mental emotions are examples of the same kind of action.

The idea, which at one time obtained, that the arteries were the seat of rhythmical contractions which had a favorable influence on the current of blood is erroneous; and it is hardly necessary to repeat the statement that the cause of the arterial circulation is the force of the left ventricle. It has been observed, however, that the arteries in the ear and certain other parts in the rabbit undergo rhythmical contractions and dilatations, these occurring ten or twelve times per minute (Schiff, Lovén, Vulpian); but these movements are not to be regarded as a contributing force in the production of the circulation. It is evident, on the other hand, that the elasticity of the arteries must actually assist the circulation. The resiliency of the vessels is

continually pressing their contents toward the periphery; the dilatation of the vessels with each systole of course admits an increased quantity of blood; and it has been shown that the same intermittent force exerted on an inelastic tube will discharge a less quantity of liquid from openings of equal caliber.

Superadded, then, to the direct action of the heart, physiologists now recognize, as a cause influencing the flow of blood in the arteries, the resiliency of the vessels, especially of those of large size, this force being derived originally from the heart. Thus it will be seen that the arteries are constantly kept distended with blood by the heart; and by virtue of their elasticity and the progressive increase in the capacity of this system as they branch, the powerful contractions of the central organ serve only to keep up an equable current in the capillaries. The small vessels, by the action of their contractile walls, regulate the local circulations.

Locomotion of the Arteries and Production of the Pulse.—With each contraction of the heart, the arteries are increased in length and many of them undergo a considerable locomotion. This may be readily observed in vessels which are tortuous in their course, and is frequently very marked in the temporal artery in old persons. The elongation may also be observed by watching attentively the point where an artery bifurcates, as at the division of the common carotid. It is simply the mechanical effect of sudden distention, which, while it increases the caliber of the vessel, causes an elongation even more marked.

The finger placed over an exposed artery or one which lies near the surface experiences a sensation at every beat of the heart as though the vessel were striking against it. This has long been observed and is called the pulse. Ordinarily it is appreciated when the current of blood is subjected to a certain degree of obstruction, as in the radial, which can readily be compressed against the bone. In an artery imbedded in soft parts which yield to pressure, the actual dilatation of the vessel being very slight, pulsation is felt with difficulty, if at all. When obstruction of an artery is complete, as after tying a vessel, the pulsation above the point of ligature is very marked and can be readily appreciated by the eye. The explanation of this exaggeration of the movement is the following: Normally, the blood passes freely through the arteries and produces, in the smaller vessels, very little movement or dilatation; when, however, the current is obstructed, as by ligation or even compression with the finger, the force of the heart is not sent through the vessel to the periphery but is arrested and therefore becomes more marked and easily appreciated. In vessels which have become undilatable and incompressible from calcareous deposits, the pulse can not be felt. The character of the pulse indicates, to a certain extent, the condition of the heart and vessels.

Under ordinary conditions, the pulse may be felt in all arteries that are exposed to investigation; and as it is due to the movement of the blood in the vessels, the prime cause of its production is the contraction of the left ventricle. The impulse given to the blood by the heart, however, is not felt

in all the vessels at the same instant. Marey registered simultaneously the impulse of the heart, the pulse of the aorta and the pulse of the femoral artery, and ascertained that the contraction of the ventricle is anterior, in point of time, to the pulsation of the aorta, and that the pulsation of the aorta precedes the pulse in the femoral. This only confirmed the views of other physiologists, particularly Weber, who described this progressive retardation of the pulse, estimating the difference between the ventricular systole and the pulsation of the artery in the foot at one-seventh of a second.

It is evident from what is known of the variations which occur in the force of the heart's action, the quantity of blood in the vessels, and from the changes which may take place in the caliber of the arteries, that the characters of the pulse must be subject to great variations. Many of these may be appreciated simply by the sense of touch. Writers treat of the soft and compressible pulse, the hard pulse, the wiry pulse, the thready pulse etc., as indicating various conditions of the circulatory system. The character of the pulse, aside from its frequency, has always been regarded as of great importance in disease.

Form of the Pulse.—It is evident that few of the characters of a pulsation, occupying as it does but one-seventieth part of a minute, can be ascertained by the sense of touch alone. This fact has been appreciated by physiologists, and within the last few years, instruments for registering the pulse have been constructed, with the view of analyzing the dilatation and movements of the vessels. The idea of such an instrument was probably suggested by the following simple observation: When the legs are crossed,
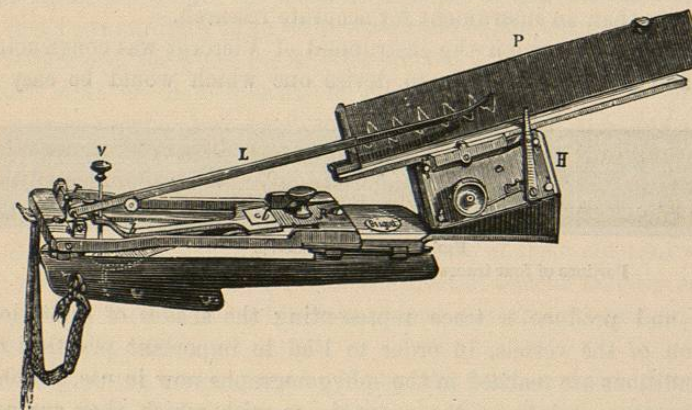

FIG. 24.—*Sphygmograph of Marey.*
The apparatus is securely fixed on the forearm, so that the spring under the screw V is directly over the radial artery. The movements of the pulse are transmitted to the long and light wooden lever L and registered upon the surface P, which is moved at a known rate by the clock-work H. The apparatus is so adjusted that the movements of the vessel are accurately amplified and registered by the extreme point of the lever.

with one knee over the other, the beating of the popliteal artery will produce marked movements of the foot. If a lever provided with a marking-point in contact with a slip of paper moving at a definite rate could be applied to an artery, the point of the lever would register the movements of

the vessel and its changes in caliber. The first physiologist who put this in practice was Vierordt, who constructed quite a complex instrument, so
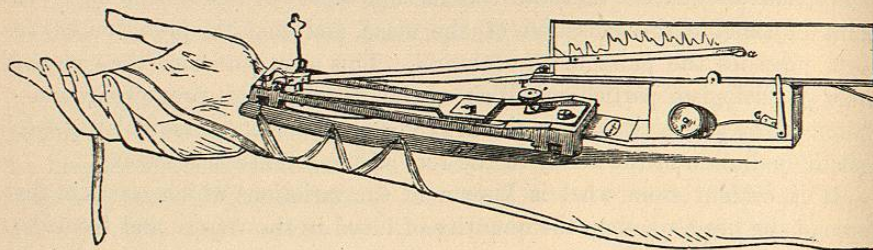

FIG. 25.—*Sphygmograph of Marey applied to the arm.*

arranged that the impulse from an accessible artery, like the radial, was conveyed to a lever, which marked the movement upon a revolving cylinder of paper. This instrument was called a sphygmograph. The traces made by it wer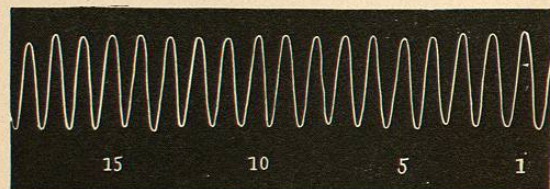e perfectly regular and simply marked the extremes of dilatation — exaggerated, of course, by the length of the lever—and the number of pulsations in a given time. The latter can be easily estimated by more simple means; and as the former did not convey any very definite physiological idea, the apparatus was regarded rather as a curiosity than an instrument for accurate research.

FIG. 26.—*Trace of Vierordt.*

The principle on which the instrument of Vierordt was constructed was correct; and it remained only to devise one which would be easy of ap-

FIG. 27.—*Trace of Marey.*
Portions of four traces taken in different conditions of the pulse.

plication and produce a trace representing the shades of dilatation and contraction of the vessels, in order to lead to important practical results. These conditions are realized in the sphygmographs now in use, which differ from each other mainly in the convenience with which they are applied, the principle of all being substantially that of the sphygmograph of Marey, which is shown in Figs. 24 and 25. The modern sphygmographs simply amplify the changes in the caliber of the artery incident to the pulse; and although their application is, perhaps, not so easy as to make these instruments generally useful in the practice of medicine, in the hands of Marey and other physiologists, they have led to a definite knowledge of the physiological characters of the pulse and its modifications in certain diseases, information which could hardly be arrived at by other means of investigation.

In short, their mechanism is so accurate, that when skillfully used, they give on paper the actual "form of the pulse." The modern instruments, applied to the radial artery, give traces very different from those obtained by Vierordt, which were simply series of regular elevations and depressions. A comparison of these with the traces obtained by Vierordt gives an idea of the defects which have been remedied by Marey; for it is evident that the dilatation and contraction of the arteries can not be so regular and simple as would be inferred merely from the trace made by the instrument of Vierordt.

Analyzing the traces taken by Marey, it is seen that there is a dilatation following the systole of the heart, marked by an elevation of the lever, more or less sudden, as indicated by the angle of the trace, and of greater or less amplitude. The dilatation having arrived at its maximum, is followed by reaction, which may be slow and regular, or may be, and generally is, interrupted by a second and slighter upward movement of the lever. This second impulse varies very much in amplitude. In some rare instances, it is nearly as marked as the first and may be appreciated by the finger, giving the sensation of a double pulse following each contraction of the heart. This is called the dicrotic pulse. As a rule, the first dilatation of the vessel is sudden and is indicated by an almost vertical line. This is followed by a comparatively slow reaction, indicated by a gradual descent of the trace, which is not, however, absolutely regular, but is marked by a slight elevation indicating a second impulse. The amplitude of the trace, or the distance between the highest and the lowest points marked by the lever, depends upon the degree of constant tension of the vessels. Marey has found that the amplitude is in an inverse ratio to the tension; which is very easily understood, for when the arteries are but little distended, the force of the heart must be more marked in its effects than when the pressure of blood is very great. Any condition which facilitates the flow of blood from the arteries into the capillaries will, of course, relieve the tension of the arterial system, lessen the obstacle to the force of the heart, and increase the amplitude of the pulsation, and *vice versâ*. In support of this view, Marey has found that cold applied to the surface of the body, contracting, as it does, the smallest arteries, increases the arterial tension and diminishes the amplitude of the pulsation, while a moderate elevation of temperature produces an opposite effect.

In nearly all the traces given by Marey, the descent of the lever indicates more or less oscillation of the mass of blood. The physical properties of the larger arteries render this inevitable. As they yield to the distending influence of the heart, reaction occurs after this force is taken off, and if the distention be very great, gives a second impulse to the blood. This is quite marked, unless the tension of the arterial system be so great as to offer too much resistance. One of the most favorable conditions for the manifestation of dicrotism is diminished tension, which is always found co-existing with a very marked exhibition of this phenomenon.

Marey accurately determined and registered these various phenomena, by