ON ARTIFICIAL VOICE PRODUCTION*

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In describing my own models of vocal cords it must be emphasized that the lecturer is well aware of the restricted information, which can be had from such investigations, but I strongly feel that any means to extend our knowledge should be found. The disadvantages of model experiments are evident. Neither the excised larynx nor the rubber models is able to change the inner tension of the vibrating medium. A medially directed pressure on the lateral parts of the model (Johs. Müller, van den Berg, Svend Smith) has always been the way of replacing this very important trait of the mechanism of the larynx.

This disadvantage is clearly felt in the question of the importance of that part of the muscle group which sends fibres into the lower part of the conus elasticus. Already Merkel in his explanation of the activity of the Stratum ary-syndesmicum (Merkel, *Antropophonik*, 1863, p. 140, fig. 48,8) – and referring to Garcia – pointed to the importance of the abductory activity of these strata: "Die Wirkung dieser Schicht ist, den Streif des elastischen Gewebes, welcher sich an die untere Zone des Stimmbands anschliesst, anzuspannen, ihn schief nach aussen zu ziehen, und so, wie es scheint die Mitwirkung der untern Zone des Stimmbandes bei der Stimmbildung auszuschliessen." Merkel continues: "Durch diese Aus- und Aufwärtsziehung des subvokalen elastischen Gewebes wird ausserdem auch bewirkt, dass die beiden folgenden Schichten den bei Schluss der Glottis sich vergrössernden Raum zwischen Schildknorpel und den Stimmbändern u.s.w. gehörig ausfüllen, was sonst nicht vollkommen zu erreichen wäre."

Grützner (1879) and other authors much later (e.g. Negus) repeated this explanation. Grützner makes it clearly understood in just a few words: the lower parts of the vocal cords are pulled upwards and are thus indirectly active in adduction of edges of the

* *Own films and articles on this subject:* Smith, Svend: First Modelfilm of the movements of the vocal cords shown in Paris 1955: *Membrane-cushion theory of the vocal cords* (Statens Filmcentral, Copenhagen); Smith, Svend, "Théorie aérodynamique de la vibration des cordes vocales," *Larynx et Vibration*, Paris, 1955, pp. 71–74; Smith, Svend: Second Modelfilm on *Head: Chestregister* shown in Bad Harzburg, 1956 (Statens Filmcentral, Copenhagen); Smith, Svend, "Chest register versus head register in the Membrane-Cushion Model of the Vocal cords", *Folia Phoniatrica*, Vol. 9, pp. 32–37 (1959); Smith, Svend: Third Modelfilm *On pitch variation* shown in Chicago 1957 (Statens Institut for Talelidende, Hellerup); Smith, Svend, "On pitch variation," *Folia Phoniatrica*, Vol. 11, pp. 173–178 (1959); Smith, Svend: Fourth Modelfilm *On dicrotic voice* shown in Salzburg 1958 (Statens Institut for Talelidende, Hellerup); Smith, Svend, "Diplophonie und Luftschallbewegungen," *Arch. f. Ohren- etc. Heilk.*, Vol. 173, pp. 504-509 (1958).

vocal cords. This situation has been impossible to imitate in any model of the larynx. Neither has anyone been able to imitate this in experiments with the excised larynx.

The idea of the vocal cords having rather sharp edges ("prismatic" shape of the cords) used to be a favourite description and dates from one of the models made by von Kempelen (1791). Two pieces of flat rubber were stretched across the opening of a tube - either horizontally or with abutting edges of about 60° degrees angle.

This led to the thought of explaining the vocal cords as a double – reed instrument. Realizing the fact that the vocal cords are not stiff as are the oboe and other double reed instruments, Johs. Müller gave the name of a membranous double reed to the vocal cords.

Of all physiologists dealing with explanations of the functioning of the larynx, Merkel was the one who was most clearly aware of the fact that deeper "zones" were important in voice production.

The experiments of Cagniard Latour (around 1830) with an ordinary rubber tube are among the most interesting observations on models made in the nineteenth century. He noticed that vibrations of the upper end of the rubber tube were achieved with only little difficulty if he stretched the tube not *at* the edge, but immediately *below* it. Without knowing it he imitated in this way the typical tension factors in the vocal cords in the case of chest register. We know to day that a relative looseness at the edge of the vocal cords is characteristic of the chest register function.

But Cagniard Latour himself was – as were other physiologists of his time – unaware of the role of plicae vocales and plicae ventriculares. C.L. believed that the true cords were there only to create a narrowing ("retrécissement") in order that the false cords could vibrate. (Grammont, *Traité de phonétique*, 1932, still believes that plicae ventriculares is responsible as a sound generator for some vowels.)

The idea of the necessity of a narrowing in order that the cords may vibrate, dates from the first use of models for demonstration purposes. It was customary to build von Kempelens model on top of a stethoscope. One was then able to have a firm edge for the two horizontal rubber pieces to be kept tight with a string, and the rubber tube served as a flexible mouth piece for blowing.

Nagel in his *Handbook of Physiology*, Vol. 4, II, p. 734, complains, that it is impossible to have von Kempelens horizontal model vibrate (membranes stretched on an *ordinary* tube). I had the same difficulty myself until I found that a narrowing such as is found in the stethoscope below the two horizontally stretched pieces of rubber was necessary in order to have this model vibrate with ease.

The air stream is in this case pointing arrowlike towards the middle part of the edges on the model and vibrations start without any difficulty.

A decisive change in the understanding of the functioning of the vocal cords took place when in the seventies Carl Müller an expert physicist in vibration of membranes investigated the membrane models. His publication (1876) shows a marked negative attitude towards "membrane" ideas. He emphasized that the muscles of the vocal cords were the important part of voice production.

He was inclined to this view because he could not by means of membranes alone produce a tone as deep as man's voice. Only when the membrane was attached to a soft support he was able to lower the tone. But he could find no clue to the mechanics of the vocal cords through these experiments and he concluded "dass ein Vergleich überhaupt nicht statthaben kann". Now followed the first model in which one tried to imitate the "bodypart" of the vocal cords. Ewald (1898) called his model a "Polsterpfeife" emphasizing the similarity of the mass of the vocal cords to an elastic cushion. Ewald was not himself too sure of the value of his model. He says: "vielleicht stellt der Kehlkopf eine Mittelform zwischen der Membranpfeife und der Polsterpfeife dar."

Later Ewald tried to define the principle of his model, but the theory of how an elastic cushion actually did vibrate was missing. Scripture mentioned this in 1902, but could not find any solution himself.

Wethlo in 1913 changes the cushion model, using – instead of mass – two rubber tubes filled with compressed air. He sought to imitate the variable lateral pressure by means of varying the pressure of the air enclosed in the rubber tubes. But in this way Wethlo changed the model more closely to resemble a bird's syrinx and later investigations on this model (as e.g. the very thorough investigations of Herman Gutzmann in 1932) have less value, because the model used now was too unlike the vocal cords in man. A high speed photo of the Wethlo model made by Gerhart Lindner, Berlin, in 1960 does not show any similarity to the typical pictures as viewed in the Bell high speed film of the vocal cords, even when they in Wethlo's model have a rounded profile – as have the vocal cords in rest.

Musehold was of the opinion that the vocal cords during vibration were shaped with a rounded profile – and believed again that this was the effect of contraction of the inner vocal muscle.

His ideas were based on stroboscopic observations, but we know today that his pictures – on account of the old stroboscopic technique with a dial and a flash of light of relatively long duration – must have been badly blurred. His misinterpretation was universally followed and the blurred photo of the vocal cords in the stroboscopic illumination has often been printed together with his explanation: "Es werden so die gesammten Massen der Stimmbänder nach der Mitte zu gedrängt und dadurch relativ dicke nicht membranartige Stimmbänder in Bewegung gesetzt." The idea of medially directed lateral forces in the vocal cords as necessary for voice production thus became the favourite explanation in the literature, until we now in later years have changed our general concept on this point, realizing that it is the air stream itself, which after adduction of the cords keep them vibrating through alternating pulling them together and pushing them apart.

Whereas Museholds stroboscopic method could not show less than 1/8 to 1/10 of the whole vibratory cycle, modern photography has been able to show utterly sharp pictures of about one twenty thousandth of the whole vibratory cycle (see my pictures in Folia Phoniatrica 1954).

High speed film and modern stroboscopy have shown the variety of profiles within one full vibration which could not possibly be observed by the old technique and which no one could imagine. Additionally we have to remember that what is observed is the surface (mucosa), not too correctly identified with movements of the *body* of the muscles.

Another concept than the one introduced by Carl Müller was the idea of Lootens on the importance of ventriculi Morgagni. The existence of eddies was claimed by Guillemin (1897) and Morat and Doyon (1918). Gradually the concept developed that the vocal cords were vibrating as a consequence of formation of eddies at the level of vocal cords, the cords themselves playing a more passive role. Desider Weiss in the thirties partly followed these ideas, although on the other hand by 1928 he had rejected the idea, which later developed into the theories advocated by Husson.

Husson in 1936 published a paper in which he mentions, that "nombreux auteurs croient a la passivité du phenomène" (*Revue française de phoniatrie*, 1936, p. 22). Trendelenburg (*Arch. f. d. ges. Phon.*, 2 Abt., Bd. 6, 1942) also believes in the possibility of eddies formed by "dem schnellen Austritt der Luft aus der Kehlkopfenge im mittleren und oberen Kehlkopfraum". That the ventricular bands are unnecessary for the formation of glottal sound we know from numerous physiologists from Grützner to van den Berg.

The question remained as to whether experiments with models would support the theory of formation of eddies in the normal vibration modus of the larynx.

By means of smoke blown through the vibrating model made by von Kempelen (horizontal rubber pieces) it was shown that eddies at the level of the vocal cords with an intimate contact to the surface were found only in von Kempelens model.

Von Kempelens model vibrates as do two vocal cords which are completely paralyzed and stretched-namely alternating up and down. Thus eddies at the level of vocal cords can only occur in rather specific case as e.g. bilateral paralysis. Schönhaerl, Erlangen and Behrendes, Marburg, observed in man in pathological cases the alternate up and down movements of the two cords.

It is furthermore unlikely that in normal chestregister eddies be found at the level of the cords.

The edges are gradually disappearing in the surface immediately following the explosion. This means that the prerequisite of a building up of eddies at the level of the cords: a sharp edge is not found. A certain static phase characterized by a sharp-edged contour is missing and accordingly there will be no time for building up eddies at cord level.

But eddies *above* the level of the model of the vocal cords are normally found as soon as two vertically orientated rubber pieces are used. The airstream leaves the cords column-shaped and above the cords eddies are found in a mushroom shaped cloud of the smoke.

All experiments carried out by me in the early fifties failed, when I just used some sort of "body" to represent the vocal cords in a model of the larynx.

Later when I realized that an attachment of a loose sliding surface on my "body" was necessary in order to have vibrations similar to the high speed pictures of the vocal cords, I understood why the cleft palate speaker,who often uses a narrowing in the vestibulum nasi as an obstacle for the escape of air through the nose (as e.g. on pronouncing an "s" sound) never generates a "voice" in this part of the nose. The reason is simply that there is no sliding mucosa inside the vestibulum nasi.

We must look upon the sliding mucosa between the vocal cords as an initial vibrator and we know that in man there are easy means of transmitting the surface movements of the mucosa to the body because there is found below the edge an attachment to the underlying connective tissue and again to the muscle fibres. We thus have theoretically a double system, which in normal conditions would always act together in one vibratory pattern. In inspiratory voice (see later) one part (sc. mucosa) may act independently of the underlying mass.

Illustrative details of this theory were shown in my first model film on the larynx. In the said film the eliptic line of pressure in the "cushions" of the cords is shown.

Imagine for a moment two skipping ropes circling against each other at ground level.

A subglottal adductory movement of cushions plus membrane will result from this and the loose membranes will eventually independently be brought into contact by means of the sucking effect of the air stream.

In my models the cushion was as a rule represented by two pieces of foam rubber. Stiffening or immobilization of deeper parts of these cushions at one or at both ends always gives a rising pitch in the chest register function.

As soon as a stiffness along the upper edge was introduced the timbre changed to a headvoice function and the subglottal parts never came into contact before the edges closed (contrary to the chest register function, where the thin rubber surfaces always met before the edges closed, the closure time thus being constituted by a contact sliding from below as against the edges). A head voice character on deeper tones takes place when the thin rubber membranes meet and explode already below the edges of the model and thus only badly transmit the energy to the "body".

Experiments with feeding this laryngeal source (blown by mouth, kept by fingers) into an electroacoustic filtering device were carried out at the *Bell Telephone Labs.*

It seemed as if the apparent naturalness in listening to the resulting vowels was dependent not only on the vocal resonance circuits and the proper choice of spectrum source but also on the slight irregularity of successive periods, which are found in a model kept by fingers and not found in an electronic voice generator.

In von Kempelen's book *Mechanismus der menschlichen Sprache* we find a description of people talking incessantly on exspiration and inspiration.

Some writers have found a parallel in the technique of some musicians (players of clarinet, hautbois and similar reed instruments), when they listened for the incessant stream of notes from their music. But this is a misunderstanding. The musician who can do this does not blow his reed instrument on inspiratory air-stream. He demonstrates his special technique when he blows through a small tube held between lips and with the open end dipped in a glass of water. He is then able to blow an incessant sequence of airbubbles, and he never sucks water up in the mouth i.e. never an inspiratory activity is found. The technique differs from the technique of the talker who *must* use inspiratory voice, when he wants to speak without a pause. In the case of the reed player the air is kept in the mouth, cheeks are inflated and soft palate closes as against the back of the tongue. The reed tones are now formed by means of the gradual compression of air in the mouth itself. While this takes place the inspiration activity is carried out through the nose and the patent pharynx and when the lungs are filled the velum jumps up and executes its valvular action against the back wall of the pharynx and the air now passes from the lungs through the mouth to the reed. Musicians who are able to do this are still found (e.g. in Skopje, Yugoslavia, personally investigated by me).

Inspiratory voice is the rule in some animals. Thus in the cat the stratified epithelium starts at a much lower level than in man and the immediate supralaryngeal cavity is coneshaped, whereas in man we find the immediate sublaryngeal space to be coneshaped. In man we find an opening between the arytenoids in inspiratory voice and we can watch the subglottal mucosa vibrating actively.

Stroboscopic observations on an excised larynx of a 65 year old woman showed me how the vibrations in the case of inspiratory voice (the larynx turned upside down and air blown from the vocal tract side) proceeded as two travelling waves one on each side disappearing gradually in the surface of the mucosa. These waves are not arrested by any mass, which is attached to the mucosa. Down to the first tracheal ring the mucosa is sliding with no attachment on the sides this being the reason for the gradual disappearance of the travelling waves.

Exactly the same phenomenon can be seen with rubber models made according to the membrane-cushion theory and has been shown in my first film on the movements of the vocal cords.

Usually the inspiratory voice has a higher pitch than has the expiratory voice, the reason being that the energy of the travelling wave motion does not make any underlying tissue vibrate, i.e. there is no additional vibrating mass. And less mass means higher pitch. But also the relative tenseness or looseness of the sliding mucosa is important. It is well known that in animals—where no exact boundaries of the larynx can be delineated, the voice may be inspiratory and as deep as the expiratory voice, assuming loose surface vibrations at the moment of phonation.

The physiology of the rather low pitched inspiratory voice in man looks similar.

When vocal cords are kept in a slightly abduced position, the loose surface of the mucosa can be watched stroboscopically below the edge of the cords executing a travelling wave motion in caudal direction and at the same time a rather deep pitched voice is heard.

It is not only the construction of the glottis in man which makes him more suited for expiratory than inspiratory voice. It is also the very fact that in man pharyngeal and oral cavities – contrary to what is often found in animals – are connected to one tube, which is highly variable in shape.

The variety of possibilities in colouring, which is caused by this lucky combination of two cavities makes it possible for man to create the almost unlimited number of vowels, which we find in some languages but at the same time it calls for a sound generator which is built in such a way that full use can be made of these vocal cavities

A sudden explosion and a sudden implosion by means of the voice generator are two physical events which are highly desirable. To that end the vocal ligamentum is practical. It can be held stretched by a slight outer tension (cric. thyreoid.) in such a way that the explosion can take place as an almost momentary event. The cords are eventually sucked toward each other because of the existence of a pliant structure of the subglottal (i.e. below the exploding edge) mucosa, and the pull from the air stream. This possibility of sudden opening and closure gives the unique result in man of creating sufficient (i.e. up to 4–5000 c/s) harmonics in the supralaryngeal cavities, which perform the colouring of the acoustical input to be used in the sign language of man.

Only few experiments have been made from my side in using the sound from the vocal cords model as an acoustical input for a mechanical vocal tract.

I have constructed a variable vocal tract (at the *Bell Labs.*), which allows for a quick change of cavity sizes and connecting tubes, but the adjustment of any of my own models for this turned out to be impossible.

An altogether different voice source may be used for this, namely an artificial larynx, driven electrically. This idea of combining an artificial vocal tract with a membrane at one end which was made vibrate mechanically without air, was known within experimental phonetics already in 1913, when ter Kuile (*Neues zur Vokal- und zur Registerfrage*) constructed small vowel cavities out of wood and made a tuning fork or an electric hammer exert pulses on the bottom of the box, which was made out of cardboard. Later Chiba (*The Vowel*, 1941, Tokyo), p. 129, used a telephone receiver placed inside a lead case in order to make artificial vowels.

The idea of using a telephone receiver as a voice source also came to be one of the *Bell Telephone Laboratories* constructions, but now it was used for the exitation of vowel cavities of living man i.e. patients who were laryngectomized.

As is well known an artificial electric larynx is a sound generator to be placed on

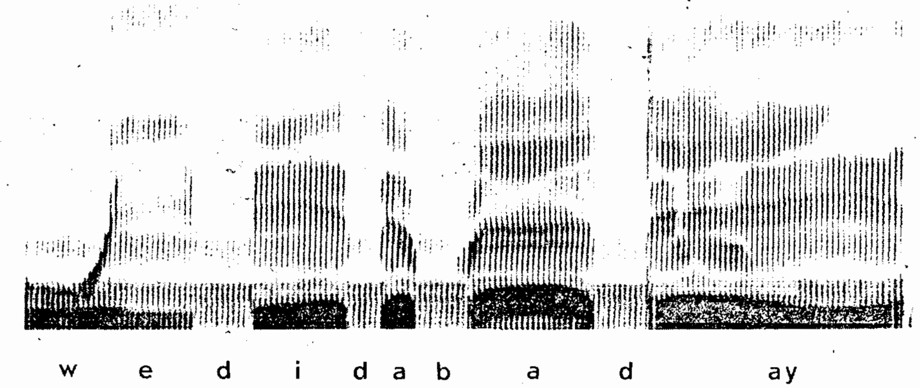

Fig. 1

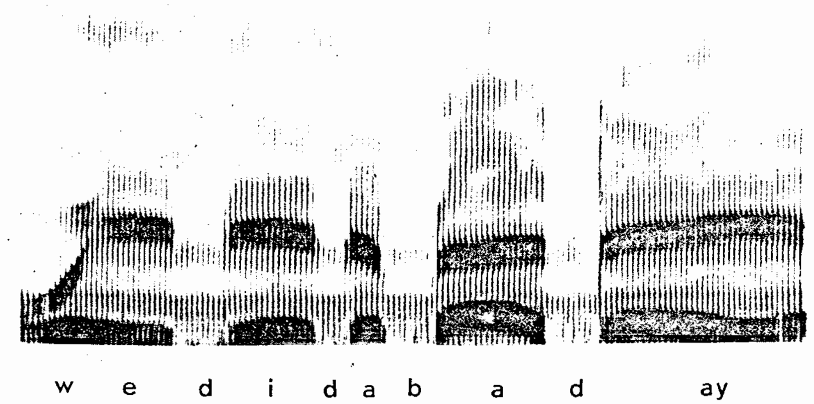

Fig. 2

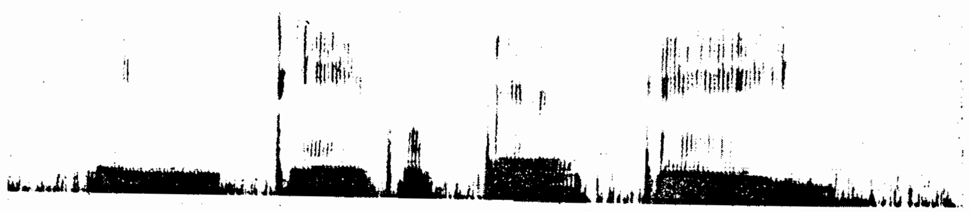

Fig. 3

Fig. 4

the skin below the mandible, transmitting pulses through the tissue into the pharyngeal cavities (used by some Laryngectomees). A brief nontechnical description of the 5 A artificial larynx which was constructed at the *Bell Telephone Laboratories* will be necessary. This type, which is a throat-type electric larynx like the Wright Electrolarynx, differs from any other type in the following way: The diaphragm is magnetically attracted by the permanent magnetism of the pole pieces of an ordinary coil – the diaphragm itself is the size of a telephone membrane. This system was only slightly changed at the *Bell Labs.* A short pulse from an electric circuit (duration about 1/1000 sec) demagnetizes the pole pieces and the diaphragm suddenly rises from the pole pieces, reaches its resting position (flat shape) and is eventually dragged down again on the pole pieces attaining again its slightly bowl-like profile. The field of magnetism around the pole pieces is an important factor in the shaping of the diaphragm. The designers of the 5 A artificial larynx have selected a certain size and thickness of plate which is spot welded to the center of the flat telephone membrane.

This sound generator now has its specific spectrum, which can be changed in the following way. A small plate or ring is cut from the material commonly used for telephone membranes. This plate is now placed on top of the diaphragm of the artificial larynx. Mechanically this patch is not fixed at all to the telephone membrane. The magnetic field which extends well above the diaphragm itself keeps it in position.

This additional mass will now act to a certain degree independently of the diaphragm because it is only attached by means of the magnetic attraction.

The specific spectrum of this 5 A sound generator without a ring (or plate) shows a resonance around 800 c/s and a steep downward slope above this when a recording is made of the sound in open air. Another high resonance is found around 5600.

It would be most natural to understand this 800 c/s resonance as the natural mode of the diaphragm resting on its fixed base ring (the wholly free vibration on the diaphragm suspended in air would be around 13–1400) -and to assume that the high resonance originates from the clapping of the diaphragm the moment the magnetic force claps it against pole pieces.

When the loose ring is now put on top of the diaphragm the intensity rises as a whole. The difference of the over-all intensity lies around 10 db, when the 5A artificial larynx is held at a distance of about 40 cm from the microphone of the Kay Electric Spectrograph.

This amount may vary, but once the ring is put on top of the diaphragm the over-all intensity always goes up. The energy distribution is now totally changed. Spectrograms show how the energy distribution is broadened out in the range of F 1, as well as in the range of F 2. When the 5 A artificial Larynx is placed against the throat below the mandible the effect on speech can be observed on spectrograms. We observe here that more energy is displayed within the F 2 range when the ring (plate) is put on top of the diaphragm (see Figs. 1 and 2).

By means of stroboscopic light a travelling wave spreading radially and evenly from the center towards the outer edges of the diaphragm may be seen. The frequency was estimated to be around 7-8 times the fundamental (being 100 c/s at this experiment), the natural mode of the diaphragm. This is the typical situation when no ring or plate is placed on top of the diaphragm.

The moment the ring is placed there the whole picture changes. In stroboscopic light it is now observed that soon after the upward movement of the diaphragm the ring leaves the diaphragm to be pulled down a little later by the magnetification which has returned to the pole pieces. This time of suspension in free air may vary. Often it takes up about 1/4 of the whole period (of 1/100 sec) before the ring touches the diaphragm again (and not always simultaneously with its whole circumference). Immediately following this both the loose ring and the diaphragm are pulled tight to the pole pieces. When this happens a very striking thing takes place. The natural mode of the diaphragm is damped. The stroboscopic light allows us to see the diaphragm start on its n.m. vibration as long as the ring is up in the air – to be squeezed out at the moment the ring returns to its seat.

A saw-tooth shaped mechanical movement has been created. An oscilloscopic investigation of the back e. m. f. showed the same phenomenon, a quick dampening of the natural mode of the diaphragm when the ring is placed on top of the 5 A artificial larynx diaphragm. These experiments were carried out in Ann Arbor (*Gordon F. Peterson*).

We can now conclude that the sharper pulse acquired by means of the ring is the responsible factor for the change in the harmonic contents, which gave a stronger F 2 in the vocal tract. The mechanical reason for this is the following:

Whereas the diaphragm has to follow its own natural mode and for a frequency of around 80-100 c/s vibrate several times per cycle and thus is relatively restricted in applying a full explosive blow on the skin of the neck – the ring will take over the function and force the pulse to its maximum, being thrown away by the elastic force of the diaphragm and continuing its vibration in free air without the mechanical impedance which adheres to the central part of the diaphragm itself being loaded with the stiff mass of the outer part around its center. The distance of the diaphragm from the pole pieces is important for the relative amount of energy in the upper part of the F 1 range.*

The above experiments on an artificial larynx have been important to me in my understanding of the necessity for sufficient energy distribution in a voice generator within the F 2 range.

The effect of a relatively stronger energy in the F 2 range has not been dealt with except occasionally in technical literature. In *Visible Speech* by Potter, Kopp and Green, a few spectrograms in the chapter on Dysphonia (pp. 330-32) show a marked deficiency of the second formant.

* At this point I want to express my thanks to the Bell Telephone Labs. for all their assistance in these experiments and express my deep appreciation for the help I received from the late Harold Barney.

The authors do not know whether to attribute this phenomenon to "discontinuity of resonance" or "deficiency of harmonics". A study by Delattre, Libermann, Cooper and Gerstman (*Word*, Vol. 8, No. 3, 1152) states that the effect of a smaller reduction of the intensity of the second formant causes the vowel to acquire a quality that can best be described as "dull". Further reductions in the intensity of F 2 tend to change the vowel character. In this case we have clearly a variation in spectrum source (less light is reflected from the less dense white painted formulas in the speech-synthesizer). The first thing which apparently takes place is that the recognizability (I. Lehiste and Gordon F. Peterson, *Phonetica*, 1959) is reduced. A further reduction changes the identification of some of the vowels.

This means that if a person thus does not speak at "the best of norms" – which I would prefer to call "normative" we may expect to find a deficiency in the spectrum source. That this actually may take place is well known to the speech therapist, who in treating a patient with a faint (soft, weak, dull) voice notices that the voice develops from a dark timbered muffled color to a light colored "tight" timbre which gradually develops "on top of" the darker voice during pedagogic treatment.

Recordings of numerous patients have been made and examined at the Laboratory of Experimental Phonetics in Copenhagen and it has been found that voices improve after treatment in the sense that more energy distribution is found above 1000 c/s.

It has been interesting to find that a specific sound generator – model such as e.g. the 5 A artificial larynx can have its vibration mode changes so as to produce a different sourcespectrum, and that as a consequence of this, the timbre of the issuing voice (the quality) can be changed irrespective of changes in resonance (see Figs. 3 and 4).

Consequently it would be wrong to say that a change of the quality of voice takes place only above the two important formant regions for vowels namely in F 3 and F 4 range (Ochiai and Fukumura, 1956). The brilliancy in timbre (or a lack of the same) may be attributed to this region, but the quality of voice is also determined by the energy distribution within the range of the vowel formants (F 1 & F 2). As it is understood from Delattre et al, there is no sharp limit for the quality component in the region of F 2. The lack of energy there may cause a change in the vowel character or it may just cause a "dull" voice. This fact is not unlike the importance of F 3 which partly is of a quality changing nature and partly may contribute to the identification of certain (front) vowels.

The artificial electric larynx was thus able to show that a change of the spectrum of the generator may be responsible for a change, which is similar to a pathologic condition in voice production.

The membrane – cushion model on the other hand is able to show a variety of abnormal conditions which together with its ability to demonstrate the typical chest register function, and head register function, inspiratory voice function, the function of changing pitch by means of augmented subglottal pressure and also of lateral pressure and finally decrease of the amount of mass vibrating, makes it a valuable tool for demon-

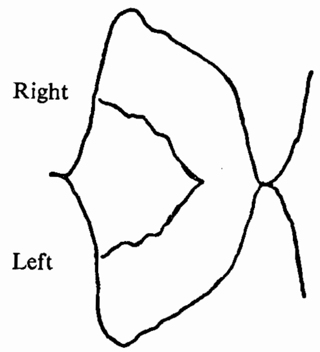

Fig. 5

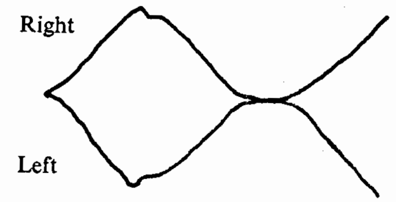

Fig. 6

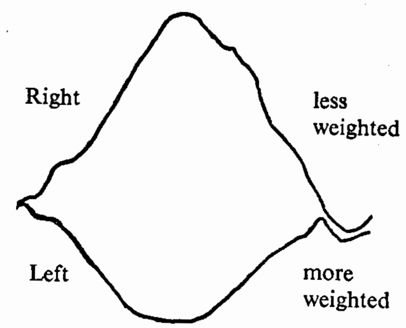

Fig. 7

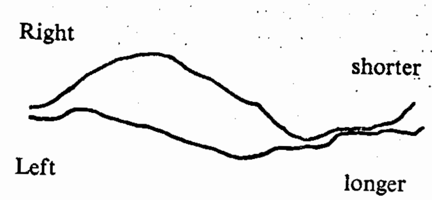

Fig. 8

stration purposes. The important factor for initiating vibrations seemed to be the existence of two loose thin surfaces in a vertical orientation.

This is important because this allows for a simplification of the model situation, where only two thin surfaces (without the cushion attached) were able to give the characteristic picture of the above mentioned functions.

A toy ("munyo") was made and in the hands of a skilled player all functions mentioned could be imitated including the "Strohbass" (dicrotic voice).

My model film Nr. 4 demonstrates the mechanics of this "Strohbass" and the theory was explained in Salzburg. Studying the high speed pictures of this phenomenon in man taken by von Leden and Paul Moore you are able to follow the tightness of closure at the edge from one full vibration to the next. It is clearly seen that every other vibration is a tight closure and every other is not.

Together with the findings of the actual frontal travelling wave-like opening along the edges of different size it gives the understanding of the existence of two harmonics in the material at the edge region.

This idea of a vibration (subglottally) creating a subharmonic at the edges (on account of the extreme looseness at that level) blended with the first harmonic is explained in the above mentioned article and does not belong in its entity to this paper.

Other experiments of imitating abnormal voice functions were done later.

At the above mentioned Institute of Laryngology (*Gould Foundation*) Paul Moore and the author used high speed photography in order to show some malfunctions on my models.

Figs. 5, 6, 7 and 8 show the measurement of the opening and closing phase following the same technical procedure as used in the articles by Leden, Moore et alia. Fig. 5 is one of chest register showing the almost immediate closing movement of subglottal parts of the model after explosion at the edge. The timbre was chest registerlike. Fig. 6 shows typical head register movements in the model (just in and out edge-movements).

Fig. 7 shows a difference in amplitude of the two vocal "cords" – one lip being more weighted than the other.

As is often the case with one paralyzed live cord and sufficient air pressure, the movements of the less weighted cord is more ample (see von Leden, Paul Moore and Rolf Timcke, *Laryngeal Vibrations*, Part III). The similar vibration modus is found on the model.

Another model where the two edges of the vocal cords were out of level showed a pronounced phase shift and asymmetry in the vibrations (Fig. 8).

Normally the vocal cords meet in the middle line and we might say that in normal vibration modus there is a phase difference of 180°. In case two vocal cords would move both of them simultaneously in the same direction we would accordingly explain this as being movements with no phase difference.

This situation together with an asymmetry often happens for part of a double vibration in the living man (von Leden, Paul Moore). In many of these cases there is a difference of height of the two cords (oedemas or one vocal cord paretic) and a model as the above explained in high speed pictures now gives the explanation:

The two crests of the travelling wave from below which constitute typically an ordinary vibratory cycle do not stop at the same level. The travelling wave of the higher positioned mass of one vocal cord continues its movement cranially while the travelling wave of the lower side continues either down in the mass of the muscle or laterally on the surface. The lower positioned cord would in both cases recur laterally while the higher positioned still bulges towards and past the midline, creating asymmetry and phase shift in the movements of the cords.

Voice breaks as in the adolescent voice can best be imitated without exerting a variation of the longitudinal pull along the edges of the membrane cushion model.

In order to have the frequency break the cords of one end of the model are slightly abduced. The vibrations may now take place exclusively in the membrane below the edges of the glottis and the frequency is higher. In this way it is possible to have a typical break of the voice by means of simply a quick ad – and abduction of one end of the vocal cords on the model.

Experiments with models both imitating normal voice production and pathologic voice production point to the fact that it is the relative stiffness distribution in the vertical plane of the vibrating mass which is the essential factor for the variety of normal and abnormal vocal cord patterns.

The parallel of the vocal cords with the pendulum (e.g. a flexible brass lamina with weight attached) is not a bad one – but imagination has to turn the pendulum upside down and visualize two of them (not necessarily identic) with all varieties of elastic stiffness located in different regions along the vertical axis. We thus come back to the theory of Scripture. He stressed that we have in the vocal cords a fixed system consisting of conus elasticus with an attached mass, (sc. vocal muscles). This thinking is the natural background for the understanding of variations of elasticity along the vertical axis, and may be a more valuable approach than visualizing the important events to take place in the horizontal plane.

The apparent difficulty in having such a system vibrate with ease in an air stream is solved by the assumption of an initial vibrator i.e. the surface mucosa being two vertically orientated "membranes" between the two "cushions" (the cushions consisting of conus elasticus plus vocal muscles).

It was planned to demonstrate the asymmetric movements and the phase shifts on a model film Nr. 5: Pathologic conditions on the simplified (vertical) model of the vocal cords). Unfortunately the lecturer had to send a message of excuse with the result that the film was not brought to the conference.