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While, as earlier papers at this conference have indicated, the forces that determine laryngeal adjustment are complex, muscular forces are extremely important. In recent years, techniques for studying muscle activity in general have improved, and with these developments, the study of the laryngeal muscles in normal alert humans has become possible using the techniques of electromyography. In this paper, I will discuss some properties of muscles, and of the laryngeal muscles in particular, techniques for EMG recording, and, finally some results of studies on the muscular control of the larynx.

MUSCLE PROPERTIES

The building block for a consideration of muscle activity is the motor unit. This term was coined by Liddell and Sherrington (1925) to include the motoneuron and the muscle fibers it supplies. The contractile response to one impulse in one motor neuron is a twitch contraction in the innervated muscle fibers. Thus, the smallest unit of muscular activity is a contraction of the muscle fibers of a single motor unit, and the smoothly graded contraction of a muscle is accomplished by temporal and spatial summation of the activity of a number of motor units.

The muscles of the body have somewhat different tasks, and their properties are well-correlated with these tasks. For example, some muscles, such as the muscles of the fingers, must make finely tuned movements, while others, such as those of the leg, must support the body against the forces of gravity for long periods of time. These muscles differ in the size of their motor units, and in the histochemical properties of the individual muscle fiber properties that determine their resistance to fatigue.

Table 1 presents some data on motor unit size in the intrinsic laryngeal muscles, with data on one of the eye muscles and the biceps for comparison.

Table 1

Data on the Innervation Ratio of the Intrinsic Laryngeal Muscles, with
Some Comparison Information on One of the Eye Muscles and the Biceps

Source	Larynx					Other	Biceps
	CT	TA	IA	PCA	LCA	Rectus Oculi Lateralis	
man (Faaborg-Andersen, 1957)	166		247	116			
man (English & Blevens, 1969)	30						
cat (English & Blevens 1969)	55	90		64			
man (Buchtal, 1973)						13	750

    CT   Cricothyroid
    TA   Thyroarytenoid
    IA   Interarytenoid
    PCA   Posterior cricoarytenoid
    LCA   Lateral cricoarytenoid

While different authors have found differences in the number of fibers in a motor unit, there is a general agreement that the laryngeal muscles have low innervation ratios, though not quite so low as those of the eyeball and middle ear; the muscles of the limbs and trunk have generally far higher ratios.

The muscle fibers themselves consist of a number of myofibrils, made up, in turn, of a parallel, overlapping array of actin and myosin filaments. In contraction, the actin and myosin filaments slide relative to each other, so that the muscle shortens and develops tension. In normal physiological conditions, this shortening is initiated by the release of a chemical transmitter, acetylcholine, at the nerve-muscle junction, the motor end plate.

When a muscle fiber is at rest, there is a potential difference across the cell members of about -90 mV, due to the difference in its permeability to sodium and potassium ions. When a nerve impulse reaches the motor end plate, acetylcholine is released, which changes the permeability of the membrane to sodium and potassium ions. If this depolarization reaches sufficient levels, the change in potential becomes self-regenerating, and travels along the muscle fiber. During the passage of this action potential, the membrane potential rises, then reverses its sign and finally returns to its resting value of -90 mV. The movement of ions, and the associated changes in potential, are, of course, the events generating the electromyographic signal. The ionic currents at the membrane apparently release calcium ions within the muscles; the diffused calcium activates the contractile component of the muscle, producing the mechanical effect of muscle shortening or tension development (Carlson & Wilkie, 1968).

While the fibers of striated muscles share many properties, they show some adaptations to their individual tasks. The muscles of the larynx must be well designed for rapid adjustment; however, because of their participation in respiration, they must have some capacity for sustained activity without fatigue. Muscle fibers are of two basic types, red and white, although there are variants in different systems in different animals. The "red" and "white" designations refer to a difference in the fiber color, familiar from the light and dark meat of chicken. The two types differ in their metabolic properties, with red muscle more suited to sustained contraction due to the fatigue resistance and white more suited to rapid phasic contraction. Most muscles of the body, including the muscles of the larynx, show mixed red and white fibers. Any single motor unit, however, is composed of fibers of a uniform type (Brandstater & Lambert, 1973) although, since adjacent motor units have overlapping territories, a cross-section of a muscle will show a checkerboard pattern of red and white.

Biochemical and histological studies of the laryngeal muscles to that date (1970) were summarized by Sawashima. He concluded that, with respect to metabolic properties, the intrinsic laryngeal muscles as a group appeared to be intermediate between skeletal and heart muscles. However, he found disagreements among the authors he reviewed as to similarities and dissimilarities within the group.

Since that review, there have been further studies of the histochemistry of the intrinsic muscles of the larynx. Data from one of them (Edström, Lindquist, & Mårtensson, 1974) are shown in Table 2, showing the percentages

Table 2

Data on Histochemical Properties of the Intrinsic Laryngeal Muscles
in Cat, after Edström, Lindquist, and Mårtensson (1974)

	TYPE I		TYPE II		
	(1)	(2)	(1)	(2)	(3)
Fiber type in skeletal muscle (Kugelberg, 1973)	–	I	–	IIA	IIB IIC

Overall % in laryngeal muscles,
with most common subtype starred

	TYPE I			TYPE II		
	(1)	(2)		(1)	(2)	(3)
CT		40% *				60% *
TA	10% *			90% *		
PCA	40% *					60% *
LCA	10% *				90% *	

Table 3

Data from Atkinson (1978) on the Mean Response Time for Some Intrinsic
and Extrinsic Laryngeal Muscles

	Intrinsic Laryngeal Muscles			Strap Muscles	
	CT	TA	LCA	ST	SH
Mean Response Time	40	15	15	120	70

of Type I and Type II (red and white) fibers found for each of the four laryngeal muscles examined. While some of the fibers were like Type I and Type II fibers found in limb muscles, others were variants of previously identified types. It is interesting to note that Type II variants are far more common in the thyroarytenoid than in the cricothyroid.

A second study (Sahgal & Hast, 1974) examined the histochemical reactions to ATP and three oxidative enzymes in cricothyroid and thyroarytenoid. The results show some differences between the muscles, which the authors believe are also related to the differences in the speed of contraction of the muscles.

Thus, differences in the histochemistry of the muscles appear to be reflected in their contractile properties. We have seen that the laryngeal muscles are composed predominantly of Type II fibers, like the intraocular muscles in man (Kugelberg, 1973). The laryngeal muscles are generally agreed to be fast muscles, although different authors have obtained different values for their contraction time, the time from nerve or muscle stimulation to the peak of the muscle tension. Figure 1, adapted from Sawashima's review (1970), summarizes the results. The thyroarytenoid is consistently found to be faster than the cricothyroid, which is consonant with the difference in proportion of Type II fibers in the two muscles and, according to Sahgal and Hast (1974), with the difference in their histochemical properties.

Contraction time for the intrinsic laryngeal muscles has been estimated by a very different technique by Atkinson (1978) at Haskins Laboratories. He reasoned that if a causal relationship between f_o and the EMG activity of various laryngeal muscles were assumed, there should be a correlation between f_o and gross EMG activity, at some time delay determined by the mechanical properties of the muscle. Thus, cross-correlation analysis should provide clues to relative contraction time.

He asked speakers to produce sentences varying in stress and intonation, thus varying f_o, and cross-correlated average f_o and rectified and averaged EMG activity, at varying delay times. Table 3 shows the delay times at which correlation reached peak value for different muscles. The finding of shorter mean response time for thyroarytenoid and lateral cricoarytenoid than for cricothyroid, with longer response times for the strap muscles, is like the results obtained by more conventional techniques, summarized in Figure 1, and also parallels the histochemical grouping of TA with LCA, shown in Table 2.

THE ELECTROMYOGRAPHIC SIGNAL

The origin of the electromyographic signal is discussed above in only very general terms. If the signals from the laryngeal muscles are to be considered in detail, the recording procedure itself must be discussed. Figure 2 (Geddes, 1972) shows a muscle with a pair of recording electrodes on its surface. The fibers are aligned parallel to each other. When a muscle fiber or the nerve is stimulated, a wave of depolarization passes along each stimulated fiber. However, since each recording electrode is most sensitive to the fiber closest to it, the event recorded will be weighted by the distance between the pickup and the active fiber, as shown in the figure. As
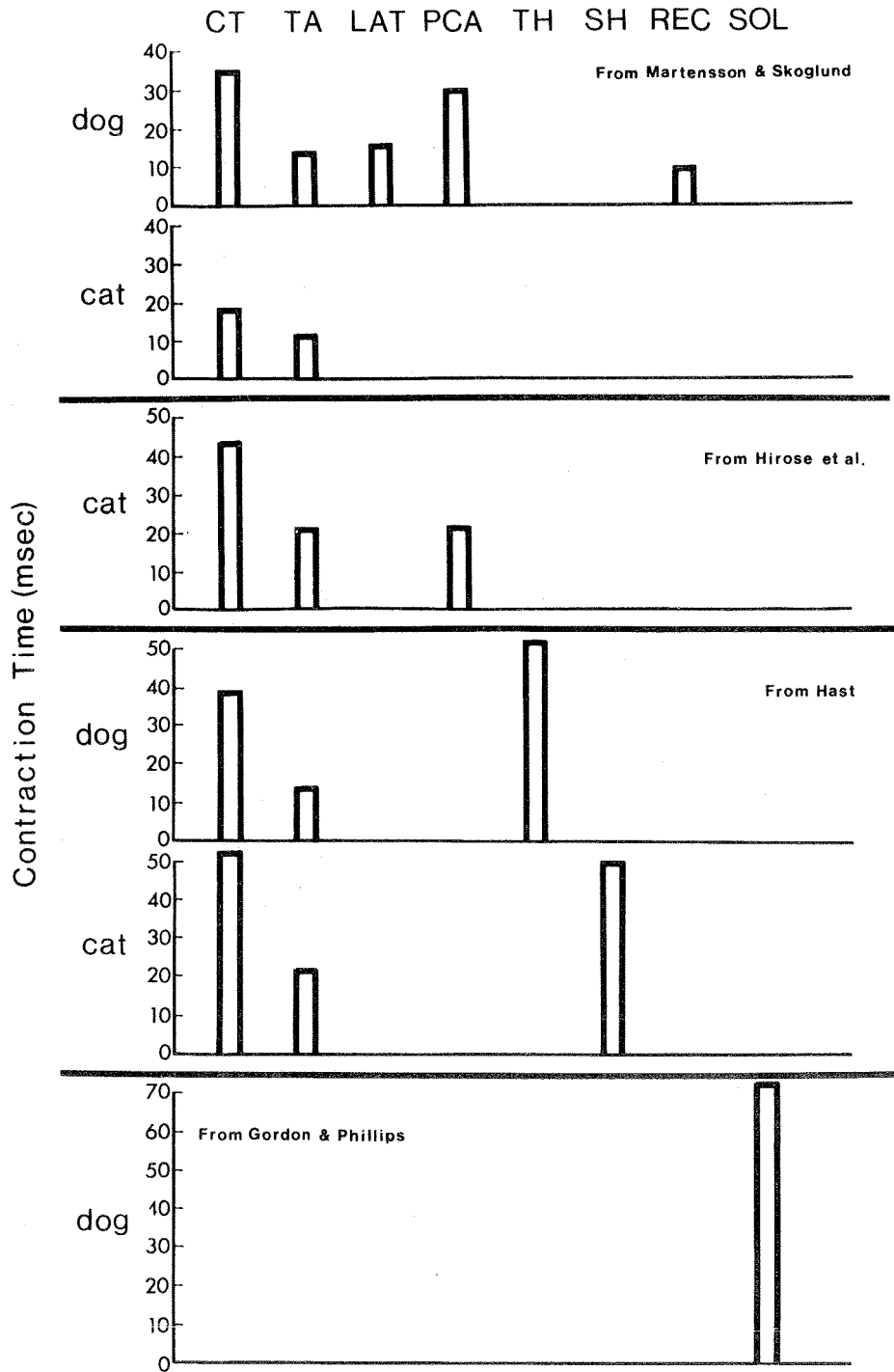
CT TA LAT PCA TH SH REC SOL

From Martensson & Skoglund

dog

cat

From Hirose et al.

cat

From Hast

dog

cat

From Gordon & Phillips

dog

Contraction Time (msec)

Figure 1. Contraction time in msec for various laryngeal muscles. This
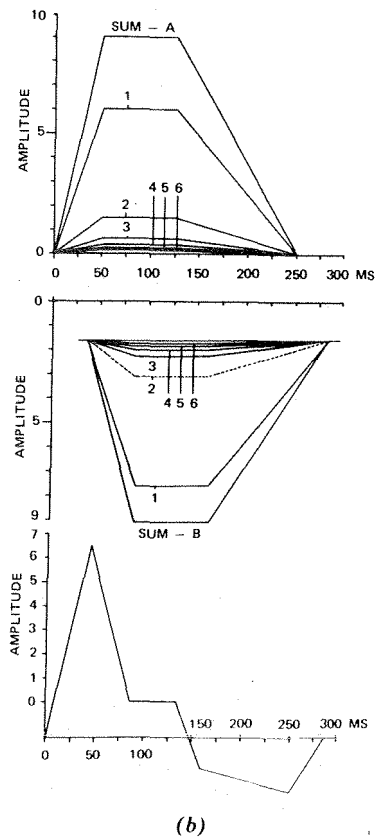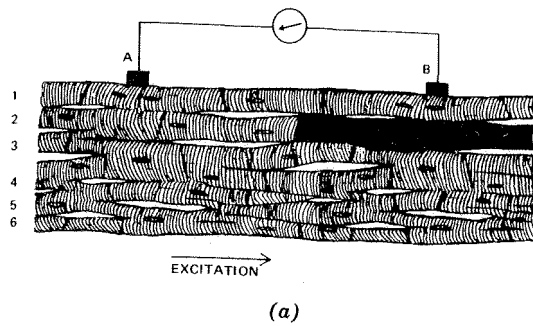figure is adapted in part from Table 1, Sawashima, 1970.

(a)

(b)

Figure 2. Schematic diagram of electromyographic recording. In part (a), two
electrodes are shown positioned over six muscle fibers. In (b),
the summed potential differences are shown for electrodes A and B,
with the contributions from each fiber, and their difference.
Reprinted from Geddes, 1972.

the wave of depolarization sweeps down the fibers and reaches the second electrode, it becomes negative. The event recorded also reflects the timing of the action potential passage at the two electrodes, and the size of the recording surface. In the example shown, there is a period when the fiber is depolarized under both electrodes; hence, the signal returns to zero before reversing its sign. Another factor determining the signal picked up by the electrodes is the intervening tissue. In general, the presence of tissue creates a low-pass filtering effect whose bandwidth decreases as distance increases (DeLuca, 1978).

While it is possible to record from a single muscle fiber (Ekstedt & Stålberg, 1973), the more usual recording represents events in a motor unit, or an aggregate of motor units. Under normal conditions, an action potential propagating down a motor nerve activates all the fibers of its motor unit. The fibers of a single motor unit are intermingled with each other in such a way that the territory of one unit is about 20 times the cross-sectional area of the fibers of the unit (Buchthal, Erminio, & Rosenfalk, 1959). Since a portion of a muscle might contain fibers belonging to any of fifty motor units, an electrode in the vicinity might detect activity in any or all of them. The signal reaching a pair of electrodes in active tissue is the weighted sum of the activity of each of the fibers of a motor unit, with the filtering properties of the tissue between the electrode and the active fiber taken into account. Since the orientation of the fibers of each motor unit with respect to a fixed recording site will be unique, the shape of the resulting recorded action potential will similarly be unique, and can be used to recognize the unit (LeFever, 1980).

When a muscle is activated, the electrical manifestation of a motor unit action potential is accompanied by a twitch of the activated fibers. In muscle contraction in physiological conditions, the motor units are repeatedly activated, whether the type of contraction is isometric (the muscle does not shorten, but develops tension) or anisometric (the muscle shortens).

THE ELECTRODE

In recordings from the laryngeal muscles, or any others, it is often possible to recognize individual motor units by visual inspection, especially when levels of contraction are low, so that only a few motor units are active. An example is shown in Figure 3, a recording from the cricothyroid muscle (Faaborg-Andersen, 1964). Alternatively, it is possible to record from such a large number of active fibers that individual components cannot be recognized, as in Figure 4. The signals shown here are a so-called "interference pattern." That is, the pattern represents the activity of a large number of fibers. The experimenter may wish to record single motor units or interference patterns, depending on the purpose of the experiment, and makes a choice of electrode accordingly.

Three general types of electrodes have been used in speech research; surface, needle, and hooked wire electrodes. Of these, hooked wire electrodes have been most useful for recording from the laryngeal muscles. The muscles of the larynx are aligned in a way that signals picked up by an electrode on the neck surface are ambiguous as to which muscle is the signal source. Thus,
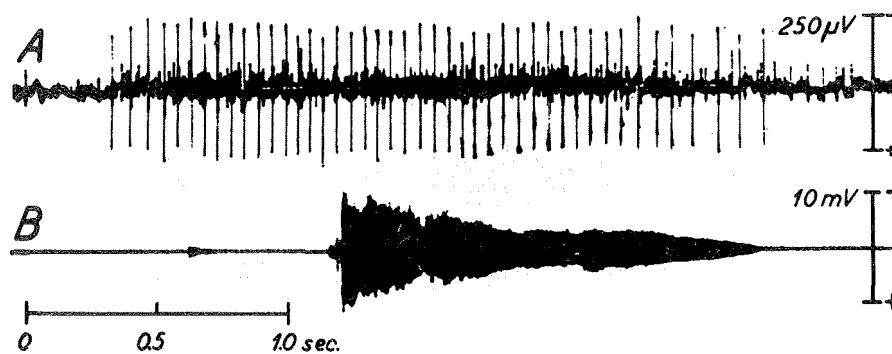
8

Figure 3. Action potentials of a single motor unit during phonation. A. Cricothyroid muscle. B. Microphone recording. Reprinted from D. Brewer, 1964.
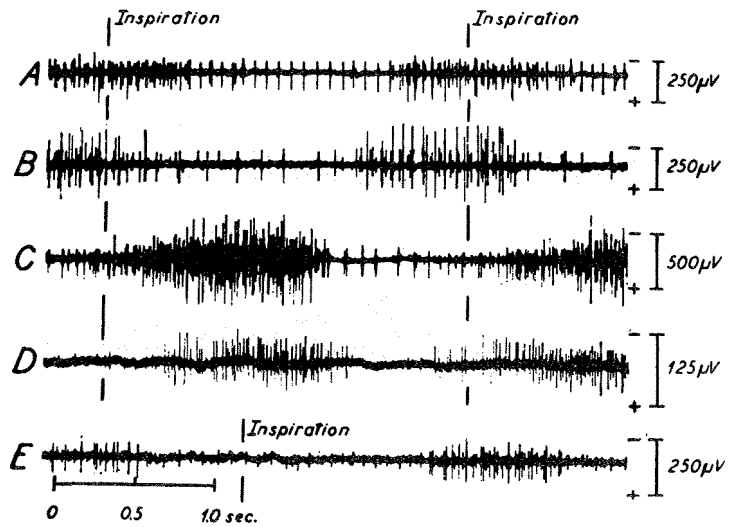
Figure 4. Quiet respiration. The onset of inspiration is indicated by the vertical stippled lines. A and B: Cricothyroid muscle. C and D: Vocalis muscle. E: Posterior cricoarytenoid muscle. Reprinted from D. Brewer, 1964.

although attempts have been made to use surface recordings from locations over the thyroid cartilage in a biofeedback application (Guitar, 1975), it seems unlikely that much further application will be made of such techniques. Needle electrode insertions into the laryngeal muscles are not generally feasible for posterior cricoarytenoid and interarytenoid muscles, although such insertions were used by Faaborg-Andersen in his classic study. The work of the past decade was done almost entirely with hooked wire electrodes, except for some clinical work to be described by Hirose.

Figure 5 shows the classic version of the hooked wire electrode (Basmajian & Stecko, 1962). Some technical details and possible variants of this type of electrode are discussed by Basmajian (1978). This type of electrode has been used in recording from the laryngeal muscles by a number of investigators besides ourselves (Hirano & Ohala, 1969; Shipp, Fishman, & Morrissey, 1970). Using them, we have been able to record from all of the intrinsic laryngeal muscles (and a wide variety of other speech muscles) using techniques developed collaboratively with Dr. Hajime Hirose and his colleagues at the Institute of Logopedics and Phoniatrics at the University of Tokyo (Hirose, Gay, & Strome, 1971).

If the investigator is interested in recording from a very small volume of tissue, the recording surfaces of the electrodes must be made as small as possible, while if the investigator is interested in a representation of the activity of the whole muscle, the recording surface must be as large as possible, while still remaining within the confines of the same muscle. Obviously, since the laryngeal muscles are small, some conventional configurations of electrode may record activity from more than one muscle (Dedo & Dunker, 1966). In the conventional hooked wire electrode, the hooks, which hold the wire in the muscle, also act as the recording points for the bipolar pickup, through their cut ends. However, the spacing between the two points is set arbitrarily by the way that the electrode happens to hook into the muscle, and, indeed, may change within the recording session (Jonsson & Komi, 1973). Since this type of electrode apparently records from a very small volume of tissue, the fact that the distance between the electrode tips is not fixed seems a design flaw. At Haskins, we have been exploring the various designs in which the functions of stabilization and recording are separated, and the field size is fixed by the separation between recording points.

PROPERTIES OF MOTOR UNITS

Exploring the relationship between ideal electrode and experiment requires a systematic discussion of the events within a muscle as we now know them, largely from studies of limb muscles. Most issues of muscle characteristics have only been explored with a limited number of muscles.

Let us begin with the single motor unit. In constant force contractions, it will fire with an overall mean interspike interval and standard deviation (DeLuca & Forrest, 1973; Figure 6), which can be used to characterize the unit, and, perhaps, the muscle itself. MacNeilage (1973) has shown that single motor units from CT and PCA fire at mean frequencies of about 15 impulses per second, during low frequency phonation. He suggested that these rates were intermediate between rates for limb and trunk and intraocular

A strand of Nylon
Karma Alloy wire looped
through a 27 gauge Hypodermic
needle

Nylon insulation
burned off Distally
and Proximally

Distal ends staggered

Staggered distal
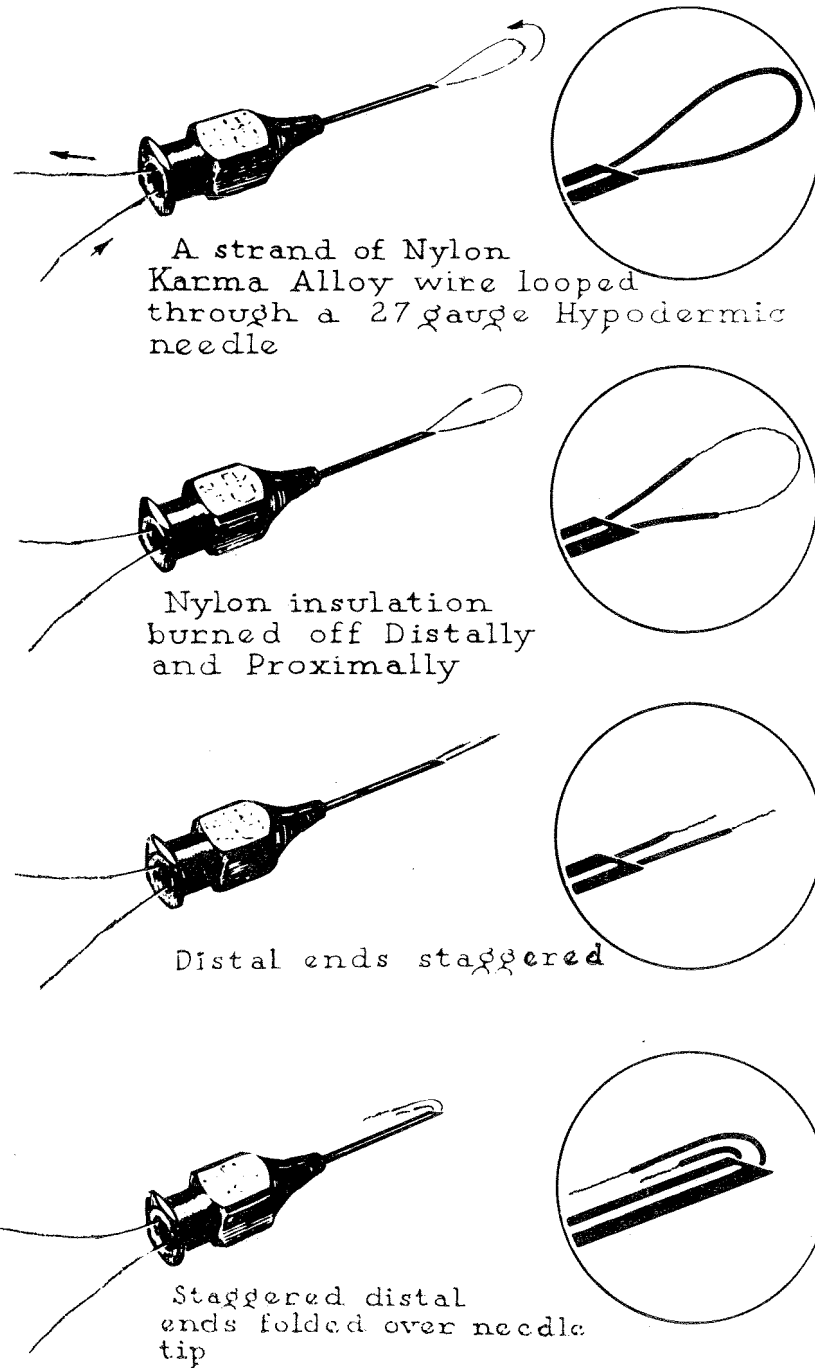ends folded over needle
tip

Figure 5. Steps in making a bipolar fine-wire electrode with the carrier
needle used for insertion. Reprinted from Basmajian and Stecko,
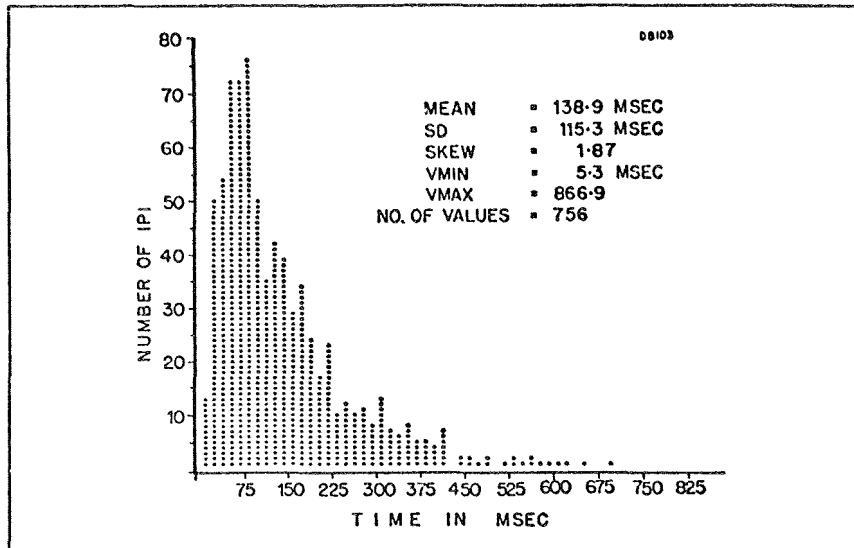1962.

Figure 6. Distribution of interpulse intervals from a single motor unit.
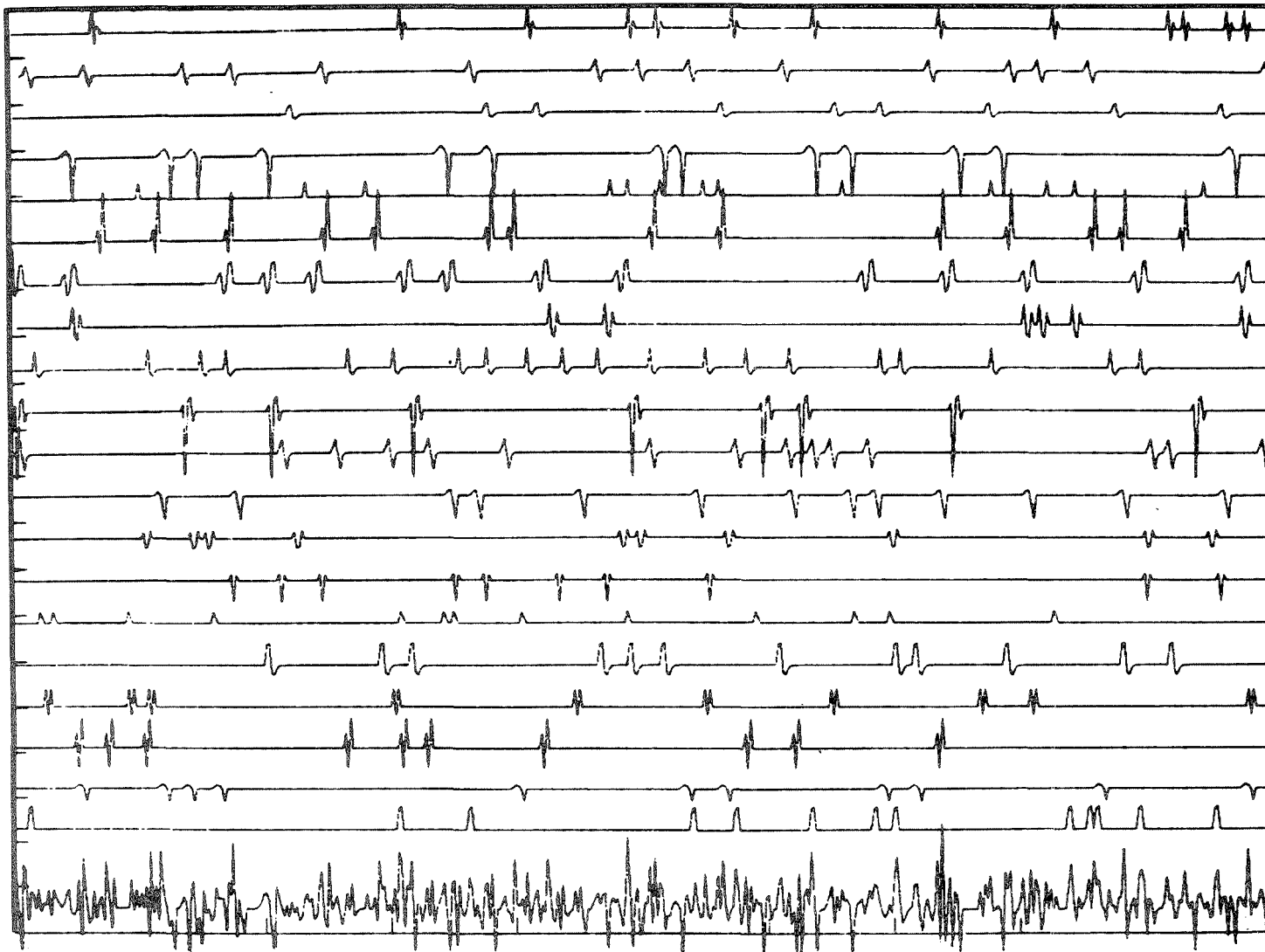Reprinted from DeLuca and Forrest, 1973.

Figure 7. Synthetic interference pattern. The interference pattern at the bottom is the sum of the twenty "motor units" in the upper lines. C. DeLuca.

musculature, as we might expect from these other properties. However, he found no evidence for the different kinds of units, tonic and kinetic, postulated by Tokizane and Shimazu (1964), to be identifiable on the basis of the relationship between variability and firing rates (MacNeilage, Sussman, & Powers, 1977). Other authors (DeLuca & Forrest, 1973; Hannerz, 1974; Leifer, 1969) have found continuous distributions of single unit properties for various limb muscles.

During force-varying isometric contractions, there is a complex relationship between variation in firing rate and recruitment. At low forces, force tends to be increased by the recruitment of additional units, with successively recruited units having higher firing rates at recruitment. As force increases, individual units increase firing rates, and at the highest force levels, very little recruitment occurs. Synchronization of firing of units may occur as the muscle fatigues (DeLuca, 1978).

The most consistent observation of motor unit behavior is the relationship between the size of the unit, and force output and order of recruitment with increasing muscle force, the "size principle" (Henneman, 1975). While this relationship has not been observed for any of the laryngeal muscles, it has been demonstrated for the masseter in humans (Yemm, 1977) and for the anterior belly of the digastric by MacNeilage, Sussman, Westbury, and Powers (1979), and there is no reason to believe that the laryngeal muscles behave in a very unusual way in this respect. However, for all muscles, there is some question as to whether there are reversals of recruitment order for rapid, anisometric contractions.

Since the territories of motor units overlap with increasing forces of contraction, it is increasingly difficult to identify individual units. For studies of such questions, electrode size must be reduced, and sophisticated programs for the identification of motor units developed (LeFever, 1980).

THE INTERFERENCE PATTERN

Most electromyographic studies of the laryngeal muscles have been concerned, not with the properties of individual motor units, but with the functions of the muscles as a whole. Typically, the studies have related the characteristics of a given muscle activity to some sort of output, such as pitch. The electromyographic signal studied is usually an interference pattern, the signal from a large number of motor units. As an aid in visualization, it is interesting to look at a synthesized interference pattern, Figure 7 (LeFever & DeLuca, personal communication). The figure shows 20 motor units of shapes that would be characteristic of those found in an electrode field during a constant force, isometric contraction. Their sizes and the relative extent of positive and negative deviations from baseline vary with distance from and orientation to the electrode. The sum of positive and negative deviations is shown in the bottom line of the figure. Obviously, there is summing and cancellation of signals from individual units, depending on their phase relations. The resultant signal is noisy, and difficult to deal with quantitatively. If the electrode size is reduced, so that fewer units are represented in the signal, the interference pattern becomes more variable as a function of time (Figure 8A).
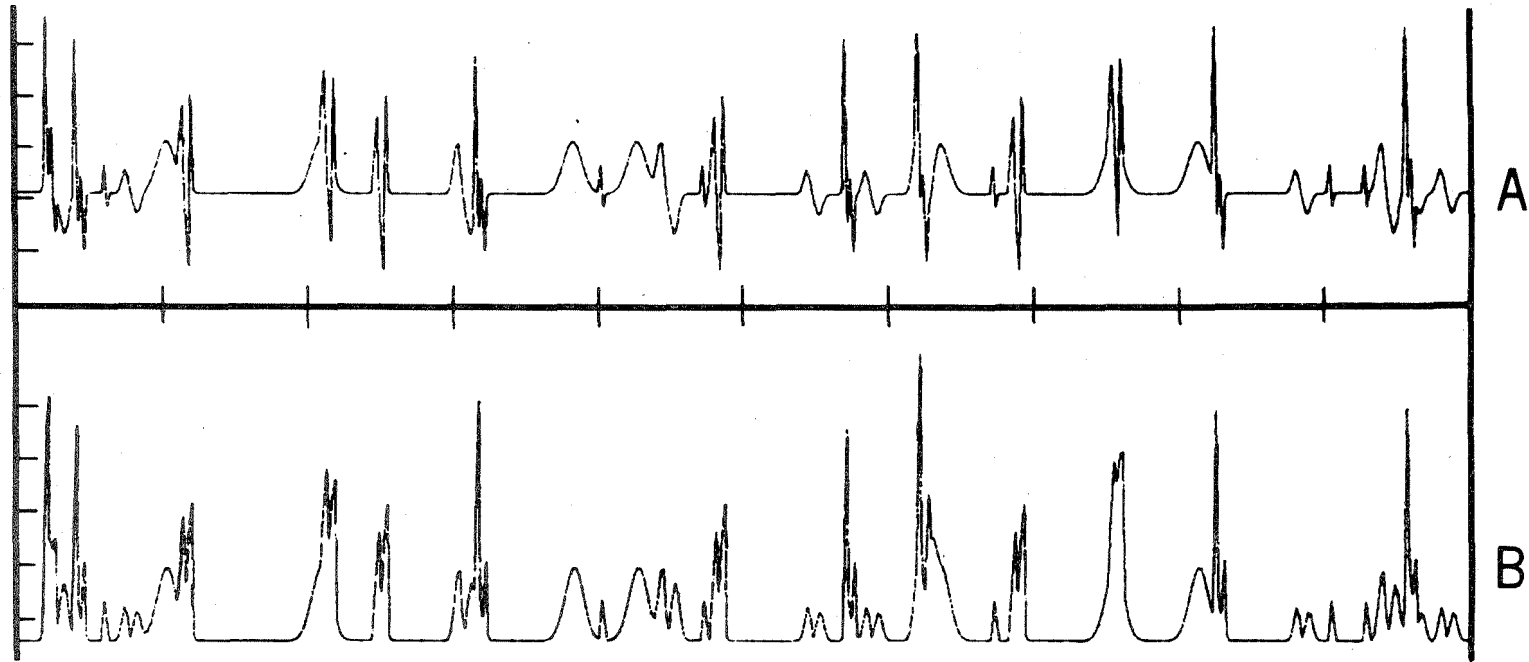
Figure 8. A. Synthetic interference pattern, sum of 5 motor units. B. The same interference pattern, after rectification. C. DeLuca.

A number of steps must be taken to deal with such signals. The usual approach has been to rectify and integrate. The effects of rectification are shown in Figure 8B. The traditional use of the rectified and integrated EMG signal is based on a large body of research investigating the relationship between the magnitude of the EMG signal so obtained and the force output of the muscle (Bigland & Lippold, 1954; Bouisset, 1973; Bouisset & Maton, 1973; Inman, Ralston, Saunders, Feinstein, & Wright, 1952; Lippold, 1952; Zuniga & Simons, 1969). This measure ("integrated EMG") varies roughly linearly with force for isometric contractions at moderate force levels, but at higher levels of force the relationsip becomes nonlinear. The situation becomes far more complex for anisometric contractions, in part because the mechanical efficiency of a muscle depends on its length as well as its velocity of shortening or lengthening. Since the events of interest in speech research are typically of this latter sort, we can expect the magnitude of the EMG signal to provide no more than an overall index of mechanical performance.

A possibility that we have explored informally at Haskins is calculating the variance of the interference pattern, which is equal to the sum of the variances of the motor unit action potential trains contributing, and hence, does not lead to the loss of contributions of motor units due to cancellation as does the more conventional measure.

We have said very little about the time constant to be used for integration. We use a 5 millisecond hardware integration window and smooth further algebraically, using software programs in which a time constant may be chosen. Individual tokens recorded with hooked-wire electrodes show sizable fluctuations that are not represented in the mechanical output of the muscle as a whole. For speech, time-smoothing is useful only to the point where it does not obscure the sequencing of underlying articulatory events. An alternative way of smoothing is ensemble averaging. The effects of time-smoothing and ensemble averaging are shown in Figure 9, which shows averaged and integrated signals from repeated utterances. The details of these analysis procedures are discussed at greater length in laboratory reports (Kewley-Port, 1973, 1974).

LARYNGEAL MUSCLE STUDIES

Having reviewed the general properties of muscles, and of the laryngeal muscles in particular, as well as some technical problems, we turn now to the results of electromyographic studies of the function of these muscles in speech. The most primitive question, is, perhaps, what muscles should be considered as laryngeal muscles? Traditionally, the muscles of the larynx have been divided into two groups, intrinsic and extrinsic. The identity of the intrinsic muscles is readily agreed upon; they are the cricothyroids (CT), the thyroarytenoids (TA), the interarytenoids (IA), the lateral cricoaryteno-ids (LCA), and the posterior cricoarytenoids (PCA). The identity of the extrinsic laryngeal muscles is more difficult to specify. If we take the empirical point of view that any muscle that affects the positions of thyroid, cricoid, and arytenoid cartilages relative to each other may be considered to be an extrinsic laryngeal muscle, then a wide variety of muscles, not normally considered in relation to the larynx, must be included. For example, Painter (1978) has produced some evidence that genioglossus activity may influence

17

Utterance: fazmap

levator palatini

| unsmoothed | smoothed | intraoral air pressure | amplitude envelope | pitch | velar elevation |

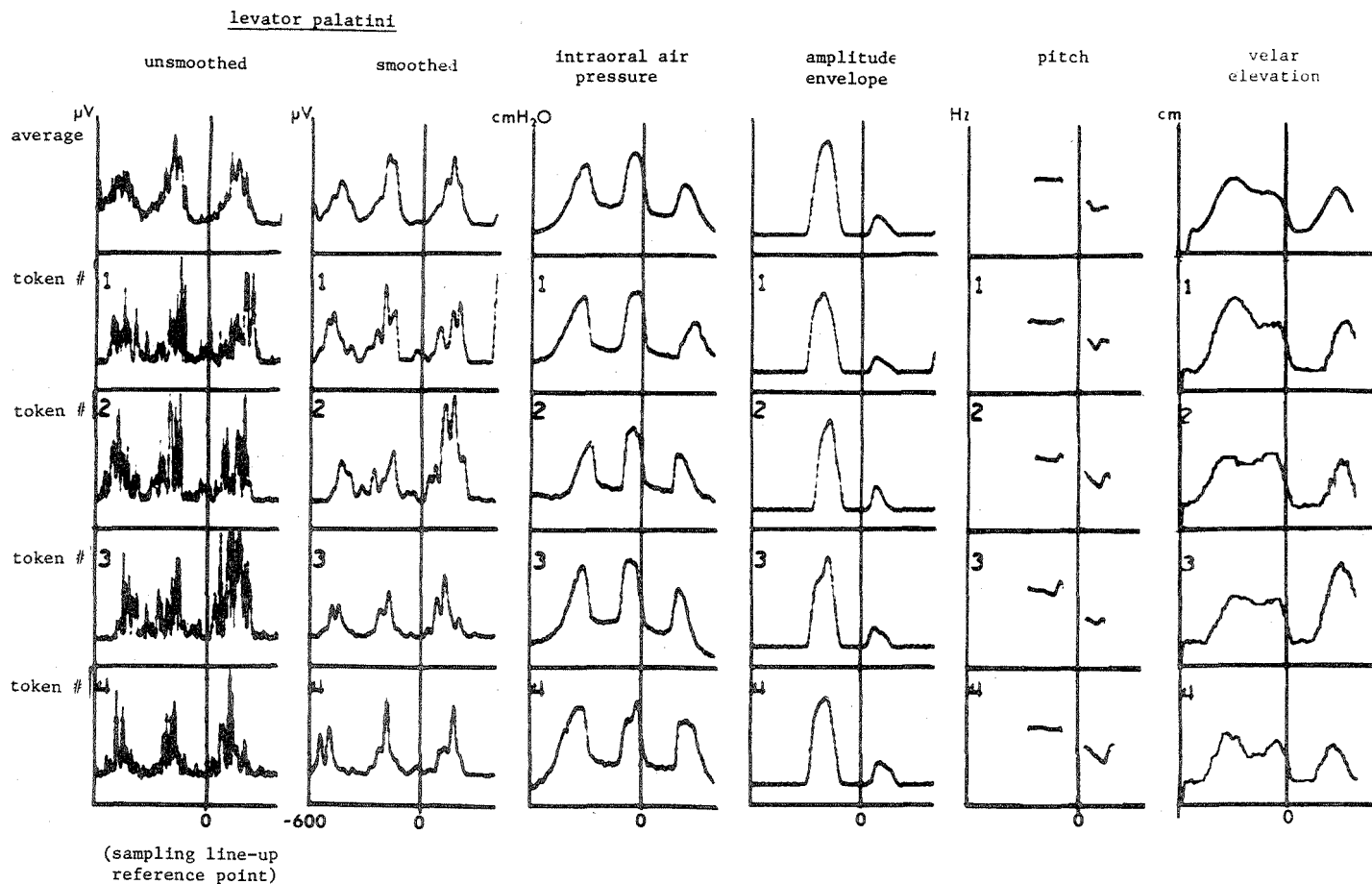(sampling line-up
reference point)

Figure 9. Individual and averaged tokens for the spoken utterance "faz
map." The top row represents averages of 20 tokens. Four tokens
are shown beneath the average. The first two columns show EMG
output from the levator palatini, after sampling and rectification,
before and after smoothing. The remaining columns show intraoral
pressure, audio amplitude, fundamental frequency, and measured
velar height. Haskins Laboratories.

pitch, and Erickson, Liberman, and Niimi (1977) have produced the same sort of evidence for geniohyoid. The implication is that a wide variety of muscles may affect pitch, as Sonninen suggested many years ago (1956). However, given the lack of detailed information about secondary effects on vocal fold adjustment, only the three strap muscles, the sternohyoid, the thyrohyoid, and the sternothyroid will be considered as extrinsics here.

Fundamental Frequency Control. Electromyographic studies on the regulation of pitch have been reported by many authors. More recent electromyographic studies have included those of Hirano, Vennard, and Ohala (1970), Shipp and McGlone (1971), Gay, Hirose, Strome, and Sawashima (1972), and Baer, Gay, and Niimi (1976).

These studies all conclude that cricothyroid activity increases as the pitch is raised, at least over most of the pitch range, as we might have expected from the mode of action of this muscle in producing torque around the cricothyroid joint. This action presumably underlies the observed lengthening of the folds with increasing f_o.

The activity of TA also increases as the pitch is raised over most of the pitch range, although it is more active in chest voice than in falsetto (Hirano, Ohala, & Vennard, 1969; Hirano et al., 1970; Baer et al., 1976), but the function of this activity is obscure. The thyroarytenoid could act, of course, to produce a shortening force in opposition to CT, although this cannot be its primary function, since its activity increases with pitch rise rather than pitch fall. One theory, by van den Berg (1960), as to its primary function suggests that it exerts "medial compression," limiting the horizontal extent of vocal fold vibration, permitting the more effective play of aerodynamic forces. An alternate possibility is that its tension is adjusted with compensating adjustments of CT, to tune the natural vibrating frequency of the muscle itself, considered as a tissue mass, since the muscle makes up the bulk of the folds and so determines, in large part, their vibratory characteristics. A secondary problem in the characterization of TA activity is that there is disagreement in the literature as to whether there are functional or anatomical differences between lateral and medial (vocalis) parts of TA, so that an adequate description of the function of one part may not suffice for the other (Sawashima, 1970).

Reports on the other laryngeal adductors, IA, LCA, and the more lateral parts of TA, tend to show increasing activity with increasing pitch. Van den Berg (1960) suggested, on the basis of cadaver experiments, that the IA might be active without the laterals at very low pitches, but this possibility has never been experimentally verified.

Some authors (e.g., Dedo, 1970; Gay et al., 1972; Baer et al., 1976) report increases of PCA activity at the highest f_o's when intensity is great, although there is not universal agreement on this point (Shipp & McGlone, 1971). Although this muscle is normally an abductor, its activity at high f_o is thought to brace the arytenoids against the anterior pull of the vocal folds. The observations of Gay et al. are summarized in Figure 10.

Control of f_o by the extrinsic muscles of the larynx is less well understood than control by the intrinsic muscles. The larynx, and f_o, move up
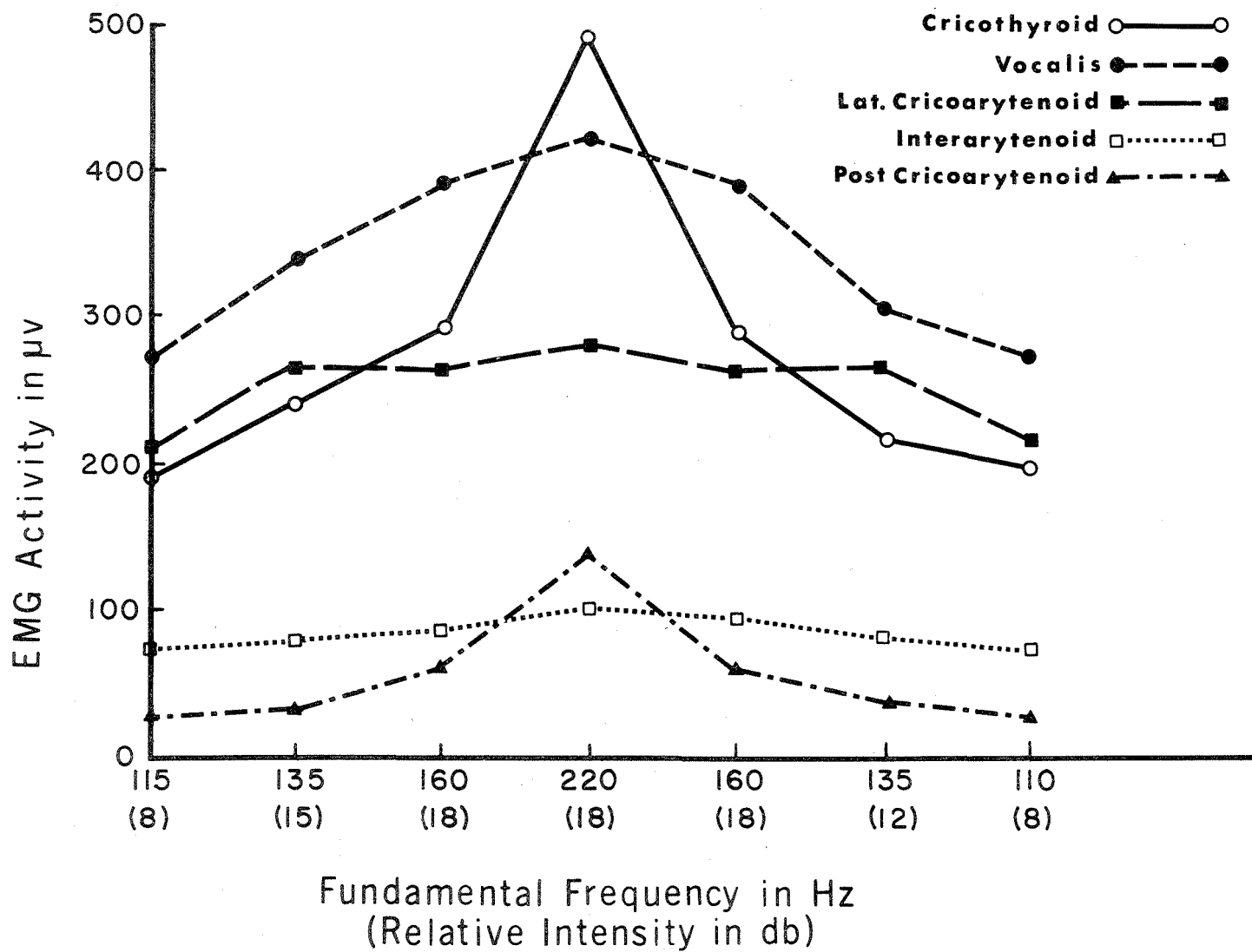
19

Figure 10. EMG activity for various laryngeal muscles as a function of frequency. From Gay, Hirose, Strome, and Sawashima, 1972.

and down during singing by untrained singers, or during speech, although trained singers learn to keep the larynx at an approximately constant low position (Sonninen, 1956; Shipp & Izdebski, 1975). These movements are produced largely by activity of the extrinsic attachments to the larynx, especially by the strap muscles.

Strap muscle activity (sternohyoid, sternothyroid) is correlated with f_0 at both its highest and lowest levels. Although Kakita and Hiki (Note 1) have reported differentiation among these muscles, the weight of the evidence is that they act together in controlling pitch. This finding is supported both by electromyographic measurements (Faaborg-Andersen & Sonninen, 1960; Baer et al., 1976) and by clinical observation of patients who have had these muscles sectioned (Sonninen, 1956). Although, on anatomical grounds, it would seem that the sternothyroid muscle ought to increase f_0 by tilting the thyroid cartilage down and forward, and that the thyrohyoid ought to decrease f_0 by tilting the thyroid cartilage up and back, Sonninen showed that the situation is more complex. In experiments with cadavers and in stimulation experiments with patients undergoing thyroidectomy, he found that the effect on the larynx of activity of these muscles depended on posture and head position. The sternothyroid, in particular, can tilt the thyroid cartilage either way.

Sonninen developed an "external frame function" theory to account for f_0 raising, based on his own results and those of other investigators. According to this theory, all the strap muscles work in conjunction with the anterior suprahyoid muscles. Although the strap muscles may or may not raise the larynx, their main function is to pull the thyroid cartilage forward. At the same time, activity of the cricopharyngeus and downward pull of the esophagus exert a downward and backward force on the posterior part of the cricoid cartilage.

Since the mechanism for application of the "external frame function" theory to f_0 lowering has been elusive, alternative theories have been advanced. One of these is the passive theory, stating that f_0/larynx lowering is due to relaxation of the mechanisms for f_0/larynx raising. Although passive lowering can explain some of the observed relationships, two facts support the notion of at least an ancillary active mechanism. Electromyographic activity accompanies lowering as we noted above, and studies of vertical larynx position show that the position during low frequency phonation is lower than that in rest position (Shipp & Izdebski, 1975). A second theory, attributed to Ohala (1972), suggests that raising and lowering the larynx affects f_0 directly through adjustment of the vertical tension of the vocal fold cover, which is continuous with the lining of the trachea. This theory cannot be adequately evaluated without improved understanding of the vibratory mechanism of the vocal folds and actual measurements of "vertical tension" in raised-larynx and lowered-larynx configurations. Finally, a theory accounting for f_0 lowering by laryngealization has been proposed by Lindqvist (1969). This theory asserts that the vocal folds are shortened (and, incidentally, transglottal pressure is reduced) by activity of the muscle fibers of the aryepiglottic sphincter. This mechanism does not appear to require lowering of the larynx and hence does not explain the observed movements or associated EMG activity. It may operate jointly with or independently of other mechanisms.

21

Results of studies of strap muscle function in speech first suggested that although f_o falls were always accompanied by an increase in strap muscle activity, the activity did not always precede f_o falls, and showed substantial effects of segmental variables (Collier, 1975; Hirano et al., 1969). Later analysis, however, suggested that strap activity does precede pitch drops from a mid to low range (Atkinson & Erickson, 1977; Erickson et al., 1977).

A problem in studying pitch control in speech has been the difficulty of analyzing the relationships among f_o, subglottal pressure, and the antecedent activity of the large number of relevant muscles. One technique, which has been found useful, cross-correlates f_o and integrated EMG (Atkinson, 1978). The delay at which the correlation reaches a maximum can be used to estimate the response time of the muscle. The magnitude of the correlation at this delay can then be used in estimating the magnitude of that muscle's contribution to pitch control. The analysis can be further refined by dividing the fundamental frequency range into subranges. Atkinson's study shows the contribution of strap muscle activity to be greatest at low frequencies, while CT activity has its greatest effects at high frequencies. Although the data analyzed in the study were extremely limited, further exploitation of the technique seems warranted.

There is, nonetheless, a limit to the amount of reliance one can place on the results of gross correlation studies. An ingenious new technique for studying the relationship of f_o and the activity of the various laryngeal muscles has been suggested by Baer (1978). The technique was adapted from one originally designed for the study of skeletal muscles (Milner-Brown, Stein, & Yemm, 1973). Continuous records were made of electromyographic activity from laryngeal muscles and of voice fundamental frequency from a subject producing steady, sustained phonation at low f_o. The fundamental frequency record exhibits small perturbations around a nominally constant value. If we assume that these perturbations represent the response to the firing of single motor units in those muscles that control pitch, then an average-response computation of fundamental frequency triggered by single motor unit firing of any muscle should exhibit a systematic deviation in the interval immediately following the firings. Figure 11 shows the results of following this procedure for CT. Using this technique, muscles whose activity is grossly inter-correlated can be uncorrelated to examine their individual effects on some variable. We feel that this technique shows great promise in the application just suggested, and others.

## Stricture Control and Voicing Features

A second dimension of laryngeal adjustment in speech is stricture control, the degree to which the laryngeal sphincter is closed by the approximation of the vocal folds. While these adjustments can be used to produce overall changes in voice quality, most speech studies of this dimension have been aimed at understanding the mechanism of consonant voicing.

Fiberoptic visualizations of the glottis (Sawashima, Abramson, Cooper, & Lisker, 1970; Kagaya, 1974) show that voiced and voiceless consonants are characterized by differences in glottal opening. It is the timing of the abduction and adduction of the folds, relative to the movement of the upper articulators, that distinguishes consonant classes within and across languages.
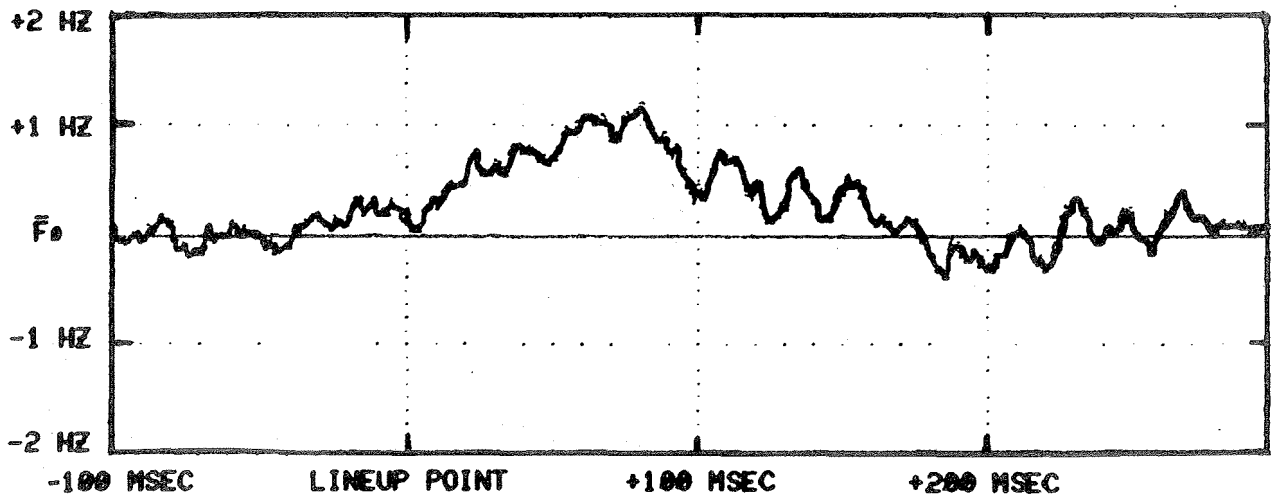
CRICOTHYROID MUSCLE

N = 19

$\overline{F_0}$ = 100 HZ
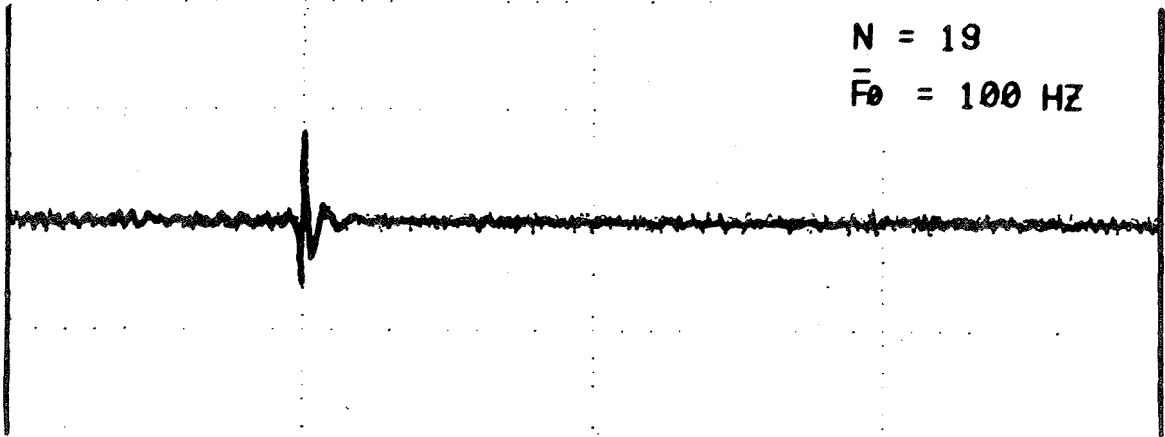
RAW EMG: ALIGNED AT SINGLE FIRINGS AND AVERAGED

+2 HZ

+1 HZ

F_0

-1 HZ

-2 HZ

-100 MSEC   LINEUP POINT   +100 MSEC   +200 MSEC

PITCH PERTURBATIONS (AROUND $\overline{F_0}$):

ALIGNED AS ABOVE AND AVERAGED

Figure 11. Single motor units of the cricothyroid, aligned and averaged, with
parallel measure of pitch perturbation. See text for explanation.
From Baer, 1981.

Anatomically, the five intrinsic laryngeal muscles can be divided into three functional groups with respect to stricture control: adbuctor (PCA), adductor (INT, TA, LAT), and tensor (CT). The question can then be asked whether the muscles function in speech in ways that the classification would suggest. Is there active abduction and adduction in voicing maneuvers? Do the adductors function together? Finally, is the activity of adduction and abduction accompanied by changes in tensing?

Abduction and adduction for voicing are clearly accomplished by the action of PCA and INT activity in a reciprocal way, as has been demonstrated in a number of studies (Hirose & Gay, 1973; Fischer-Jørgensen & Hirose, 1974; Hirose & Ushijima, 1976).

Figure 12 shows a fairly typical pattern obtained for this pair of muscles (Hirose, Lisker, & Abramson, 1972). The general conclusion is that the abductor (PCA) contracts, the adductor (INT) relaxes. The relationship has been quantified. Hirose (1977) showed that for a series of utterances containing voiced and voiceless stops, produced by a Japanese talker, the value of the correlation coefficient ranges between -.85 and -.65. The analysis does not make it clear what variables affect the value in a critical way.

The extent to which the activity of the adductor group is correlated in such maneuvers is still unclear. Some time ago, van den Berg and Tan (1959) showed, in cadaver experiments, that the different adductor muscles can be used to close the cartilagenous and membraneous parts of the larynx separately. Thus, we might expect some differences between the activity patterns of INT on the one hand, and LAT and TA on the other. Such differences have been seen in studies of Korean stops (Hirose, Lee, & Ushijima, 1974; Danish stød (Fischer-Jørgensen & Hirose, 1974) and glottal stops (Hirose & Gay, 1973). Apparently, the activity of LAT and TA is connected to the necessity for strong medial compression in these productions. However, the detail effects of differential contraction of these muscles on the shape of the glottis are not known. Figure 13 shows the contrast in activity of INT and VOC (TA) for the three types of voiceless stop found in Korean. The important point to note, apart from the obvious overall differences, is that there is a sharp peak in VOC activity for the glottalized Korean stop at consonant release, probably associated with increased tension of the folds.

A recent experiment by Yoshioka (1979) also suggests circumstances in which we perhaps will observe differentiation among laryngeal adductors in stricture control. He found that /h/ and /s/ may be produced with equal glottal widths, and equivalent patterns of reciprocal PCA and INT activity, but still differ in the presence of vibration at the edges of the membranous portions of the folds in some examples of /h/. An obvious possibility is that other intrinsic laryngeal muscles show differences in activity for stricture control for the sounds.

A third question associated with the activity of the vocal folds in voicing control is whether activity of CT is associated with abduction or adduction. Stevens' model of glottal activity suggests that the tension of the vocal folds will affect the likelihood of vibration, for a given pressure drop across the glottis. It is therefore possible that some stops are
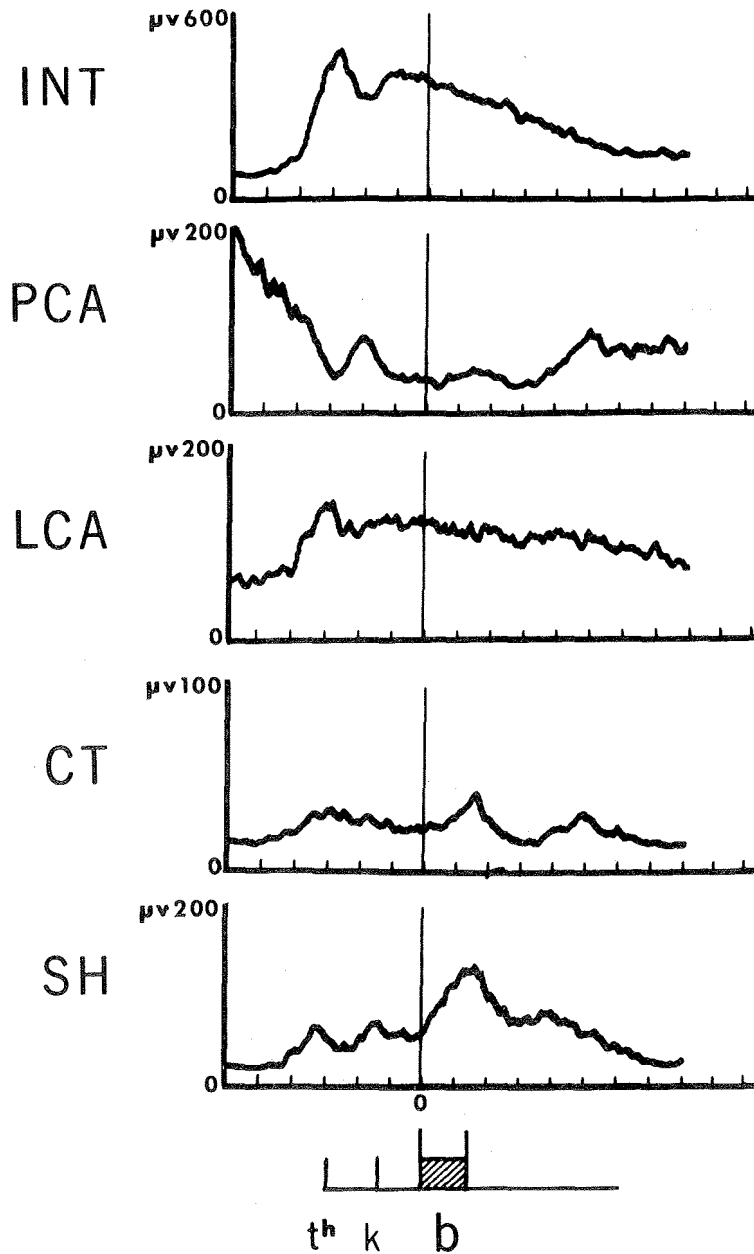
tʰɪkib̲i

Figure 12. Intrinsic laryngeal muscle outputs for an utterance with a medial explosive voiced inaspirate [b]. The shaded interval at the bottom of the figure represents the duration of voicing during the [b] occlusion. From Hirose, Lisker, and Abramson, 1972.
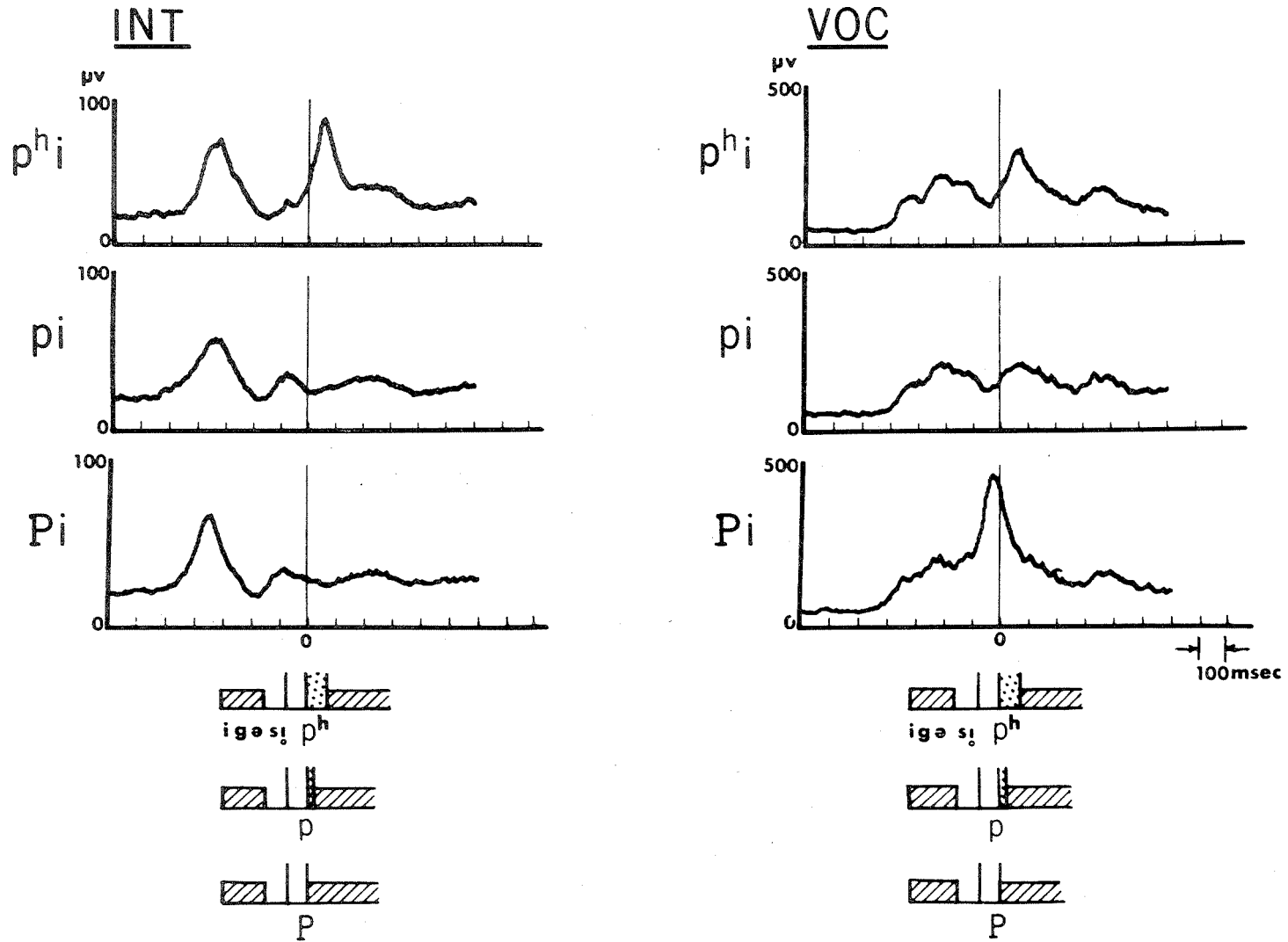
Figure 13.   Averaged EMG curves for INT and VOC for the three bilabial stops of
Korean.   [pʰi] is voiceless and aspirate, [p] is voiceless and
slightly aspirated, and [p] is voiceless and glottalized.   From
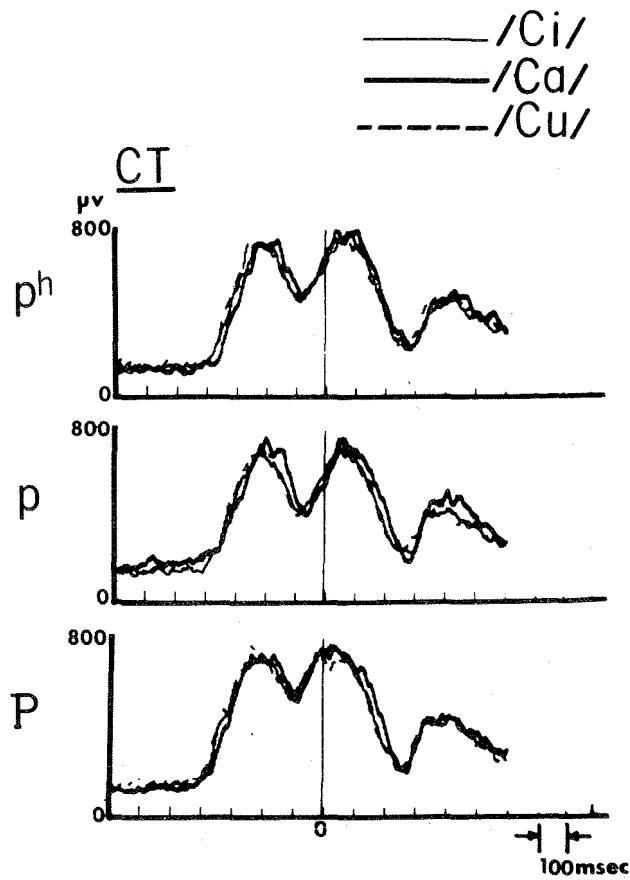Hirose, Lee, and Ushijima, 1974.

Figure 14. Cricothyroid activity for the three bilabial stops of Korean. The three curves in each box represent utterances containing the vowels /i/, /a/, and /u/. From Hirose, Lee, and Ushijima, 1974.

characterized by contrasts in CT activity, particularly those that contrast in degree of aspiration, like those of Korean (Hirose et al., 1974). A study of stop production in a single speaker (Figure 14) fails to support the hypotheses of CT differentiation, but small differences in CT activity accompanying voicing contrasts have been found from time to time.

The brief summary of laryngeal muscle function in this section and the preceding one reveal that we now have a gross qualitative sketch of the activity patterns, and the technical means at hand to elaborate this picture, to match models and observations of the larynx developed in other ways. However, we might now ask what clinical uses might be made of EMG using presently available techniques.

ELECTROMYOGRAPHY IN FUTURE DEVELOPMENTS

At present, EMG is widely used in diagnosis of neuromuscular disorders. It has not been used this way for the laryngeal muscles, although it perhaps could be. For example, it seems possible to detect abnormal single motor unit firing patterns in these muscles, abnormal synchronization of motor unit firings (Hirose, 1977), or, perhaps, to differentiate peripheral neurogenic and myogenic disorders.

Another use, from my point of view a very exciting one, is to use EMG as a technique for examining articulatory programming and its breakdown. The work described in this paper, and others, can be used to show a very tightly time-constrained coordination of laryngeal and supra-laryngeal events in running speech. Aspects of this coordination appear to break down in stuttering (Freeman & Ushijima, 1978), and in apraxia (Freeman, Sands, & Harris, 1978). While the broad perceptual consequences of breakdown in laryngeal coordination have often been described (e.g., Darley, Aronson, & Brown, 1975), it seems far more direct to look at the underlying failures of patterning. One of the most unfortunate consequences of the description of normal and abnormal speech in terms of transcriptional entitites has been to focus description of speech motor behavior on the attainment or failure of attainment of stationary acoustic or articulatory targets, rather than on the temporal prescription for coordinated activity. For normal speakers, we need to investigate what maintains these prescriptions, by systematically attempting to disrupt them. For abnormal speakers, we need, first, to describe the disrupted speech in terms of the constituent articulatory acts, and second, to investigate the relative roles of various factors, such as feedback, in maintenance of existing coordinations.

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