Phonetica *25:* 140–164 (1972)

The Activity of the Intrinsic Laryngeal Muscles in Voicing Control

An Electromyographic Study[1]

H. Hirose[2] and T. Gay[3]

Haskins Laboratories, Inc., New Haven, Conn.

Abstract. The primary purpose of this experiment was to systematically investigate the actions of the intrinsic muscles of the larynx during the production of voiced and voiceless consonants.

Generally speaking, computer-averaged EMG curves for the laryngeal muscles showed participation of the posterior cricoarytenoid for voiceless consonants and suppression for voiced consonants. The reciprocal pattern was found for the interarytenoid muscle. Similar reciprocal patterns were evident along the timing dimension. These results are discussed in terms of recently proposed laryngeal feature systems.

Introduction

Although a considerable number of laryngeal electromyographic (EMG) studies on the mechanism of phonation have been conducted during the past decade, EMG studies of the intrinsic laryngeal muscles during speech are still in their preliminary stages. This is due, mainly, to the technical difficulties in data acquisition using conventional needle electrodes during complex and rapid movements of the articulators in speech gestures and, also, in extracting subtle changes in muscle activity patterns from raw EMG data. However, recent advances in EMG recording and processing techniques have helped us overcome these technical problems. In particular, the use of double-ended hooked-wire electrodes [3] gave us a combination of electrode stability in the muscle with little discomfort to the subject. Also, the

---

[1] This article is an expanded version of a paper presented at the 1971 Convention of the American Speech and Hearing Association, Chicago, November 1971. The research was supported by Grant No. DE-01774, National Institute of Dental Research, National Institutes of Health.

[2] On leave from Faculty of Medicine, University of Tokyo.

[3] Also University of Connecticut Health Center.

use of a digital computer system to obtain an averaged EMG activity pattern for a number of tokens of a given speech utterance provides a convenient and accurate means for quantifying a pattern of contraction of a given muscle or muscle group.

Most of the previous studies in laryngeal physiology generally support the classical division of the intrinsic laryngeal muscles into three functional groups – abductor, adductor and tensor. However, there still are many unanswered questions concerning the function of individual laryngeal muscles in speech articulation.

In particular, the participation of the posterior cricoarytenoid muscle (PCA) in speech has not been systematically studied, although the function of the PCA as a respiratory muscle has been well documented [22, 27]. As far as PCA activity in phonation is concerned, Faaborg-Andersen [6] reported that EMG activity of the PCA decreased during sustained phonation. Kotby and Haugen [19] on the other hand, observed increasing activity in the PCA during phonation and postulated that the PCA is not solely an abductor muscle. Dedo [5] also reported increasing activity in the PCA during phonation in some of his clinical cases. However, the data of these authors are concerned exclusively with sustained vowel phonation, when fundamental frequency is not specified.

Hiroto *et al.* [16] examined laryngeal muscle activity for some Japanese words containing an intervocalic fricative /s/ and stated that there was a temporary change in the electrical activity of all the intrinsic laryngeal muscles (except for the cricothyroid) corresponding to voiceless consonant articulation. What they observed in their data was an apparent increase in PCA activity accompanied by a decrease in the activity of the adductors for articulation of the intervocalic /s/. Hirano and Ohala [10] showed one example of a raw EMG record of the PCA, illustrating increasing activity for release of glottal stops with reciprocally decreasing activity in the interarytenoid.

As far as the adductor laryngeal muscles are concerned, there has been, again, no systematic description of their function in speech articulation, although the possibility of functional differentiation of the adductor muscle group was suggested by one of the present authors in a previous report [12].

The primary purpose of the present study was to systematically investigate the actions of the intrinsic laryngeal muscles in speech with special reference to the articulation of segmental features of American

English. Particular attention was directed to the function of the PCA. An attempt was also made to investigate the temporal aspects of consonant production by studying the timing relationships between laryngeal and supralaryngeal muscle activity patterns.

Procedures

Subjects

The present experiment was performed on two adult male subjects, both native speakers of American English; for one subject, two separate retest recordings were made, thus giving a total of four sets of data. Table I lists the muscles examined in each session for the experiment.

Preparation and Insertion of Electrodes

Hooked-wire electrodes, after the type developed by BASMAJIAN and STECKO [3] were used in the present study. Briefly, these electrodes are produced by threading a pair of thin wires through the cannula of a hypodermic needle and bending the exposed ends of the wires back over the needle to form a pair of hooks. The entire assembly is inserted into the muscle, after which the needle is withdrawn. This leaves only the hooked ends of the wires anchored into the muscle. Removal of the wires requires only a light tug. In this experiment, a platinum-iridium alloy (90–10%) wire (0.002 in diameter and polyester-enamel coated) was used in conjunction with either a No. 26 or No. 27 gauge needle.

The posterior cricoarytenoid (PCA) and the interarytenoid (INT) muscles were reached perorally while the vocalis (VOC)[4], lateral cricoarytenoid (LCA) and cricothyroid (CT) muscles were reached percutaneously, after the procedure described by HIRANO and OHALA [10]. Premedication consisted of the administration of 5–10 mg Valium and 7–10 drops of Tincture of Belladonna by mouth. Subjects were seated in an examining chair throughout the experiment.

For the peroral insertions, an anesthesia procedure utilizing Cetacaine spray and a gargle of 2 ml of 2-percent Xylocaine was sufficient to desensitize the pharyngeal and laryngeal areas to a point where indirect laryngoscopy could be easily tolerated. A Xylocaine-soaked cotton swab was then applied to the specific areas selected for electrode insertion. The posterior cricoarytenoid and the interarytenoid were reached by using an L-shaped rod with the carrier needle epoxy-bonded to the shorter arm. The needle was threaded in the conventional manner. The entire assembly was directed to the point of insertion by indirect laryngoscopy [15].

The percutaneous insertions were preceded by topical administration of 2-percent Xylocaine through a Pan Jet-70 air jet [13], at the site of the needle insertions. The electrode insertion techniques for the vocalis, lateral cricoarytenoid and cricothyroid are described in detail in previous reports [8, 15].

In all cases, correct electrode placement was verified by monitoring an oscilloscope during various functional maneuvers. At the same time, the muscle signals were amplified and fed to a loudspeaker for auditory monitoring [13].

Data Recording and Processing

In order to obtain a convenient quantitative record of muscle activity, the raw EMG signal can be easily transformed into a display of amplitude versus time by the process of

---

[4] By reason of both past experience and the verification techniques employed, we are confident that we isolated the vocalis portion (vocalis muscle) of the thyroarytenoid. However, since the insertion was not viewed directly, we cannot be virtually certain that the electrode field did not include any potentials from the 'external' thyroarytenoid.

Table I. Muscle insertions for both subjects

Subject L.L.
  Posterior cricoarytenoid
  Interarytenoid
  Vocalis
  Cricothyroid

Subject L.J.R.
  Series A
  Posterior cricoarytenoid
  Vocalis
  Cricothyroid

  Series B
  Posterior cricoarytenoid
  Lateral cricoarytenoid
  Orbicularis oris
  Genioglossus

  Series C
  Posterior cricoarytenoid
  Interarytenoid

full-wave rectification and RC smoothing (integration). Generally speaking, the envelope of the integrated curve is an indication of the strength of the muscle contraction. This is only an approximation, however, as the amplitude of the recorded signal varies with the distance between the electrodes and the active motor units of the muscle. Further, since the integrated curve represents the vector sum of a number of asynchronously discharging motor unit potentials, and since productions of identical utterances vary from one token to the next, a number of these curves must be averaged before a reasonably stable picture of muscle activity at a given electrode position can be obtained.

The basic data processing procedure followed in this experiment was to collect EMG data for a number of tokens for each of the test utterances and, using a digital computer, average the integrated EMG signals at each electrode position.

A block diagram of the EMG recording and processing system used in the present study is shown in figure 1. The system contains 14 data channels of which 8 are for the recording of EMG signals. The other imputs are for the acoustic signal, air pressure data, a banter channel for the experimenter's comments, and finally, 2 channels for a clock track and digital code pulse. In addition, a calibration signal alternates with the EMG signals intermittently throughout the run. This signal is used by the computer to calculate the EMG levels in actual microvolts.

The purpose of the digital code pulse (octal format) is to identify each utterance for the computer. This pulse code is laid down on the tape, automatically, at 1-sec intervals. Before actual processing, the computer receives instructions on how the various tokens of a given utterance are to be superimposed or lined up with each other. This is done by marking the time interval between the nearest code pulse and any preselected line-up point, which can vary for each utterance type. During the data-processing run, all calculating and tabulating operations are done automatically. The averaged output curve is plotted on a strip chart recorder.

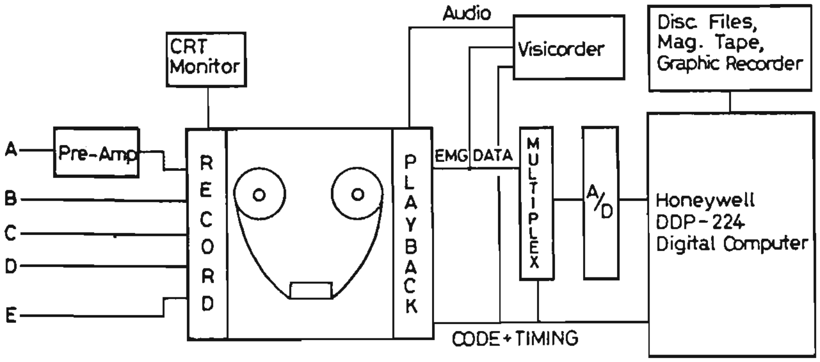

Fig. 1. Blockdiagram of the EMG data acquisition and processing system. A = EMG (8 channels), B = air pressure (2), C = voice, D = banter, E = digital code and timing.

Table II. Test words used for both subjects

əCʌp
bʌCe
əbʌC
ʌbəC
pʌpə
hʌpə

Timing measurements were obtained from a Honeywell visicorder optical oscillograph, and fundamental frequency measurements were made from sound spectrograms.

Experimental Conditions

The subjects were required to read randomized lists of the stimulus words sixteen times each. Stimulus words consisted of disyllabic nonsense words containing voiced and voiceless consonant pairs in both pre- and post-stressed positions. Typical examples of test words are given in table II. For one subject, only /p/ vs. /b/ and /s/ vs. /z/ contrasts were examined, while pairs of three stops and four fricatives were examined for the other subject.

Results

1. Voiced/Voiceless Contrast in Word Medial Position

Averaged EMG curves for the voiced/voiceless contrast are shown in figures 2–5. The curves in figure 2 represent the averaged muscle activity levels for the PCA, INT and VOC during the production of /p/ and /b/ in medial prestressed position (in /ə p ʌ p/ and in /ə b ʌ p).

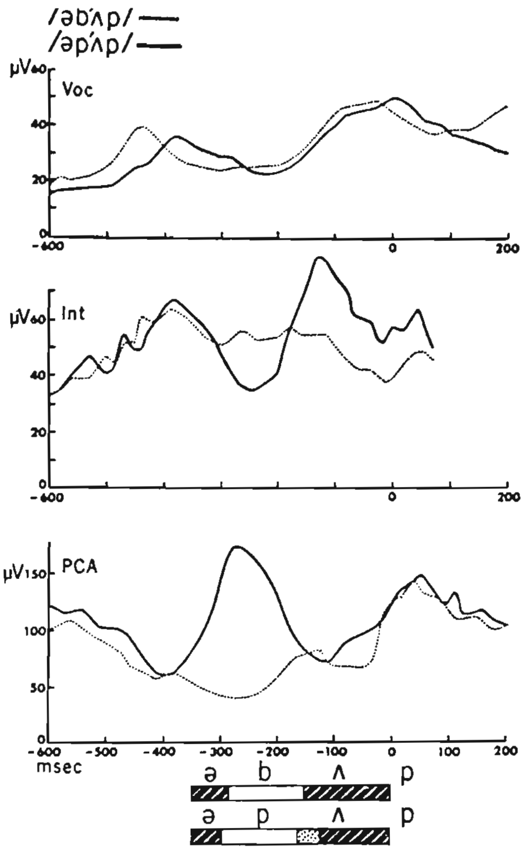

Fig. 2. Superimposed averaged EMG curves of vocalis, interarytenoid and posterior cricoarytenoid muscles of subject L.L. for the utterances, /ə p ʌ p/ and /ə b ʌ p/. The line-up point (0 on the abscissa) indicates voice offset of the stressed vowel.

It is quite obvious that the PCA shows marked activity for production of /p/ while it is suppressed for /b/ as well as for vowel production.

For /ə p ʌ p/, PCA activity starts to decrease approximately 250 msec before the onser of /ə/. The activity then begins to increase 100 msec prior to stop release, after which it immediately begins to decrease again with the vowel production. It then shows another peak for final /p/, followed by a relatively higher level of activity, presumably for inspiration, after completion of the utterance.

For /ə b ʌ p/, on the other hand, PCA activity stays low throughout the voiced period from the initial vowel to the stressed vowel, including

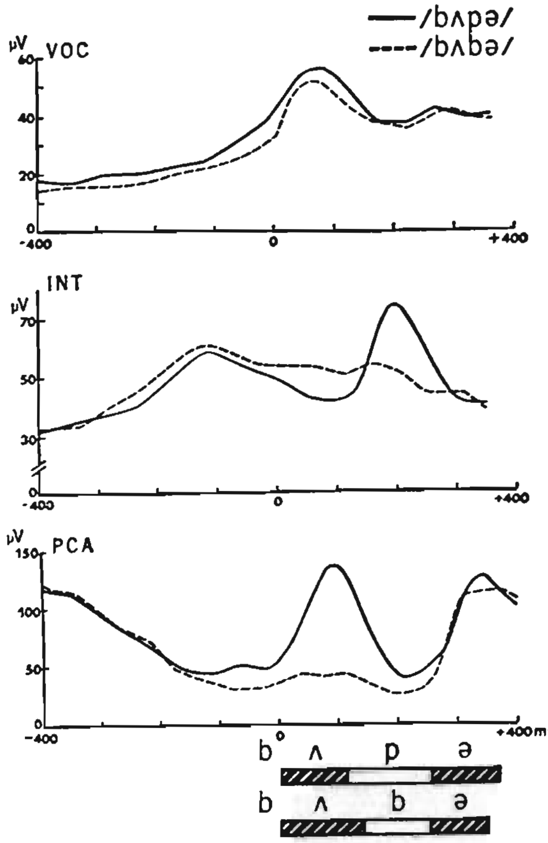

Fig. 3. Averaged EMG curves for /b ʌ p ə/ and /b ʌ b ə/ (subject L.L.). The line up point is the onset of the stressed vowel.

intervocalic /b/. It should be noted, however, that the EMG curve ascends slightly at about 110 msec prior to the release of /b/, then descends again approximately at the time of the release, and finally rises steeply 40 msec before /p/ closure.

For both consonants, the INT shows a sort of reciprocal pattern of activity when compared to the PCA. INT activity begins to increase at about 250 msec prior to initial vowel production. For /ə p ʌ p/, activity reaches a peak when the PCA reaches a valley and vice versa. For the articulation of /ə b ʌ p/, the INT shows more or less continuous activity, although there is some decrease in activity for intervocalic /b/ when compared to the preceding vowel segment.

The VOC shows two peaks, each of which appears to correspond to vowel production, with a higher peak for the stressed vowel. This higher peak for the stressed vowel is consistent across all samples regardless of whether the stressed vowel is preceded or followed by the unstressed vowel. Between the two peaks, activity stays low for the intervocalic consonantal segment, regardless of voicing distinction.

Figure 3 shows the medial /p/ vs. /b/ contrast in poststressed position for the same subject. For this condition, each muscle shows essentially the same features as observed in the previous example, that is, the PCA shows increasing activity for the voiceless segment, while INT activity is higher for the voiced segment. The VOC again shows two peaks with the higher one accompanying the stressed vowel.

When we compare the peak EMG values of the PCA for medial /p/ production in two different phonetic conditions (as shown in fig. 2 and 3) activity is higher for prestressed /p/ than poststressed /p/. This is consistent with the findings for another subject in which a comparison was made for three voiceless stops in pre- and poststressed conditions. Here, too, peak PCA activity for the medial voiceless stop production was always higher for the prestressed condition than the poststressed. Further, the duration of PCA activation for voiceless stop production was also found to be longer for prestressed than poststressed conditions.

The data in figures 2 and 3 also provide some information on the timing relationships between laryngeal and oral articulatory gestures.

In order to compare the timing relationship between the glottal gesture and oral stop closure, three different points on the averaged PCA curve were measured with reference to implosion and release of the stop closure of medial /p/. These points were: (1) the point where PCA activity begins to increase for stop production ---P_1; (2) the point where the activity reached its peak ---P_2; and (3) the point where its activity decreased to its minimum for the production of the post-consonantal vowel ---P_3.

Table III shows these time intervals for both the pre- and poststressed conditions. It is shown for both subjects that the time intervals thus specified are always larger for poststressed stops than for prestressed stops. It is worth noting, in particular, that P_3 always occurred earlier than or synchronously with stop release for poststressed stops, while it never did so for prestressed stops. In other words, stop closure is released after complete suppression of PCA activity in the case of

Table III. Time intervals for PCA activity in relation to stop closure and release in msec. A negative value indicates stop release preceding complete PCA suppression

		Interval between		
		P_1 and stop closure	P_2 and stop release	P_3 and stop release
Subject 1				
/p/	prestressed	110	110	−55
	poststressed	135	165	40
Subject 2				
/p/	prestressed	110	60	−90
	poststressed	150	130	10
/t/	prestressed	70	45	−140
	poststressed	160	95	0
/k/	prestressed	85	40	−165
	poststressed	155	140	30

poststressed stops, while for prestressed stops, stop release occurs before the completion of PCA suppression.

Figure 4 compares the activities of the same three muscles for the prestressed /s/ vs. /z/ contrast in the pair; /ə s ʌ p/ vs. /ə z ʌ p/. Here, the PCA again shows a large peak for the voiceless consonant while it is suppressed for the voiced segments. The activity of the INT is, in this case, too, higher for the voiced consonant /z/ than for voiceless /s/, but the level difference is less marked when compared to that for /b/ and /p/. This is probably because its activity is considerably lower for the consonantal segment of /z/ in comparison to its neighboring vowel segments. This tendency of INT activity to be lower for a voiced fricative than for a vowel is also observed in figure 5, where the poststressed /s/ vs. /z/ contrast is shown for the pair /b ʌ s ə/ vs. /b ʌ z ə/. It should be further noted in figure 5, that the PCA shows increasing activity for the segment of /z/ compared to the neighboring vowel segments, the time course of which appears to correspond to a dip in INT activity.

Figures 6 and 7 summarize PCA and VOC activity for the intervocalic voiced/voiceless contrast for subject LJR. The data points in the middle of each figure indicate the mean of peak EMG values for seven different pairs of voiced and voiceless consonants, while the vertical bar represents the entire range of sample variation. The circles at either end indicate the mean EMG activity at 100 msec prior

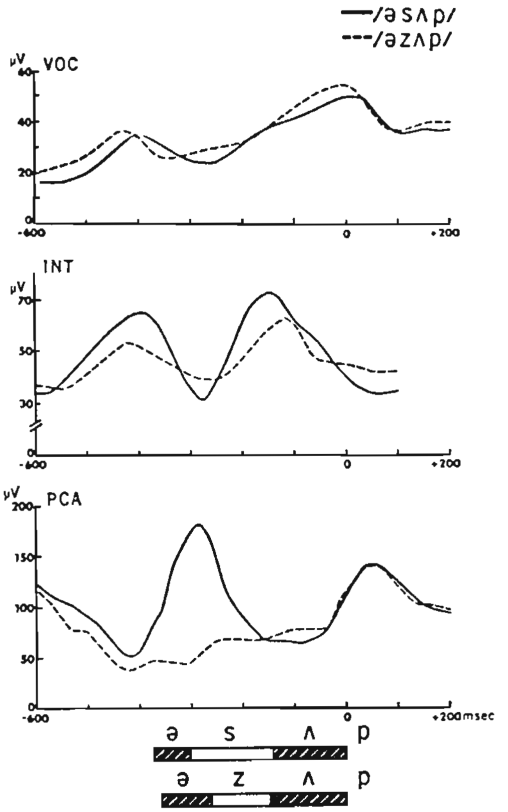

Fig. 4. Averaged EMG curves for /ə s ʌ p/ and /ə z ʌ p/ (subject L.L.).

to and after the peak for each consonant. In figure 6, it is clearly shown that PCA activity is definitely higher for the production of a voiceless consonant than for a voiced consonant.

In the case of the VOC, however, there is no apparent difference in the pattern of activity with respect to the voiced/voiceless contrast. In figure 7, the end data points indicate the mean of peak EMG values for the vowel segments, while the circles in the middle represent the mean of the minimum values between the two peaks. It is shown that VOC activity is suppressed during the period of consonant production between the two peaks for the vowel segments regardless of the difference in voicing distinction. As far as the peak height for vowel production is concerned, it appears to be higher for a stressed vowel than for an unstressed vowel.

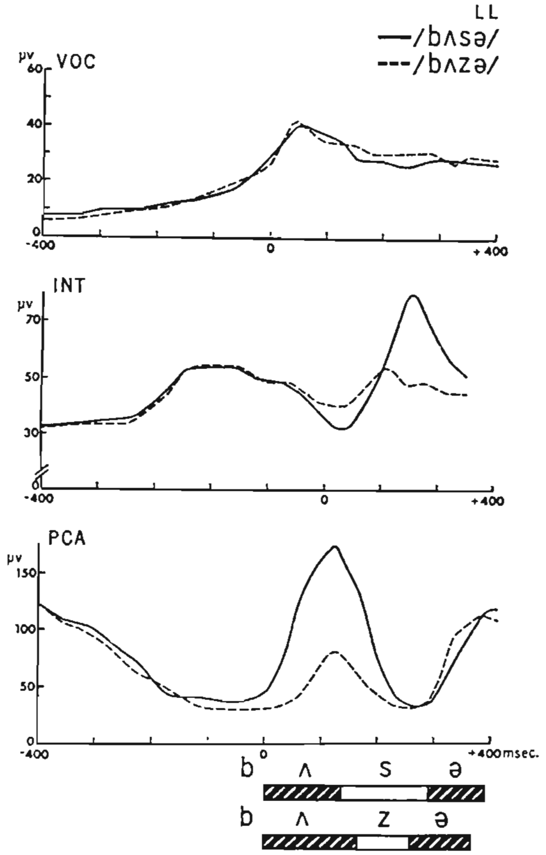

Fig. 5. Averaged EMG curves for /b ʌ s ə/ and /b ʌ z ə/ (subject L.L.).

In addition, we have also observed that the pattern of LCA activity appears to be similar to that of the VOC, showing increasing activity only for vowel segments with higher peak for the stressed vowel. Its activity decreases for intervocalic consonantal segment regardless of voiced-voiceless distinction.

Figure 8 shows the averaged activity of the CT for the pairs: /ə k ʌ p/ vs. /ə g ʌ p/ and /b ʌ k ə/ vs. /b ʌ g ə/, for subject LJR. The general pattern of muscle activity is similar for each pair; one large peak is always observed, apparently corresponding to the position of stress in the test word (i.e., where the F_0 contour reaches its peak). There are no discernible differences in the averaged EMG curves with respect to the voiced/voiceless distinction.

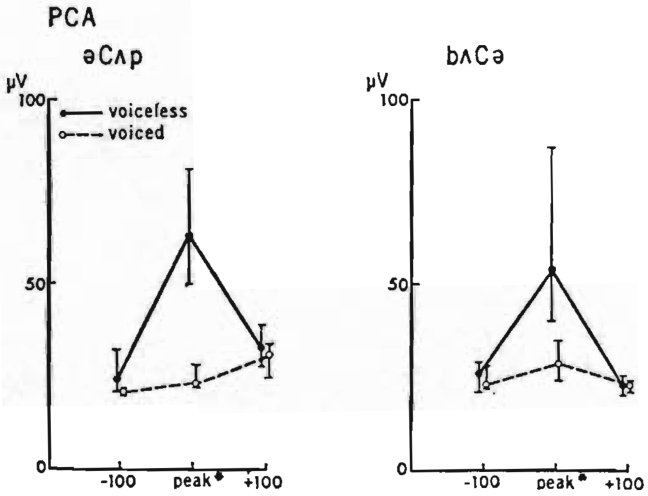

Fig. 6. Comparison of PCA activity for the medial voiced and voiceless consonant production (subject L.J.R.). A peak in activity was clearly present for only the group of voiceless consonants. EMG values for the voiced group were taken at the corresponding time moment.

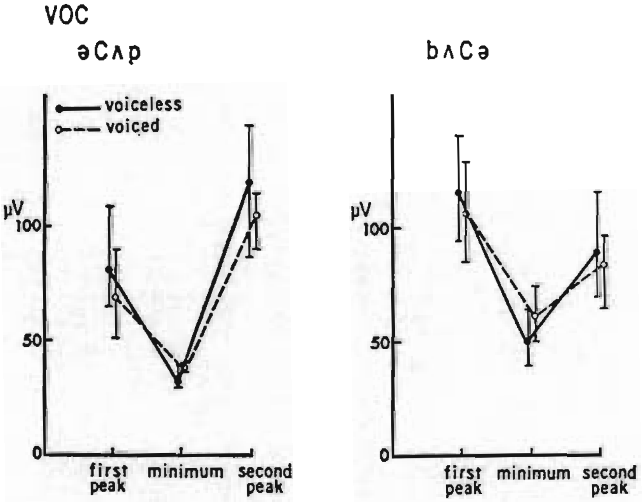

Fig. 7. Comparison of VOC activity for medial voiced and voiceless consonant production (subject L.J.R.).

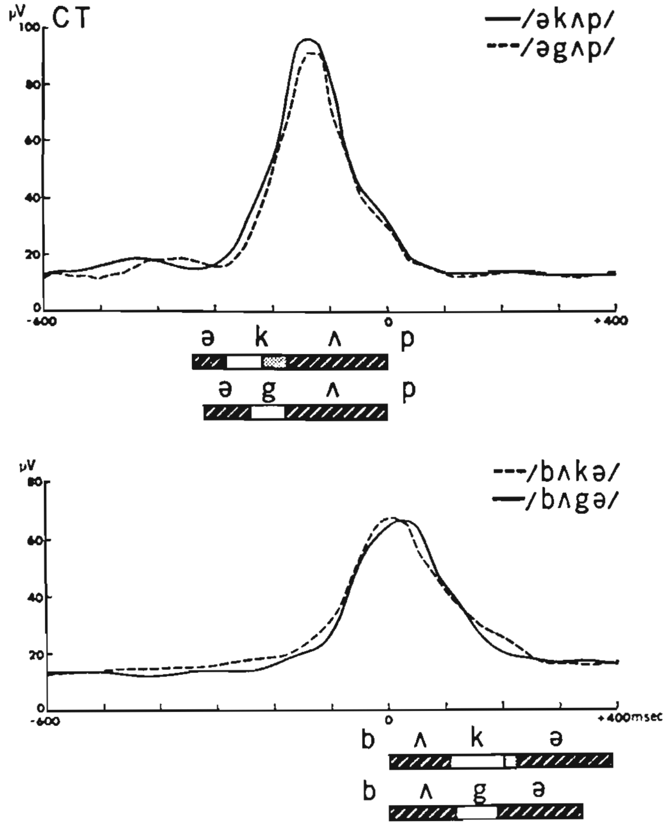

Fig. 8. Superimposed averaged EMG values of CT activity for the pairs /ə k ʌ p/ and /ə g ʌ p/; and /b ʌ k ə/ and /b ʌ g ə/ (subject L.J.R.).

2. *Voiced/Voiceless Contrast in Word Final Position*

Figures 9 and 10 show the EMG curves of the PCA and the INT for the /p/ vs. /b/ contrast in the final, poststressed and postunstressed positions. It is apparent in figures 9 and 10 that the PCA shows high activity for the voiceless consonant, during which time, INT activity is suppressed. Conversely, PCA activity is continuously suppressed when the interconsonantal vowel is followed by final /b/, at which time, the INT shows higher activity. In addition to the final rise, there is also a slight ascent in PCA curves in both these examples, apparently associated with initiation of the stressed vowel.

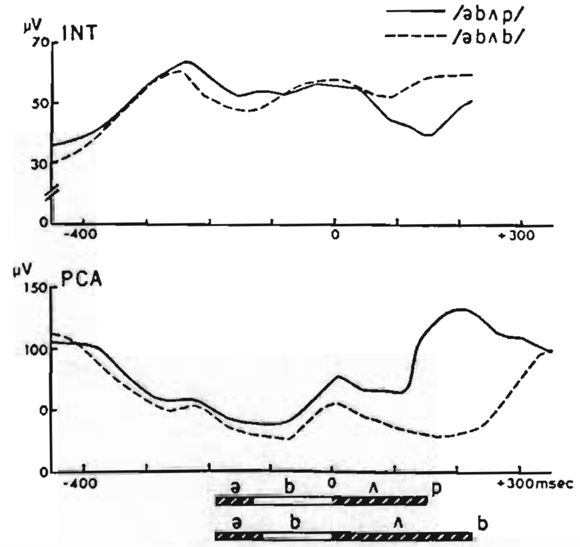

Fig. 9. Superimposed averaged EMG curves of INT and PCA activity for the utterances /ə b ʌ p and /ə b ʌ b/ (subject L.L.). The line up point is the onset of the stressed vowel.

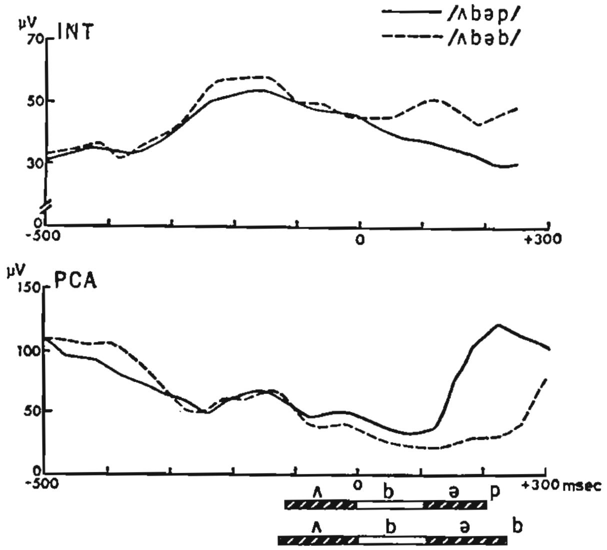

Fig. 10. Averaged EMG curves for /ʌ b ə p/ and /ʌ b ə b/.

In figure 11, PCA activity for subject LJR, is schematically shown during the time period including the final consonantal segment. As before, averaged EMG values compared here for voiced and voiceless pairs at three time moments: at the line up-point (time 0), 100 and 200 msec after the line-up, as given on the abscissa. The values in the figures again represent mean EMG values for seven different kinds of consonants. Both graphs clearly show that PCA activity is higher for the final voiceless consonants.

VOC activity is likewise compared in figure 12, where averaged EMG values were taken at the time when the EMG curve reaches its second peak[5] and 100 and 200 msec thereafter. Both graphs show that VOC activity is higher for the final voiced consonants than for the voiceless consonants. This same tendency was observed for LCA activity, which also appeared to be higher for the voiced pairs.

It has often been observed that English vowels are of greater duration before voiced than before voiceless consonants. Thus, there is a possibility that the higher VOC or LCA activity for the final voiced consonant is an effect of preceding vowel segment. In other words, the higher VOC or LCA activity levels might be associated with greater vowel duration rather than any distinctive consonant feature.

In order to examine this possibility, the activity of other articulatory muscles (the genioglossus and the orbicular oris) were later recorded simultaneously with LCA and PCA activity. The genioglossus (GG) is one of the extrinsic lingual muscles responsible for /ɪ/ production, while the orbicularis oris (OO) is important for lip closure. Data for all four muscles are shown in figure 13. It is clearly shown in figure 13 that the duration of the vowel /ɪ/ preceding the final consonant is greater for /ə p ɪ b/ than for /ə p ɪ p/ and that GG activity stays higher for the former than for the latter. The OO shows two peaks for the medial and the final bilabial stops and the interval between the two peaks indicates the duration of /ɪ/, which is longer for /ə p ɪ b/. These findings suggest that the duration of muscle activity for /ɪ/ is longer for /ə p ɪ b/ than for /ə p ɪ p/. If we attempt to slide the EMG curve of the LCA for /ə p ɪ b/ to the left on the abscissa in order to synchronize the end of the vowel /ɪ/ with that of /ə p ɪ p/, the descending portions

---

[5] The VOC and the LCA show two peaks in the EMG curves for these test words, each of which appears to correspond to vowel production. The second peak thus specifies the EMG peak for the vowel preceding the final consonant.

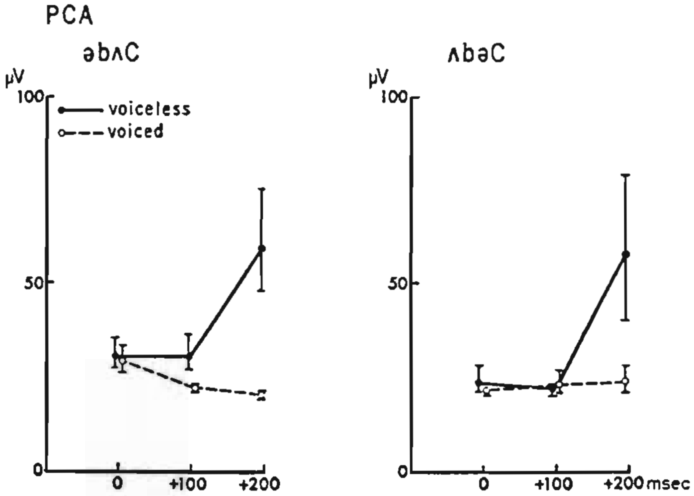

Fig. 11. Comparison of PCA activity for final voiced and voiceless consonant production (subject L.J.R.). '0' on the abscissa indicates the line up point.

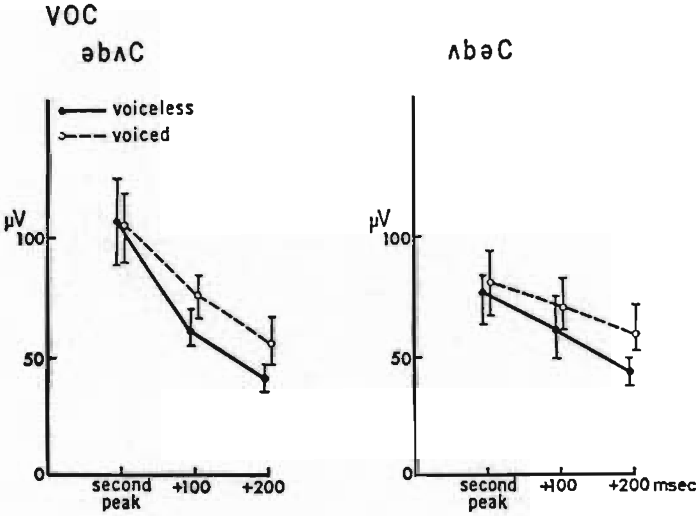

Fig. 12. Comparison of VOC activity for final voiced and voiceless consonant production (subject L.J.R.).

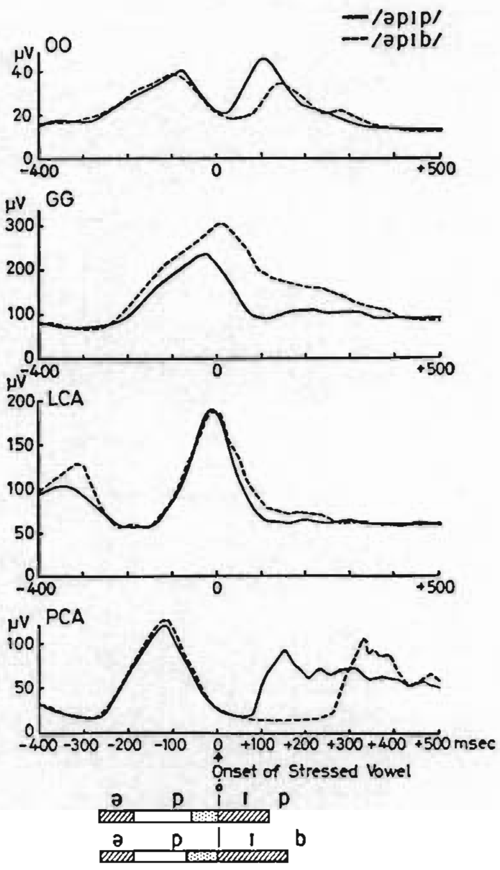

Fig. 13. Superimposed averaged EMG curves of orbicularis oris, genioglossus, latera cricoarytenoid and posterior cricoarytenoid for /ə p ɪ p/ and /ə p ɪ b/ (subject L.J.R.).

of the two LCA curves will be almost superimposed together. Thus, it seems reasonable to consider that the apparently higher LCA activity near the end of the test words for /ə p ɪ b/ in figure 13 corresponds to the vowel /ɪ/ preceding the final /b/. However, PCA activity stays higher for /ə p ɪ p/ and is suppressed for /ə p ɪ b/ near the end of the test words even when the sliding of the EMG curves is attempted as above. Therefore, it can still be concluded that PCA activity is higher for a voiceless consonant than for a voiced consonant, even in final position.

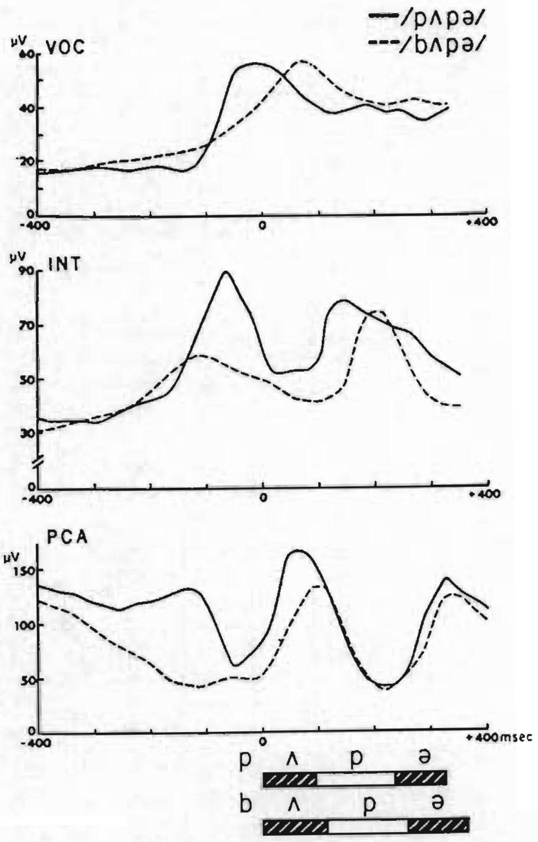

Fig. 14. Superimposed averaged EMG curves of vocalis, interarytenoid and posterior cricoarytenoid for /p ʌ p ə/ and /b ʌ p ə/ (subject L.L.). The line up point is the onset of the stressed vowel.

3. *Voiced/Voiceless Contrast in Word-Initial Position*

Comparisons of EMG activity levels for a voiced/voiceless consonant pair in initial position were made only for the pair, /p ʌ p ə/ vs. /b ʌ p ə/, the results of which are shown in figure 14.

For /p ʌ p ə/, PCA activity stays higher before lip closure and then decreases steeply approximately 110 msec before the onset of /ʌ/. An increase then follows for the medial /p/. INT activity shows a steep rise when the PCA shows the steep fall. The same tendency is seen in VOC activity, which also shows a steep rise, but which starts somewhat later than the INT.

Discussion

1. Functional Characteristics of the Individual Laryngeal Muscles in Articulatory Adjustments

a) The posterior cricoarytenoid (PCA): It was revealed in the present study that the PCA actively participates in laryngeal articulatory adjustments, particularly for the voiced/voiceless distinction. There is a consistent increase in PCA activity for voiceless consonant production regardless of phoneme environment. For all utterance types, PCA activity shows a transient increase before the onset of phonation, presumably for prephonatory inspiration. Its activity then starts to decrease for initial vowel production unless a voiceless consonant is placed in the absolute initial position of the test utterance. If a voiceless consonant is in initial position, PCA activity stays at about the level of the initial prephonatory rise or even higher (fig. 14, /p ʌ p ə/). For the production of a voiceless consonant in the medial or final position, the PCA always shows a marked increase in activity before the onset of consonant closure. As far as the voiced/voiceless distinction in final position is concerned, PCA activity appears to be significantly higher for a voiceless cognate, even if differences in the duration of the preceding vowel are taken into consideration as another possible cause of prolonged PCA suppression.

It should also be mentioned that the PCA does not only show a simple all-or-none pattern of activity but rather shows a pattern of fine adjustment. As seen in figure 5, the PCA shows partial activation for the production of the poststressed voiced fricative /z/, which seems to indicate a less complete glottal closure. In a transillumination study of the larynx, LISKER *et al.* [20] found that a high percentage of voiced fricatives were produced with at least a partially open glottis. Incomplete closure of the glottis during voiced fricative production can be obtained either by partial activation of the PCA or slight suppression of the adductors, particularly the INT. In the case of the poststressed /z/ mentioned above, both factors appear to work together, while in the case of the prestressed /z/ (as in figure 4), suppression of INT activity is more manifest.

Another interesting finding is the small PCA peak just before the onset of an initial or medial stressed vowel (fig. 2, 4, 9, and 10). Interpretation of this transient PCA activity is not perfectly clear as yet, but it is conceivable that the PCA acts to counterbalance the strong contraction of the adductors at the onset of the stressed vowel. In a study of the EMG activity of the laryngeal muscles in phonation [8], we observed that PCA activity is generally suppressed for sustained phonation, except for an increase at the highest range in chest register. The increasing PCA activity in that extreme condition may reflect the counterbalancing function of the abductor for the strong contraction of the adductors, as suggested in the literature [22, 27]. Another possibility is that functionally different motor units are participating in the execution of muscle contractions during different types of phonation, since there is evidence, at least in animal experiments, that the PCA contains several kinds of motor units [27].

Although the function of the PCA, particularly during sustained phonation, should be a subject for further investigation, the role of the PCA as a pure adductor in speech articulation is well demonstrated in the present study.

abductor

b) The interarytenoid (INT): The present data indicate that there is apparent reciprocal activity between the PCA and the INT. In this sense, the INT can be considered to be a pure adductor of the vocal folds.

In general, there is an apparent difference in the degree of INT activity for vowel segments depending on the preceding consonant. More specifically, INT activity for the production of a postconsonantal vowel appears to be higher after a voiceless consonant than after a voiced consonant (fig. 2, 3, and 5). Since EMG activity represents the muscle activity necessary for obtaining effective force and/or displacement, the degree of the activity of a given muscle can also be higher if, for example, the displacement is greater. Since glottal width is larger during the articulation of a voiceless consonant than for a voiced consonant [23, 25], it is reasonable to assume that the activity of the INT, which is responsible for adduction the vocal folds, should be greater after a voiceless consonant.

As seen in figure 4, INT activity is apparently lower for voiced consonants, namely fricatives, than for vowels. This would also indicate that glottal closure is likewise less tight for voiced consonants than for vowels.

c) The vocalis (VOC) and the lateral cricoarytenoid (LCA): The VOC and the LCA are considered to have complex functions in laryngeal articulatory adjustments. Both muscles appear to be activated for the vowel segment of the test words but rather suppressed for the consonantal segment, regardless of the voiced/voiceless distinction. It is conceivable, therefore, that the apparent glottal closure usually observed during the production of voiced obstruents can be achieved without increasing the activity of either the VOC or the LCA. Or, one can also argue that glottal closure during voiced obstruent production is less tight because of the absence of increased VOC and LCA activity. In any case, the function of the VOC and LCA as adductors seems different from that of the INT.

For the articulation of the vowel segment, both the VOC and LCA show higher activity for a stressed vowel than for an unstressed vowel, regardless of whether the stressed vowel is preceded or followed by the unstressed. This finding suggests that these two muscles participate in the control of the suprasegmental features as well, possibly in pitch raising. It has been reported that theVOC and the LCA participate in the mechanism of pitch rise [11], particularly when the activity of these two muscles increases simultaneously with the cricothyroid. In this sense, the VOC and the LCA can also be considered to function as tensors of the larynx, although in the case of singing, these two muscles do not seem to be contributing equally to pitch regulation [8].

In an EMG study of vowel devoicing in Japanese, Hirose [12] postulated the possibility of functional differentiation between the VOC and the LCA. The present study, however, does not seem to substantiate this differentiation, but rather shows fairly similar patterns of EMG activity for these two muscles, at least for those utterance types examined.

d) The cricothyroid (CT): The CT showed a temporary increase in activity for a stressed vowel but did not seem to participate in the voiced/voiceless distinction. This was not unexpected, as the CT is universally considered as a prime pitch raiser [2, 7, 8, 26].

2. *Coordination and Timing of Muscle Activities*

It is conceivable in the living human that most of the articulatory muscles are activated in a well-coordinated fashion during normal speech production. More specifically, some muscles behave in reciprocal fashion, while others are synergetic, depending on the particular articulatory condition.

As far as segmental features of the present test words are concerned, the PCA and the INT showed consistent reciprocity in both the level of EMG activity and the timing of activation.

It is also worthy to note that timing relationships between laryngeal muscle activity and supraglottal articulatory events vary, depending on phoneme environment (table III). It has also been reported that in the case of unaspirated voiceless stops, the arytenoids resume a closed position just after oral release, while for aspirated stops, arytenoid closure is completed well after oral release [21, 25]. This is coherent with the present EMG data where suppression of PCA activity was not yet complete at the moment of oral release in the case of prestressed voiceless stop production (suggesting that the glottis remains at least partially open at that moment), while in poststressed stops, PCA suppression is complete before oral release.

The timing relationships found here are also relevant to more general questions concerning the nature of timing control in speech articulation, i.e., are the observable differences in voice onset time the consequence of other physical and physiological features such as subglottal pressure, glottal aperture, etc. [4, 17], or a separate independent physiological mechanism [1, 21]?

If timing differences are responses of the system to force other than direct muscular control, we would expect that the timing of muscle activity patterns would be the same across various contrasts. In other words, the gestures would be organized in the same way but differentially modified according to prevailing glottal conditions.

Our data though, do not support this concept but rather show differences in the relative timing of muscle activity patterns and thus, active muscular control of glottal configuration. In other words, our data would suggest the ubiquity of an independent timing control mechanism. At the same time, however, the possibility that other laryngeal features are, themselves independently controlled.

The degree of overall activity of the PCA appeared to higher for prestressed than for poststressed voiceless stops. This finding agrees with both fiberoptic [25] and transillumination data [20], which indicated that the degree of glottal opening is greater for the prestressed voiceless stops than for the poststressed.

Based on the acoustical and mechanical aspects of vocal cord vibration, HALLE and STEVENS [9] proposed a scheme of laryngeal features to classify certain obstruents, glides and vowels. They postulated that there are two independently-controlled parameters: the stiffness of the vocal cords (adjusted by the thyroarytenoid and the cricothyroid) and static glottal opening. These two parameters yield four features: spread glottis, constricted glottis, stiff vocal cords and slack vocal cords. In addition, nine distinct phonetic categories can result from combinations of these four features.

Although an EMG model might not be the only analog of such a feature system, muscle contraction properties are certainly important correlates. Assuming then, a relationship between 'stiffness' and muscle activity, our present data do not support their system with respect to certain points. For example, HALLE and STEVENS postulated the [+ stiff] feature for both the voiceless unaspirated stop [p] and the voiceless aspirated stop [pʰ]. However, the present data show that the CT, VOC and LCA are suppressed for the production of these consonants. Thus, there is no EMG evidence, in the form of increased CT, VOC or LCA activity, to support the concept of [+ stiff] vocal cords for the production of voiceless obstruents. Further, the proposed feature of [– spread] glottis for the voiceless unaspirated stop [p] is not supported by the present data either, since this consonant is associated with high PCA activity and suppressed INT activity for an open glottis.

Although the present data are quite straightforward, it is obvious that more extensive experiments, including a combined EMG-fiberoptic approach are needed to provide further information on the relationships among muscle activity, glottal configuration and distinctive features.

Zusammenfassung

Die Aktivität der inneren Larynxmuskeln bei der Kontrolle der Stimme. Eine elektomyographische Untersuchung

Das Hauptanliegen dieses Experiments war es, die Aktionen der inneren Larynxmuskeln beim Hervorbringen von stimmhaften und stimmlosen Konsonanten systematisch zu untersuchen.

Zusammenfassend kann man sagen: Vom Computer gemittelte EMG-Kurven von den Larynxmuskeln zeigten die Beteiligung des hinteren Cricoarytenoidus bei stimmlosen und Dämpfung bei stimmhaften Konsonanten. Umgekehrt ist es bei dem musculus interarytenoidus. Ähnlich gegensätzliches Verhalten der Muskeln zeigte sich bei der zeitlichen Koordinierung. Diese Ergebnisse werden im Hinblick auf neuerlich vorgeschlagene Systeme laryngaler Merkmale diskutiert.

Résumé

Le rôle des muscles intrinsèques du larynx dans le contrôle de la production vocale : une étude électromyographique

Le but essentiel de cette étude était d'examiner systématiquement l'activité des muscles intrinsèques du larynx pendant la production de consonnes voisées et de consonnes sourdes.

De façon générale, les courbes EMG des muscles laryngés, moyennées par computer, indiquent une participation du cricoaryténoïde postérieur pour les consonnes sourdes et sa non-participation pour les consonnes sonores. L'inverse de produit pour l'interaryténoïde. Une semblable opposition apparaît sur l'axe du temps.

Ces résultats sont discutés à la lumière de récentes théories sur le système laryngien.

References

1 Abramson, A. S. and Lisker, L.: Laryngeal behavior, the speech signal and phonological simplicity. Proc. 10th Congr. Int. Linguist., vol. 4, pp. 124–128 (Academy of Romania, Bucharest 1970).

2 Arnold, G. E.: Physiology and pathology of the cricothyroid muscle. Laryngoscope *71:* 687–753 (1961).

3 Basmajian, J. V. and Stecko, G.: A new bipol

arytenoidus. Ähnlich gegensätzliches Verhalten der Muskeln zeigte sich bei der zeitlichen Koordinierung. Diese Ergebnisse werden im Hinblick auf neuerlich vorgeschlagene Systeme laryngaler Merkmale diskutiert.

Résumé

Le rôle des muscles intrinsèques du larynx dans le contrôle de la production vocale: une étude électromyographique

Le but essentiel de cette étude était d'examiner systématiquement l'activité des muscles intrinsèques du larynx pendant la production de consonnes voisées et de consonnes sourdes.

De façon générale, les courbes EMG des muscles laryngés, moyennées par computer, indiquent une participation du cricoaryténoïde postérieur pour les consonnes sourdes et sa non-participation pour les consonnes sonores. L'inverse de produit pour l'interaryténoïde. Une semblable opposition apparaît sur l'axe du temps.

Ces résultats sont discutés à la lumière de récentes théories sur le système laryngien.

References

1 Abramson, A. S. and Lisker, L.: Laryngeal behavior, the speech signal and phonological simplicity. Proc. 10th Congr. Int. Linguist., vol. 4, pp. 124–128 (Academy of Romania, Bucharest 1970).

2 Arnold, G. E.: Physiology and pathology of the cricothyroid muscle. Laryngoscope *71:* 687–753 (1961).

3 Basmajian, J. V. and Stecko, G.: A new bipolar electrode for electromyography. J. appl. Physiol. *17:* 849 (1962).

4 Chomsky, N. and Halle, M.: The sound pattern of English (Harper & Row, New York 1968).

5 Dedo, H.: The paralyzed larynx. An electromyographic study in dogs and humans. Laryngoscope *80:* 1455–1517 (1970).

6 Faaborg-Andersen, K.: Electromyographic investigation of intrinsic laryngeal muscles in humans. Acta physiol. scand. *41:* suppl., vol. 140 (1957).

7 Gårding, E.; Fujimura, O., and Hirose, H.: Laryngeal control of Swedish word tones. A preliminary report on an EMG study. Ann. Bull. Res. Inst. Logoped. Phoniat., Tokyo *4:* 45–54 (1970).

8 Gay, T.; Hirose, H.; Strome, M., and Sawashima, M.: Electromyography of the intrinsic laryngeal muscles during phonation. Ann. Otol. Rhinol. Laryng., St. Louis (in press).

9 Halle, M. and Stevens, K. N.: A note on laryngeal features. Quart. Progr. Rep. MIT. *101:* 198–213 (1971).

10 Hirano, M. and Ohala, J.: Use of hooked-wire electrodes for electromyography of the intrinsic laryngeal muscles. J. Speech Res. *12:* 362–373 (1969).

11 Hirano, M.; Vennard, W., and Ohala, J.: Regulation of register, pitch and intensity of voice. Folia phoniat. *22:* 1–20 (1970).

12 Hirose, H.: The activity of the adductor laryngeal muscles in respect to vowel devoicing in Japanese. Phonetica *23:* 156–170 (1971).

13 Hirose, H.: Electromyography of the articulatory muscles. Current instrumentation and technique. Status Rep. on Speech Res., Haskins Lab. SR-25/26, pp. 73–86 (1971).

14 Hirose, H.: An electromyographic study of laryngeal adjustments during speech articulation: A preliminary study. Status Rep. on Speech Res., Haskins Lab. SR-25/26, pp. 107–116 (1971).
15 Hirose, H.; Gay, T., and Strome, M.: Electrode insertion technique for laryngeal electromyography. J. acoust. Soc. Amer. *50:* 1449–1450 (1971).
16 Hiroto, I.; Hirano, M.; Toyozumi, Y., and Shin, T.: Electromyographic investigation of the intrinsic laryngeal muscles related to speech sounds. Ann. Otol. Rhinol. Laryng., St. Louis *76:* 861–872 (1967).
17 Kim, C. W.: A theory of aspiration. Phonetica *21:* 107–116 (1970).
18 Konrad, H. R. and Rattenborg, C. C.: Combined action of laryngeal muscles. Acta oto-laryng., Stockh. *67:* 646–649 (1969).
19 Kotby, M. N. and Haugen, L. K.: Critical evaluation of the action of the posterior crico-arytenoid muscle, utilizing direct EMG-study. Acta oto-laryng., Stockh. *70:* 260–268 (1970).
20 Lisker, L.; Abramson, A. S.; Cooper, F. S., and Schvey, M.: Transillumination of the larynx in running speech. J. acoust. Soc. Amer. *45:* 1544–1546 (1969).
21 Lisker, L. and Abramson, A. S.: Distinctive features and laryngeal control. Language *47:* 767–785 (1971).
22 Pressman, J. J.: Physiology of the vocal cords in phonation and respiration. Arch. Otolaryng. *35:* 335–398 (1942).
23 Sawashima, M.: Movements of the larynx in articulation of Japanese consonant. Ann. Bull. Res. Inst. Logoped. Phoniat., Tokyo *2:* 11–20 (1968).
24 Sawashima, M.: Glottal adjustments for English obstruents. Status Rep. on Speech Res., Haskins Lab. SR-21/22, pp. 187–200 (1970).
25 Sawashima, M.; Abramson, A. S.; Cooper, F. S., and Lisker, L.: Observing laryngeal adjustments during running speech by use of a fiberoptic system. Phonetica *22:* 193–201 (1970).
26 Simada, Z. and Hirose, H.: Physiological correlates of Japanese accent patterns. Ann. Bull. Res. Inst. Logoped. Phoniat., Tokyo *5:* 41–49 (1971).
27 Suzuki, M. and Kirchner, J. A.: The posterior cricoarytenoid as an inspiratory muscle. Ann. Otol. Rhinol. Laryng., St. Louis *78:* 849–864 (1969).

Authors' address: Hajime Hirose, MD and Thomas Gay, PhD, c/o Haskins Laboratories, 270 Crown Street, *New Haven, CT 06510* (USA)