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ORIGINAL ARTICLES.

AN EXPERIMENTAL INQUIRY INTO THE CAUSES OF THE VARIATIONS OF PULSE-WAVE VELOCITY AND DURATION OF THE CARDIO-AORTIC OR PRESPHYGMIC INTERVAL OBSERVED IN MAN.

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"In every truth attained there is utility, either at hand or among the certainties of the future."—PAGET.

The work of the present essay was devised and prosecuted with the conviction that the points to be established were of interest and importance, and that the graphic method afforded the facility for their successful study.

Our knowledge of velocity of the pulse-wave has all been acquired within a comparatively recent period, and still later are our acquisitions in regard to the interval between the beginning of ventricular systole and rise of the aortic pulse. Previous to the

present investigation, it had been determined that the pulse-wave velocity and duration of the cardio-aortic interval

were both subject to variations, but the real causes of the variations remained to be determined by experimental inquiry and observation.

If, in the following pages, we make frequent reference to our own previous observations, it is because they are in the line of the present investigation, and have led up to the extension we hope to develop.

The experiments were made with the author's apparatus for simultaneous inscriptions (see cut), which, as known, differs from Marey's, notably in transmitting by water instead of air. This mechanism, on account of convenience and accuracy, was found admirably adapted to the work in hand. Also the author's accustomed method was followed in the measurements of the time intervals, and preparation of the slides for illustration.

Whilst the movements were being written, the chronograph also wrote the time in fifths of seconds. Immediately after an experiment, the slide was re-passed, and while halted at selected points, the levers, by manipulating the membrane or tube of the explorers, were made to describe their curves across the line of traces; and it was usually arranged so that the proximal lever would cross at or near the beginning of the waves, in order to simplify the measurements and render the time-relations more apparent to

the eye. These lines are synchronous signals cutting the traces at the same instant, and always indicate the exact time-relation to each other of the movements recorded.

The measurements were carefully made on the slides, by means of a transparent isinglass scale, ruled in 1-100ths of an inch. With this measure and the chronogram, and a magnifying glass, it was easy to compute the time in fine fractions of a second. This was done, and the results written on the slides.

The engravings are faithful reproductions throughout. The lines were photographed on wood, using the glass slides as negatives, and then the engraver, with great care and skill, followed the lines without deviation. So perfect is this work, that the fine measurements

A—Compound Sphygmograph, or apparatus for simultaneous inscriptions.

made on the glasses are found to hold good in the reproductions.

CHAPTER I.

EXPERIMENTS ON THE SCHEMA UNDER VARIOUS CONDITIONS, BEARING UPON THE CAUSES OF THE VARIATIONS OF PULSE-WAVE VELOCITY OBSERVED IN MAN.

The schema employed was very simple, yet satisfactory in its working. (See diagram.) The tube

or system conducting the liquid waves connected at either end with one of the horizontal limbs of a hollow T piece. The opposite limb of the proximal T connected with a tube twelve inches long, leading to the egress neck of an elastic bulb or pump. The ingress neck of the pump connected with a tube of convenient length leading to a reservoir. The opposite limb of the distal T connected with a flexible tube, three feet long, provided with a stop-cock one

foot from its outer end, and communicating near its middle with a water manometer graduated in inches. The vertical limbs of the Ts communicated with the transmission tubes of the recording apparatus, through the media of circular chambers, each divided transversely by a delicate elastic diaphragm; said receptacles being substituted for the ordinary explorers, and here termed "receivers."

Thus the reservoir supplied the liquid; the pump sent the waves along the conduits; the stop-cock regulated the discharge; the manometer measured the pressure; the T pieces and receivers permitted the waves to act directly upon the recording mechanism, and the latter registered their form and time as they manifested at the points of observation. The exit tube could be placed to discharge again into the reservoir, or a separate vessel. The pressure could be raised to any height by working the pump with the exit stop-cock closed, or partially so. A current as swift as desired could be created through the tubes by elevating the reservoir and opening the exit tube placed to discharge at a lower level. Different conduit tubes could readily be placed between the T pieces. The form of the waves could easily be varied by the manner of working the pump. The conditions could be changed at will, and the graphic apparatus would faithfully record the results.

It will be observed that our experiments on liquid waves in elastic tubes differ from Marey's and others—first, in the character of the graphic apparatus; second, in transmitting the waves directly from the interior of the schema; and third, in the close showings and estimates of the time intervals and wave velocities as manifesting under a variety of conditions.

These experiments were essential to the success and completeness of results aimed at in the investigation; and, as will be seen, the results when comparable with those of other experimenters, are sometimes confirmatory, other times contradictory.

PROBLEM I. To determine the influence of tubes of different degrees of stiffness or elasticity on the velocity of the liquid waves sent along their interior.

First experiment: A glass tube, three-sixteenth inch bore, and six feet long, bent in $\subset$ form, was placed in communication with the two Ts of the schema. The water in the reservoir was at such level that the pressure in the tube measured four inches by the manometer. The exit stop-cock was open, and the pump worked rhythmically by the hand with medium quickness and force. The graphic apparatus in order, with smoked glass in position and chronograph running, the carriage was started, and traces of the waves simultaneously obtained from the two points. Immediately the carriage holding the slide was passed through again, halting it where the upper lever would be opposite, or nearly, the beginning points of the proximal waves, and then striking both levers across the line of the traces. These lines made by the lev-

ers serve to indicate the distance between the beginnings of the proximal and distal waves, and this distance measured¹ on the corresponding part of the chronogram gives the time difference between them. In this experiment, Fig. 1 shows the result. The

Fourth experiment: A lighter tube than last, $\frac{1}{8}$ inch bore and same length, employed. Result in Fig. 4. Formula, $\frac{7}{12}$ of $\frac{1}{5} = \frac{1}{8.5}$ second; wave velocity 51 feet per second.

Fifth experiment: A tube of last description was

FIG. 1.—Glass tube, $\frac{3}{16}$ inch bore, 6 feet long; interval measured at $\frac{1}{36}$ second.

retardation of the distal waves on the proximal is seen to be extremely short. It seems to measure about $1\frac{1}{2}$ hundredths of an inch, while the fifths of seconds measure 11 hundredths, which would give a time difference of $\frac{1}{36}$ second, and a wave velocity over the six feet of distance of 216 feet per second.

Second experiment: A thick, firm rubber tube of the same bore and length was substituted for the glass, and the experiment under all other conditions conducted precisely as in the preceding. The result is shown in Fig. 2. The measurement is placed

made very soft and lax, and expanded to $\frac{3}{16}$ inch bore, by steeping in gasoline, and then put in experiment. The first pair of waves of Fig. 5, traced under parallel conditions with the others, shows the result. Formula, $\frac{11}{23}$ of $\frac{2}{5} = \frac{1}{5.2}$ second; wave velocity 31 feet per second.

Sixth experiment: Not being able to find in the market tubes of the thinness desired, we prepared one from a strip of delicate rubber cloth, by cementing the edges. This tube, $\frac{3}{16}$ inch bore and two feet long, placed in experiment, gave Fig. 6 as result.

FIG. 2.—Stiff rubber tube, $\frac{3}{16}$ inch bore, 6 feet long; int. $\frac{1}{27.5}$ sec.

at $\frac{2}{11}$ of $\frac{1}{5} = \frac{1}{27.5}$ second, and which gives a wave velocity of 165 feet per second.

Third experiment: A softer and more yielding tube of the same bore and length was employed. Fig. 3 shows the result. Formula, $\frac{5}{12}$ of $\frac{1}{5} = \frac{1}{12}$ second;

Formula, time-difference $\frac{1}{4}$ second for 2 feet, would make $\frac{3}{4}$ second for 6 feet; wave-velocity 28 feet per second.

Seventh experiment: A chicken's intestine, averaging $\frac{1}{4}$ inch diameter and two feet long, placed in

FIG. 3.—Ordinary rubber tube, $\frac{3}{16}$ inch bore, 6 feet long; int. $\frac{1}{12}$ sec.

wave velocity 72 feet per second.

¹Measurements are readily made by hair dividers and a hundredths inch scale, but more conveniently still by the use of a transparent scale of fine divisions.

experiment, gave Fig. 7. Time-difference $\frac{1}{8}$ second, equal to $\frac{3}{8}$ second for 6 feet; wave-velocity 16 feet per second.

Eighth experiment: A calf's aorta, averaging $\frac{1}{2}$

inch diameter, and 18 inches long, with the branches tied, gave Fig. 8. Time-difference, $\frac{1}{8.5}$, or $\frac{2}{17}$ second for $1\frac{1}{2}$ feet, equal to $\frac{8}{17}$ second for 6 feet; wave-velocity 12.75 feet per second. This arterial tube was very soft and elastic, but apparently firmer than the chicken's intestine. We shall see further on that size of tube is an important factor of modification.

and tracings taken at various pressures, and many experiments made, but always with the same negative result. Fig. 9 was taken with the chicken gut, before described, at 10 inches pressure. The time-difference measures the same, viz.: $\frac{1}{10}$ second, under the opposite modes of impulsion. Another illustration of this fact is shown in Fig. 11.

FIG. 4.—Lighter tube, $\frac{1}{8}$ inch bore, 6 feet long; int. 1-8.5 sec.

These experiments demonstrate in a specific manner, that the velocity of liquid waves in elastic tubes is proportional directly to the stiffness, inversely to the elasticity of the tube traversed. And as bearing upon the rate of pulse propagation in living arteries, they indicate the important modifying influence

This negative result was unlooked for, and is at variance with observations announced by Marey. Nevertheless, in view of our numerous and varied and carefully conducted experiments, to the end of testing this point, we are compelled to accept the fact as shown and stated.

FIG. 5.—Tube softened in gasoline, $\frac{3}{16}$ inch bore, 6 feet long; int. 1-5.2 sec.

which the state of the arterial walls as to stiffness or elasticity must exert upon the same. In the next chapter will be given actual verifications from man of a positive ratio between the velocity of the pulse-wave and degree of arterial stiffness.

PROBLEM II.—To determine whether the velocity

Obviously the fact teaches that the rate of pulse propagation is not modified directly by the manner of the heart's action; whether it beats quick, launching a sharp wave, or slow, sending a sloping wave, the pulse-wave velocity along the arteries is all the same.

FIG. 6.—Thin rubber tube, $\frac{3}{16}$ inch bore, 2 feet long; int. 1-14 sec. for 6 feet.

of liquid waves in the interior of elastic tubes is modified by the mode of impulsion.

Experiments:—Under stated conditions whilst tracings were being taken, the pump for one part of the run was worked with quick, and for another part with slow impulsion. Different tubes were employed

PROBLEM III.—To determine whether the velocity of liquid waves in the interior of elastic tubes is modified by the size of the tube.

It was first sought to solve this problem by the use of ordinary elastic tubing found in the shops, and so a tube $\frac{3}{8}$ inch bore and six feet long was put in ex-

periment to obtain results comparable with those of Fig 3. Fig. 10 was obtained. The time-difference is $\frac{1}{10}$ second.

But this experiment and result is not sufficiently conclusive, inasmuch as the larger tube was notably stiffer than the smaller, and this quality, as we have

To the same end Figs. 7 and 8 may also be compared, for, although the gut was laxer than the artery, the fact that the latter gave a slower rate of transmission shows the result was due alone to the larger size.

From this positive result we learn that, other things

Fig. 7.—Chicken's intestines, average 1-4 inch diameter, 2 feet long; int. 1-3 sec.—3-8 sec. for 6 feet.

seen, would of itself cause a swifter propagation of the waves. However, as the time intervals in the two tubes were the same, the speeding effect of stiffer walls must have been counter balanced by a slowing effect of larger size.

To more successfully test the point, it was nec-

being equal, the pulse-wave travels slower along larger and faster along small arteries.

PROBLEM IV.—To determine whether the velocity of liquid waves in elastic tubes is modified by a longer or shorter distance from the pump.

For this solution the receivers were placed on a

Fig. 8.—Calf's aorta, average 1-2 inch diameter, 1 and 1-2 feet long; int. 1-8.5 sec. 4.8.5 sec. for 6 feet.

essary to experiment with tubes of different diameters but of the same thickness and elasticity. Accordingly a tube one-half inch diameter and two feet long was prepared from the same rubber-cloth and in the same manner as the tube 3-16 inch diameter, which gave Fig. 6. An experiment with this tube gave

continuation of the 3-16 inch rubber tube, each six feet further from their original positions, and the waves traced at this remoter distance under like conditions as obtained in the production of Fig. 3.

Fig. 12 shows the result—time-difference $\frac{1}{12}$ second, the same as in figure 3, which represents the

Fig. 9.—Chicken gut, showing negative effect of opposite modes of impulsion.

Fig. 11, in which the time-difference is 1-9 second.

It will be noticed that the interval in Fig. 6 is 1-14 second, so this comparative experiment shows that wave propagation is slower in larger and faster in smaller tubes. Compare also Figs. 13 and 14.

neader distance. However, it appears that the points of the waves are slightly further removed from the beginnings as the distance from the pump increases.

We are informed through this experiment that distance from the heart neither accelerates nor retards the velocity of the beginnings of pulse-waves.

PROBLEM V.—To determine the influence of different pressures on the velocity of liquid waves in elastic tubes.

First experiment:—Result shown in Fig. 5, where with the softened tube the pressure was successively raised for each wave traced, as shown in the figure. It will be observed that the time-difference is the

Fifth experiment:—The calf's aorta, before described, employed and traces taken at different pressures. Fig. 15 shows the result.

Intervals respectively 2.17 second at 4 and 10 inches pressure, 2.21 second at 20 inches pressure, 2.25 second at 30 inches pressure, and 2.29 second at 40 inches pressure. Another positive result.

FIG. 10.—Tube $\frac{3}{8}$ in. X 6 ft. long; int. 1-12 sec. Compares with figure 3.

same at 4, 30, 40 and 50 inches pressure respectively.

Second experiment:—Result shown in Fig. 7, where with the chicken gut, after the first waves taken at the usual four inches, the pressure was successively raised as indicated. The result here is seen to be positive, the time-difference at four inches is $\frac{1}{8}$

Reviewing these experiments it is shown, the modifying influence of different pressures is small at best, and requires for development considerable difference of pressure in tubes very soft and elastic. The thin rubber tubes, delicate as they were, failed to make manifest any difference in velocity, while the animal

FIG. 11.—Thin tube 1-2 inch diameter, 2 feet long; int. 1-9 sec. Compares with figure 6.

second, at 30 inches 1-15 second, at 40 and 50 inches 1-18 second.

Third experiment:—Thin rubber tube, 3-16 inch, at different pressures. Result in Fig. 13.

The showing is negative, the time-difference running 1-14 second throughout.

tubes, although with thicker parietes, really more easily yielding, showed increased velocity coincident with marked increases of pressure.

These results have an important relation to the question of influence of blood-pressure on pulse-wave velocity. They indicate that variation of blood-

FIG. 12.—Longer distance from pump; int. 1-12 sec. Compares with figure 3.

Fourth experiment:—Thin $\frac{1}{2}$ inch rubber tube, at different pressures. Fig. 14 gives the result.

Showing again negative, the time-difference measuring uniformly 1-9 second at 4, 20, and 30 inches pressure, while at 40 inches the interval is really a little longer.

pressure tends to produce variation of pulse-wave velocity directly as the pressure; but in such pressure changes as occur in the organism and mixture of modifying agencies with which they act, it would be expected, in view of these results, that such effect would be of uncertain manifestation and slight when

FIG. 13.— $\frac{3}{16}$ inch thin tube, at increasing pressures; showing negative result. FIG. 14.— $\frac{1}{2}$ inch thin tube, at different pressures; showing negative result.

FIG. 15.—Calf's aorta, at different pressures; showing swifter velocity with higher pressure.

FIG. 16.— $\frac{3}{16}$ inch 6-foot tube, with a current; showing negative effect. FIG. 17.—Thin $\frac{3}{16}$ inch 2-foot tube, under a current; showing negative result.

observed. According to these experiments the current teaching on this point requires modification.

PROBLEM VI.—To determine whether the velocity of liquid waves in elastic tubes is modified by rapidity of current through the tubes.

Hitherto our experiments have been made with the liquid at rest in the tubes, except as sent forwards

By this we may know that, whether the blood in the arteries flows fast or slow, the velocity of the pulse-wave is not affected.

PROBLEM VII.—To determine whether the velocity of liquid waves in elastic tubes is modified by branches issuing therefrom.

Two rubber tubes, each $\frac{3}{16}$ inch bore and 6 feet

FIG. 18.—Showing negative effect of branches on main tube.

at each impulsion of the pump. To test the effect of a continuous current on the velocity of waves implanted upon it, the reservoir was elevated thirty-six inches (the supply tube lengthened accordingly), and the distal tube left to discharge freely into a vessel on the table below; and, whilst thus the water was

long, were branched on the $\frac{3}{16}$ inch 6 feet tube a few inches below the upper receiver, their distal ends turned into the reservoir. Traces of the waves were then taken with the result shown in Fig. 18, which signals a negative effect.

Again, the $\frac{3}{16}$ inch 6 feet tube was branched on

FIG. 19.—Chicken gut, with branch; showing negative effect.

flowing rapidly through the tube, the experiment was made. Fig. 16 gives the result with the $\frac{3}{16}$ inch six-foot elastic tube. The time difference, 1-12 second, is the same as that of figure 3, given by the same tube with the liquid at rest.

Fig. 17 is the result of a parallel experiment with

the chicken's intestine, and Fig. 19 obtained at 10 in. pressure, the first part without, the second part with, communication with the branch. It will be seen that the effect is again negative, the intervals measuring 1-10 second under both conditions.

In application of this experiment, in seeking to

FIG. 20.— $\frac{3}{16}$ inch 6-foot tube, with solution of starch; negative result.

the $\frac{3}{16}$ inch 2-feet thin rubber tube. This compares with Fig. 6, given by the same tube with the liquid at rest. It will be observed that the time differences are the same, viz., 1-14 second.

Liquid waves, then, travel along elastic tubes with the same speed, whether the liquid be at rest or freely flowing.

determine the cause of different rates of pulse-propagation for different articles, we may now exclude as of no effect the different conditions as to branches.

PROBLEM VIII. To determine whether the velocity of liquid waves in elastic tubes is modified by the consistence of the liquid.

A solution of boiled starch, as thick as would flow through the tubes, was substituted for water, and experiments made as with water. Fig. 20 shows the result with the 3-16 inch 6 feet tube, comparable with Fig. 3; and Fig. 21 shows the result with the chicken gut, which is comparable with Fig. 7. Results negative.

From this experimentation we learn that waves are delayed by great obstruction of the tube, and that the delay occurs at the point of obstruction, and is not caused by lessening of the rate of transmission below.

The bearing of these facts upon the influence of arterial obstruction in modifying the time of the

FIG. 21.—Chicken gut, with solution of starch · negative result.

This fact teaches that whether the blood be dense or watery, the pulse wave velocity is all the same.

PROBLEM IX. To determine the effect of obstruction of the tube on the time of the wave below the obstruction.

In Fig. 22, with the 3-16 inch thin tube, the waves

pulse wave, is at once apparent.

PROBLEM X. To determine the effect of an elastic pouch communicating with the tube, as an aneurism with an artery, on the time of the wave below the pouch.

A thin rubber bag, easily distensible, was placed in

FIG. 22.—3-16 inch thin tube; showing the effect at obstruction of the tube.

were traced first under the usual conditions, and then, whilst the tube was compressed just below the upper receiver, and then again just above. The measurements are 1-14 seconds with tube free, 1-11.3 seconds with obstruction below, and 1-14 second with obstruction above, the receiver. These fairly repre-

relation with the 3-16 inch 6 foot tube, so that communication between it and the tube could be opened or closed at will. Tracings were then taken, first with the sack shut off, and next with the sack in free communication. Fig. 23 shows the result. The retardation is sufficiently striking.

FIG. 23.—3-16 inch 6-foot tube, with elastic pouch.

sent the results of many similar experiments. The delay is small, but always discernable when the passage of the liquid is greatly obstructed below the near receiver. Obstruction above never causes delay. Also, we found the same result when the obstruction was created by plugging the tube so as to leave a very small aperture for passage of the liquid.

Next the pouch was placed in the same manner in relation with the chicken-gut, and the experiment proceeded with in the same way. Fig. 24 shows the result, which is negative as to delay.

Again, the pouch was associated with the 3-16 inch thin tube, and in continuity, instead of by lateral

communication; and to make the experiments strictly comparable a section of the same tubing of the same length as the pouch was interposed for the normal experiment, and that with the pouch above the receiver. First, the pouch was placed closely above the upper receiver and traces obtained shown in the first part of figure 25; next, it was removed and, the

our subject, and given somewhat in detail the experiments and results relating thereto, the following resumé of the facts arrived at will now be in order:

1. The velocity of liquid waves along the interior of elastic tubes is proportional directly to the stiffness, inversely to the elasticity of the tube traversed.
2. It is not sensibly modified by the mode of im-

FIG. 24—Chicken gut, with elastic pouch.

original connection having been restored, the middle part was obtained; third, it was placed immediately below the receiver (the section of tube having been removed), and the latter part obtained.

It will be noticed that the interval with the sack above the receiver, and that under normal conditions,¹

pulsion, a quick wave and a slow wave being transmitted along the same tube in equal times.

3. It is proportional inversely to the largeness of the tube.
4. It is not sensibly modified by different distances from the pump.

FIG. 25—Thin 3/16 inch tube, with elastic pouch in different positions

without the sack, measure the same; while that with the sack below the receiver is considerably longer.

In the first experiment the pouch was notably more distensible than the tube and so absorbed the wave to the extent of delaying its time of appearance at the lower receiver; while in the second experiment the contrast in yieldingness between the pouch and gut was not great, and so no retarding effect was contributed.

The third experiment demonstrates that the wave-delay incident to an elastic pouch begins and ends at the pouch, and that the wave which passes through travels on with undiminished velocity. It shows also in connection with the others that the retarding effect is more easily produced by a sack in continuity than by one with lateral connection.

We appreciate the significance of these facts in their bearing upon the subject of delay of the pulse produced by aneurism.

Having thus experimentally investigated the problems that seemed most pertinent to this branch of

5. It increases with increase of pressure of the liquid in very soft yielding tubes, but in all other elastic tubes, it shows no modification.

6. It is not modified by rapidity of current through the tube.

7. It is not modified by branches connected with the main tube.

8. It is not modified by liquids of different consistence.

9. The distal wave is notably delayed by obstruction of the tube, although its velocity of propagation is not appreciably diminished thereby.

10. The distal wave is delayed by communication with an elastic pouch more easily distensible than the tube, while if the pouch and tube are nearly equally yielding, there is no increased delay; yet the velocity of the distal wave is not perceptibly diminished from this cause. Hence,

11. The increased delay of the distal wave in arterial obstruction and distensible pouch arises from arrest at the site of obstruction and site of the yielding pouch.

¹The longer normal interval than those before shown for the same tube is attributed partly to the length of the tube having been increased by so much as the sack and its connections would increase it, and partly to relaxation of the tube from use and soaking in water.