XXVII. *On the Physiology of the Human Voice.* By JOHN BISHOP, *Esq., F.R.S.*

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THE human voice is susceptible of several modifications, such as *timbre*, or quality, intensity, and pitch; including those successive transitions of tone from one pitch to another which constitute melody. The organs of voice comprise the thorax with the muscles of respiration, the lungs, trachea, larynx, pharynx, mouth, tongue, nasal cavities, nerves, and blood-vessels. Of these, the thorax and lungs may be considered an air-chest or bellows, the trachea a portevent or air-pipe, and the glottis a complex reed. The trachea varies in length and diameter with the age and sex of individuals, until they arrive at the adult period of life. By its structure the trachea is endowed with elasticity, together with the power of longitudinal extension and relaxation, and of increasing or diminishing in diameter: the acoustic effect of these properties will presently be investigated.

The sum of the diameters of the two bronchi is greater than that of the trachea; by which adaptation the latter is more readily supplied with air during the vocalization of the breath. In all Mammalia, Birds, and Reptiles, the axes of the bronchi are inclined to that of the trachea at a greater or less angle. With reference to the voice, the larynx is the most important organ in the whole apparatus. The mouth, fauces, tongue, and nasal organs are not necessary to the production of voice; nevertheless they exercise a considerable effect on its quality, and are indispensable for the production of articulate language. The thorax is sufficiently capacious to contain as much air after a full inspiration as will sustain the glottis in a state of vibration, when the tone is of moderate intensity, during the space of fifteen seconds, which will enable a person to pronounce in rapid succession from thirty to forty monosyllables at one expiration*.

The phenomena of the voice of animals must at a very early period have afforded to physiologists proof of the susceptibility of membranous structures to enter into a state of vibration; and it is now generally known that membranes, whether twisted into a cord like the string of a violin, or in the form of a parallelogram stretched in one direction as the vocal ligaments, or in that of discs stretched all round as the head of a drum, are all capable of producing musical sounds when properly excited.

The theory of the vibratory movements of stretched membranous surfaces has occupied the attention of many of the most celebrated mathematicians, such as

* Having already described in the Cyclopædia of Anatomy and Physiology the minute anatomy of the larynx, the author considers it unnecessary to encumber this paper with details of that nature.

EULER, BERNOULLI, RICCATI, BIOT, POISSON, Sir JOHN HERSCHEL and others. It is a subject requiring the most profound analysis, and the solution of problems of much greater complexity than those either of strings or bars, but in order to bring the theory of vibrating membranes within the reach of computation, the membranes are supposed to be homogeneous and of equal thickness and elasticity. Now these hypotheses will not satisfy the conditions of the vibratory movements of the vocal organs, such as the windpipe for example, which is composed of tissues of variable thickness, density, and elasticity; it would therefore be futile in the present state of the science of acoustics, to attempt any mathematical solution of the laws of the equilibrium and movements of the heterogeneous masses of the vocal tube. When, however, a membrane is stretched in one direction only, it obeys the same laws as a string.

Having adapted two laminas of India rubber to a pipe connected with the bellows of an organ, M. BIOT caused a current of air to pass over their free edges, by which means he obtained sounds of different pitch with facility. The Rev. Mr. WILLIS made similar experiments with leather and caoutchouc, but with these substances could not produce so great a range of tones as the glottis will yield, and therefore concluded that the vocal ligaments possess greater elasticity. Mr. WILLIS has also investigated the position in which it is necessary that membranous laminas should be placed, in order that they may be excited and sustained in a state of vibration. He has likewise given a satisfactory explanation of the mode of action of the air on reeds, such as those of the organ pipe, which applies also to free reeds, and every other case where a vibratory motion is maintained by a current of air.

The experiments and theory of Mr. WILLIS are exceedingly important, for he has shown that in ordinary breathing the vocal cords remain inclined to each other, at an angle which prevents any vibratory motion; whereas when their surfaces lie in the same plane the breath immediately excites them into a state of vibration; the natural position of the vocal cords in these two states is seen in Plate XXX. figs. 1 and 2. MÜLLER also made some experiments on stretched membranous bands, both isolated, and in connection with a tube, from which he concludes that the force of the current of air influences the *pitch* of the note produced, so that a strong current will produce a more acute tone than a weak one, and *vice versâ*; but the author has not found this to be the case in any of the experiments which he has made. To obtain a pure quality of tone when two membranous bands are stretched across a tube, it is necessary that they should be of equal weight and length, and subjected to equal tension, otherwise they cannot vibrate freely in equal periods of time. According to CAGNIARD LA TOUR, if two membranous laminas of equal length and weight be stretched by unequal forces, so that there is an interval of a fifth between the notes they yield separately, the note resulting from their combined action is the intervening third. MÜLLER is disposed to doubt the accuracy of LA TOUR, but his own views do not differ materially from those of the latter, as he says that when one tongue is most

readily thrown into vibrations by the current of air, the sound is emitted by it alone, but if the blast is such that it throws them both into motion, they may both vibrate together, and by reciprocation produce a simple sound intermediate between the fundamental note of the two vibrating separately; they may also emit two distinct sounds, or the blast being modified, the two sounds may be produced in succession. From these researches it appears, that membranous laminas, stretched in imitation of the thyro-arytenoid ligaments, will not only vibrate readily, but produce a range of musical tones. It has been remarked that sounds are most readily produced when the two laminas are stretched in the same plane, and that a smaller volume of air is required the nearer the edges of the laminas approach each other, and a still smaller one when their edges actually touch. DE KEMPELEN states, that to produce sound, the edges of the glottis must be approximated to within $\frac{1}{12}$th, or at least $\frac{1}{10}$th of an inch. These experiments upon artificial vibrating tongues perfectly agree with those the author has made on the larynxes of animals. Owing to the nature of the articulation of the thyroid with the cricoid cartilage, and the manner in which the crico-thyroid muscles act, an equal tension of both the thyro-arytenoid ligaments is simultaneously secured, supposing the arytenoid cartilages to be at the same time in corresponding positions, which is a necessary condition for the production of a synchronous vibratory motion in the two lips of the glottis.

If the larynx of an animal is dissected out, and the vocal cords are stretched, they will vibrate like a piece of caoutchouc or leather in a current of air. In conducting these experiments, it is necessary to secure the same conditions as those which are required in the laminas above-mentioned; for instance, the inner edges of the glottis must be turned towards each other till they are in the same plane and parallel to one another, before they will produce any sound; hence we infer, that when the tension of the arytenoid ligaments takes place in the living animal, they turn upon their axes till their planes (which in the state of relaxation are inclined to the axis of the vocal tube) become perpendicular to it, and as the edges of the glottis approximate, and its chink is nearly or entirely closed up, they acquire the true vibrating position. The production of the most simple tones of voice requires the associated actions of a most extensive range of organs, and it is calculated that in the ordinary modulation of the voice, more than one hundred muscles are brought into action at the same time.

The lungs having been first supplied with air by the muscles of inspiration, and the air in the chest and trachea having subsequently been condensed by the muscles of expiration, a portion of the edges of the glottis yields to its pressure, and is curved upwards, so as to form an angle with the axis of the vocal tube, leaving between them a narrow aperture through which the air escapes. The tension and elasticity of the vocal ligaments tend to restore them to the plane of the vibrating position; the air having been rarefied below the glottis during their elevation, becomes condensed on their depression, and the necessary force is again accumulated to re-elevate the vocal ligaments. An oscillating movement, consisting of a partial opening and closing

of the glottis, then takes place, which being communicated to the contiguous air, the sounds of the voice are produced.

The relative length of the vibrating edge of the glottis is regulated by the pressure of the column of air in the trachea, and the resistance of the vocal ligaments. The intensity of the voice in the same medium, and under similar collateral circumstances, depends on the pressure of the column of air in the trachea, and the range of motion performed by the vibrating edges of the glottis. The vocal ligaments do not vary the pitch of the voice by their tension alone, but by their variations in length and tension conjointly. The author has learnt this from his own experiments on the vocal functions of the larynx, which have been confirmed both by MAJENDIE and MAYO; the former having observed in the larynx of a dog that a longer portion of the ligaments of the glottis vibrated during the utterance of grave tones, and that the length was diminished as the tones became acute. The latter had an opportunity of inspecting the movements of the glottis in a man who had made an attempt to destroy himself by cutting his throat. In this case the larynx was divided immediately above the vocal cords, and in consequence of the oblique direction of the wound, the arytenoid cartilage and the vocal cord on one side were injured. During respiration the glottis was observed to assume a triangular form, but when a sound was uttered, the chordæ vocales became nearly parallel, and the rima glottidis of a linear form. The posterior part of the aperture did not appear to be closed. In a second case of this kind, he observed that the arytenoid cartilages, as long as the vocalization of the breath continued, maintained the position which they had assumed when the glottis was closed entirely*. The vibrations of the thyro-arytenoid ligaments are considered by FERRIEN† to be analogous to those of strings; hence he denominated these ligaments (though improperly) chordæ vocales. He imagined that the longitudinal tension of these cords alone governed the pitch of the voice. Mr. WILLIS‡ has embraced the hypothesis of FERRIEN; he observes, that to obtain the various notes of the glottis, it is only necessary to vary its longitudinal tension after the ligaments have been placed in the proper position; but M. BIOT§ remarks, "Qu'y a-t-il en effet dans la glotte qui ressemble à une corde vibrante? Comment pourroit-on en tirer jamais des sons d'un volume comparable à ceux que l'homme produit? Les plus simples notions d'acoustiques suffisent pour faire rejeter cette étrange opinion."

On inspecting the larynx from above, we see two very nearly rectangular-shaped laminas, one on each side the chink of the glottis, but nothing resembling an isolated cord. The mucous membrane which lines the thyro-arytenoid ligaments (to which it closely adheres), as well as the rest of the vocal tube, must be considered as forming a part of the weight of the vibrating surface upon which the air acts; the thyro-arytenoid ligaments confer on this membrane the requisite tension and resistance during vocalization, and it is this membrane which gives the sides of the glottis their

* Mayo, Outlines of Physiology, p. 991.

† Mémoires de l'Académie.

‡ Cambridge Philosophical Transactions, vol. iv.

§ Précis, Elem. de Phys. tom. i. 398.

laminated figure. The vocal ligaments, with their lining membrane, are stretched by the thyro-cricoid muscles, not all round like a drum, but in one direction only, namely, in that of their length, being attached on three sides, leaving one only free to vibrate. The vocal cords are, as has been seen, rectangular-shaped membranes, and from experiments made on the larynx after death by FERRIEN, MÜLLER, and others (which the author has repeatedly verified), are found to vibrate like cylindrical cords; we will therefore apply to the former, the well-known formulas which regulate the vibrations of the latter.

In cords composed of the same material, and of uniform thickness, the time of a complete musical vibration, or *double* oscillation, is

$$t=2\sqrt{\frac{lp}{2g\mathrm{P}}}, \qquad (1.)$$

where l is the length of the cord, p its weight, P the force with which it is stretched, and $g=16\frac{1}{12}$ feet.

In order to apply this formula to the vocal ligaments, let a be their depth, b their breadth, and δ their specific gravity; then p will be equal to $abl\delta$, and equation (1.) becomes

$$t=2l\sqrt{\frac{ab\delta}{2g\mathrm{P}}}; \qquad (2.)$$

and the number of such vibrations in 1″ will be

$$\mathrm{N}=\frac{\sqrt{2g\mathrm{P}}}{2l\sqrt{ab\delta}}. \qquad (3.)$$

We observe in the first place, that if all other things remain the same, the number of vibrations varies inversely as the length of the cord; hence, if the vocal ligaments were divided by nodes into n ventral segments, each segment might be considered a separate vibrating ligament, whose length would be $\frac{1}{n}$th of the vocal cord, and consequently the number of its vibrations in a given time would be n times as many as that of the whole cord.

Owing to the elasticity of the thyro-arytenoid ligaments, their lengths, when in a state of repose, differ considerably from those which they present under the greatest tension. They differ also in the two sexes. In a series of experiments by MÜLLER, the differences of length were observed to be as represented in the following table, the figures of which are in inches and decimals of an inch. From these experiments it appears that the lengths of the male and female vocal cords in repose are nearly as 7 to 5, and in tension as 3 to 2. In boys at the age of fourteen, the length is to that of females after puberty as 6·25 to 7, so that the pitch of the voice is nearly the same. These experiments afford an idea, although an imperfect one, of the elasticity of the vocal ligaments. It has always been a subject of surprise, if the thyro-arytenoid ligaments obey the laws of strings, how such short and narrow laminas should produce such very grave tones as many bass singers are capable of uttering; and this

struck M. Biot as one of the circumstances which in his opinion prove their mode of vibration to be unlike that of strings. He asks, "Où pourroit-on trouver la place nécessaire pour donner à cette corde la longueur qu'exigent les sons les plus graves ?"

Subjects of experiment.	No. of experiments.					
	1.	2.	3.	4.	5.	6.
Male in a state of repose	0·7087	0·63	0·63	0·83	0·748	0·748
Male in the state of greatest tension...	0·83	0·83	0·984	1·0236	0·9055	0·9055
Female in a state of repose	0·47244	0·47244	0·551	Boy of 14 in repose. 0·414		
Female in the state of greatest tension	0·63	0·59	0·63	Boy of 14 greatest tension. 0·571		
Mean length in male	In repose. 0·72834	Greatest tension. 0·912070				
Mean length in female	0·49868	0·61679				

The author is acquainted with some bass singers who can produce the note C which results from sixty-four musical vibrations. Let us now investigate this phenomenon more closely, and endeavour to explain how such grave tones are produced by such extremely short membranes. Müller has contrived several ingenious pieces of mechanism, seen in Plates XXXI. and XXXII., by means of which he was enabled to estimate the amount of tension, lateral compression, and atmospheric pressure on the vocal cords, during the production of sound. In order to find the variations in the amount of condensation of air in the vocal organs in the production of sounds differing in pitch and intensity, the apparatus was furnished with a manometer, Plate XXXI. fig. 3. *v*. From that portion of the experiment which was confined to the investigation of the effects produced by tension of the vocal, compared with that of musical cords, he obtained results which are comprised in the following table.

No. of experiments.	Weights employed.		
	4 loths*.	16 loths.	64 loths.
1	C^1	A^1	$G^2\sharp$
2	$C^1\sharp$	B^1	$A^2\sharp$, A^2
3	$G^1\sharp$	$C^2\sharp$	C^3
4	A^1	D^2	C^3
5	$A\sharp$	$F^1\sharp$	G^2
6	$A\sharp$	$G^1\sharp$	G^3
7	D^1	C^2	A^2
8	$D^1\sharp$	B^1	A^2
9	G	G^1	G^2 both octaves imperfect.

The notes of the different octaves from C to C are distinguished in the above

* A loth =225·5531 grs. English.

table by ciphers, the C^1 answering to 256 vibrations; the notes below C have no cipher. MÜLLER states that the numbers of vibrations in these experiments are not exactly in direct ratio of the square roots of the stretching forces, and that the weights 4, 16, 64 did not produce the octaves, but generally from a semitone to two or three tones lower. Now this result should have been anticipated; but it does not seem to have occurred to him that whilst he increased the tension he at the same time increased the length, and we know (eq. 3.) that the number of vibrations in this case varies as $\frac{\sqrt{\text{tension}}}{\sqrt{\text{length of cord}}}$, and consequently the numbers actually produced by the weights above-mentioned, ought (agreeably to MÜLLER's experiments) to be less than those which correspond with octaves. We see by the first experiment in the above table that the tension sufficient to produce 818 musical vibrations is 64 loths, or very nearly 33 ozs. If, therefore, we take the mean length of the vocal ligaments under the greatest tension at ·91 of an inch, and substitute in equation (3.) their values for all known quantities, remembering that P represents the tension of one vocal cord, we shall find the weight of each ligament, viz.

$$abl\delta=\frac{g\,\mathrm{P}}{2l\,\mathrm{N}^2}=1\cdot 144 \text{ grs.} \quad \ldots\ldots\ldots \quad (4.)$$

In an adult male I found that the two vocal ligaments, when divested of mucous membrane, weigh one grain, which is scarcely one-half their weight by theory; hence it appears that a considerable portion of mucous membrane is connected with the vocal cord in the production of sound, which agrees with the anatomy of these parts.

It is now necessary to offer some explanation respecting the vital state of the vocal ligaments. The state of repose is the ordinary condition of the vocal ligament in the living subject, when the voice is not exercised; but we must not therefore conclude it to be incapable of further contraction. In fact, the state of repose during life is a state of tension, for the ligaments being connected with the thyro-arytenoid muscles, not in a few points, but continuously throughout their whole length, must obey the motions of these muscles, which, like all muscles, are in a state of tension during repose. We also know by experience that when we produce a sound lower than the usual pitch of our voice, the crico-thyroid chink is opened principally by the contraction of the same muscles, and the ligaments must therefore at the same time be relaxed. It appears, then, both from the anatomy and physiology of the human larynx, that the ordinary state of the vocal cords is one of considerable tension, which admits of being lessened, and thereby produces the range of lower notes. If we suppose the glottis to be partially closed when we are talking, that is at the ordinary pitch of our voice, and to be more opened as the tones become graver, this of course will cooperate with the relaxation of the vocal cords. In the production of the higher notes the crico-thyroid chink closes, and the thyro-arytenoid muscles, and consequently the ligaments are elongated. Since, therefore, the vocal ligaments have been proved to extend and contract for acute and grave tones respectively, and

after death vibrate in a great measure like musical strings, we think it may be fairly inferred that they likewise obey, to a certain extent, during life the laws of the vibrations of such strings, and that the conclusions which we have derived from the foregoing formulas are not far removed from the truth. A further confirmation of these views may be derived from the following considerations. The length of a cord of invariable weight varies directly as the tension, and inversely as the square of the number of vibrations. Now, if we assume the length of the vocal cord, which gave $G^2\sharp$ under a tension of 32 loths to be ·91 inch, which is the mean length of the male vocal cord in its greatest tension, according to the first table, and which gave the notes A^1, C^1 under the tension 8 and 2 loths respectively, the corresponding lengths of that cord, according to the formula, will be ·83 inch and ·58 inch*; but ·58 inch is less than the least length in repose in the table. This result is, however, quite consistent with the theory here proposed; because after death the thyro-arytenoid muscle becomes of itself elongated, and consequently the vocal ligament attached to it, and therefore the length of the ligament must be greater in this state than when it is in that which we have defined to be the state of repose before it has lost its vitality.

In experiments made on the larynx by stretching the vocal ligaments with given weights, and by forcing a current of air through the glottis, care must be taken to keep the organs moist, and of the same temperature which they possess during life. The amount of condensation of the air in the vocal tube has been ascertained by CAGNIARD DA TOUR, and MÜLLER, the former in the living, and the latter in the dead subject. In a person who had an opening in the windpipe after the operation of bronchotomy, CAGNIARD LA TOUR found that the tension of the air in the vocal tube, whilst blowing the clarionet, was equal to a column of water of thirty centimetres in height, and that to produce a simple vocal sound in the same person, a tension of sixteen centimetres was necessary. MÜLLER found that he could produce sound in a larynx artificially by a tension of 3·4 centimetres, but for very loud sounds an increased tension was requisite. The discrepancy between the experiments of LA TOUR and MÜLLER may be ascribed to the circumstance that the one operated on the living vocal organs, but in a state of disease, the other on the organs after death.

Variations in the hygrometric and thermometric states of the air exert very powerful influence on the pitch of the voice; during the prevalence of a cold moist state of the atmosphere, especially in England, the voices of singers become lower by two or three notes, and regain their usual pitch when the air becomes dry†. In thus tracing

* N varies as $\frac{\sqrt{P}}{\sqrt{l}}$ $\therefore$ l varies as $\frac{P}{N^2}$, then ·91 inch : length of cord for A^1 : : $\frac{32}{(818)^2}$: $\frac{8}{(427)^2}$, the length of the cord for A^1=·83 inch; and the length for C^1=·58 inch.

† When GRASSINI came to this country, owing to the change from the air of Italy to that of England, her voice became one octave lower: after singing for two or three seasons, her natural voice returned, but it had lost its attractions with the low tones which had obtained her the greatest applause.—Trans. Lond. Med. Society, New Series, vol. i. 1846; Art. Aphonia, p. 36.

out the analogy between the laws of stretched cords and those of the vocal ligaments, it is not intended that those ligaments should be considered as stringed instruments, but only that this analogy is accurate so far as relates to the velocity with which an impulse is propagated along them. DODART supposed the tension of the vocal cords to be merely subservient to an alteration in the size of the aperture of the glottis, and that the difference of $\frac{1}{54}$th of a fibre of silk, or $\frac{1}{384}$th of a hair in the dimensions of that aperture, was sufficient to alter the pitch of the voice; but this has been so completely refuted by more recent physiologists, and is so directly at variance with acoustic principles, that we need not give illustrations of its fallacy. M. SAVART considered that the action of the air in its passage through the ventricles of the larynx, between the superior and inferior ligaments, is really the source of sound, and analogous to the mechanism of the bird-call or dog-whistle*. There is certainly a great resemblance in the structure of that instrument to the space above-mentioned in many of the higher animals, which might easily have led to this ingenious hypothesis; but, as we find neither superior ligaments nor ventricles of MORGAGNI in many of the order Ruminantia, in which the voice is very sonorous, this theory (as MÜLLER remarks) is untenable.

We next come to the consideration of the alleged analogy between the action of the vocal ligaments and that of the reeds of musical instruments. This opinion is maintained by MM. BIOT, CAGNIARD LA TOUR, MAJENDIE, MALGAIGNE, MÜLLER and several other distinguished scientific men. It is opposed principally by M. SAVART, who observes that the *essential* principle of the action of reeds consists in the periodical opening and shutting of the orifice through which the stream of air passes, but that this is wanting in the glottis; and that were the latter a reed, the edges of the thyro-arytenoid ligaments which form the sides of the chink would be alternately forced asunder by the column of air in the larynx, and brought together by their tension; whereas, he found by experiment, that air blown through the glottis produced sound although its edges were from one-sixth to one-fourth of an inch asunder. M. SAVART has however clearly mistaken the circumstance wherein the *essential* principle of reeds consists, since those of the clarionet, bassoon, hautbois, &c. do not entirely close the apertures through which the breath passes; and this is likewise the case with the natural reed formed by the lips of players on the flute and horn. There is in all probability a double action of the vocal cords in the production of sound; the one being a vibratory motion throughout their length similar to that of a musical string, and the other an oscillation like that of a reed, forming a partial opening and closing of the glottis. The author is led to adopt this view of the functions of the vocal organs from considering that every circumstance which he has established in his previous investigation of their action when treated as cords, is perfectly consistent with the hypothesis of their vibrating like the tongues of reeds; for let us now suppose them to be simply membranous tongues. In this case the axis of motion is the

* See Plate XXX. fig. 1′, *g*.

edge of the ligament attached to the thyro-arytenoid muscle; the vibrations take place in a plane perpendicular to the axis of that muscle, and the *length* of the tongue is the *breadth* of the ligament. The author has observed in repeated experiments on the larynx after death, that the chink of the glottis was partially opened and closed in the production of sound, and MÜLLER found that by decreasing the breadth of the ligament he rendered the note more acute; but as this breadth is so small, being in its ordinary state in an adult generally less than one-tenth of an inch, it is extremely difficult to measure the variations corresponding with different notes; and the author cannot learn that any one has yet succeeded in determining these varying lengths with sufficient accuracy to form data for the application of the mathematical formulas of elastic vibrating tongues*. We know that the number of vibrations made by the same tongue in a given time varies inversely as the square of its length. If, therefore, a tongue whose length is only ·1 inch give any note, the length necessary to produce the octave will be ·07 inch, that is, the variation will be only ·03 inch; we see then how minute must be the changes answering to the intermediate notes, and consequently how much more difficult it is to determine them in the vocal ligament when considered as a tongue, than as a stretched membrane or cord. It is moreover observable that the extension and relaxation of the vocal cord, which, as we have seen, are analogous to those of a musical string, produce a corresponding shortening and elongation of its axis, regarded as a tongue; and lastly, since one tone only is produced at a time, the vibrations resulting from the double action which appears to exist in the vocal apparatus must be synchronous.

We have seen how nearly, when we take into account the delicacy and difficulty of the experiments, their results agree with the theory that the vocal cords are subject to the same laws as other stretched laminas, and it would be highly interesting to compare these results with the simultaneous variations which they undergo transversely, and thus discover how far the laws of vibrating elastic tongues may be applied to them. It might possibly be objected to the idea of this twofold action, that the production of sound by the vocal cords is sufficiently accounted for by supposing them to vibrate merely as elastic tongues, but then it is found by experiment, that by artificially dividing their length into two ventral segments, there results the octave of the fundamental note, which proves that at all events they vibrate as cords. In conclusion, we must ever bear in mind the vast difference between natural and artificial mechanism, and however complicated a problem it may be to determine that constitution of the vocal apparatus, by which the thyro-arytenoid ligaments may simultaneously obey the laws of cords and tongues, yet to a physiologist who is accustomed to meet with the most admirable contrivances and combinations in the

* The formula of GIORDANO RICCATI is $N=\frac{n^2D}{L^2}\sqrt{\frac{2gR}{G}}$, where N is the number of vibrations, D the thickness, and L the length of the tongue or rod, R its rigidity, G its specific gravity, g the space through which a body falls by gravity in 1″, and n a number constant, for each mode of vibration, depending on the number of nodes.

animal frame, the difficulty of finding a strictly mathematical solution is, in such a case, no objection to its truth, when the facts, so far as they have been observed, are decidedly favourable to its reality. Were the movements of the glottis independent of any tube or column of air, the study of the functions of the vocal organs would be much more simple, but we find it situated nearly in the centre of the vocal tube of which the trachea and bronchi are the inferior, and the upper part of the larynx, pharynx, nose and mouth, the superior portion; we have therefore to consider the influence of this tube, and of its inclosed column of air in the production of voice.

In order to investigate the mutual relations between a reed and a pipe, two methods may be adopted: one of these is to vary the pitch of the reed while the length of the pipe remains constant, and the other, to vary the length of the pipe with a reed sounding one tone only, when detached from the tube. In the construction of reeded pipes for musical purposes, it is incumbent on the mechanician to adjust the length of the tube to the pitch of the reed. When a free reed is used on the principle of Kratzenstein or Grenié, it is found that, if the pipe be not in perfect unison with the reed, the purity of the tone decreases within certain limits, as the discordance between the reed and pipe increases. The researches of MM. Biot, Weber, Willis and Müller, have greatly enlarged our knowledge on this subject. We learn from their experiments how great an influence is mutually exerted between a pipe and its reed, when the pitch of the one is made to vary whilst the other remains constant, and we may conclude that analogous effects are produced between the vocal tube and the glottis. The slightest knowledge of acoustics is sufficient to inform us that the pitch of any pipe, such as the organ, the flute, the trumpet, in short of all musical tubes vibrating in a similar manner, depends on the velocity of an impulse propagated in the air within, and is determined by the length of the pipe. So long as the tubes of musical instruments remain rigid, the nature of the materials which compose them, does not affect the pitch of the sound, but merely influences the quality of the tone, and it is indifferent whether we employ metal, wood, or paper in their construction; each of these substances will yield a tone of a particular *timbre*, or quality, depending on the nature of the motions produced among its particles by the friction of the air on its surface; but the pitch will be the same in each, if the lengths of the pipes be equal, proving that the air itself is the source of sound. When however the sides of the tube are composed of flexible membranes, the inclosed air has a vibratory motion, conjointly with, and subordinate to that of the parietes of the tube, whereby the pitch of the sound is affected, as well as its quality. M. Savart found that by taking tubes composed of layers of paper of constant length, but varying in thickness, graver sounds were produced as the parietes became thinner, and that the gravity of the sound was increased by moistening and relaxing the sides of the tubes. We shall presently see the application of these facts to the vocal apparatus.

We find the flexibility of the trachea and bronchi capable of being varied by the operation of two forces, the one longitudinal or parallel to the axis of the tube, the

other transverse. The first of these comprises the muscles which elevate and depress the larynx; the latter, the cartilaginous segments of rings perpendicular to the axis of the tube having muscular fibres attached to their posterior extremities, the contraction and elongation of which regulate the diameter of the trachea. The pharynx, mouth and nasal cavities, which form the superior extremity of the vocal tube, are also provided with muscles to modify the tension of that part of the tube so that it may vibrate synchronously with the rest. The necessity for this change in the dimensions of the tube, in order that it may vibrate in unison with the glottis, is in accordance, not only with the joint system of pipe and reed above described, but also with what actually takes place in the vocal organs of living animals. When the voice is raised in the scale from grave to acute, a corresponding elevation takes place in the larynx towards the base of the cranium. By placing the finger on the pomum Adami this motion can be easily felt, and at the same time the thyroid cartilage is drawn up within the os-hyoides, and presses on the epiglottis; the small space between the thyroid and cricoid closes, the pharynx is contracted, the velum palati is depressed and curved forward, and the tonsils approach each other: the reverse of these phenomena takes place during the descent of the voice. These are the principal phenomena common to most Mammalia which can be recognised by external observation, the other changes being, on account of their situation, invisible.

The effects of these variations on the tone of the voice have been hitherto little understood. It has always appeared incomprehensible why the vocal tube should apparently increase in length in the production of the acute tones, and shorten in the grave; a circumstance which theoretically presents an acoustic paradox. DODART and many others have conceived the elevation of the larynx to be merely for the purpose of shortening the vocal tube in the supra-laryngeal cavity, and have considered the trachea as producing no effect on the pitch of the tone. M. MAJENDIE has also pointed out the shortening of this part of the tube. In order to ascertain the effect of these changes, the following experiments were made on the dead body. Having laid bare the vocal organs of an adult male, I raised the larynx to the position it would occupy by the elevation of the voice to an octave, being about half an inch, and at the same time minutely observed the position of the lowest ring of the trachea in reference to the sternum. By this operation I found the trachea was raised out of the chest, nearly to the same extent as the larynx had been elevated towards the base of the skull. The next step was to examine whether any change had taken place in the diameter of the tube. For this purpose, having measured the diameter of the trachea in its natural position, the larynx was again elevated to the same extent as before, when the diameter was found diminished one-third. These experiments prove that, contrary to the general preconception, the elevation of the larynx *shortens* the tube independently of the contraction between the thyroid cartilage and os-hyoides, and at the same time lessens its diameter. The same effects may easily be detected during life by placing the finger on the trachea immediately above the sternum

during the elevation of the larynx, when the trachea is found to ascend out of the chest, and afterwards to return to its former position; a movement in which the lungs and bronchi participate. The alteration of the tube in diameter may also be perceived by grasping the trachea with the finger and thumb during the elevation and depression of the larynx*. These movements are so striking as to lead irresistibly to the conclusion, that there exists a constant adaptation between the tension and the vibrating length of the thyro-arytenoid ligaments and the walls of the vocal tube, in the production of tones of the ordinary register; for we have seen that the variations of the vocal cords, at least so far as relates to the modulation of sound, are perfectly independent of the length of the vocal tube, and consequently the changes in its length which we have just described are not at all *necessary* for that purpose. Again, the vocal tube is so short, that, as has been ascertained by WEBER and others, it could not, were it rigid, affect the pitch of the note produced by the glottis. As however this tube is composed of flexible materials, its effects are similar to those observed in M. SAVART's experiments; that is, the relaxed state of the parietes compensates for its want of length, and enables it to vibrate synchronously, and therefore to give forth sounds equally grave with those of the glottis, thereby reinforcing the tone which would indeed be produced, though with much less intensity, without this aid.

The falsetto, or *voce di testa*, has always been considered a most embarrassing subject of research, and its peculiar quality has excited the attention both of the physiologist and of the musician. Its most remarkable characteristic consists in its being less reedy in tone, and partaking nearly of the quality of the harmonic sounds of stringed and wind instruments. The change produced in the voice when passing from the falsetto into the common tone, or the reverse, is in some persons very sensible to the ear, whilst in others it is almost imperceptible. Some individuals, moreover, have the faculty of producing in the same pitch as many as eight or ten tones, possessing either the falsetto or the common character. The falsetto has been generally ascribed to some particular adaptation of the upper ligaments of the larynx. DODART† has attempted to prove that it is a supra-laryngeal function, and that the nose becomes the principal tube of sound instead of the cavity of the mouth. BENNATI‡ also considered these tones to be modulated by the supra-laryngeal cavity alone. This hypothesis however is untenable, since it supposes the column of air not to be influenced by the trachea, which is contrary to experience. In order to detect some of the movements of the larynx while the voice is passing from the first to the second, or falsetto register, it is only necessary to place the point of the finger in the crico-thyroid chink, when it is found that at the moment the transition from the primary to the secondary register takes place, this chink, which was closed during the production

* Essays by the author in the London and Edinburgh Philosophical Magazine, for September, October and November, 1836.

† Mém. de l'Acad. 1707.

‡ Recherches sur le Méchanisme de la voix humaine.

of the highest note of the ordinary register, suddenly opens on the production of the first note of the falsetto register, and consequently the thyro-arytenoid ligaments are relaxed at the same moment the larynx falls, and the vocal tube is lengthened, although during these changes *the tones become more acute*. As soon as this has taken place, the larynx again rises as the voice becomes more acute. In a mezzo soprano voice endowed with a double falsetto, or third register consisting of several tones of each register, with the power of producing tones of the same pitch either of the ordinary or the falsetto quality, we observed that the larynx fell at the commencement of each register, and that the thyro-arytenoid ligaments were twice relaxed, but in a much smaller degree. These observations have since been verified by many musical persons.

In order to explain the phenomena as connected with the production of falsetto tones, we must remember that at the highest note of the primary register, the crico-thyroid muscles are contracted as much as possible in closing the crico-thyroid chink, and therefore that no further tension of the vocal cords can take place. In this state of things the thyro-arytenoid muscles are at their maximum of elongation, and their transverse section is a minimum, consequently neither can a higher note be produced by an extension of the ligaments, nor are these muscles in a condition to affect the dimensions of the glottis; hence the necessity of some alteration in the state of the larynx in order to effect the scale of the falsetto, which is an octave above the ordinary register, and to prevent the mere repetition of the same series of sounds. This alteration might be produced in two ways; one of these is a partial closing of the aperture of the glottis caused by the action of the thyro-arytenoid muscles when they have returned to their ordinary condition, and are in a favourable state to produce that effect under the influence of the laryngeal nerves. For, let us suppose the larynx to be in the same state as at the commencement of the primary register, except that the chink of the glottis is half-closed; the consequence will be that as only half the length of the ligaments can be made to vibrate, the *octave* of the lowest note in that register will result from the same tension which produced that note, and this will manifestly be repeated in consecutive notes of the range of the falsetto. This range is limited in general to a few notes, owing probably to the chink being soon completely closed by the stretching of the vocal cords. It is also owing to this partial closing of the glottis that a much less quantity of air is required for the falsetto than for the ordinary scale, which is proved by our being able to sustain a given note in the falsetto a much longer time than we can sustain the corresponding note in the primary register. The partial closing of the glottis was observed by MAJENDIE in his experiments on the dog, and by MAYO in the human subject. Another explanation was suggested by GOTTFRIED WEBER, namely, that the falsetto range is caused by a nodal division of the vocal cords producing harmonics of the fundamental notes, by which means the glottis acquires the same pitch as if it were half-closed. If we consider the glottis as a reed, it is evident that since the number of

vibrations must in this case be the same for the same note as when we suppose the ligaments to obey the laws of cords, the axis of vibration or the *breadth* of the ligament must be duly diminished, which may be brought about by the rotation of the thyro-arytenoid muscle on its axis.

Having thus considered how the glottis may act in the falsetto range, let us now examine in what way the vocal tube contributes to its formation. We have seen that this tube gradually shortens during the ascent of the primary register, suddenly falls to its original length when the falsetto commences, and again diminishes during the secondary register. Now it appears from Savart's experiments that, notwithstanding the shortness of this tube, the wave length of a column of air vibrating within it is the same as that of a rigid pipe of much greater length, and we have therefore strong grounds for believing that the notes of the primary register are reinforced in consequence of the vibrations of the glottis being always in unison with the fundamental pitch of the walls of the tube; hence in the falsetto, when the vocal apparatus has resumed its original condition, there will be less reinforcement of the sound, since the parietes of the vocal pipe are no longer in unison with the glottis, but give its grave octaves. We have found, by numerous experiments, that a flexible disc will vibrate to almost any pitch, but will reinforce the sound in a trifling degree only, unless the pitch be in unison with its fundamental note; and on the same principle we may suppose the intensity of the notes in the second register to be diminished, and their quality to be modified by the forced vibration of the walls of the tube, whilst in the primary, all things concur in augmenting the effects produced by the glottis. Müller agrees with Lehfeldt in opinion, that the falsetto notes are produced by the vibrations of the inner portion of the borders of the vocal ligaments, and the variation of the pitch by their tension; and, although he does not mention by what mechanism this is effected, he seems to attribute it chiefly to the agency of the thyro-arytenoid muscles. The author's explanation is in many points coincident with that of Müller, but he has taken into account one or two circumstances which appear to have escaped Müller's attention. The natural key or pitch of the vocal organs may be found by sounding the voice, without either elevating or depressing the larynx. The grave octave of that note will be the fundamental sound of the vocal ligaments vibrating in their most relaxed state, with the glottis entirely open. Any tones of a graver pitch, produced by an unusually relaxed state of the vocal cords, lose both their quality and intensity, and cannot be included in the compass natural to the voice. According to the preceding principles, the pitch of the voice being usually an octave, or a fifth graver than the length of a column of air within the vocal pipe, we see the cause why a falsetto quality of sound cannot be obtained except during the production of acute tones. In many persons the speaking pitch is an entire octave graver than corresponds to the length of a tube, which would enable a column of air to produce the same sound; and in such persons the falsetto can seldom be effected. In consequence of the pitch of the vocal organs thus occupying a middle or central position between the acute and grave

notes, a great facility is afforded to their action in modulating the voice. The vocal tube, like any other tube open at both ends, is said to be capable of producing the harmonics of its fundamental tone in the ratio of the series of natural numbers, 1, 2, 3, 4. These harmonic sounds have been described by KNECHT of Leipsic, and by Dr. YOUNG. I have occasionally thought that I have heard them during the forcible expiration which attends the boisterous laughter of children. The density of the air inspired is said to affect the pitch of the voice as in rigid tubes.

The influence of the epiglottis on the voice has been the subject of divers hypotheses. MM. BIOT, MAJENDIE, and MAYO have inferred from the experiments of GRENIÉ, that the epiglottis prevents the tones from becoming more acute when they increase in intensity. LISCOVIUS, on the other hand, states that neither its depression, elevation, nor even its entire removal has any effect on the voice*. HALLER appears to have deduced the same opinion from the circumstance of birds being destitute of this organ. "Epiglottis equidem nihil facit ad vocem, cum ea (vox) nata sit et perfecta quamprimum aer ex glottidis rima prodit, et absque epiglottide aves suavissime canant." According to MÜLLER, the influence of this organ on the pitch of the voice is exercised during its depression only, rendering the tones graver, and at the same time duller. He thinks we evidently employ it in this way during the production of very deep tones; and observes that, by introducing the finger at the side of the mouth, the epiglottis will be found to maintain the same position during the utterance of musical notes, whether they be of the falsetto character, or of the ordinary scale. I am disposed to ascribe to the functions of the epiglottis much the same value as MÜLLER; since it is clear that its presence is not essential to the mere formation of voice, for it may be removed, together with the superior ligaments of the glottis, the ventricles of the larynx, and the capitula laryngis of SANTORINI, without impeding the vibratory movements of the glottis.

The art of singing consists in the application of the vocal organs to produce a certain succession of tones in some determinate order, which constitutes melody. This can be accomplished with precision by those only who can accurately discern with the ear, and imitate with the voice, the variations of a musical instrument, or other sounding body. In many persons the perception of sound is defective; so that, whatever may be the purity and intensity of their notes as single unconnected musical sounds, they can never be used for musical purposes, that is, for sounds succeeding each other at regular intervals, governed by fixed rules. Many persons can imitate the voices of birds and beasts, and diversify the character of their tones to an indefinite extent. These performances illustrate the perfection of the human voice, but the artifices by which they are effected have no reference to the subject under investigation. The musical varieties of the human voice are classed according to their *pitch*, or the middle note of their primary register, which depends on the dimensions and physical constitution of the vocal ligaments. These varieties are, the *Bass*, the

* Physiology, lib. ix. p. 572.

Tenor, the *Contralto*, and the *Soprano*; the usual compass of each kind in the adult is represented in the annexed table.

Alto. Soprano*.

$C\,D\,E\,F\,G\,A\,B\,C^1\,D^1\,E^1\,F^1\,G^1\,A^1\,B^1\,C^2\,D^2\,E^2\,F^2\,G^2\,A^2\,B^2\,C^3\,D^3\,E^3\,F^3\,G^3\,A^3\,B^3\,C^4$

Bass. Tenor.

In addition to these characteristic and principal divisions of the voice, there are certain others called the *Baritone*, the *Mezzo-soprano*, and the *Soprano-sfogato*, which are subdivisions of the foregoing, and the place of either of which in the scale is indicated by its name. We see by this table what an extensive variety of harmonious sounds may be produced by the combinations of the different kinds of voice. In ordinary singers the range seldom exceeds two octaves, except in those endowed with a falsetto. There have been some celebrated singers, such as Catalani, Malibran, and others, whose compass has even exceeded three octaves, but such instances are rare. The voices in both male and female are nearly of the same pitch until the age of puberty, at which period the voice of males sinks an octave. This change of pitch is owing to a sudden enlargement of the larynx, whereof the antero-posterior diameter is augmented by from one-fourth to one-third, with a simultaneous lengthening of the vocal ligaments. During this process the voice is hoarse, and there is a temporary inability to regulate it. Eunuchs do not undergo this change. Bennati is of opinion that the voice should not be exercised at this time of life, and in support of his views he cited the cases of Donzelli and Donizetti, of whom the latter lost his voice by singing, whilst the former retained it by abstaining from singing at that period. There are, however, many examples of persons possessing fine voices, who never paid the least attention to this rule.

The oral, nasal, and pharyngeal cavities exercise an important influence on the quality of sounds after their production by the larynx. Further effects are ascribed by Bennati to the arches of the palate, the uvula, and velum, all of which appear to contract with the acute, and relax with the grave tones, and are in constant motion during the modulation of the voice. The contraction of these parts during the production of acute sounds has also been observed by Fabricius ab Aquapendente, Meyer, Gerdy, and Dzondi. Bennati conceived, as has been already mentioned, that the falsetto notes, which he calls notes "sur laryngiennes," are produced exclusively in the superior part of the vocal tube, but it has been shown that this hypothesis is contrary to acoustic principles, and that the same motions of the palate are also equally observable during the production of acute tones of the ordinary register.

* The two first of these belong to the male sex, and the two last to the female. In this table C is the pitch of the 8-feet organ pipe, or the fundamental of the fourth string of the violoncello; the ciphers denote the octaves, that is, C^1, C^2, &c. are the first and second octave of C.

MÜLLER also states that the arches of the palate may be touched by the finger without altering the pitch, which could not be the case on the hypothesis of BENNATI. It is to be remarked that neither MÜLLER nor BENNATI mentions the opening of the crico-thyroid chink on sounding the first note in the falsetto register; neither do they mention the simultaneous falling of the larynx, and they deny the existence of a third register. According to the hypotheses of LEHFELDT and MÜLLER, any increased intensity of vocal sound ought to raise the pitch of the voice; but if this were the case, the performance of prolonged vocal sounds on the same note, but of variable intensity, would be rendered impossible without a simultaneous adjustment between the tension of the vocal ligaments and the current of air; whereas, by examining the state of the crico-thyroid chink during the utterance of such sounds, it is found that no such adjustment takes place. The exquisite quality of the sounds of the larynx, when modified by the oral and nasal cavities, renders the human voice far superior to any artificial musical instrument; since its tones glide through all the en-harmonic intervals between successive notes, an effect which no such instrument can perfectly imitate. DODART estimates the number of tones, which can be produced by the voice and appreciated by the ear in the compass of an octave, at three hundred: a striking proof of the complete control exercised by the laryngeal nerves over the vocal apparatus.

The action of the vocal organs in producing speech is a distinct branch of the physiology of voice which the author does not intend now to investigate. It is well known that the vowel sounds have been imitated by KRATZENSTEIN, DE KEMPELEN and WILLIS by means of mechanism, and that the principles on which they depend have been successfully analysed by the latter: but this is a subject which would require a very lengthened examination to render it the justice which its importance demands*.

Having now completed the investigation of the physiological character of the human organs of voice, and having for the sake of simplicity considered them in three distinct lights; namely, as membranous ligaments obeying the laws of musical strings, as a reeded instrument, and as a membranous pipe with a column of air vibrating within it, the results of the various experiments which have been noticed would certainly seem to warrant the conclusion that each of these views is correct; for it cannot be denied that these experiments clearly show the vocal apparatus to be influenced by the air expelled from the chest in precisely the same way as if it were a stretched cord, a reed, or a vibrating tube. Why then should we hesitate to adopt the obvious conclusion that the vocal organs do in fact combine the properties of these various instruments, and are themselves the perfect types of which these instruments are only imperfect imitations? The error of those who have preceded the author in this inquiry seems to consist in viewing the organs of voice, not as a com-

* The Abbé MICAL, FABER and Mr. WHEATSTONE have succeeded in producing articulate language by means of artificial mechanism; the Abbé, having so far completed the apparatus as to be capable of performing almost any sentence, appears to have destroyed his machinery owing to pecuniary disappointment.

Fig. 1.

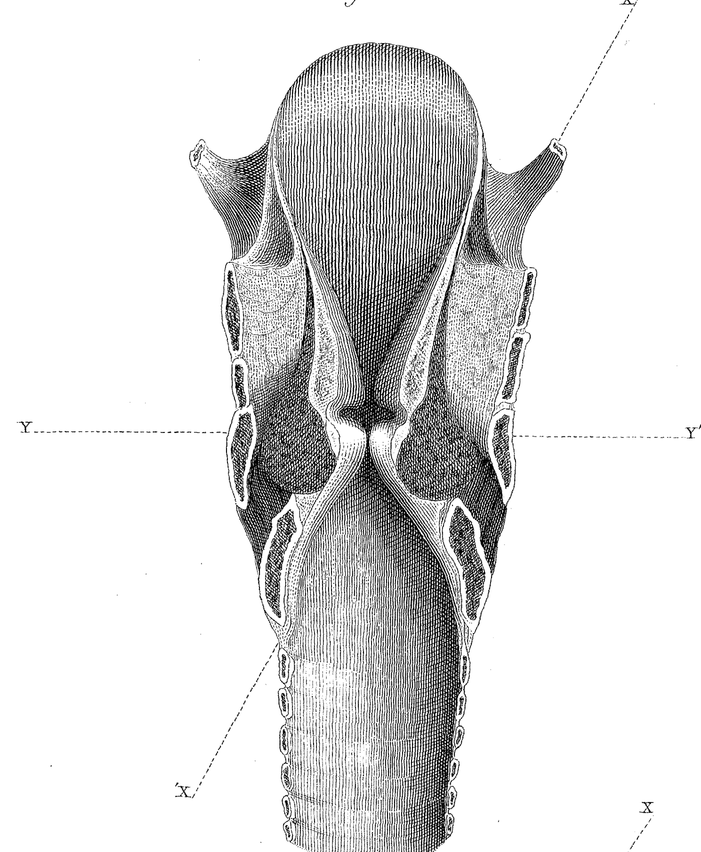


Fig. 1'.

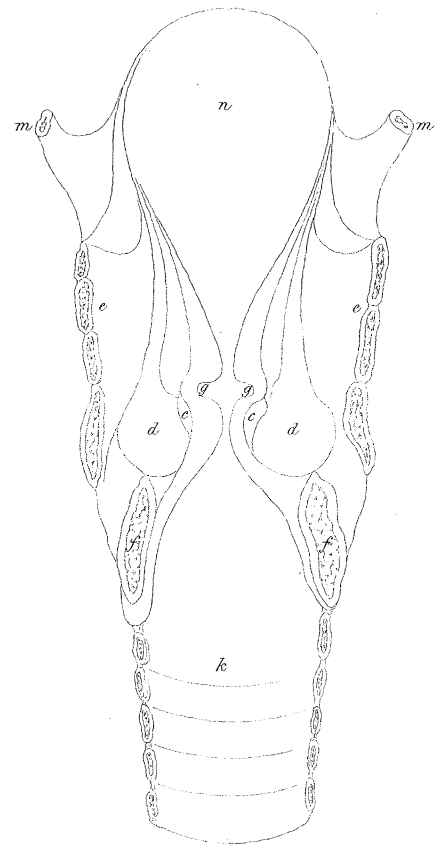


Fig. 2.

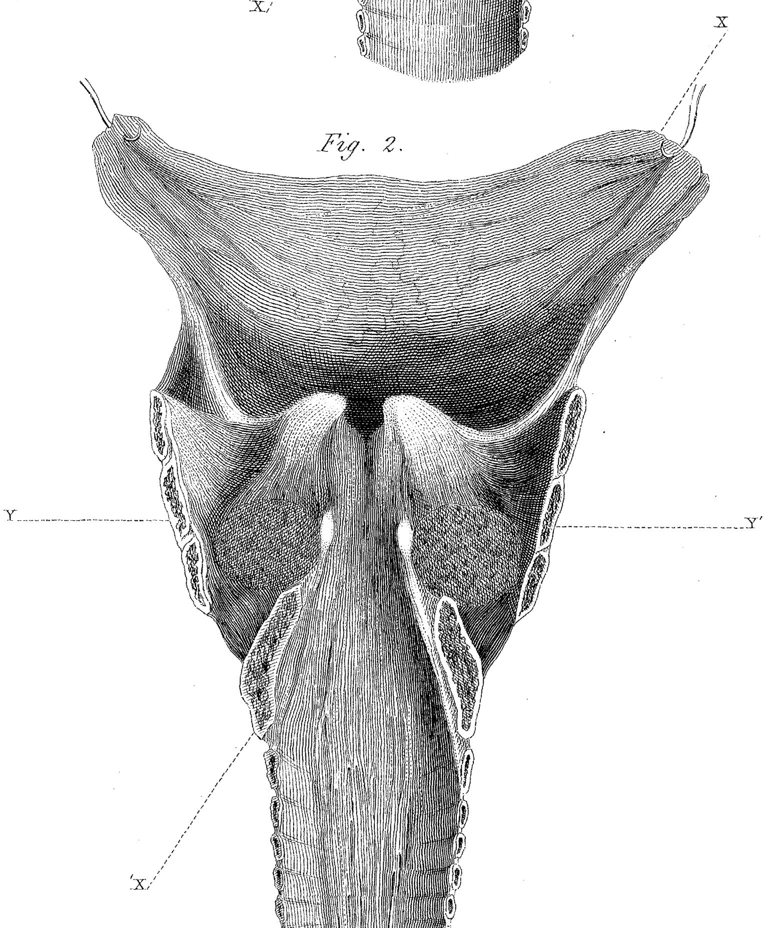
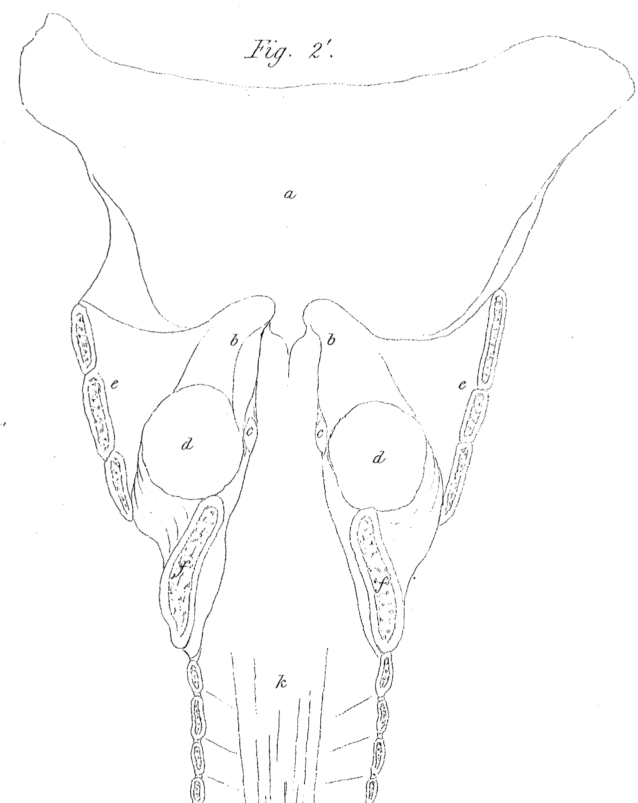


Fig. 2'.



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plex, but as a simple apparatus; with some the favourite hypothesis has accordingly been that of musical strings, with others that of a reed, whilst experiments are equally in favour of both.

It cannot be expected that in this brief treatise, a subject, wherein, notwithstanding the attention hitherto bestowed on it for many years by men of the highest philosophical talent, so little comparatively has been effected, shall be at once exhausted, and all its difficulties removed; but the inductive method, the only satisfactory mode of reasoning on such subjects, has been most scrupulously pursued, and whatever explanations have been offered of the phenomena of the voice are at least founded on facts which are incontrovertibly established.

Description of the Plates.

PLATE XXX.

Figs. 1 and 2. The internal structure of the larynx brought into view, by making a transverse section through the central portion.

YY′. The plane of the vibrating position of the vocal ligaments.

XX. The plane of the respiratory position in which the vocal ligaments are found to lie in their most relaxed state.

Figs. 1′ and 2′ are outlines descriptive of figs. 1 and 2.

Fig. 1′. Anterior section of the larynx.

n. The epiglottis.

mm. Os hyoides.

ee. Internal surface of the thyroid cartilage.

ff. The cricoid cartilage.

dd. Thyro-arytenoid muscles.

gg. The ventricles of Morgagni.

cc. Inferior vocal ligaments.

k. The trachea.

Fig. 2′. *a*. The pharynx.

b. The arytenoid cartilages. The letters *c*, *f*, *d*, *k*, &c. represent the parts corresponding to the same letters in fig. 1′.

PLATE XXXI.

The apparatus employed by Müller for making experiments on the human larynx.

Fig. 3. N. Shaft or column for the attachment of the larynx.

f. The forceps for compressing the larynx laterally.

u. The bellows.

v. The manometer connected with the tube *u* for estimating the tension of the air used in the experiments.

M. O. Columns for the attachment of the pulleys x' and y'.

x. A line by means of which the vocal cords are extended in the direction of their length; it passes over the pulley x'.

y. A line passing over the pulley y', by means of which the vocal cords may be relaxed and reduced to their minimum length, thus performing the office of the crico-thyroid muscle.

z. A line by means of which the vocal cords may be extended by drawing them downwards and forwards.

Fig. 4. Apparatus for the lateral compression of the vocal cords in the production of the chest tones.

a. A rod, to which the pincers *f* are attached, as *a*, fig. 3.

b. Cross beam, to which the pincers being attached may, by means of the part *c*, be moved backwards and forwards, in order to adjust them to the proper position for the length of the vocal cords, as *b*, fig. 3.

d. Screw for adjusting and securing the piece *c*.

e. Screw for adjusting the rod *a* to the height required for compressing the vocal cords.

f. The pincers.

Fig. 5. Compressor, with graduated scale for measuring the position of the legs *g*, *h*.

c, *d*. Screws for the approximation or separation of the legs *g*, *h*.

e. Projection by means of which the position of the leg *g* is indicated on the scale.

a b. The slab on which the compressor is fixed. It passes through the part *b*, represented in the apparatus, fig. 3, and may by these means be fixed in the required position.

Fig. 6. Compressor, with two moveable legs, for making experiments on the human larynx for the chest voice. The parts *c*, *d*, to which the legs *e*, *f* are attached by hinges, move in joints on the part *a b*, and may be fixed by screws. *g*, *h* are small cords, by means of which the legs may be made to approach by the application of weights.

Fig. 7. The glottis prepared for experiments. The arytenoid cartilages are firmly secured together behind the chink by means of a strong pin, and united by a ligature which serves to attach them securely to the column. The supe-

Fig. 4.

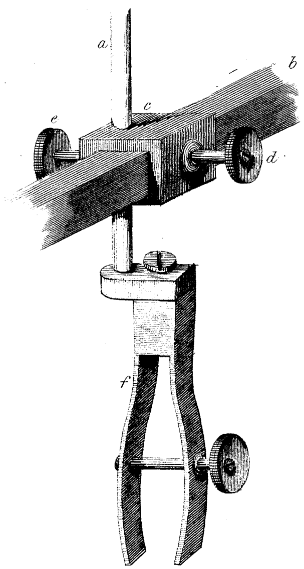

Fig. 3.

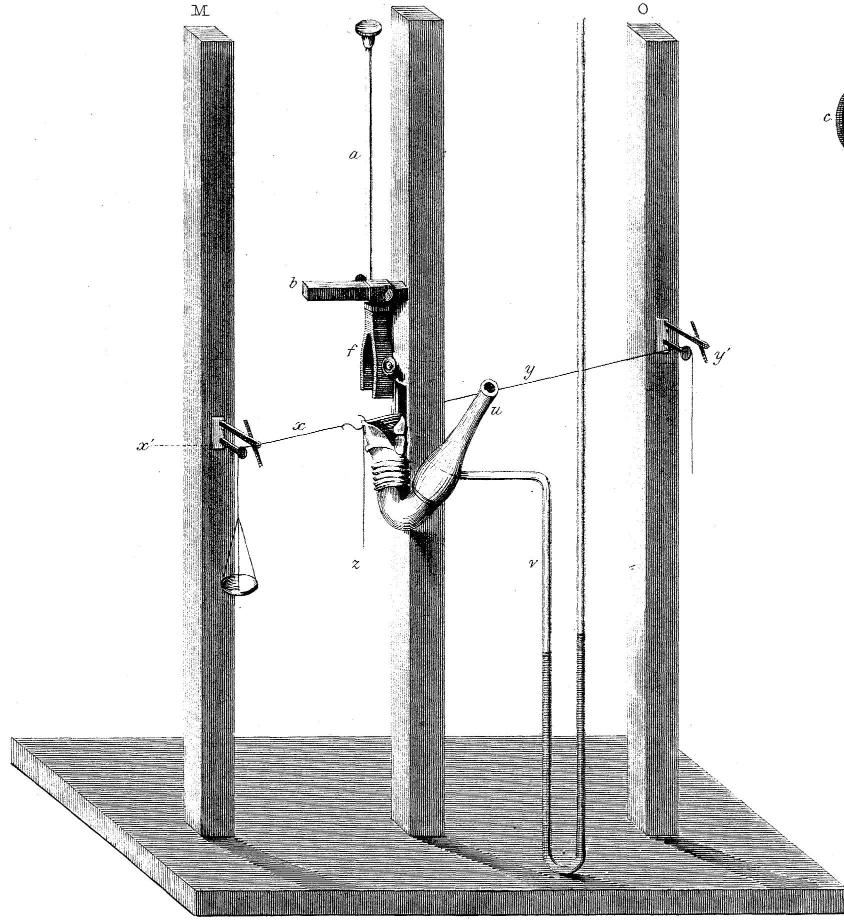

Fig. 5.

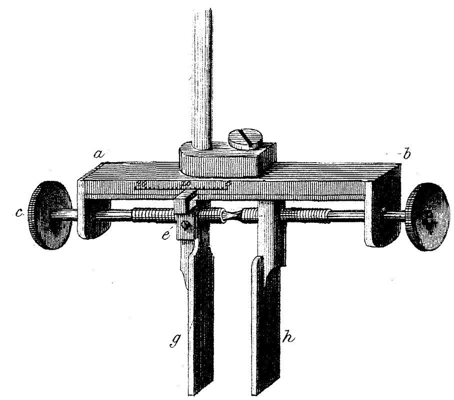

Fig. 6.

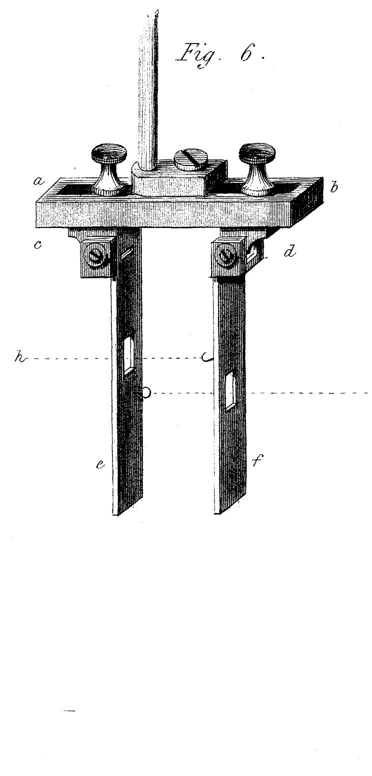

Fig. 7.

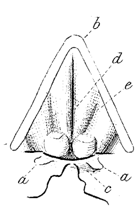

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Fig. 10.

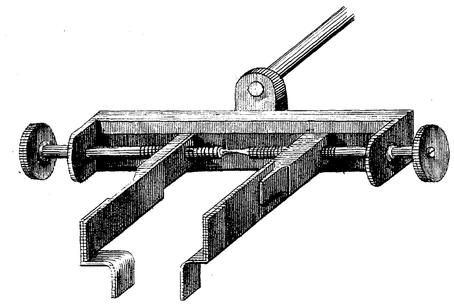


Fig. 9.

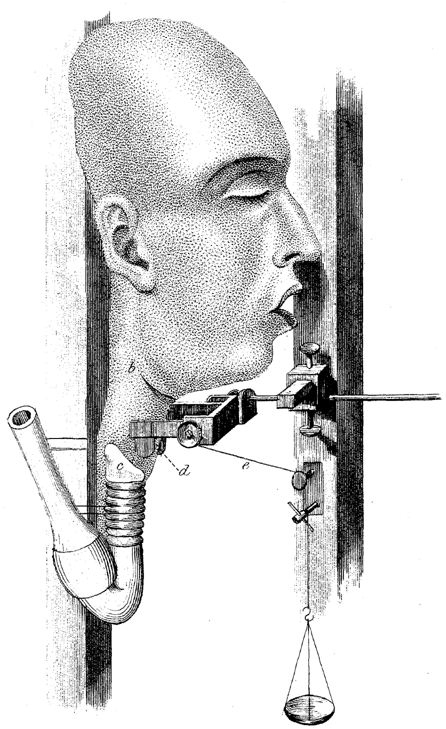
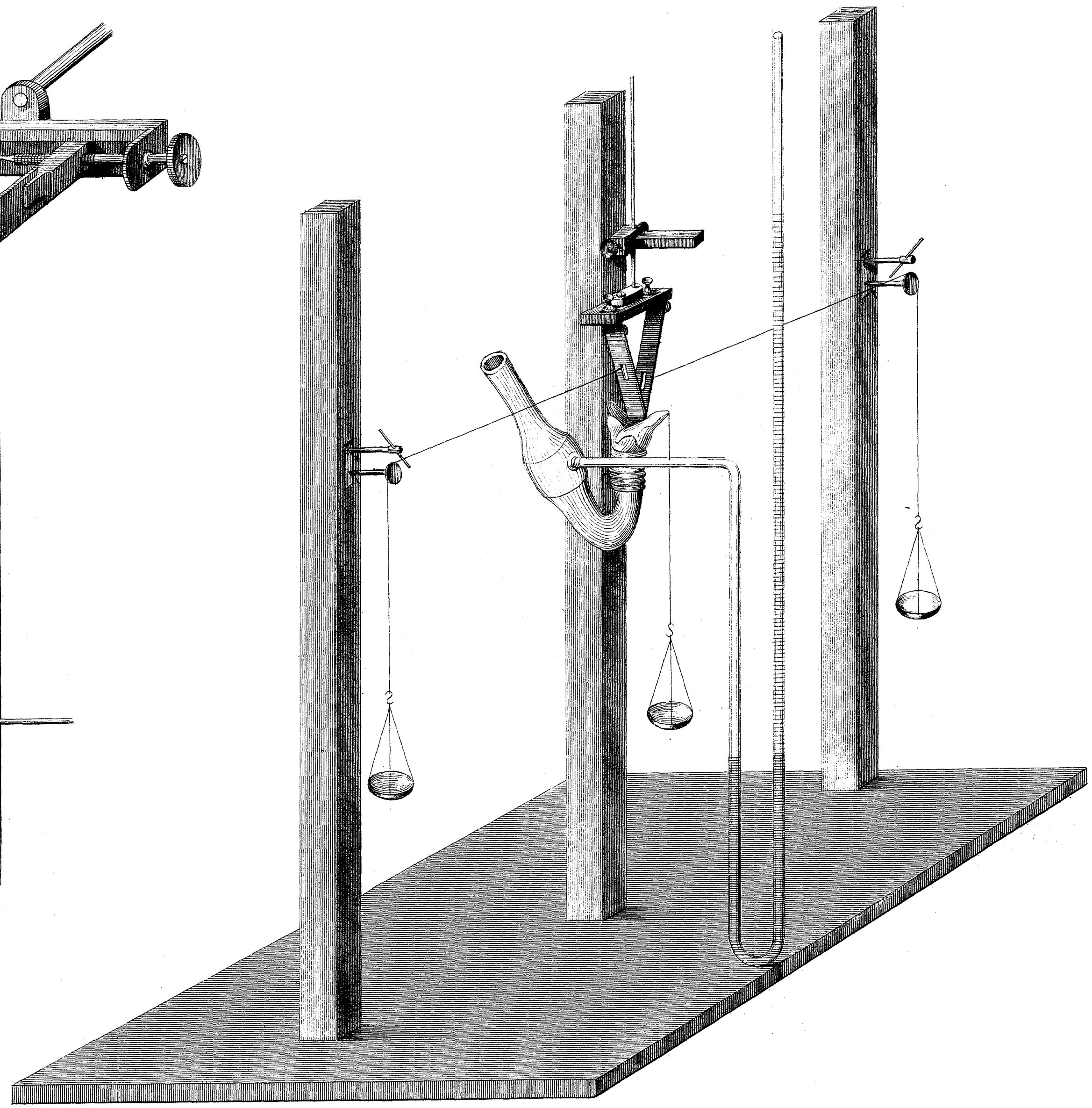


Fig. 8.



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rior portion of the arytenoid cartilages and the thyroid, with all the parts above the inferior vocal cords, are removed, in order to leave the sides of the vocal cords free to admit the application of the compressor.

aa. The bases of the two arytenoid cartilages secured by a pin, and bound together.

b. Thyroid cartilage.

c. Cricoid.

d. Vocal cords.

e. Thyro-arytenoid muscles.

PLATE XXXII.

Fig. 8. Apparatus for experiments on the chest voice, under a graduated lateral compression of the vocal cords by means of the compressor.

Fig. 9. Represents the head and vocal organs prepared for experiments. The cervical vertebræ are removed, and the œsophagus opened behind the arytenoid cartilages, which are fixed together by a strong pin and ligature; the latter is brought through the opening, which is then firmly sewed together, and the lower opening of the œsophagus is also closed up. The larynx is laid bare, and the superior portion of the thyroid cartilage carefully removed so as not to injure the mucous membrane of the larynx. The parts thus prepared are firmly fixed against the column, to which the arytenoid cartilages are also attached by the cord which binds them together. The trachea is connected with a pipe and bellows for the supply of air.

a. The trachea.

b. The os hyoides.

c. The cricoid cartilage.

d. Portion of the thyroid cartilage remaining for the attachment of the cords *e*, by means of which the vocal cords may be extended.

Fig. 10. Compressor used in the apparatus, fig. 9, on a larger scale.