

Preliminary Draft

EMPIRICAL DEMONSTRATION OF RESPIRATORY CIRCUMFERENCE  
CHANGES (PULSATIIONS) IN VARIOUS BODY PARTS

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BJÖRN CHRISTIANSEN and CHARLES SNYDER

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Does the human body show rhythmical circumference changes accompanying respiration? That the torso exhibits such changes is self-evident due to the interdependence of the respiratory muscles, the intricate interplay existing for instance, between the diaphragm and the intercostal and abdominal muscles, and between the intercostal and the neck and shoulder muscles. As far as the trunk is concerned the relationship between respiratory movements and circumference changes is easy to understand and explain. More difficult to grasp is the conception of rhythmical circumference changes in the head, in the arms, and in the legs, circumference changes synchronized with the respiratory excursions.

In a previous monograph (Christiansen, 1963) it was suggested not only that peripheral respiratory circumference changes do take place, but that the character - i.e. the amplitude and the synchronicity, of these waves do have important repercussions on an individual's self-awareness and psychic functioning. As a preliminary step in testing such a hypothesis it would be necessary to demonstrate that individual differences are present as far as the waves are concerned. We would furthermore have to inquire into the physiological mediating mechanisms involved. But the very very first step would be to demonstrate empirically that such waves actually do exist. In the present paper we are going to focus on this latter topic mainly.

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\* The study to be described was done in the Spring of 1962 at the Menninger Foundation, Topeka, Kansas.

\* Fellow of the Foundation' Fund for Research in Psychiatry while participating in this study.

\*\* Research Associate at the Menninger Foundation.

Brief historical review.

Plethysmographic recordings of changes in limb volume have been a standard physiological procedure for the measurement of blood flow since the turn of the century. The changes of the volume of the hand, the fingers, the forearm, and the toes, have been extensively studied. However, practically all of these studies have been focused upon grosser volume changes following occlusion, while the problem of "microscopic" spontaneous volume changes have been largely neglected. One of the most systematic investigations in this latter area is a study by Burch, Cohn and Neumann (1942) dealing with spontaneous changes in the finger, the toe and the ear of resting human subjects.

Not only do the investigators report variations in limb volume over time, but they also claim that the variations observed naturally fall into five easily recognizable rhythms: 1) pulse waves, 2) respiratory waves, 3) alpha waves, 4) beta waves, and 5) gamma waves. By designating some of the waves as alpha, beta and gamma, they want to convey that the waves in question show periodicities that don't correspond to any known physiological processes. As regards the rate and size of the various waves in the finger tip, Burch et al. present the following data:

Type of waves	Average volume change of the finger tip	Average rate
Pulse waves	0.14 %	72 per min.
Respiratory waves	0.04 %	12 per min.
Alpha waves	0.30 %	8 per min.
Beta waves	0.60 %	1.3 per min.
Gamma waves	3.00 %	4 per hour.

It is pointed out that the respiratory waves, i.e. the waves corresponding to the respiratory cycle, usually are more pronounced in the finger tip than in the ear and in the toe tip. Furthermore, individual differences are found in the size of these waves, variations ranging for instance, from 0.002 to 0.1 % of the finger tip volume.

In view of Burch et al. findings we would assume that respiratory waves could be picked up in all bodily parts, not only in the finger tip but also in the hand and the arm; not only in the toe tip but also in the

foot and the leg, etc. No-one has yet - as far as we know, carried out such a study. Probably the greatest obstacle has been the device of a suitable recording technique.

A number of methods have been developed for the recordings of volume changes. Most common has been the air and water plethysmograph. For example, in the study of Burch et al. just mentioned, a water plethysmograph was employed. In recent years a number of other methods have been developed, however. Hertzman has developed a photoelectric method, Nyober an electrical impedance method, and Whitney an electrical strain gauge technique. In planning our own study our attention was drawn toward the latter method.

#### The strain gauge method.

The electrical strain gauge method (Whitney, 1949, 1953, 1954) is an indirect method as far as volume measurements are concerned. It is directed toward the recording of changes in limb girth. In order to get at volume changes, the girth changes have to be converted into volume changes. As a basis for this transformation Whitney points out - that if the limb in question is of roughly circular cross-section, the percentage change in volume is twice the percentage change in girth. Since our own interest is primarily in circumference or girth changes - the problem of transformation is not present.

The principle behind the strain gauge method is to record the changes in electrical resistance occurring in a mercury column, filling up completely the bore of a rubber tube, the tube itself being fastened around the limb being measured. Stretching the tube lengthens and narrows the mercury column, with resulting increase in its electrical resistance. The changes in resistance of the gauge are recorded continuously by making the mercury-filled tube one element in a conventional bridge circuit, the bridge being powered by a battery, and the changes in balance of the bridge being amplified and recorded.

The method can be made very sensitive, it is unobtrusive and is easy to apply, and the gauge itself is the only part of the apparatus that needs to be near the subject - that is to say, the recording apparatus proper may be placed in another room than the one used for experimentation.

The method, although initially constructed for the measurement of blood flow, can easily be adapted for the recording of thoracic and abdominal respiratory movements (Ackner, 1956). It is much less cumbersome than the conventional pneumographic method and has the great advantage of to a much lesser extent drawing the subject's attention to his respiration, the restriction imposed by the method during inspiration for instance, being practically unnoticeable by the subject. Finally, it is possible to convert the recorded curves into absolute measures as regards the subjects' body circumference and respiratory amplitudes.

Being well suited for the recording of respiratory circumference changes of the trunk, we felt that the method would be of equal value in the recording of "spontaneous" circumference changes taking place in other body parts with a roughly circular cross-section - the neck, the head, the arm, the leg, the foot, the toe, etc.

#### Empirical demonstrations.

In what follows we will present some illustrations of curves obtained through the mercury-in-rubber strain gauge technique. The curves are based upon recordings from various body parts of one and the same subject. The recordings were taken with the subject resting in a supine position. The magnification used varied from 0.67 to approximately 500. As appears from the tracings, the subject's respiration rate while the first recordings were taken, was fairly constant and fairly low - around 6 cycles per minute.

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Insert Fig. 1

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Figure 1 shows a three-channel recording of respiratory movements (circumference changes) from around the subject's upper thorax (the gauge under the arm pits), lower thorax (the gauge over the xiphoid process), and abdomen (the gauge being placed 3 cm. above the crest of the ilium).

The mean respiratory amplitudes indicate the largest movements to take place in the abdominal region. This is brought out by converting the amplitudes recorded into percentages of the body circumferences (mean expiratory position) at the various places the recordings were taken. The percentages in question amounts to 0.8, 0.6, and 2.0.

Figure 1 shows of course only a well-known phenomenon - that respiratory circumference changes may be found at different levels of the trunk. We want to emphasize may be found, because great individual differences apparently exist in the extent to which the trunk is globally involved in respiration. Some researchers, for instance, have claimed that in individual subjects the lower abdomen is practically "dead" and immobile, and that in other subjects the very same is true as regards the upper part of the thorax. Furthermore, it is said that in some subjects there is a clear synchronicity in the start of each respiratory cycle in the thorax and abdomen, while in others - the one or the other of the two regions have a tendency to precede the other one, and that in extreme cases, the direction of movement in the thorax and abdomen may be completely opposite in phase. In the figure presented, there is a fairly high synchronicity although the upper thorax is shown consistently to be a little preceded by the lower thorax and abdomen.

If the findings presented in Figure 1 point to a common-place phenomenon this can hardly be said about the tracings shown in the next figure.

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Insert Fig. 2

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Figure 2 again shows a three-channel recording. This time the recordings are taken from around the head (around forehead about 25 mm. above eyebrows and back of head, passing just above ears), around the neck (below the adamsapple), and around the upper thorax (around trunk, just under arms, slightly below manubrium sternum, that is, at the same place as that used for the upper tracing in Figure 1).

From all the three channels we notice rhythmical circumference changes, and not only that, but changes having practically the same periodicity. Another interesting fact emerges too. Both the forehead and the neck tracings seem to be out of phase with the upper thorax tracing. Specifically clear is the dissynchronicity between the neck and the thorax - the neck circumference increasing while the thorax decreases, and vice versa. Of course, this may be due to the fact that what we are picking up as a circumference increase in the neck is the result of a relatively greater air pressure during expiration, the greater pressure expanding the trachea and thereby also the neck's external circumference. The upper tracing is much more difficult to explain by reference to such a mechanical factor.

Comparing the neck and forehead tracings more closely we discover that the cyclical changes in the latter are not exactly desynchronized with the former; in fact, the forehead tracings seem to be better described as following nearly half-a-cycle after the thoracic tracings than going in the opposite direction of the latter one. This is brought out most clearly by the fact that the forehead tracings regularly start to ascend some time before the thoracic curve starts its descending deflections.

The head waves shown in the figure obviously require an explanation. If the oscillations had followed clearly in the opposite direction of the thoracic movements we would immediately have suggested the possible influence of respiratory hydraulic blood pressure changes. As the curve looks this seems a rather unlikely explanation. This is further emphasized by the tracings shown on the next figure.

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Insert Fig. 3

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Figure 3 shows simultaneous recordings of circumference changes from the upper thorax, left upper arm, left forearm, left hand, and left index finger tip.

A most striking feature is the synchronicity of periodic expansions and contractions in all the body regions being recorded from. Each descending deflection of the thoracic curve is followed nearly simultaneously by an abrupt downward deflection in the tracings from the upper arm, forearm and hand.

Another interesting feature is the fact that the amplitudes expressed in terms of percentages of the limb circumferences show a falling trend as we go from the upper thorax to the most peripheral part of the arm, the percentages being 0.7, 0.04, 0.03, 0.03, 0.02 for the upper thorax, upper arm, forearm, hand, and index finger respectively. Converting the last measure into volume fluctuations by means of the formula suggested by Whitney, we arrive at the fluctuations in volume of the finger tip being around 0.04 % which is equal to the magnitude reported by Burch et al. as characteristic for respiratory waves. Finally, it should be emphasized that the synchronicity of the direction of the thoracic and finger-tip deflections again goes counter to the hypothesis that we are confronted with hydraulic blood pressure waves.

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Insert Fig. 4

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Figure 4 shows simultaneous circumference tracings from abdomen, left thigh, left calf, left foot, and left second toe.

Most striking is again the similarities of the waves shown in the various tracings, with the exception perhaps of the ones found in the recording from the second toe. The latter tracing shows deflections with the same periodicity, although they look like they are a little delayed compared to the rest and inverted as regards direction. The toe starts to ascend a little after the rest of the leg has started to descend. The circumference of the toe consistently seems to reach its maximum a short time (around 3 seconds) after the rest of the leg has reached its minimum circumference. The respiratory waves seen in the toe, furthermore, look like they are superimposed upon deflections of a slower rate.

Compared to the tracings from the arm, the leg tracings show greater smoothness, specifically in their downward deflections. On the other side, in the leg too we find a tendency for the amplitudes, expressed in terms of percentages of limb circumferences, to become smaller as we go from the abdominal region to the most peripheral part of the leg, the percentages being 2.00, 0.10, 0.06, 0.03, and 0.01, for the abdomen, the thigh, the calf, the foot, and the second toe respectively.

Converting the toe's circumference changes into volume measures we arrive at volume fluctuations around 0.02 %, that is, fluctuations smaller than those found for the finger tip. However, this again fits quite elegantly into Burch et al. observation that respiratory volume changes usually are of a somewhat smaller magnitude in the toe tips as compared to the finger tips.

The fact that the toe-tip changes are dissynchronized with abdominal respiratory movements supports the hypothesis of a hydraulic respiratory factor. However, both the time lag between the descending abdominal and ascending toe tip deflections, and the striking synchronicity between the respiratory deflections found in the trunk and in the leg generally, fairly definitely reject such an explanation.



Experimental studies of respiratory waves.

Several times in the preceding section we mentioned the possible effect of a hydraulic respiratory factor. Some explanations might be in order.

Accompanying respiration we find changes in intrathoracic pressure, changes affecting the blood flow and the blood pressure in the thoracic cavity. As the pressure increases during expiration, it produces a rise in the pressure on the incompressible blood contained in the large thoracic arteries, and this pressure on the arteries is subsequently transmitted peripherally along the arterial tree to the head and the extremities. We are confronted with a pressure transmission similar to that found in connection with the heart beat. In the latter case we are talking about the pulse. The pulse is the pressure changes created by the ejection of blood from the heart into the already full aorta, pressure changes propagated as a wave through the blood column and arterial wall to the periphery of the organism giving rise to peripheral circumference changes. We may consider the peripheral respiratory waves as mediated by a similar mechanism. When we are talking about a hydraulic respiratory factor we are referring to such a mechanism, that is, we are referring to a possible physiological explanation of respiratory waves.

Hydraulic respiratory waves have been observed in blood pressure recordings taken directly from the arterial lumen. When in the previous section we questioned the presence of a hydraulic factor, we were not denying the existence of such a mechanism. What we questioned was only the possibility of explaining our peripheral respiratory tracings by a hydraulic respiratory mechanism.

In order to arrive at a more definite opinion on these matters we decided to do some supplementary recordings from the same subject's arm and leg before and after arterial occlusion by means of an ordinary pressure cuff. If the waves in the tracings peripheral to the occlusion cuff should stop abruptly after the application of appropriate pressures we would have shown that the waves were caused by changes in blood pressure (and/or blood flow), while if the waves should continue after the occlusion, we would have shown that the waves in question most

probably are transmitted peripherally by neural impulses.

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Insert Fig. 5 and Fig. 6

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Comparing the left and the right side of Figure 5, we see the results of arterial occlusion (300 mm.Hg), applied above the knee, on the respiratory waves in the calf, foot and toe.

All three tracings show considerably reduced pulse waves after the occlusion - indicating that our occlusion technique has been fairly successful. On the other hand, in both the calf and foot - respiratory waves are seen after the occlusion procedure. Both tracings show a certain rise in circumference after occlusion which might probably be explained as cuff artifacts, and also, in view of the descending toe deflection, as the result of a slight redistribution in the filling of venous beds.

The lack of continuous waves in the toe tracing, in spite of the preocclusion waves in the toe being of practically the same amplitude as in the calf, is somewhat bewildering. At this point we can only suggest that it might have some relation to the possible emptying of venous beds, but it is worth recalling that also in the first recording did we find the toe to behave somewhat differently than the rest of the leg.

Looking at the pre-occlusion tracing of the toe on the left of Figure 5, we notice some of the same features previously mentioned. The peaks of the toe waves seem to precede the peaks of the other waves or to lag nearly one cycle behind them. The toe seems to start to ascend a little before the rest of the leg has finished descending. The toe waves seem to be superimposed upon slower waves. Thus we may start to wonder whether the respiratory toe waves represent another type of waves than those picked up elsewhere in the leg.

Turning to Figure 6 we notice again that our occlusion procedure seem to have worked pretty well. Neither in the tracings from the forearm or finger tip do we find any pronounced pulse waves after the occlusion (200 mm. Hg) was applied above the elbow.

The apparent abrupt rise in circumference of the forearm and finger tip indicates the time at which the occlusion was started. Probably the rise is a mechanical artifact due to movements of the arm

and finger caused by the pumping of the occlusion cuff.<sup>1)</sup> More difficult to explain is the progressive rise in the circumference of the forearm after occlusion. It might be due to the fact that our occlusion procedure has not worked perfectly but permitted a small amount of arterial blood to ooze into the arm during the experiment and that the inflow has not yet been balanced off; but it is also possible that we are confronted with a circulatory reflex similar to the one described by Davis (1957). The upward deflection looks considerable on the figure but represents in terms of absolute circumference change less than 0.2 %.

However, the most remarkable aspect of the figure is the continuation of respiratory waves in both forearm and finger tip after the occlusion. In the case of the finger tip the pre-occlusion period recorded shows respiratory waves superimposed upon an ascending and descending deflection. The deflections in question correspond to those described by Burch et al. as Alpha waves. Notice also that the mean respiratory period during this experiment amounts to around 5.6 seconds.

Before exploring further the nature of what we have started to call respiratory waves, it might be in order to demonstrate that the waves really do follow respiration, that they do stop during breath-holding.

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Insert Fig. 7

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Figure 7 shows tracings from upper thorax, abdomen, left forearm and left index finger before and during breath-holding.

The tracings from both forearm and finger tip show disappearance of respiratory waves during breath-holding.

The sudden rise in the circumference of the forearm at the time the subject starts to hold his breath raises the question whether we

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1) At this point one might in fact go one step further and ask whether our respiratory waves from the arm and leg are not themselves mechanical artifacts of the recording procedure - the subject showing longitudinal movements with respiration causing the gauges to move along somewhat more on the upper surface of the extremities than beneath due to the friction of the couch and the subjects body. In a couple of experiments (not to be reported in this paper) we have controlled this factor by making recordings with the subject in a standing position, with the subject in a supine position with the arm hanging freely at heart level supported by a rope around the wrist, and with the subject in a supine position while the leg was hanging freely at heart level supported by a rope fastened to the ankle allowing the leg free longitudinal movement with respiration. The results of these experiments support fairly definitely that respiratory circumference changes in the head and the extremities do take place.

are faced with a mechanical artifact (body movement in a longitudinal direction) or an increase in the circumference of the forearm proportionate to the increase in thoracic and abdominal amplitude. The fact that the forearm starts increasing after both the thoracic and abdominal circumference have reached their breath holding level makes it difficult to ascribe it to either of these factors. More probable is an explanation in terms of the closing of the glottis and the relaxing of the thoracic wall after the initial deep inspiration, resulting in an increased intrathoracic pressure in turn being followed by increased blood flow to peripheral parts of the body. The little downward slope at the time of the start of breath-holding in the thoracic tracing certainly supports such an interpretation.

Turning to the finger tip we notice the possible continuation of Alpha deflections uninterrupted by the breath-holding. The average time per deflection is approximately 6 seconds, a little longer before than during breath holding (8 versus 6 seconds). Evidently, Alpha waves are not dependent upon respiration.<sup>1)</sup>

Studying the respiratory waves superimposed upon the Alpha deflections on the left side of the figure (before breath-holding), we notice once more that they are not completely in phase with the respiratory waves in forearm and trunk. In general, they seem to be a little less than half-a-cycle delayed.

Since Alpha waves were not detectable in our tracings recorded during arterial occlusion (while respiratory waves were), and since respiratory waves were not noticeable during breath-holding, we may go one step further and ask what will happen in the case of simultaneous breath-holding and arterial occlusion. Figure 8 gives the result of a supplementary experiment done in order to throw light on this question.

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1) Neumann (1942) rules out that Alpha waves are manifestations of fluctuations of arterial blood pressure. In a still later article by Neumann et al. (1943), it is suggested that Alpha waves are dependent upon changes in the size of small blood vessels, being affected by spontaneous, rhythmical bursts of sympathetic discharges. Keeping with the latter assumption, Burch (1959) suggests that Alpha waves reflect the net changes in the calibre and tone of precapillary vessels, and consequently that they are related to blood flow, their ascending and descending deflections being associated with an increasing and decreasing rate of digital inflow.

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Insert Fig. 8

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Focusing on the bottom tracing in Figure 8 we notice first an increase in the circumference of the finger following the arterial occlusion at the wrist. Again we are probably faced with an artifact of the cuff, the increasing pressure of the cuff obstructing venous out-flow a little earlier than arterial inflow, and finally pushing tissue peripherally.

In the second place we notice the continuation of respiratory waves after occlusion and their complete disappearance during respiratory arrest. That these waves are transmitted through blood flow or hydraulic fluctuations in blood pressure seems by now certainly most unlikely.

However, a third phenomenon attracts our interest, namely the fairly slow deflections seen in the tracing after arterial occlusion, deflections seemingly uninfluenced by breath-holding and with a period varying from 25 to 35 seconds. In terms of periodicity they correspond fairly closely to those designated by Burch et al. as Beta waves, although Burch et al. mention at one place that Alpha waves may occasionally be stretched out to such a degree that they are practically indistinguishable from Beta waves. However, the differentiation between Alpha and Beta waves is at this point of minor interest as compared to the fact that some types of rhythmical circumference changes, beside the respiratory ones, obviously seems to take place independently of peripheral blood flow.

Turning to the left of the same tracing we again notice that the peaks of the respiratory waves in the finger tip tend to be a little delayed as compared to the peaks in the respiratory wave recorded from the trunk and forearm. Focusing on the tracing from the forearm exclusively we notice the same phenomena previously mentioned, the disappearance of respiratory waves during breath holding and an abrupt increase in the circumference of the arm following the closure of the glottis and the probable pressure increase in the intrathoracic cavity as the thoracic wall relaxes. Still another aspect of the forearm tracing attracts our interest, the remarkable decrease in the average amplitude of the respiratory waves following arterial occlusion, a decrease being

paralleled by a small decrease in the abdominal amplitude and a somewhat faster rate of breathing.

This latter observation leads us over to a question so far left completely out of our discussion - namely, the relationship between respiration proper and peripheral respiratory waves. In order to throw some light on this problem some additional supplementary studies were undertaken.

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Insert Fig. 9

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Figure 9 shows three sample recordings taken a few seconds apart from the same testing session. The center tracings show a slightly more shallow breathing than the left (preceeding) and the right (succeeding) tracings.

Of particular interest is to note the near disappearance of respiration waves in the finger tip during the period of more shallow breathing. Also the amplitude of the respiratory curves in the forearm shows a declining tendency. The near disappearance of the respiratory curves in the finger tip as well as the consistent finding that these curves seem to be delayed as compared to the rest of the arm, may indicate that they at least in part are propagated from more central areas.

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Insert Fig. 10

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Figure 10 shows the results of an experiment in which the subject was instructed to vary voluntarily his respiratory rate while no restriction was placed upon the amplitude of his breathing. As would be expected in such a case we find that the thoracic amplitude increases proportionally as the respiratory periods are increased successively from 3 to 12 seconds.

Of importance in the present context is to note the successive increase in the amplitude of peripheral respiratory waves recorded from the upper arm and hand. The proportionality of the respiratory amplitudes in thorax and upper arm is fairly constant (around 70:1), while the thorax-hand amplitude ratio shows a consistently falling tendency - maybe, because of the hands smaller absolute circumference it will much sooner reach a progressively increasing resistance toward further expansion. The curves to the far right of the figure look extremely large but still represent circumference changes of only 0.1 % and 0.07 % of the upper arm and hand respectively.

Summary.

Summing up our results so far we may say that we have demonstrated at least in one subject, circumference waves in the head, arm and leg accompanying respiratory circumference changes in the trunk. We have found these peripheral respiratory waves to be dependent upon the thoracic respiratory period and amplitude. We have further found that the waves do not seem to be transmitted through blood flow or through the propagation of blood pressure changes from alterations in intrathoracic pressure. We have found that the waves in the arms and the legs may be closely synchronized with thoracic and abdominal respiratory tracings, but that both the finger tip and the toe tip may behave a little differently than the rest of the arm and the leg respectively. Finally, we have found that the waves seem to be smaller both absolutely and relatively the more peripheral in the extremities the waves are recorded.

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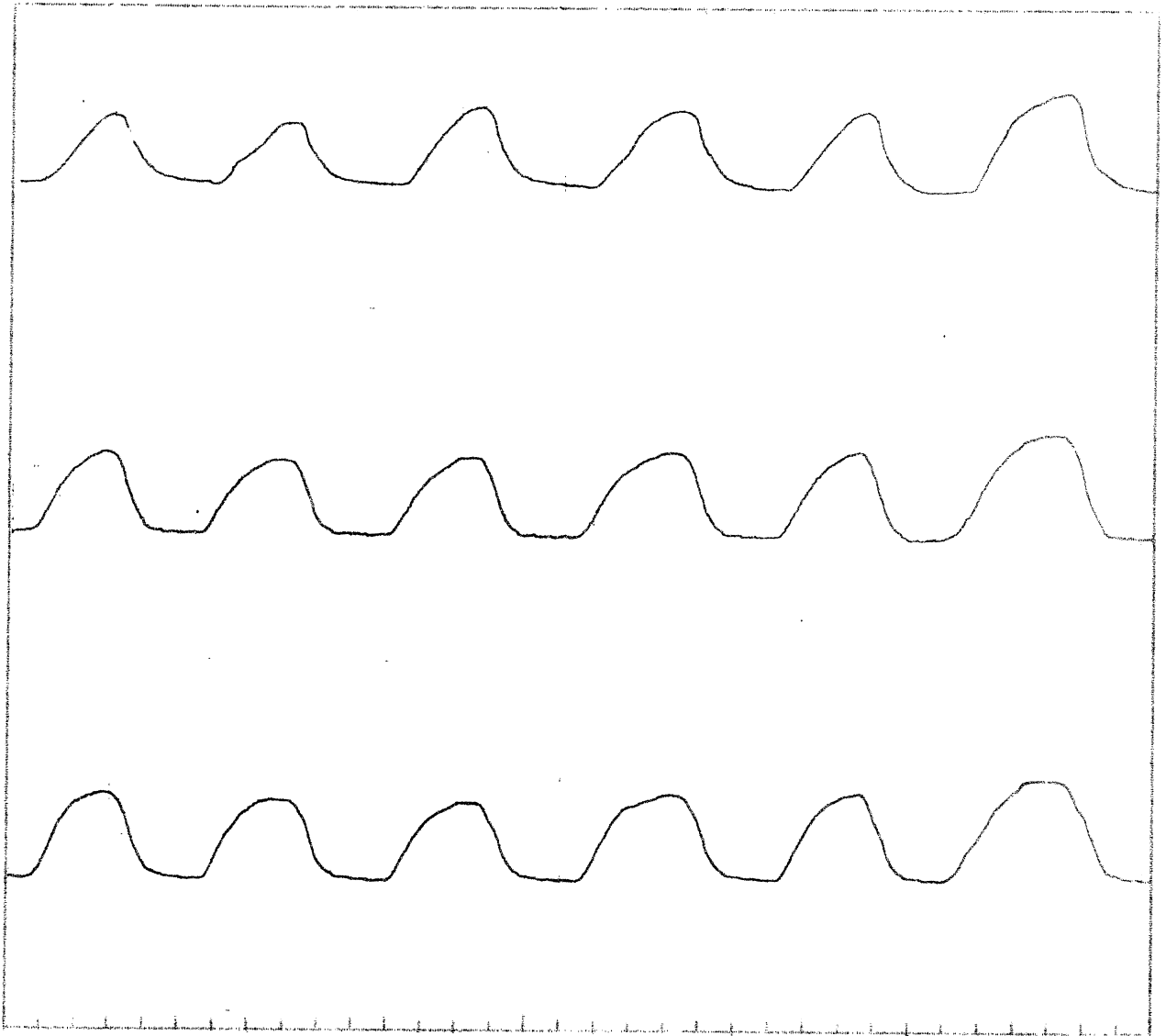


Fig. 1. Demonstration of respiratory waves in different body parts: I. The trunk. Changes in circumference are from upper thorax, lower thorax, and abdomen (from top down). Magnifications of recording are 1.33, 2.00, and 0.67, respectively. Mean respiratory amplitudes are 8.0, 5.9, and 18.0 mm., respectively. One horizontal division equals 2 seconds.

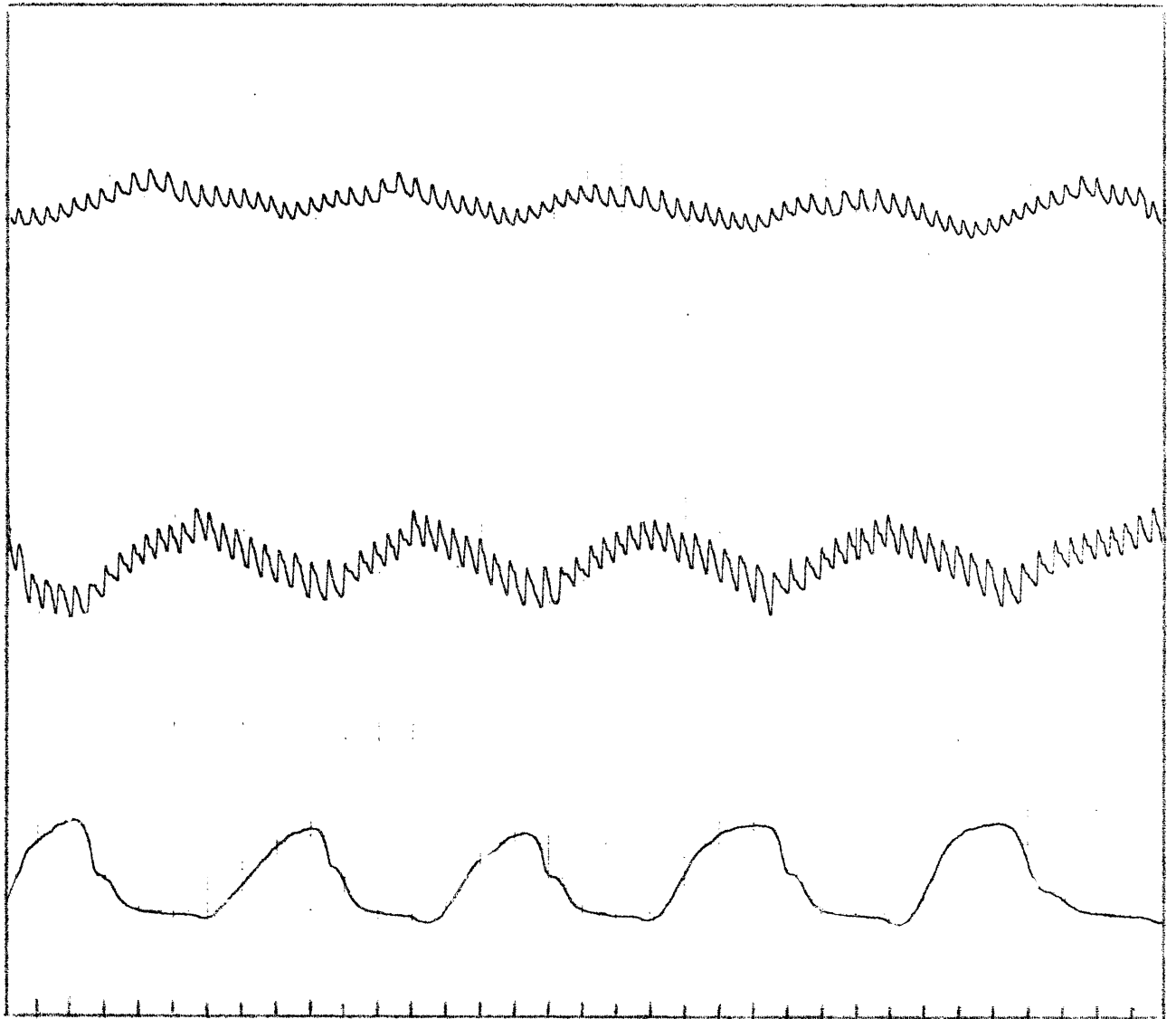


Fig. 2. Demonstration of respiratory waves in different body parts: II. The head and neck. Changes in circumference are from forehead, neck, and upper thorax (from top down). Magnifications of recording are 100, 20 and 1.33, respectively. Mean amplitudes of respiration are 0.04, 0.44, and 10.4 mm., respectively. One horizontal division equals 2 seconds. The upper two curves also exhibit pulse waves.

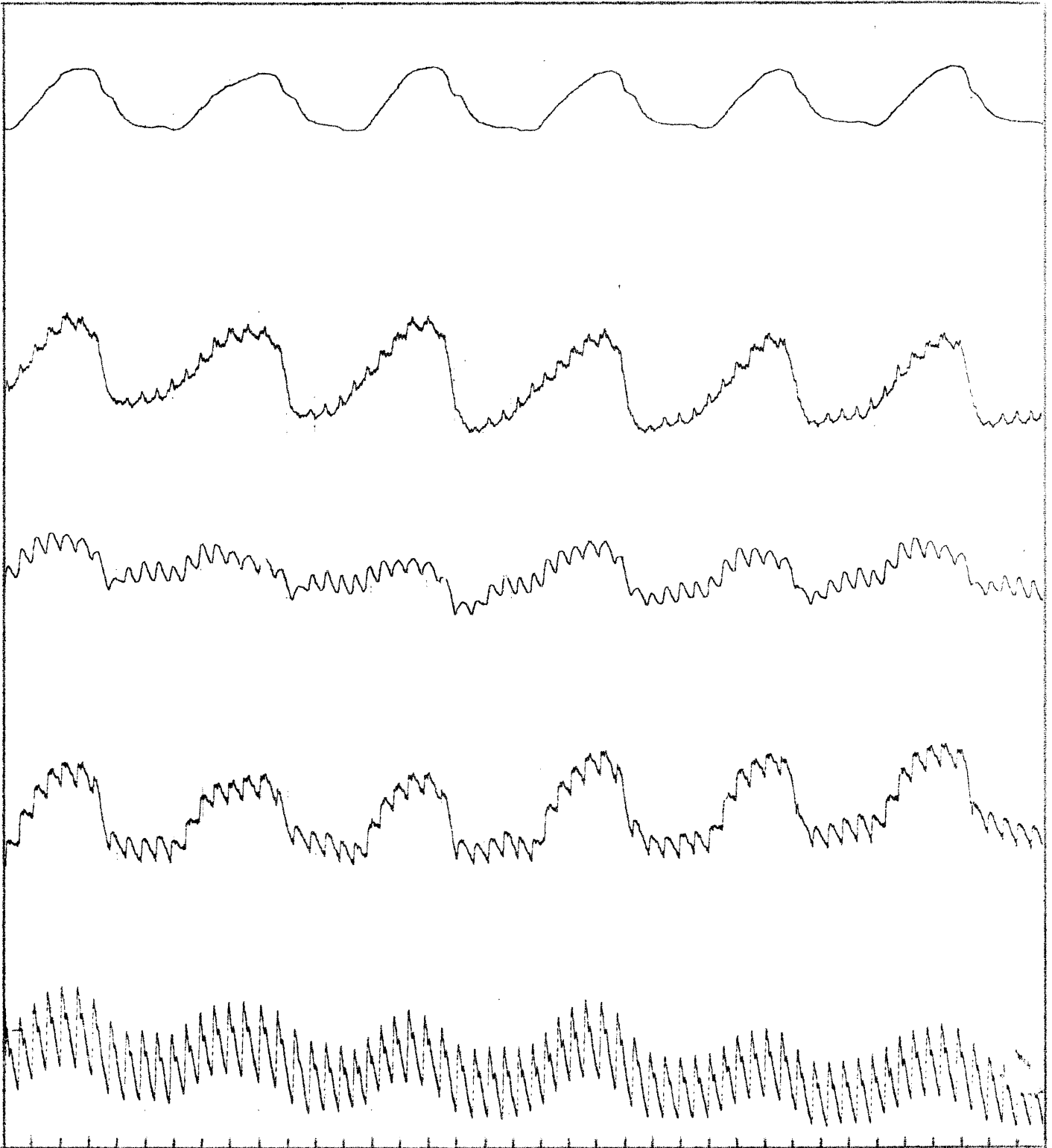


Fig. 3. Demonstration of respiratory waves in different body parts: III. The arm. Changes in circumference are from upper thorax, left upper arm, left forearm, left hand, and left index finger tip (from top down). Magnifications of recording are 1.33, 125, 100, 200, and approximately 500, respectively. Mean respiratory amplitudes are 7.72, 0.112, 0.070, 0.066, and 0.012 mm., respectively. One horizontal division equals 2 seconds. The lower four curves also exhibit pulse waves.

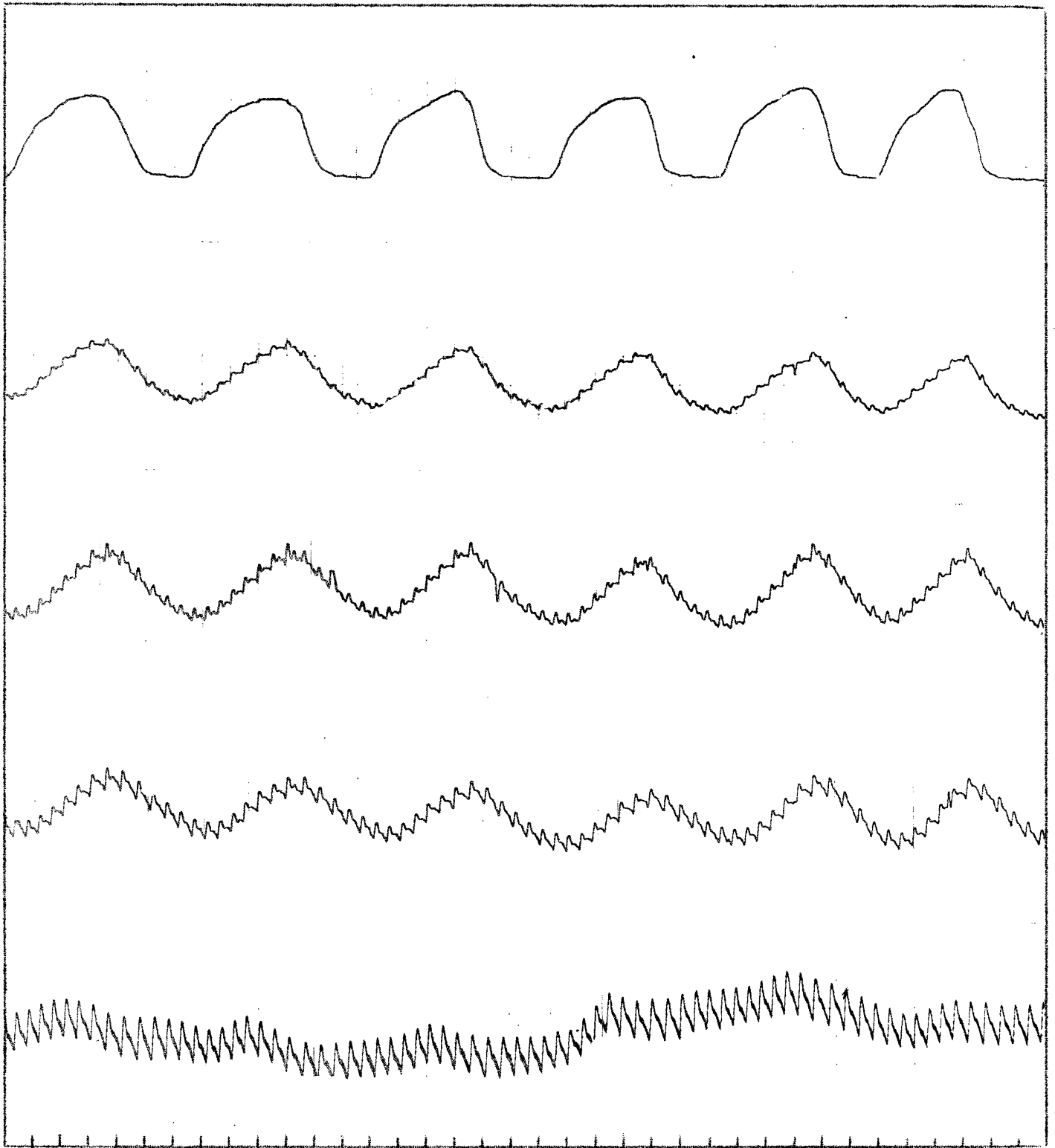


Fig. 4. Demonstration of respiratory waves in different body parts: IV. The leg. Changes in circumference are from abdomen, left thigh, left calf, left foot, and left second toe (from top down). Magnifications of recording are 0.67, 20, 50, 100, and approximately 500, respectively. Mean respiratory amplitudes are 22.5, 0.48, 0.21, 0.08, and 0.006 mm., respectively. One horizontal division equals 2 seconds. The lower four curves also exhibit pulse waves.

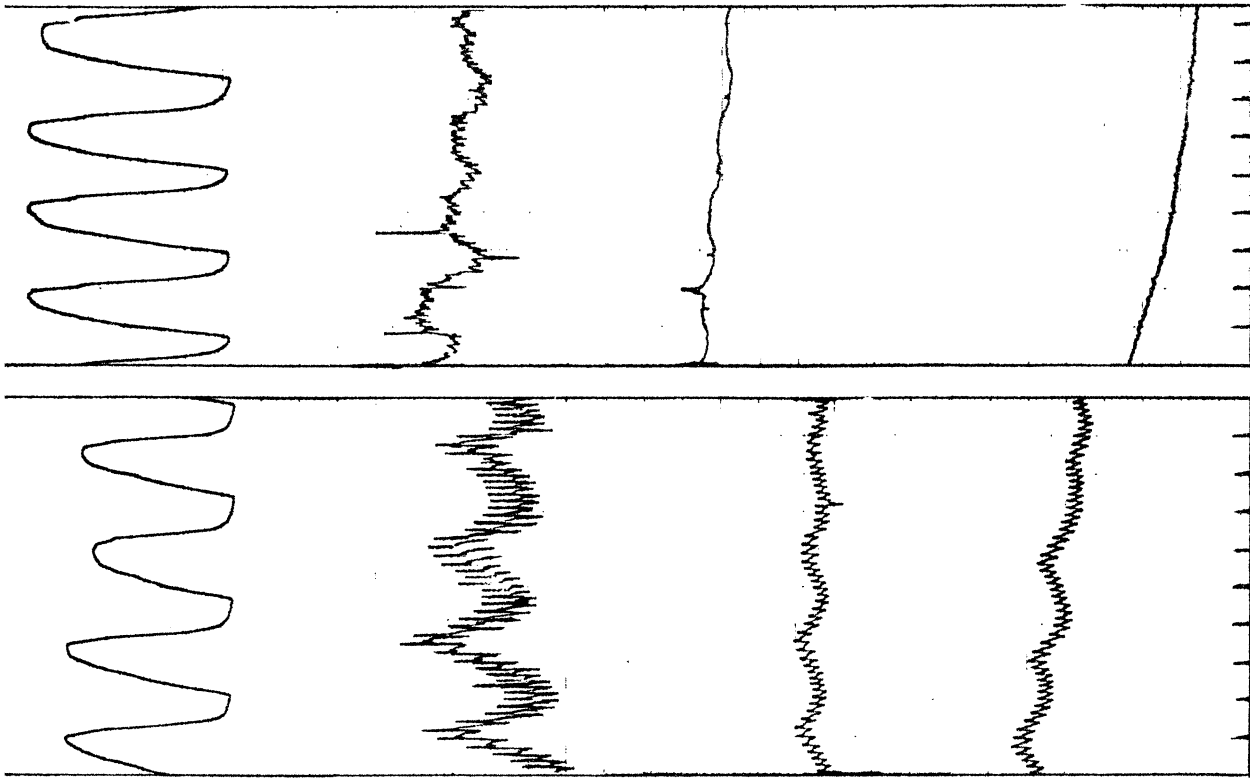


Fig. 5. Respiratory waves in calf, foot, and toe before (left) and after (right) arterial occlusion (300 mm. Hg) above knee. The circumference curves from top down are from abdomen, left calf, left foot, and left second toe. Magnifications of recording are 1, 100, 100, and approximately 500, respectively. One horizontal division equals 5 seconds. Notice the continuation of respiratory waves in calf and foot.

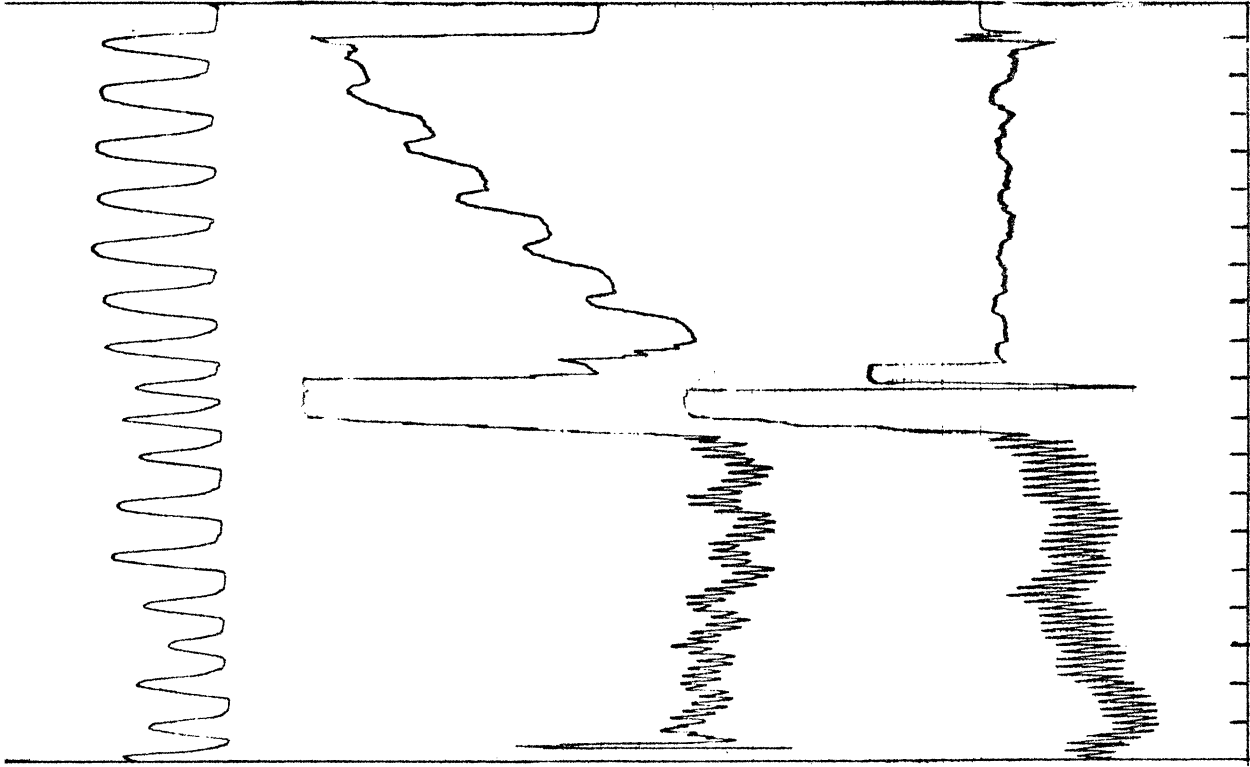


Fig. 6. Respiratory waves in forearm and finger tip before (left) and after (right) arterial occlusion (200 mm. Hg) above elbow. The circumference curves from top down are from abdomen, left forearm, and left index finger tip. Magnifications of recording are 4, 100 and approximately 500, respectively. One horizontal division equals 5 sec. Notice the continuation of respiratory waves in the forearm and finger tip.

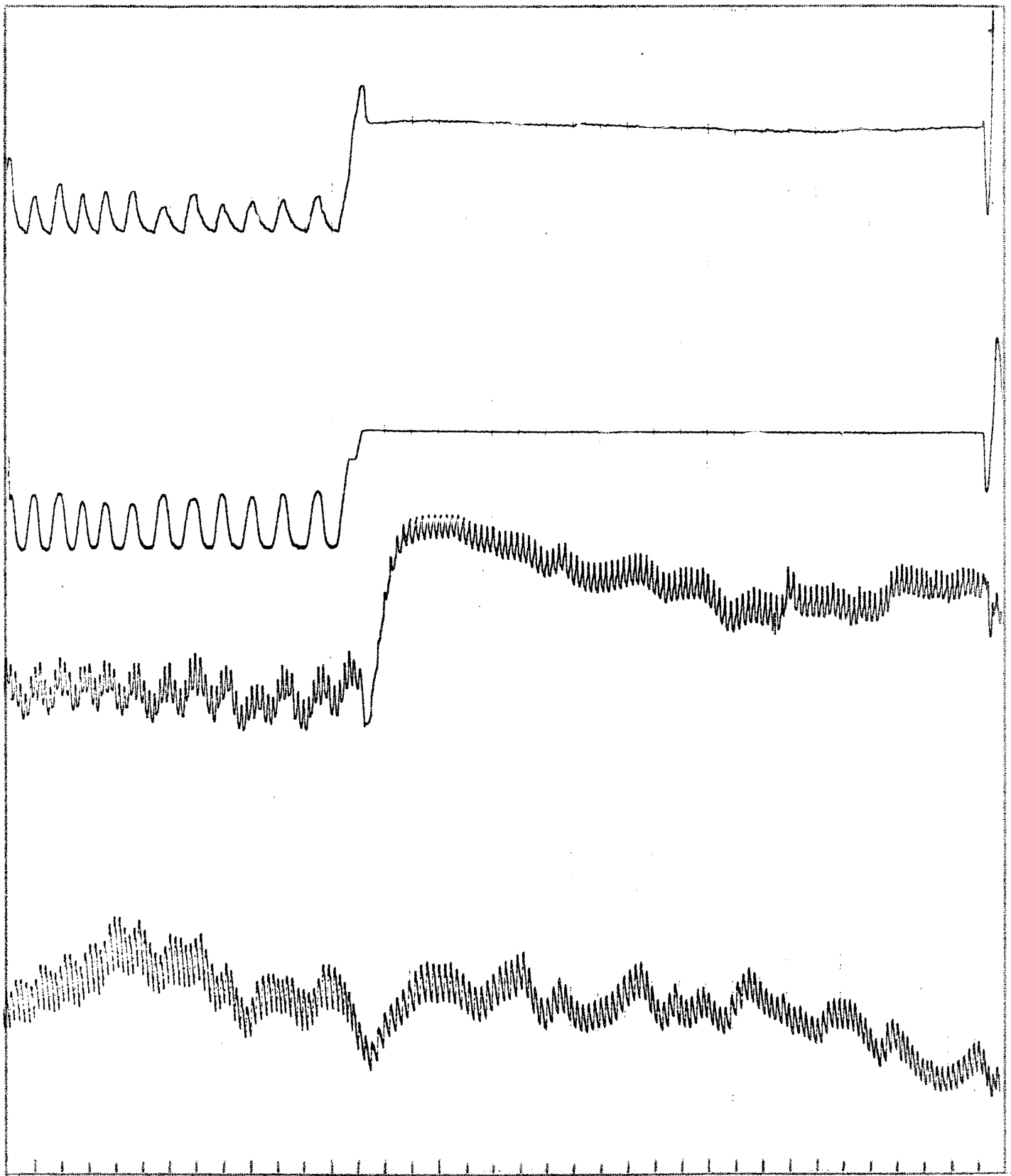


Fig. 7. The disappearance of respiratory waves during breath holding. Circumference curves are from upper thorax, abdomen, left forearm, and left index finger tip (from top down). Magnifications of recording are 10, 4, 100, and approximately 500, respectively. One horizontal division equals 5 seconds.

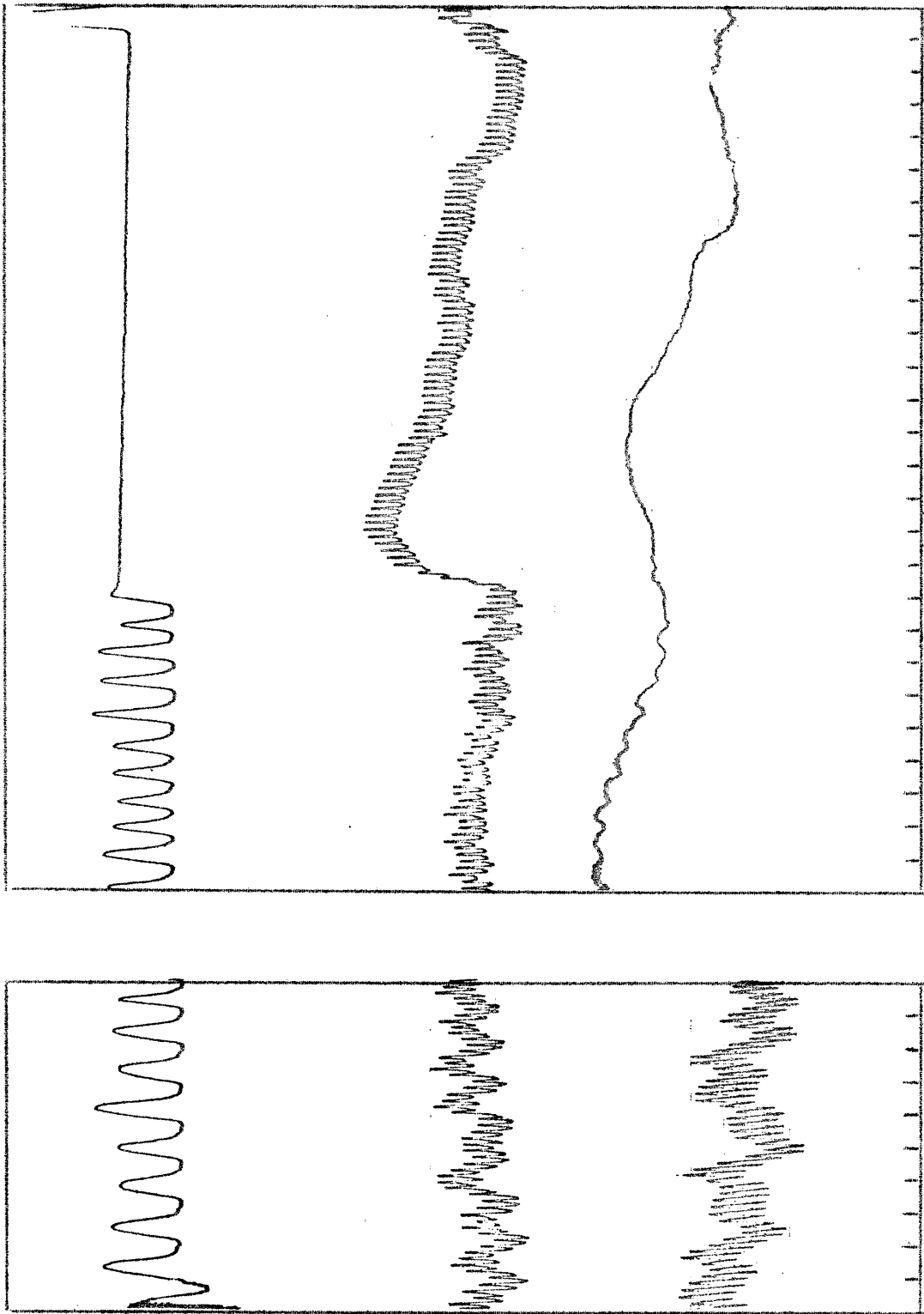


Fig. 8 Respiratory waves in forearm and finger before (left) and after (right) arterial occlusion (200 mm. Hg) at wrist, and before and during breath holding (far right). The circumference curves are from abdomen, left forearm, and left index finger tip (from top down). Magnifications of recordings are 4, 100, and approximately 500, respectively. One horizontal division equals 5 seconds. Notice the continuation of respiratory waves in the finger after arterial occlusion, and their disappearance during breath holding.



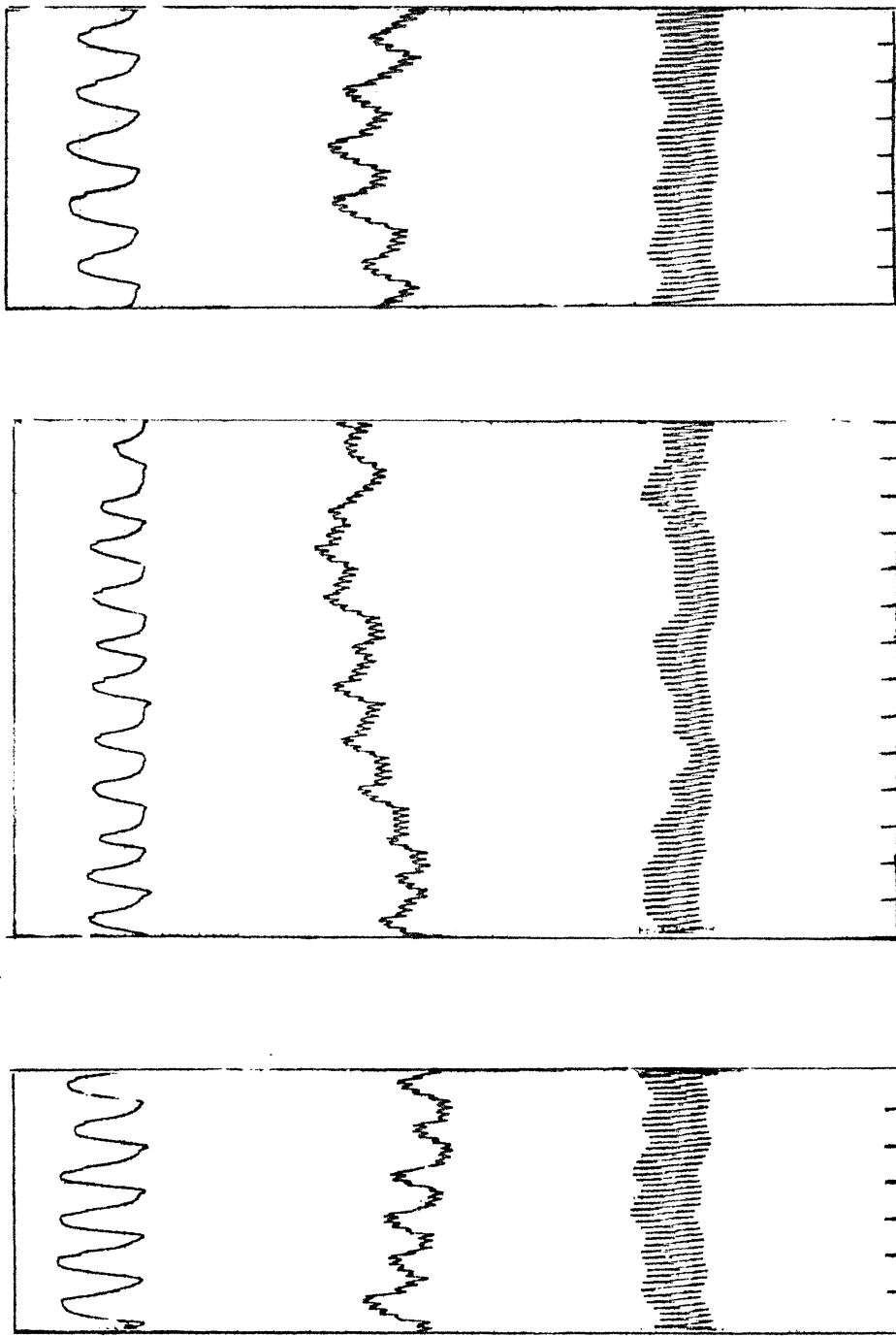


Fig. 9 Comparison of respiratory waves in forearm and finger tip during slightly deeper (left and right) and slightly more shallow breathing (center). The circumference curves are from upper thorax, left forearm, and left index finger tip (from top down) with recording magnifications of 2, 100, and approximately 500, respectively. One horizontal division equals 5 seconds. Notice the disappearance of respiratory waves in the finger tip during shallow breathing.

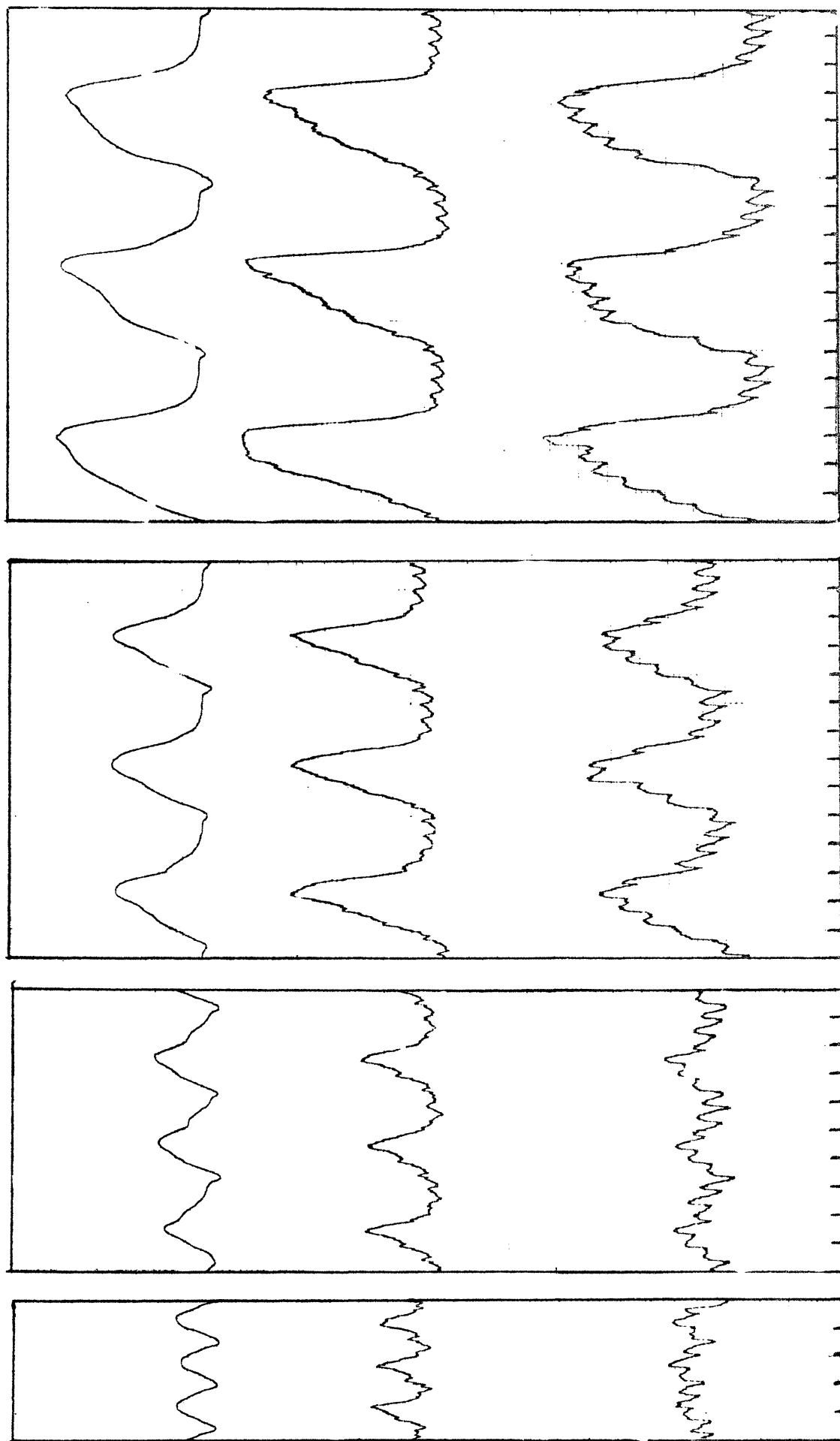


Fig. 10. Proportionality of respiratory amplitudes in upper thorax, upper arm, and hand (from top down) during voluntarily-controlled respiratory periods of 3, 6, 9, and 12 seconds (from left to right). Magnifications of recording are 1.33 (thorax), 125 (arm), and 200 (hand). The mean thoracic respiratory amplitudes are 5.25, 7.50, 12.75, and 19.3 mm. (from left to right). The thorax-arm amplitude ratios are 73, 74, 63, and 73. The thorax-hand amplitude ratios are 210, 188, 128, and 125. One horizontal division equals 2 seconds.