RESPIRATORY WAVES OF BLOOD PRESSURE, WITH
AN INVESTIGATION OF A METHOD FOR
MAKING CONTINUOUS BLOOD PRES-
SURE RECORDS IN MAN.*

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PLATE 57.

Lewis,¹ in 1908, called attention "to the widespread misunderstanding of the relations which exist between respiration and blood pressure." He states that in books on the subject one finds usually only the results obtained by Einbrodt in the dog, and by Klemensiewicz in man. Essentially these consist of a rise of pressure during inspiration and a fall during expiration, although the rise during inspiration may be preceded by a fall of pressure, and the fall during expiration by a rise. An analysis of the literature, however, seems to indicate that there is little justification for these conclusions. Different investigators,² dealing with the same species of animal, have recorded diametrically opposed views, so that it seems unreasonable, in Lewis's opinion, to maintain the existence of but a single type of blood pressure wave.

In the case of man, the results of different investigators are likewise discordant, although it would seem that the majority do not agree with Klemensiewicz, in that they find a pure fall of pressure in inspiration and a pure rise in expiration. The minority, nevertheless, find just the reverse to be the case in man. The variability of these results has been attributed to the use of faulty methods, and to differences in the type of respiration.

In order to determine in man the effects of respiration upon

* Received for publication, February 9, 1912.

¹ Lewis, *Jour. Physiol.*, 1908, xxxvii, 213.

² For the literature see Lewis, *loc. cit.*

blood pressure, some method must be employed that permits of continuous, or almost continuous observations of the blood pressure. It is not our purpose to discuss here all the methods that have been used for this purpose. It will be necessary, however, to call attention to those that seem to have a more or less direct bearing on the subject of this paper, with the more important results they have yielded.

Mosso³ and his pupil Kiesow⁴ have employed the Mosso sphygmomanometer for the purpose of making continuous records of blood pressure changes. With this instrument, a pressure about equal to the arterial mean is put upon the fingers. The base line of the oscillations thus obtained shows fluctuations synchronous with the respirations. It was assumed that the elevation and depression of the base line indicated a rise and fall, respectively, of the blood pressure. Interpreted in this way, the records, according to Mosso, prove that the blood pressure rises in inspiration and falls in expiration. This criterion is, however, open to the same objections that apply to the sphygmograph as a blood pressure indicator. However this may be, when the criterion described and used in the present research is employed in the interpretation of Mosso's curves, careful mensuration shows that the blood pressure in Mosso's experiments falls during inspiration and rises during expiration. What the changes in the level of the base line indicate cannot be determined with any degree of certainty, and a discussion of the possibilities, whether muscular movement, active or passive changes of the caliber of the blood vessels, etc., would carry us too far afield.

That there are objections to the use of the sphygmograph for the purpose of recording blood pressure changes is generally admitted. The level of the record is altered not only by changing arterial pressure, but also by changing venous pressure,⁵ by the changing tension of the band holding the instrument to the arm, produced by muscular movements and alterations in the vascularity

³ Mosso, *Arch. ital. de biol.*, 1895, xxiii, 177; 1905, xliii, 128.

⁴ Kiesow, *Arch. ital. de biol.*, 1905, xliii, 198.

⁵ Hill, Barnard, and Sequeira, *Jour. Physiol.*, 1897, xxi, 147.

of the part (plethysmographic effect), and by the changing fullness of the artery. It is possible that with the suspended sphygmograph, as employed recently by Lewis,⁶ some of these objections are eliminated, but the principle of the suspended sphygmograph is not entirely clear to us. It would seem that the position of the body of the instrument with respect to the spring (it is this, mainly, that determines the position of the writing point) is determined by the weight suspended from the instrument. With the same weight, their relative positions, barring the effects of friction and inertia, must always be the same, irrespective of the level of the pad resting on the artery. For instance, should the caliber of the artery increase, as a result either of a rise of the arterial pressure or of an increase in the fullness of the artery, the instrument would rise just as far as the pad, thus leaving the position of the writing lever as it was. That the suspended sphygmograph shows pulsations at all, and waves simulating those produced by arterial pressure changes, can be explained, it seems to us, only upon the assumption that, in the first case, its inertia is sufficient to permit of the recording of some of the pulse, and that, in the second case, recovery of the tissues from deformation is sufficiently slow to permit of the recording of some of the slower changes of arterial volume.

Lewis's results with the suspended sphygmograph confirm, in the main, those published by Marey in 1881; namely, that in man during thoracic breathing the pressure falls during inspiration and rises during expiration, the reverse occurring in abdominal breathing. The suspended sphygmograph, as employed by Lewis, revealed no respiratory waves of blood pressure with natural, quiet respiration; while with natural but deep breathing, waves were seen which were "due entirely to a change in size and rate of the individual pulse beats." This type of pulse "represents most nearly the type occurring in natural breathing." It was obtained by Lewis from seventeen young adult subjects. Despite this absence of respiratory waves of pressure on his sphygmograms, Lewis himself admits that they are occurring, since they can be "seen in the tracings yielded by Erlanger's sphygmomanometer." Lewis makes no at-

⁶Lewis, *Jour. Physiol.*, 1906, xxxiv, 391.

tempt, however, to utilize for the purposes of his problem the waves shown by the sphygmomanometer.

By subjecting the arm to approximately mean systolic pressure with a Riva Rocci instrument, and noting the phases of respiration during which pulse waves succeeded in reaching a sphygmograph attached to the wrist, Lewis showed that with abdominal breathing the pulse passes the obstruction only during inspiration, while with thoracic breathing the pulse passes only during expiration. It was inferred that this result confirms those obtained with the suspended sphygmograph. While this may be true, it is important to bear in mind that this method shows the variations of the systolic pressure only, while the sphygmograph is supposed to indicate the mean or diastolic pressure.

Sahli⁷ attempts to account in still another way for the discrepancies in the literature. Assuming that the main factor determining the respiratory waves of blood pressure is the changing capacity of the pulmonary bed, he argues that in rapid breathing the blood pressure should fall during inspiration and rise during expiration. When the respirations are slow, however, the initial fall of inspiration should be succeeded, he believes, by a rise, and the initial rise of expiration by a fall of pressure. The experimental basis for these conclusions is not given.

Still another method has been employed for the purpose of making continuous observations of blood pressure variations in man. If a pressure lying anywhere between systolic and diastolic be applied to an artery through a recording sphygmomanometer adapted to employ the principle of Marey, an oscillation is recorded whose amplitude is larger than that obtained at systolic pressure, and smaller than that obtained at diastolic pressure. If, while this pressure on the artery is maintained, the arterial pressure should rise, that is, if the intra-arterial minimum pressure should approach the extra-arterial pressure, the amplitude of the recorded waves should, as a result, increase; and, *vice versa*, should the intra-arterial pressure fall, the amplitude of the recorded waves should

⁷ Sahli, Lehrbuch der klinische Untersuchungsmethoden, 5th edition, Leipzig, 1909, 126.

decrease. Thus it should be possible to make continuous records of blood pressure variations. This principle, as far as we are aware, was first used by one of us⁸ in a study of the blood pressure fluctuations in a case of Stokes-Adams disease.⁹ Later it was employed by Eyster¹⁰ in connection with his researches on Cheyne-Stokes respiration. In the course of this work, Eyster incidentally recorded the respiratory waves of blood pressure during normal breathing. The only statement bearing on the subject that appears in his paper is to the effect that the pressure rises in inspiration and falls in expiration.¹¹ This conclusion, it will be seen, is exactly contrary to ours. It is unfortunate that, owing to the absence from his figures of marks indicating the positions of synchronous points, it is impossible to account for this discrepancy except as an error in the interpretation of the records.

In 1910, some time after the present research had been completed, there appeared a paper by Groedel¹² in which are recorded some observations on the influence of respiration upon blood pressure. Groedel employed the Uskoff sphygmotonograph for the purpose of measuring the blood pressure, using the change in amplitude of oscillation under continuous pressure as a guide to blood pressure changes. Groedel did not find respiratory waves of blood pressure in all subjects, but only in those that showed no respiratory alterations in heart rate,—in cases of what Groedel terms “labile hearts.” In the latter, the blood pressure fell during inspiration. No changes in blood pressure were seen when the heart rate showed the usual changes, not even with forced respirations. Groedel believes that the fall of blood pressure with inspiration affects only the diastolic pressure, not the systolic. This conclusion is based on the fact that with pressures upon the arm approaching systolic, no respiratory waves of pressure were seen, or as Groedel

⁸ Erlanger, *Jour. Exper. Med.*, 1905, vii, 676.

⁹ We were formerly (Erlanger, *Jour. Am. Med. Assn.*, 1906, xlvii, 1343) of the opinion that Mosso had employed this method in 1895. Further study of his papers, as well as of the work of his student, Kiesow, has convinced us that we were in error.

¹⁰ Eyster, *Jour. Exper. Med.*, 1906, viii, 565.

¹¹ Eyster, *loc. cit.*

¹² Groedel, *Ztschr. f. klin. Med.*, 1910, lxx, 47.

puts it, "the maximum inspiratory fall of blood pressure is seen in the vicinity of minimum pressure." "If one wishes," he consequently says, "to study the influence of respiration upon the blood pressure, it is advisable to do it at minimum pressure." Anticipating somewhat the discussion of our results, it may be stated here that with the Erlanger sphygmomanometer the respiratory waves of blood pressure are seen in all subjects (none but normal subjects have been studied), and not alone in the vicinity of the diastolic, but at all pressures, and, as a matter of fact, most clearly in the vicinity of maximum pressure. This, the main difference between our results, undoubtedly is to be attributed to the instruments employed. The Uskoff sphygmotonograph, as has been shown elsewhere,¹³ is not equally sensitive at all pressures; at average diastolic pressures (70 to 80 millimeters of mercury), it is more than twice as delicate as at normal systolic pressures (110 to 120 millimeters of mercury), and consequently all variations of arterial pressure are magnified more at low than at high sphygmomanometric pressures.

Another principle, which, it was thought, might prove of value for the purpose of recording consecutive arterial pressure changes in man, is based upon the observation that when the extra-arterial pressure, while steadily falling, passes below the systolic pressure, the recorded oscillations not alone increase in amplitude, but also suffer a change in form,—the space between the anacrotic and catacrotic limbs at the foot of the wave widening distinctly.¹⁴ For the sake of brevity, this alteration in the sphygmomanometric record will be designated simply as the "change of form." It may consequently be assumed that when the brachial artery is put under a systolic pressure, fluctuations of the arterial pressure above and below the average systolic level will result not only in increases and decreases in amplitude of oscillations, but also in the reappearance and disappearance of the "change of form." Both of these methods have been employed for some years by our students in class experiments designed for the purpose of demonstrating respiratory

¹³ Erlanger, *Arch. Int. Med.*, 1912, ix, 22.

¹⁴ Erlanger, *Proc. Am. Physiol. Soc.*, in *Am. Jour. Physiol.*, 1908, xxi, p. xxiv.

waves of blood pressure in man. It was the results obtained by students that suggested the reinvestigation of this subject.

ESTABLISHMENT OF THE VALIDITY OF THE INDIRECT METHODS OF
RECORDING CONSECUTIVE CHANGES OF BLOOD PRESSURE.¹⁵

The validity of the principles described above had first to be subjected to the test of experiment. These tests were made on dogs anesthetized with morphin and ether. A long segment of the carotid artery was laid bare and placed in a rigid case, which has been described elsewhere under the name of arteriograph,¹⁶ through which air pressure can be applied to the artery in the same way as to the arm with the cuff of the sphygmomanometer. The arteriograph, like the cuff, is connected with the sphygmomanometer. A record can thus be made of the pulsations of the artery while and where it is being subjected to any desired pressure. Simultaneous records were made with the Hürthle kymograph (enumerated from above downward in the order in which they appear in the tracings) of the time in seconds, the oscillations of the sphygmomanometer, the pressure in the sphygmomanometer (recorded by means of a float operated by its mercury manometer), of the respirations (downstrokes marking inspiration), of the pressure in the brachial or femoral artery with the Hürthle or mercury manometer, of the arterial base line, and of the signal. The signal record is 7 millimeters above the sphygmomanometric base line; consequently 14 millimeters must be added to the measurements of the sphygmomanometric pressure made from this line.

In interpreting the records, it should be borne in mind that the Hürthle manometer does not accurately record the systolic and diastolic pressures. It can be made exact, as has been shown by Dawson,¹⁷ only by controlling the fling of the lever by comparison with the values obtained by means of a maximum-minimum mercury manometer. This was not done in the present research,

¹⁵ The main results recorded in this part of the paper were reported in abstract before the American Physiological Society in December, 1909.

¹⁶ Erlanger, *Johns Hopkins Hosp. Rep.*, 1904, xii, 53.

¹⁷ Dawson, *Am. Jour. Physiol.*, 1905-06, xv, 244.

because it was not necessary to know the exact pressures. The fling of the Hürthle manometer raises the crest of the pulse wave more than it depresses the trough, so that the systolic pressure, as measured on a Hürthle record, will be too high by a larger value than the diastolic pressure will be too low.

For the purpose of illustrating the methods of experimentation employed and the results obtained, three typical records will be described in detail.

The record reproduced in figure 1 shows the results obtained when the pressure on the artery is permitted to fall slowly and constantly, as in making blood pressure records in man. The Hürthle manometer records the brachial pressure. This shows distinct respiratory waves, the systolic and diastolic pressures fluctuating approximately between 108 and 116, and 163 and 170 millimeters of mercury, respectively. The main fall of pressure occurs during inspiration, the main rise at the beginning of expiration, although toward the end of expiration the pressure falls slightly.

Shortly after the extra-arterial pressure begins to fall, oscillations appear on the sphygmomanometric record. These, however, become distinct only after the extra-arterial pressure has fallen to the level of 154 millimeters of mercury; that is, 16 millimeters of mercury below the maximum systolic pressure (the systolic at the crest of a respiratory wave). The first indication of the change in form is seen at a sphygmomanometric pressure of 142 millimeters of mercury; that is, 28 millimeters of mercury below the maximum systolic pressure. The oscillations definitely diminish in amplitude when the extra-arterial pressure reaches 112 millimeters of mercury. This is about 4 millimeters of mercury above the minimum diastolic pressure (lowest pressure of the respiratory wave) at this time. The sphygmomanometric record also shows respiratory waves. They are scarcely discernible when, in the region of mean extra-arterial pressures, the oscillations are high; they are largest in the part of the record made while the extra-arterial pressure is in the vicinity of systolic; and they become distinct again when, at diastolic pressure, the amplitude of oscillations begins distinctly to diminish. These, the systolic and diastolic regions of the sphygmo-

manometric record, are the two points at which slight changes of extra-arterial pressure, and consequently of intra-arterial pressure, produce the largest changes in the amplitude of oscillations. It is for this reason that the respiratory waves are specially large in these locations, and for this reason only. And the fact that on this record the sphygmomanometric respiratory waves are larger in the vicinity of systolic pressure than at or below diastolic pressure, does not necessarily mean that the respiratory fluctuations of the intra-arterial systolic pressure are larger than those of the diastolic pressure. It may mean merely that one and the same change of intra-arterial pressure produces a greater change in amplitude of oscillations when it occurs at systolic than when it occurs at diastolic pressure. As a matter of fact, in this particular case the systolic and diastolic intra-arterial respiratory pressure variations had, within the limits of error, the same amplitude; namely, 8 and 7 millimeters of mercury, respectively.¹⁸ The height of oscillations in a respiratory wave varies directly as the blood pressure of the corresponding pulse wave. The intra-arterial respiratory pressure waves are indicated also by the change in form of the oscillations, which, as long as the extra-arterial pressure is in the vicinity of the systolic pressure, reappears and disappears as the arterial pressure rises and falls.

The tracing reproduced in figure 2 illustrates the effect upon the oscillations of the sphygmomanometer of a slight fall of arterial pressure, while the pressure on the artery is maintained at a constant level. At the beginning of the record, the arterial pressures, systolic and diastolic, were 138 and 100 millimeters of mercury, respectively. The pressure within the sphygmomanometer was held at 116 millimeters of mercury. Allowing for fling, this pressure was probably a trifle below the intra-arterial systolic. However this may have been, the oscillations of the sphygmomanometer show clearly the separation at the foot of the pulse wave. With the second stimulation of the central end of the vagus nerve, the arterial systolic and diastolic pressures fell to 122 and 80 millimeters of mercury, respectively. The pulse rate was slightly slowed. Allow-

¹⁸ Compare with Groedel's conclusion as given above (page 374).

ing for fling, we may assume that the systolic pressure was now lower than the extra-arterial pressure. Examination of the record shows that at this time the amplitude of the sphygmomanometric oscillations is small, despite a slight increase of the arterial pulse pressure. At the same time, the separation of the anacrotic and catacrotic limbs at the foot of the oscillations disappears.

The third record, figure 3, is reproduced for the purpose of illustrating the effects of respiratory waves of the blood pressure, as well as the effect of a large decrease of arterial pressure, upon the sphygmomanometric oscillations, when obtained at different, though constant extra-arterial pressures. The Hürthle manometer is here recording the femoral instead of the brachial pressure; otherwise designations are the same as on the previous tracings. The reader should be reminded here of the fact that in the femoral artery of the dog, the systolic pressure is considerably higher than in the carotid artery. In comparing the sphygmomanometric systolic with the arterial systolic pressure, it becomes necessary, therefore, to allow in this case for a double error.

The femoral pressures at the beginning of the tracing are 145 and 95 millimeters of mercury. The respiratory waves of pressure have an amplitude of about 5 millimeters of mercury; the pressure, upon the whole, rises during expiration and falls during inspiration; both the systolic and diastolic pressures are affected by the respirations, and practically to the same extent.

At the beginning of the record, the pressure exerted upon the carotid artery through the arteriograph is 120 millimeters of mercury. This pressure is 25 millimeters of mercury below the femoral systolic, and probably not more than 5 millimeters of mercury below the carotid systolic pressure. The oscillations of the sphygmomanometer show wave-like variations in amplitude, synchronous with respirations, their height increasing during expiration and diminishing during inspiration. The pulse was then slowed and the arterial pressure lowered by stimulation of the peripheral end of the cut vagus nerve. In consequence thereof, the sphygmomanometric oscillations diminish almost to the point of disappearance, and this, despite an increase of the intra-arterial pulse pressure to more than

one and one half times its original amplitude. In other words, the fall of pressure produced either by inspiration or by vagus stimulation diminishes the amplitude of the oscillations of the sphygmomanometer when the extra-arterial pressure is in the vicinity of the arterial systolic pressure.

The pressure on the artery was then lowered to 102 millimeters of mercury. The amplitude of the sphygmomanometric oscillations increases. Although the intra-arterial respiratory waves of blood pressure still recur with undiminished amplitude, they now are so small on the sphygmomanometric record that their relation to the phases of respiration can be determined only with difficulty. The fall of pressure due to stimulation of the vagus nerve again diminishes the amplitude of the sphygmomanometric oscillations, but not nearly to the same extent as during the first stimulation. The extra-arterial pressure was then lowered to 91 millimeters of mercury; that is, to a point just below the intra-arterial diastolic pressure. The amplitude of the oscillations of the sphygmomanometer diminishes markedly; while the respiratory waves become somewhat more distinct again, though now their sign is changed, the inspiratory fall of arterial pressure increasing, instead of diminishing the amplitude of oscillations. Furthermore, the fall of pressure due to stimulation of the vagus nerve now causes a marked increase, instead of a decrease, in the amplitude of oscillations of the sphygmomanometer. With further lowering of the extra-arterial pressure, the changes just described are seen even more strikingly.

This analysis of figures 1 to 3, as well as of many other records, therefore, demonstrates the validity of the principles which have been used for the purpose of making continuous blood pressure observations in man.¹⁹ It shows, furthermore, that there is an exact correspondence between the respiratory waves of blood pres-

¹⁹ It was by means of methods similar to those here employed that the Erlanger sphygmomanometer was originally tested. The results obtained in the present research, as illustrated by the records herein described, fully confirm the earlier experiments in showing (1) that the diastolic pressure is indicated by the last of the highest oscillations, and (2) that the diastolic, and also the systolic pressure can be accurately determined by indirect methods.

sure in the artery of the dog, and on the record of the sphygmomanometer connected with the carotid artery of the same animal,—a fall of pressure in the former being denoted, as long as extra-arterial pressure is above the intra-arterial diastolic, by a diminution of the amplitude of the oscillations of the latter. The clearest records are obtained with the sphygmomanometer when the pressure on the artery is somewhat below the intra-arterial systolic. At this pressure, the change in the form of the oscillations with the rise and fall of the arterial pressure above and below the extra-arterial pressure also permits of the recognition and interpretation of blood pressure waves in the artery. Finally, the analysis of the figures shows that these principles yield clear indications as to the sign of blood pressure changes, even when they are associated with changes in the amplitude of the pulse pressure in a direction tending to mask the result. It is not intended to give the impression, however, that changes in the amplitude of pulse pressure do not determine corresponding changes in the amplitude of oscillations of the sphygmomanometer. The latter is dependent, in one and the same individual, mainly upon the amplitude of the pulse pressure and upon the proximity of the extra-arterial pressure to the diastolic pressure. Ordinarily, however, as the experiments on animals demonstrate, pulse pressure changes do not mask blood pressure changes. Nevertheless, one should keep in mind the danger of drawing conclusions from continuous blood pressure records without, at the same time, taking into consideration all the factors at work in producing the changes.

It may be objected that the respiratory waves on the sphygmomanometric record are the result of motion imparted to the arteriograph by contractions of the surrounding muscles. This objection is, however, easily met. In the first place, the waves on the sphygmomanometric record always bear the same relation to the phases of the arterial pressure waves, but no constant relation to the phases of respiration; *i. e.*, to the muscular movements of respiration. In the second place, when the arteriograph is moved with the hand as it might be moved by respiratory movements, no changes in the form of the record are seen. When, however, the arteriograph is moved

much more extensively by hand, waves result that bear no resemblance to those produced by arterial pressure changes. The latter are characterized by changes in amplitude only, the former by alterations of the level of the base line, the amplitude of oscillations remaining practically unaltered.

RESPIRATORY WAVES OF BLOOD PRESSURE IN MAN.²⁰

The experiments to determine the effects of respiration on the blood pressure in man were performed by one of us²¹ and were modeled after the animal experiments described in the foregoing section. As in the animal experiments, the mercury manometer of the sphygmomanometer was provided with a float with which the pressure exerted upon the artery was recorded simultaneously with the base line, the oscillations of the sphygmomanometer, the respirations, and the time in seconds. The pneumograph was held in place by a tape that encircled the body at the level of the lowest ribs. After the first few trials, the following sequence of procedure was adhered to in each experiment: (1) the blood pressure was first determined; (2) then the pressure of the sphygmomanometer was set at a level that was 5 to 10 millimeters of mercury below the arterial systolic pressure and a continuous record was made while the breathing of the subject was (*a*) normal, (*b*) slow, (*c*) fast, (*d*) thoracic, and (*e*) abdominal; (3) the observation was concluded by again recording the blood pressure. The subject sat as still as possible in a comfortable chair, resting his forearm horizontally upon an arm rest. Each subject was carefully instructed in the part he was to take in the several steps of the experiment, especially as to the proper way of making thoracic and abdominal respiratory movements.

It will be seen at once that the conditions under which the indirect blood pressure observations in man and in the dog were made, present certain differences. In the case of the dog, the arteriograph

²⁰ The records and notes forming the basis of this part of the paper are from a thesis submitted by F. G. Festerling for the Master's degree. It was filed with the Librarian of the University of Wisconsin, June, 1909.

²¹ Festerling.

surrounds the artery alone, whereas in the case of man, it surrounds the whole arm, which includes, besides the larger arteries, several structures that might actively affect the sphygmomanometer; namely, the muscles, the arterioles, and the veins.

Actual tests have shown that such slight movements of the arm as are sometimes imparted to it by the deepest respirations, when made voluntarily during suspended breathing, produce no obvious effect upon the record. More extensive movements of the arm, as well as active contractions of the muscles under the cuff, affect the sphygmomanometric record by altering the pressure within the pressure space, the result upon the record being quite similar to that produced by altering in the usual way the amount of air within the pressure space. Waves so produced could not possibly be confused with true respiratory waves of arterial pressure. They are characterized, in the first place, by a form quite similar to that observed when, in the animal experiments, the arteriograph is moved with the hand. There are no marked changes in the amplitude of the oscillations; the waves so produced being characterized by an almost parallel rise and fall of the crest and trough line. In the second place, the slight pressure changes resulting in the sphygmomanometer from accidental movements of the arm can be recognized on the record of the sphygmomanometric pressure, which was made in every experiment. Due allowance for them was made. They gave rise to no confusion whatever in the interpretation of the records.

It is well known that the discharge of the respiratory center influences the vasoconstrictor center in such a way as to produce Traube-Hering waves, properly so called. According to Fredericq,²² the blood pressure rises during inspiration and falls during expiration. It is, however, impossible to determine just how these vasomotor changes would affect the record of the sphygmomanometer, since it is not known whether such vasomotor waves as may occur in man, affect directly or secondarily the arterioles of the arm. In any event, had they occurred, they would have manifested themselves on our records through rhythmical alterations of the pressure within the sphygmomanometer, and could have been allowed for.

²² Fredericq, *Arch. de biol.*, 1882, iii, 55.

It is scarcely conceivable that respiratory waves of venous pressure could affect appreciably the oscillations of the sphygmomanometer. Furthermore, it is believed that if they did have an effect, it would be just the reverse of that actually produced by respirations. During inspiration, the venous pressure falls: the tendency during inspiration would, therefore, be toward the lowering of the pressure within the cuff, and toward a reduction of the turgidity of the tissues under it,—two conditions that would lead to an increase in the amplitude of oscillations of the sphygmomanometer, the reverse of what actually occurs on our records during inspiration. As a matter of fact, the respiratory waves of pressure do not disappear, nor are they altered in any respect whatever when the veins above the arm cuff are temporarily closed by a middling band.

The effects of respirations have been studied by one of us in fourteen normal subjects. In addition, notes have been kept for some years of the results obtained by students in similar experiments made upon themselves. The record reproduced in figure 4 serves to illustrate what has been recorded in practically every test. So complete has been the correspondence between the human and animal experiments in every respect pertaining to respiration, that a detailed description of this record would be superfluous. To convince one's self of the validity of this statement, it is merely necessary to reread, with this figure in view, the section describing the results of the animal experiments. There is but one difference. In the case of man, it seems that the inversion of the waves of oscillation associated with respiration does not take place when the extra-arterial pressure falls below the intra-arterial diastolic. At present, we have no explanation to offer for this difference. It should be added, however, that at this stage of the experiment the oscillations are so small that accurate measurement of their amplitudes becomes difficult, and for the same reason it becomes difficult to eliminate completely experimental errors. The arterial pressure falls during inspiration and rises during expiration, whether the breathing is normal (slow or fast), abdominal, or thoracic. As a rule, these effects are coterminous in our experiments. The only

exception has been in extremely slow breathing, when the blood pressure waves may gain on the respirations,—the blood pressure beginning to fall before the end of expiration, and to rise before the end of inspiration. The respiratory changes in blood pressure seem to be greatest during abdominal breathing, although, owing to the difficulty of gauging exactly the depth and rate of respiration in passing from one type of breathing to another, it is difficult to obtain definite proof of this assertion.

As is usual in normal respiration in both man and animals, the pulse rate in our records begins to increase during inspiration and to decrease during expiration. Since the systolic output of the heart, other factors remaining constant, is greater the slower the heart rate, it is justifiable to conclude that the pulse pressure on the whole is larger during expiration than during inspiration. Might it not be possible, then, to attribute the respiratory waves on the sphygmomanometric record to pulse pressure changes, rather than to blood pressure changes?

This question is answered in part by the observation recorded above, that in animals such large pulse pressure changes as are produced by stimulation of the peripheral end of the vagus nerve do not obscure the concomitant blood pressure changes. It is fully answered by some of the records obtained from man. The tracing reproduced in figure 5 shows the effects of very slow deep respirations. Unfortunately the time was not recorded. A good idea as to time relations can, however, be obtained from the number of pulse waves elapsing. At the beginning of the tracing, the respirations were at the rate of ten pulse waves each. As the subject has a normal pulse rate, we may consequently assume that the respiratory rate is one half of what it is normally. The amplitude of the oscillations increases at the beginning of expiration but decreases before expiration is completed. This decrease occurs even while the pulse rate is slowing; that is, despite the concomitant increase of pulse pressure. And the decrease in the height of the oscillations continues into inspiration, after the rate of the heart beat has begun to increase. It may be concluded, therefore, first, that the height of the oscillations is not materially influenced

by such pulse pressure changes as probably result from the changing systolic output; and second, that the wave-like variations in the height of oscillations are produced by the respiratory waves of blood pressure. Attention should here be called to the fact that in this same experiment (No. 5) with respirations that were slightly faster, though slower than normally (1 respiration to 7 pulse waves), there was the usual relation between respiration and blood pressure: the pressure fell during inspiration and rose during expiration.

When it is taken into consideration that in man the sole or main effect of inspiration is to lower the blood pressure, the thought is suggested that perhaps in man the acceleration of the heart rate during inspiration and the retardation during expiration are due to the action of the blood pressure upon the medullary centers. In the case of animals, the condition may be different. In them it frequently happens that the relation between the respirations and the respiratory waves of blood pressure is not nearly so simple nor so constant as seems always to be the case in man. In animals, therefore, the changes of pulse rate with respiration cannot be explained entirely as an effect of the blood pressure upon the centers. For this, as well as for other reasons, Fredericq²³ has contended that in animals the changes in heart rate are due to an associated activity of the nerve centers in the medulla. However this may be, it does not seem necessary, in view of the different relations that obtain between blood pressure and respirations, to transfer to man results that have been obtained through the study of the conditions in animals.

Inasmuch as the present research has not included an attempt to determine the mechanism producing the respiratory waves of blood pressure in man, it would be out of place to discuss this problem here. We are inclined to believe, however, that the cause will be found to lie mainly, as Sahli has surmised, in the changing capacity of the blood-vessels of the lungs. This factor may be found to be much more important in large than in small animals, and if so, it would account for the differences in the behavior of the respiratory waves of blood pressure in animals and in man.

²³ Fredericq, *loc. cit.*

EXPLANATION OF PLATE 57.

FIG. 1. The effects upon the sphygmomanometric oscillations of permitting the extra-arterial pressure (sphygmomanometric pressure) to fall constantly and steadily. 1 = time in seconds; 2 = oscillations in the sphygmomanometer; 3 = pressure in the sphygmomanometer; 4 = respiration; downstroke records inspiration; 5 = pressure in the brachial artery with the Hürthle manometer; 6 = Hürthle base line; 7 = sphygmomanometric base line and signal.

FIG. 2. The effects upon the oscillations of the sphygmomanometer of a slight fall of arterial pressure. At the point indicated by the signal, the central end of the vagus nerve was stimulated.

FIG. 3. The effect on the oscillations of the sphygmomanometer of respiratory waves of blood pressure, and of a large fall of arterial pressure with the sphygmomanometric pressure at different levels. At the points indicated by the signal, the peripheral end of the vagus nerve was stimulated. The Hürthle manometer measures the femoral pressure. Otherwise, the designations are the same as in figure 1.

FIG. 4 (*a* and *b*). Respiratory waves of blood pressure in man, (*a*) while the sphygmomanometric pressure was maintained at approximately 100 millimeters of mercury, and (*b*) while the sphygmomanometric pressure was steadily falling from 142 to 46 millimeters of mercury. The systolic and diastolic pressures were 106 and 72 millimeters of mercury, respectively. The upper tracing shows the oscillations of the sphygmomanometer; the lower tracing gives the respiration. The tracings of the time, sphygmomanometric pressure, and base line have been omitted.

FIG. 5. Respiratory waves of blood pressure in man during slow breathing. The upper tracing gives the sphygmomanometric oscillations; the lower gives the respirations.

FIG. 4.

FIG. 5.

FIG. 6.

FIG. 7.

FIG. 8.

FIG. 9.