ON THE RELATIONS OF DIAPHRAGMATIC AND COSTAL RESPIRATION, WITH PARTICULAR REFERENCE TO PHONATION.

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I.

THE object of this part of our paper is to emphasize the physiological relations already known to exist between the different groups of respiratory muscles, and to call attention to the fact that they are frequently simultaneously employed in the opposite phases of inspiration and expiration; a class of phenomena here known as the "complementary movements of respiration."

The respiratory muscular machinery may, for physiological purposes, be divided into two separate working groups, the first including the numerous muscles which produce changes in the capacity of the thorax by direct movement of its bony framework, the second embracing the diaphragm and muscles of the abdominal wall.

The mechanical relations of the parts are such that we should expect to find in normal respiration no complete severance of action between the two groups; common observation has, however, given rise to the differentiation of two distinct types of breathing, "abdominal" or "diaphragmatic," and "costal."

The latter type may be further sub-divided into, 1st, "clavicular" respiration, characterised by isolated lifting of the upper ribs and the clavicles, a mode which teachers of vocal art appear to unite in condemning; 2nd, a costal respiration characteristic of males, in which the amplitude of rib movement appears to increase from above downward and is probably chiefly produced by contraction of the *external intercostals* and *levatores costarum*; 3rd, a costal type, most common in females, in which the movement is chiefly confined to the superior half of the chest, and which may normally involve the action of that great group of muscles which connect the upper ribs and sternum to the shoulder girdle and spinal column.

Experimenters have not yet made clear the physiological relationship of these various mechanisms which are so rarely used as a whole but all of which subserve the same general purpose in the body. Looking at the question from an *à priori* standpoint we should expect to see normal quiet respiration carried on by that group of muscles which with least expenditure of energy could bring about the introduction of the greatest amount of oxygen and the elimination of the greatest amount of carbon dioxide in a given time; the other mechanisms being chiefly reserved for special and excessive respiratory needs. Observation confirms the anticipation that the muscular apparatus used in quiet breathing is largely determined by the modified resistance to inspiratory expansion such as produced by tight fitting clothing or even by the posture of the body.

Hutchinson[1] studied the respiratory movements chiefly by his sense of touch in subjects seated and divested of clothing. He makes the well known classification of the two types of costal and abdominal respiration; the first is the normal quiet breathing of women, the latter of men. In abdominal respiration the inspiratory movement always commences at the diaphragm. He says, "the ribs and sternum nearest the abdomen gently follow this movement, until the motion, like a wave, is lost over the thoracic region....In costal breathing the upper ribs move first and the abdomen second. This is the ordinary breathing in women. All difficult, sudden and extraordinary breathing is costal; we at such times direct all our powers towards the apex of the thorax, first expanding that region, and gradually those below it. When we determine the order of breathing by sight we must be careful to take the position of the body into account. If the patient be recumbent (supine), we may notice extensive costal movement, and, indeed, it may be true costal breathing; but place the patient erect, and the breathing may be diaphragmatic. When recumbent all the motion is thrown forward, the natural lateral and backward motions of the ribs being prevented; and so sensitive are the breathing movements to impediments that they may either take a reverse action, or, all the motion being thrown forward, will give a preternatural movement of the ribs, which may be mistaken for costal respiration."

Hutchinson concluded that the difference between the types of breathing in men and women was not due to the restraints of

[1] Art. "Thorax." Todd and Bowman's *Cyclopedia of Anat. and Phys.*

clothing among the latter, for he found costal breathing in young girls who had never worn tight fitting dress.

Rosenthal[1] quotes Boerhaave as having observed the difference in the types of male and female respiration in infants of one year; while others, as Beau and Maissiat, Walsche and Sibson attribute the difference to external impediments.

But in any case it must be admitted, as Rosenthal points out, that costal breathing in females has become more or less firmly fixed by heredity into what Darwin calls "a secondary sexual character."

Dr Mays of Philadelphia has recently published an account of observations made by means of the graphical method on the respiratory movements of female descendants of an uncivilized race. He writes, "In all I examined the movements of eighty-two (82) chests, and in each case took an abdominal and a costal tracing. The girls were partly pure and partly mixed with white blood, and their ages ranged from between ten and twenty years. Thus there were thirty-three (33) full-blooded Indians, five (5) one-fourth, thirty-five (35) one-half, and two (2) were three-fourths white. Seventy-five (75) showed a decided abdominal type of breathing, three (3) a costal type, and three (3) in which both were about even. Those who showed the costal type or divergence from the abdominal type, came from the more civilized tribes, like the Mohawks and Chippewas, and were either one-half or three-fourths white; while in no single instance did a full-blooded Indian girl possess this type of breathing."

Dr J. H. Kellogg of Battle Creek, Michigan, has furnished us with data of unpublished observations to the same effect. Kellogg's experiments were made with the aid of a Marey's stethograph and a rotating cylinder. He writes, "I observed the breathing of 20 Chinese women and the same number of Indian women and I found the abdominal type very marked in every case. The tracings given by the Chinese women were not like those of robust men, but were identical with those from men of sedentary habits....Of the Indian women, 14 were of the Yuma tribe, the most primitive Indians in the United States....The majority of them still wear their bark dresses, the only garment in addition to this is a long strip of red cloth thrown over the shoulders and folded about the body....The waist is not restrained in the slightest degree. In these women the abdominal movements were 4 to 6 times as great as the

[1] Hermann's *Hdb. d. Phys.* Bd. IV. Th. II. S. 216.

costal movements. I examined several of the Cherokee and Chickasaw women in the Indian Territory. These women had all worn civilized dress and some of them had worn corsets. Those who had worn corsets and tight dresses gave tracings like civilized women; those who had worn only loose dress gave normal tracings. I also found a few civilized women who had never worn corsets or tight bands and obtained from them tracings like those from the Chinese and Yuma women."

Mosso[1] recorded simultaneously tracings from the thorax and abdomen of persons in the recumbent position by means of a Marey's stethograph applied to the chest and a Vierordt's sphygmograph on the abdomen. He found the abdominal movement relatively more prominent in the waking, and the costal movement in the sleeping state. It would appear from his tracings that in sleep the inspiratory movement of the chest considerably precedes that of the abdomen while in the waking state the order is reversed or the movements are simultaneous. Our own experiments in this connection will be described further on. It should always be borne in mind that movements of the abdominal wall only indicate motions of the diaphragm in so far as these produce an uncompensated change in the volume of the abdominal cavity. In inspiration, for example, the increase in the abdominal cavity afforded by the expansion of the lower ribs may neutralize to a considerable extent the reduction in the volume of the cavity produced by contraction of the diaphragm; there would, in this case, be no movement of the abdominal wall to indicate the inspiratory motion of the diaphragm. On the other hand, the diminution in the volume of the abdominal cavity following collapse of the lower ribs might balance a considerable increase of that cavity produced by expiratory elevation of the arch of the diaphragm. The position of the body probably influences, also, to a marked degree the tension of the resting diaphragm. A cord tied closely round the abdomen of a person standing upright, becomes loose when the recumbent position is taken. The difference is no doubt due to the fact that in the one case the weight of the abdominal viscera must in part be borne by the abdominal wall, and in the other not.

By the complex muscular apparatus of respiration the dimensions of the lungs may be changed in all directions; and though the ordinary respiration of one person may be of the pure abdominal type

[1] *Arch. f. Anat. u. Physiol.* 1878, S. 441.

and of another of a nearly pure costal variety, there can be no question but that occasionally parts which are commonly unused take up the motion, or that the whole apparatus is, at periods, set in action. While watching a person quietly breathing it will be observed that at irregular intervals the character of the respirations changes, the regular rhythm being broken by long drawn inspirations of a sighing nature, and these may involve the predominant action either of diaphragm or ribs. And in a condition of drowsiness the stretching yawn in which every inspiratory muscle is brought into play, is most admirably adapted to renew to the fullest extent the air in the lungs and relieve the tissues which are suffering from an accumulation of wastes and a depletion of oxygen.

A secondary but very important function of the respiratory movement is to aid in the circulation of the blood.

Costal inspiration exerts an aspiratory force upon the blood in the veins; and as changes in the volume of the thorax brought about in this manner are, as will be seen later, considerably greater than those produced by movements of the diaphragm alone, the suction force of the rib motion must be of correspondingly greater consequence.

But the contraction of the diaphragm not only acts as an aspiratory power by enlarging the thoracic cavity, but by pressure upon the abdominal viscera it must have a very important function in squeezing the blood and lymph out of them towards the heart. From these considerations it would appear that under ordinary conditions, when so large a portion of the blood is contained in the viscera, the diaphragmatic type of breathing would most economically fulfill the needs of the body. During active muscular effort, on the contrary, probably a large part of the blood is transferred to the voluntary muscles and we would expect to find, what is, indeed, the fact, the costal movements magnified; for by such means not only is there more vigorous aspiration by the thorax, but a more voluminous renewal of air in the lungs.

There is another relation of diaphragmatic respiration which seems to have hitherto escaped attention. We have found by measurements made in the dissecting room that the distance from the division of the bronchi to the lower, outer margins of the lungs is about twice as great as that from the bronchi to the lateral or superior border of the organs; and it is the lower, outer parts of the lungs which are chiefly influenced by diaphragmatic movements.

The tidal air drawn into the lungs by an ordinary inspiration does not penetrate beyond the bronchial vessels, and by no effort of the will can the pulmonary air be completely renewed at a single respiration. The movements of respiration simply serve to mix fresh air with that which has already remained a longer or shorter time in the lungs. It is probable that the diminution of oxygen and the excess of carbon dioxide are proportional to the distance from the division of the bronchi. We would suggest that, for equal quantities of air respired, diaphragmatic, as compared with costal, respiration better subserves the physiological purposes of the act. For, in the former case, the chief movement of the lungs is in those parts furthest removed from the exterior and by this means there is provided the renewal of that air which is presumably richest in carbon dioxide and poorest in oxygen. Moreover, a current of air set in motion by expansion and contraction at the bottom of the lungs must cause a tolerably complete gaseous mixture in the air vessels of superior portions, even though these themselves do not perceptibly share in the respiratory movements. From the considerations that have been presented it would appear that easy diaphragmatic respiration has peculiar value not only in assisting mechanically the circulation of the blood but in causing in the most perfect manner possible the mixture of fresh with foul air; and it should be borne in mind that the function of respiratory movement is simply to bring about this mechanical mixture.

In his classical studies on respiration Hutchinson made no attempt to discover the relative vital capacity of the lungs determined by isolated movements of a diaphragm and ribs respectively. Since teachers of the vocal art not infrequently make the positive statement that a greater volume of air can be drawn into the lungs by a diaphragmatic than by a costal inspiration, the matter seemed at least worth an experimental test. One of us[1] accordingly made a long series of observations by means of the spirometer with the view of testing, as far as possible, all the volumetric relations of diaphragmatic and costal respiration. Similar observations were afterwards made upon a number of adult male students with like results. After some practice, full respiratory movements with either ribs or diaphragm can be made without sensible confusion of the two actions. Each figure in the following table represents the average of from 20 to more than 100 separate observations extending over a period of about 8 days.

In the first set of experiments the fullest possible inspiration was taken and then the air was expelled as completely as possible by

[1] Miss Pollard.

isolated contraction of the abdominal or expiratory chest muscles respectively. In the second set the full inspiration was taken only by

		Diaphragm.	Ribs.	Sum of volumes determined by diaphragm and ribs.
I.	Vital capacity determined by expiratory movement of diaphragm or ribs alone after full inspiration by all the muscles.	1590	2087	3677
II.	Vital capacity determined by using either diaphragm or ribs alone in both inspiration and expiration.	1341	2139	3480
III.	Amount of air expelled in a natural expiratory movement of either diaphragm or ribs after a full general inspiration.	741	1168	1909
IV.	Vital capacity measured in the ordinary way, i.e. by one full inspiration and expiration with all the muscles.	2500—3000		

the diaphragm the chest remaining at rest, or the reverse, and the amount of air so inspired was fully expelled by the single set of muscles, and measured. In the third series after a full inspiration by all the muscles it was attempted to measure the amount of air expelled by a gentle and natural expiratory relaxation of one set of them, either those of the ribs or the diaphragm; the difficulty of limiting the outflow of breath to the phase of ordinary expiration, however, invalidates the accuracy of the observations under this head.

The average full vital capacity, as generally understood, is represented in the last line, IV, of the table. All volumetric measurements are expressed in cub. cm.

The figures given leave no room for doubt that the vital capacity as determined by costal is much in excess of that determined by diaphragmatic respiration; and this result agrees with the fact that breathing is always of the costal type when the respiratory needs of the body are unusually urgent. It will be noted also, as would have been expected from the anatomy of the parts, that the sum of the vital capacities determined by movement of ribs and diaphragm separately is considerably in excess of that which measures the extent of the simultaneous action of all the muscles.

Attention has already been called to the fact that the character and rhythm of the respiratory movements do not for long periods continue unchanged in the same individual; it has been pointed out that these changes of movement have definite physiological value in renewing the air in those parts of the lungs where it is most needed, but there is no experimental evidence as to the cause of such variations of rhythm and character of movement. In this connection may be quoted the work of Hering and Breuer[1] in which it was made probable that the discharges from the respiratory centres are determined, both as to rhythm and character, by afferent impulses proceeding to them from the lungs along the vagi nerves. According to these observers it is probably the state of mechanical distension of the lungs which determines the excitement of the inspiratory or expiratory centre respectively. There is reason to believe that what seems true for the whole lung will hold for any part of it, and that separate afferent impulses proceed from the various pulmonary areas and provide in an automatic manner that no part shall long remain quiescent.

There is a type of respiratory movement which seems nowhere to have received special attention but which a study of respiration both in man and the lower vertebrates shows to be very important. As has been already insisted the air in the breathing apparatus increases in its content of carbon dioxide and loses oxygen progressively from the external orifice to the lung alveoli, and the movements of respiration, so far as concerns the demands of the body, simply cause a more complete mixture of gases already in the lungs. It is easily seen that if the glottis be closed and such respiratory movements be made as to stir together the gases already contained in the air cavities, the physiological result will be the same as that of genuine respiration with open glottis. The respiratory needs of the body may be thus fairly well satisfied for a considerable time without inhaling fresh air. This hypothesis was confirmed by the following experiments: after a full inspiration the breath was held as long as possible without muscular movement and the duration of this period noted. The observation was then repeated, with the difference that when distress for want of air became urgent the patient voluntarily set up alternate movements of chest and diaphragm, causing the ribs to collapse as the abdomen protruded, and *vice versa*. By this second

[1] *Wiener Sitzbericht*, Nov. 1868.

method the breath could be held very much longer, sometimes nearly twice as long without respiring, than by the first method. We will refer to such simultaneous inspiratory and expiratory actions of the two sets of respiratory muscles as the "complementary movements of respiration;" and would include under that term all those varied actions of the respiratory mechanism by which the internal mixture of air is furthered without the advent of fresh air from without. The essential character of such movements has long been known but their importance seems never to have been fully recognized. A swimmer under water when in need of air often alternately puffs out and relaxes his cheeks; the result is essentially the same as that from the complementary movements of chest and diaphragm. When a person inspires and holds the breath as long as possible, rhythmic, involuntary complementary movements of ribs and diaphragm set in as the first sign of distress, and increase in violence as the suspension is continued. It is easy to conceive that semi-aquatic mammals should owe their power of remaining under water for long intervals to a highly developed capacity for such complementary movements, and it would seem that there are few powers more likely to be preserved by natural selection.

It is certainly a significant fact that after the deepest possible inspiration the abdomen is always depressed, and a very considerable change in the shape of the lungs, and therefore mixture of the contained air, can be brought about by easy compression of the ribs with simultaneous protrusion of the abdominal wall. The inspiratory retraction of the latter is due to the enlargement of the abdominal cavity caused by spreading of the lower ribs; whether there is coincident relaxation of the diaphragm is an interesting but unsolved question.

Graphical tracings taken simultaneously from chest and abdomen do not ordinarily manifest that alternation in phase of rib and diaphragm action which constitutes the complementary movements of respiration. In tracings taken by us, in a manner to be described later on, the movements are seen occasionally; and in those taken by Mosso[1] from persons in deep sleep inspiration begins with an elevation of the chest and is accompanied during nearly half the full period of inspiration by a retraction of the abdominal wall, which latter then begins its inspiratory protrusion.

A most interesting field of investigation is presented by the associations of the muscular movements involved in the various involuntary

[1] Mosso, *loc. cit.*

modified respiratory actions known as coughing, sighing, sobbing, &c. In some varieties of laughter the complementary movements of respiration are rapid, extensive and powerful. A laugh may be chiefly either costal or diaphragmatic in character, and the respiratory phases of the muscular action of ribs and diaphragm may either be the same or opposite in direction. Laughter is notoriously "good for the digestion;" and the physiological reason is plain when we consider the active kneading of the lungs and stirring up of the air in them involved in these easily accomplished complementary movements.

Respiratory actions having the same physiological value and of analogous character are apparently wide-spread among vertebrated animals. Motions of the breathing apparatus whose meaning is otherwise obscure are often easily understood if considered as provisions for mixing the gases already contained in the lungs. To illustrate by a definite example, the respiratory movements in the frog have been clearly demonstrated by Martin[1] and others to consist of two distinct series. In the one oscillations of great amplitude and slow rhythm involve nearly synchronously both the throat and flanks of the animal. At a certain phase of this period the larynx is raised, the glottis opened and air is expelled from and taken into the lungs. But interpolated between these movements which bring about renewal of air, are others of less amplitude and quicker rhythm involving likewise both throat and flank muscles. If a frog's skull be amputated anterior to the optic lobes it will be seen that the glottis is not opened during the smaller throat movements, but the larynx is nevertheless slightly raised at each throat retraction and at the same time the flanks slightly contract. This latter movement is passive on the part of the flank muscles, for if they be cut away the lung will be seen to start forwards at each elevation of the larynx. These gentle churning movements of the lungs produced by the minor movements of the hyoidean apparatus in which the glottis remains closed must be of definite physiological value in causing a more rapid mixture of the air contained in the lungs than could be brought about by simple diffusion. While the respiratory movements of the frog are carried out largely by the swallowing apparatus and are thus apparently distinct from those of the mammal, the close functional relationship between the centres of deglutition and respiration has been pointed out by Steiner; and Garland[2] showed that in the dog there is a pharyngeal respiration

[1] This *Journal*, Vol. I.

[2] This *Journal*, Vol. II. p. 82.

whose movements are rhythmic with those of the chest; pharyngeal contractions and expansions corresponding with the phases of inspiration and expiration respectively. There is also in the human being some relation between the two mechanisms which makes a swallowing movement the necessary culmination of a deep and satisfactory inspiration.

If a study of physiological function can disclose any evidence on the ancestral relationships of animals, there would seem to be no more fruitful field than that of the comparative physiology of the minor respiratory movements.

II.

The chief object of this part of our paper is to show that the so-called complementary movements of respiration have, both from a physiological and an artistic point of view, an important relation to vocalization.

The management of the breathing apparatus in vocalization, either in the use of the singing or the speaking voice, is evidently of the highest importance both from an artistic and a hygienic point of view. The value of this subject is generally admitted by teachers of vocal culture who inculcate a more or less definite system of rules for breathing according to their individual notions of the proper method. But there is little unanimity in the *dicta* of the various schools, and a sound physiological basis for the teaching is evidently generally wanting.

Vocalization is an unessential attribute of the respiratory apparatus, and it may be taken for granted that only such methods of the art are right or natural which least interfere with, if they do not actually aid, the fundamental respiratory function. From some of the preceding considerations it would appear that, other things being equal, phonation with diaphragmatic breathing, in which the abdominal muscles are used as the expelling force, would most economically subserve the physiological needs of the body; for by such means moderate effort probably causes a more complete renewal of air in the lungs than does the costal movement and, moreover, there is no reason for supposing that the chemical constitution of the expired air influences its sound producing qualities.

There is foundation for the belief that it is by no means indifferent for the welfare of the lungs whether powerful movements are impressed upon them from the diaphragm or the ribs. One who is afflicted with a sensitive pulmonary apparatus has frequent occasion to distinguish between a painless abdominal and a painful costal cough.

In phonation, however, we have to consider not only the muscular actions which most economically fulfill the functions of respiration, but those, if such there be, which impress the thorax in a manner to augment or modify the vocal effects produced by vibration of the laryngeal apparatus. The power and quality of a voice depend not so much on the mere trembling of the vocal reeds as on the sympathetic vibration of the air in the resonance chambers above and below the larynx. A blast of air driven through an isolated larynx could no more produce the normal voice than the vibrating violin string removed from its box could give the note it sounds when bound in its natural position. Helmholtz[1] clearly demonstrated that the difference in quality of tones having the same pitch depends upon the nature and relative power of the various upper partials which accompany the fundamental in every musical tone. He showed that the difference in tone quality constituting the various vowel sounds in the human speech depends upon the change in the selective resonance of the oral and nasal chambers determined by their shape, size and degree of intercommunication. Mills[2] is even of the opinion that the pitch as well as the quality of the laryngeal sound may be modified by the upper resonance cavities.

Comparatively little attention, however, has been paid to the function of the thorax as a resonance chamber in virtue of which it may modify the power or quality of the sounds produced by vibration of the vocal cords.

The following observations are offered as a preliminary contribution to this subject, and the results appear to us to point out a line of scientific enquiry which may lead to conclusions of no small value to vocal art.

It is generally admitted that the chest by virtue of the condensation of air within it during phonation responds with more powerful resonance to the sounds emitted by the larynx than do the cavities above that organ. But, so far as we know, no attempt has been made to show that there is in the chest a power, so to speak, of selective resonance analogous to that manifested by the oral and nasal chambers in determining the sound qualities of the different vowels; much less have

[1] *Tonempfindungen.*

[2] This *Journal*, Vol. IV. p. 133.

we any definite information as to the management of the chest best adapted to bring out its various powers of resonance.

From physical considerations we should expect that the perfection of resonance in the chest would vary with the tension of the bounding walls, and that its fundamental note and overtones would be altered by change in size and shape of the cavity, with the accompanying variation in the contained air channels. The results of experiments undertaken with a view of testing this point respond decidedly in the affirmative.

The attention of one of us was first directed to this point by observing that in singing the musical scale the ascent was made more easily and with a purer, more brilliant tone when the sound producing air-current was driven by the contraction of the abdominal muscles, but with a simultaneous movement of the upper chest of an inspiratory character.

On the contrary, in descending the scale a lower note could be reached when the chest muscles were used as a driving force and the diaphragm was progressively depressed. The experiment was varied in the following way. The voice was sounded in unison with the ordinary musical *c* fork under two conditions; in the first case the chest was held expanded throughout, the air being expelled by the abdominal muscles; in the second the abdomen was kept protruded during the vocal effort, the chest muscles acting as the driving force.

The difference in the quality of the two notes was quite perceptible. In the former case the note sounded clearer and more brilliant, in the latter it appeared to be flattened. This result is readily explained if we suppose that with decrease in its vertical and increase in its transverse diameter the chest cavity so changes in its resonant properties that its fundamental note is elevated, while with diminution of its transverse section and increase of the vertical dimension the proper note of the chamber is lowered. A further experiment gave evidence in favor of this explanation. A stick, about 4 feet long by 2 inches square, of seasoned wood was laid across the back of a person at about the origin of the 5th rib and held in position by his leaning against one side of an open doorway. The ends of a thin wire were made fast to the stick on either side of, and without touching, the body. From the middle of this wire another similar one was led off over a pulley screwed in the opposite side of the doorway and was kept stretched by a weight suspended from its free end. The apparatus being adjusted, the observed person standing with back pressed against the doorway, the weighted string was plucked. It was expected that the note of the vibrating string would be modified by the resonance of the thorax which was in close contact with the stick to which the wire was attached. The wire was plucked under two different conditions; first, while the observed person held chest expanded and abdomen depressed; second, while the chest was collapsed and abdomen distended. The musical note produced was markedly different in the two cases. In the first instance it seemed to be made up both of higher overtones and a higher fundamental than in the second; but as no analysis of the tone was made, it is better to describe it simply as of higher quality in the first case than in the second.

Admitting, then, that the form of the thoracic cavity determines the pitch of its fundamental note, and knowing that changes in this form are under control of the will, we may reasonably expect that observations on this subject, together with such as have preceded, may form a basis for a set of practical rules for such management of the respiratory apparatus in phonation as shall at once both best subserve the physiological needs of the body and answer the demands of the cultivated ear. It would be expected that, as regards the shape of the thorax, the best conditions for voice formation would be those in which the sympathetic vibration of the air in the lungs most nearly harmonizes with the vibration of the vocal cords. Superadded to this artistic advantage there is reason to suppose a physiological value under the same conditions; for it is probable that less exertion is required on the part of the nerve-muscle apparatus concerned in adjusting the vocal cords for the production and maintenance of any note when the resonance chamber whose sympathetic vibration gives volume to the voice is most nearly in unison with the note given out by the cords. The greater ease with which any musical note may be sustained when sung in a room having strong sympathetic resonance, is a matter of common observation.

After these considerations which were based partly on theoretical and partly on experimental grounds, it was sought to determine by actual observation the exact changes in the form of the thorax during the utterance of sounds of varied pitch and loudness. In these experiments simultaneous graphical records were made of movements of the upper chest, lower chest and abdomen.

The abdominal tracings were obtained from a Marey's stethograph whose steel plate was usually applied just superior to the umbilicus. The strings fastening the stethograph to the body were not passed directly round the person, for in such a case movements of the lower ribs are more or less confused with those of the abdomen in the tracings. The strings were made fast to a stick laid across the small of the back, or below it, and as they did not touch the person, abdominal movements only could be impressed upon the instrument. The stethograph communicated by a rubber tube with a Marey's tambour writing in the usual way upon a rotating cylinder. The pneumograph employed upon the chest gave results quite similar to those obtained from the former, but were of a modified form determined by a desire for economy of time and expense in construction.

The instrument (Plate V. Fig. 1) was made of two pieces of board $\frac{1}{2}$ inch thick and of the dimensions $2\frac{1}{2} \times 2\frac{3}{4}$ and $2\frac{1}{2} \times 2\frac{1}{4}$ inches, respectively in area. The pieces were connected together by a hinge along one edge, and in the opposite edge of the larger piece a pair of eyelets were screwed for the attachment of a string by which the instrument could be suspended from the neck. A large sized stiff rubber tube about $\frac{1}{2}$ inch in bore and 5 inches long, plugged at one end and ending in a tapering, open glass tube at the other, was placed crosswise between the hinged boards, the larger of which, when in position, lay against the chest wall, while to the lateral edges of the smaller one were fastened hooks for the attachment of a cord passing round the body of the observed person. At every inspiratory movement the two boards would be approximated and squeeze the included rubber tube, while at expiration the elasticity of the tube would separate the boards to their original position. The open end of the rubber tube was connected in the usual way with a recording tambour which, however, was inverted on its upright support so as to give tracings homologous with those obtained from Marey's stethograph. Ascents in the curves represent depressions of chest or abdomen, and therefore expiratory movements, while descents in the curves were produced by elevations of the body surface, or inspiratory movements.

Both pneumographs were placed on the sternum, one at about the level of the 4th and the other at that of the 8th rib. The three tambours and under them a time-marking seconds pen were made to write in the same vertical line upon the cylinder surface. The displacement of the tracing from the true vertical due to the circular movement of the lever point introduced no important error unless the arcs described by the various levers were of very different amplitude.

Eighteen university teachers and students, including four ladies, were made the subjects of observation. Pains were taken to insure that the clothing worn during the experiments should offer no impediment to the respiratory movements. All the persons experimented on were singers, most of them with but a slight amount of training, and two were professional elocutionists. Only one of the number was at all informed of the hypothesis to be investigated.

While the person observed stood erect, breathing quietly, a series of respiratory tracings was taken. The movements of inspiration seemed to begin either simultaneously along the whole front of the body or to flow like a wave from the upper ribs downward; the latter order of sequence was the more common; but even in this case the extreme inspiratory expansion was reached at about the same moment by each part observed, and the expiratory relaxations were usually simultaneous.

Comparative tracings taken from two individuals in the three positions of standing, sitting and lying on the back, show that in the latter case the beginning of the inspiratory movement at the abdomen was proportionately later than at the upper chest.

The first effort on the part of the observed person was to sing on the same syllable, and more or less discretely, the musical scale through an octave, up and down, usually taking breath between the ascent and descent.

The lowest note struck was commonly the middle c of the piano, though various other ranges of the scale were also voiced. But the most significant results were obtained from those rapid and continuous changes of pitch necessary in "slurring" the octave. In this method the voice, after slightly dwelling on the initial note of the octave, rapidly and smoothly glides over the remaining ones. The "slur" may occur either in the ascent or descent of the scale, and has here the value of bringing into immediate contrast the positions which the chest assumes in sounding notes of different pitch. Again, when sounding a note either in the lower or upper part of the compass, it was sought to determine the muscular movements employed in suddenly strengthening the sound without change of pitch. The seconds pen was struck by the finger of the experimenter at definite periods in the observations, so that voice movements could afterwards be identified with characters in the tracings.

In simply singing the scale, whether up or down, there was usually steady, simultaneous expiratory movement of both chest and abdomen. But in four of the persons examined, including three females and a trained male elocutionist, the abdominal muscles acted as the principal expelling force while, during the ascent of the scale, the chest either remained fixed in a variable state of expansion, or continued to expand throughout the voicing, or expanded during part of that time, usually the latter part. In descending the scale chest expansion occurred during the emission of the highest notes and then contraction followed. About three seconds was the time usually occupied in ascending or descending the octave, and in the former case gradual expansion of the chest sometimes continued throughout that interval. There was a general, but by no means constant, parallelism between the upper and lower chest tracings; but these in turn were quite distinct from those of the abdomen whose movements during phonation were steadily expiratory.

The most significant tracings, however, were, as stated above, those obtained when the musical pitch was suddenly changed as in gliding or slurring over the notes of the gamut. Though there is considerable individuality in tracings taken from different persons, and some variation in the character of those from the same person, from the tabulation of a great many observations the following conclusions may be drawn. In the ascending glide, in which the first note is slightly prolonged, the succeeding ones very rapidly emitted and the last note held, there is throughout the voicing a marked expiratory movement of the abdomen which becomes more abrupt or rapid with the more sudden elevations of pitch. During the time while the lowest note of the octave is held the diaphragm may ascend very gently, or even remain in inspiration, the air being expelled by contraction of the chest muscles. The movements of the chest are strikingly different. While the pitch of the voice is rising the chest usually moves throughout with inspiratory expansion, contraction only occurring as the upper note is continuously held.

In descending the scale in the same fashion the tracings are different. The abdomen begins actively to contract at the first sound, but as the pitch suddenly falls, the abdomen either actually protrudes as in inspiration, or remains, as is more usual, either nearly or completely stationary while increase in chest contraction makes up for this loss of motion. In descending the scale during emission of the highest note the chest may move in an inspiratory manner, or it may slightly contract, but it usually remains simply expanded; as the pitch is suddenly lowered the chest uniformly contracts. Thus the movements of chest and diaphragm are largely complementary, that is, are simultaneously in opposite respiratory phases. During rapid elevation of pitch the chest expands while the abdominal muscles are contracting;

and when the pitch is lowered the chest contracts while the abdomen is more or less positively protruded.

The general results just described representing the actual movements of the respiratory apparatus for variations of vocal pitch, agree remarkably well with the working hypothesis with which we started; namely, that increase in the transverse section of the thorax and decrease in its vertical diameter elevate the pitch of its fundamental note, while the reverse conditions lower it; and there seems to be on the part of vocalists an unconscious effort to adjust the thorax in such a manner as to secure the best physical conditions for sound production.

Plate V. Figs. 2—4 are examples of the more characteristic tracings obtained by us in illustration of these points.

The upper curve in each figure represents the movements of the upper part of the chest, the middle curve those of the lower part, while the third and last curve was produced by the movements of the abdominal wall. The tracing of the seconds marker is at the bottom of each figure. The parallel vertical lines drawn through the tracings show the phases of respiratory movement occupying the chest and abdomen at the same moment. The tracings are all to be read from left to right. The tracings were taken from two adult male students who stood upright while under observation. Movements of inspiration and expiration are represented respectively by descents and ascents in the tracings. Figs. 2 and 4 were from the same individual in whom the costal movements were very pronounced, while in him from whom (Plate V. fig. 3) was obtained the abdominal movements were proportionately greater. In fig. 2, at a certain signal, the observed person sounded a musical note (g) and rapidly ascended the scale from that point. At a second signal the high note was struck first and then the scale descended with a slur to the original starting point.

a on the tracing represents the moment when the lower note was first sounded, and *b* the instant at which the highest note was just reached. The note was always held a variable time after it had been reached and in fig. 4 *c* represents the moment at which voicing ceased. *d* indicates the beginning of the descent of the scale and *e* its culmination. It is seen that in ascending the scale the ribs are the air expelling mechanism during emission of the slightly held lower note while during the rapid glide upwards the abdominal muscles are the driving power while the chest actually makes a movement of inspiration. In descending the scale, on the other hand, the quick downward glide owes its voice power to the rib movement while the abdominal wall remains stationary, if it do not actually protrude. About the same explanations apply to figs. 3 and 4; in the former the inspiratory movement of the chest in the ascending glide is unusually well marked.

It is interesting to observe that, as shewn in the tracings, at the end of a period of voicing of whatever sort there succeeds a longer or shorter interval of physiological apnœa in which the respiratory mechanism is at rest in the phase of expiration.

From a physiological point of view it is important to observe that the elevation of the chest during abdominal contraction which we have found to occur so frequently in that voice production requiring the greatest muscular effort, is a real movement of costal inspiration, although the air was supplied from below rather than from above. Of like nature is the less usual reverse condition in which the diaphragm descends while the chest contracts.

Such movements must cause a more or less active mixture of gases in the lungs, notwithstanding the continuous expulsion of vocalized air, and they fall strictly within the class of so-called complementary movements of respiration discussed above.

Such a provision for gaseous mixture within the lungs during phonation cannot be physiologically unimportant, and the period of respiratory rest described above as following any vigorous vocal effort is significant as indicating that such exercise has satisfied to an unusual degree the respiratory needs of the body.

It was also attempted to determine the modifications of muscular movement accompanying simple increase of *force* in sounding a note without change of pitch; but no useful conclusion could be drawn from the results.

Turning now from the singing to the speaking voice, it is a question of the highest interest whether the complementary movements of chest and diaphragm naturally keep up their varying play with the ever changing accents of speech.

We were able to enter but a little way into this broad field, though a single series of observations made upon Professor Trueblood, a trained elocutionist, gave a decided confirmation of the results already described in connection with the singing voice. The speaker had no knowledge of the hypothesis to be tested, but answered our request by repeating in as natural a manner as possible the sentence "I defý him." The syllable "-fy" was the only one emphasized and that with a markedly rising accent, except during the latter part where the sound died away on the descending scale. The marking pen was depressed on the cylinder at the three points corresponding with the utterance of "I," "fy" and "him." It was clear that the vocalized air was propelled chiefly by contraction of the abdominal muscles, this being particularly vigorous during production of the emphatic syllable. The movements of the chest were of less amplitude but were likewise expiratory with the significant exception that there was a considerable and sudden inspiration of the chest at the utterance of the syllable with the rising accent.

Other experiments in which the *emphasis* was changed without alteration in *accent* gave results which strengthened the belief that it is chiefly or only accent which is associated with the peculiar complementary movements of chest and diaphragm.

The foregoing experiments are offered simply as preliminary observations on the little studied relations between the science and art of vocalization. The general conclusion to be drawn from these considerations seems to be that, while the main volume of the vocal blast is properly supplied by the steady sweep of diaphragm and abdominal muscles, the *accent* which gives life to song and speech is accompanied and supported by a characteristic play of chest and diaphragm in which the rapid changes of the fundamental note of the great thoracic resonator adjust it anew for every note sent out from the vocal cords.

DESCRIPTION OF FIGURES. PLATE V.

Fig. 1 represents the form of pneumograph employed on the chest. *a* is the wooden plate applied to the chest. *e*, the eyelets for attachment of the cord by which the instrument is suspended round the neck. *b* is the wooden plate hinged to *a*. *d*, one of the hooks for fastening the cord round the body. *c*, the rubber tube whose compression affects the tambour through the transmitting tube *g*.

Figs. 2, 3 and 4. For description see p. 176.

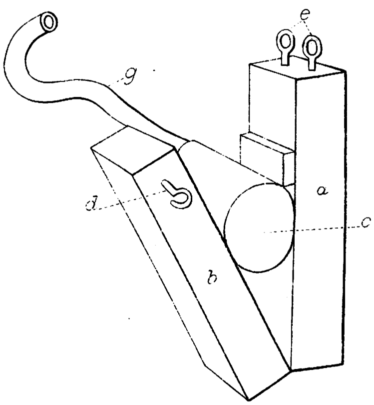

Fig. 1

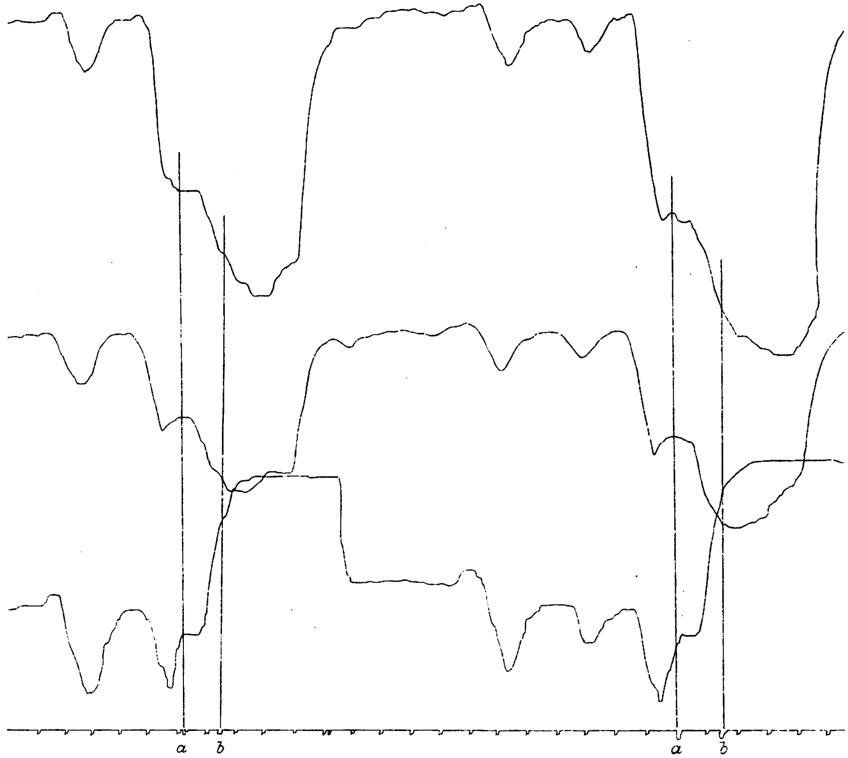

Fig. 3.

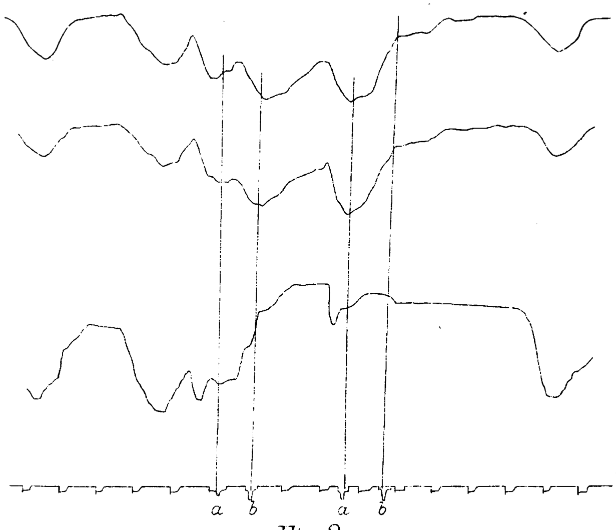

Fig. 2.

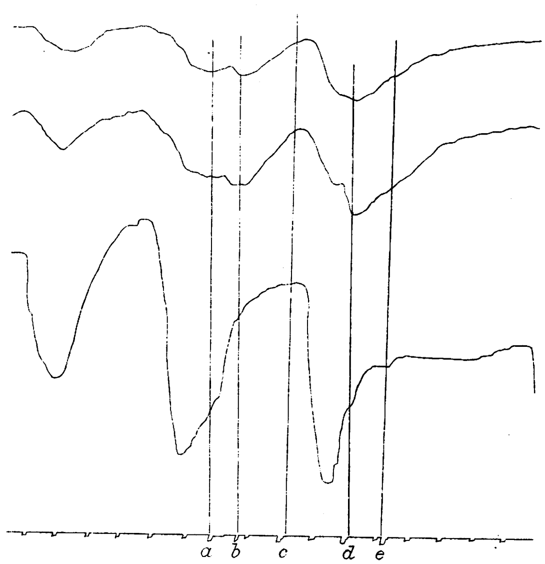

Fig. 4.

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