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An Experimental Transistorized Artificial Larynx

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A new experimental artificial larynx, which makes use of transistors and miniaturized components to provide a voice for those who have lost the use of their vocal cords by surgical removal or paralysis, is described. The larynx operates by introducing a substitute for the sound of the vocal cords into the pharyngeal cavity by means of a vibrating driver held against the throat. The acoustic principles of normal and artificial speech production that were followed in arriving at the new design are presented, along with descriptions of the transistor circuit and its operating characteristics.

I. INTRODUCTION

It is sometimes necessary, for the health of an individual, to remove his entire larynx by surgery. His trachea is then terminated at an opening (stoma) in the throat, and no connection between the lungs and the vocal tract remains. Since the normal source of energy for the speech process is provided by the lungs, such an individual loses his natural means of speaking.

These persons are usually advised by their surgeons and speech therapists to learn esophageal speech, and classes for this purpose are set up in various centers. In producing esophageal speech, the upper end of the esophagus serves as the substitute larynx and provides the necessary complex tone at an appropriate point in the vocal tract — the bottom of the pharynx. The esophageal speaker must learn to swallow air, or force air into the esophagus and then control its escape, in such a manner as to cause sustained vibrations of tissues at the upper end of the esophagus. Not all patients can do this successfully. In fact, surveys have shown that about a third of all larnygectomized patients are unable to master esophageal speech for one reason or another.[1] In addition, the quality of speech produced by this method is generally rather unpleassant — to such a degree that, in a comprehensive comparison test, listeners were unanimous in their preference for speech produced by a reed-type artificial larynx rather than esophageal speech.[2]

The use of an artificial larynx is therefore frequently desirable, and is often a necessity if the laryngectomized patient is to communicate by speaking. At the present time, there are several different artificial larynges available, including the Western Electric reed-type which has been distributed by the Bell System since 1930. However, both doctors and users are generally agreed that there are various deficiencies in the performances of all the available models, and that none are really efficient in their function. In the past few years, suggestions for the improvement of the Western Electric reed-type larynx have been received with increasing frequency, along with suggestions that a totally different design making use of transistors could provide improved performance. Accordingly, it was decided to investigate the problem further to see how modern components and techniques might be used to make an improved artificial larynx.

The experimental artificial larynx to be described here is a result of these studies. Its characteristics are such that it provides an efficient means of communication for laryngectomized patients, while being more convenient and less conspicuous in use than the Western Electric Model 2 or other available larynges. It includes, in one small hand-held unit, a modified telephone receiver used as a vibrating driver that is held against the throat, a transistorized pulse-generating circuit and a battery power supply. When the pulse generator is switched on, vibrations are transmitted through the throat wall into the pharynx cavity and transformed into speech by the normal use of the articulatory mechanisms of the vocal tract. The loudness of the speech obtained with this unit is comparable with that of a normal person speaking conversationally. The artificial speech so produced sounds somewhat mechanical, but it is quite intelligible. By the use of an easily operated inflection control, a degree of naturalness heretofore unobtainable in artificial larynges may be achieved.

II. HISTORY OF BELL SYSTEM ARTIFICIAL LARYNX WORK

There is substantial evidence that artificial larynges were used as early as 1874, but it was not until 1925 that the Bell System became concerned with this area of communications. F. B. Jewett, who was president of Bell Telephone Laboratories at that time, suggested the development of an artificial larynx. His suggestion was prompted by discussions with a friend who had been laryngectomized and had impressed him with the need for a device that was more satisfactory than any then obtainable.

The Laboratories' initial efforts resulted in an instrument that employed rubber bands stretched in a manner to simulate the vocal cords, and was designated type 1A. These rubber bands deteriorated rapidly and were a source of considerable dissatisfaction. Consequently, during 1929 a new larynx, designated type 2A, was developed that incorporated several refinements,[3] including the substitution of a vibrating metallic reed for the elastic bands. It is this model, with a few minor changes, that is currently being manufactured by the Western Electric Company and distributed by the Bell System operating companies. The method of operation of the 2A artificial larynx is illustrated by the sagittal section view of the head in Fig. 1. The metallic reed is connected by tubing to the stoma in the throat, so that the user's breath can actuate the reed. The sound of the vibrating reed is conducted through another tube into the mouth, and this sound is used in the production of artificial speech sounds with normal tongue, lip and jaw movements.

In all, about 200 of the Model 1A larynges were made between 1926 and 1930, and about 5500 of the Model 2A larynges have been made to date. Since about 1950, the demand has remained constant at approximately 300 per year, although the number of laryngectomies performed annually has increased steadily. This leveling-off has occurred partly because there has been a marked increase during the last ten years in the use of esophageal speech, with the establishment of many speech clinics for the purpose of training laryngectomized patients in this method of speaking.

However, as noted previously, about a third of the total number of laryngectomized patients are unable to use esophageal speech, and consequently the need for an improved artificial larynx has become more urgent. In response to this need an advisory committee on artificial larynges was set up in 1956 by the National Hospital for Speech Disorders in New York, and its recommendations have provided helpful stimulation and guidance in the development of the new experimental model.

III. DESIGN OBJECTIVES FOR AN IMPROVED ARTIFICIAL LARYNX

In determining objectives toward which artificial larynx experimentation should be directed, preliminary discussions were held with the committee mentioned above, whose members include several surgeons, speech therapists and postlaryngectomized patients. To supplement the information obtained from them, all of the artificial larynges that were commercially available were studied and analyzed to ascertain their individual advantages and deficiencies.

The primary requirements, of course, were that the artificial speech be loud enough and natural enough so that the speaker could be easily understood. For the speech to sound natural, it should have pitch inflection, and, like the natural voice, should have a suitable fundamental pitch accompanied by harmonics that can be used to produce the various vowel sounds. These objectives were discussed in some detail in a recent paper.[4]

Secondary to the above, but still of great importance to the user, were the objectives that the device be inconspicuous and hygienic. It is in

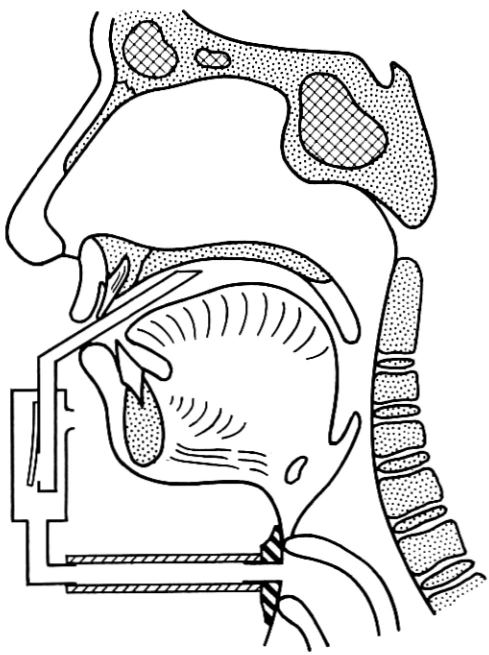

Fig. 1 — Sagittal section showing method of operation of reed-type larynx.

these respects that most of the presently available devices are deficient. If the user has to insert a tube into his mouth, it not only calls attention to his disability, but is also hygienically undesirable. Any connection at the opening in the throat, such as that required for the Western Electric Model 2, leaves much to be desired from the hygienic standpoint. In electrical devices, dangling wires leading to battery cases are also embarrassing and are liable to become entangled with other objects. The importance of making prosthetic devices inconspicuous may be inferred from the great efforts that hearing aid manufacturers have expended to make their product less noticeable in use.

Other desirable characteristics were simplicity of operation, reliability and low cost. Simplicity of operation is very desirable so that the patient will require only a minimum of training and, as soon as possible, gain the psychological benefits of vocal communication with his family and friends. Reliability and low cost can probably be attained most easily by the use of components that are already available commercially.

The design objectives, therefore, can be listed as follows:

(1) having output speech volume equal to that of a normal speaker,

(2) having output speech quality and pitch inflection like that of normal speech,

(3) inconspicuous,

(4) hygienically acceptable to the user,

(5) simple to operate,

(6) reliable,

(7) inexpensive.

IV. ACOUSTIC FACTORS IN PRODUCTION OF ARTIFICIAL SPEECH

4.1 *Types of Sound Source Needed*

In the production of normal speech, two types of sound energy are involved. One is a periodic tone produced by the vocal cords. It is variable in frequency and rich in harmonics, and is introduced into the pharyngeal cavity of the vocal tract. Except in whispered speech, this tone is always used in vowels and semivowels, including the nasal consonants, and is present in some other "voiced" consonants.

This normal vocal cord tone is completely lost when the larynx is removed. The esophageal speaker has learned to substitute the vibration of membranes at the mouth of the esophagus. But, if this sound cannot be produced and controlled adequately, another tone source must be supplied, and this is the chief function of the artificial larynx. For intelligibility of the speech produced, it is essential that the tone contain a wide range of harmonics, and, for naturalness, the harmonic amplitudes should fall off toward higher frequencies at the same rate that the real vocal cord tone does. Also, the tone should match that of the normal larynx in fundamental frequency and in frequency variability.

The second type of sound energy in speech is random noise, which is produced when the breath stream passes through a constriction formed by tongue or lips. It is present in stop and sibilant consonants, sometimes alone and sometimes in combination with the vocal-cord tone. These sounds are vital for the intelligibility of speech.

The normal means of generating random noise by the breath stream is also lost in the usual laryngectomy. However, it is not necessary to supply a substitute in an artificial larynx. Air trapped in throat and mouth can be forced out in such a way as to take the place of the normal breath stream in forming most of these sounds. Some deficiencies occur, such as a shortening of continuants like "s" and "sh", due to an insufficient volume of the trapped air; and the sound "h" is usually completely lost. The Western Electric reed-type artificial larnyx improves the ability to make some of these sounds, by allowing some breath stream to pass through the reed chamber into the mouth.

4.2 *Point of Application of Substitute Tone*

To match as nearly as possible the natural speech process, the artificial tone should be applied in the pharyngeal cavity. This requirement is not met in the Western Electric reed-type artificial larynx, yet understandable speech is produced. It is of interest to see just what changes in the quality of speech sounds result from a change of source application from pharynx to mouth.

It may be shown theoretically that a change from throat to mouth application, keeping the vocal tract configuration constant for a given vowel, does not change the resonant frequencies characteristic of that vowel. It does, however, change the relative amplitudes of the different resonances. The extent of the change depends upon the degree of constriction imposed by the tongue, which is different for different vowels. Another manifestation of the change is the appearance of antiresonances, which are not present when the source is in the throat.

To confirm these conclusions, two experiments were performed. In the first, an artificial tone was introduced into the pharynx of a human subject. A tube was attached to a transducer that produced the tone, and passed through the nose of the subject and into his pharynx until the opening of the tube was not far from his vocal cords.

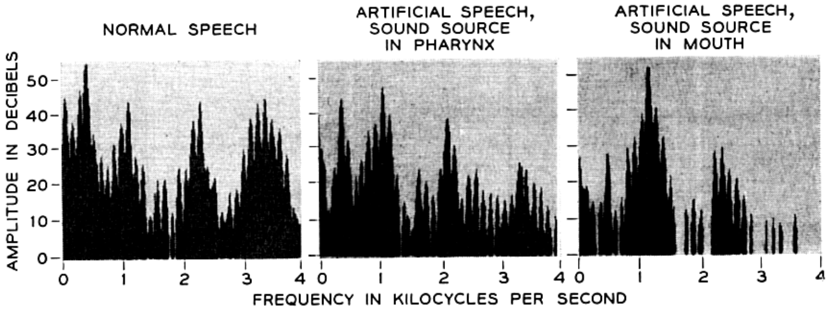

Fig. 2 — Sound spectra of vowel sound "oo" (as in "book") spoken normally and as produced artificially with sound source in pharynx, and in mouth.

Fig. 2 shows spectra taken as the subject made the vowel sound of "book". The first was made with his own vocal cords. The same vowel made with the artificial source yields the second spectrum. Although some pains were taken to make the spectrum at the output of the tube approach that of the real cord tone, some differences can be seen. The third spectrum was produced with the artificial source withdrawn from the pharynx and placed in the mouth of the subject. Particularly to be noticed are the change in relative amplitudes of the first two resonances and the "holes" in the mouth spectrum due to the antiresonances.

The second experiment made use of the Electrical Vocal Tract,[5,6] an analog of the vocal tract in which cavities are represented by lengths of transmission line and constrictions by inductances placed in series with the line (the tongue), or at its termination (the lips). An electrical complex tone can be applied easily to either throat or mouth cavity. Settings of such a device can be held constant more easily than a human subject can maintain a particular vocal tract configuration. On listening to the output of the artificial tract, it was found that vowel sounds changed considerably in character when the source was moved to the mouth. However, some but not all of their original naturalness could be restored by manipulation of the settings. It seems likely that the reed-type larynx user makes these readjustments naturally under the guidance of his own hearing, and that this accounts for the fact that his speech is still very intelligible.

Fig. 3 shows transmission measurements made with a sine-wave input on the Electrical Vocal Tract, in the three settings determined by previous listening tests: (1) the vowel "oo" (as in "fool") with a source in throat, (2) the same settings with source in mouth and (3) with controls readjusted to restore "oo" as nearly as possible.

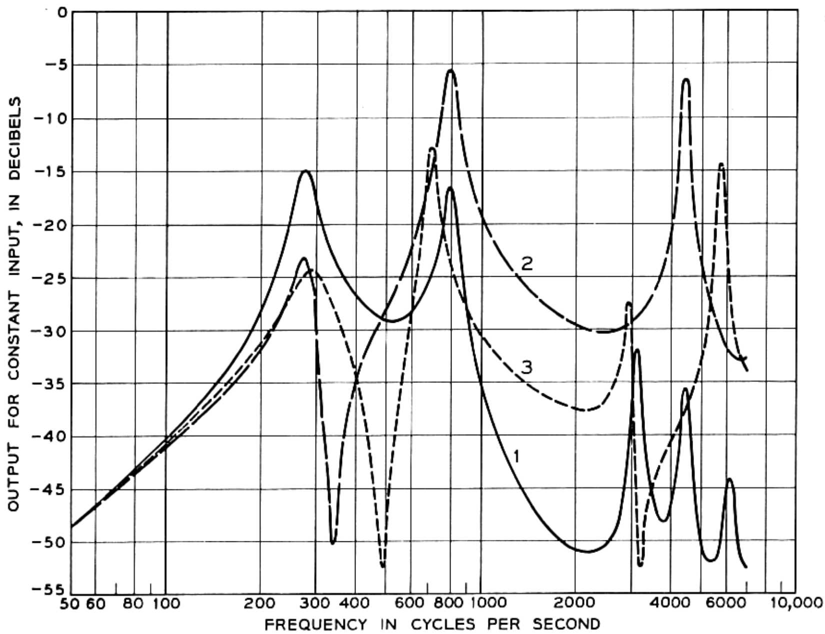

Fig. 3 — Transmission vs. frequency characteristic of electrical vocal tract: (1) adjusted for vowel "oo" (as in "fool") with source in throat position; (2) same settings, but with source in mouth position; (3) with source in mouth, but with controls readjusted to restore the "oo" sound as nearly as possible.

Although it would seem that excitation in the mouth is not as disadvantageous as it at first appears, pharynx excitation is still preferable. It is, of course, not practicable to introduce the sound through the nasal cavities as was done for the subject in the experiment described. In fact, insertion of any outside bodies into throat and mouth tends to be unhygienic. However, sound can be introduced into the throat from outside by transmission through the throat wall. This principle was used in an artificial larynx designed by Wright.[7] In the present development, it has been found possible to produce an adequate spectrum in the pharynx by this method, while at the same time limiting to a reasonable level the sound radiated directly from the device.

4.3 *The Use of a Throat Vibrator to Provide Substitute Vocal-Cord Tone*

The experiments just described indicate that the preferred position for the sound source is in the pharynx. Some thought was given to the use of a transducer surgically embedded in the throat. However, this would require a second operation for those who already had been laryngectomized, and the opinions of doctors consulted on the subject were divided as to its advisability. Accordingly, it was considered to be outside the scope of the present artificial larynx project. The problem then became one of transmitting through the flesh and cartilage around the pharynx a complex signal with a broad frequency spectrum. In order to obtain natural-sounding speech, the source spectrum must have strong low-frequency components. The total frequency range required extends from about 100 to several thousand cycles per second.

Experiments were conducted using a variety of vibrating devices held against the outside of the throat. Some of these were constructed especially for these tests and the rest were devices obtainable commercially. Of all these, the HA-1 telephone receiver used in the type 300 telephone sets proved the most promising.[8] However, when pressed against the throat, the loading on the diaphragm was far different from what it is when working into air, since the characteristic mechanical impedance of flesh is some 4000 times that of air. This heavy loading made desirable a number of modifications in the receiver to enable it to give a greater amplitude of vibration into the throat. These modifications are described in Section 5.4.

V. CIRCUIT AND MECHANICAL CONSTRUCTION

The circuit of the new experimental artificial larynx uses a highly efficient arrangement of transistors powered by mercury batteries to provide a compact, self-contained unit. In its design, an objective was to use commonly available, inexpensive components wherever possible. Fig. 4 illustrates the cylindrical configuration of the unit, with the combined on-off switch and pitch-inflection control knob arranged for operation by thumb or forefinger.

5.1 *Transistor Circuit*

A schematic diagram of the circuit is shown in Fig. 5. It is essentially a two-stage relaxation oscillator followed by a power stage that works into a transducer. The relaxation oscillator uses a p-n-p transistor, Q_1, and an n-p-n transistor, Q_2, coupled together with regenerative feedback. The frequency of oscillation is determined by the pitch-control resistance, R_1, in combination with capacitance C_1. The output of the relaxation oscillator appears across resistance R_5 as a series of short periodic pulses. The width of these pulses is determined by resistance R_2 and capacitance C_1. The values shown in Fig. 5 give a pulse width of 0.0005 second.

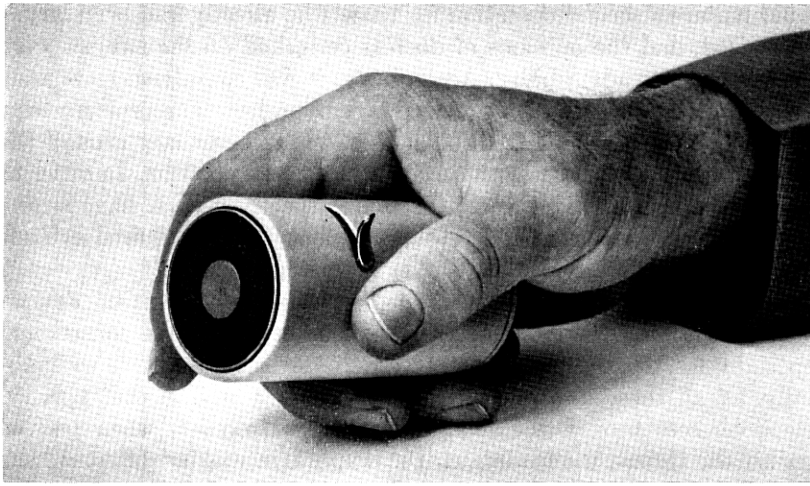

Fig. 4 — Picture of artificial larynx showing thumb-operated on-off switch and inflection control.

The periodic pulses generated in the relaxation oscillator are transmitted through the semiconductor diode, CR_1, to the base of power transistor Q_3. The HA-1 receiver is connected in the collector circuit of Q_3, and receives short periodic current pulses of about 0.45 ampere peak value at the oscillation frequency.

The range of oscillating frequency may be adjusted by changing the range of resistance R_1 available in the pitch-control rheostat, to simulate either a man's or a woman's pitch range. For men, the range is from 100 to 200 cycles and, for women, it is from 200 to 400 cycles. This is an octave range in either case, and is sufficient to duplicate the pitch inflection used in normal speech. The on-off switch and pitch-control rheostat are arranged so that the switch is closed at the lowest oscillating frequency, and further movement of the control causes the frequency to increase. The control knob is spring-loaded so as to return it to the off position when released.

Two 5.2-volt mercury batteries in series provide the necessary power to operate the circuit. Although the peak is 0.45 ampere, the pulse duty factor is so small that the average current drain from the batteries is only about 22 milliamperes. The rating of the batteries is 250 milliampere hours.

As an alternative to the self-contained mercury batteries, a small rectifier operated from 115-volt, 60-cycle line voltage may be substitued. This arrangement may be useful at an office desk or other fixed location.

When the rectifier power supply is plugged into the auxiliary power jack shown in Fig. 5, the batteries are disconnected from the circuit.

5.2 *Selection of Pulse Duty Cycle*

The average current drain on the batteries, the spectrum of the acoustic output of the artificial larynx and the loudness of the output, are all functions of the pulse width, assuming a fixed supply voltage. For widths of a few tenths of a millisecond, the average current drain would be low, and the spectrum would have a wide frequency band with strong harmonics running up to several thousand cycles per second, but the acoustic output would be weak. Fig. 6 shows the relation between acoustic output and pulse width, and also the relation between current drain and pulse width. The acoustic outputs displayed were obtained by measuring the output from a single subject saying "ah" at a distance of 3 feet from the sound level meter. Pulse widths of 0.5 to 0.6 millisecond gave near-maximum output. For wider pulses, the acoustic output decreased, and the speech became somewhat muffled and nasal in quality. A pulse width of 0.5 millisecond was adopted. Correspondingly, the average current drain was 22 milliamperes at a frequency of 100 pulses per second. Sound spectrograms of speech using the 0.5-millisecond pulse width indicated a satisfactory spectrum.

5.3 *Mechanical Construction*

For simplicity of construction, a cylindrical container was chosen to house the artificial larynx. The dimensions of the experimental model are

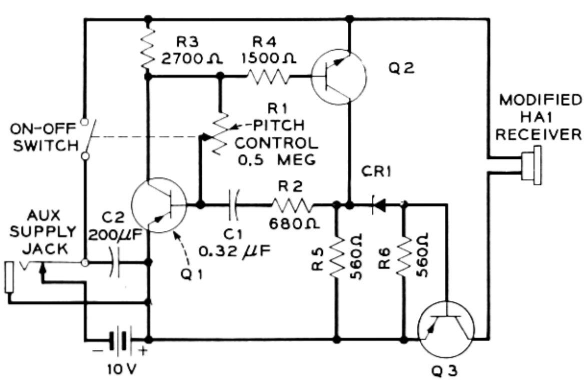

Fig. 5 — Schematic of artificial larynx circuit.

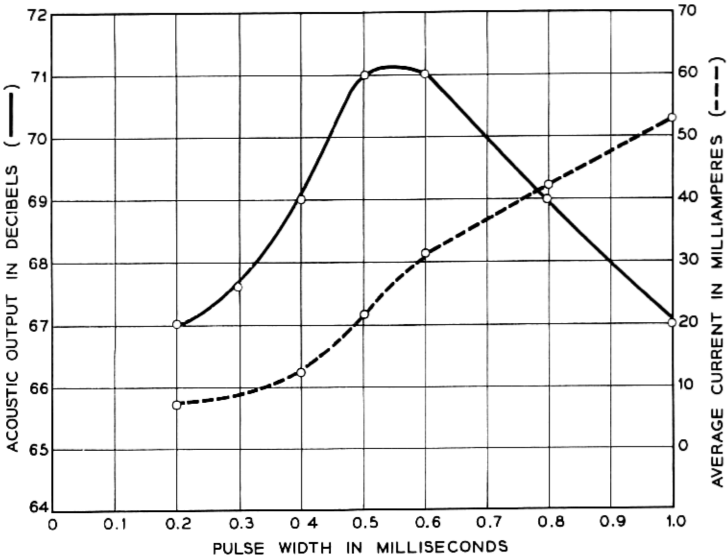

Fig. 6 — Characteristics of acoustic output vs. pulse width, and average battery supply current vs. pulse width.

$1\frac{3}{4}$ inches in diameter and $3\frac{1}{4}$ inches long. The weight, including batteries, is 8 ounces. To package all the components in this volume, a modular type of construction was used, as shown in the exploded view in Fig. 7.

The HA-1 receiver is at the front end of the unit, with the diaphragm flush with the end of the cylinder. The back of the receiver is wrapped with sponge rubber, and two discs of sponge rubber and one of thin brass sheet are placed between it and the adjacent components to attenuate the backward radiation of sound. Were it not suppressed, this direct radiation back through the shell and into the surrounding air would tend to mask the speech sounds and contribute a buzzy, mechanical quality to the over-all effect.

The next two modules back of the receiver contain the pitch-control rheostat, the transistors and associated circuit elements. The last module contains the two mercury batteries in a plastic shell and the jack for the external power supply. The back plate may be removed by unscrewing a single machine screw which has a slot large enough so that a thin coin may be used in place of a screwdriver. This permits convenient access to the mercury batteries for changing them without disturbing the rest of the circuit.

While the experimental model is a compact unit, some further miniaturization could be achieved by the use of printed circuit techniques and closer component spacing.

5.4 *HA-1 Receiver Modifications*

The HA-1 receiver as normally used in a telephone set has a protective metal grid and cloth cover over the diaphragm. For use in the artificial larynx these are removed. And, in order to achieve greater efficiency in terms of output volume of artificial speech for a given battery supply power, several additional modifications were made.

The permanent magnets were magnetized to full strength, instead of being only partially magnetized. The diaphragm was correspondingly shimmed out from the pole pieces, so that it would not be pulled into contact with them. The spacing between diaphragm and pole pieces in this condition measures between 0.002 and 0.003 inch, and a slight push on the diaphragm is sufficient to make it adhere to the pole pieces. The electrical pulses from the transistor circuit are so poled as to oppose the permanent magnet field and release the diaphragm to spring outward. This driving polarity gives higher speech volumes than the opposite one.

In order to obtain sufficient current from the 10.4-volt supply to counteract the permanent magnetization, it was necessary to decrease the impedance of the receiver winding by connecting its two coils in parallel instead of in the usual series arrangement. In order to improve the match of mechanical impedances between the receiver and the throat, a diaphragm of 0.0083-inch permendur was used in place of the standard 0.011-inch thickness provided in the HA-1. A series of tests was made with a range of thicknesses from 0.0065 to 0.011 inch, and it was found that the highest speech volumes were obtained with a thickness in the order of 0.0083 inch.

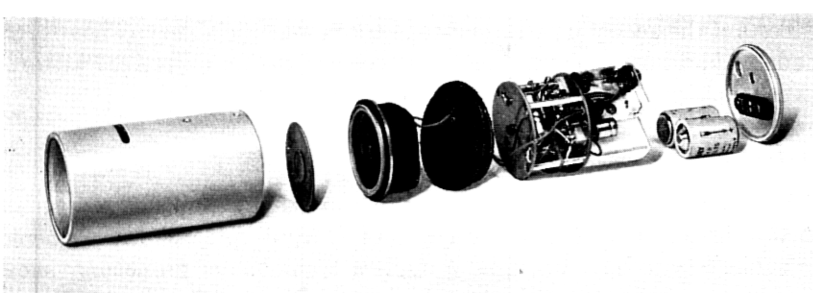

Fig. 7 — Exploded view of artificial larynx, showing modular construction.

In order to reduce the magnetic saturation of that area of the diaphragm between the pole pieces, a small center patch of permendur, 0.54 inch in diameter and 0.011 inch thick, was spot-welded to the diaphragm before heat treatment. This addition improves the magnetic circuit and does not materially affect the stiffness of the diaphragm.

The HA-1 receiver normally has a small resonance damper provided by a cloth-covered hole in the plastic back under the diaphragm. This damps the natural diaphragm resonance, which in air falls at about 3000 cycles. The cloth covering this hole is removed in the artificial larynx, and diaphragm damping is obtained by contact with the flesh of the throat. Removal of the cloth damping patch slightly increases the output of high-frequency harmonics in the artificial speech.

5.5 *On-Off Switch and Inflection Control*

The arrangement of the on-off switch and inflection control was designed for ease of manipulation. With practice on the present arrangement, either rising or falling inflection can be achieved at the beginning or ending of voicing.

Several other methods of control were tried. One made use of a rack and pinion gear arrangement, in which a button was pushed straight into the shell of the unit. Precise control of frequency was not easily obtained with that method. It was found more satisfactory to push the control sideways over a distance of a half-inch or more. Another early version depended for control on application of pressure along the longitudinal axis of the artificial larynx. This seemed satisfactory from the functional standpoint, but was more difficult to implement mechanically than the arrangement finally adopted.

VI. ACOUSTIC PERFORMANCE

Tests of the acoustic performance of the new artificial larynx have been made to find how nearly it meets the original design objectives with respect to output volume and speech quality.

6.1 *Loudness*

A little practice is required to find the proper pressure and placement on the throat that yield the best results. Output volume measurements on subjects who have acquired a moderate amount of proficiency show sound pressure levels on the vowel peaks of 70–75 db above 0.0002 microbars at a distance of three feet from the speaker's mouth. This is approximately a normal conversational level. However, in an environment so noisy as to require a speaker to raise his voice appreciably above the normal level, this volume would limit the separation between talker and listener to shorter distances than those possible for a normal speaker.

6.2 *Frequency Spectra*

Speech quality has been checked by comparisons of frequency spectra, and by measurement of the ratio of speech signal to directly radiated buzz. Spectrograms[9,10] of the words "artificial larynx" and amplitude sections of ten vowel sounds were made from the speech of one subject, using both the new artificial larynx and his natural voice. These are reproduced in Figs. 8 and 9 respectively. In Fig. 8, it may be seen that the "f" and "sh" sounds in the word "artificial" are shorter in duration for the artificial larynx speech than for the normal speech. With the artificial larynx, the speaker must make such sounds by means of the air trapped in his mouth and pharynx since his normal air supply is cut off.

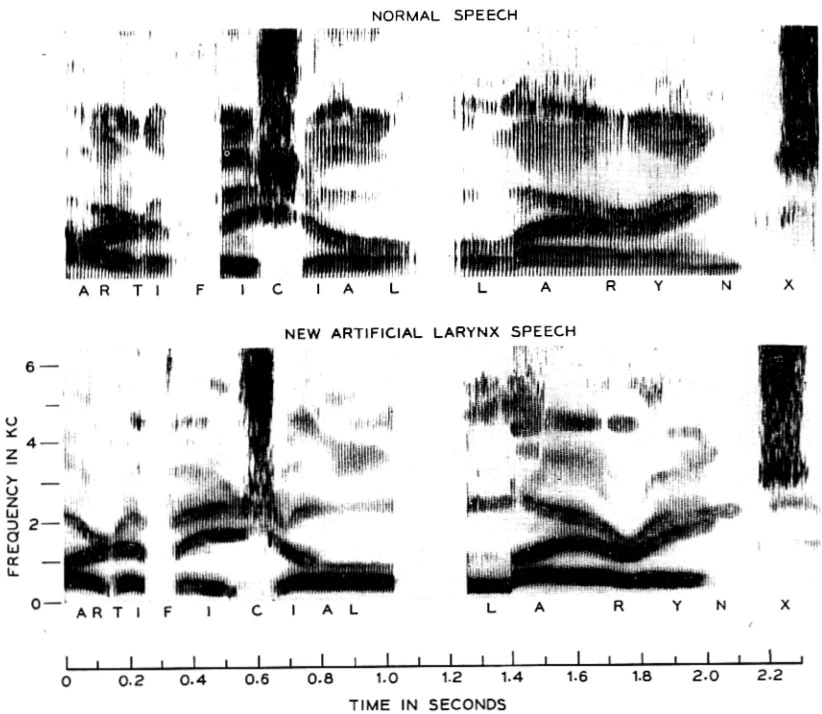

Fig. 8 — Sound spectrograms of the words "artificial larynx" as spoken normally and with the new experimental artificial larynx.

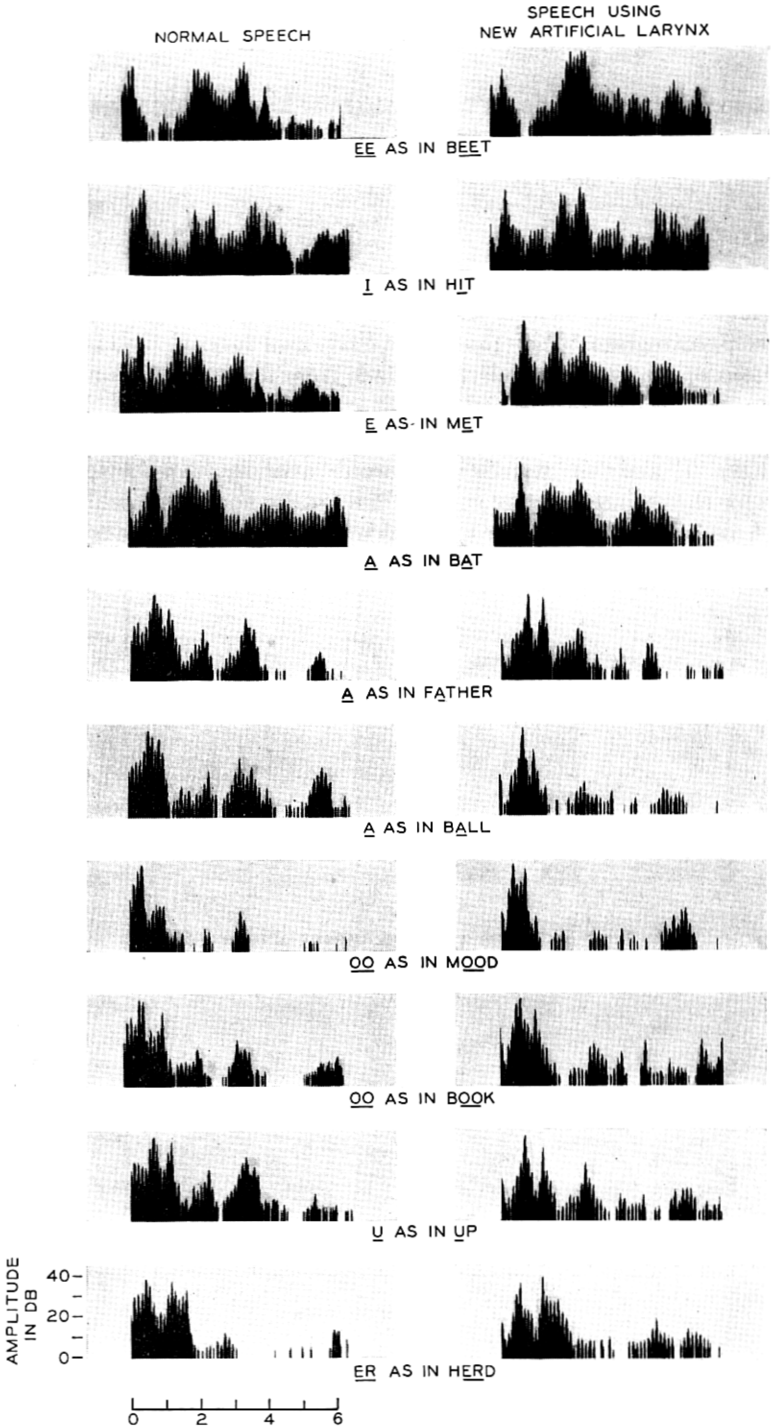

Fig. 9 — Sound spectra of ten sustained vowel sounds as spoken normally and with the new experimental artificial larynx.

This small air supply thus tends to shorten fricatives and sibilants, but the spectrogram indicates that they can be made satisfactorily. Some practice was required to make the "sh" sound in "artificial" as long as that which is shown.

In using the artificial larynx it is more convenient to leave it turned on through several syllables or words than to turn it on and off as one does in natural voicing. That this does not make the speech as unnatural as one might expect is indicated also in Fig. 8. The instrument was turned off between the two words, but it can be seen that, for the "t", "f", "sh" and "x" sounds, very little of the voicing comes through, although the device was operating while those sounds were being produced. For the unvoiced fricatives and stop consonants, the sound transmission path from the pharynx is evidently nearly closed off.

In the comparison of the vowel spectra shown in Fig. 9, it is apparent that the new artificial larynx is able to transmit sufficient power into the pharynx throughout the spectrum to permit satisfactory development of the high-amplitude regions (formants) of the vowel sounds. It has been indicated[4] that the harmonics in the source spectrum of the natural voice are strongest at the low frequencies, dropping in amplitude toward the high frequencies at about the inverse 1.5 power of the harmonic number. A cross comparison in Fig. 9 shows that, for some vowels, the difference in the high- and low-frequency amplitudes is greater for the natural source, and, for others, it is greater for the artificial source. This observation leads to the conclusion that, on the average, the artificial source has approximately the right spectrum.

6.3 *Externally Radiated Interference*

Some of the sound produced by the vibrating diaphragm does not pass through the speaker's throat but is radiated directly by the instrument itself or from areas of the throat around the place where the unit is pressed. This external radiation, of course, would interfere with the intelligibility of the speech if it were not well suppressed. Measurements taken in an anechoic chamber with the unit pressed against the throat but with the mouth closed showed an intensity level for this interference 20–25 db below the level when the vowel "ah" was being voiced. When the unit is operated with the vibrating end working into a sound-absorbing cavity, the level is about 6 db lower still, indicating that most of the interfering sound is from the throat areas immediately adjacent to the artificial larynx rather than from the instrument itself. If it should be desirable to reduce this noise still further, the end held against the throat might be specially shaped to reduce the external vibration of the throat tissues.

6.4 *Reactions of Laryngectomized Users*

In collaboration with the Advisory Committee on Artificial Larynges tions. Four units of the new design were used in the field test; two were assigned to two laryngectomized patients for the entire period of four weeks, and the other two units were used for shorter periods by several other patients. In all cases, favorable comments were made on the speech quality and the lack of externally radiated buzz. Comments of friends and relatives of the patients using the new model generally indicated that they liked the intelligibility and speech quality of the artificial speech produced by it.

One comment was made to the effect that, for optimum comfort in use, the diameter of the unit should be somewhat less. Adoption of this suggestion would preclude the use of the HA-1 receiver. The Advisory Committee on Artificial Larynges of the National Hospital for Speech Disorders felt that, for nearly all patients, the present diameter of $1\frac{3}{4}$ inches would be satisfactory, and did not recommend such a change.

Battery life was indicated to be satisfactory in these tests. The new units were used alternately with other models by the two patients who had them for the entire test period, and it is not known just what their cumulated operating times were. One of the two patients estimated that he had used the new unit for about half of his talking. None of the four units in the limited field test required a change of batteries during the four-week period.

VII. ARTICULATION TESTS

Articulation tests using speech produced by practiced talkers with previously available artificial larynges have been carried out. These tests were intended as a guide in the development of the new instrument. A second set of tests was made after the new experimental model was available, comparing it with previous types.

7.1 *Tests with Previous Types*

For the first test, it was possible to obtain two experienced users of esophageal speech, of the reed-type artificial larynx, and of an

TABLE I — PERCENTAGES OF PB WORDS HEARD CORRECTLY, FROM NATURAL AND SUBSTITUTE-LARYNX SPEECH

Natural voices	97.3 96.6
Esophageal speech	79.0 64.1
Reed-type artificial larynx	63.4 40.3
Throat-type artificial larynx	58.1 40.3

available type using throat application. These individuals were asked to read five of the Harvard PB (phonetically balanced) lists of 50 monosyllabic words.[11] Their utterances were recorded on tape and presented later, in a suitably mixed order, to a crew of seven listeners who recorded their responses. Two speakers with normal voices were included for comparison. The percentages of words heard correctly are given in Table I.

To understand the significance of these scores, it has been found that a 60 per cent articulation from such isolated words corresponds to a sentence intelligibility of more than 95 per cent, and that even 40 per cent in the word score means that more than 90 per cent of sentences would be understood.

In a test supplementary to the above, it was found that the articulation score with the throat type tested could be improved to about 70 per cent if the directly radiated sound were reduced about 20 db.

The number of individuals in the tests was too small to indicate an over-all ranking for the different types. It can be concluded, however, that either the reed type (with mouth application) or the external throat type could be sufficiently intelligible to give good conversational ability. The choice between these types could therefore be made by other criteria.

7.2 *Comparison of New with Best of Older Types*

The second set of tests was abbreviated, and was intended to provide a comparison between the new larynx and the previous types. Thus, only the higher-scoring individuals using the reed and throat types in the previous tests, with two PB lists (100 words) each, were incorporated. These utterances were compared with 100 words from the new experimental model. Because of changed conditions (principally the use of a crew of listeners who were less familiar with laryngectomized speech) the results shown in Table II are not directly comparable with the previous tests. They are comparable with each other, however.

With regard to population averages, these figures cannot be considered indicative. The differences, however, are favorable for the new model.

VIII. CONCLUSIONS

An artificial larynx has been developed that is hygienic, convenient and inconspicuous. It has a fundamental tone that is similar in pitch

TABLE II — ARTICULATION SCORES FROM NEW EXPERIMENTAL ARTIFICIAL LARYNX AND FROM THE MORE SUCCESSFUL USERS OF OLDER TYPES

Older throat type	43 per cent
Reed type	52 per cent
New experimental model	59 per cent

range and variability to the real voice, and near enough in spectrum to produce natural-sounding speech. The loudness of the speech produced with it is comparable to that used in normal conversation, and the speech is generally free of masking effects of directly radiated noise. The essential characteristics and performance of this experimental model will be incorporated into a commercial design to be manufactured by the Western Electric Company. Distribution of the new model, beginning some months hence, will be through the Bell System operating companies, following procedures similar to those used with the Model 2 reed-type larynx for the past 30 years.

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