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The Velocity of the Pulse Wave in Man.

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In an investigation now being carried out by us at Manchester observations are being made, under various conditions, upon the velocity of the pulse wave in man. As a preliminary to this investigation it was thought advisable to study the theory of the transmission of the pulse wave, and the following pages contain the results arrived at, together with an account of experiments upon the velocity of the pulse wave in an isolated human artery.

The pulse wave in man travels in the arteries at a speed of 4 to 10 metres per second. Its velocity depends, to a small degree, on the velocity of the blood in the artery considered, but chiefly upon the elastic condition of the arterial wall, which is affected by a variety of factors in health and disease. As regards the former, the pulse wave must be considered as travelling, like a ripple on moving water, relatively to the fluid in which it occurs. The arterial wall merely exerts an elastic constraint upon the surface of the fluid, and in the simplified theory of the transmission of the wave (which it is necessary for practical purposes to adopt) the inertia of the wall, and of the tissues outside it, exerts no influence on the velocity of the wave. Thus any experimentally determined value must represent the velocity of the wave relatively to the blood, *plus* the velocity of the blood in the artery. Taking 0·75 metres per second as an average maximum velocity of the blood in the aorta, and 0·25 metres per second as an average maximum in the carotid artery (4), we see that the correction for the velocity of the blood itself is small, but not negligible, in comparison with the velocity of the wave. Any considerable increase in the velocity of the blood, caused, *e.g.*, by local or general exertion, will cause an equal increase in the velocity of the pulse wave.

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Moreover, the velocity of the blood in the aorta, and to some degree in any artery, varies considerably at different moments of the cardiac cycle; such differences will cause one part of the pulse wave to be transmitted with a greater velocity than another, and so will lead to a certain modification in the apparent form of the wave. In the absence of definite knowledge of the velocity of the blood in any given case it is not possible to make any allowance for it; it is necessary, however, to bear in mind that it may, under certain circumstances, appreciably—though not considerably—affect the velocity and modify the form of the transmitted wave.

Considered in its full complexity the theory of the transmission of the pulse wave is difficult. There are, however, two factors which allow us to simplify it: (*a*) the distance over which the wave travels is relatively short; (*b*) the wave form, owing to the elastic nature of all the tissues producing it, shows no very sharp discontinuities or changes of curvature. In consequence of (*b*), in the analysis of the wave into a system of simple harmonic waves, the shorter wave-lengths are relatively unimportant, and it is the transmission of these waves which would have required the more complicated treatment. With the help of Mr. E. A. Milne, of Trinity College, Cambridge, a fuller theory of the wave transmission has been worked out; it is unnecessary to give this theory at length, but it may be stated that, with the type of wave occurring in arteries, and within the limits of experimental error, the formula given by Moens (7) in 1878 is sufficiently accurate for our purpose. We will consider the meaning and application of this formula.

If v be the velocity of the front of the pulse wave, y the radius of the artery at the end of diastole, c the thickness of the arterial wall, E the modulus of elasticity of the artery for lateral expansion, and ρ the density of the blood, the following relation holds:

$$v = \sqrt{(\mathrm{E}c/2\rho y)}.$$

Assuming that ρ is constant, and equal (say) to 1·055, this formula contains three variable factors, on which the value of v depends, viz., E, c and y. In this form the expression is of little value, since E, c and y vary from artery to artery, and none of them express any easily measurable factor. By a simple transformation, however, a formula may be obtained which throws much light upon the mechanics of the circulation. A small rise δp in pressure may be shown to cause a small increase, $\delta y = y^2\delta p/\mathrm{E}c$, in the radius y of the artery, or a small increase, $\delta \mathrm{V} = 2\pi y^3\delta p/\mathrm{E}c$, in its volume V per unit length. Hence $2y/\mathrm{E}c = d\mathrm{V}/\mathrm{V}dp$, from which

$$v = \sqrt{(\mathrm{V}/[\rho d\mathrm{V}/dp])}.$$

In this equation p is measured in dynes per square centimetre, and v in

centimetres per second. Expressing p in millimetres of Hg, and v in metres per second, and substituting $\rho = 1{\cdot}055$, this equation becomes,

$$v = 0{\cdot}357\sqrt{(\mathrm{V}/[d\mathrm{V}/dp])}.$$

But $(d\mathrm{V}/dp)/\mathrm{V}$ is the relative increase in the volume of the artery, per millimetre of Hg increase of pressure. Working in percentages, therefore, the equation finally becomes

$$v = 3{\cdot}57/\sqrt{(\text{percentage increase in volume per millimetre of Hg increase of pressure})}.$$

This is the form most intelligible and convenient in use. It requires no knowledge of the elastic coefficient as such, nor of the radius and the thickness of the arterial wall, but only of one simple and directly observable function of these, the rate of increase of volume with pressure. Thus an observation of the velocity of the pulse wave in any particular vessel tells us at once, in absolute units, the degree of extensibility of that vessel.

The energy expended by the heart, per beat, has been shown by Rhode (2) and others, to depend (other things being equal) on the pressure developed by it. Thus, if the heart is to work efficiently, the output for a given pressure should be as large as possible, which implies a large increase in the volume of the arteries per millimetre of pressure developed, and—from the formula—a low velocity of the pulse wave. Another sign of an efficient circulation is that the flow through the capillaries should remain as high and as constant as possible during diastole, which implies a large diminution of volume of the arteries for a given fall of pressure, and again a low velocity of the pulse wave. Hence a low velocity of the pulse wave is a sign, both of an efficient and continuous circulation and of an economical functioning of the heart. Thus the velocity of the pulse wave is one important criterion of the general efficiency of the circulation.

In a paper by Roy (3), in 1880, is given a series of curves showing the relation between volume and pressure, in the case of arteries and veins, made by an ingenious method, commanding every confidence in its accuracy. Replotting these curves in rectangular co-ordinates, and measuring their slopes at various points, it is possible to deduce the percentage increase in volume per millimetre of Hg, and so to calculate the velocity of the pulse wave at various pressures. The following results are obtained by so doing :—

Table I.

I. Fig. 6, Roy's Paper.—Inferior Vena Cava of Cat.

p (mm. of Hg)	5	10	20	30	40
v (m.p.s.)	1·55	2·2	3·1	4·3	5·0

II. Fig. 7.—Femoral Artery of Rabbit.

p	20	40	60	80	100	120	140	160
v	2·21	2·27	2·12	2·33	3·10	5·05	7·15	9·22

III. Fig. 9.—Carotid of Rabbit, immediately after death.

p	20	40	60	70	80	100	120	140	160
v	3·15	3·15	3·08	3·1	3·48	4·7	7·0	10·7	17·8

IV. Fig. 11.—Thoracic Aorta of Cat.

p	20	40	60	80	100	120	140	160
v	3·4	3·6	3·5	3·6	3·6	3·8	4·3	5·4

V. Fig. 10.—Carotid of Emaciated Dog, suffering from ill-treatment and chronic illness.

p	20	40	60	80	100	120	140
v	3·1	4·0	5·1	6·0	7·3	8·4	8·9

The most striking fact about these figures is that in a normal healthy artery (II, III, and IV) the velocity is constant as the pressure rises from a low value up to about 80 mm., after which it increases, at first slowly and then more rapidly. At high pressures the velocity is very considerably increased. In V the velocity increases considerably throughout. Secondly, the velocities in II, III, and IV, at pressures of 80 mm. (about equal to the normal diastolic pressure in man), are noticeably less than those observed in man. This may be characteristic of the animals investigated, but it seems more probable that it is due to the following factor. All living tissues, and especially arteries and muscles, show the phenomenon of elastic "after-action," continuing to extend for some time if the load or tension be maintained. Roy attempted to avoid errors due to this by making his observations

very slowly, allowing the tissue a long time to reach its final equilibrium. From the point of view of the static effect of the diastolic pressure on the arteries, he succeeded; from that, however, of the dynamic effects occurring in the rapid cycle of events associated with the pulse, his precautions aggravated the error, and must have caused the increase of volume per millimetre of Hg to be much larger than that occurring in a rapid change of pressure. It is quite conceivable that a pressure, lasting (say) for 0·1 second, causes an expansion not greater than half of that resulting from an equal pressure maintained for 10 minutes; in this case a calculated velocity based on the latter would be only about two-thirds of an observed velocity depending on the former. This elastic "after-action" therefore probably causes all the velocities in Table I to be too low; the effect is similar in character to that caused by adopting the formulæ for the *isothermal* expansion of a gas in calculating the velocity of sound. The safest thing to do is to measure the velocity directly, and so to deduce the constants of the true *adiabatic* expansion. Finally, we see (in I) that in a vein the calculated velocity at low pressures is very low, a conclusion which agrees with an observation of Morrow (6), and must be borne in mind in comparing the time relations of the jugular pulse with those of other events in the heart or circulation.

The most important point brought out by Table I is the dependence of the velocity upon the pressure. In the case of man, the pressure involved is the diastolic pressure, that on which the wave is superimposed. This implies a decrease in extensibility with increase in length, an effect analogous to that occurring in muscle. This is important in various ways, but particularly in experimental work, where it shows the necessity of recording the diastolic pressure at the same time as the velocity of the pulse wave. Its magnitude is emphasised in the experiment described below.

It is often suggested that in the living animal the velocity of the pulse wave may be affected by contraction of the involuntary muscle around the arteries. In so far as the contraction of involuntary muscle may affect the extensibility of the artery this will be the case, but in no other way. The part of the wave whose velocity is measured is the very rapid rise at the opening of the aortic valves, a rise which is detectible in a few thousandths of a second. It is inconceivable that a contraction of slow involuntary muscle, as we ordinarily know it, could affect the rate at which such a sudden rise is transmitted. The transmission of the pulse wave, therefore, is a purely mechanical phenomenon, its velocity being an indicator of the elasticity of the vessels, as modified by any conditions (muscular or otherwise), obtaining at the moment.

The chief difficulty in the observation of the velocity of the pulse wave in

an isolated artery lies in the fact that no considerable length of artery can be obtained, and the time-interval available for measurement is therefore very small. By replacing the blood with mercury, however, this interval can be increased 3·58 times, and the utilisation of this fact makes it possible to measure the velocity in an isolated artery with fair accuracy, and then to obtain the velocity in an artery containing blood by multiplication by 3·58. The reason for this is as follows: the velocity of the pulse wave is inversely proportional to the square root of the density of the fluid in the vessel, so that replacing blood ($\rho = 1{\cdot}055$) with mercury ($\rho = 13{\cdot}5$) decreases the velocity in the ratio $\sqrt{13{\cdot}5/1{\cdot}055}$, *i.e.*, of 3·58:1. This principle is embodied in the

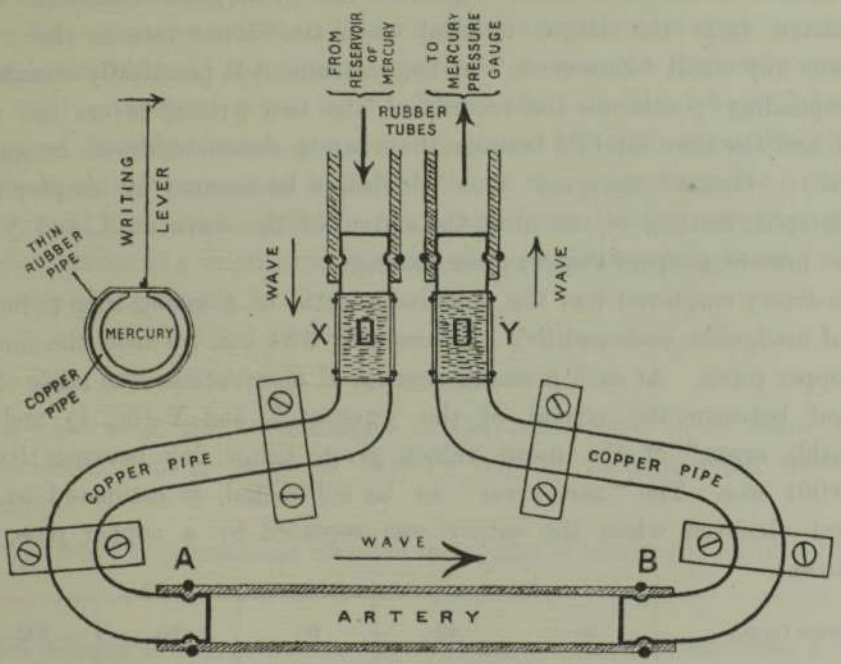

FIG. 1.

apparatus shown in fig. 1. A length of artery is tied firmly at A and B on to the copper pipes, which are clamped rigidly to a board. These copper pipes, at their other ends, are firmly joined to two long rubber tubes, one of which goes to a mercury reservoir capable of being raised and lowered, the other to a mercury pressure gauge. Thus the pressure in the artery filled with mercury (with bubbles carefully eliminated) can be adjusted to any required value. At X and Y in the copper pipes are two small windows, as shown in the diagram on the left. Over each window a small thin piece of rubber tube is carefully and firmly fixed, and on the rubber, over the *edge* of the window, is glued a minute aluminium angle-piece carrying the finest possible bamboo

writing lever. The two levers, lying close together, write upon the same revolving drum, and indicate the moments of arrival of a wave in the mercury, at X and at Y respectively. The wave is set up by hitting or squeezing the left-hand rubber pipe at some distant spot. Its arrival at X causes a sharp movement of the writing-point at X, it is then transmitted with very high velocity through the almost rigid copper pipes, being delayed, however, in its arrival at Y by the slow transmission across the elastic artery between A and B.

After the experiment on the artery is completed, the artery is replaced by a rigid copper pipe from A to B, and the observations are repeated, the small time interval observed when the rigid tube lies on the path of the wave being subtracted from the larger interval when the elastic tube is there. In this way any small "zero error" in the instrument is practically eliminated. Corresponding points on the records of the two writing levers are compared, and the time interval between them can be determined with reasonable accuracy. Greater accuracy could doubtless be secured by employing a photographic method of recording the arrival of the wave at X and Y, but for the present purpose this was not necessary.

The artery employed was the common carotid of a young man (who had died of malignant endocarditis). It measured 6·84 cm. between the ends of the copper pipes. At each pressure a series of observations was made of the interval between the arrival of the wave at X and Y (fig. 1), and the "probable error" of the mean values given below, lay between 0·0005 and 0·001 secs. The "zero error" to be subtracted, as estimated by the interval observed when the artery was replaced by a copper pipe, was as follows:—

Pressure (mm.)	20	40	60	80	100
Zero error (secs.)	0·0135	0·0142	0·0150	0·0157	0·0165
Pressure (mm.).....	120	140	160	180	200
Zero error (secs.)	0·0174	0·0182	0·0190	0·0198	0·0206

The following Table shows the results of a series of observations on the artery. The values for blood are obtained by multiplying by 3·58.

Pressure (mm.)	25	57	78	92	110	152	200
Interval observed (secs.) ...	0·079	0·086	0·0665	0·052	0·0465	0·0380	0·0338
Zero error (secs.)	0·014	0·015	0·0156	0·016	0·0170	0·0187	0·0206
Difference (secs.)	0·065	0·071	0·0509	0·036	0·0295	0·0193	0·0132
Velocity (metres p.s.)	1·05	0·96	1·34	1·90	2·32	3·55	5·18
Velocity, blood (m.p.s.) ...	3·76	3·45	4·81	6·80	8·3	12·7	18·5

We see here the same effect of pressure as was shown by the calculation from Roy's curves: the velocity increases comparatively slowly as the pressure rises to about 80 mm., then more rapidly, and finally at high pressures very considerable velocities are observed. As regards the absolute value, we may compare the velocity given in the above Table with that found, at the same (diastolic) pressure, in a normal living subject. According to Gallavardin (5) the average normal value of the diastolic pressure in man is 70 to 75 mm. Much higher values, however, are given by the use of the Pachon oscillometer (80 to 110 mm.). In normal healthy young men our observations (to be described elsewhere) have given velocities from 5·8 to 7·4 metres per second. Compared with the velocity interpolated in the above Table, for a pressure of 70 to 75 mm., these velocities are high: accepting the higher estimate of the diastolic pressure in man, the observed velocities agree well with those given in the Table; the velocities 5·8 and 7·4 m.p.s. correspond roughly there to pressures of 85 and 102 mm., respectively. On the whole, therefore, we may be satisfied that the pulse-wave has a velocity in the living man not far different from that in an isolated artery, and that its transmission is a mechanical phenomenon depending only on the elastic properties of the vessels.

Summary.

The theory of the transmission of the pulse-wave in a blood vessel is considered, and it is shown that its velocity, in metres per second, is given by

$$v = 3{\cdot}57/\sqrt{(\text{percentage increase in volume of artery per millimetre of Hg increase of pressure})}.$$

This velocity is relative to the blood in the vessel, and must have a small correction applied for the velocity of the blood itself. An observation of the velocity, therefore, gives directly the degree of extensibility of the vessel, and is shown to be one criterion of an efficient circulation. The experiments of Roy (1880) on the extensibility of vessels may be used to calculate the velocity of the pulse-wave: the calculation shows: (*a*) that pressure has a considerable effect on the velocity, a fact which is confirmed by experiments on an isolated human artery, filled with mercury in order to slow the transmission of the wave; and (*b*) that the velocity so calculated is lower than observed in man, a fact which is attributed to the phenomenon of elastic "after-action," which affected Roy's measurements. The experiments on an isolated human artery gave a velocity comparable with that observed in man, and it is concluded that the transmission of the pulse-wave is a purely

mechanical effect, its velocity depending on the extensibility of the vessels as modified by any condition (muscular or otherwise) obtaining at the moment.

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On a Remarkable Bacteriolytic Element found in Tissues and Secretions.

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(From the Laboratory of the Inoculation Department, St. Mary's Hospital.)

[Plate 9.]

In this communication I wish to draw attention to a substance present in the tissues and secretions of the body, which is capable of rapidly dissolving certain bacteria. As this substance has properties akin to those of ferments I have called it a "Lysozyme," and shall refer to it by this name throughout the communication.

The lysozyme was first noticed during some investigations made on a patient suffering from acute coryza. The nasal secretion of this patient was cultivated daily on blood agar plates, and for the first three days of the infection there was no growth, with the exception of an occasional staphylococcus colony. The culture made from the nasal mucus on the fourth day showed in 24 hours a large number of small colonies which, on examination, proved to be large gram-positive cocci arranged irregularly but with a tendency to diplococcal and tetrad formation. It is necessary to give here a very brief description of this microbe as with it most of the experiments described below were done, and it was with it that the phenomena to be described were best manifested. The microbe has not been exactly identified, but for purposes of this communication it may be alluded to as the *Micrococcus lysodeikticus*.