Recoil Curves as Shown by the Hot-Wire Microphone.

By Lieut.-Colonel C. B. Heald, C.B.E., M.D., and Major W. S. Tucker, R.E., D.Sc.

(Communicated by Prof. C. S. Sherrington, P.R.S. Received November 15, 1921.)

[Plates 5–8.]

Introductory Remarks.

The subject matter of this paper deals largely with a description of a process which, in its bearing, appertains to physics rather than physiology, but as the application is entirely physiological, it has been decided to submit it as a physiological contribution.

In 1916, one of us (W. S. T.), while at work on the perfection of the hot-wire microphone, which he had invented for the location of enemy guns, realised the possibilities of the hot-wire microphone for obtaining records of the pulse, apex beat, etc., and had actually taken records both from the wrist and neck, and had shown these to members of the medical profession.

In the same year, when one of us (C. B. H.) was working upon the examination of cadets for pilots' certificates in the Royal Flying Corps, a converted "penny-in-the-slot" weighing machine was used for recording the weight. It was noticed that the machine would not permit an absolutely steady reading to be taken, as the point of the hand was in constant movement. Closer observation of this movement showed that it took place in time with the heart beat.

The obvious explanation of the movement of the hand was that the propulsion of the blood from the left ventricle of the heart towards the head during the first stage of systole was accompanied by a corresponding opposite movement of the body towards the feet. If this assumption were correct, then, knowing the weight of the body, measurement of the actual distance through which it was moved would provide a useful factor in determining the efficiency of the heart when regarded as a mechanical pump.

This simple observation with the weighing machine sufficed, however, to attract attention to the importance of employing the recoil of the body for the measurement of heart efficiency, the heart being considered as a pump.

The only previous work along these lines appears to be that undertaken by Prof. Yandell Henderson (7), who used a swinging table, in which lateral movements were prevented by an ingenious device; he was thus able to

record upon a smoked drum the movements of the table multiplied by 100. His remarks on this table are interesting :—

"With such a table, the heart beat causes not only longitudinal, but also lateral movements. The latter have not yet been examined in detail. In fact, it is necessary, in order to record the longitudinal movements with accuracy, that the lateral movements should be prevented. It is also necessary, not only that the person under examination should lie absolutely still, *but that he stop breathing during the time the heart beats are recorded.* Herein, indeed, lies the chief difficulty of the investigation, for while the total amplitude of the recoil movements is only a tenth of a millimetre, and some of the features of the curve amount to less than a tenth of this distance, respiration swings the body through a distance of many millimetres. Lastly, in order to avoid, so far as possible, errors from the table swinging back, after being moved out of plumb by the recoil, a pendulum period many times longer than the cardiac cycle was found necessary."

This author's comments, even with these precautions, showed that at least three great difficulties arose :—

(1) Periodicity in the recording apparatus.

(2) Errors due to respiratory movements.

(3) Errors due to the records having to be taken when the breath is either held, or the subject is blowing on a whistle.

He considers that if these difficulties could be overcome, our knowledge of the factors controlling the physical efficiency of the cardio-vascular system would be improved.

It appeared reasonable to think that the hot-wire microphone would give faithful records without encountering any of the difficulties above referred to, and, at the same time, provide a means of measurement and calibration.

It was realised that if such measurements and calibration could be accomplished, the results would be of value in examinations for determining physical efficiency, especially in the case of aeroplane pilots.

The recording apparatus (fig. 1) may be divided into three parts :—

(1) The microphones.

(2) The galvanometer and timing device.

(3) The photographic apparatus.

It may be here stated that some of this apparatus has already been in use in sound ranging of guns, but important modifications have been made in order to cope with the special difficulties of the method.

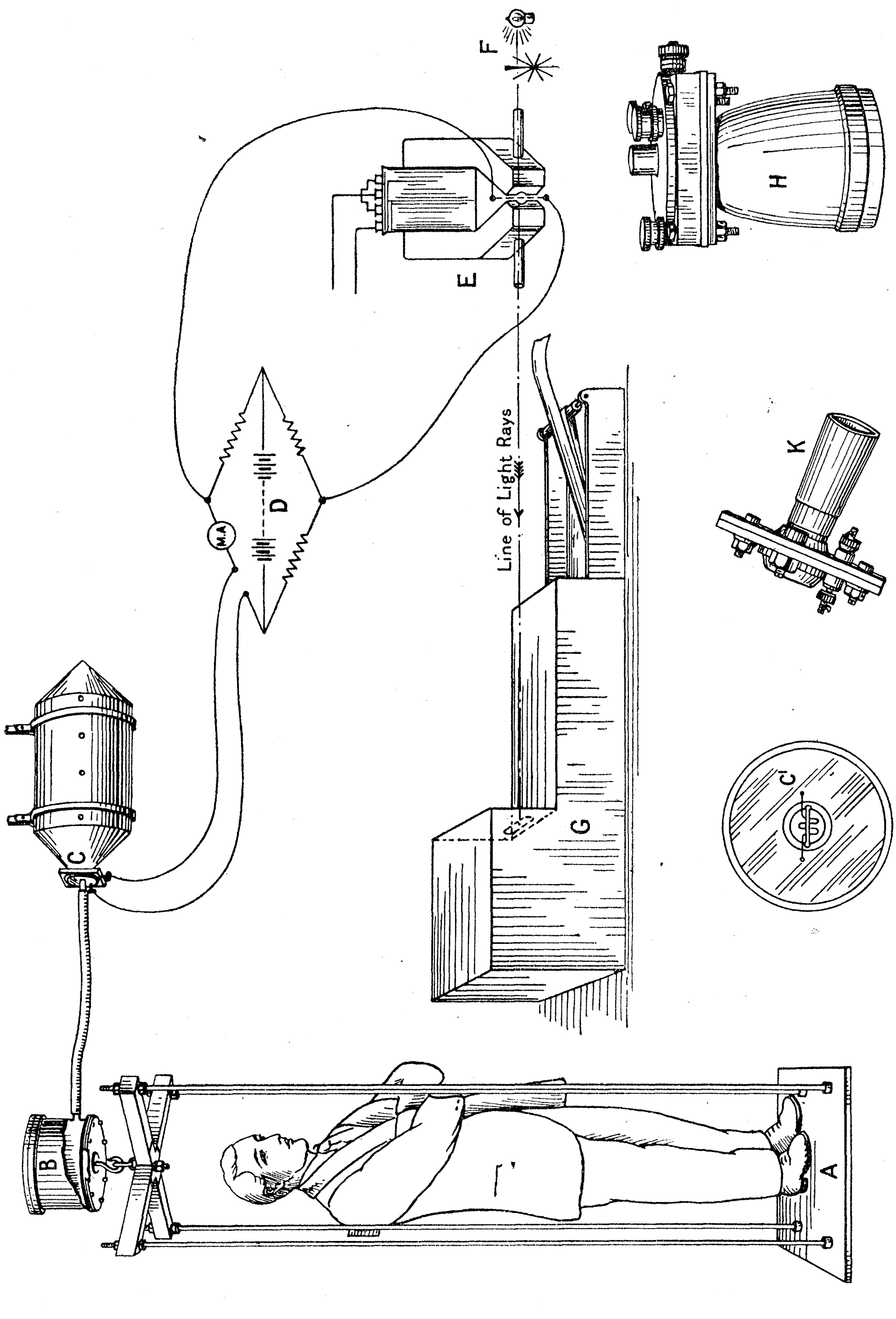


Fig. 1.

A, platform; B, drum and diaphragm; C, microphone and accessory cylinder; C¹, microphone grid; D, Wheatstone bridge circuit; E, Einthoven galvanometer; F, source of light and time wheel; G, camera and automatic developer; H, pulse microphone; K, breathing microphone.

1. *The Microphone.*

The hot-wire instrument is specially capable of dealing with low-frequency vibrations such as those imparted to the human body by the heart. It consists essentially of two iron drums, connected together by a short piece of rubber tubing.

One of the drums is fixed to the ceiling of the room in which the work is done. It consists of a cylinder, the side of which is about half its diameter. The platform on which the patient is standing is supported by a hook from a diaphragm which forms the circular end of the drum. When, therefore, the heart-beats cause motion of the body, the diaphragm responds, thereby altering the pressure within the drum in a corresponding way.

A side tube, let into the wall of the drum, permits the passage of air which is set in motion as a result of these changes. This tube is connected by the rubber tube above mentioned to a second cylinder of about twice the capacity, and having conical ends, in one of which is a fitting containing the hot-wire microphone grid. The air blasts, transmitted along the rubber tube from the first drum, are passed into the second drum through a tube opening, and are projected past the hot-wire grid, thereby cooling the grid and diminishing to a corresponding extent its electrical resistance.

Records of apex beat or carotid involved the use of a second microphone, simply consisting of an open cup whose rim is of ebonite and whose base contains the microphone fitting with its grid, and the image of the "string" recording these effects is thrown on the same recording strip as the recoil curve by means of a right-angle prism. The cup is pressed with its rim against the chest or neck, and the pulse changes are indicated by air blasts passing the grid into the open air (fig. 1).

The breathing microphone (fig. 1) consists of a single strand of hot-wire, mounted on an appropriate fitting attached to a stem resembling that of an ordinary tobacco pipe, but with a much wider air channel. The mouthpiece is held in the mouth, and the temperature of the grid is simply varied by that of the air or of the breath which passes inwards or outwards.

Periodicity of the breathing is thus indicated. A very small electric current is used, just sufficient to indicate change in resistance on the galvanometer.

2. *The Galvanometer and Timing Device.*

The galvanometer employed is of the Einthoven type. Body movements are measured by deflections of a very fine wire mounted between the poles of a strong electromagnet. The instrument employed is the Souttar galvano-

meter. It is less sensitive than the galvanometer used with the electro-cardiograph apparatus.

The galvanometer used for pulse or breathing records is of the same type as the instrument used in the Sound Ranging apparatus. It is less sensitive than the Souttar galvanometer.

All the records obtained, whether of body movement, apex beat or breathing, are obtained from one of these galvanometers acting in a Wheatstone bridge circuit.

The timing device is a rotating toothed wheel, kept in rotation by a synchronous motor, and the current which operates it is supplied from a circuit containing a contact opened and closed by a vibrating tuning fork electrically maintained. In this way, the time-wheel can only rotate at a constant speed satisfying the above conditions, and making the record in hundredths and tenths of a second.

3. *The Photographic Apparatus.*

For the production of permanent records, use was made of the automatic developing apparatus employed in gun sound ranging. This consists of a camera with a roll of sensitised paper which can be fed continuously behind a cylindrical lens; the paper thereafter passing automatically through a developing and fixing bath. The speed of the sensitised paper can be regulated at will, and is capable of being varied from 6 inches per second to $\frac{1}{16}$ inch per second.

It will be noted from fig. 1, that the diaphragm which receives the body impulses is very highly damped by the rubber ring that supports it. The microphone container is purposely made double, with rubber connection, since the latter will damp out very efficiently any resonance the air in the system might have.

The vibration galvanometer is heavily shunted so that, although sensitivity is sacrificed, the instrument is practically dead-beat. Fig. 2 shows the record of a make and break of 1 ohm change in the resistance of the microphone. This record also indicates sensitivity, and enables us to standardise all records taken from day to day (Plate 5).

With a standard microphone grid, working with a given electric current, and with a galvanometer of one definite sensitivity, quantitative comparisons of the various records can be made. The recording of minute air currents by the microphone is a special feature of our method as distinct from that employed by Yandell Henderson, and has been dealt with in a paper by one of us (W. S. T.) and Capt. E. T. Paris, on "The Selective Hot-Wire Microphone" (15).

The air, with its small inertia, here takes the place of the mechanism of the swinging table. The movements of the air are recorded faithfully and without measurable lag by the change in the temperature and electrical resistance of the hot-wire microphone.

The microphone is subject to resistance variation through change in the temperature of the room, thus changing the zero. This effect, however, can be overcome by simply adjusting the balance of the Wheatstone bridge.

In order to use the microphone—which has a resistance of about 150 ohm when heated—it is inserted in one arm of a Wheatstone bridge, the other arm being adjusted by a rheostat to give balance with the string galvanometer. The pulsating currents of air which cool the microphone grid, give a corresponding variation of resistance, but it must be noted in this investigation that motions of the air, whether positive or negative in direction, always produce positive deflections on the galvanometer wire, since all air movements produce a fall in temperature and a diminution in resistance of the microphone grid.

Another point to be emphasised is that deflections of the galvanometer wire are not proportional to the displacements of the body in a given direction, but are proportional to some function of the velocity of the body under recoil. What this function is, may be indicated by reference to the previous work done on the theory of the hot-wire microphone.

The deflection of the galvanometer, which may be considered to be proportional to the change in electrical resistance of the microphone, is dependent not only on the vibratory motions of the air set up by the heart action, but also on a certain amount of direct air current set up by convection, as a result of the disposition of the microphone grid in the orifice through which the vibrations are transmitted. Convection effect was reduced to a minimum in this investigation, by setting the plane of the microphone grid vertical, so that convection currents tend to be perpendicular to the displacements of the vibrating air. These currents, however, could not be completely eliminated, owing to the lack of complete symmetry of the enclosure on the opposite sides of the grid.

It has been shown in the paper above referred to that for a certain type of grid similar to that in use and under similar conditions, receiving vibrations $\mathrm{U}\sin pt$, the total resistance change

$$\delta \mathrm{R} = -0{\cdot}15\,\mathrm{U}^2 + 0{\cdot}15\,\mathrm{U}\sin pt + 0{\cdot}15\,\mathrm{U}^2\cos 2pt,$$

where U is the velocity of the air at any moment past the grid, $2\pi/p$ the period of vibration of the air. Other terms may be added to the above series, but have been shown to be so small as to be negligible. The con-

vection current in direction parallel to the displacements of the vibrating particles, is entirely responsible for the term containing U sin pt and from the equation it is seen that a simple harmonic vibration in the air is recorded by :—

(i) a displacement of the mean position proportional to the square of the velocity;

(ii) a periodic term in tune with the air vibration, of amplitude proportional to the velocity;

(iii) a periodic term an octave above this vibration proportional to the square of the velocity.

Terms (i) and (iii), therefore, are proportional to the kinetic energy in the air, while (ii) is proportional to the square root of that energy.

This relation has been checked by means of an artificial vibrating system fixed to the platform referred to above, and consisting of a spiral spring supporting a weight which, when displaced, vibrates vertically up and down. The spring becomes, for the time, an artificial heart, imparting its vibrations through the platform to the diaphragm and to the air in the microphone chamber.

The diaphragm is put under the same tension, etc., by placing weights upon the platform equal to the weight of the case under comparison.

Fig. 3A gives the galvanometer record which closely agrees with the above equation in which the maximum velocity of the vibrating air is 2 cm. per second, and the convection current about 2 cm. per second (Plate 5).

One complete vibration corresponds to two peaks, the higher one of which indicates a displacement of the vibrating air in the same direction as the air current.

At any point, the deflection of the galvanometer is proportional to the function of U as quoted in the above equation, but if the function be integrated with respect to time for a complete cycle, *i.e.*, for a time $2\pi/p$ the periodic terms vanish and a quantity proportional to U^2, *i.e.*, to the kinetic energy of vibration, is obtained.

If now the amount of kinetic energy contained in the spring is calculated from the mass of the spring, its periodic time and its displacements, we can calibrate the records in terms of such kinetic energy.

The vibrating spring, however, fails to resemble the heart in its action since, as seen from the record, the spring loses very little energy per period, *i.e.*, it is a nearly undamped vibrating system. Had it been heavily damped, the spring would rapidly come to rest and the record would show markedly decreasing amplitudes.

With the heart quite a different condition obtains. The projected blood

constitutes the mass of the spring and the muscles of the heart the spring itself, but the energy which is imparted to the blood, and therefore to the body as a whole, is immediately absorbed so that the vibrations appear to be dead beat. It is nevertheless true that the resistance variation, though not to be expressed by so simple an equation as that quoted above, can be treated in a similar manner, and for a heart cycle, consisting as it does of a number of vibrations, superimposed or consecutive, between two so-called heart beats, a process of integration can be carried out, and the result will give a quantity from which the periodic terms vanish, and which has a value proportional to a $(\text{velocity})^2$, *i.e.*, to the kinetic energy imparted to the body during the cycle.

The process of obtaining the kinetic energy of recoil of the body resolves itself, therefore, into the measurement of an area bounded by the heart curve and the zero axis, dividing this by the time, and expressing the result in any desired units of energy, by comparing with a similar area divided by time, given by the vibrating spring of known energy.

The kinetic energy contained in the spring was found from the relation $\frac{1}{2}\mathrm{M}p^2d^2$, where d is the amplitude of the spring and M the effective mass which is maintained in vibration with a periodicity of $p'/2\pi$. This corresponds during calibration to an amplitude in the Einthoven string of a.

The photographic record shows an amplitude of b, so that the kinetic energy of the spring as recorded is:—

$$\mathrm{M}p^2d^2b/2a.$$

In the case under consideration this quantity works out to 22×10^4 ergs and may be measured by the mean ordinate of the spring curve—say Y.

Dealing now with the heart curve, examination is made over a complete breathing cycle of six heart beats, and the mean ordinate for these is obtained (fig. 3, B). Calling this y, the kinetic energy exhibited in the body corresponds to

$$y/\mathrm{Y} \times 22 \times 10^4 \text{ ergs}$$

and this is completely absorbed, the time corresponding to it being t seconds.

Hence the kinetic energy produced averages for a breathing cycle

$$y/\mathrm{Y}t \times 22 \times 10^4 \text{ ergs per sec.}$$

In this determination $y/\mathrm{Y} = \frac{1}{2}$ and $t = 4{\cdot}23$ secs., so that the heart output creates a kinetic energy in the body of

$$2{\cdot}6 \times 10^4 \text{ ergs per sec.}$$

or

$$0{\cdot}18 \text{ gramme-metres per heart cycle.}$$

The figures obtained do not represent the total kinetic energy of the heart but are, we suggest, proportional to it. They must not, therefore, be compared directly with the work done by the heart, which, as given by Starling (12), is

in the neighbourhood of 82·3 gramme-metres per beat, of which 81·6 units represent work done against arterial pressure, and 0·7 units are measured in kinetic energy at the root of the aorta. The latter again is considerably greater than the value obtained by our experiments, since our measurements are integral of all movements footward and headward.

One other point should be referred to before proceeding. Yandell Henderson obtained records of displacement variation, and these in a given mass, that of the patient with the platform that supports him, are also records of the potential energy of that mass.

Thus it will be seen that the measurements made by Yandell Henderson and ourselves are complementary, since in any vibrating system the total energy at any time is the sum of its potential and kinetic energies. The two quantities will be out of phase $\pi/2$, maximum potential energy corresponding to minimum kinetic energy, and *vice versâ*.

The peaks of the displacement curve correspond to the minima of the records of this paper. Also, while the displacement curves can indicate positive and negative values, the curves of our records only give positive values. Allowing now for the change of phase of $\pi/2$ on passing from one curve to the other, and remembering that the values of the kinetic energy curves are always positive, it is possible to show a resemblance between the two sets of curves.

Fig. 4 is a reproduction of a diagram from Yandell Henderson's paper. Taking fig. 3, B, to represent a characteristic heart record obtained by the process described in this paper, the curve of fig. 4 can be approximately reproduced by reversing alternate peaks to allow for positive and negative

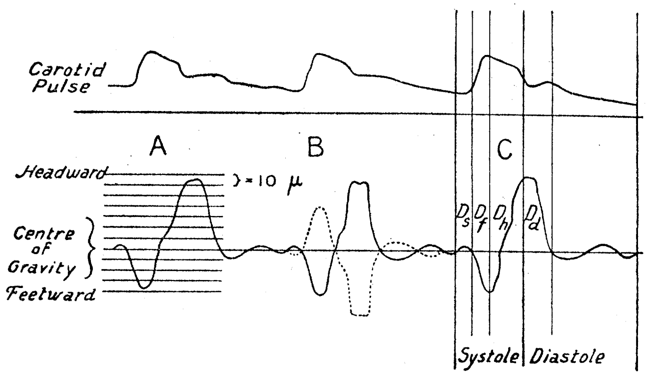


Fig. 4.

effects. The change of phase would be imposed by moving the curves as a whole through the width of half a peak, bearing in mind also that whereas

Yandell Henderson's curve reads from left to right, the record of fig. 3 reads from right to left.

Theoretical Considerations.

The maintenance of life depends ultimately upon the efficiency of the circulation.

Since circulation is maintained by the pumping action of the heart, any measurement of its output gives an effective method of testing the controlling engine of the body.

Yandell Henderson used the displacements in the body recoil in an attempt to measure the volume discharged from the heart per unit weight of the body at each contraction. Thus, a body of weight W would suffer a displacement D, corresponding to the propulsion of blood of weight w displacing an amount d at each heart contraction, where

$$w = \mathrm{WD}/d.$$

With accurate measurements of body displacement a figure is thus obtained proportional to the volume of the discharge per systole. It is obvious, however, that the actual work done in producing the movements of the body is not the reaction movement of the left ventricle only, but the algebraic sums of all the movements of blood or body fluids during the period of estimation.

The difference between our measurements and those of Yandell Henderson can now be clearly indicated. His curves are effective indications of the potential energy in the body at any moment, and changes in such energy are proportional to systolic discharge. The curves we obtain are indications of the complementary kinetic energy of the body, changes in which are proportional to the changes in potential energy. If Yandell Henderson's curves, therefore, measure systolic discharge, the same claim can be made for the curves given by the hot-wire microphone.

The advantage of obtaining kinetic energy curves rather than those of displacement shows itself in one important way. The displacements of the body produced by causes other than those due to heart action may be considerable. In the act of breathing, for example, the movements obtained may be many times greater than those due to propulsion of the blood. For this reason, Yandell Henderson took special precautions, such as holding the breath or causing the patient to blow steadily through a whistle. In our case, however, we are concerned with velocities rather than displacements, and the velocities in the body resulting from breathing are so small as to be negligible. The same applies also to slow muscular movements in the body, incidental on digestion, etc. Velocities of the air resulting from the

diaphragm displacement in the microphone container are here exceedingly minute, and we are thus able to assume that they produce no appreciable change in the electrical resistance of the microphone.

We are able to show, however, that breathing does produce a marked effect in systolic discharge, as will be clearly indicated in the records described later.

Experimental Work.

The earliest records were obtained by the simple process of seating the patient on a microphone container. It was found that the "spring" of the walls sufficed to produce measurable effects. In order to avoid change in zero of a balanced electric circuit, the resistance variations were conveyed to the galvanometer through the agency of a transformer.

The next development was that in which the patient was seated in a chair which was bolted to a wall of the container at a point beneath its centre of gravity. Both of these methods involved careful balance of the body, and in any case could give no quantitative results. The chair was then slung by chains from the under surface of the diaphragm in the apparatus described earlier in the paper, and a foot rest was fitted so that the patient could be seated at ease. Here, again, the effect, though more consistent, and though to some extent capable of comparable measurement, depended on the attitude of the subject, and records showed that marked differences were given when the knees were bent to different extents, or when the head was erect or bowed. Finally, the subject to be tested was placed on the swinging platform, in an absolutely erect position, with a shoulder rest to steady the body.

A change was also made in the electrical arrangements. It was found possible to replace the transformer method by that of the simple Wheatstone bridge. This latter arrangement enabled us to get more faithful records of the resistance changes of the microphone. Contrary to expectation, the zero of the record was found to be quite steady.

Consideration and Analysis of the Curves.

The Normal Recoil Curve.—The normal recoil curve is undoubtedly very similar to that shown in fig. 5. This curve and the majority of those reproduced in this paper have all been obtained from one subject (Mr. A. Reading), whose general physical standards are equal to those found in the best type of pilot. In addition, the electro-cardiogram and orthodiagrams of this case are normal (Plate 5).

Very similar records, which need not be reproduced here, were given by many other normal subjects.

As will be seen from the figure, the main features of the normal curve

consist of (reading from right to left) a small peak, followed immediately by two considerably larger peaks, and then by two smaller and somewhat flatter peaks. These peaks have been numbered 1 to 5 in the diagram. These five peaks, since they are nearly always present in every curve, may be considered as the essential elements of the normal recoil curve. In some of the heart cycles in the figure other smaller peaks may be observed, and it is generally these secondary peaks that tend to become exaggerated, or entirely absent, from case to case.

Fig. 5 shows also a simultaneous record taken over the carotid by means of the special hot-wire microphone previously described. On this record, the time relations of the various peaks of the recoil curve in relation to the phenomena of a heart cycle have been purposely omitted. This has been done to avoid confusion and error, as the peak of the "hot-wire" carotid curve, which indicates the maximum of velocity, does not occur at the same time as that on the ordinary carotid curve. It is, as shown previously, a curve out of phase with the ordinary curves which record changes in pressure. When the simultaneous records of figs. 5 and 6 were taken we had no comparator at our disposal and therefore have not given an exact figure for the time interval between the commencement of the first heart sound and the commencement of the carotid peak.

In the heart-sound microphone, the deflections caused by the commencement of the first and second sounds, corresponding, as they do, to the closure of the auriculo-ventricular and semilunar valves, fix very definite points of time in the heart cycle for comparative purposes on simultaneous tracings.

As heart-sound records are free from the difficulty inherent in any comparison between potential and kinetic energy curves, a simultaneous record of recoil and heart sounds has been prepared, and this is shown in fig. 6, while the relation of the two sounds has been more clearly defined by lines drawn through their commencement to cut the recoil curve.

As it is undesirable to introduce the recoil curve into the standard composite diagram representing changes of pressure in auricles, ventricles, aorta and carotid, a special diagram, fig. 7, has been prepared, in which the kinetic energy curves of body recoil and carotid are co-ordinated with heart sounds. For the time relations of the various events in a heart cycle, the data given by Lewis (10) have been used.

From figs. 5 and 7 the commencement of the carotid curve is seen to coincide with the beginning of the first or small peak of the recoil curve. This peak (1) is, therefore, probably caused by the feetward movement of the body corresponding to the headward movement of blood as it is projected from the left ventricle shortly after the beginning of each systole. The

interpretation of the two peaks (2 and 3) is, we think, as follows: The first is probably due to the movement of the body headwards as the mass of blood

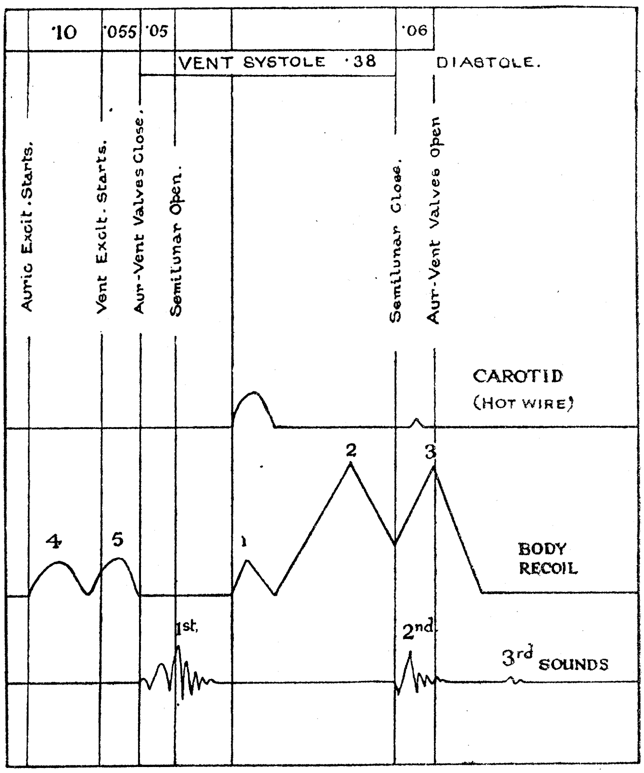


FIG. 7. (Read left to right)

passes down the aorta, while the second is caused by the return of the displaced body to normal.

The interpretation of the two smaller peaks (4 and 5) is, however, not easy, as it is difficult to believe that a recoil of this magnitude can be produced entirely by auricular systole.

In this connection, it should not be forgotten that patients with large and heavy hearts, not necessarily dilated *post-mortem*, frequently shake the whole bed. The question, therefore, arises whether, or not, some of the features of the recoil curve are due to the actual movement of the heart itself. It has been shown by needles passed into the base centre and apex that the base moves downward during systole. The elastic recoil of the distended aorta also requires taking into consideration. These questions have been left for subsequent investigation.

The interpretation put forward here of the recoil peaks must be considered, at present, as purely tentative.

In fig. 5 it will be seen that the recoils increase and decrease at regular intervals of time, and the relation of these increases and decreases to respiration are well shown in fig. 8. In this figure, the shorter parts of the breathing record correspond to inspiration, and it will be seen that, in agreement with other physiological observations, the maximum recoil occurs just after expiration has commenced (Plate 6).

The effect on the recoil curve, when the breath is held in deep inspiration and deep expiration, is well shown in fig. 9.

The recoils, which are so largely increased in inspiration and diminished in expiration, are undoubtedly due to the normal physiological variations in output during respiration. During inspiration, the descent of the diaphragm increases the positive pressure in the abdomen, thereby tending to press blood out of the abdominal veins, and at the same time the negative pressure in the thorax is increased, and greater suction exerted. The heart, therefore, will be better supplied during inspiration with blood than during expiration, and in consequence the output will increase, and enlarged recoils be the result.

The variation in curves given by apparently healthy individuals may be seen from fig. 10, where the first example demonstrates a simplified type of curve, in which only the primary peaks are recognisable, and from which secondary peaks are practically absent (Plate 7).

The second example shows the type in which the secondary peaks are so enlarged that they occasionally make recognition of the primary peaks difficult without dividers.

The third example, taken very shortly after the two upper curves, and without any alteration of the apparatus, is from the standard normal subject (A. Reading).

The meaning of these variations is the subject of investigation along two lines, one anatomical, and the other physiological. Small variations in the anatomical position of the axis of the heart, or in the disposition of the great vessels, may, as referred to above, alter the proportion of the total kinetic energy of a contraction acting in the long axis of the body. Or, as Krogh and Lindhard (9) have shown, individuals may have a high or low coefficient of oxygen utilisation, with a consequent small or big volume output from the heart, *i.e.*, a small or big recoil curve.

Variations in Blood Pressure.—As soon as it became evident that the recoil curves were subject to wide normal variations from subject to subject, a certain number of experiments were carried out to determine

the variations which made their appearance in the normal subject under different conditions.

Curves were therefore taken before and after meals over a series of consecutive days at the same hour; and before and after exercise.

It was thought at first that the variations in the recoil might bear some simple relation to the blood pressure. A number of healthy individuals were, therefore, examined from this point of view, but yielded no definite evidence that small differences of systolic, diastolic or pulse pressure readings could be correlated with alterations in the size of the recoil.

As Tigerstedt (13) had shown, with his *Stromuhr*, that nitro-glycerine increased the minute-volume and lowered the blood pressure, while adrenalin tended to the opposite effect, it was decided to try the effect of small doses of vaso-constrictors and vaso-dilators, liquor adrenalin and nitro-glycerine respectively, taken by the mouth. Accepting Tigerstedt's results as applicable to the normal human subject, it would seem that enlarged recoils are the result of increases in volume output rather than raised blood pressure, as is clearly shown by fig. 11. In this figure, the only curve showing a definite increase of recoil is (*d*), *i.e.*, the one taken five minutes after a small dose of nitro-glycerine. Curve (*c*), taken after a small dose of adrenalin, is not appreciably different from any of the control curves.

It is true that the dose of liquor adrenalin is very small, and was given by the mouth, but the effect of the nitro-glycerine is very striking.

Curves were also obtained after taking by the mouth 0·02 grm. of the vaso-constrictor tyramine, a drug which is definitely known to be absorbed, and recoils of diminished amplitude were obtained.

The results are not conclusive, but, taken in conjunction with the variations during respiration, are suggestive that alterations in the volume output are the chief factors affecting the magnitude of the recoil; this agrees with the theory of the action of the microphone dealt with above.

The result of experiments carried out to show the effect of increased heart work on the recoil indicates that all the features of the normal curve become enlarged, especially the smaller peaks. An example of a curve taken before, immediately after, and some time after exercise, is shown here to illustrate this point (fig. 12, Plate 8).

It would not, however, be justifiable to assume, at this stage, that a curve such as (B) of fig. 10 is produced because the subject's heart is doing more work.

All the experiments that have been carried out have been directed solely towards ascertaining the nature of a normal curve, and the variations to which it is subject. As a single control to these experiments, the recoil

curve from a case of aortic regurgitation with a high blood pressure, and a very large heart, was taken. It is shown here (fig. 13) as an example of the extreme deflection caused by the hot-wire microphone, when abnormal movements of the body are transmitted to the air in contact with it.

Conclusion.

A careful examination of the above records shows that there is an additional periodic effect, besides that of the heart cycle and of breathing. This reveals itself in the variation in heights of the two highest peaks. At certain parts of the record, the first peak is higher, in other parts it is lower than the second peak, while we also get the intermediate conditions of equality of peaks. One of these effects can be partially explained by the difference in sensitivity of the microphone according to the direction of the air current; but some physiological explanation is required to account for the whole phenomenon, as instrumental variations have been reduced to a minimum. This effect will be the subject of further study.

The apparatus employed for the recoil measurements is now being further modified, so that the patient can be examined in a recumbent position. Records could then be obtained when the muscles are completely relaxed and might easily be taken during sleep.

This further modification will also permit us to measure the recoil in directions perpendicular to the body axis, so that information regarding the whole of the body movements should then be available.

Summary.

This paper deals with a new method of measuring body recoil as the result of heart action. Attempts have been made to eliminate the disturbing factors operating against the success of Yandell Henderson's method. To effect this, the hot-wire microphone with suitable galvanometer and recording apparatus has been employed, and the records actually made measure quantities proportional to the kinetic energy imparted to the body by motions of the blood. In this way slow-moving displacements, such as those of breathing, fail to be recorded.

The apparatus is of such form that it can be standardised, giving the same responses from day to day for the same body recoils.

A method is indicated of expressing this kinetic energy of the body in C.G.S. units. Attention has been concentrated on the records obtained from a favourable subject, and an analysis of these curves shows that the events of a heart cycle can be recognised.

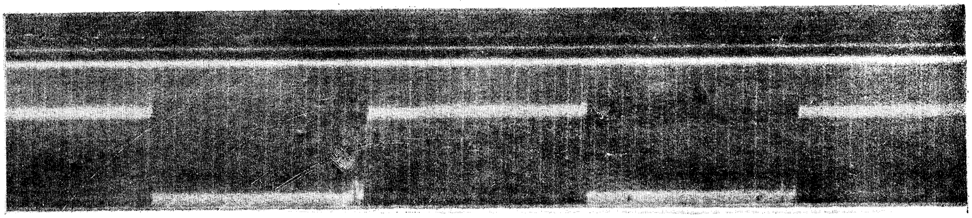


Fig. 2

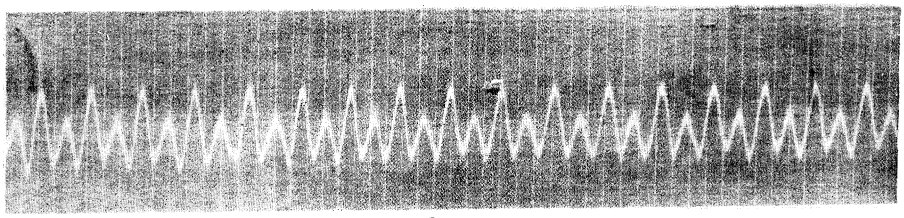


Fig. 3 A

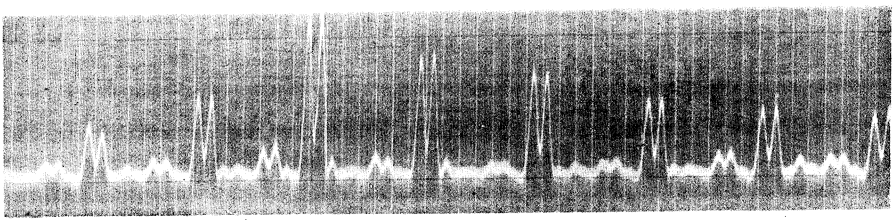


Fig. 3 B

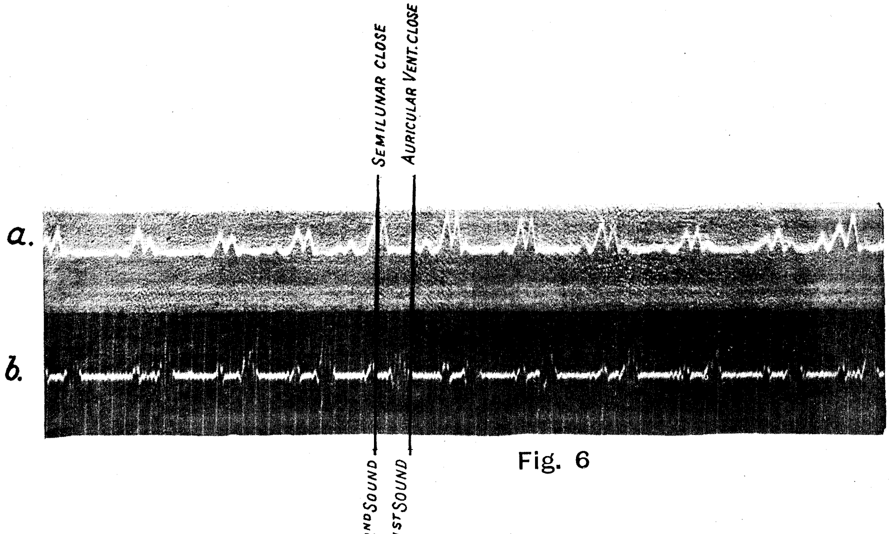


Fig. 6

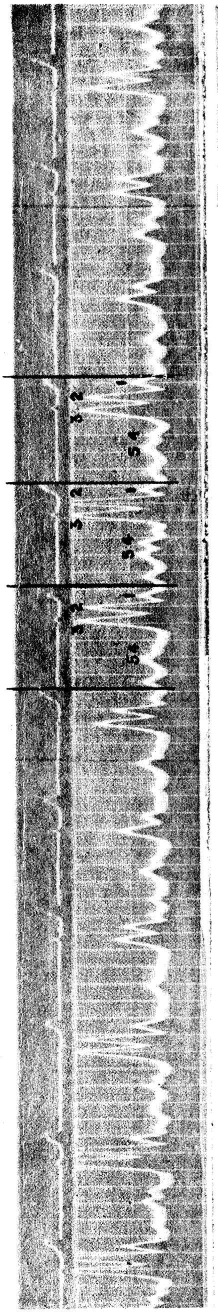


Fig. 5

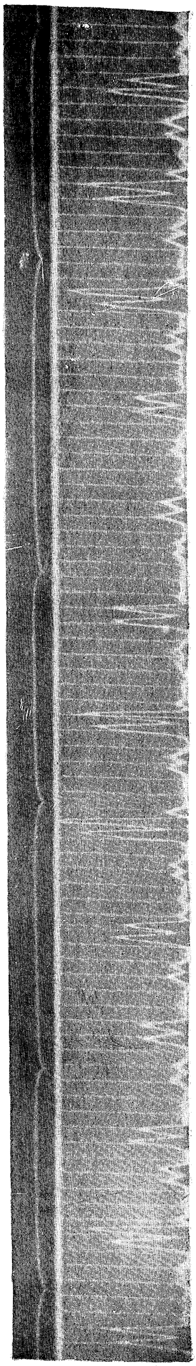


Fig. 8

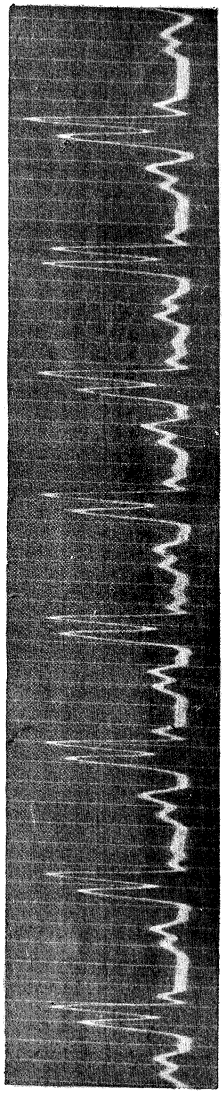


Fig. 9 INSPIRATION (held)

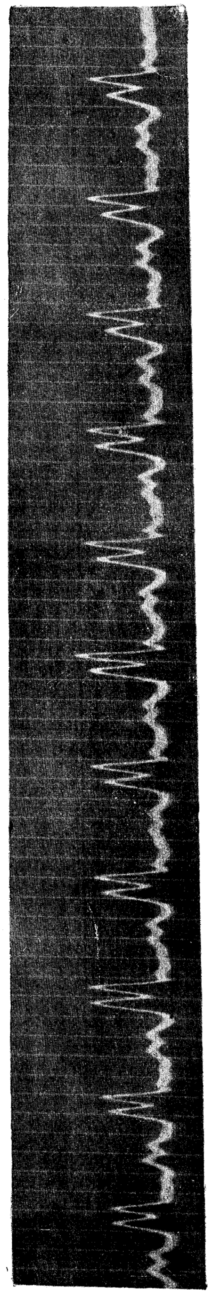


Fig. 9 EXPIRATION (held)

Fig. 10

A

B

C

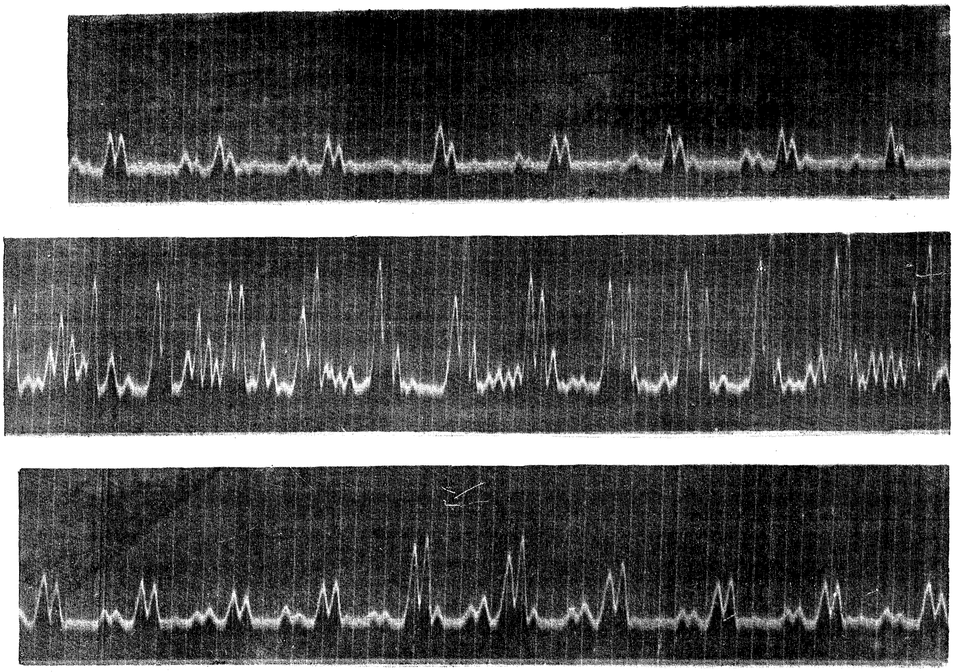


Fig. 11

(a) Normal Recoil Curve as general Control.

(b) 5 minutes after 1 ounce of Peppermint Water (to demonstrate presence of a psychological effect, if any). Showing no psychological effect produced.

(c) 5 minutes after 1 ounce of Peppermint Water, to which 15 drops of Liquor Adrenalin had been added.

(d) 5 minutes after 1 ounce of Peppermint Water, to which 1/150 grain of Nitroglycerin had been added. Showing great increase in second and third peaks.

(e) Control curve taken half-an-hour after (d), showing complete return to normal.

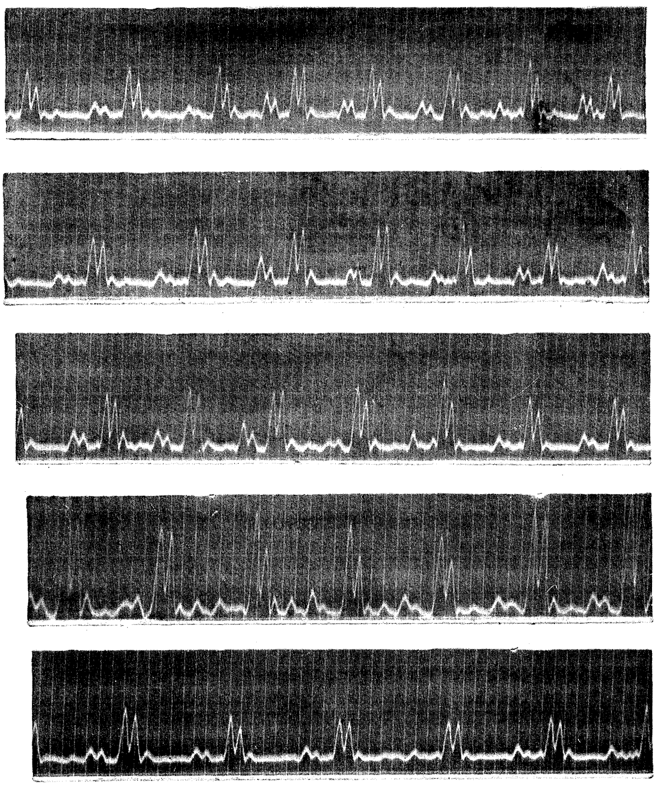
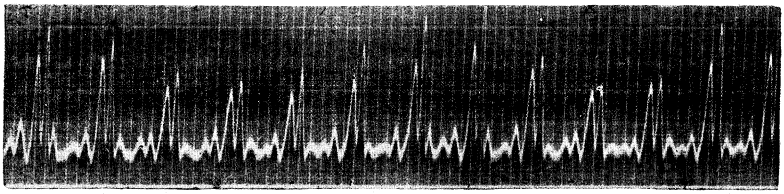


Fig. 12

NORMAL HEART RECORD BEFORE EXERCISE

IMMEDIATELY AFTER EXERCISE



60 SECONDS AFTER EXERCISE

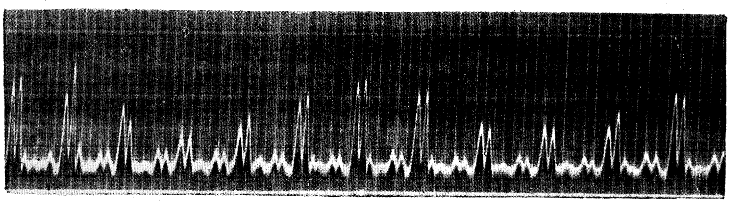
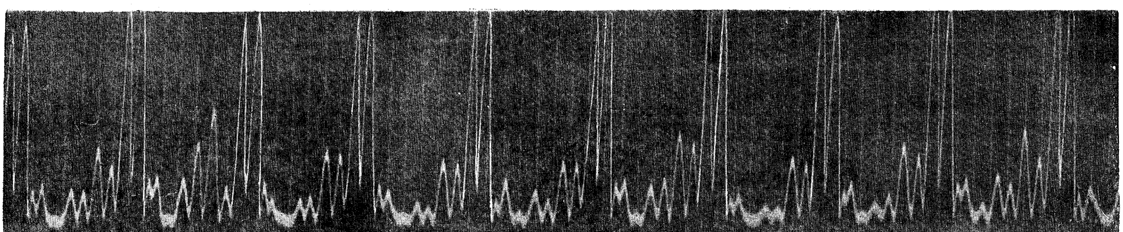


Fig. 13



The results so far obtained are consistent with accepted physiological data as to the variations in the systolic output of the heart, as affected by exercise, respiration or the action of vaso-constrictors and vaso-dilators.

In conclusion, the authors wish to express their appreciation of the help and assistance given to them in carrying out this work by Sir Frederick Sykes, the Controller-General of Civil Aviation, and Lieut.-Colonel Cusins, Chief Experimental Officer of the Signals Experimental Establishment, where the work was carried out. They further desire to express their indebtedness to Prof. Yandell Henderson, Dr. A. W. Stott for his kind collaboration during the preliminary stages, and to Dr. P. Hamill, when correlation with the electro-cardiograph was required, as well as for advice on the physiological aspects of the paper.

The authors particularly wish to recognise the help given by Mr. A. Reading, who, besides providing them with a very useful subject for heart recording, also manipulated the apparatus most skilfully.

REFERENCES.

(1) Bainbridge, F. A., 'The Physiology of Muscular Exercise,' London, 1919; "The Influence of Venous Filling upon the Rate of the Heart," 'Jnl. of Physiology,' vol. 50, p. 65.

(2) Bainbridge, F. A., and Hilton, R., "The Relations between Respiration and the Pulse Rate," 'Proc. Physiol. Soc.,' p. 65; 'Jnl. Physiol.,' vol. 52.

(3) Barcroft, J., "Measurement of the Blood Flow through the Chest of the Goat," 'Proc. Physiol. Soc.,' London, 1919; "The Measurement of the Work Performed by the Heart," 'Proc. Physiol. Soc.,' London, 1919.

(4) Cannon, W. B., "Auscultation of the Rhythmic Sounds (Telephone Records) produced by Stomach and Intestines," 'American Journal of Physiology,' 1905.

(5) Dunn, J. S., "Measurement of Pressure in the R.V.," 'Proc. Physiol. Soc.,' London, 1919.

(6) Golla, F. M. (Croonian Lectures, R.C.P.), "The Objective Study of Neurosis." 'Lancet,' 16/7/21, 30/7/21, 6/8/21, 20/8/21.

(7) Henderson, Yandell, "The Mass Movements of the Circulation, as shown by a Recoil Curve," 'American Journal of Physiology,' 1905.

(8) Hill, A. V., "Electrical Recording of the Pulse," 'Lancet,' 9/10/20; "Hot-Wire Microphone," 'Lancet,' 30/10/20.

(9) Krogh, August, and Lindhard, J., "Measurements of the Blood Flow through the Lungs of Man," 'Skand. Archv. für Physiol.,' vol. 27, p. 100 (1912); "On the Influence of the Venous Supply upon the Output of the Heart," 'Skand. Archv. für Physiol.,' vol. 27, p. 126 (1912); "The Regulation of the Supply of Blood to the Right Heart," 'Skand. Archv. für Physiol.,' vol. 27, p. 227 (1912).

(10) Lewis, T., 'The Mechanism and Registration of the Heart Beat,' London, 1920.

(11) Mackenzie, J., (*a*) 'Diseases of the Heart,' London, 1913; (*b*) 'The Study of the Pulse, Arterial, Venous, and Hepatic, and of the Movements of the Heart,' London, 1902.

(12) Starling, E. H., 'Principles of Human Physiology,' London, 1912.

(13) Tigerstedt, C., "Zur Kenntnis der von dem linken Herzen herausgetriebenen Blutmenge in ihrer Abhängigkeit von verschiedenen Variabeln," 'Skand. Archv. für Physiol.,' vol. 22, p. 173 (1909) *et seq.*

(14) Tigerstedt, R., "Neue Untersuchungen über die von dem linken Herzen herausgetriebenen Blutmenge," 'Skand. Archv. für Physiol.,' vol. 19, p. 25 (1907) *et seq.*

(15) Tucker, W. S., and Paris, E. T., "A Selective Hot-Wire Microphone," 'Phil. Trans.,' A, vol. 221, pp. 389–430.

The Velocity of the Pulse Wave in Man.

By J. Crighton Bramwell,* M.B., M.R.C.P., and A. V. Hill, F.R.S.

(Received February 4, 1922.)

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.

* Working for the Medical Research Council.

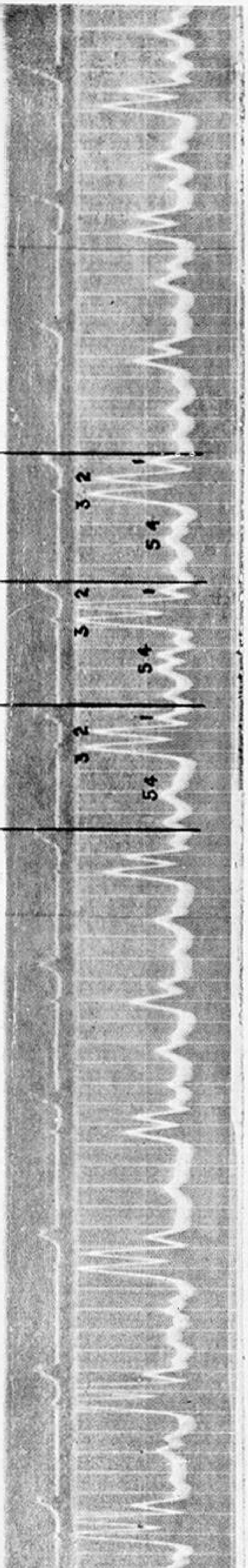


Fig. 5

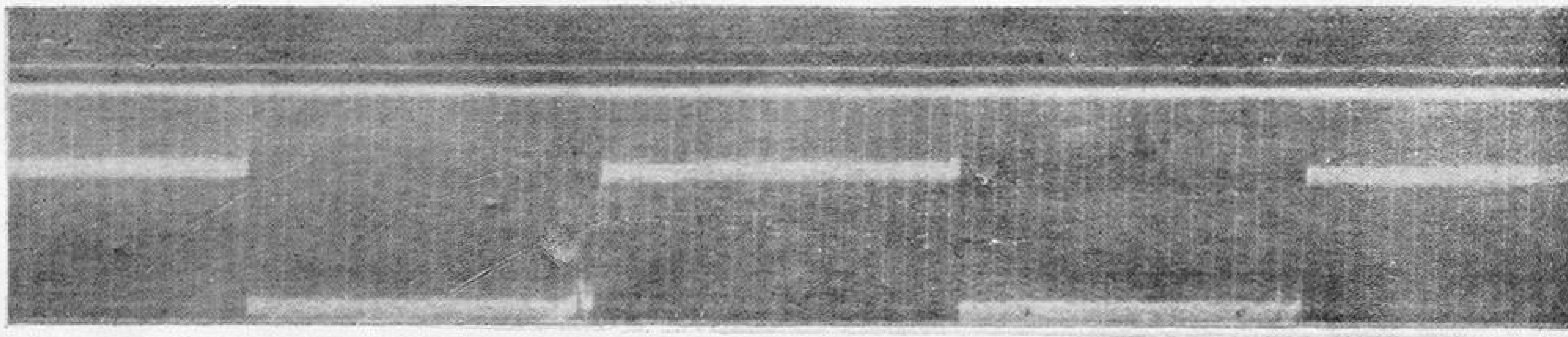


Fig. 2

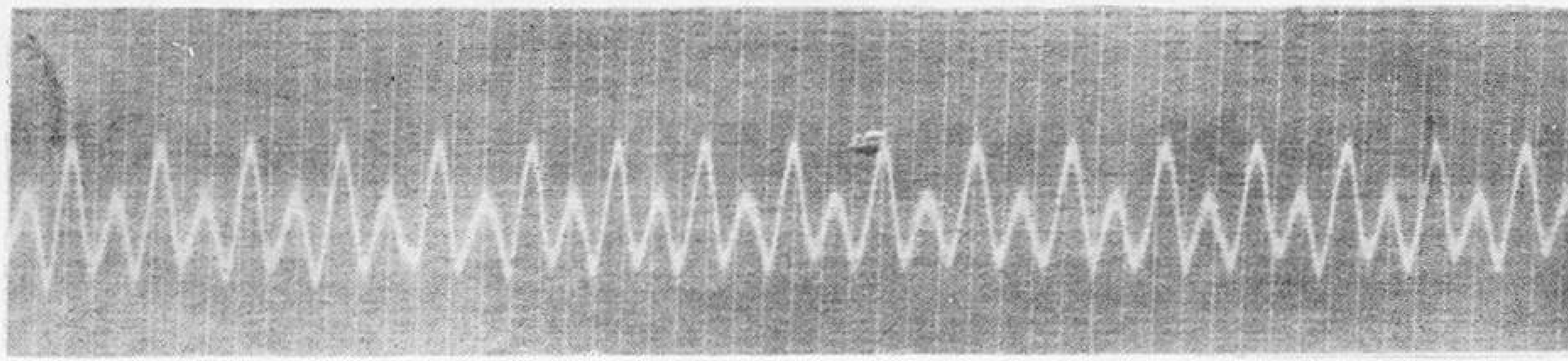


Fig. 3 A

Fig. 3 B

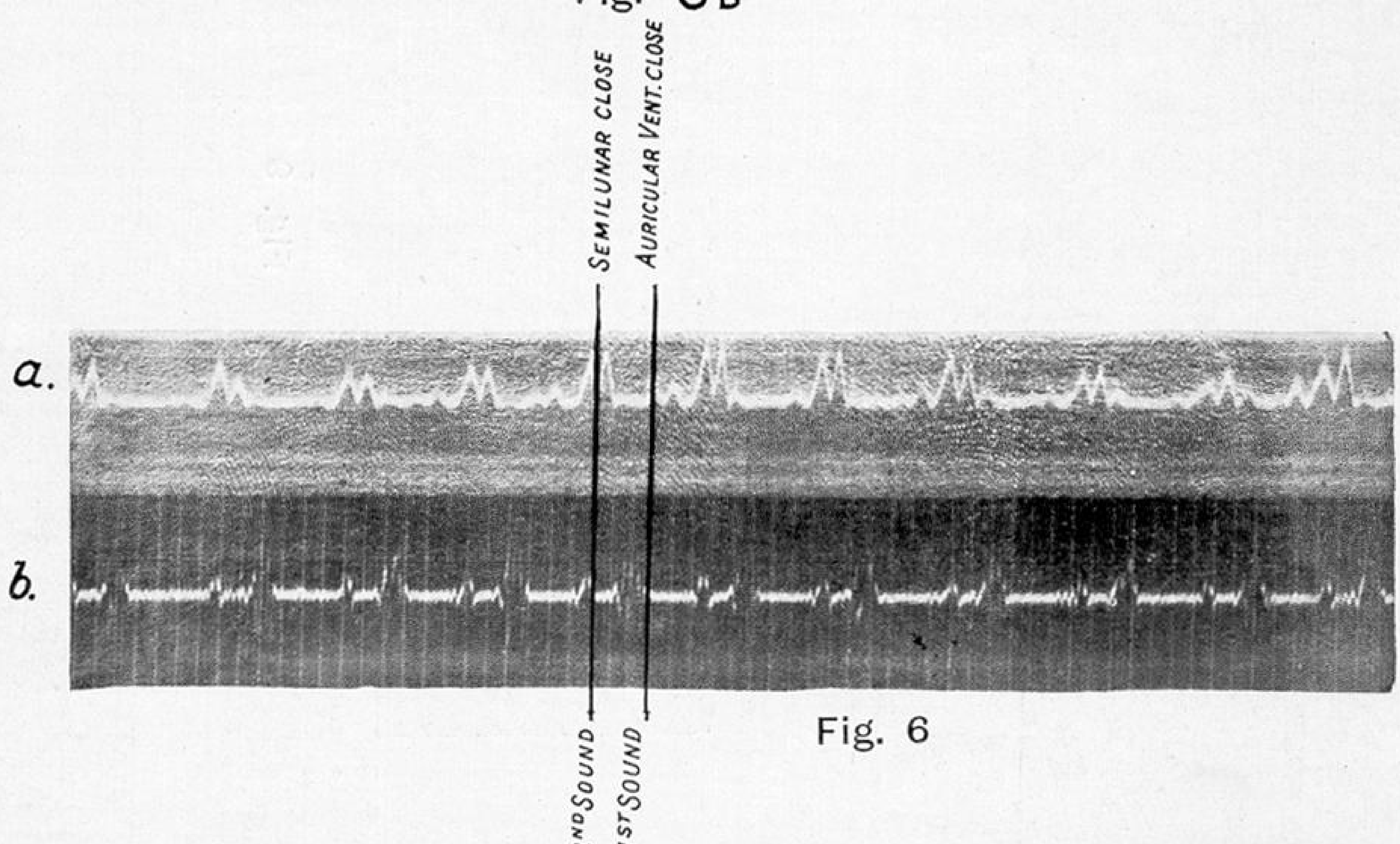
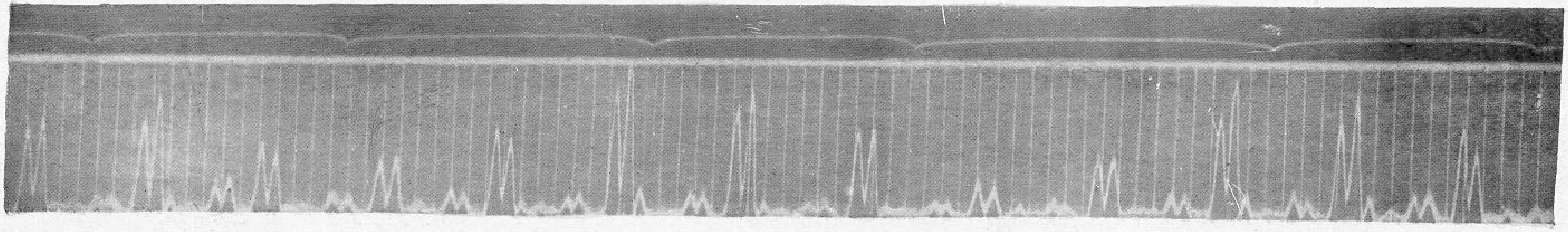


Fig. 6

Fig. 8



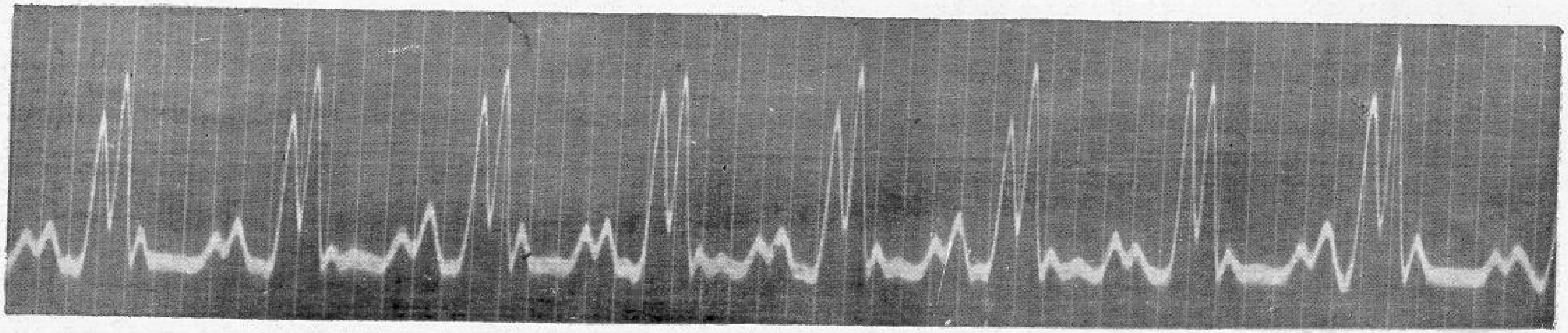


Fig. 9 INSPIRATION (held)

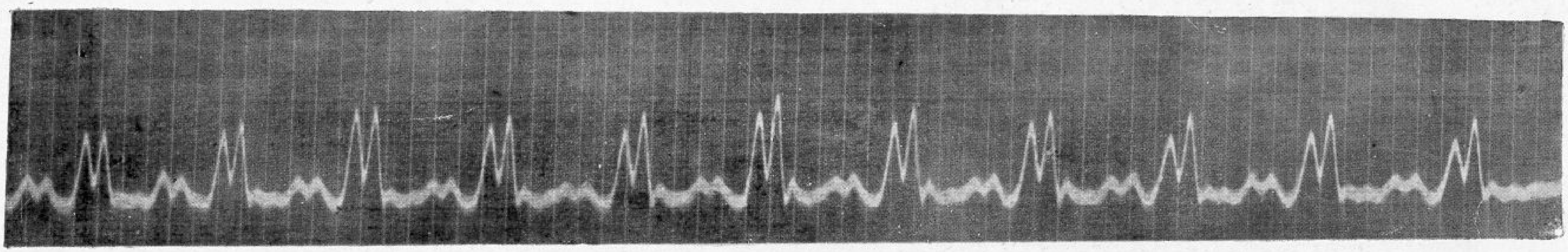
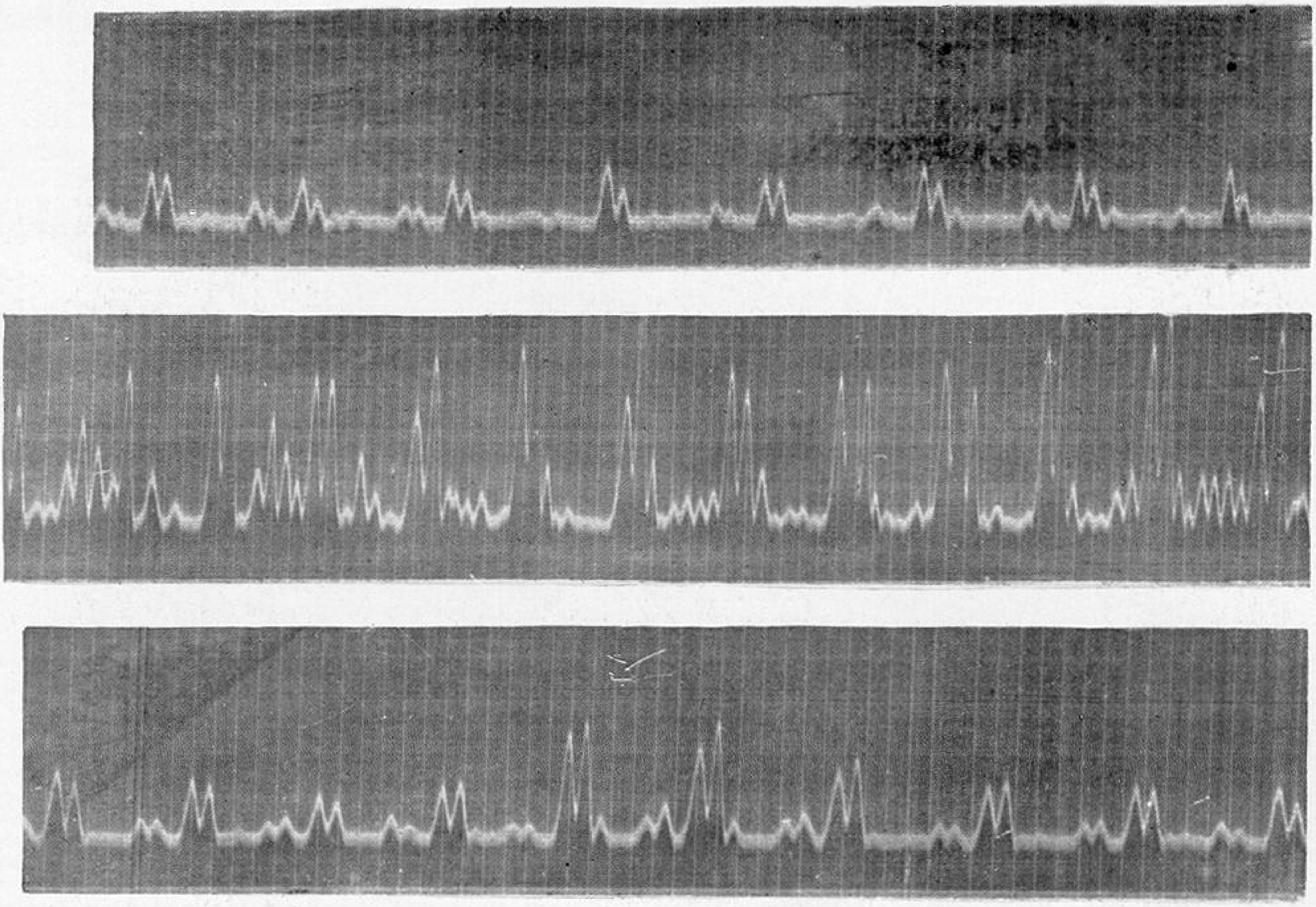


Fig. 9 EXPIRATION (held)

Fig. 10

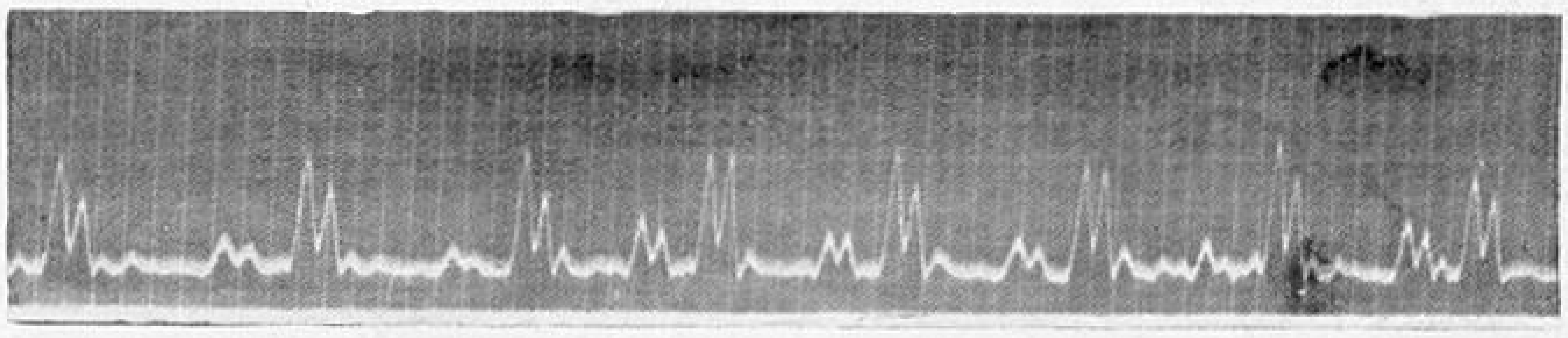


A

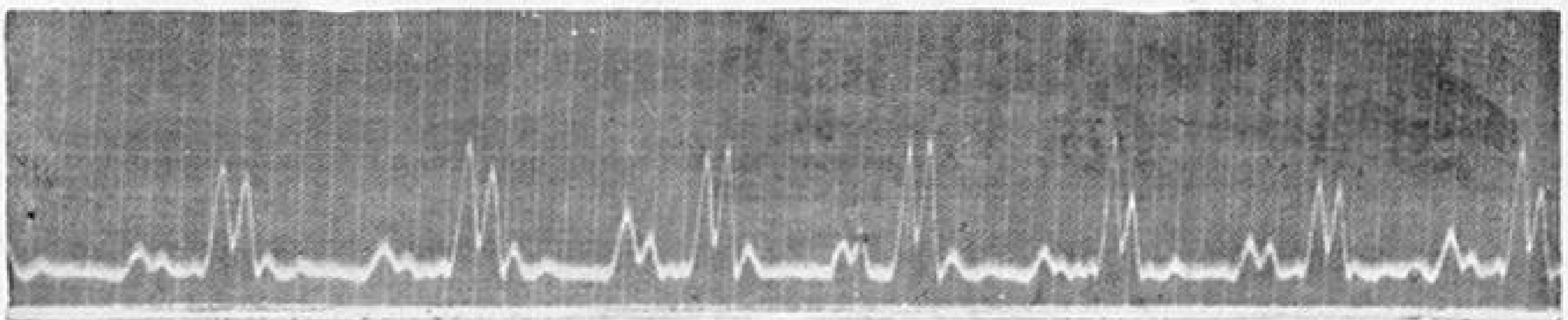
B

C

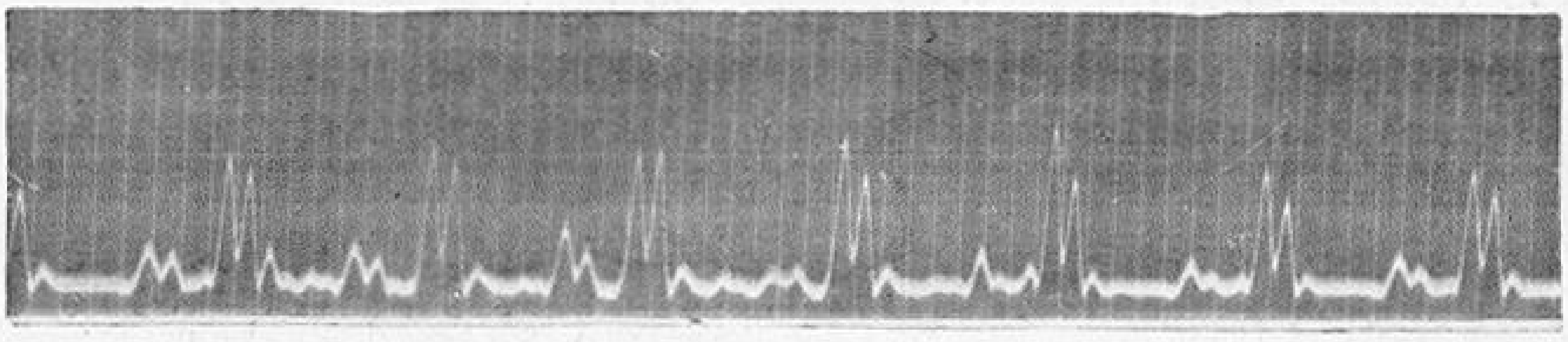
Fig. 11



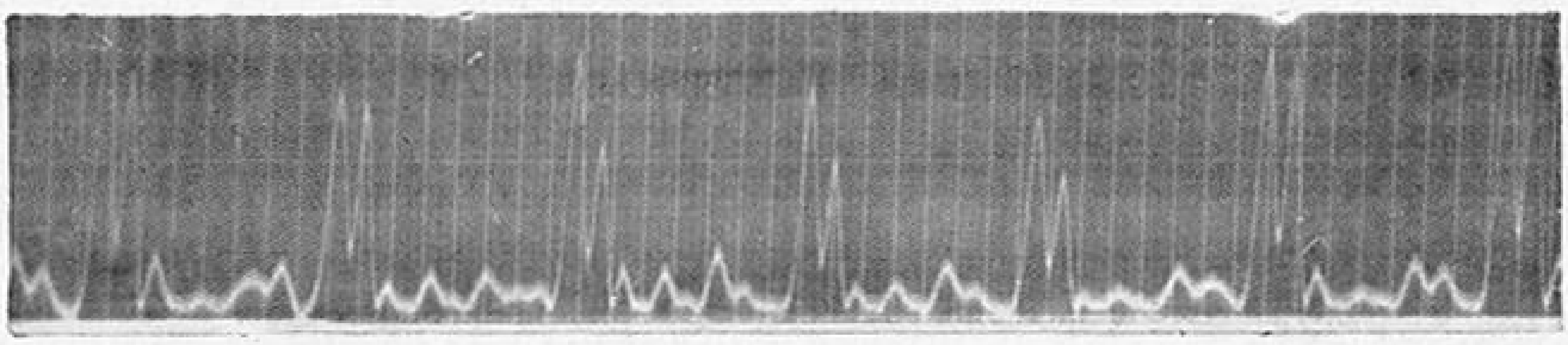
(a) Normal Recoil Curve as general Control.



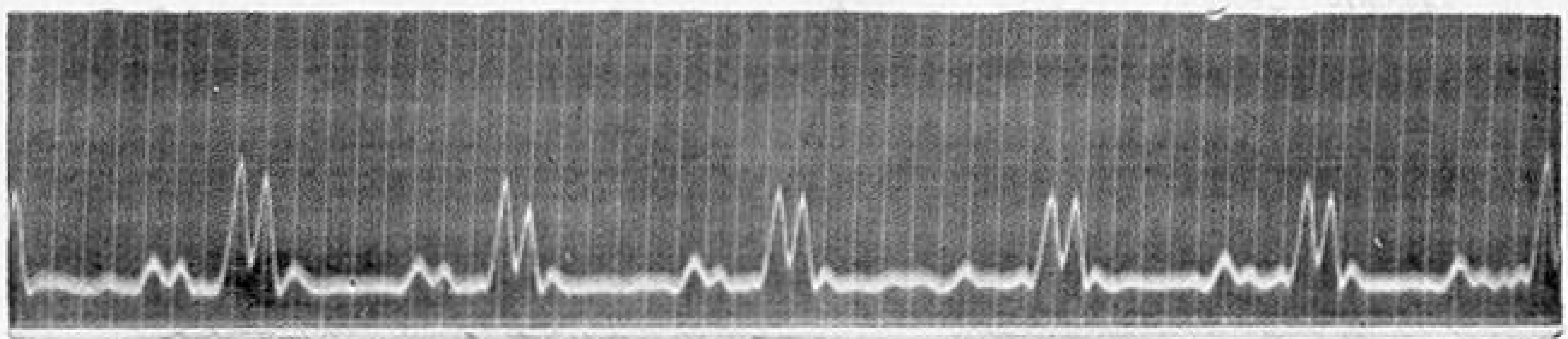
(b) 5 minutes after 1 ounce of Peppermint Water (to demonstrate presence of a psychological effect, if any). Showing no psychological effect produced.



c) 5 minutes after 1 ounce of Peppermint Water, to which 15 drops of Liquor Adrenalin had been added.



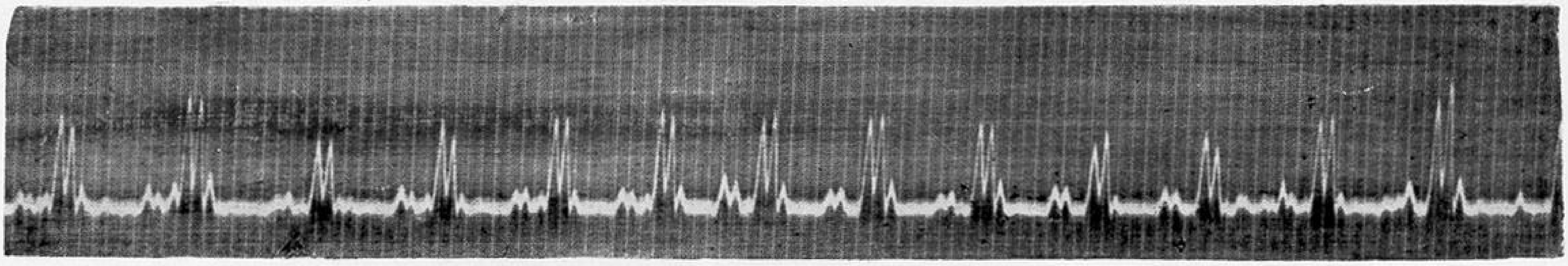
(d) 5 minutes after 1 ounce of Peppermint Water, to which 1/150 grain of Nitroglycerin had been added. Showing great increase in second and third peaks.



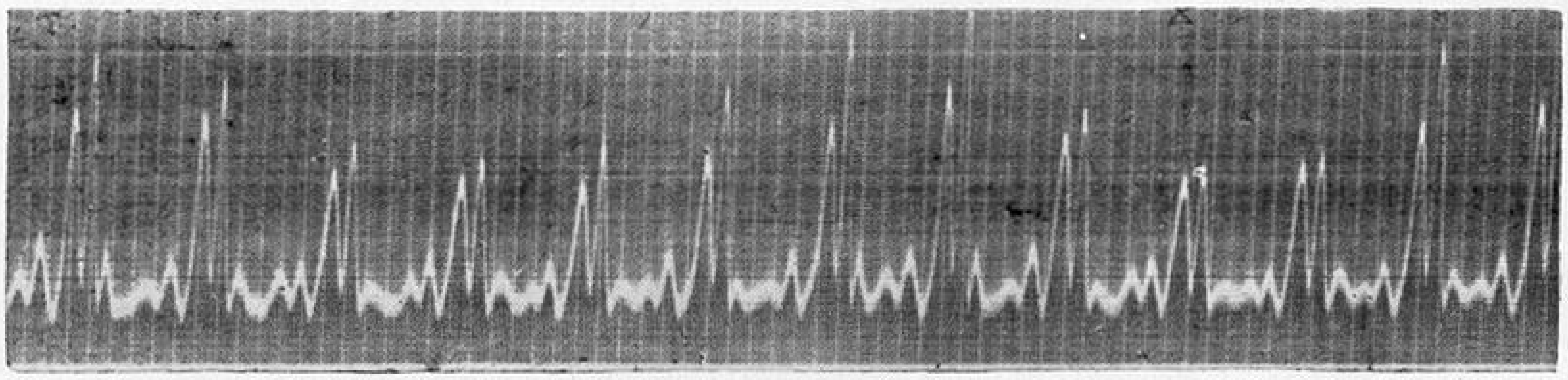
(e) Control curve taken half-an-hour after (d), showing complete return to normal.

Fig. 12

NORMAL HEART RECORD BEFORE EXERCISE



IMMEDIATELY AFTER EXERCISE



60 SECONDS AFTER EXERCISE

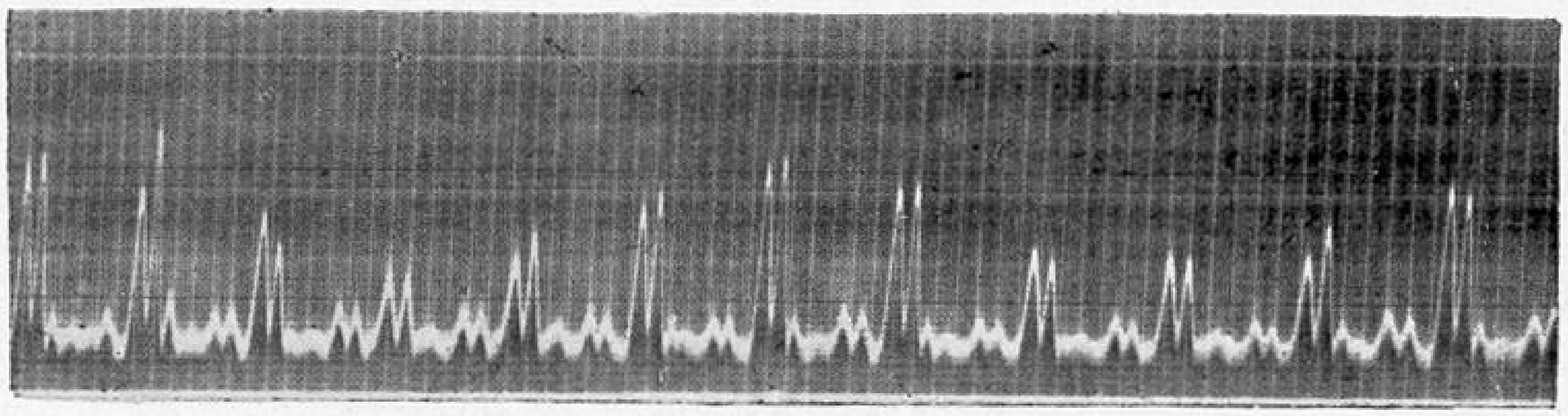


Fig. 13