di situazione del problema relativo alle Corse del Cavallo sopra qualunque scacchiere. 4to. *Roma* 1872. The Author.

The original manuscript Memorial from the President and Council to George III., praying that observers might be sent out to observe the Transit of Venus in 1769. Among the signatures are:—Lord Morton, P.R.S., Nevil Maskelyne, Astron. Royal, Gowin Knight, B. Franklin.

Copy of Diploma on Vellum, with scientific symbols in margin. Engraved for the Society during the Presidency of the Earl of Macclesfield, temp. George II. Presented by Dr. Diamond

---

"On some Points connected with the Circulation of the Blood, arrived at from a Study of the Sphygmograph-Trace." By A. H. GARROD, B.A., Fellow of St. John's College, Cambridge, Prosector to the Zoological Society. Communicated by Dr. GARROD, F.R.S. Received March 12, 1874. Read April 23*.

[Plate 5.]

Since my first communication to the Royal Society "On the relative Duration of the Component Parts of the Radial Sphygmograph-Trace in Health" (P. R. S. vol. xviii. p. 351), it has not been my good fortune to find any similar observations by other physiologists, either in favour of or in opposition to my statements. From that time my attention has been continually directed to similar phenomena; and the employment of similar methods has led to results which seem to have an important bearing on the problem of the action of the heart. It is evident that a thorough knowledge of the nature of the pulse in the arteries, when combined with that acquaintance with the anatomical mechanism of the heart and arteries that can be arrived at from *post mortem* examination, is sufficient basis for a fairly thorough study of the circulation of the blood. It has been my endeavour, by the employment of the sphygmograph as constructed by M. Marey, to obtain an amount of information from the curves which it produces, sufficient to generalize on the nature of the cardiac action in some of its details which have not as yet attracted attention. The results will be stated in the form of propositions.

Prop. I. The length of the interval between the commencement of the

* See Proceedings, vol. xxii. p. 291.

ventricular systole at the heart and the closure of the aortic valve does not vary when the pulse-rate is constant, and varies as the square root of the length of the pulse-beat—being found from the equation $xy=20\sqrt{x}$, where x=the pulse-rate, and y=the ratio borne by the above-named part to the whole beat.

This law, in a somewhat modified form, was enunciated by myself in a paper published in the 'Journal of Anatomy and Physiology' (vol. v. p. 17), where the peculiarities of the curves taken in the lying posture misled me as to the point of commencement of the ventricular systole, and led me to state that posture had an effect on the duration of the systole. Such, however, is not the case; for, while lying, the weight of the heart is apparently sufficiently great to neutralize the effect on the trace of the auricular contraction, and to make the thus taken trace deficient in the rise which at other times results from that contraction. At all events if this assumption be made, it is found that the lengths of the different parts of the beat are not influenced by posture, and they agree exactly with the above-stated law.

The following are measurements made since the publication of the original paper, which tend fully to confirm the above statement:—

Pulse-rate.	Number of times the first part is contained in the whole beat.	Calculated ratio of first part to whole beat on formula $xy=20\sqrt{x}$.
46	2·925	2·93
48	2·8, 2·88	2·885
49	2·85	2·86
52·5	2·71	2·765
56	2·63	2·675
57	2·75	2·66
58	2·65	2·625
60	2·63	2·59
64·5	2·556	2·49
69	2·45	2·4
74	2·28	2·325
79	2·23, 2·275	2·24
80	2·24375, 2·207	2·225
81·5	2·2, 2·185, 2·093	2·2
84	2·105	2·175
85	2·09	2·16
86	2·17, 2·053	2·155
88·5	2·245, 2·275	2·11
90·5	2·062	2·1
92	2·12	2·09
92	2·0875	2·08
94	2·14125	2·05

Prop. II. The length of the interval between the commencement of the primary and the dicrotic rises in the radial artery is constant for any given pulse-rate, and varies as the cube root of the length of the pulse-beat—being found from the equation $xy'=47\sqrt[3]{x}$, where x=the pulse-rate, and y'=the ratio borne by the above-named part to the whole beat.

This law was enunciated in the paper before referred to as read before this Society by myself, and published in its 'Proceedings' (vol. xviii. p. 351). Since that paper was read a fresh series of measurements have strongly confirmed its accuracy, and practice in manipulation has diminished my limits of experimental error so far that a difference of 5 per cent. from the calculated results is rarely found.

The following Table contains some of the more recent results and one or two more careful measurements of old traces:—

Pulse-rate.	Ratio borne by sphygmosystole to whole beat, as	
	Found by measurement.	Calculated from equation $xy'=47\sqrt[3]{x}$ (approximately).
38	4·175	4·18
43·5	3·825	3·8
44·5	3·7875	3·75
56	3·29	3·22
58	3·195	3·135
59	3·185	3·0
63	2·911	2·96
63·5	2·938	2·95
64	2·904	2·93
65	2·83, 2·821	2·9
67	2·825, 2·788	2·84
66·5	2·889	2·795
69	2·7	2·78
73	2·625	2·685
105	2·132	2·13
140	1·735	1·75

Prop. III. The length of the interval between the primary and the dicrotic rises follows the same law in the carotid and posterior tibial that it does in the radial artery.

That such is the case as far as the femoral and posterior tibial arteries are concerned is shown by Dr. Galabin in a paper "On the Secondary Waves in the Pulse," recently published (Journal of Anat. and Phys. 2nd series, No. xiii.). It is not necessary, in proving this law, to undertake any large series of measurements; for if *all* those which are taken agree exactly with the calculated results obtained from the radial equation, the probability that it is correct is almost infinitely great. In a boy, ætat. 16, whose radial pulse was previously proved to

follow the above law exactly, the following are the results obtained by measuring the carotid tracings :—

Pulse-rate.	Ratio borne by sphygmosystole to whole beat, as	
	Found by measurement.	Calculated from radial equation.
67	2·899	2·84
68	2·827, 2·6	2·8
72	2·7144	2·7
77	2·583	2·59
77	2·594	2·59

In another subject, ætat. 22, the following are the results :—

77	2·6625	2·595
78	2·575	2·575
85	2·443	2·44

With regard to the posterior tibial artery, most of the results were obtained by the employment of the double sphygmograph, to be described further on, in which the superposition of the simultaneous posterior tibial trace on that from the radial artery showed that the interval between the commencing primary and dicrotic rises is the same in both. The following are a few independent measurements from tracings from the artery behind the ankle :—

Pulse-rate.	Proportion borne by first part to whole beat in ankle trace.	Proportion borne by first part to whole beat in radial trace (approximately).
70	2·7	2·76
73	2·675	2·685
80	2·596	2·525
82	2·4575	2·5
82·5	2·517	2·495
88	2·378	2·378

Corollary.—The length of the interval between the primary and secondary rises being exactly the same in the carotid, radial, and posterior tibial arteries, which are three vessels at very different distances from the heart, it is evident that *the length of this interval is constant throughout the larger arteries, and must be of the same duration at the origin of the aorta that it is in the radial artery at the wrist.*

The corollary to Proposition III. leads to theoretical results of considerable importance; for as the duration of the different elements of each beat in the radial artery is the same as that in the commencing aorta, by superposing the sphygmograph-trace upon the cardiograph-trace at any given pulse-rate, a comparison can be made between the duration of the different physiological changes going on in the heart and those going on in the commencing aorta; in other words, the time during which the ventricular and arterial systoles are continuous can be ascertained with precision by an indirect method, which alone is possible in the human subject.

Taking the equations given in Prop. I. and Prop. II., the length of the systolic portion of each beat in the cardiograph- and sphygmograph-traces may be calculated with facility for any value of x. From the equations above given, namely, $xy=20\sqrt{x}$ and $xy'=47\sqrt[3]{x}$, it is found that the length of the arterial systole is shorter than the cardiac, as would be expected, because the cardiograph-trace is an indication of the movements in the muscular walls of the heart, and not of the contained blood, and because a certain tension must be reached by the intraventricular blood at the commencement of the systole before it can push open the aortic valves.

The sphygmosystole being therefore shorter than the cardiac systole, it becomes a question, when an attempt is made to superpose them exactly, as to whether they correspond at the commencement or the end of the cardiosystole. This is easily answered; for independent observations show the points in both at which the semilunar valves of the aorta close. These points in the traces must evidently be simultaneous, which is therefore the same thing as saying that the interval between the greater cardiosystole and the shorter sphygmosystole is at the commencement of the cardiosystole. This interval, the existence of which is well indicated in Marey's cardio-aortic tracings from the horse, may be termed the *syspasis* (the time during which the ventricles are raising the pressure of their contained blood); and the following Table, obtained from the two equations just mentioned, gives its length at different pulse-rates:—

·0018753′	at	$x=36$	approximately.
·00132986′	,,	$x=49$	,,
·000931′	,,	$x=64$	,,
·00004199′	,,	$x=81$	,,
·0003766′	,,	$x=100$	,,
·00024645′	,,	$x=121$	,,
·000118′	,,	$x=144$	,,
·000000′	,,	$x=170$	,,

From this Table it is evident that the syspasis varies considerably with different rapidities of pulse, decreasing rapidly with increase in the

pulse-rate and becoming *nil* when it is 170 a minute, which may be fairly conceived to be very near the limit of cardiac rapidity in man.

That this interval (the syspasis) should vary so considerably in length with differeut pulse-rates is not easy to explain at first sight; nevertheless a careful review of the different processes which are in operation in the heart at the time has suggested to me an explanation which seems reasonable. It depends on the fact that the extreme shortness of the diastole makes any variation in its length have a marked influence on the amount of blood which enters the capillaries of the walls of the heart, and consequently influences the amount of work which the muscular fibres of the ventricle have to perform in emptying their interstitial vessels before they can commence contracting on the blood in their contained cavity. Experiment shows that the rapidity of the pulse does not depend on the pressure of the blood in the arterial system*; consequently the length of the syspasis is not influenced by the arterial blood-pressure, which is the same thing as saying that the force of the cardiac contraction varies directly as the blood-pressure; for then the muscular power of the ventricular walls to overcome the intramural distention, varying with it, prevents its duration from being modified.

It has been my endeavour to show elsewhere † that the force of the heart's contraction is modified by the length of diastole, varying as its square root. Such being the case, it is evident that the length of the syspasis must vary with that of the diastole, though not to the extent that is found to occur. But the diastolic period being always so short, it is evident that the longer it is, the more thoroughly does the heart-tissue get permeated with blood, in a way which can have little or no influence on its nutritive power, but a great effect in modifying the length of the syspasis in the direction which is found to occur.

Again, referring to the results of the cardio-sphygmograph observations published by me in the 'Proceedings' of this Society (vol. xix. p. 318), that paper contains a Table of the length of the different cardio-arterial intervals; and if from the first cardio-arterial interval, as there defined, the length of the syspasis be subtracted at the corresponding rates, it will be found that the remainder of the interval is of exactly the same length as the second cardio-arterial interval, which, on the assumptions made, it could only be, as both the systole and the shock of the closure of the aortic valve are propagated along the arteries from the same point under similar circumstances. The following Table gives the lengths of the first cardio-arterial interval from which that of the syspasis as above determined has been subtracted, and by their side the lengths of the second cardio-arterial interval, as copied from the Table in the communication referred to; *their similarity cannot be the result of simple coincidence*, as they are derived from independent sets of measurements.

* Journal of Anatomy and Physiology, Nov. 1873.

† *Ibid.* vol. viii.

Pulse-rate.	First cardio-arterial interval with syspasis subtracted.	Second cardio-arterial interval.
36	·0023982′	·00239821′
49	·00233314′	·00233342′
64	·002274′	·00227425′
81	·00220541′	·00220546′
100	·0021875′	·00218745′
121	·00208455′	·0020847′
144	·0020185′	·0020185′
170	·0019704′	·0019729′

After the completion of the cardio-sphygmograph tracing above referred to, it was my endeavour to obtain satisfactory double sphygmograph tracings from arteries at different distances from the heart. Two or three unsuccessful attempts suggested the plan which has proved successful. It was soon evident that there is only one artery, other than the radial, which it is possible to manipulate with any degree of facility, especially when the experimenter is the subject of experiment. This artery is the posterior tibial at the ankle, where it runs in the interval between the internal malleolus and the tuberosity of the os calcis, just before it gives off the internal calcaneal branches. On myself, this artery is as superficial and as easily reached as the radial; in the sitting posture it is quite under command when the foot is crossed over the opposite knee; it is considerably further from the heart than the radial; and to obtain as great a difference as possible, the right wrist was on all occasions the one experimented on, the wrist and the ankle being, as far as can be estimated on the living body, 29 inches and $52\frac{1}{2}$ inches respectively from the aortic valves.

Before going further it will be necessary to consider *the sphygmograph-trace from the posterior tibial artery at the ankle.* Wolff * has published the results of his observations on the *dorsalis pedis* artery; and as they correspond with those from the ankle trace of the posterior tibial, they may be recapitulated. He remarks that the pulse at the foot has a general resemblance to that at the wrist, it differing in the primary ascent being less abrupt and the summit less acute. In the descent the secondary undulation is remarkably insignificant. The other minor undulations are less constant. My observations confirm the above with respect to the general similarity between the two pulses, the greater obliquity of the primary rise, and the less constant character of the minor undulations; the secondary rise has, however, never struck me as peculiarly insignificant, though it has peculiarities, to be mentioned immediately.

The ankle trace of a pulse at about 70 a minute, as taken with an

* Characteristik des Arterienpuls.

ordinary sphygmograph, differs from that at the wrist in more than one point. The primary rise, as previously mentioned, is less abrupt; the following fall is more considerable, and is not broken by the notch nearly constantly seen in wrist traces of this rapidity. The secondary rise starts from a lower level and is well marked, reaching its climax considerably nearer the next primary rise than in the wrist trace. There is, however, another feature in the early part of the secondary rise in the ankle trace, which deserves special attention because of its general occurrence. As is well known, in wrist traces the secondary rise commences promptly and is quite uniform in character, but in ankle traces there is nearly always a short horizontal continuation of the curve immediately following the primary fall, the point of departure of the two lines being clearly indicated by an abrupt, though not considerable, change in direction. This horizontal portion of the trace is not of any considerable length, being in a pulse of 70 a minute about one eighth of the whole beat; it is followed by a well-defined secondary rise, which is much longer and more gradual than the primary. Though described above as horizontal, this short interval between the two undulations is not so always, being frequently slightly oblique, sometimes in one direction, sometimes in the other. When its curve is downwards (that is, when it tends in the same direction as the primary fall), it may appear to be part of that event, which would then look as if broken; when its curve is upwards (that is, when it tends in the same direction as the secondary rise), it makes the trace appear more normal in comparison with that from the wrist.

Having now explained the ankle sphygmograph-trace, in considering the simultaneous wrist and ankle traces it will be necessary to commence with the description of the instrument employed to obtain them. A drawing of it from above is seen in Plate 5. fig. 1, from the side in fig. 2, and a double sphygmogram is given in fig. 4.

The double sphymograph is constructed from two of the ordinary sphygmographs of Marey, as first constructed by Breguet. One, that employed in taking the ankle trace, retains all its original parts, except the side lappets for fixing it to the arm, and its recording-apparatus receives the double trace. A second lever is fixed in connexion with it by two uprights so placed as to allow the axis of the second lever to be parallel to and above the one belonging to the instrument, sufficient room being left to allow the latter to move unobstructed up to the top of the recording paper. This second lever, which is a *facsimile* of that used in the sphygmograph, is placed so that it will write on the same recording-paper as the first; but its position is reversed. The accompanying sketch (fig. 3) will show this point, it representing a side view of the ordinary knife-edge lever upside down—that is, with the surface (*s*) on which the knife-edge ought to slide uppermost. The object of this arrangement will be seen immediately.

The second sphygmograph has the watchwork removed, as well as the

brasswork which is fastened to the spring that presses on the pulse, to the end of which a small wire loop is soldered. In addition, a small piece of wood is screwed into the nearer of the two holes by which the watchwork was fixed, in such a way that it can be made to revolve with difficulty. The two instruments are fastened together by means of a screw and nut in the foot-sphygmograph, which bind a brass plate in that for the wrist. This screw is fixed on a plate of brass which is attached to the end of the instrument furthest from the watchwork in the manner shown in the figure. The brass plate in the other sphygmograph, which it binds, is fixed on the side of the body of the instrument close to the arbor of the lever. The exact position of these additional pieces of brasswork has to be determined by the direction that a silk cord takes when, fixed at one end to the arbor-end of the inverted lever mentioned above, it is threaded through the loop on the tip of the spring of the wrist-sphygmograph. This cord has to be parallel to the sides of the ankle-sphygmograph, when the two instruments are fastened together with the nut at right angles to one another.

On commencing to take a double trace, the nut is unscrewed, and the two instruments are separated from one another. The wrist-sphygmograph is then bound, as usual, on the right arm. The silk cord attached to the arbor-end of the wrist-pulse lever (the upper one in the ankle-sphygmograph) is then threaded through the loop at the tip of the wrist-spring, and the binding-screw to fix the two instruments is passed into the hole in the plate of the wrist-sphygmograph made to receive it; after which, the nut being screwed fast down, the two sphygmographs form a single mass. The silk cord is then carried round the piece of wood at the watchwork end of the wrist-sphygmograph, and, after being slightly tightened, is fixed in a groove on its side. The whole is now ready for commencing the trace. To do this the ankle instrument (with that for the wrist attached to it and to the arm) is placed over the left foot, which has to rest on the right knee, parallel to the direction of the leg, with the watchwork towards the body. The recording-paper is placed in position; the silk thread is tightened, by slightly turning the wooden peg to which it is fixed, and the wrist-lever is made to pulsate by it towards the upper part of the recording-paper. The ankle-sphygmograph, held by its watchwork end in the left hand, and attached at the other extremity to the right wrist, is then pressed down on the inside of the left foot (which rests on the right knee), in such a way that its pulse-pad compresses the posterior tibial artery where its pulsation is most manifest. The lever is made to record on the lower part of the smoked paper, below the one connected with the wrist. When both levers are found to be working freely, the recording-paper is set moving by liberating the watchwork-catch with the left thumb, which is close to it. The respiration must be checked during the time the recording-paper is moving, to prevent irregularities in the trace.

Results arrived at from the study of the simultaneous wrist and ankle tracings.

In employing the tracings obtained from the above compound instrument, two objects were kept in view—*first*, to find the interval between the commencement of the primary rises in the wrist and ankle curves; and *secondly*, to observe whether or no the superposition of the one trace upon the other verified or falsified the statement made in Prop. III., that the lengths of the different parts of each element of the curve were the same in the two arteries.

The following Table contains the measurements of the lengths of the intervals between the commencement of the primary rise in the wrist and ankle tracings at different rapidities of pulse, from which it is clear that this interval varies very slightly within the range that can be obtained, and that the tendency is for it to be very slightly longer in the slower pulses.

Rapidity of pulse.	Length of interval between commencement of systolic rise at the wrist and at the ankle.					
62	·00115′	occurring	14·08	times	in each	beat.
63	·00125′	,,	12·7	,,	,,	,,
67	·001343′	,,	11·11	,,	,,	,,
,,	·0013278′	,,	11·24	,,	,,	,,
70	·001222′	,,	11·7	,,	,,	,,
71	·00136′	,,	10·2	,,	,,	,,
,,	·00124′	,,	11·41	,,	,,	,,
,,	·0013′	,,	10·8	,,	,,	,,
72	·0012′	,,	11·7	,,	,,	,,
,,	·001206′	,,	11·52	,,	,,	,,
79	·001145′	,,	11·06	,,	,,	,,
80	·00126′	,,	9·96	,,	,,	,,
81	·001233′	,,	10·37	,,	,,	,,
82	·001123′	,,	10·86	,,	,,	,,
,,	·00122′	,,	10	,,	,,	,,
95	·00122′	,,	8·67	,,	,,	,,
98	·001085′	,,	9·7	,,	,,	,,
99	·00116′	,,	8·607	,,	,,	,,

which gives an average length of ·0012314 of a minute for all the rates.

It being possible to estimate with considerable accuracy the distance from the aortic valves of the spots on the arteries at which the instrument is usually applied, it becomes a point of interest to determine from the facts arrived at the rapidity with which the primary undulation travels from its origin (the heart) to the peripheral vessels. The radial artery at the wrist and the posterior tibial artery at the ankle are, as nearly as can be determined, 29 inches and 52½ inches respectively from the origin of the aorta in myself (on whom all the tracings have been taken), as previously mentioned; and as the time of transit of the wave

varies very little with different rapidities of pulse, a single example may be taken to illustrate the point in question. With the heart beating 100 times in a minute, the time taken by the primary wave in reaching the wrist (that is, the length of the first cardio-radial interval with the syspasis subtracted) has been shown in a previous Table to be ·0021875 of a minute. Adding to this the interval between the radial and ankle primary rise at the same rapidity, which is very nearly ·00116 of a minute, ·0033475 of a minute is the time taken by the systolic wave in travelling from the heart to the ankle. But if this wave went the extra distance to the ankle, (52·5—29 =) 23·5 inches, at the same rate at which it reaches the wrist, the length of the first cardio-malleolar interval would be ·00459375 of a minute (29 : 52·5 : : 21875 : 459375); but it is only ·0033475 of a minute, which is considerably less; consequently *the wave augments in rapidity as it gets further from the heart*, a phenomenon beyond my power to explain.

By superimposing the wrist trace from a simultaneous sphygmogram on that from the ankle, it is found that the components of each are of exactly similar duration, though the peculiar short interval following the dicrotic notch in the latter sometimes complicates the results. This exact similarity in length of the different elements of the two pulses is not, as will be found by those who attempt to measure them practically, self-evident from the tracings themselves; because the one being slightly later than the other, and the watchwork varying in rapidity, gradually increasing and then declining, the radial, which is the earlier, is slightly the shorter in the commencement of the trace and the longer towards its end. In the middle of the recording-paper the two coincide. It may therefore be said that the compound sphygmograph-trace is entirely in favour of the correctness of Prop. III.

In conclusion, the following is a summary of the results arrived at in this communication:—

I. The lengths of the different elements of the pulse-beat being the same in arteries at different distances from the heart, the radial sphygmograph-trace expresses their duration in the aorta.

II. The cardiosystole being longer than the sphygmosystole at all possible pulse-rates, the excess in the length of the former expresses the time required by the heart to reach, from a state of rest, a systolic pressure sufficient to open the semilunar valves. This interval, termed the *syspasis*, is constant for any given rapidity of cardiac action, and rapidly decreases as the pulse gets quicker, becoming *nil* at a rate of 170 a minute.

III. The interval between the commencement of the primary pulse-rise in the radial and that in the posterior tibial artery is less than would be estimated from the time taken by the same wave in travelling from the aortic valve to the radial artery.

The woodcut (p. 151) will assist in illustrating the mutual relations of the different component parts of the cardiac revolution, as its different elements are there shown in their actual relations one to the other.

Garrod.

Fig. 1.

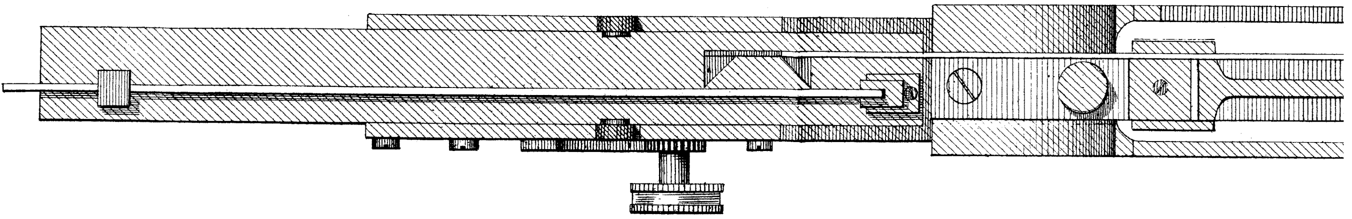


Fig. 2.

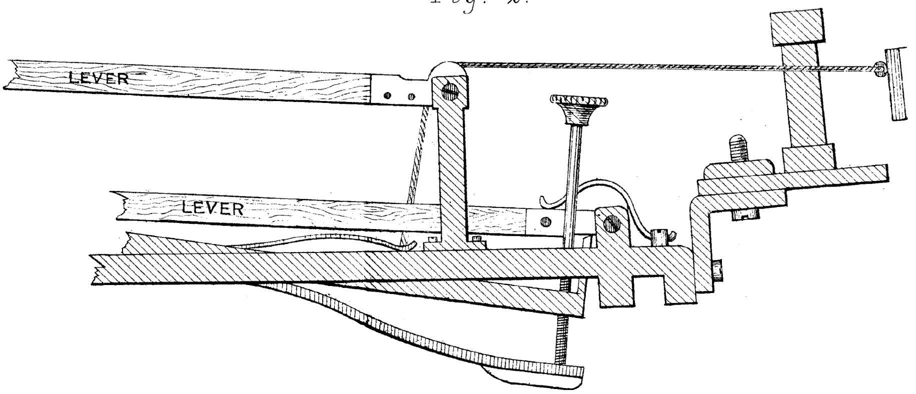
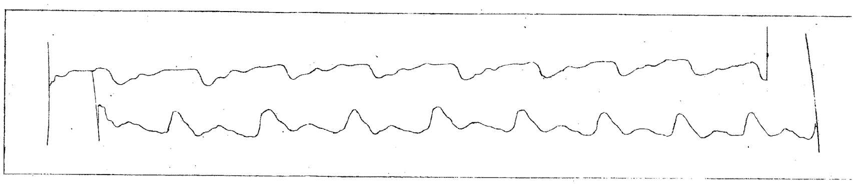
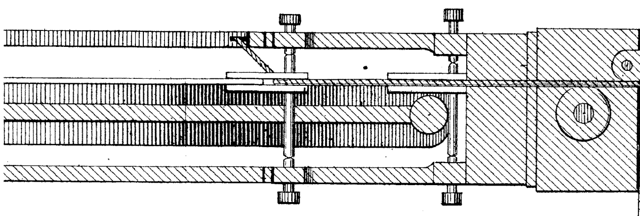
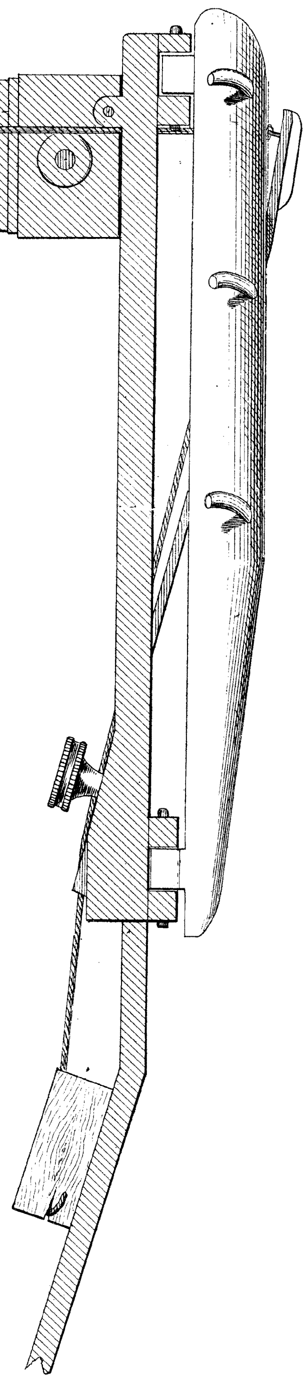


Fig. 4.



W.H.Wesley sc.





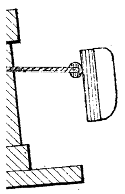
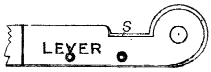
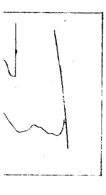


Fig. 3.





W. West & C° imp

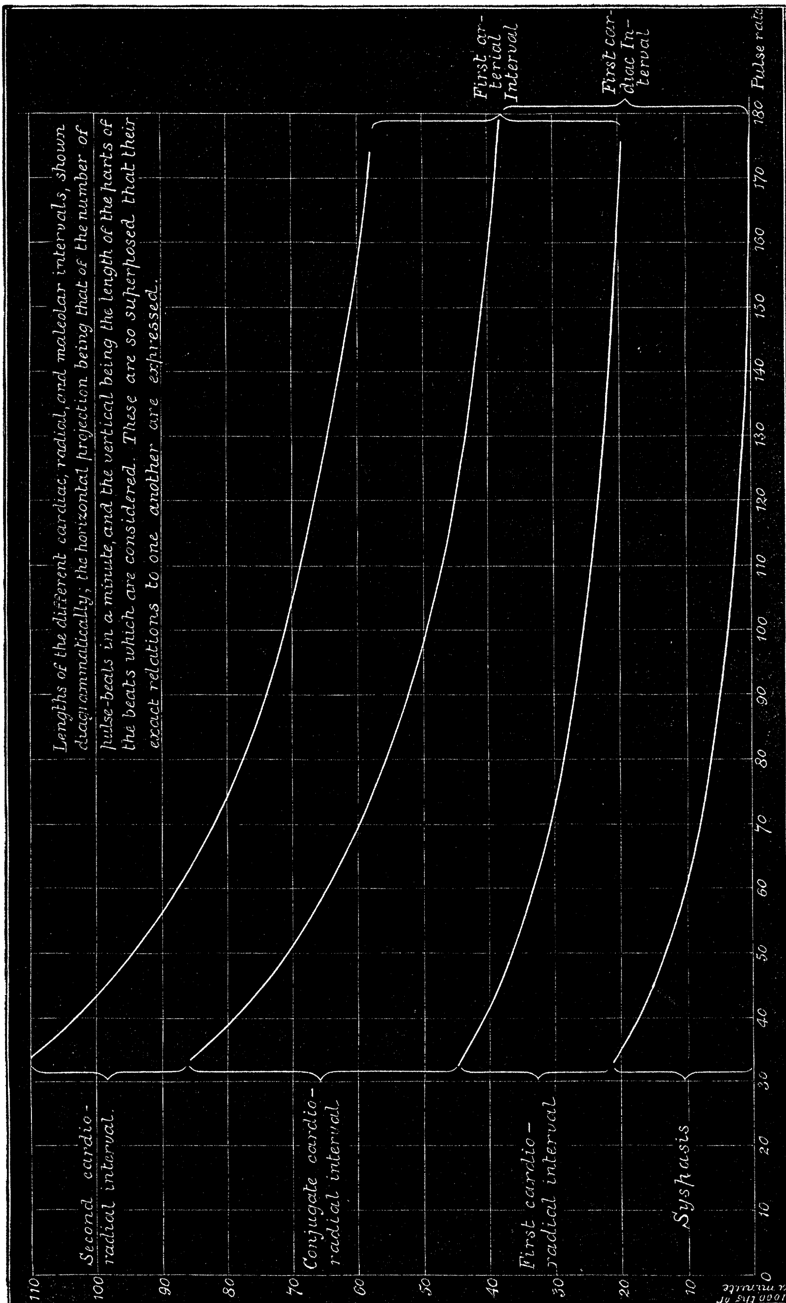

Lengths of the different cardiac, radial, and maleolar intervals, shown diagrammatically; the horizontal projection being that of the number of pulse-beats in a minute, and the vertical being the length of the parts of the beats which are considered. These are so superposed that their exact relations to one another are expressed.
First arterial Interval
First cardiac Interval
Pulse rate
Second cardio-radial interval.
Conjugate cardio-radial interval
First cardio-radial interval
Syphasis
1000ths of a minute

Fig. 1.

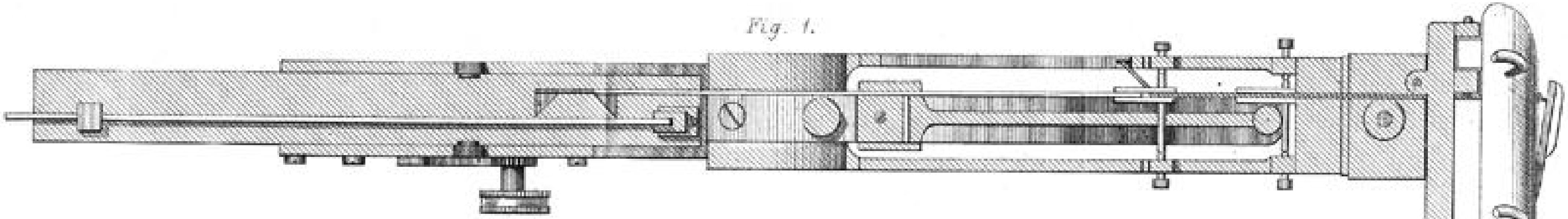
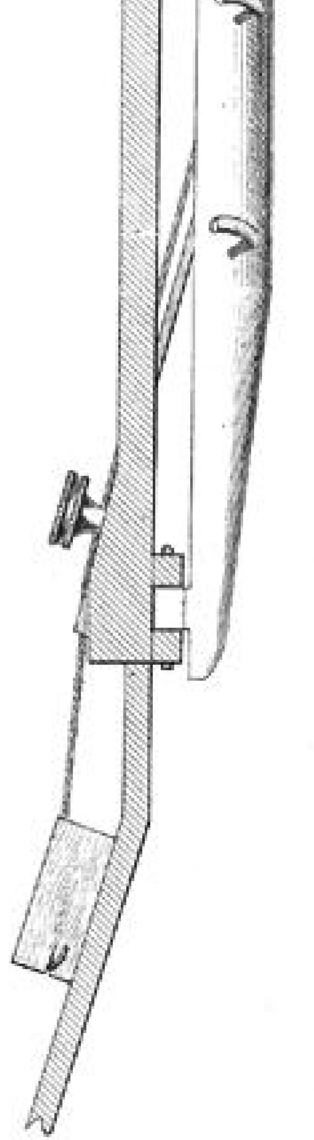



Fig. 2.

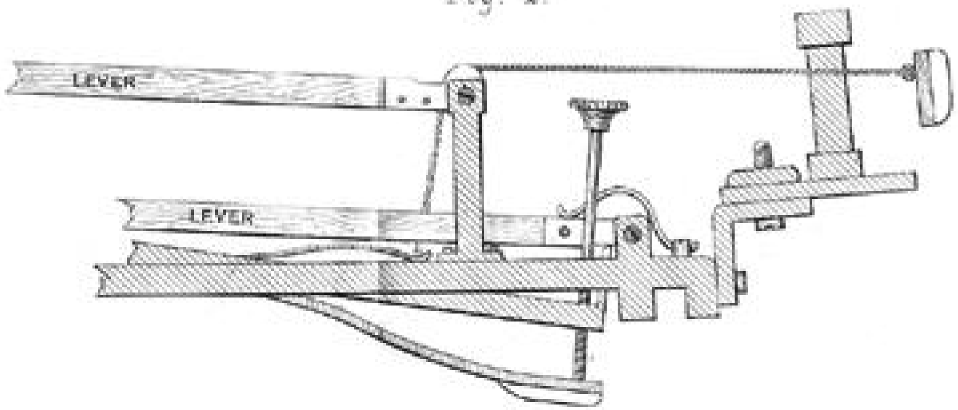
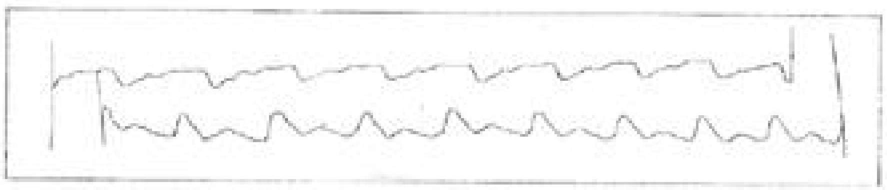


Fig. 3.

Fig. 4.



W.H. Wesley sc.

W West & Co imp.

Garrod.

Fig. 1.

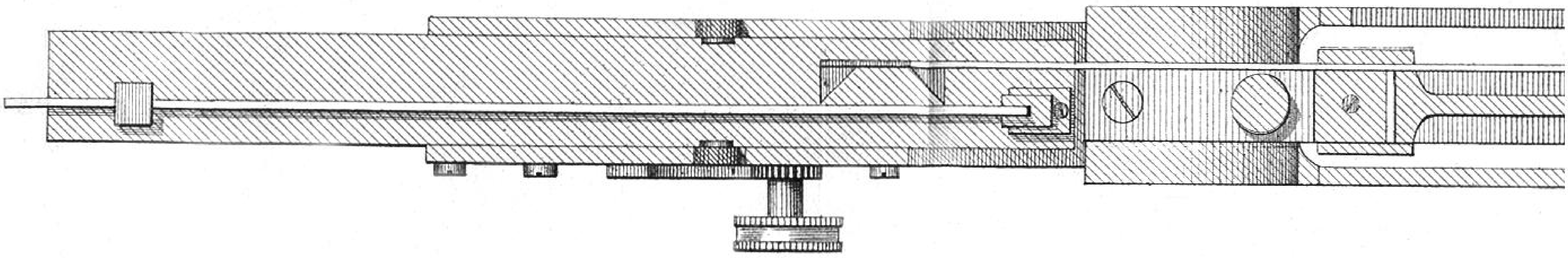


Fig. 2.

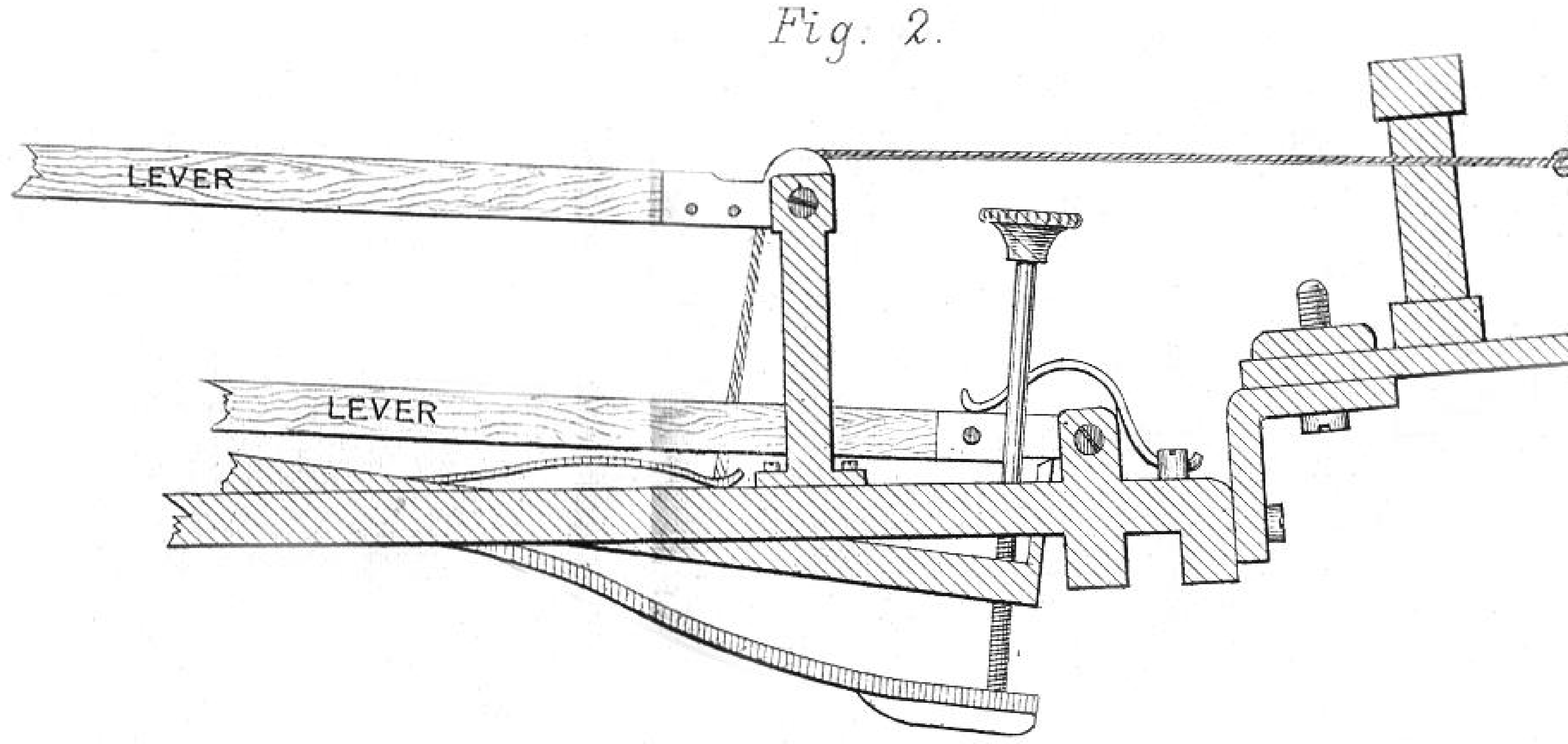
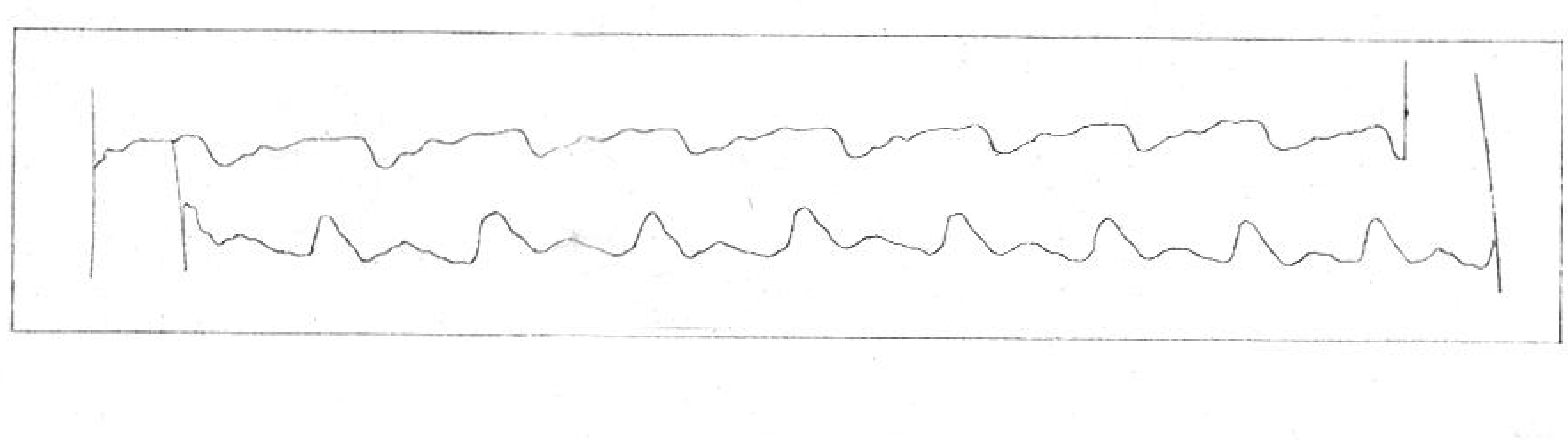
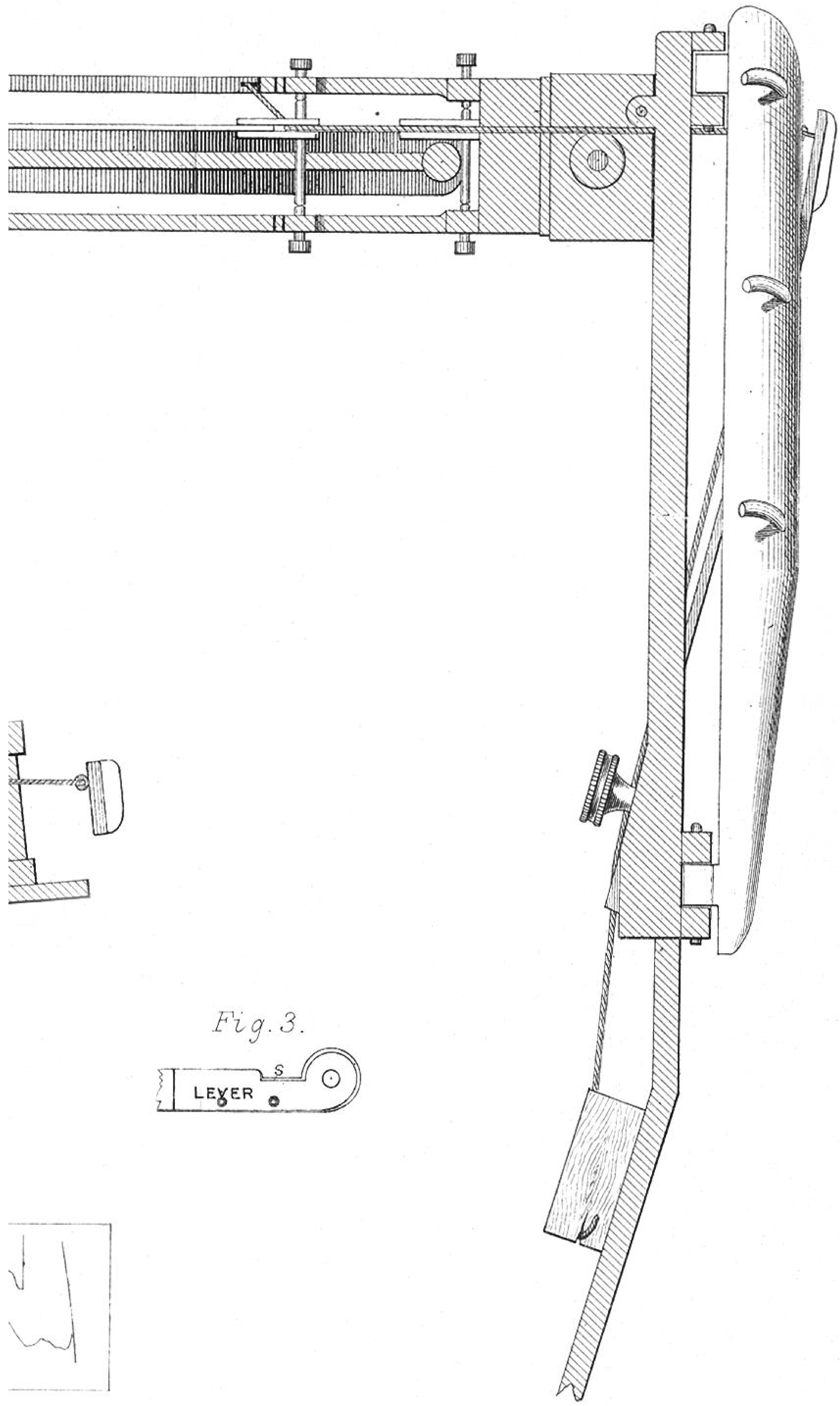


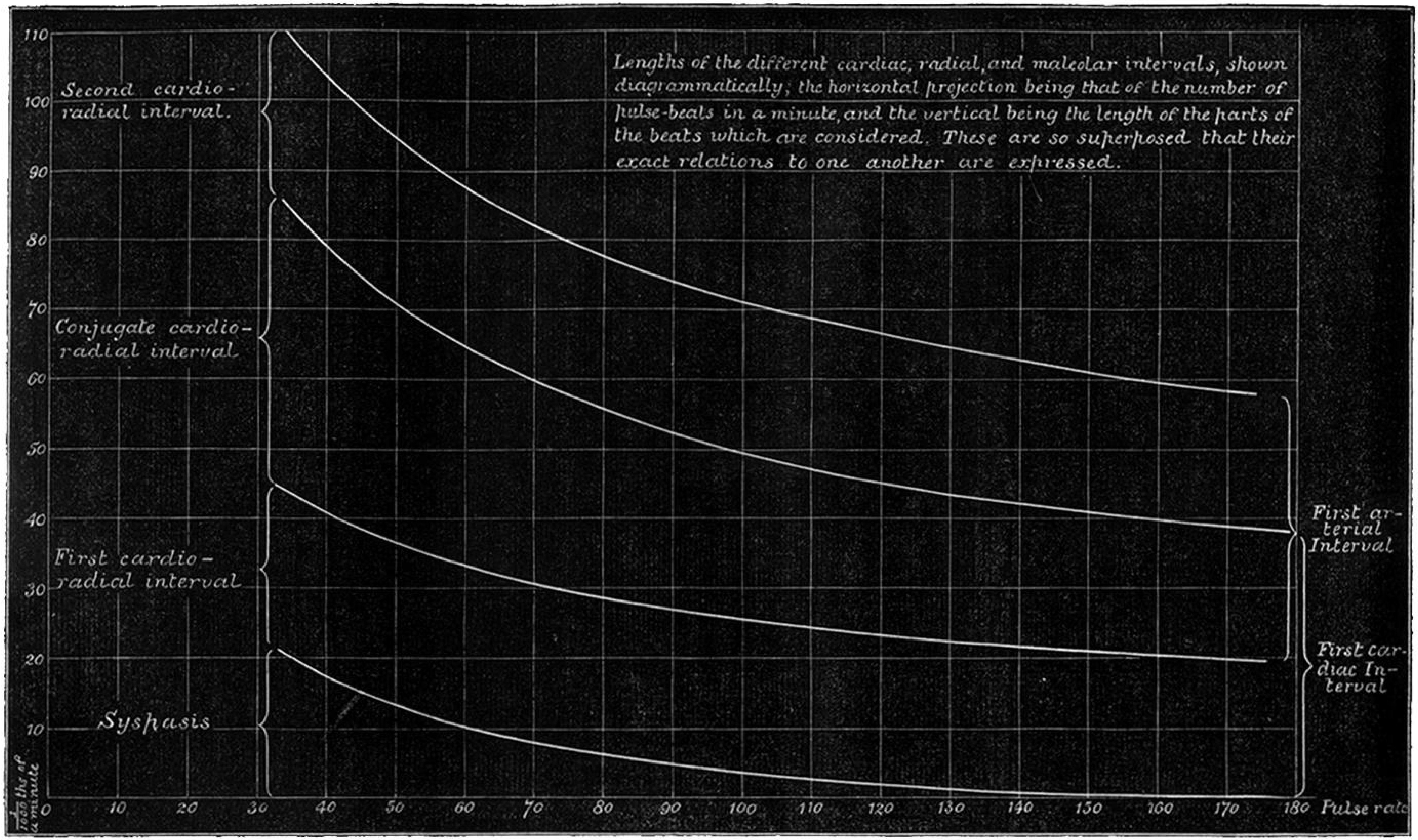
Fig. 4.



W.H.Wesley sc.



W. West & Co. imp.


Lengths of the different cardiac, radial, and maleolar intervals, shown diagrammatically; the horizontal projection being that of the number of pulse-beats in a minute, and the vertical being the length of the parts of the beats which are considered. These are so superposed that their exact relations to one another are expressed.
Second cardio-radial interval.
Conjugate cardio-radial interval
First cardio-radial interval
Syspasis
First arterial Interval
First cardiac Interval
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Pulse rate