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FIBEROPTIC ELECTROMYOGRAPHIC AND ACOUSTIC ANALYSES OF HINDI STOP CONSONANTS

Ryohei Kagaya and Hajime Hirose

1. Introduction

Stop consonants in Hindi may be classified into four types based on the difference in the manner of articulation for the same place of articulation. The four types may be called the voiced unaspirated, the voiceless unaspirated, the voiced aspirated and the voiceless aspirated, respectively. Considerable research has been done paying attention to different aspects of speech production in order to clarify the acoustic and physiological correlates that can differentiate these manner categories. The aim of the present study is to further attempt to specify the properties of Hindi stops by combining acoustical analysis with physiological measurements.

2. Experimental Methods

In the present experiment, a 44 year old male native speaker of Hindi served as the subject. He was born at Badayur, near Kanpur in Uttar Pradesh State, and stayed in Kanpur, Agra and Delhi until the age of 24. Then he moved to Calcutta and has been living there since [1]

2.1. Fiberoptic Observation of Laryngeal Gestures

Sixteen mm films of the glottis were taken during the production of test utterances, by use of a fiberscope, at a (film) rate of 50 frames/sec. As the test utterances, the subject read a list of trisyllabic nonsense phrases /t^hikiCi/ in isolation, where /C/ stands for one of the four types of labial stops /b, p, b^h, p^h/ or the dental stops /d, t, d^h, t^h/ and the word-final vowel is stressed. The whole series was repeated three times. In addition, he uttered disyllabic nonsense phrases /CiCi/, where the first vowel is stressed, embedded in a meaningful carrier sentence /didi, — boliye/ (elder sister, say —) in isolation, where /C/ stands for each type of the consonants mentioned above. This series was also repeated three times. Thus, 12 samples were obtained for each stop type including both labial and dental. The speech signals were recorded simultaneously on a magnetic tape in order to relate each film frame to the corresponding acoustic events (Sawashima and Hirose, 1968; Sawashima and Ushijima, 1972).

The glottal width was estimated by measuring the distance between the vocal processes frame by frame (Kagaya, 1974).

2.2. Electromyographic Study of the Intrinsic Laryngeal Muscles

Separately from the fiberoptic experiment, electromyographic (EMG) recordings were made from the laryngeal muscles of the same subject. Bipolar hooked-wire electrodes were inserted into the interarytenoid (INT) perorally and into the vocalis (VOC), cricothyroid (CT) and lateral crico-arytenoid (LCA) percutaneously. Insertion into the posterior cricoarytenoid (PCA) was also attempted but failed due to technical difficulty. After the electrodes were fixed, the subject read the same utterance samples as those used for the fiberoptic experiment 12 to 16 times each in isolation and the EMG signals were recorded on a multichannel FM recorder together with speech signals. The EMG data were then reproduced and averaged by PDP-9 computer along the time axis with reference to the predetermined speech events, i. e, the implosion of the stop consonants in question.

The method of computer processing was essentially the same as reported previously (Hirose, 1971) with some modification. The reproduced signals were fed to the computer through an A/D converter. Both EMG and acoustic signals were sampled every 250 microseconds and digitized into 6-bit levels. The absolute values were taken and then integrated and smoothed over a range of 10 msec. For a selected 10 to 14 samples for each item, the integrated values as functions of time were added together with reference to the line-up point as described above.

2. 3. Acoustic Analyses

The speech signals recorded during the fiberoptic experiment were used for detailed acoustic analyses. As supplemental data, different utterance types were separately recorded in an unechoic room. In this session, nonsense syllables in the forms of /Ci/ and /iCi/, where /C/ stands for one of the dental stops, were uttered five times in isolation. All the speech signals were subjected to analysis on sound spectrograms and oscillographic tracings. The speech signals recorded during the EMG experiment were analyzed only on sound spectrograms. Since the results were essentially identical to those of the other samples mentioned above, no further detailed analyses were made.

3. Results

3.1. Temporal Change in the Glottal Width

It is observed that the time course of the glottal width for the given consonant type from the end of the preceding vowel portion to the beginning of the succeeding vowel portion is essentially the same in the two different contextual environments: /t^hikiCi/ and /didi, CiCi boliye/. In other words, the glottal gesture is essentially identical for the same stop type regardless of whether the consonant is placed in word-initial or in medial position, although the degree of glottal opening is slightly less in the latter environment. No vertical movement of the glottis is found for any of the four types.

In the voiced unaspirated type, a complete contact of the vocal processes is always observed throughout the articulatory closure period, with uninterrupted vocal fold vibration.

For the other three types, separation of the glottis is observed for the consonantal portion of the test utterances. Fig. 1 shows contours of the temporal changes in the glottal width for all the samples of the three stop types in the fiberoptic experiment. In each subset, the curves for the three labial or dental stop types in each series are superimposed with line-up points at articulatory release. The temporal characteristics of each type are quite similar to those reported by Hirose, Lisker and Abramson (1972) (2 or by MacNeilage (1974) (3

For the voiceless unaspirated type, the glottis begins to open at the articulatory implosion. The contour of the temporal change in the glottal width shows a well-defined bell shape. The maximum width of the glottal opening is about a half of that for the voiceless aspirated type (see infra). The articulatory explosion takes place at the instant when the glottis becomes completely closed, or immediately before. During the closure period, no vibration of the vocal folds is observed. The vibration of the vocal folds in the succeeding vowel portion starts immediately after the explosion, where the vocal processes show a complete contact in the majority of the cases (7 cases out of 12).

For the voiced aspirated type, the temporal course of the glottal width is similar to that of the voiceless unaspirated type. Also, the peak value of the glottal width is comparable to that of the voiceless unaspirated type. However, the timing relationship between the articulatory release and the instant when the glottal width reaches the maximum is considerably different from the two voiceless types. That is, in the case of the voiceless unaspirated type, the articulatory release occurs about 60 msec after the glottal width reaches the maximum, whereas in the voiced aspirated type, it occurs about 30 msec before, when the glottis is in the course of opening. The vocal fold vibration is always observed irrespective of the temporal change in the glottal width.

For the voiceless aspirated type, a bell-shaped contour is also observed, but the maximum glottal width is considerably wider than that of the other types. The glottis starts to open at the implosion in the majority of the cases (8 out of 12), and the explosion occurs around the moment when the glottal width reaches the maximum. The glottis is slightly open at the voice onset.

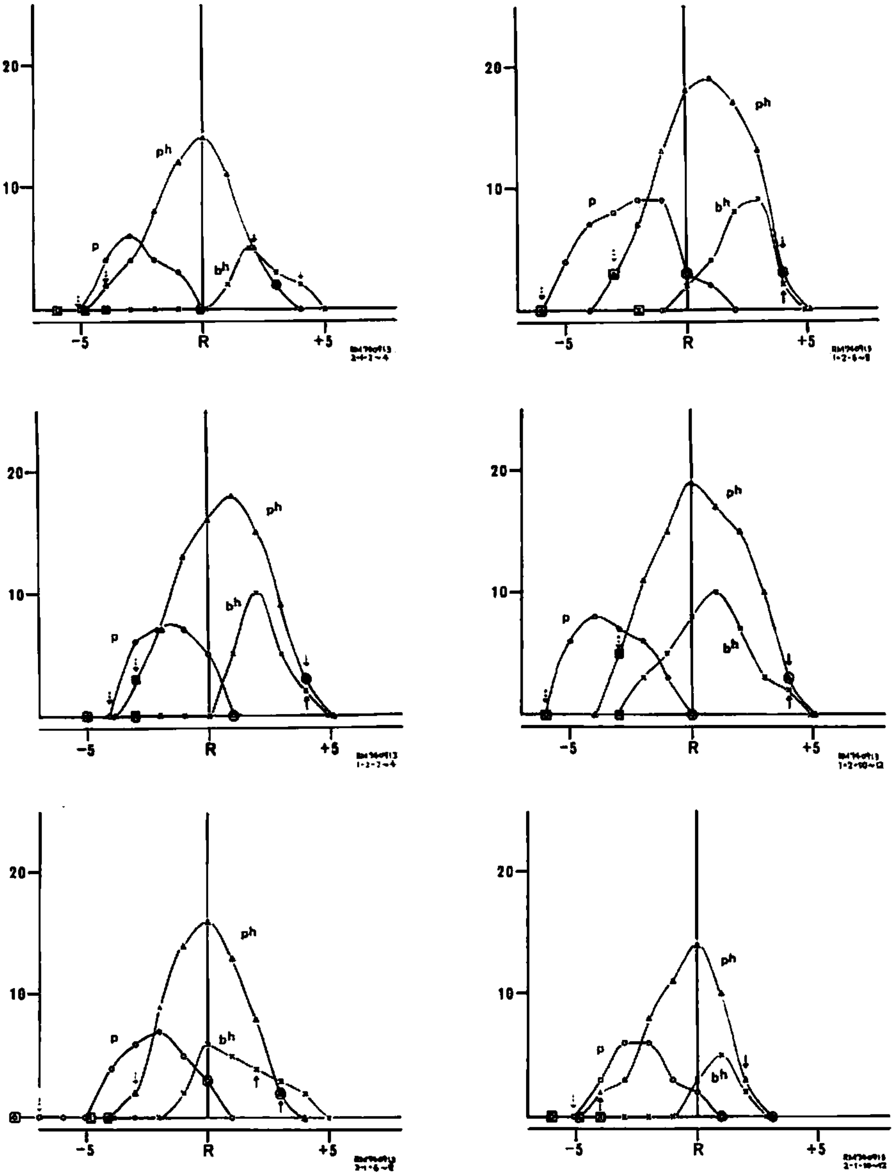

Fig. 1 (a)

Fig. 1 (a & b): Typical contours of glottal width for each type of labial (Fig. 1a) and apical stops (Fig. 1b) in the context /didi–i–i/. The open triangles represent the voiceless aspirated type, the filled triangles the voiced aspirated type, the open circles the voiceless unaspirated type and

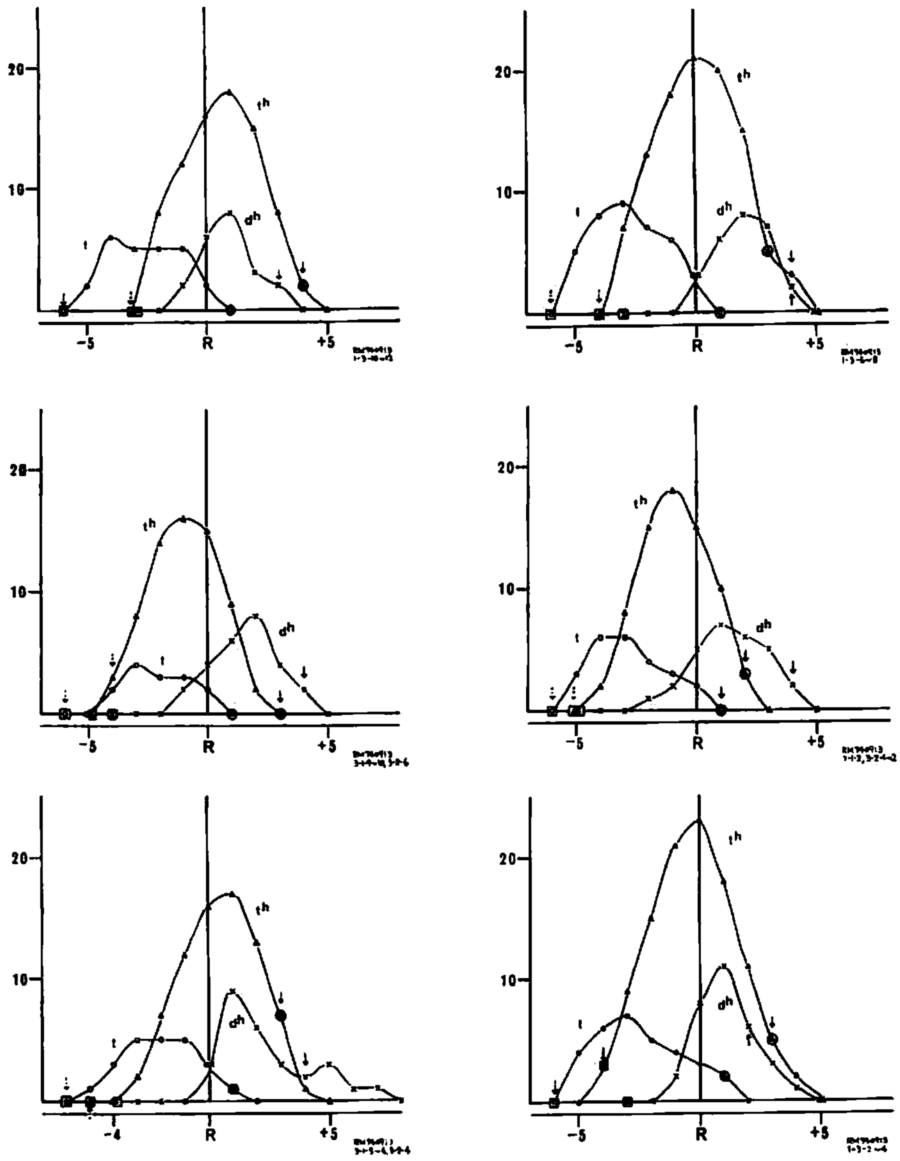

Fig. 1 (b)

the filled circles the voiced unaspirated type. The abscissa represents the frame number counted back from the time of articulatory release, one frame corresponding to 20 msec, and the ordinate the apparent glottal width in an arbitrary scale. Also, "o" means the voice onset, "□" the articulatory implosion, "↓" the frication offset, and "⇣" the voice offset of the preceding vowel.

The results of measurement of the glottal width at selected time points are given in Table I.

3.2. Result of EMG Study

Figures 2-5 illustrate the averaged curves of INT, VOC, LCA and CT for each stop type embedded in the frame word /t^hikiC̲i/, respectively.

The activity of INT is suppressed for the production of aspirated stops, particularly for the voiceless aspirated type. The activity is also slightly suppressed for the voiceless unaspirated type but not for the voiced unaspirated type. The timing of suppression is different depending on the stop type. For the voiceless aspirated type, the suppression starts as early as 200 msec before the line-up, i. e., implosion of the stop closure, and INT activity gradually reaches its minimum approximately 30 msec after the line-up. The suppression starts somewhat later for the voiced aspirated type and it follows a steeper course. For the voiceless unaspirated type, the suppression starts as early as or a little earlier than for the voiceless aspirated type.

For all the stop types, there is a tendency toward suppression of VOC activity. The suppression starts 30-40 msec before the line-up and the degree of suppression is more marked for the aspirated types than for the unaspirated types. The activity of VOC appears to be higher for the vowels following stops than for those preceding.

It appears that LCA activity is also suppressed for all the stop types but the timing is different, i. e., the suppression starts approximately 80 msec before the line-up for the voiced types, but immediately before the line-up for the voiceless types. The timing of activation after the suppression is also different depending on the stop types and the activity rises earlier for the voiced types than for the voiceless types.

In the present experiment, the numbers of recorded neuromuscular units of CT are not large enough to give a smooth configuration even in the averaged form. Figures 2-5, however, show that there is a tendency toward suppression of CT activity starting approximately 100 msec before the line-up for all the stop types. Except for the voiced unaspirated type, CT activity appears to increase again before the line-up. For the voiceless unaspirated type, in particular, there is a tiny peak around the line-up. In the case of the voiced unaspirated type, the activity starts to increase after the line-up.

3.3. Acoustic Characteristics

3.3.1. Voice Onset Time

Voice onset time (V. O. T.) of each utterance is measured on the sound-spectrogram with an accuracy of 10 msec. The results show that V. O. T. of the voiceless unaspirated type is about 10 msec on the average and that of the voiceless aspirated type is about 70 msec on the average, while in the voiced types, the vocal folds' vibration is always observed throughout the articulatory closure period [4]. These results are comparable to those reported by Lisker and Abramson (1964), and by Dixit (1975).

	Voiced unaspirated		Voiceless unaspirated		Voiced aspirated		Voiceless aspirated	
	avg.	range	avg.	range	avg.	range	avg.	range
1. Max. Glottal Width	0;	0 ~ 0	7;	4 ~ 9	8;	5 ~ 11	18;	14 ~ 23
2. Timing of Oral Release to the Instant of Max. Glottal Opening(in msec)			+50;	+30~+80	−30;	±0~+60	±0;	−20~+20
3. Glottal Width at Implosion	0;	0 ~ 0	0;	0 ~ 0	0;	0 ~ 0	1;	0 ~ 0 (8/12)
4. Glottal Width at Voice Offset			0;	0 ~ 0			2;	0 ~ 5
5. Glottal Width at Release	0;	0 ~ 0	2;	0 ~ 5 (3/12)	4;	0 ~ 8 (2/12)	17;	14~23
6. Glottal Width at Aspiration Offset					2;	0 ~ 6	3;	0 ~ 7
7. Glottal Width at Voice Onset			1;	0 ~ 3 (7/12)			3;	0 ~ 7 (1/12)

Table I: Data obtained from fiberoptic views. For item no. 2, "+" means that articulatory release occurs after the instant, and "−" means that it occurs before the instant. Numbers without unit indicate the degree of glottal width on an arbitrary scale. Numbers in parentheses indicate the incidence of occurrence of closed glottis (glottal width = 0) out of a total of 12 samples.

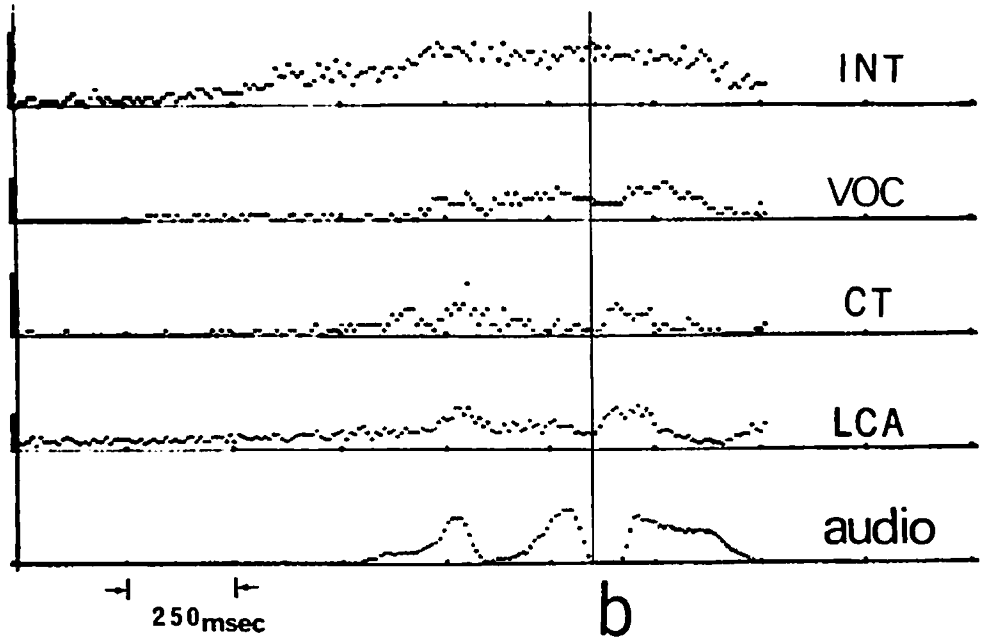

Fig. 2: Averaged EMG curves of four intrinsic laryngeal muscles for [b] in the frame [t^hikiC̲i].

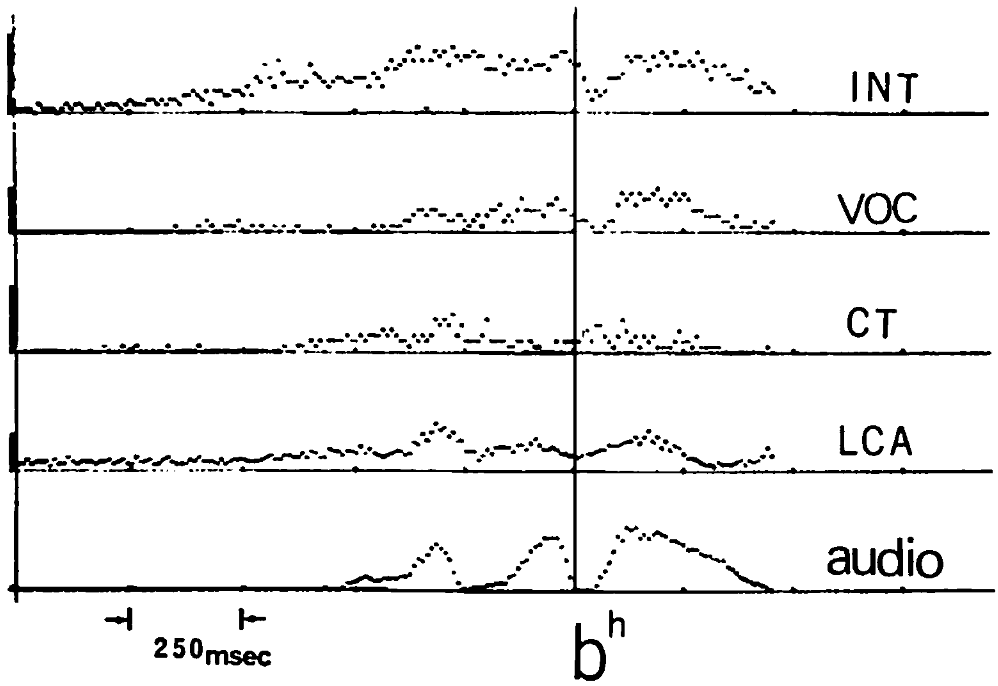

Fig. 3: Averaged EMG curves for [b^h]

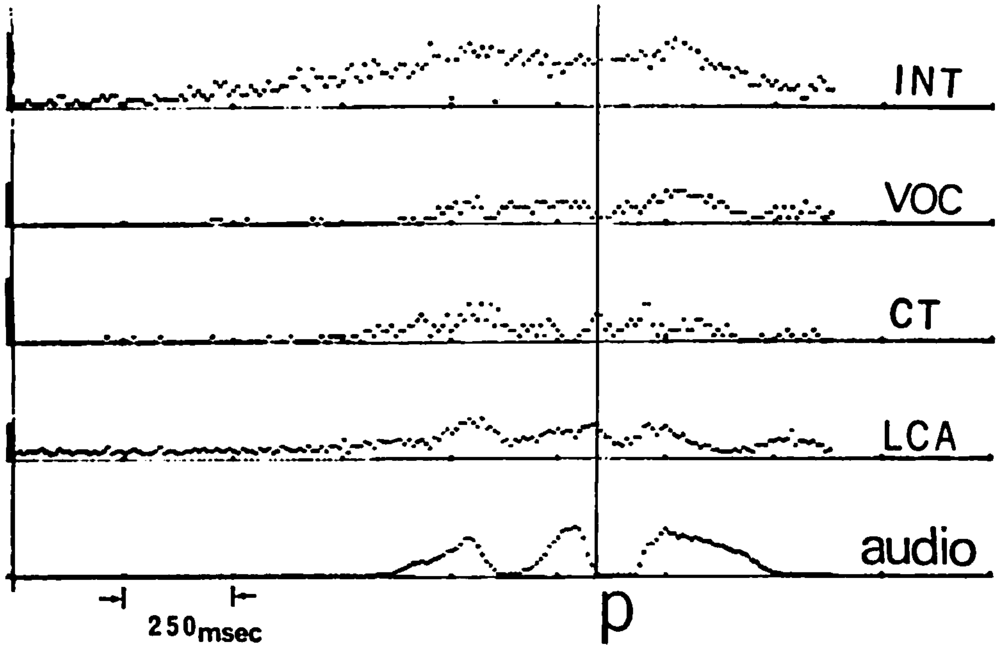

Fig. 4: Averaged EMG curves for [p]

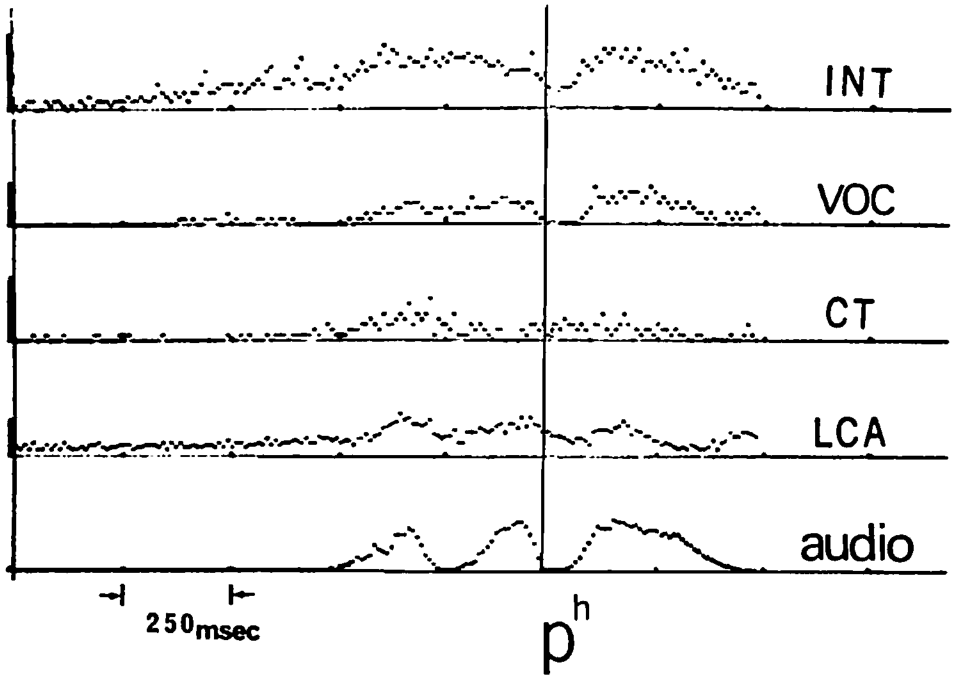

Fig. 5: Averaged EMG curves for [p^h]

3.3.2. Fundamental Frequency

Fundamental periods are measured on the oscillogram with an accuracy of 1/4 msec. Measurements are made at the portion immediately before the implosion in all four types, just after the explosion in the two voiced types and at the voice onset in the two voiceless types. For the two aspirated types, additional measurement is made at the moment when the glottis closes completely after the articulatory release. Fundamental frequency (F_0) is then obtained by averaging three fundamental periods near the moments mentioned above. The results show that F_0 just before the implosion is almost the same for the four types. For aspirated types, F_0 at the moment when the glottis completely closes after the explosion is always higher for the voiceless type than in the voiced counterpart. Also, for unaspirated types, F_0 near the voice onset is always higher for the voiceless type than for the voiced counterpart. For the voiced aspirated type, it is noted that F_0 near the explosion is very low but becomes higher when the glottis closes completely.

3.3.3. Articulatory Closure Period and Duration of Aspiration

Articulatory closure period (C. P.) and duration of aspiration (D. A.) are measured on the oscillogram with an accuracy of 10 msec [5]. The results show that C. P. for the voiceless unaspirated type is the longest, those for the voiced aspirated and the voiceless aspirated types are the shortest and that for the voiced unaspirated type is intermediate. D. A. of the voiced aspirated type is almost the same as that of the voiceless aspirated one (Table II). This tendency is comparable to that reported by Dixit (1975).

3.3.4. Others

Relative intensity of aspiration noise is compared for the voiced and the voiceless aspirated types by visual observation of the sound spectrogram. The result shows that the intensity is stronger for the voiceless aspirated type than for the voiced aspirated type.

The durations of the F_2 transient portions after the articulatory explosion are also compared with each other by visual observation of the sound spectrogram. The result shows that there is no marked difference in the duration among the four types.

The acoustic characteristics are summarized in Table II.

4. Discussion

4.1. The Pattern of Laryngeal EMG and the Glottal Gesture

It has been reported that INT usually shows activity patterns reciprocal to PCA and should be regarded as a pure adductor of the vocal fold. In the present subject, fiberscopic observation consistently revealed the glottal opening gesture for the production of the two aspirated types and the voiceless unaspirated type in all the phonetic environments examined. The suppression of INT for the production of the above three types is well correlated to the opening gesture both in its degree and timing. Although the

	voiced unaspirated	voiceless unaspirated	voiced aspirated	voiceless aspirated
	avg. range	avg. range	avg. range	avg. range
1. V. O. T. (in msec)	V. T.	+10; 0~+20	V. T.	+70; +50~+110
2. Closure Period (in msec)	100;80~130	140; 110~170	80; 50~110	90; 70~100
3. Duration of Aspiration (in msec)			70; 40~80	60; 40~80
4. Relative Intensity of Aspiration			weak	strong
5. F_0 (in Hz)				
Implosion	175;166~200	169;160~182	166; 160~174	166; 154~182
Release	154;138~174		120; 100~133	
Voice Cnset		188; 160~222		178; 166~190
At Closed Glottis After Release			165; 148~182	179; 166~190

Table II: Acoustic characteristics. "V. T." means voicing through and "+" voicing lag.

pattern of PCA activity is not available, it seems reasonable to assume that the INT suppression associated with the opening of the glottis is a very important correlate for the distinction of the stop types in the present subject.

For the three stop types (voiced aspirated, voiceless aspirated, and voiceless unaspirated) where the glottal opening is always observed, there is suppression of VOC activity, the degree of which is comparable to that of the opening. It is also shown that VOC is suppressed for the voiced unaspirated type for which INT remains active. In this sense, the pattern of VOC activity is not always similar to that of INT.

In recent years the possibility of functional differentiation of the so-called adductor muscle group has been suggested. Particularly, the difference between INT and the other two muscles, VOC and LCA, is postulated and INT is said to be the pure adductor of the vocal fold. As stated by Dixit (1975), it should not be said mistakenly that VOC and LCA do not contribute in the glottal closing gesture. Rather, it is more plausible that while a reciprocal pattern of activity between INT and PCA is principally important for the control of the glottal width in speech articulation, the other two adductors are also indispensable in gearing the larynx to the so-called speech mode.

It has generally been considered that CT is a prime laryngeal muscle for fundamental frequency rise. As for the contribution of CT in segmental gestures, most of the previous authors who investigated those languages having a two or three-way distinction between consonants found little or no correlation between the activity pattern of CT and the segmental gestures, particularly for the voiced/voiceless distinction in consonants (Hirose and Gay, 1972).

In his recent study, Dixit (1975) found in a native Hindi speaker that CT activity for the voiceless stops, both aspirated and unaspirated, is relatively higher than for their counterparts. Interestingly, he also found photoglottographically that the voiceless unaspirated type in poststressed medial position was produced without open glottis in his subject. He then postulated that increased CT activity contributes to the increase in longitudinal tension of the vocal fold, thus resulting in eliminating fold vibration. In the present subject, on the other hand, glottal opening is consistently observed in production of the voiceless unaspirated type and this gesture of the glottis can also reasonably explain the mechanism of interruption of the glottal pulsing during the closure period. One cannot deny the possible contribution of increased CT activity in the voicing distinction, since the relative elasticity or tension of the vibrating portion of the vocal fold is considered to influence whether or not the vocal folds vibrate. In this sense, apparent increase in CT activity for the voiceless unaspirated type around the implosion may contribute to some extent in facilitating the interruption of fold vibration. In the present subject, a higher F_0 value immediately after the release of the voiceless unaspirated type can also be related to the increase in CT activity. On the other hand, CT activity is not obviously high for the voiceless aspirated type, for which Dixit (1975) found high CT activity in his subject. Then, at least for Hindi stop consonants, the pattern of CT activity might not always be the primary physiological correlate of voiced-voiceless distinction for all native speakers of Hindi.

4.2. F_0 Differences Between the Voiced and Voiceless Types

F_0 near the moment when the glottis becomes closed after the articulatory release is higher for the voiceless types than for the voiced types. Since the glottis is completely closed at this moment for all four types, the F_0 difference must be explained by factors other than glottal width. Ohala and Ohala (1972) measured subglottal pressure (P_s) of the four types of Hindi stops in a female native Hindi speaker and they found no evidence of increased P_s for the aspirated types as proposed by Chomsky and Halle (1968). Rather, they found that the occurrence of reduced glottal resistance during a period when there is no accompanying oral constriction causes a momentary lowering of the pressure as observed immediately after the release of the aspirated types. The same phenomenon of transient drop in P_s is observed in Dutch for the production of consonant clusters with aspiration [Collier, personal communication]. When there is no appreciable constriction in the vocal tract, lowering of glottal impedance can result in a P_s drop provided that expiratory force is kept constant and there is a certain internal impedance in the respiratory system.

Lindqvist (1972) stated that a higher pressure drop across the glottis is required for vocal fold vibration to start than for vibration to be maintained. If his statement is correct and applicable to the present subject, the vocal fold vibration would not start in the case of voiceless types in the course of glottal closure after the release until the transglottal pressure difference became larger than that is required merely to maintain the vocal fold vibration, provided that the other glottal conditions were kept unchanged. On the other hand, the vocal fold vibration can continue for the voiced aspirated after the release with relatively lower transglottal pressure. The lower F_0 during this period can then be explained by the transient P_s drop after the release as described above. Slightly higher F_0 for the voiceless unaspirated type than for the voiceless aspirated type may be caused by higher vocal fold tension (see supra).

4.3. Transglottal Pressure Difference and Vocal Fold Vibration

Throughout the articulatory closure period, the open glottis is observed for the two voiceless types, whereas the completely closed glottis is observed for the voiced unaspirated type. For the voiced aspirated type, the glottis remains closed over half of the oral closure period. The glottis then begins to open but, during the closure period, the glottal width reaches only about a half of the maximum opening which is reached after the release (see Table I). For voiceless types, intraoral pressure (P_0) rises abruptly and the supraglottal cavity saturates at the earlier portion of the closure period mainly due to the open glottis, whereas for voiced types P_o rises slowly and the cavity does not saturate within the relatively shorter closure period. In addition, we may take the difference in supraglottic cavity size into consideration; the size is reported to be smaller or not enlarging in the voiceless types as much as in the voiced, as observed for various languages where two stop types minimally contrast in voicing (Fischer-Jørgensen, 1968; Perkell, 1969; Bell-Berti and Hirose, 1972). Thus, it may be reasonable to assume that during the closure period the transglottal pressure difference for the voiced types stays high enough for the vocal fold vibration to be maintained, while not enough so for the voiceless types. As for the glottal condition after the release, it is possible to observe vocal fold vibration even if the glottal closure is incomplete, but difficult when the glottal width becomes larger under the condition that the other physiological and/or physical factors are constant even when there is no appreciable supraglottal constriction (Halle and Stevens, 1971; Ishizaka and F lanagan, 1972). The effect of the glottal opening is clearly observed for the voiced aspirated type in this experiment, i. e., the amplitude of the sound waves becomes smaller and irregular as the glottal width becomes larger after the articulatory release.

Vocal fold vibration with open glottis has been observed in various languages. For example, Sawashima observed the glottal width and the presence and absence of vocal fold vibration in the Japanese /h/ and /s/ in intervocalic position by use of a fiberscope and photo-glottography (1968 and 1973). He stated: "At the onset of the intervocalic /h/ in /hehe/..., the vocal cords continue to vibrate while they are apart. The voicing is clear also in the sound spectrogram of the utterance (6 . ... In /h/, the vibration of the vocal cords continues throughout the non-vocalic period even though they appear to be further apart than in /s/. " He further assumed that the difference between /s/ and /h/ is due to the difference in airflow through the glottis depending on the presence or absence of a supraglottal constriction, rather than to a difference in articulatory adjustment in the larynx (1973). His photo-glottographic data also indicate that the amplitude of glottal waves of /h/ decreases when the glottal width increases (1968). The degree of the maximum glottal opening for the voiced aspirated type or the voiceless unaspirated type in Hindi stops in the present experiment is found to be almost equivalent to that for the Japanese /h/ observed by Sawashima, when one compares the angle of glottal aperature on the original film frames.

For the Swedish dental voiceless fricative /s/, Lindqvist (1972) observed that the vocal folds continued to vibrate until the glottal abduction was nearly at its maximum. Also, in his photoglottographic data the decrease in the amplitude of glottal waves is clearly observed when the glottal width approaches maximum (1972).

The vocal fold vibration in the glottal fricative /h/ in Hindi in the context /didi, — boliye/ was observed by Dixit and MacNeilage (1974). In their case, the glottal width appears almost the same as that for the voiced aspirated and the voiceless unaspirated stops in Hindi (7

For the voiceless aspirated type, the glottal resistance is to be markedly lowered because the glottis is widely open. Therefore, even after the articulatory release where there is no substantial supraglottal constriction, the transglottal pressure difference should be small regardless of whether the pulmonic effort is great (see <u>supra</u>), as stated by Dixit (1975). Thus, vocal fold vibration for the voiceless aspirated type is unlikely immediately after the release.

Also, we must take the presence or absence of vocal fold vibration into consideration. For the voiced aspirated type, the vocal fold vibration continues during the closure period, while for the voiceless aspirated type it ceases at an earlier portion of the articulatory closure, as mentioned above. As quoted in the preceding section, Lindqvist's observation may explain that the vocal fold vibration after the articulatory release is more difficult for the voiceless aspirated type than for the voiced aspirated type.

Several laryngeal feature systems have been proposed to represent the four Hindi stop types. As pointed out by Dixit (1975), however, most of them only concern static glottal conditions for some part of the time course and therefore fail to represent overall glottal dynamics characterizing each stop type. For example, in Chomsky and Halle's system (1968) the "+voice" feature specification for the voiced aspirated type represents the closed glottis during the major part of the closure period, but it is impossible to represent the open glottis after the release. In Halle and Stevens's system (1971), the "+spread glottis" for the voiced aspirated type certainly represents the open glottis after the release, but it does not represent the closed glottis during the articulatory closure period. Also, the "–spread glottis, –constricted glottis" feature specification for the voiceless unaspirated type is inadequate because of the open glottis during the closure period. Ladefoged (1971, 1973) claimed that there is a specific laryngeal control for the voiced aspirated type or, in his terminology, murmur. However, as described earlier in this paper the voiced aspirated type can be simply described in terms of the degree and timing of the opening gesture of the glottis relative to the articulatory release. Thus, his framework (1971;1973) for laryngeal gestures for the voiced aspirated type is not comparable to our results or to those presented by MacNeilage(1974), or Dixit (1975).

To compensate for the insufficiency of the existing feature specification systems, we may assume that the laryngeal gesture is specified by input motor commands to the laryngeal musculature as "open glottis" for both the voiceless unaspirated type and the glottal fricative /h/, vs. "closed glottis" for the voiced unaspirated type. Also, "high longitudinal tension of the vocal fold" in terms of increased CT activity may be assumed for the voiceless unaspirated type and "non-high longitudinal tension of the vocal fold" for both the voiced unaspirated type and the glottal fricative /h/. Then, the input command for the voiceless aspirated type is characterized by a sequence of the commands for the voiceless unaspirated type and that for the glottal fricative; and for the voiced aspirated type, by that for the voiced unaspirated type and the glottal fricative.

For the voiceless unaspirated type, the glottis is only slightly open at the release and the vocal fold vibration is initiated with completely closed glottis about 10 msec after the release. In this case, too, the absence of vibration of the vocal fold during the articulatory closure may be the main mechanism of 10 msec delay of voice onset after the release. The tension of the vocal fold again might play some role in this particular type. Considering these various factors, it seems conceivable that voicing would not start simultaneously with the articulatory release even though the glottal width is very small. For the voiceless unaspirated type, since the glottis is completely closed or slightly open near the release, aspiration is not remarkable, much in the same manner as in the case of the voiced unaspirated type.

In his article on "Theory of Aspiration", Kim (1970) defined the degree of aspiration as a function of the glottal opening at the time of release or the oral closure of a stop. We agree with his concept at least for Korean aspirated sounds (cf. Kim, 1970; Hirose, Lee and Ushijima, 1974 ; Kagaya, 1974). For Hindi stops, however, Dixit and MacNeilage (1974) studied the glottal gestures for Hindi stops and glottal fricative and reported that there was no apparent direct correlation between the degree of glottal opening at the time of oral release and the degree of aspiration. This is in agreement with our observations. The difference in the duration of aspiration between the two Hindi aspirated types does not seem to be described only by the factor proposed by Kim. We should rather refer to the relations between the articulatory release and the time when the glottal width reaches the maximum for each stop type.(See Table I).

5. Concluding Remarks

The results of acoustic, fiberoptic and electromyographic analyses of the four types of Hindi stops are summarized.

On the acoustic level, the four types of stops are clearly distinguishable by V. O. T. and presence or absence of aspiration, as stated by many researchers. Also, there is a difference in F_0 after the articulatory release between the voiceless and the voiced types, i. e., F_0 is higher in the voiceless types than in the voiced types.

By fiberoptic observations, it is revealed that each of the four types shows a characteristic time course of the glottal width for the consonantal portion of the test utterances.

EMG analyses show considerable difference in the activities of LCA, INT and VOC, which are considered to contribute to the glottal abduction-adduction gestures. The longitudinal tension of the vocal folds around implosion for the voiceless unaspirated type can be slightly higher compared with that of the other three types.

Based on the results of the present experiments, the characteristics of the four Hindi stops in our subject can be summarized as follows:

1. The voiced unaspirated type is characterized by closed glottis throughout the articulatory closure period and by short duration of the closure period, both of which are favorable for the vocal fold vibration to be maintained during the period.

2. The voiceless unaspirated type is characterized by an open glottis, which facilitates voicelessness. The slightly higher vocal fold tension may also be related to the acoustic characteristics.

3. The voiced aspirated type is characterized by the closed glottis mostly during the articulatory closure period and by the open glottis immediately before and after the release. The former glottal condition facilitates vocal fold vibration during the closure period and the latter aspiration. Voicing is maintained through the aspiration period because of the absence of supra-glottal constriction.

4. The voiceless aspirated type is characterized by wide-open glottis during the entire consonantal portion, which facilitates voicelessness and gives rise to a considerable period of aspiration.

The time course of the glottal width for each stop type in word-initial position is similar to that reported by Hirose, Lisker and Abramson (1972), MacNeilage (1974) and Dixit (1975). Also, the time course in poststressed word medial position between vowel segments is similar to that reported by Dixit (1975) except for that of the voiceless unaspirated type. In the case of the voiceless unaspirated type in poststressed word-medial intervocalic position, Dixit (1975) reported that this stop type is produced with closed glottis and that EMG activity in the cricothyroid muscle is relatively higher in Hindi data for the unvoiced stops. Thus, he concluded that CT activity contributes to the tension of the vocal folds in eliminating voicing in both unvoiced unaspirated and unvoiced aspirated stops. His conclusion about the voiced-voiceless distinction being attributed to the CT activity is comparable to that of MacNeilage(1974) (8. In the present subject, the voiceless unaspirated type seems to be produced with slightly higher longitudinal tension of the vocal folds, but it is always produced with open glottis. It seems at least for the present subject that the voicelessness of the sound is primarily attributable to the open glottis. The inter-subject difference in the mechanism of voicelessness may be idiosyncratic.

For the voiceless aspirated type, the sequence of open glottis commands would make the glottal opening markedly wider as compared with that of the voiceless unaspirated type, because there is no closed glottis command during the consonantal portion. Absence of vocal fold vibration after the release may be explained by the wide-open glottis, or by the interruption of voicing during the closure period. In the voiced aspirated type, the closed glottis in the early part of the consonantal portion would facilitate vocal fold vibration and the open glottis in the latter part would facilitate aspiration, where vocal fold vibration is maintained because of the absence of supraglottal constriction, much in the same manner as in the case of the glottal fricative (see MacNeilage and Dixit, 1974 and Dixit, 1975). The nonhigh longitudinal tension of the vocal fold may also be taken into consideration for uninterrupted voicing. These points are summarized in Table III.

	Voiced unaspirated	Voiceless unaspirated	Glottal fricative	Voiced aspirated	Voiceless aspirated
1. Abduction-Adduction of the Glottis	–	+	+	– +	+ +
2. Longitudinal tension	–	+	–	– –	(+) –

Table III : Laryngeal input commands to the laryngeal musculature for each Hindi type. "+" stands for open-glottis command or high longitudinal tension of vocal folds, the "–" for closed-glottis or nonhigh longitudinal tension. Each of the aspirated types consists of a sequence of two command units. Perhaps the concept of longitudinal tension refers to increased CT activity. As discussed in the text, however, there was no apparent increase in CT activity for the voiceless aspirated type in the present subject. Therefore, the concept should be regarded as tentative.

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Notes

1. The subject is Dr. Ramesh Mathur, who is presently at Kansai University of Foreign Studies, Hirakata City, Osaka, Japan, as a visiting professor. We are indebted to him for his kind cooperation throughout the experiment.

2. In their study, a well-trained phonetician who was a native American English speaker, served as the subject and produced five different types of stops including the voiceless unaspirated, the voiceless aspirated and the voiced aspirated. Therefore, their results might not be directly comparable to those of the present study.

3. His subject was an adult male native speaker of Hindi.

4. The tendency is also true in the measurements of /Ci/ or /iCi/ , which are shown as follows:

/Ci/	di	ti	d^hi	t^hi	/iCi/	idi	iti	id^hi	it^hi
V. O. T. (in msec)	-130	+20	-100	+90	V. O. T. (in msec)	V. T.	+20	V. T.	+80

where "+" means voicing lag, "–" voicing lead and "V. T. " voicing through.

5. C. P. is defined as the duration between F_2 decay of the preceding vowel portion and burst at the release, and D. A. as the duration between the onset and the offset of the aspiration noise as determined by visual observation of the sound spectrogram.

6. Vocal fold vibration during the production of the Japanese glottal fricative /h/ in intervocalic position, e. g. /h/ in /gohaN/, was phonetically observed by Hattori (1951;1965).

7. This is attested by comparing the amplitude of the photoglottogram presented by Dixit and MacNeilage (1974).

8. MacNeilage (1974) stated: "The CT shows a three-way split in which both voiceless cases (aspirate and inaspirate) are associated with high level activity; while the voiced inaspirated case is associated with intermediate activity and the voiced aspirated case with low activity."

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