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FIBEROPTIC ACOUSTIC STUDIES OF MANDARIN STOPS AND AFFRICATES

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1. Introduction

Initial [1] stops and affricates in Mandarin are of two types, voiceless inaspirates and voiceless aspirates (referred to below simply as "unaspirated type" and "aspirated type"). According to a study reported by Lisker and Abramson (1964), in Mandarin two types of initial consonants can be analysed in the same timing dimension, V.O.T., as in those languages, e.g. English, which have two-way distinctions. The aim of the present paper is to clarify the physiological and acoustical properties of the Mandarin initial consonants.

2. Experimental Methods

2.1. Subjects

In the present experiments, two Japanese males served as subjects. One is a 36-year-old native speaker of Mandarin: he was born in Korea, moved to Harbin in northeast China when he was 5 years old, and remained there until he came to Japan in 1975. We will refer to him as "Subject A".[2] The other subject is one of the present authors, a 23-year-old student who began to learn Chinese at the age of eighteen. We will refer to him as "Subject B".

2.2. Fiberoptic Observation of Laryngeal Gestures

Sixteen mm films of the glottis were taken during the production of test utterance, using a fiberscope at a rate of 50 frames/sec. The test utterances consisted of the following sentences and phrases, written in Chinese characters.

Subject A:	Stops:	/ tì ī ti Cì tsɨ / [3]
	Affricates:	/ tì ī ti Cì ì /
Subject B:	Stops:	/ nǐ Cì lǐ sɨ̀ tsuə̀ /
	Affricates:	/nǐ Cī tsɨ /

In both subjects, /C/ represents one of the two stops /t, th/ or the two affricates /tɕ, tɕh/, respectively. Suprasegmental condition of the following vowel, i.e., the tone, was maintained as tone IV, the falling type, except in the case of Subject B's affricates, in which tone I, the high level type, was used. The above lists were read eight times repeatedly, and six samples were arbitrarily chosen for each type. The speech signals were then recorded simultaneously on magnetic tape in order to relate each film frame to the corresponding acoustic events (cf. Sawashima and Hirose 1968). The glottal width was estimated by measuring the distance between the vocal processes frame by frame (c.f. Kagaya 1974).

2.3. Acoustic Analyses

The speech signals recorded during the fiberoptic experiments were used for detailed acoustic analyses. All speech signals were subjected to analysis on sound-spectrograms and oscillographic tracings.

3. Results

3.1. Temporal Change in the Glottal Width

Figure I shows contours of the temporal changes in the glottal width for the six samples of the two dental stops used in the fiberoptic experiments. In each subset, the curves for two types of stop are superimposed with line-up points at the articulatory release.

3.1.1. Stops

Subject A

In the usaspirated type, vocal processes are closed throughout the closure periods in all but two samples. A spindle-shaped gap is observed in the membranous portion of the glottis, identical to that reported for the "forced type" (or tense type) stops in the CV syllables of Korean by Kagawa (1974). While vocal fold vibration is not observed during this period, it does occur at the same time or immediately after the articulatory explosion.

In the aspirated type, vocal processes begin to open soon after articulatory implosion. Glottal width reaches maximum invariably after the release, ranging from 10 msec to 50 msec. After the maximum point of the glottal opening, it abruptly decreases but remains slightly open at the voice onset. For the aspirated type, open periods of the glottis before the release are nearly identical to the periods observed in the unaspirated type, where the vocal fold vibration is not present.

Subject B

In the usaspirated type, the glottis begins to open one or two frames after articulatory implosion, reaching the maximum opening before the release. By 20-40 msec after the release it is completely closed.

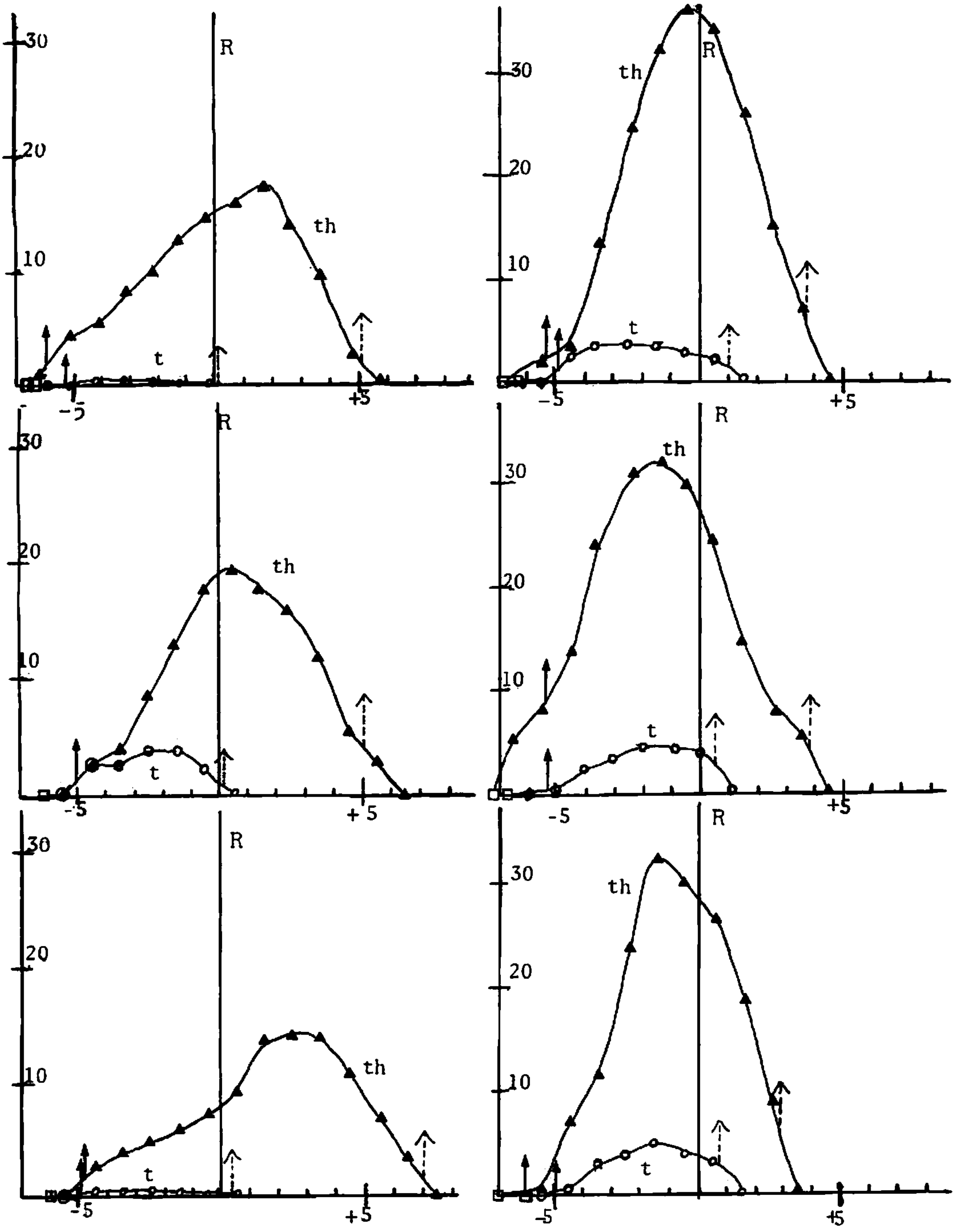
In the aspirated type, for one or two frames after the implosion, the opening of the glottis gradually increases. After that period, however, glottal width abruptly reaches its maximum always before the release, ranging from zero to 30 msec.

3.1.2. Affricates

Figure 2 shows contours of the temporal changes in glottal width for the six samples of the two palatal affricates.

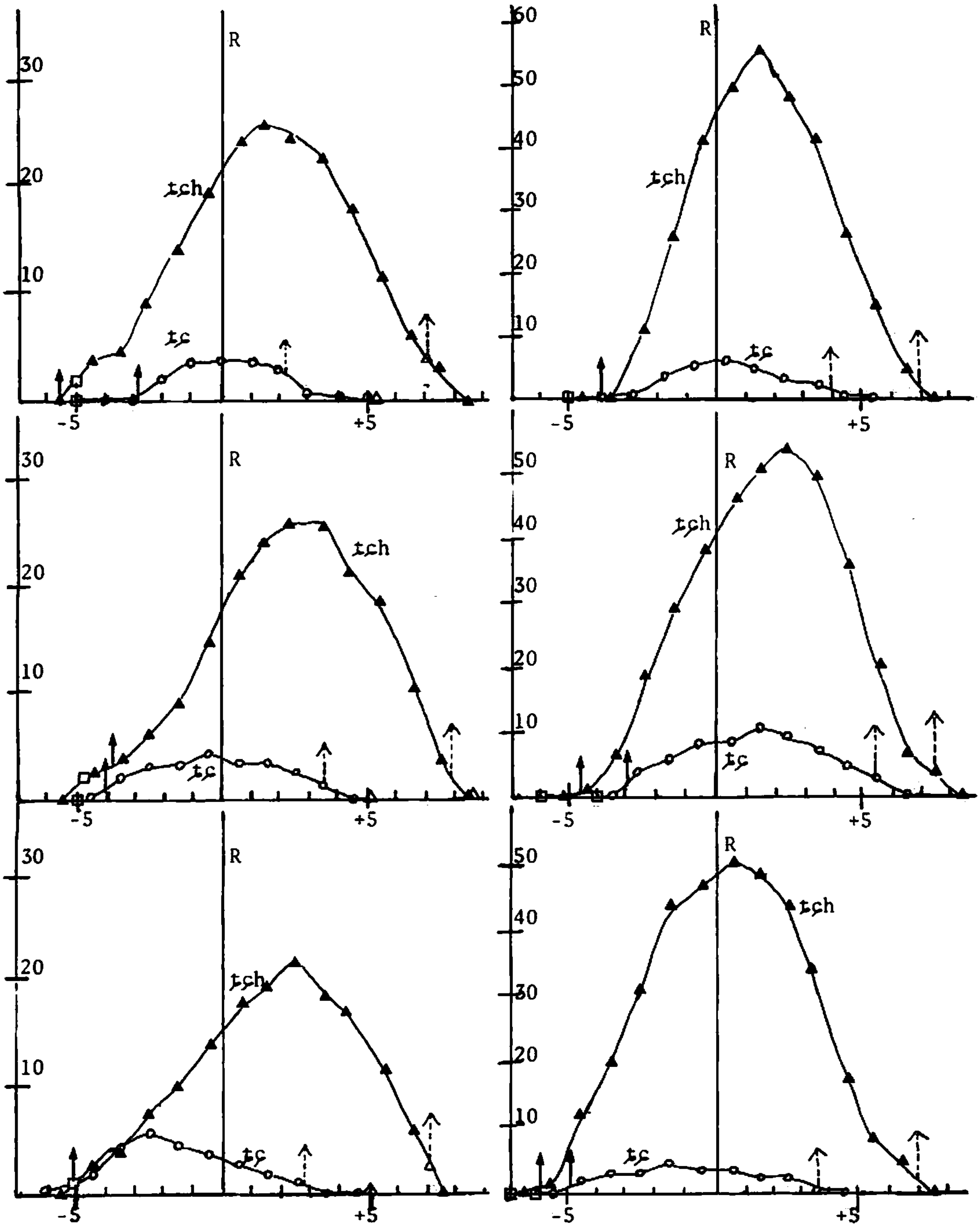
Subject A

In the unaspirated type, the vocal processes are not closed during the closure periods, unlike the case of the unaspirated stops. In most samples, vocal processes start to open even before articulatory implosion, and glottal width reaches maximum before the release. Glottal opening is still maintained after the release and even after voice onset.



Subject A Fig. I Subject B

Figs. I & II: Typical contours of glottal width for each type of dental stop (Fig. I) and palatal affricate (Fig. II). (For their contexts, see above.) The open circles represent the voiceless unaspirated type, and the filled triangles, the voiceless aspirated type. The abscissa represents the frame number counted back from the time of articulatory release, one frame corresponding to 20 msec;



Subject A Fig. II. Subject B

and the ordinate corresponds to the apparent glottal width in an arbitrary scale. "⇡" represents voice onset, "□" articulatory implosion, "↑" frication offset of the preceding vowel, and "△" frication offset of the affricates in the case of Subject A.

TABLE I: Fiberoptic Data (1) Subject A

	unaspirated stop /t/ avg.; range	aspirated stop /th/ avg. ; range	unaspirated affricate /tɕ/ avg. ; range	aspirated affricate /tɕh/ avg. ; range
1. Max. glottal width	1.0 ; 0 ~ 4	16.7 ; 14~20	4.33 ; 3 ~ 5.5	23 ; 20 ~ 25
2. Timing of oral release to the instant of max. glottal opening (msec.)		-23.4 ; -10~-50	+16.8 ; 0 ~ +50	-53.4 ; -30 ~ -70
3. Open period of glottis				
a) before release	104 ; 80~120	104 ; 90~110	94 ; 60 ~ 120	102 ; 80 ~ 130
b) after release (msec.)	0 ; 0 ~ 0	124 ; 110~150	68 ; 60 ~ 80	175 ; 150 ~ 190
c) total	104 ; 80~120	228 ; 200~260	162 ; 120~180	277 ; 250 ~ 310
4. Glottal width at implosion	0 ; 0 ~ 0	0 ; 0 ~ 0	0.83 ; 0 ~ 2	0.75 ; 0 ~ 2
5. Glottal width at voice offset of the preceding vowel	0 ; 0 ~ 0	1.25 ; 0 ~ 2	1.83 ; 0 ~ 3.5	1.9 ; 0 ~ 5
6. Glottal width at release	0.33 ; 0 ~ 2	14.33 ; 12.5~19	3.5 ; 3 ~ 4	16.8 ; 8 ~ 22.5
7. Glottal width at voice onset.	0 ; 0 ~ 0	3.17 ; 2 ~ 5	1.33 ; 0.2 ~ 2.5	3.91 ; 2 ~ 6
8. Glottal width at frication offset			0 ; 0 ~ 0	0.92 ; 0 ~ 2.5

Note: Numbers without unit indicate the degree of glottal width on an arbitrary scale. Data obtained from fiberoptic views of Subject A. In Item 2, "+" indicates that articulatory release occurs after maximum glottal opening, while "-" indicates that it occurs before maximum glottal opening. For Item 3, the whole period is divided into three parts (see above). For the unaspirated stop, however, measurements need not be taken after the release. (See discussion above.)

TABLE II: Fiberoptic Data (2) Subject B

	unaspirated stop /t/ avg. ; range	aspirated stop /th/ avg. ; range	unaspirated affricate /tɕ/ avg. ; range	unaspirated affricate /tɕh/ avg. ; range
1. Max. glottal width	4.67 ; 4 ~ 5	33.83 ; 32 ~ 36	7.17 ; 4 ~ 11	56 ; 50 ~ 63
2. Timing of oral release to the instant of max. glottal opening (msec.)	+33.4 ; +30 ~ +50	+15.0 ; 0 ~ +30	+11.6 ; -30 ~ +30	-26.6 ; -50 ~ +10
3. Open period of glottis a) before release	96 ; 70 ~ 120	115 ; 90 ~ 150	90 ; 60 ~ 110	102 ; 70 ~ 130
b) after release (msec.)	30 ; 20 ~ 40	80 ; 70 ~ 90	90 ; 70 ~ 130	150 ; 130 ~ 180
c) total	126 ; 100 ~ 160	195 ; 160 ~ 240	180 ; 140 ~ 240	252 ; 220 ~ 270
4. Glottal width at implosion	0 ; 0 ~ 0	0.33 ; 0 ~ 2	0 ; 0 ~ 0	0 ; 0 ~ 0
5. GLottal width at voice offset of the preceding vowel	0.92 ; 0 ~ 2	3.33 ; 0 ~ 10	1.6 ; 0 ~ 2.5	1.0 ; 0 ~ 3
6. Glottal width at release	3.67 ; 2.5 ~ 4.5	31.58 ; 27 ~ 35.5	6.17 ; 4 ~ 9	47.7 ; 40 ~ 58
7. Glottal width at voice onset	1.25 ; 0 ~ 2.5	3.67 ; 0 ~ 7	1.58 ; 0 ~ 3	2.17 ; 1 ~ 3

Note: Data obtained from fiberoptic views of Subject B. For the aspirated affricate /tɕh/ in Item 1, the glottis opens so wide as to be beyond the views of the film, thus making meausrement of the exact values impossible in two samples; the values are estimated. For the details of the other items, see the note appearing with TABLE I.

TABLE III Acoustic Data

	Subject A				Subject B			
	/t/ avg.; range	/th/ avg.; range	/ȶɕ/ avg.; range	/ȶɕh/ avg.; range	/t/ avg.; range	/th/ avg.; range	/ȶɕ/ avg.; range	/ȶɕh/ avg.; range
1. V.O.T. (in msec)	8.5; 0~15	95.5; 70~125	50.0; 45~60	140.0 105~165	12.5; 10~15	67.5; 60~80	80.0; 60~110	147.0; 120~170
2. Duration of frication noise			105.8; 100;115	149.0; 105 165				
3. Closure period (in msec)	116.7; 100~125	111.7; 85~135	96.7; 80~120	103.3; 90~120	125.0 120~140	131.0; 100~155	110.0; 80~120	128.0; 100~160
4. Duration of preceding vowel (in msec)	115.7; 100~150	113.6; 90~140	118.3; 90~140	120.0; 95~140 (5)				
5. Duration of following vowel (in msec)	171.4; 160~183	175.7; 135~220			225.7; 210~235	212.9; 200~230	190.9; 170~200	181.4; 170~195
6. F_o near voice onset (in Hz)	253.7; 250~261	259.5; 250~273	238.0; 220~250 (4)	261.3; 250~273 (4)				

SUBJECT A

Note; Where numbers are given in parentheses, this refers to the number of samples singled out for measurement, in all other instances, six samples were examined. For stops, V.O.T. is identical to duration of aspiration. For affricates in item 5., measurements could not be taken.

SUBJECT B

Note: For both stops and affricates, V.O.T. is identical to duration of aspiration. For item 4., measurements could not be taken. For item 6., measurements were omitted.

In the aspirated type, glottal width reaches maximum consistently after the release, but its timing is later than in the case of the stops. The absolute value of the glottal opening is wider than for the stops, although the shape of the contours is similar to those of the stops.

Subject B

The temporal course of the glottal width for the unaspirated type is essentially similar to that of Subject A.

For the aspirated type, the absolute value of the glottal width is wider and the timing of the maximum glottal opening is later than in the case of the stops.

In the above analysis, it is impossible to compare the absolute values of the glottal width between the two subjects. Comparing the samples of the two subjects in the timing dimension, however, certain differences can be pointed out, especially for the aspirated type. First, glottal width reaches maximum at different times. In Subject A, maximum is reached invariably after the release, irrespective of the manner of articulation, whereas in B it is reached always before the release in the case of stops. For the affricates of Subject B, maximum is reached at the same time as or soon after the release. Second, the open interval of the glottis before the release for Subject B is generally longer than that for Subject A in the case of the aspirated stops, while the open interval after the release is markedly longer in Subject A than in Subject B.

The results of the glottal width measurements at the selected time points are given in Tables I and II.

3.2. Acoustic Characteristics

3.2.1. Voice Onset Time

Voice onset time (V.O.T.) of each utterance is measured on the oscillogram with an accuracy of 5 msec., taking the measurements on the sound spectrogram into account. Except in the case of the two affricates of Subject A, the duration of aspiration corresponds to V.O.T. in the present analysis.

3.2.1.1. Stops

In both Subjects A and B, V.O.T. of the aspirated type is definitely longer than that of the unaspirated type. The comparison of the V.O.T. between the two subjects, however, shows that the acoustic distance between the two types of stop in Subject A is superior to that in Subject B, i.e., V.O.T. of the unaspirated type is longer in Subject B, while V.O.T. of the aspirated type is shorter in Subject B. The averaged values for Subject B are nevertheless rather comparable to those for Cantonese, as reported by Lisker and Abramson (1964).

3.2.1.2. Affricates

In the unaspirated type of Subject A, frication [4] noise which can be observed in the high frequency range continues for some time, occasionally more than twice as long as V.O.T. Note that these affricate sounds are not always voiced during the fricative periods. Such frication noise, in most cases accompanies higher formants of the vowel portion, such as F2, F3. On the other hand, in the aspirated type, duration of aspiration or frication is almost comparable to V. O. T.

In both subjects A and B, V. O. T. of the aspirated type is definitely longer than in the unaspirated type. In affricates also, the acoustic distance between the two types in Subject A is superior to that in Subject B. Moreover, in Subject A the acoustic distance between the two types is almost identical in stops and affricates.

In both Subjects A and B, V. O. T. of affricates is longer than that of stops. In subject B, in some samples, V. O. T. in the unaspirated affricates is even longer than the V. O. T. of aspirated stops.

3.2.2. Others

Articulatory closure period and the duration of preceding and following vowels are measured mainly on the oscillogram, with an accuracy of 5 msec., and deduced supplementarily on the sound-spectrogram. No significant difference between the two types can be found from these measurments.

Fundamental frequency near voice onset is measured for Subject A on the oscillogram, by averaging the values of the three fundamental periods from voice onset. The results show that in the affricates of Subject A, significant difference between the two types can be found, i. e., F_0 in the aspirated type is higher than that in the unaspirated type.

Acoustic characteristics are summarized in Table III.

4. Discussion

As reported previously (Lisker and Abramson 1964), unaspirated and aspirated consonants in Mandarin can well be discriminated acoustically in terms of V. O. T. This is further confirmed by the present study; moreover, the physiological correlates of the two types are clarified. Unlike Korean (which has three categories) or Hindi (which has four categories), however, in Mandarin (which has two categories) relatively wide range of variety in the laryngeal control seems to be permitted in the distinction of the two types of consonants.

In Subject A, the native speaker of Mandarin, during the closure period of the unaspirated stop vocal processes are, in most cases, nearly closed, although no vocal fold vibration is observed. Such findings would correspond to rather short V. O. T. In other words, the glottis appears to be adducted without vibration so as to facilitate the vibration immediately after the release (cf. Kagaya 1974).

For the aspirated type in Subject A, the glottis is open wide so that the vocal fold vibration may be difficult to be maintained. Moreover, the timing when glottal opening reaches maximum is always after the articulatory release. Furthermore, the open period of the glottis after the release becomes longer when compared with Subject B. Since the vibration does not occur until the transglottal pressure becomes high enough to initiate the vocal fold vibration (cf. Kagaya and Hirose 1975), longer V. O. T. is achieved than in Subject B.

In Subject B, the non-native speaker of Mandarin, the pattern of laryngeal control appears to be somewhat different from that of Subject A.

That is to say, the degree of glottal opening seems to play more important a role than the timing of the glottal opening or closing. In the unaspirated type, open glottis can be observed during the closure period and is still maintained after the release. In this case V.O.T. is not so short as that in the unaspirated type of Subject A. In the aspirated type, maximum glottal opening is always accomplished before the release. As a result, the open glottis period is shorter than that in Subject A, and a rather shorter V.O.T. is achieved than in Subject A. This mode of laryngeal control is Subject B can be referred to the "Theory of Aspiration" proposed by Kim (1970), who defined the aspiration as a function of the glottal opening at the oral release of a stop. However, such positive correlation between V.O.T. and glottal width at the articulatory explosion, as was reported by Kagaya for Korean (1974), cannot be found in both subjects.

For the affricates, little particular discussion is necessary. It should be pointed out, however, that the glottal opening is wider especially for the aspirated type and V.O.T. is longer than in that of the corresponding stop.

For the unaspirated affricates of Subject A, however, some discussion is needed concerning the long frication noise and low F_o near voice onset. It is probable that these two acoustic characteristics are correlated to each other. Han and Weitzman (1967, 1970) and Kagaya (1974) reported that the Korean lax-type consonants, which are slightly aspirated in the initial position and voiced in the intervocalic position, have lower F_o near voice onset than do the other types. In the unaspirated affricates of Mandarin, however, the glottis is distinctly open throughout the closure period and for a considerable time after the release in the intervocalic position. The low F_o in the unaspirated affricates would be caused by a mechanism other than that in the Korean lax consonant. We can also say that the long frication noise may be correlated with the supraglottal condition of the articulation of [ɕi], where the supraglottal configuration appears to be almost unchanged between the two segments. Further consideration should be given to this problem, although this may be an idiolectal characteristic of Subject A.

Additional experiments must be carried out acoustically and physiologically if one is to discuss the distinctive features proposed by Chomsky and Halle (1968), Halle and Stevens (1971), and Ladefoged (1973). The present study, however, indicates that at least in Mandarin the distinctions between the two types of initial consonants are not necessarily identified in terms of the distinctive features specified in these earlier researches.

For example, with regard to the "heightened subglottal pressure," which was proposed by Chomsky and Halle (1968) and defined as "a necessary but not a sufficient condition for aspiration," certain experiments on Hindi and Swedish reveal that there was found no relevant evidence of the Ps difference by the presence or absence of voicing or aspiration (cf. Ohala and Ohala (1972), Löfqvist(1975). In Korean, however, Lee and Smith (1973) found that the dynamic aspect of the Ps curve for the aspirates is the most dynamic among the three types of stops. What we should keep in mind here is that the data of the subglottal pressure is not identical to that of supraglottal pressure or the oral air pressure as was noted by Lee and Smith (see also Lisker and Abramson 1971). We should therefore take the supraglottal pressure independently of the subglottal pressure.

Concerning the supraglottal pressure or the oral air pressure, in addition to the above-mentioned thesis of Lee and Smith, it was reported by Kim (1965) and Fischer-Jørgensen (1968) that certain differences were found among the different types of consonant in Korean, French, and Danish. They considered that tensity is an autonomous, independent feature. Our own acoustic measurements of Mandarin consonants, however, show no evidence of tense/lax distinction [5] so far as we see the articulatory closure period and the duration of the preceding and following vowel. (cf. Fisher-Jørgensen 1968, Kagaya and Hirose 1975). On the other hand, Lisker (1970) reported that the supraglottal air pressure in the English stop may depend on its' different contexts, and no constant difference could be found in the two types of consonants.

5. Concluding Remarks

In the present study, two types of Mandarin initial stops and affricates were investigated by use of fiberscope with reference to acoustic measurements. It was clarified that the distinction of the voiceless unaspirated and voiceless aspirated stops and affricates which reflects in the acoustic difference of V.O.T. is generated by the various manners of laryngeal control, which is independent of features such as subglottal pressure and which will probably be specified by something like the input motor command.

Moreover, by comparing the native and non-native speaker of Mandarin, we can assume that at least two types of laryngeal control would be permitted in the articulation of the Mandarin consonants. One is the type shown in Subject A, in which the timing of the glottal opening (or closing), rather than the degree of the glottal opening, may play the major role. Another type is that shown in Subject B, in which the degree of the glottal opening seems to play the major role. The measurements of V.O.T., however, clearly indicate that the manner displayed in the former is the more effective.

6. Epilogue

Chao (1943) pointed out that several kinds of stops found in Chinese dialects can be grouped into ten types, including the voiced aspirates and the pre-glottalized implosive. In addition, we can easily note the varied quality even among the same voiceless unaspirated consonants, say between that of Pekinese and Kukienese. What then is the ultimate difference among them? Although at present there are certain phonetic observations by linguists and phoneticians available, more observations on acoustic and physiological bases are desired not only from the synchronic point of view but also from the diachronic aspect.

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Notes

1) As is well known, Chinese is a monosyllabic language. In the traditional Chinese phonology, it is customary to divide a syllable into the "initial" portion, i.e., the initial consonant, and the "final" portion, i.e., the vowels, the final consonants and the tones. In modern Mandarin, only two nasal consonants, /n/ and /ng/ are found in the final position. For an outline of Mandarin phonetics, see Kuraishi (1963).

2) Subject A is Mr. Tsukasa Itō. We wish to express our special gratitude for his kind cooperation. In order to identify Mr. Itō's language (dialect), one of the authors examined the phonological system and phonetic properties of the subject's Mandarin before the experiment was carried out. Although Mr. Itō was exposed to the Japanese language during his childhood, the influence was found negligible, and it was safely concluded that he is a spekaer of Mandarin with some dialectal or idiolectal characteristics in the phonetic level.

3) The diacritical marks above the Roman letters stand for the so-called "four tones", (—) for tone I, (/) for tone II, (V) for tone II , (\) for tone IV, and unmarked for "neutral tone". For a brief outline of Mandarin tones, see Chao (1948).

Carrier sentences and phrases are changed in the experiment of Subject A in order to avoid the effect of nasal sounds, which occasionally appeared to interfere with fiberoptic observation in the preceding experiment of Subject B.

Literal meaning of the carrier sentences and phrases are as follows, although they are almost nonsense in the case of Subject A.

Subject A

The first ____________.

- /t/ disciple
- /th/ drawer
- /tɕ/ memory
- /tɕh/ friendship

Subject B

/t/	: You substitute for Li Sɨ (person's name)
/th/	: Your younger brother, Li Sɨ, does
/tɕ/	: Your loom (or machine gun)
/tɕh/	: Your wife

4) Frication is defined to be the turbulent noise which is concentrated in higher frequencies (over 4 kHz); aspiration is the turbulent noise which is characterized by lower frequency components with relatively clear formant transition (based on the definition of Kagaya (1974)).
5) Martin (1957) states: "The aspirated stops are fortis, the unaspirated lenis. (This is a peculiarity of Mandarin which sets it apart from languages like Cantonese and Fukienese)". We cannot find any acoustic and physiological ground for the fortis-lenis distinction in his words.

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