An aerodynamic study of Korean stop consonants: Measurements and modeling

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(Received 21 December 1984; accepted for publication 10 September 1986)

Measurements were made of intraoral air pressure and oral flow of ten native speakers uttering word pairs contrasting Korean fortis and lenis voiceless stop consonants in initial position. The production of fortis stops was found to be characterized by a higher intraoral pressure before release, yet a lower oral flow after release, than corresponding lenis stops. Possible reasons for this difference were explored with the use of a computer implemented aerodynamic model, giving an output of air pressure and flow. Input parameters were adjusted in accordance with known or hypothesized variations in glottal area function, vocal tract wall tension, respiratory muscle force, and supraglottal cavity volume, as given in the literature. In addition to the previously known differences in glottal area, it is inferred from the results of the modeling experiment that fortis stops are produced with greater vocal tract wall tension than lenis stops. Speaker-specific production strategies such as larynx lowering and heightened subglottal pressure during fortis stops and differences noted between word pairs are also discussed.

PACS numbers: 43.70.Jt, 43.70.Aj, 43.70.Bk

INTRODUCTION

Techniques developed for the measurement of the aerodynamic properties of speech provide data which can also be used to study other physiological properties. Phonetic distinctions which might be thought to involve only the laryngeal level may be seen to involve elements from the subglottal and supraglottal regions as well. In such a case, the aerodynamic properties of the segments in question (i.e., subglottal and oral air pressure and glottal and oral airflow) will reflect the state not only of the glottis, but also of the subglottal and supraglottal systems, giving an indication of how these areas of the vocal tract contribute to the production of contrasting segments, if techniques can be found for distinguishing these various contributions. One case in which this kind of analysis is invaluable is in the much debated phonetic nature of the phonemic distinction in Korean initial voiceless stop consonants. Korean has a three-way contrast between voiceless stops in initial position. These are exemplified in the following minimal triplet: [p*aŋ] "bread," where the initial stop is said to be unaspirated and "tense" or "fortis"; [paŋ] "room" with a "slightly aspirated" (or "lenis") stop; and [phaŋ] "bang!," where the stop is heavily aspirated. At first glance, this would seem to be a simple difference in voice onset time as indicated by the labels "unaspirated," "slightly aspirated," and "heavily aspirated," and, certainly, the heavily aspirated stop may be distinguished on this basis alone (cf. Han and Weitzman, 1967, 1970). Although the VOT of [p] is, on the average, longer than that of [p*], these two stop types have been shown in some studies (Kim, 1967; Abramson and Lisker, 1971; Han and Weitzman, 1967, 1970) to have overlapping VOT values. Perception tests (Han and Weitzman, 1967, 1970) have seemed to indicate that duration of aspiration is not the only, or perhaps even the most crucial, cue which distinguishes these two stops. Both a shorter amplitude rise time and greater intensity at voice onset in [p*], for example, have been suggested as important factors (Han and Weitzman, 1967, 1970). It is in reference to these other dimensions in the distinction that investigators speak of [p*] as "strong" or "forced" and [p] as a "weak" stop, or refer to them, respectively, as "fortis" and "lenis" articulations. This paper is based on the assumption that VOT differences alone are not enough to distinguish these two stop types and that, consequently, further investigation is required into other possible ways in which they differ significantly from each other. Henceforth, in this paper, I will use the cover terms "fortis" and "lenis" to refer to these stops. In doing so, however, I do not intend to make any claims for the precise meanings of the terms, nor do I necessarily, by using them, mean to equate the Korean stop distinction with fortis–lenis contrasts discussed in other languages.

The present study is mainly concerned with the aerodynamic properties of the Korean fortis–lenis distinction. The only previous work in this area has been Kim's (1965) separate measurements of intraoral pressure and oral flow, Lee and Smith's (1972) study of intraoral and subglottal pressure, and Hardcastle's (1973) oral flow records. All three studies dealt with only one subject each. They will be referred to where appropriate in later sections. In the present experiment, more conclusive evidence is shown by the simultaneous pressure and flow recordings of ten subjects. This evidence is further utilized to explore possible causes for the pressure and flow differences found, by attempting to simulate them on a computerized aerodynamic model.

Before discussion of the present work, it is useful to summarize the major findings on the nature of the Korean fortis and lenis stops, in order to give a background for further speculation. Previous studies have drawn from three major areas of investigation: acoustic records, direct observation of laryngeal vibration and glottal area, and EMG records of

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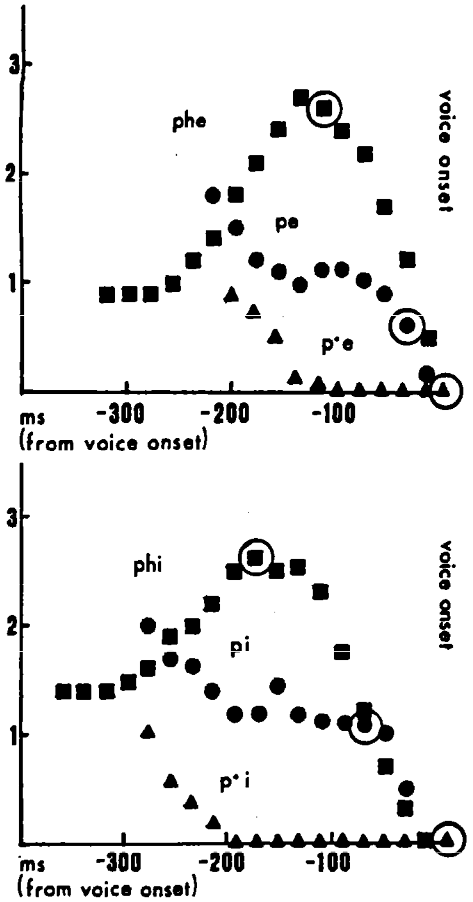

FIG. 1. Glottal adjustment on an arbitrary scale for fortis (triangles), lenis (solid points), and aspirated (squares) stops in Korean, after Kagaya (1974). Circle indicates articulatory release.

muscle activity. Acoustic studies have examined phenomena such as the intensity and fundamental frequency of the voicing just after release of the stop (Han and Weitzman, 1965, 1967, 1970; Hardcastle, 1973). It was found that after fortis stops the intensity was greater and the fundamental frequency was higher than after corresponding lenis stops.

Investigations focusing on the vibrations of the vocal folds began with Kim (1967) who, in his cineradiographic study, measured the distance between the vocal folds during utterance of the three stop types. He found the distance significantly greater in lenis stops at release than in fortis stops, a finding that was reinforced by the results of Kagaya's (1974) fiberscopic study. Kagaya photographed the vocal folds during Korean stop production with the use of a fiberscope, revealing very different laryngeal adjustments for the three stop types. It can be seen in Fig. 1 (after Kagaya, 1974) that the maximum glottal opening during occlusion was largest for the aspirated stop, intermediate for the lenis stop, and least of all for the fortis stop. The timing of the closing gesture relative to articulatory release also varied between stops. For the aspirated stops, release generally occurred near the moment of maximal glottal opening. With lenis stops, although the glottis was still quite open at release, there was a more or less continuous decline in glottal area throughout the occlusion. During the fortis occlusion, on the other hand, the vocal folds were approximated well before release.

Abberton (1972), in her laryngographic study, found waveforms resembling those of creaky voice (fry register) at the onset of voicing, following fortis stops, i.e., with a long closed phase and a slow opening phase. This is compatible with the observed smaller glottal area in fortis stops.

Hardcastle (1973) referred to "isometric muscular tension," i.e., the tensing of a muscle which does not undergo shortening as a result, present in the vocal folds and the walls of the pharynx during articulation of the fortis stop. He supported his claim by acoustic evidence such as the higher frequency of vocal fold vibration at the onset of voicing following fortis stops (an indication of tension in the vocal folds) and the sharper formant structure and more clearly defined harmonic partials which might indicate general tension in the walls of the supraglottal cavity. EMG studies (Hirose *et al.*, 1974) of the intrinsic laryngeal muscles partially support this view, showing a marked increase in lateral cricoarytenoid and vocalis muscle activity just prior to release in fortis stops, presumably resulting in tension of the vocal folds and constriction of the glottis. As far as I know, there have been no direct measurements of muscle activity in the pharyngeal and oral cavities during Korean stops, although Kim (1965) has reported greater muscle activity at the lips during fortis bilabials.

To summarize the findings thus far, we can assume that the articulation of fortis stops differs from that of lenis stops in two major ways: The vocal folds are closer together during occlusion and release and there is, perhaps, greater tension in the vocal folds and supraglottal cavity walls. The major problem, however, with all of the abovementioned studies was the lack of a sufficient number of subjects. One cannot confidently generalize from EMG data on one speaker, fiberscopic data on two others, and x-ray studies of yet another single speaker. It is not surprising that some conflicting findings have been reported, since, from such a small number of speakers, it is difficult to separate salient generalizations from speaker-specific idiosyncracies. Indeed, as will be shown, speakers *do* differ in certain systematic ways that would make interpretation of single-subject studies difficult.

In the present study, intraoral air pressure and oral air flow measurements were taken of ten subjects using a technique described below (see also Javkin and van der Veen, 1983). Since both oral pressure and flow are influenced by a change in glottal adjustment, one can infer a certain amount about the glottal state by measurement of these parameters. These inferences must be made, of course, with some caution, since other factors besides glottal state can influence oral pressure and flow (for example, changes in subglottal pressure, tension in the vocal tract walls, active expansion of the vocal tract, etc.).

I. EXPERIMENTAL PROCEDURE

Oral (and nasal) airflow was recorded using a modified respiratory mask with a fine stainless steel gauze which exhibits a known amount of resistance through which the outgoing air must pass (as described by Rothenberg, 1973). The flow was calculated from the pressure difference across the gauze. A Gaeltec catheter tip pressure transducer was inserted through a hole in the mask designed for that purpose. The

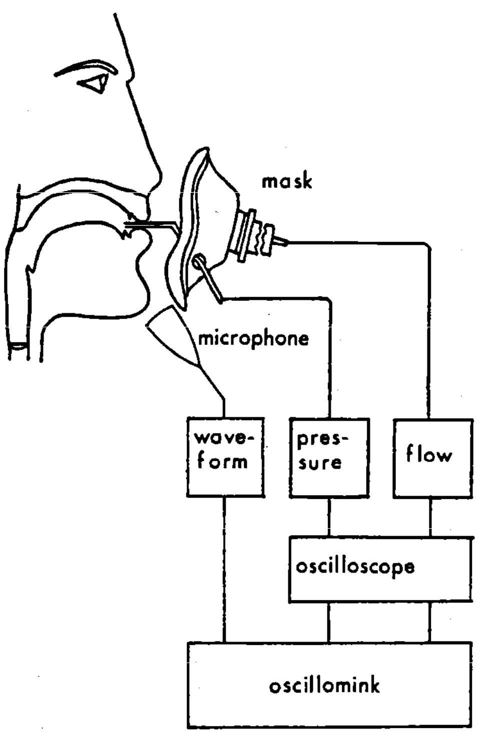

FIG. 2. Schematic diagram of the experimental apparatus.

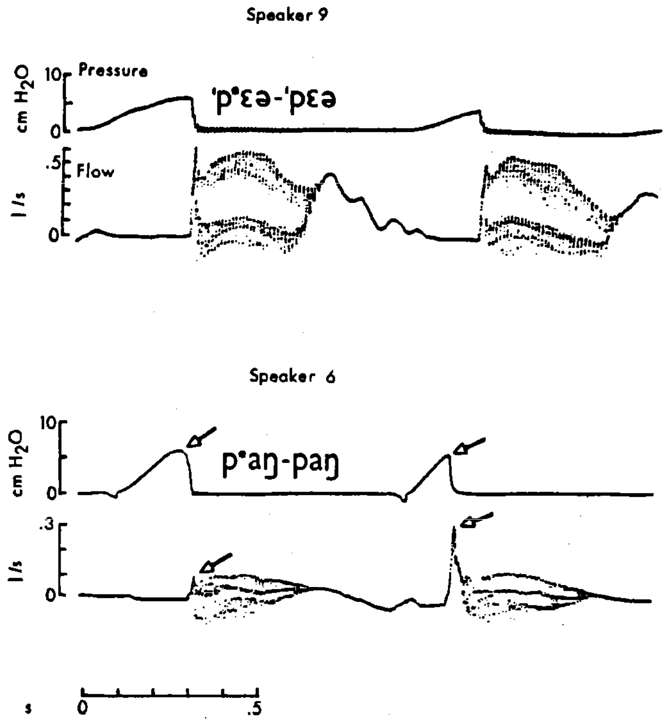

FIG. 3. Oscillomink traces of oral air pressure and flow during the production of two different Korean word pairs by two different speakers. Arrows exemplify points measured.

flexible tube containing the pressure transducer was placed between the lips of the subject in such a way that when the lips were closed, the transducer measured the air pressure inside the mouth, without touching the walls of the oral cavity and without being hit by any of the moving articulators (for this reason, the consonants were limited to bilabials). After each session, the air pressure and flow devices were calibrated, the pressure by the use of a standard U-tube manometer and the flow by introducing a known voltage (the flow mask is regularly checked to insure that it registers 0.98 V for a flow of 1000 ml/s).

The pressure and flow were monitored on an oscilloscope and recorded on an oscillomink inkwriter with a flat frequency response to 800–1000 Hz. As an aid to segmentation, an audio recording was made simultaneously on another channel. In order to get a higher quality acoustic record (since the mask muffled the sound somewhat) a separate recording was also made in a soundproof booth of the same words. The frequency response for the recording equipment was flat to 13 kHz $\pm$ 1 dB with a signal-to-noise ratio of 60 dB. Figure 2 is a schematic representation of the experimental procedure.

In addition to these recordings, an F–J electroglottograph recording was made of one of the subjects, from which the pitch was also calculated. The electroglottograph consists of two small metal plates attached to a strap around the subject's neck. The plates were positioned on either side of the larynx and a small electric current was passed between them. The variation in the impedance provides an indication of the degree to which the vocal folds are adducted (since when they are together, the electric current passes through easily).

TABLE I. Korean word pair test utterances.

Lenis	Fortis
(1a) [pjə] "rice"	(1b) [p*jə] "bone"
(2a) [paŋ] "room"	(2b) [p*aŋ] "bread"
(3a) ['piə] "empty"	(3b) ['p*iə] "sprained"
(4a) ['pɛə] "soak through"	(4b) ['p*ɛə] "pull out"

Ten native speakers of Korean were recorded, six males and four females, all between the ages of 18 and 26. Seven were speakers of the Seoul dialect, two of the Kangwon Do dialect, and one of the Kyonsang Nam Do dialect. Their residency in the United States ranged from 1 to 8.5 years, with the mean being 5.5 years. The dialectal differences (chiefly for the Kyonsang Nam Do dialect which has pitch-accent and no fortis–lenis distinction in fricatives) were not judged to affect the pronunciation of the test words, especially as all speakers were educated in a standard Korean. Variations found between speakers did not correspond to dialectal differences.

Four minimal word pairs were repeated by each subject six times, three times in the order lenis–fortis and three times in reverse order. In the following words given in Table I, the asterisk represents the fortis nature of the stop.

A typical example of an oscillomink printout is given in Fig. 3. The arrows indicate the points measured. Measurements were made of peak oral pressure during the occlusion and peak oral flow immediately after articulatory release.

II. RESULTS AND DISCUSSION

The relationship between the fortis and lenis means for each speaker is shown graphically in Fig. 4, where peak flow

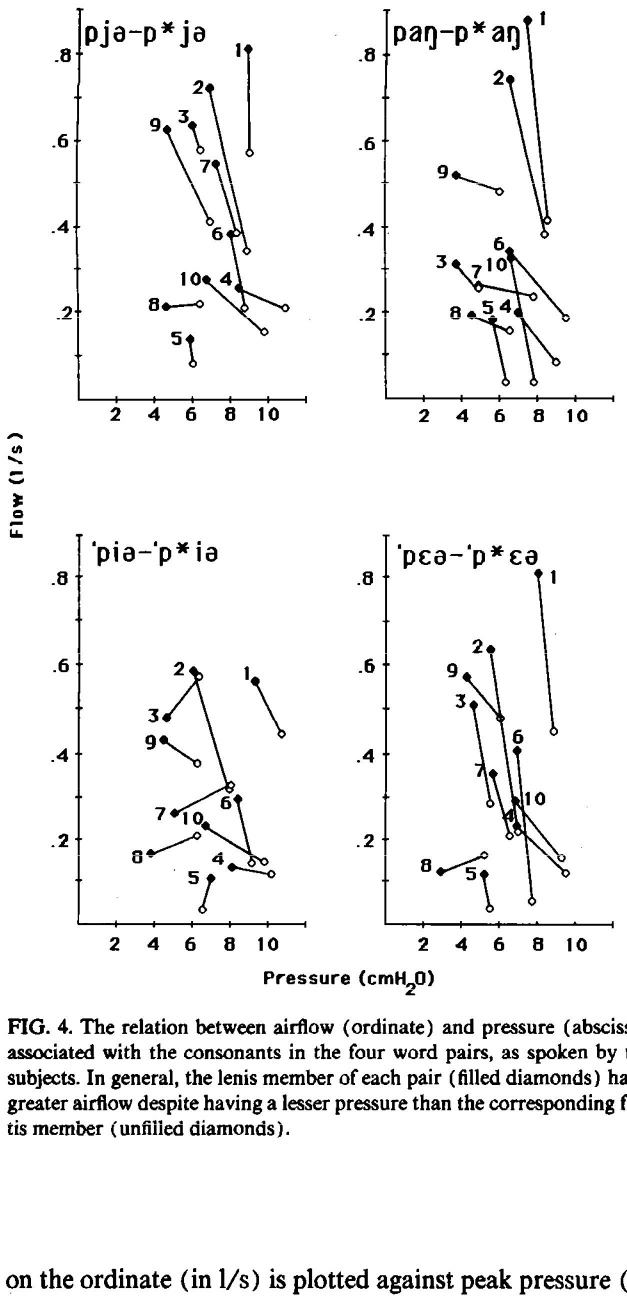

FIG. 4. The relation between airflow (ordinate) and pressure (abscissa) associated with the consonants in the four word pairs, as spoken by ten subjects. In general, the lenis member of each pair (filled diamonds) has a greater airflow despite having a lesser pressure than the corresponding fortis member (unfilled diamonds).

on the ordinate (in l/s) is plotted against peak pressure (in cm H_2O) along the abscissa for each word pair. Each point represents an average of the six tokens of the word indicated recorded from a single speaker. The filled diamonds represent lenis stops and the unfilled diamonds their fortis counterparts. A solid line connects the two points representing the word pair for each speaker.

As can be seen in the graphs, there is a great deal of variation among speakers in absolute value of pressure and flow. For each speaker, however, there exists a clear distinction between the two sounds. Although 97.5% of the means in Fig. 4 show higher pressure for the fortis stop (the one exception is speaker 5 in word pair 3) and 87.5% of the means show higher flow for the lenis stop (speaker 8 in word pairs 1, 3, and 4, and speakers 3 and 7 in word pair 3 show reversed values), the percentages in terms of individual word pair tokens are smaller, although still quite significant: 76.8% of the pairs show a higher pressure value for the fortis stop and 77% of the pairs show a higher flow for the lenis stop. Thus the general tendency is for fortis stops to have higher pressure and lower flow values than lenis stops in the same environment; 55.8% of the data showed both these tendencies in the same word pair token. An analysis of variance testing the significance of the fortis–lenis distinction across speakers shows that both flow $[F(1,9) = 13.573, 0.005 < p \leqslant 0.01]$ and pressure $[F(1,9) = 37.703, 0.0001 < p \leqslant 0.005]$ are significant in the distinction. The same is true across the four different word pairs, where pressure is highly significant $[F(1,3) = 248.373, p \leqslant 0.0001]$ and flow is weakly significant $[F(1,3) = 23.247, 0.01 < p \leqslant 0.025]$. Flow variation between word pairs will be discussed in a later section. While it is clear that both pressure and flow reflect important articulatory differences in the production of these stops, speakers appear to differ in which parameter has more importance in the distinction. Speakers 1 and 2, for example, appear to make the distinction more on the basis of flow than pressure in most of the word pairs. Speakers such as 8 and 9, on the other hand, have less of a flow difference and more of a difference in oral pressure. Yet others appear to use different production strategies in different word environments. The results of an analysis of variance testing the fortis/lenis ratio variation between speakers against the pooled within speaker token variability show it highly significant for both flow $[F(9,200) = 14.288, p \leqslant 0.0001]$ and pressure $[F(9,200) = 7.83, p \leqslant 0.0001]$.

It is interesting to consider for a moment the individual variation shown by the ten speakers. When considered pairwise, 23.75% of the word pairs showed reversed or equal pressure values (i.e., either the lenis stop had a higher pressure or the two pressures were equal) and 23% of the word pair tokens showed reversed or equal flow values. Only five word pair tokens (2% of the data) showed reversed values in one measure and equal values in the other (none was reversed for both). (Unfortunately, because of interference from the flow mask, a perception test could not be performed on these tokens to see if they remained distinguishable.) Out of the 75 tokens with one measure reversed in value, however, 60 (80%) had the other measure showing a greater than average distinction for that particular speaker. In other words, reversed values were generally compensated for in ways which made the distinction in the other measure more salient.

For purpose of discussion of the differences between individual speakers, we can divide them provisionally into two groups: those who seemed to make the distinction in a way which emphasized the flow difference and those who made the distinction in a way which emphasized the pressure difference. Figure 5 gives a visual representation of these speaker-specific production strategies, showing the average percent ratios of fortis to lenis in flow (ordinate) and pressure (abscissa) (i.e., fortis pressure/lenis pressure × 100 and fortis flow/lenis flow × 100) for each of the test words. The numbers refer to the individual speakers. Lines are drawn at the 70th percentile as a means of clarifying the divisions discussed. It can be seen that speakers 1, 2, 5, and 6 tend to have very little difference between lenis and fortis pressures (the fortis pressure is under 140% of the lenis for all word pairs). Speakers 8 and 9, on the other hand, make a

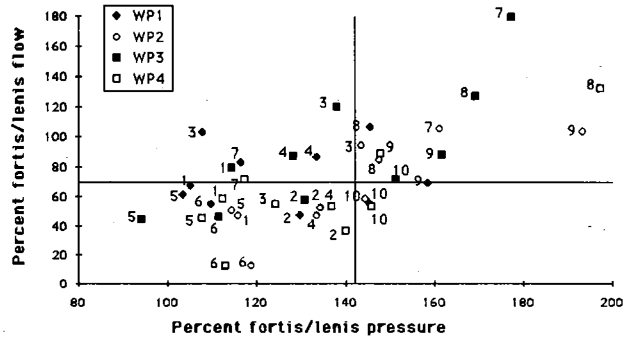

FIG. 5. Average percent ratios of fortis/lenis in flow (ordinate) and pressure (abscissa) for all speakers and word pairs. Solid diamonds are word pair 1, empty diamonds are word pair 2, solid squares are word pair 3, and empty squares are word pair 4.

larger pressure difference (fortis pressure is over 145% of the lenis pressure) and very little, if any, flow difference. Other speakers, such as 3, 4, and 7, seem to change strategy with different word pairs, while speaker 10 makes a sizable differentiation in both pressure and flow for all word pairs.

The question arises as to what articulatory and acoustic differences are associated with the observed differences in aerodynamic measures. One might expect that large flow differences would correspond to differences in VOT caused by significant variation in glottal aperture at release, such as that found by Kagaya (see Fig. 1). Pressure differences, on the other hand, could presumably come from the state of the glottis or from tension in the walls of the vocal tract as proposed by Hardcastle (1973). These hypotheses will be tested in the following section with the aid of the aerodynamic model. To begin with, an explanation is required of possible subglottal, laryngeal, or supraglottal adjustments that could lead to the observed higher pressure yet lower flow in fortis stops, since, all other things being equal, one would expect higher intraoral pressure before release of the stop to lead to a higher rate of airflow at release.

III. AERODYNAMIC MODEL

In order to understand the possible articulatory and glottal differences in stop production which result in the observed pressure and flow differences, an aerodynamic circuit model was used. Using such a model forces one to consider every variable in determining input values and helps to narrow down the possibilities for realistic interpretations of the data. Once set up for the known values, the model can serve as a testing ground for hypotheses concerning the less well-understood components of an articulation, and, in turn, the comparison with measured values of real speech tests the capabilities of the model.

The aerodynamic model used is a computer implemented electrical analog derived from Rothenberg (1968), similar to the model described by Müller and Brown (1980) and Westbury (1983) (for a detailed description of the model, see Keating, 1984). Voltage is taken to be the analog of air pressure, and current is the analog of volume velocity airflow. The model gives as its output oral pressure, subglottal pressure, flow through the glottis, and flow through the mouth opening. For simplicity in calculation, some of the input parameters are regarded as invariant during a given simulation, including some of the glottal dimensions, oral tract wall impedance, vocal tract volume and surface area. Other input parameters may vary over time, notably respiratory muscle force, distance between the articulators, distance between the vocal folds, and active expansion of the supraglottal cavity. Vocal fold vibration as such is not simulated by the model. Voicing is represented by maintaining a constant glottal area which approximates the average glottal area during vowel production. Voice onset time is determined by the difference in subglottal and supraglottal air pressures when the glottal aperture is set for voicing.

IV. INPUT VALUES TO THE MODEL AND RESULTS

The model was used to try to simulate the observed pressure and flow data reported in the previous section. Input values for the present study were estimated from results reported in the literature of fiberoptic and x-ray studies of glottal opening, x-ray studies of larynx height and pharynx width, and from acoustic measurements of VOT values for the Korean fortis–lenis distinction. In order to get an input for the model appropriate to the present experiment, the closure durations were measured from the data of all ten speakers. Closure was considered to begin as the oral pressure curve began to rise and to end at the beginning of flow rise at release.[1] It was found that the fortis closures were considerably longer than the lenis closures. This result did not differ significantly between word pairs or between speakers. The average closure duration of all lenis stops was 133.5 ms and that of all fortis stops was 188.25 ms. For modeling purposes, the lenis stop was given a duration of 135 ms and the fortis 190 ms. Each stop was given a 20-ms oral release gesture from fully closed to fully open values.

A. Glottal area function

Figure 6 illustrates the input values for the model, given the above difference in closure duration and the difference in glottal area function as estimated from Kagaya's (1974) data. It is generally agreed that during fortis stops the vocal folds come fairly closely together well before articulatory release. After release the folds gradually return to a position closer to that of normal voicing. The increase in vocal fold tension was modeled, as can be seen in Fig. 6, by a narrowing of the distance between the vocal folds. The model has no parameters directly reflecting vocal fold tension. It was presumed that greater tension would have the effect of bringing the vocal folds closer together and that by this substitution, similar results (i.e., decreased flow through the glottis) would be obtained. The hypothesized tension in the vocal folds is also supported by the results of the glottograph pitch record in the present study which showed consistently a higher pitch immediately after release of the fortis stop. The glottal area function for the lenis stop is given as a dotted line. Not only is the initial glottal opening greater than that during the fortis stop, but the vocal folds do not become adducted for voicing until approximately 40 ms after release. This is a typical average VOT for lenis stops, not only in Kagaya's study, but also in the present experiment where

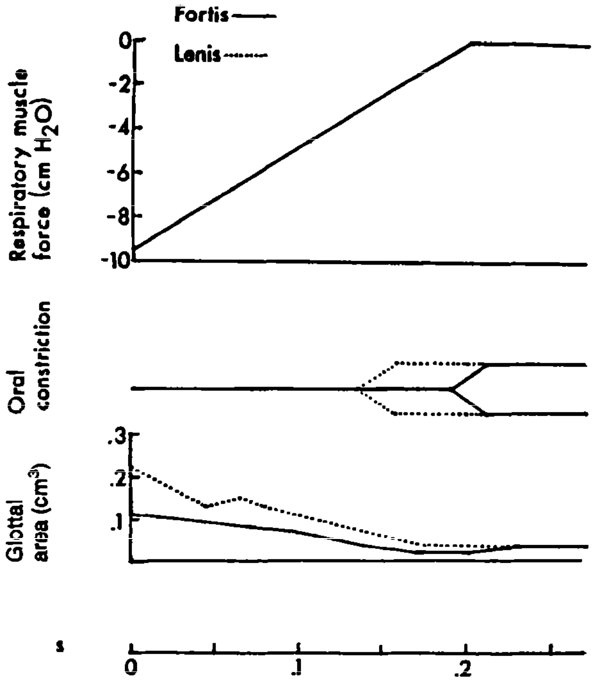

FIG. 6. Input values for the aerodynamic model simulating glottal area function and closure duration differences for Korean fortis (solid lines) and lenis (dotted lines) stops.

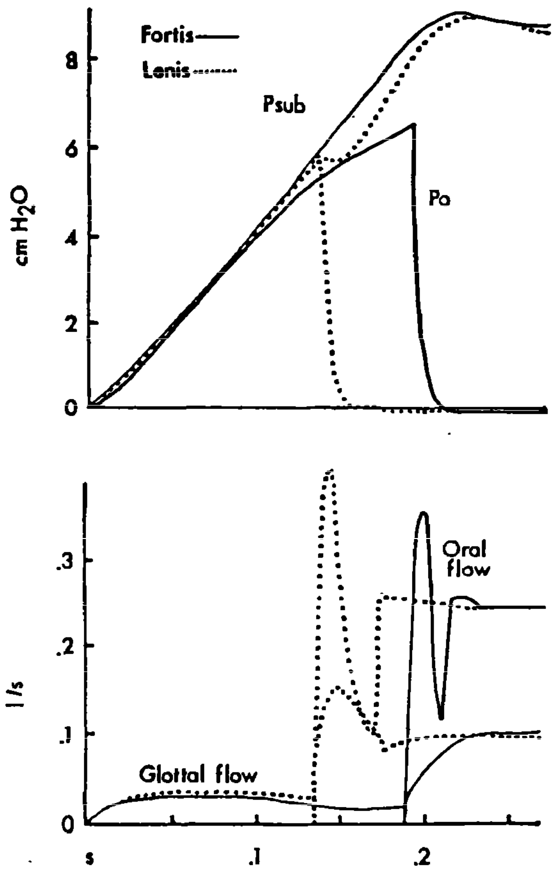

FIG. 7. Output of the aerodynamic model from the input values given in Fig. 6. Shown are subglottal pressure, intraoral pressure, transglottal flow, and oral flow for fortis (solid lines) and lenis (dotted lines) stops.

VOT was measured from spectrograms made from the high-quality acoustic recording.

If these differences in glottal area function and closure duration are modeled as shown in Fig. 6, without changing any other variables, the pressure and flow produced are as shown in Fig. 7. The peak values for the lenis stop are 5.7-cm H_2O pressure and 411-ml/s flow with corresponding fortis values of 6.6-cm H_2O pressure and 357-ml/s flow, giving percent differences of 115% pressure and 86% flow. Referring back to Fig. 5, we can see that the pair simulated would fall at the edge of the space occupied by the points, and has neither a large enough pressure difference to place it in with speakers 8 and 9 (who tended to make large pressure differences and small flow differences), nor a large enough flow difference to place it in with speakers 1, 2, 5, and 6 (who tended to make a large flow difference and a small pressure difference). Let us for a moment concentrate on the production of speakers 1, 2, 5, and 6. For these speakers, the pressure of the fortis stop averaged 116% of the lenis stop, i.e., slightly more, but not appreciably so. The difference in flow, however, was far greater, the fortis flow averaging only 48.3% of the lenis flow for all tokens. Clearly, other differences in the two stops besides glottal area function must be postulated to give realistic flow values for these speakers.

B. Vocal tract wall tension

Kim (1965), Hardcastle (1973), and others have suggested that the fortis stop is characterized by greater muscular tension in the vocal tract walls, although no direct evidence was shown. Figure 8 shows the results of modeling such a tension difference, in this case effected by giving laxer values to the lenis stop, since the default wall tension values of the model are already quite tense. The output values of pressure and flow for the lenis stop are now 5-cm H_2O and 486 ml/s, respectively, showing that a greater degree of vocal tract wall tension leads to an increase in oral pressure and a decrease in peak flow value. The pressure increase can be understood as a result of stiffening the walls, which is effectively the same as decreasing supraglottal cavity volume, since it calls for a reduction in the possibility of passive vocal tract expansion. This decrease in elasticity of the cavity walls also contributes to a lower peak flow by decreasing the amount of elastic recoil of the walls and thereby slowing down the initial flow velocity at release. These values, while still not corresponding exactly to the average values from the measured data, show a difference in the desired direction of the observed general tendency of increased pressure and decreased flow in the fortis stop, providing further indirect evidence for the hypothesized vocal tract wall tension. Comparing the results in Fig. 8 with the fortis stop in Fig. 7 we now have a fortis pressure which is 132% of the lenis pressure and a fortis flow which is 61.72% of the lenis flow. The change in wall tension, then, has created a larger difference in both pressure and flow between the two stop types, having proportionately more effect on the flow. This has brought the flow to a realistic percentage, but now the pressure difference is too great to faithfully illustrate the speech of speakers 1, 2, 5, and 6.

C. Heightened subglottal pressure

In addition to the differences in peak values, however, a distinct difference in oral pressure curve shape was also not-

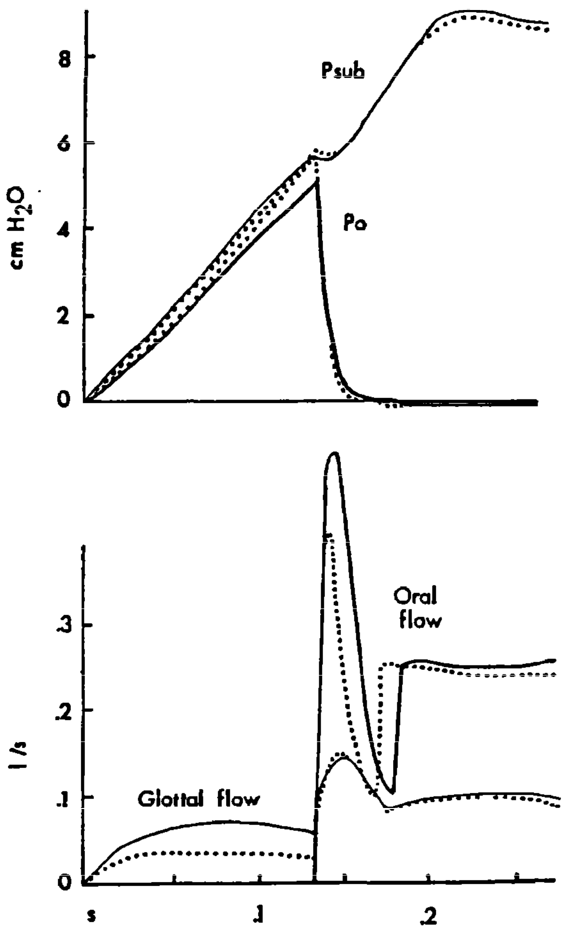

FIG. 8. Output values from the aerodynamic model inputs given in Fig. 6, showing the lenis stop as in Fig. 7 (dotted lines) compared to a lenis stop with the addition of lax vocal tract wall values (solid lines).

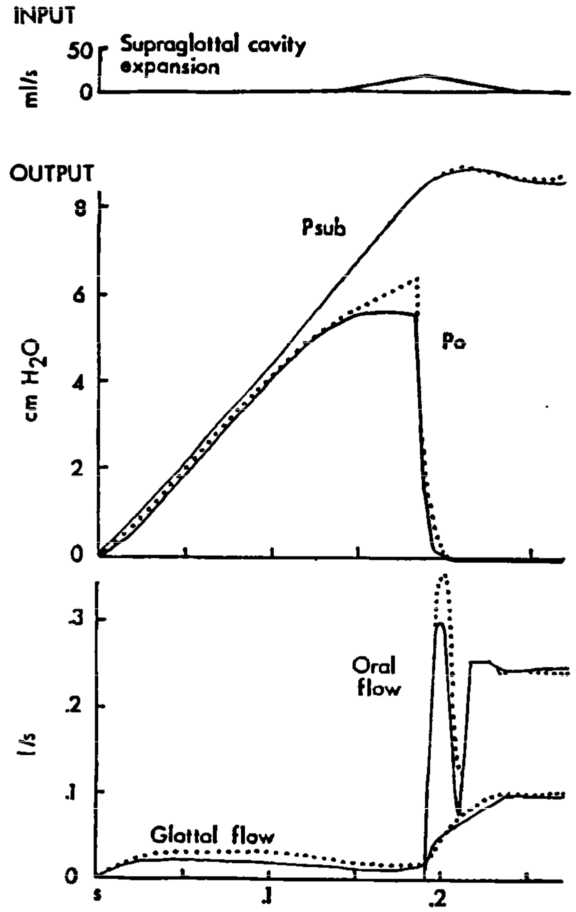

FIG. 9. Output values of the aerodynamic model comparing a fortis stop as in Fig. 7 (dotted lines) to the same stop with the addition of supraglottal cavity expansion to simulate larynx lowering (solid lines), modeled as indicated in the top part of the figure.

ed between the two stop types, as can be seen by referring back to the oscillomink traces given for speaker 6 in Fig. 3. Not only was pressure during the fortis stop generally higher than that during the lenis, but the top of the fortis curve was rounded before release, while pressure during the lenis stop went up linearly to a point at release and then dropped off abruptly. The combination of the timing differences in the release of the oral constriction, plus glottal area and vocal tract wall tension differences, did not produce these differences in oral pressure curve shape and, accordingly, some other input changes must be postulated.

Kim (1965) and Kagaya (1974) have hypothesized heightened subglottal pressure during the fortis stops, both relating it to observed vertical movement of the larynx. In Kim's study, larynx raising during the occlusion of fortis stops was considered as a result of heightened subglottal pressure (which, meeting a closed glottis, forced the entire larynx upwards). Kagaya, however, regarded the heightened pressure as a result of larynx *lowering*, which was observed in one of his two subjects. These two views, then, require different inputs for modeling. The former would be modeled by a more rapid increase in respiratory muscle force than is normally generated by elastic recoil alone and the latter by active expansion of the supraglottal cavity.

Larynx lowering, modeled as active expansion of the supraglottal cavity and shown in Fig. 9 (solid lines), caused a lowering of the pressure curve just before release which was more typical in speakers such as subject 6 in Fig. 3 and, in general, all the speakers who made a large difference in flow and a small difference in pressure. The model was not set up to vary subglottal cavity volume over time and thus it was not possible to represent larynx lowering as a simultaneous increase in supraglottal and decrease in subglottal cavity volume. To correct this, we may assume a slight rise in subglottal air pressure corresponding to the decrease in subglottal cavity volume, realizing that the difference thus created will be comparatively small because of the very large volume and surface area of the subglottal system. The only direct measurement of subglottal air pressure in Korean stops that I know of is Lee and Smith (1972), which showed a slightly higher average pressure at release of the fortis stop for the one speaker tested. When we compare the pressure and flow values illustrated by the simulation in Fig. 9 with the measured values of speakers 1, 2, 5, and 6, we see that Fig. 9 not only illustrates the observed pressure curve shape, but also the small pressure difference (fortis pressure is 120% that of lenis pressure) and large flow difference (fortis flow is 61.3% that of lenis flow) observed in those speakers.

We may now turn to speakers such as 8 and 9 who make the distinction in a way which resulted in a large pressure difference and a minimal, if any, flow difference between the two stop types. Obviously, they must use a different strategy from the other speakers observed. Clues as to the nature of this strategy can be gleaned from close observation of the data obtained. In the first place, only 33% of the fortis tokens of speakers 8 and 9 showed a rounded pressure curve like that just discussed, compared to 81% of the tokens obtained from the speakers who made a large flow difference. This can be seen in the example given from speaker 9 in Fig. 3. We may suppose then, that larynx lowering is not a major factor for these speakers. Figure 10 shows the results of modeling a more rapid increase in respiratory muscle force during the first 150 ms of the stop closure. Such a strategy increases pressure and results in the convex, but not rounded, curve which is typical of speakers 8 and 9.

Another difference noted between the two groups of speakers was that the lenis VOT, measured from spectrograms of speakers 8 and 9, was about half or less of the lenis VOT measured from speakers 1, 2, 5, and 6. In fact, slight overlap in VOT for the two stop types was observed for these two speakers. To make the simulation more realistic, time to adduction for the vocal folds after release was shortened in the lenis stop from 40 to 20 ms. The output from this simulation is shown by the solid lines in Fig. 11. The peak values for the lenis stop thus shown are 4.75-cm H_2O pressure and 431-ml/s flow, compared to 5-cm H_2O pressure and 456-ml/s flow in the lenis simulation with lax walls in Fig. 8 (shown again in Fig. 11 by the dotted lines), illustrating that shortening the glottal gesture results in a lowering of both pressure and flow. Final percentages comparing the fortis stop with a more rapid increase in respiratory muscle force in Fig. 10 to the lenis stop with shorter VOT in Fig. 11 are 162.5% pressure and 94.6% flow, which are quite close to the averages of speakers 8 and 9 of 150.5% pressure and 87.7% flow.

The previously discussed simulations suggest the factors that could be involved in the speaker-specific production strategies observed. The rapid increase in respiratory muscle force in the fortis stop (Fig. 10) and small VOT

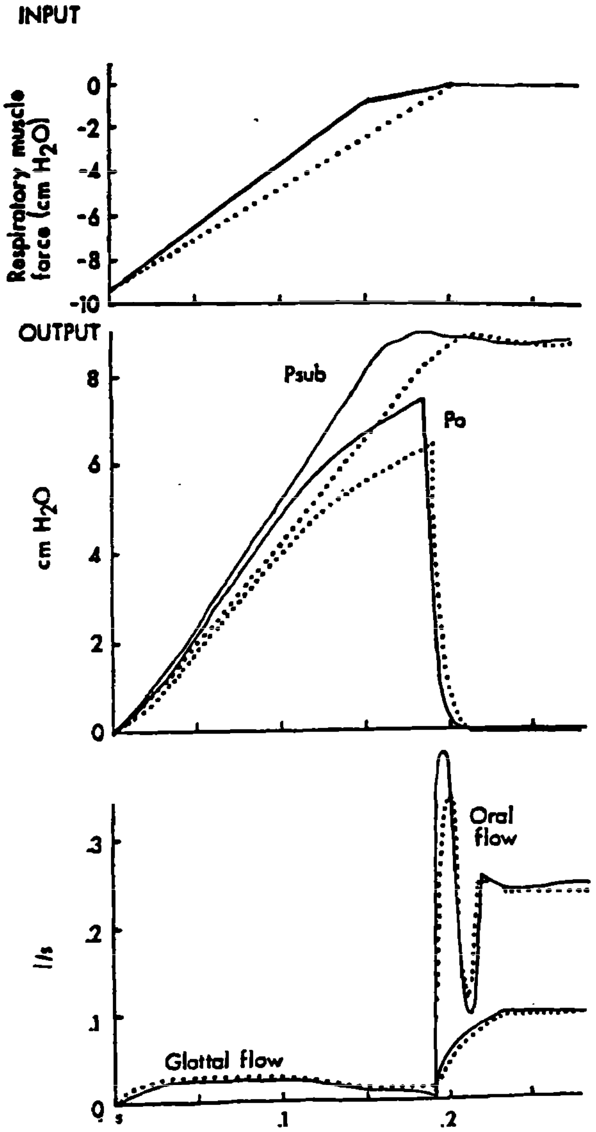

FIG. 10. Output values of the aerodynamic model comparing a fortis stop as in Fig. 7 (dotted lines) to the same stop with the addition of a more rapid increase in respiratory muscle force (solid lines), as shown in the top part of the figure.

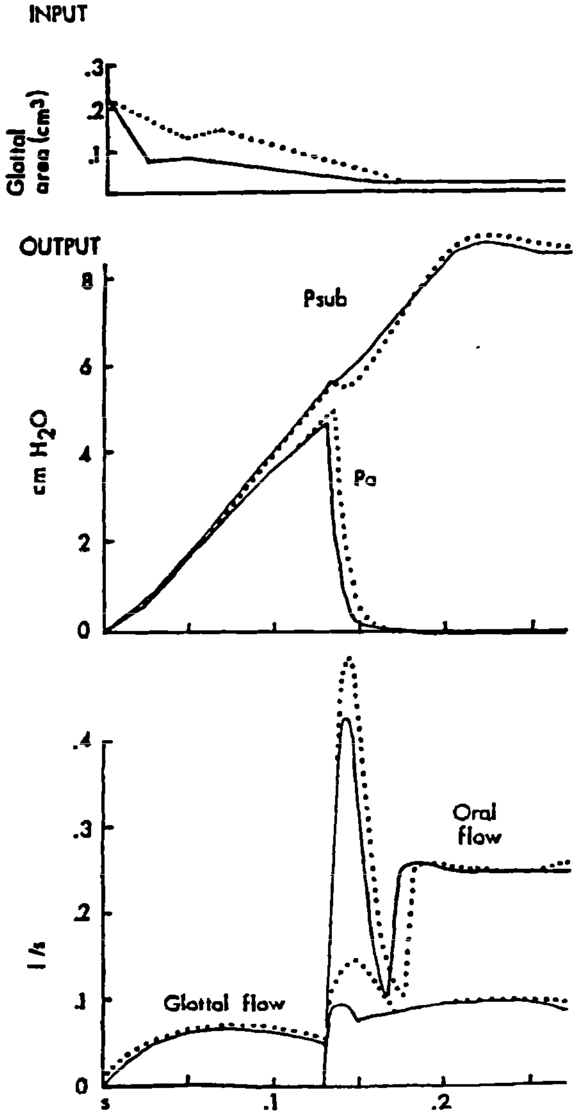

FIG. 11. Output values of the aerodynamic model comparing the lenis stop with lax wall values in Fig. 8 (dotted lines) to the same stop with a shorter time to adduction (solid lines), modeled as shown in the top part of the figure.

difference between stops gave a large pressure difference and a small flow difference, whereas the expansion of the supraglottal cavity (Fig. 9) resulted in a large flow difference and a small difference in oral pressure. These figures correspond to measured differences within the tokens for single speakers.

V. VARIATION BETWEEN WORD PAIRS

It was also noted that, to a certain extent, typical pressure and flow differences between lenis and fortis stops varied from one word pair to another. An analysis of variance testing the between word pairs effects against the pooled within speaker token variability shows that the variation in fortis/lenis ratios between word pairs is significant for flow [$F(3,200) = 8.132$, $p<0.0001$], but not for pressure [$F(3,200) = 1.908$, $0.10 < p < 0.25$]. In all, the word pair which showed the least differentiation between fortis and lenis flow was word pair 3, [ˈpiə]–[ˈp*iə]. Referring back to Fig. 4, we can see that for most of the speakers the reason seems to lie in an unusually low flow for the lenis member of the pair. Indeed, for speakers 3, 7, and 8, the lenis flow is actually lower than the fortis flow. We could hypothesize that this is due to the following stressed high front vowel. It has been claimed that high vowels have more oral volume than low vowels because of greater pharyngeal width (Smith and Westbury, 1975). This would mean greater surface area in the vocal tract and a corresponding decrease in the initial flow rate at release, since more flow would be absorbed by the elasticity of the vocal tract wall tissue. Another factor which might influence flow rate is the degree of lip opening which is smaller in high vowels than in low. A smaller oral constriction would allow less air through and consequently decrease the flow rate after release. The same effect could be attributed to the narrow palatal tongue constriction in the high front vowel. A combination of these factors could decrease the flow in this particular word pair.

We might also expect to see a lowered flow in the lenis member of word pair 1 [pjə]–[p*jə] because of the presence of the high front glide [j]. In fact, *t* tests comparing lenis and fortis flow for all speakers in each word pair show that although the flow difference is significant for all word pairs ($p<0.0005$ for word pairs 1, 2, and 4 and $0.0005 < p \leq 0.005$ for word pair 3), the *t* values for word pairs 1 and 3 are, respectively, 5.758 and 3.086, both lower than the *t* values for word pairs 2 ($t = 7.227$) and 4 ($t = 7.962$, DF for all the above $= 59$). It appears from this that word pair 1 is similarly affected, but to a lesser degree than word pair 3. The flow difference is least in word pair 3, presumably because the high front vowel is stressed whereas, in word pair 1, the glide itself is not stressed and therefore is not as likely to reach its "target" value.[2]

The problem of why the flow decreases should show up mainly after the lenis stops was explored using the aerodynamic model. By simulating a high front vowel following the stop (i.e., modeling an increase in supraglottal cavity volume and a decrease in the area of oral constriction representing the lip opening), a decrease in flow was observed in both the lenis and fortis stops. The decrease was slightly greater, however, in the case of the lenis stop. This is perhaps due to the fact that the lenis stop was modeled with lax vocal tract wall values which, with the increase in supraglottal cavity volume, gave effectively a greater volume increase because of the elasticity of the walls.

VI. CONCLUSION

To summarize, Korean fortis stops can be said to be generally characterized aerodynamically by higher oral pressure and lower oral flow than their lenis counterparts, although speakers tend to differ in their tendency to adopt articulatory measures which give more emphasis to the flow or to the pressure difference. The differences noted in these measurements are due, in part, to the closely adducted vocal folds before release of the fortis stop which has been observed with the aid of a fiberscope (Kagaya, 1974). In addition, evidence from modeling leads us to postulate tenser vocal tract walls for the fortis stop. For some speakers, larynx lowering or other supraglottal cavity expansion appears to occur just before release of the fortis stop. Other speakers may show a more rapid increase in respiratory muscle force during the closure and, at least as was found in the present study, these same speakers may have a smaller VOT difference between the stop types effected by a shorter time to adduction of the vocal folds in the lenis stop.

ACKNOWLEDGMENTS

I would like to thank Hyo Sang Lee for his invaluable aid in gathering subjects and supplying the word list. I am grateful to Peter Ladefoged, Pat Keating, and Mona Lindau for their continued advice and assistance throughout the project and for criticisms of earlier versions of this paper. I am also indebted to B. H. Repp for advice on the statistical analyses. The paper was presented in a shortened form at the 106th meeting of the Acoustical Society of America in November 1983 [S. N. Dart and P. A. Keating, J. Acoust. Soc. Am. Suppl. 1 74, S115 (1983)]. The work was supported by USPHS Grant NS 18163-02 to Peter Ladefoged.

[1]According to Müller and Brown (1980), oral pressure may begin to rise before complete closure is achieved. The above measurement technique is, however, sufficiently accurate for comparing different types of stop consonants.

[2]The genioglossus muscle activity during stressed and unstressed high front vowels given in Bell-Berti and Harris (1981) shows greater activity during stressed vowels, presumably indicating a higher tongue position.

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