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SYLLABLE FINAL "GLOTTAL STOP" IN CHINESE DIALECTS ——A FIBEROPTIC AND ELECTROMYOGRAPHIC STUDY——

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1. Introduction

The glottal stop phylogenetically functions in protecting the trachea against foreign bodies as usually observed in swallowing and coughing. As a speech sound it is often employed in the vocal initiation and the demarcation of morpheme boundaries (Gårding,1971; Fujimura & Sawashima,1971; Lindqvist,1972b; Hirose & Gay,1973; Sawashima and Hirose,1983).

In Chinese dialects, specifically in many of the southern dialects(southern area of Huaihe 淮河) as well as the northern dialects in Shanxi(山西), the glottal stop often functions in ending a syllable, while it is either distinctively or optionally employed in vocal initiation. What is of interest in Chinese dialects is that there is an interaction among glottal stop, vowel length, voice quality and tone. The glottal stop usually appears with the so-called "entering tone"("rusheng" in Chinese), and the duration and quality of the vowel is generally shorter and neutralized compared with "non-entering" tones.

Historically, the syllable final glottal stop (indicated occasionally by "-ʔ" hereafter) in the entering tone syllable developed from oral stops -p,-t,-k in Ancient Chinese and further evolved into zero(-∅), i.e. an open syllable, in Pekinese (Standard Chinese) as well as in the northern dialects of the Central Plain. Syllable final -p,-t,-k are still preserved in some of the major dialects in south China, such as Yue (Cantonese), Min (Fukienese) and Hakka. As we reported previously (Iwata et al. 1979,1981), -p,-t,-k in these dialects are acoustically characterized by the absence of oral release and physiologically by a supraglottic laryngeal constriction with a closed glottis. The so-called "supraglottic constriction" in this particular case is formed by adducting the false vocal cords and decreasing the size of the anterior-posterior dimension of the supraglottic structure. This type of laryngeal gestures is what we usually find in the production of the "glottal stop". It was also observed in earlier experiments that the features of the "glottal stop" disappeared and that the laryngeal features for -p,-t,-k were assimilated to those of the following segments when these sounds were uttered in sentences or words.

In the present study, experiments were conducted on three Chinese dialects, Suzhou(蘇州 , Jiangsu Province), Taigu(太谷 , Shanxi Province) and a Taiwan dialect of South Min (閩南 , referred as "Fukienese" in Iwata et al. 1979). Among these, Suzhou and Taigu have already lost the -p,-t,-k endings but still preserve the entering tone syllables with a -ʔ ending, while in South Min -p,-t,-k and -ʔ are co-existent because of complicated

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historical reasons. Since the basic features of laryngeal control for -2 in South Min have already been reported in Iwata et al. 1979, the experiment was conducted for this dialect mainly in order to reveal the coarticulatory characteristics of -2 with following segments.

2. Brief description of the dialects

Each dialect in the present investigation has five or seven lexical tones, among which two are entering tones co-occurring with syllable-final glottal stop. The tones for each dialect are shown below with syllables which have voiceless unaspirated [t] or its breathy equivalent [tɦ] as a initial, and [i] or a somewhat neutralized vowel as a final. The numerals at the right of the phonetic characters represent the tone values, i.e. rough sketches of the pitch contours, which are shown by a five-point scale (Chao,1930). Entering tones are marked with asterisks. Vowel length is indicated, if it is long, by two or three numerals, if it is short, by one numeral, and if it is not so short but relatively shorter than long ones, by two underlined numerals.

Suzhou	Taigu	South Min
1. [ti55]	1. [ti33]	1. [ti55]
2. [tɦi24]	2. [ti412]	2. [ti24]
3. [ti52]	3. [ti452]	3. [ti51]
4. [ti412]	*4. [tiə23]	4. [ti21]
5. [tɦi231]	*5. [tiə2412]	5. [ti33]
*6. [ti$\underline{1}$25]		*6. [ti$\underline{221}$]
*7. [tɦi$\underline{1}$$\underline{223}$]		*7. [ti$\underline{25}$]

The phonetic realization of each tone in sentences and words is often not identical with that uttered in isolation, since there are complicated sandhi phenomena in these dialects. For phonetic details in these dialects see reports like Xie (1982) and Liao (1983) for Suzhou, Yang (1983) for Taigu[1)] and Luo(1930) and Dong et al.(1967) for South Min. It should be noted for the tone system in each dialect that any entering tone in pitch contour has its counterpart among non-entering tones, e.g. the pitch contours of the entering tones 6 and 7 resemble the non-entering tones 1 and 2 in Suzhou. Therefore, it can be assumed that the segmental features, vowel length, its quality, and--according to the former description--the presence or absence of the final glottal stop are mainly responsible in distinguishing between entering and non-entering tone syllables.

The duraion of vowels in Suzhou and Taigu are shown in Table I. For Suzhou, measurements were made on the speech events recorded in EMG experiment; the test words were uttered in the carrier sentence cited in section 3-2 (A)(1), giving no tone sandhi, and are better considered as citation forms or quasi-isolated forms. As for Taigu, the recording was made separately from the fiberoptic experiment; since the vowel duration and pitch contour for each tone were varied depending on whether the syllable was uttered in isolation or in a sentence, measurements were made on both isolated forms and those uttered in the carrier sentence, [ŋgie41 ɕie41_____ts1452]"I write this character

_____". In each table, vowel duratios are presented in ms.

Table I
(a) Vowel durations in Suzhou (in citation)

	Avg.	Max.	Min.	Std.	No.
1. ti55	235.1	250.5	207.4	13.4	7
2. thi24	382.2	424.2	345.1	27.9	7
3. ti52	229.6	270.6	193.6	22.5	8
4. ti412	359.0	433.1	345.8	26.9	7
5. thi231	246.6	276.1	224.3	15.4	7
6. tiɪ25	85.5	97.5	72.5	8.6	8
7. thiɪ223	119.3	133.5	104.9	9.3	7

(b) Vowel durations in Taigu

In isolation(no.:3)

	Avg.	Max.	Min.
1.ti33	237.9	292.4	207.4
2.ti412	335.0	378.3	285.8
3.ti452	194.3	198.1	189.9
4.tiə23	172.3	187.6	146.7
5.tiə2412	286.9	326.9	249.3

In carrier sentence(no.:5)

	Avg.	Max.	Min.
1.ti33	224.0	245.8	206.6
2.ti41	138.4	152.1	128.4
3.ti45	207.8	223.0	187.9
4.tiə23	117.4	128.3	96.1
5.tiə241	106.8	113.4	98.1

There is a remarkable difference in vowel duration between entering and non-entering tone syllables in Suzhou. However, in Taigu the difference between entering tones 4,5 and non-entering tones 1,2 is much smaller in the isolated forms but is significant in the sentence. Thus in Taigu the isolated forms are discriminated mainly in terms of vowel quality and-- according to Yang1983--presence or absence of -2.

3. Subjects and test utterances

3-1. Subjects

In the present experiments three native speakers of Chinese dialects served as subjects.
Suzhou: male, a researcher of Chinese dialects (Wu dialects in particular) living in Japan to teach Chinese, born in 1949.
Taigu: female, a graduate student studying in Japan, born in 1957.
South Min(Taiwan dialect): male, a graduate student studying in Japan, born in 1959.

All the subjects spoke their native dialects very fluently. For South Min subject, syllables with tone 6 in isolation were sometimes found to lose their -2 ending and change pitch contour from low-falling to high- or mid-falling.

3-2 Test utterances

Test words and carrier sentences, most of which were used in fiberoptic observation, are introduced below.

(A) Syllables with -2(entering tone syllables) read in isolation or in citation

The following monosyllabic morphemes, written in Chinese characters in the experiments, were read in isolation. In the experiments for Suzhou and South Min, syllables without glottal stop endings were also observed for comparison.

Suzhou: [ti55] [tɦi24] [ti52] [ti412] [tɦi231] [til25] [tɦiI223]
[iI55] [ɦiI24] [iI52] [iI412] [ɦiI231] [iI25] [ɦiI223]
Taigu: [tiə23] [liə23] [ȶiə23] [iə23] [tɕyə23][ȶyə23]
[tiə2412] [ȶiə2412] [syə2412]
South Min: [ti25] [ti221][i55] [i24] [i51]

In the experiment for Suzhou, those syllables cited above were observed in citation forms by embedding them in the following carrier sentences. Carrier sentence (i) was also used for EMG recording.

(i) [li55 kʻø41 _____ kɦə21 kə25 z̩31]
"He looks at this character _____ "
(ii) [kɦə21 kə25 z̩31 in55 ta25 _____ iI25 iã412]
"This character, its pronunciation is identical with the character _____ "

Tone values in sentences and words are noted in sandhi forms here and below.

(B) Syllables with -2(entering tone syllables) followed by various types of sounds

The coarticulatory gestures for syllables with -2 were observed in the following carrier sentences or phrases.

Suzhou: [li55 tɕʻiI25 _____] "He eats _____"
rTaigu: [ŋgie41 tə23 _____] " My _____"
South Min:[tʃi33 tʃia221 pi221 _____?] "Is this tortoise _____?"

Words or phrases were embedded in each sentence(phrase), and the laryngeal gestures for [tɕʻiI25] in Suzhou, [tə23] in Taigu[2)] and [pi221] in South Min were observed respectively. The embedded words or phrases were initiated by sounds varying in terms of manner of articulation: vowels, voiced consonants, voiceless inaspirates and aspirates, voiceless fricatives and /h/. For instance in South Min, A-not-A questions; [ʃin55 m̩ ʃin55]"new?", [hɤ51 m̩ hɤ51]"good?", [tiŋ51 m̩ tiŋ51]"hard?", [bin51 m̩ bin51]"energetic?", [kʻin m̩ kʻin]"light?" and an adjective [e21 kʻo 21 e1]"reliable" were embedded in the sentence.

Bisyllabic words with final -2 in the first syllable were also used as test words to examine the coarticulatory laryngeal gestures:

Suzhou:
[sə25 i412]"comfortable",[sə25 həu52]"be on fire",[tso25 dY 44] "bamboo", [tɕiI25 tsɥ 35]"spider", [iə 25 tsʻiI44]"one thousand", [ho25 ɕiɪ52] "thunder" /[zə223 iI25]"eleven",[lo223 ɦiI25]"fallen leaves",[ho223 ziɪ 25]"study",[zə223 tɕiY21]"nineteen",[zə223 tsʻiɪ 25]"seventeen",[zə223 s̩21]"fourteen"

Taigu:
[hə23 ie452]"midnight",[kuə23 ly33]"sheep",[kə23 tei33]"doorstep" [yə23 tia33]"comfortable",[yə25 s̩41]"key" / [sə242 iəu33]"oil",

[kə242 lər452]"lane",[kə242 pə23]"arm",[ɕyə242 ɕiau452]"school",
[sə242 huei33]"lime"
South Min:
[pe221 hue55]"lime",[pe221 bi51]"(polished) rice",[pe221 dʒin24]
"the white of the eye",[pe221 ki24]"white flag",[pe221 tʰŋ24]
"white sugar",[pe221 tʻi221]"galvanized iron"

4. Experimental procedures

A flexible laryngeal fiberscope was inserted through a nostril and laryngeal views were recorded on VTR at a rate of 30 frames (60 fields) per second. The speech signals and timing marks were recorded simultaneously in order to relate each frame (field) to the corresponding acoustic events. A larygeal view was observed on a TV monitor through video disk and then transferred to a personal computer. The trace programme was devised in order to analyse each laryngeal view on the monitor of the computer. The measurements were made on the distance between the two false vocal folds as well as between the tubercle of the epiglottis and the posterior commisure when the glottis was closed, and on the distance between the vocal processes when the glottis was open. In the fiberoptic experiment the intraoral pressure was measured simultaneously by introducing a miniature pressure transducer through the nostril and placing it in the oropharnx above the glottis. The data were used in the present study in order to estimate the closure duration of the stops.

Laryngeal electromyographic (EMG) recording was made on the Suzhou subject on the same day but separately from the fiberoptic experiment. Test words and carrier sentence was those cited in 3-2(A). Successful recordings were obtained for the cricothyroid (CT), thyroarytenoid (Vocalis,VOC) and sternohyoid (SH), but only the data for the CT and VOC will be presented in the present paper. The data for the SH, being highly valuable in considering the the complicated phenomena in the initial portion of the syllables (see section 5-1,1) below), will be reported in the near future. In the experiment, conventional hooked wire electrodes were inserted through the skin of the anterior neck. The EMG signals were recorded on a multichannel data recorder simultaneously with the acoustic signals. The signals were rectified and integrated with a period of 5 ms and then sampled at 1 kHz for EMG and at 5 kHz for the audio. Finally, averaging was done on rectified-integrated EMG signals.

The fundamental frequency was extracted mainly by a pitch extracting system using a personal computer and a DSP (Digital signal processor)(Imagawa and Kiritani,1989, Masuko et al.,1989) and supplementarily from a sound spectrograph in the case the exact F0 extraction was unobtainable by the former system.

5. Results

5-1. Direct observation of the larynx by a fiberscope

1) Basic laryngeal features for syllables with entering tones (evidence observed for isolated forms)

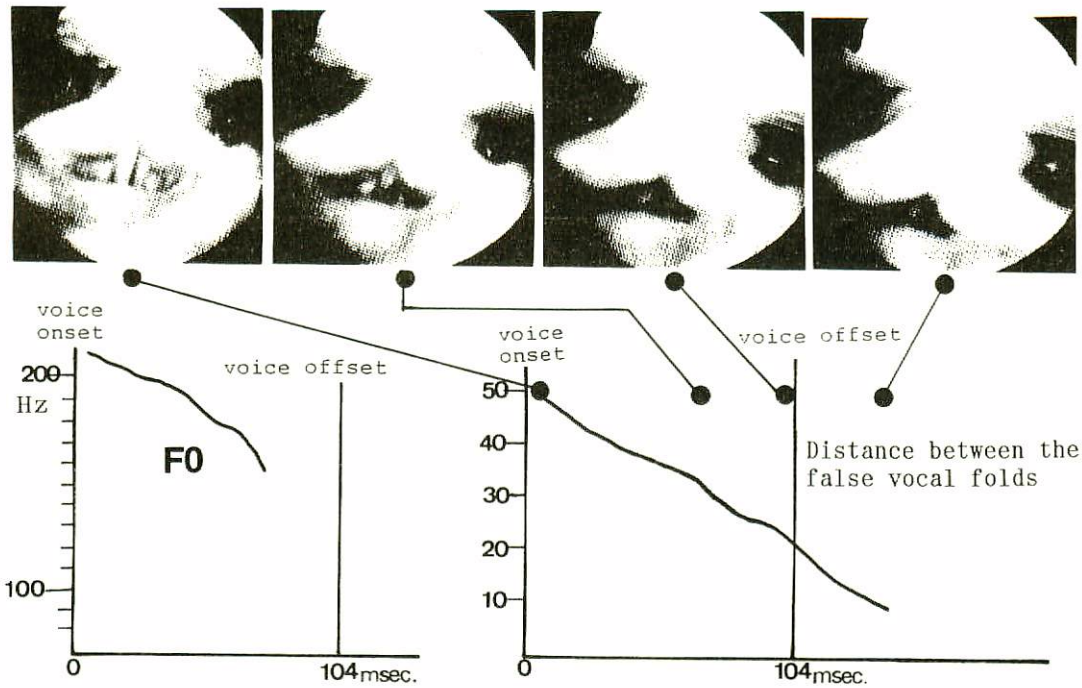

Fig. 1 Selected laryngeal views for Suzhou(苏州) [tiɪ 25] in the isolated form, with the temporal contour of the F0 and the distance beteen the false vocal folds for vowel [iɪ].

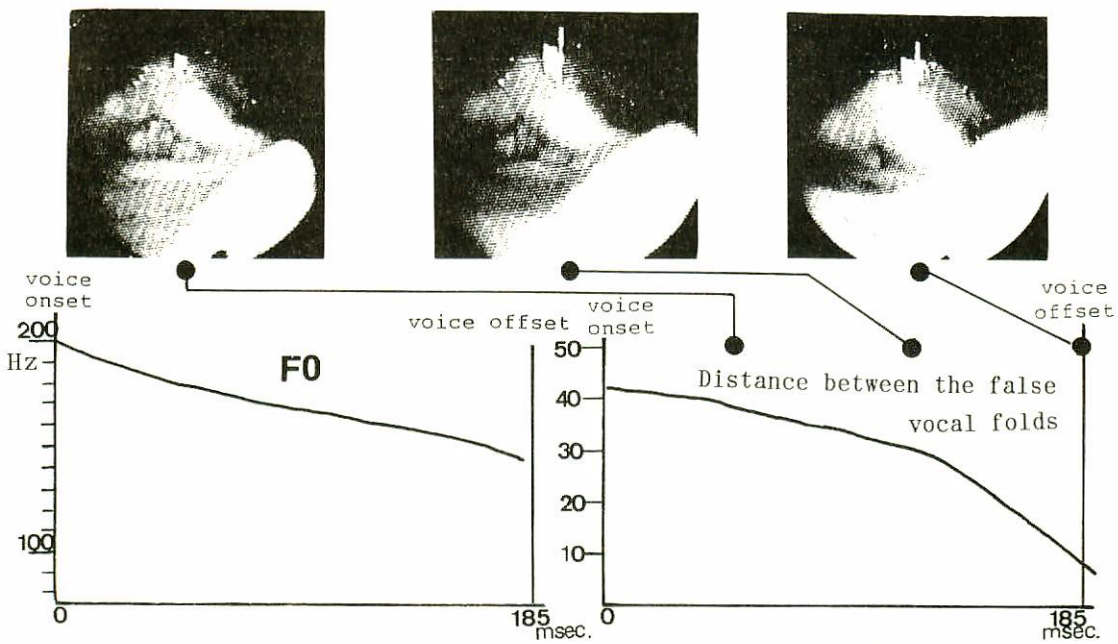

Fig. 2 Selected laryngeal views for Taigu(太谷) [tiə23] in the isolated form, with the temporal contour of the F0 and the distance between the false vocal folds for vowel [iə].

(A) Glottal stop with "level" tones

Figs. 1 and 2 show selected frames of the laryngeal views for typical samples of the isolated monosyllables, Suzhou's [tiɪ 25] and Taigu's [tiə 23]. In both samples, the supraglottic area can be observed to be constricting toward the end of the syllable. Below the pictures are shown the temporal contours of the distance between the edges of the false vocal folds and the F0 contours for the vowels. In Fig.1(Suzhou's [tiɪ 25]), the false vocal folds gradually adduct soon after the onset of the vowel, with the distance between the false vocal folds reaching its minimum after voicing cessation. For [ti25] in South Min (no figures), the adducting pattern of the false vocal folds was observed to be similar in timing to that in Suzhou [tiɪ 25][3]. In Fig.2(Taigu's [tiə 23]), on the other hand, the adducting gesture is just initiated at the latter part of the syllable and proceeds rapidly toward the moment of voicing cessation, sometimes resulting in a complete closure of the false vocal folds. Note here that in the present experiments the vowel [iə 23] in Taigu is generally longer in duration than [iɪ 25] in Suzhou when they are uttered in isolation(see Table 1). In Fig.2 it can also be observed that the size of the anterior-posterior dimension of the laryngeal cavity decreases as the adducting gesture of the false vocal folds is carried out, whereas in Suzhou [tiɪ 25] this particular feature is not so prominent. Our observations on the three dialects further indicate that the larynx moves rapidly upward after voicing cessation.

In syllables with -2, the fundamental frequency is in most cases observed to gradually fall toward the end of the syllable. We reported on this particular feature for [ti221] in South Min(Iwata et al.1979,pp.69,71). The present experiment confirmed this evidence for short syllables which have, as far as linguists' ears can perceive, "level" tones (Suzhou's [iɪ 25], Taigu's [iə 23] and South Min's [i25]). The F0 drop is within the range of about 20-60 Hz for the present samples.

(B) Glottal stop with "rising" tones

A gradual fall in F0 at the end of the syllable is observed even in "rising" tones. Fig.3 shows selected frames of the laryngeal views for a typical sample of Suzhou [tĥiɪ 223], together with its F0 contour. In this particular sample, the F0 does not actually rise but falls toward the end of the syllable. Admitting that this is an extreme case and that F0 in this tone[23] does rise at initiation in most samples (see F0 contours in Fig.6), it is true that F0 more or less falls without exception at the end of the syllable. It is observed in the views that the false vocal folds adduct toward the end of the syllable, but their edges are obscured because of a sort of supraglottic constriction. This constriction is formed between the arytenoids and the tubercle of the epiglottis and is observed throughout the entire syllable. In Suzhou, this particular feature, which can be called the "ary-epiglottic constriction", is associated with "breathy" phonation, which is characterized by the "breathy" consonants usually indicated by [ĥ] and vowels with low pitch initiations (see our forthcoming paper for details).

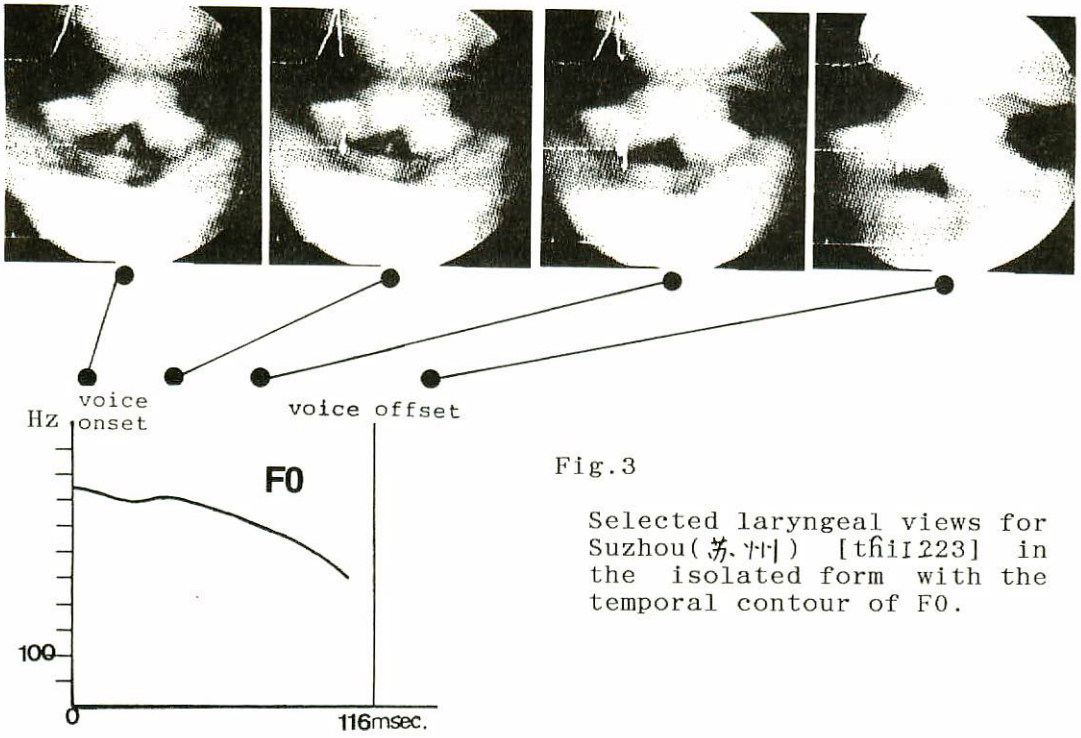

Fig.3

Selected laryngeal views for Suzhou(苏州) [thiI223] in the isolated form with the temporal contour of F0.

Syllables with tone 5 ([412]) in Taigu are longer in duration than those with tone 4 ([3]) in their isolated forms(see Table I). Fig.4 shows the temporal contour of the distance between the false vocal folds for Taigu [tiə2412]. It is noted that a rapid adduction of the false vocal folds takes place at the lattermost part of the syllable. In the views, the false vocal folds appear to gradually adduct in the early part of the syllable and then slightly abduct at the middle. This adductive-abductive movement, however, may be a visual illusion presumably due to the downward-upward movement of the larynx, which reflects the pitch change of the falling-rising tone.

2) Laryngeal features for syllables with non-entering tones

The glottal stop gesture can often be found also in syllables with "non-entering" tones, which have normally been considered by linguists to have no glottal stop endings. We reported on this point for Cantonese (Iwata et al.,1981,p.47).

In Suzhou, voicing cessation is often achieved by a supraglottic laryngeal constriction--particularlly for syllables with "high level" and "rising" tones ([55][24][412]). For syllables with a "falling" tone([51][231]), the constriction is lesser in degree or can not be observed at all. Fig.5 shows temporal contours of the distance between the false vocal folds for Suzhou [ti55], together with [tiI25](the sample shown in Fig.1) for comparison. The false vocal folds are rapidly adducted at the

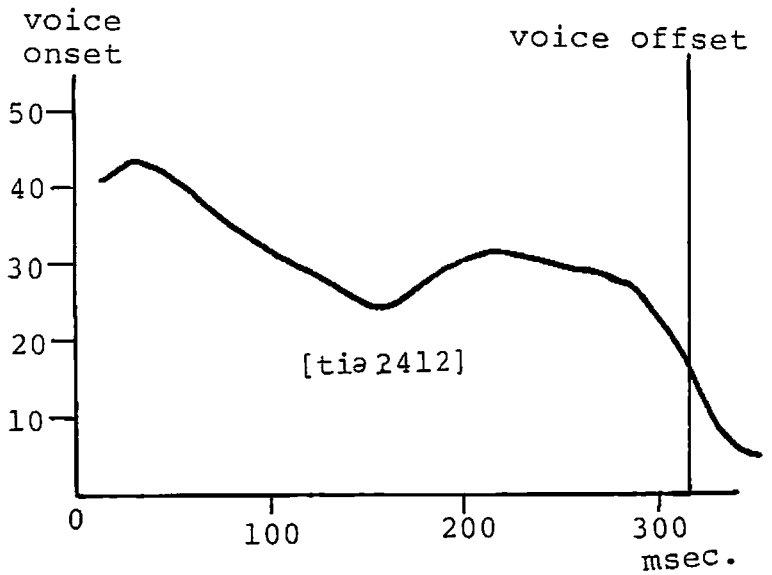

Fig. 4
Temporal contour of the distance between the false vocal folds folds for Taigu(太谷) [tiə2412].

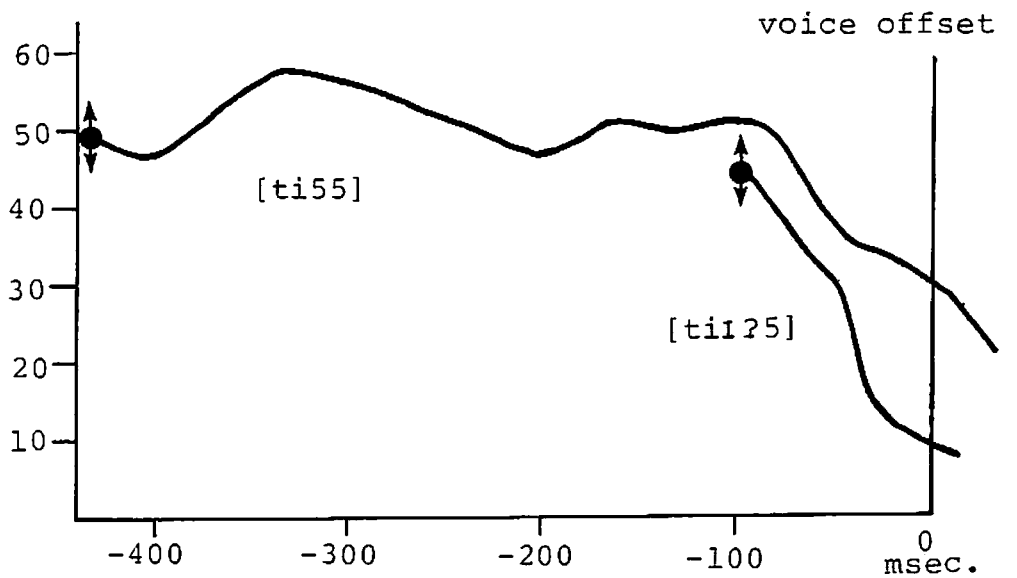

Fig. 5
Temporal contour of the distance between the false vocal folds for Suzhou(苏州) [ti55] and [ti1?5]. The points of voice onset are indicated by closed circle on each line.

latter part of the syllable in [ti55]. It is also worth noting in the figure that the absolute time interval from the initiation of adduction to the voicing cessation shows no significant difference between [ti55] and [til25] in spite of the fact that the adduction in [ti55] seems lesser in degree than that in [til25]. F0 falls slightly at the end in the "non-entering" tone syllables with "high level" or "rising" contours. In this particular sample for [ti55], a F0 fall (about 10 Hz) starts from about 60 ms before voicing cessation (see pitch contours in Fig.7).

In Taigu it was amazing for us to find that every utterance, irrespective of the number of its syllables, was terminated with the glottal stop gestures in the present subject's phonation. Accordingly, it can be said that the presence or absence of -2 are irrelevant to the distinction between "entering" and "non-entering" tone syllables in this dialect.

3) Coarticulatory laryngeal features for syllables with entering tones

When entering tone syllables are uttered at non-final positions in sentences or words (those cited at 3-2,B) above), they undergo the influence of the following segments, and the glottal stop gesture can only be observed in limited phonetic circumstances. The coarticulatory laryngeal features in each dialect are summarized in Table II. In the table, "G" implies that the glottal stop gesture is initiated during the vowel period of the entering tone syllable continuing until the beginning of the following syllable; "V", voicing through without any glottal stop gesture; SO and WO, no glottal stop gestures in the entering tone syllable and the glottis is left open immediately after the voice offset of the syllable, respectively.

Table II

Dialect / Following segment	Suzhou	Taigu	South Min
Vowel	V (G)	G, V	G, V
Voiced Consonant	V	V (G)	G, V
/h/	WO	WO	G, WO
Voiceless Inaspirates	SO	SO	SO
Voiceless Aspirates	WO	WO	WO
Voiceless Fricative	WO	WO	WO

G: Glottal Stop

V: Glottal Vibration

SO: Slight Opening of the glottis

WO: Wide Opening of the glottis

The following two features are invariably observed in each of the three dialects.

1) When the entering tone syllable is followed by a voiceless sound(except /h/), supraglottic laryngeal constriction is not observed during the vowel period, and the glottis is left open immediately after the voicing cessation.

2) In bisyllabic words in which the entering tone syllable is closely connected with the following syllable without any phonetic pause, supraglottic laryngeal constriction is not observed irrespective of the type of the following segment.

Supraglottic laryngeal constriction, if present at all, is observed when the entering tone syllable is followed by a vowel, voiced consonant or /h/. The laryngeal features under these conditions appear to be variable to a certain extent depending on the dialects and the type of test utterance.

Suzhou:

Constriction is hardly seen not only in bisyllabic words but also in the sentence([li55 tɕiɪ25_____]), irrespective of the type of the following segment. It is only observed in the present experiment when the entering tone syllables are uttered in the carrier sentence (ii)[kʱə21 kə25 z131 in55 ta25_____ iɪ25 iã412] (see 3-2(A)), in which the embedded syllable is followed by the vowel [iɪ]. In this particular case there is a voiceless interval between the target syllable ([tiɪ25],[tʱiɪ23]) and [iɪ25]. For the non-entering tone syllables, however, the constriction is not observed, voicing continuing throughout the two syllables. On the other hands when the syllables are uttered in the carrier sentence (i)[li55 kʼø41_____ kʱə21 kə25 z131], in which the embedded syllable is followed by breathy type stop [kʱ][4], the constriction is not observed either in entering or non-entering tone syllables.

Taigu:

1) In the phrase([ŋgie41 tə23 _____]), the constriction is observed for [tə23] consistently when the syllable is followed by a vowel and sometimes when it is followed by a voiced consonant ([l]). When it is followed by a voiceless consonant, the constriction is never observed.

2) The constriction is not observed in bisyllabic words irrespective of the type of following segment.

South Min:

In an earlier paper (Iwata et al.1979) we examined the influence of speech tempo (or syntactic boundary) on laryngeal control in this dialect.

1) When the sentence([tʃi33 tʃia221 pi221_____]) is uttered at a relatively slow tempo with a phonetic pause after [pi221], the constriction is consistently observed for the syllable irrespective of the type of following segment.

2) When the sentence is uttered at a faster tempo with no phonetic pause after [pi221], the constriction is consistently observed if the syllable is followed by a vowel, and occasionally if followed by a voiced consonant ([b]) or /h/, while it is not observed if the syllable is followed by any voiceless consonant except /h/.

3) In bisyllabic words the constriction is not observed irrespective of the type of following segment.

The brevity of the entering tone syllable is preserved in Suzhou even when the glottal stop is lost in the coarticulation. In Taigu, the vowel duration is even shorter than in the isolated form (See Table I). For South Min, it is mentioned in some reports (such as Dong et al.1967,pp.17-8) that -ʔ is lost and the entering tones 6 ([21]) and 7 ([5]) are, respectively, changed to tone 3 ([51]) and 4 ([21]) in the non-final position of a sentence. This observation implies that entering tone syllables lose their brevity and become longer in duration unless they precede certain syntactic/phonetic boundaries. In the present experiment, the target word [pi221]"tortoise" (as a subject in a subject-predicate construction) precedes a boundary and does preserve its brevity whether or not it loses the glottal stop; whereas in bisyllabic words in which the morpheme [pe25]"white" precedes any other morpheme without any intermediate boundary, the tone in [pe25] is changed to [21] and is obviously longer in duration than in the isolated form.

5-2. EMG data

In Figs. 6,7,8 and 9 are shown the averaged EMG signals of CT and VOC with their pitch contours and speech waves for Suzhou's seven tones uttered in the carrier sentence (i)[li 55 kʻɸ412_____kfiə21 kə25 z131]. It should be noted here that the speech tempo in the EMG experiment was generally slower than in fiberoptic experiment, moreover the present subject sometimes made a brief pause after the target syllable. A voiceless interval was observed after the target syllable and the breathy stop [kfi] in the following syllable was voiceless in most samples(see Note 4)).

It can be observed in the figures that the activity of CT corresponds quite well to the pitch contour. The increased activity of CT corresponds to the high F0 and the suppressed or decreased activity to the low F0. But there is a timing difference in CT activation between the tone types. In "high level" tones ([55],[5]) and "high falling" tones ([52],[412]), i.e. high pitch initiation, CT activity increases well before the voice onset of the vowels, whereas in "rising" tones ([24],[231],[23]), i.e. low pitch initiation, and the final portion in [412], the CT activity and F0 rise seem to be concomitant. An inspection of each integrated sample reveals that in "rising" tones, the CT peaks always precede the F0 peaks but CT activity is maintained to a certain degree even after the F0 peak.

VOC activity is prominent in entering tone syllables as well as in non-entering tone syllables with a high or rising termination. The activities of CT and VOC are reciprocal at the latter part of syllables: as CT activity decreases, VOC activity increases.

In [tiI25] VOC activity steeply increases soon after the onset of the vowel, while in [tfiiI223] it gradually increases at the beginning and mid portion of the vowel and then shows a steep increase at the end of the syllable. Recall that in this carrier sentence, where the target syllable is followed by the breathy stop [kfi], the supraglottic structures are not constricted and an

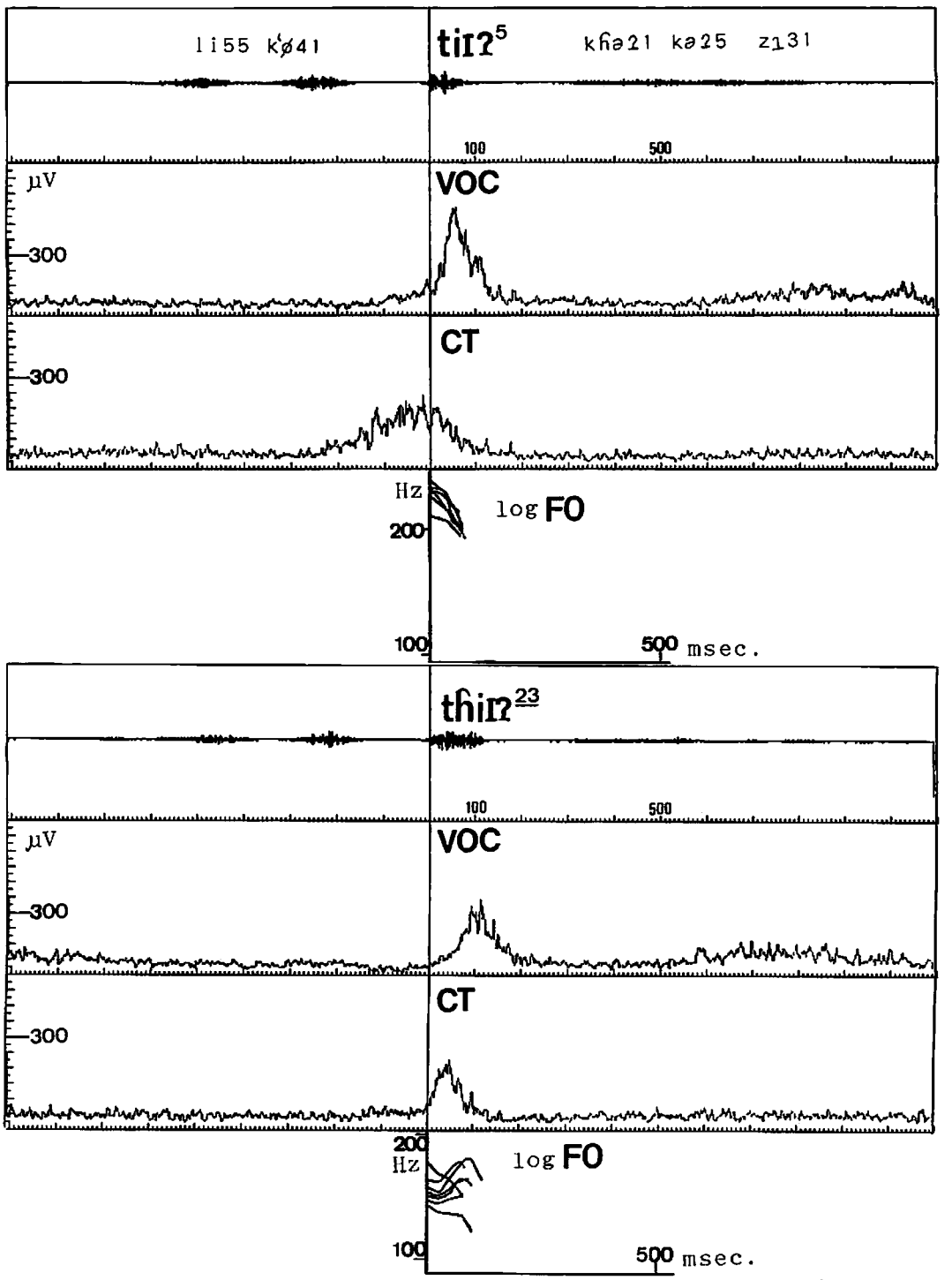

Fig. 6 Averaged EMG signals of CT and VOC for Suzhou(苏州) [tiɪ 25] and [tɦiɪ 223] with the F0 contours and the audio signals.

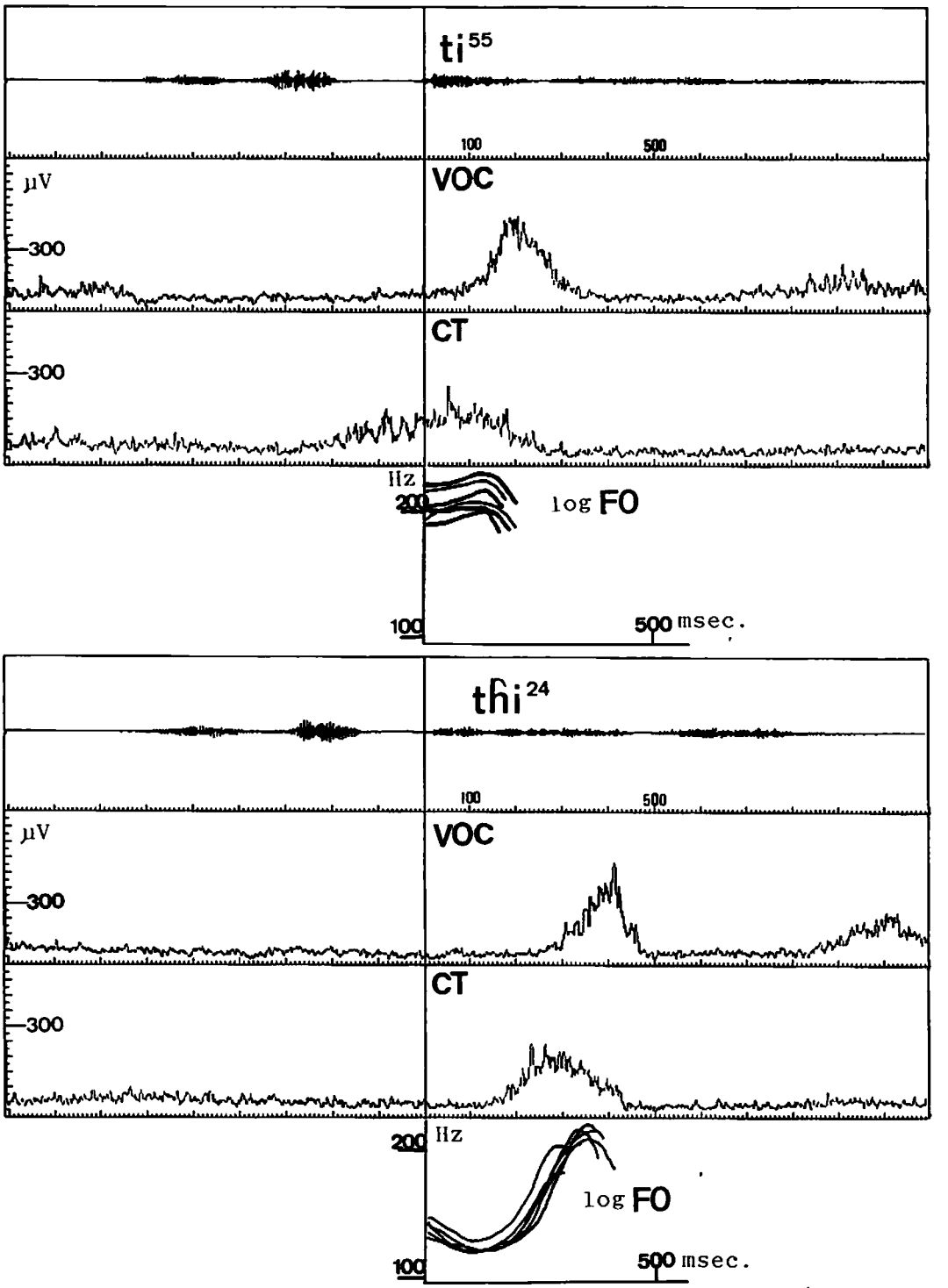

Fig. 7 Averaged EMG signals of CT and VOC for Suzhou(苏州) [ti 55] and [thi24] with the F0 contours and the audio signals.

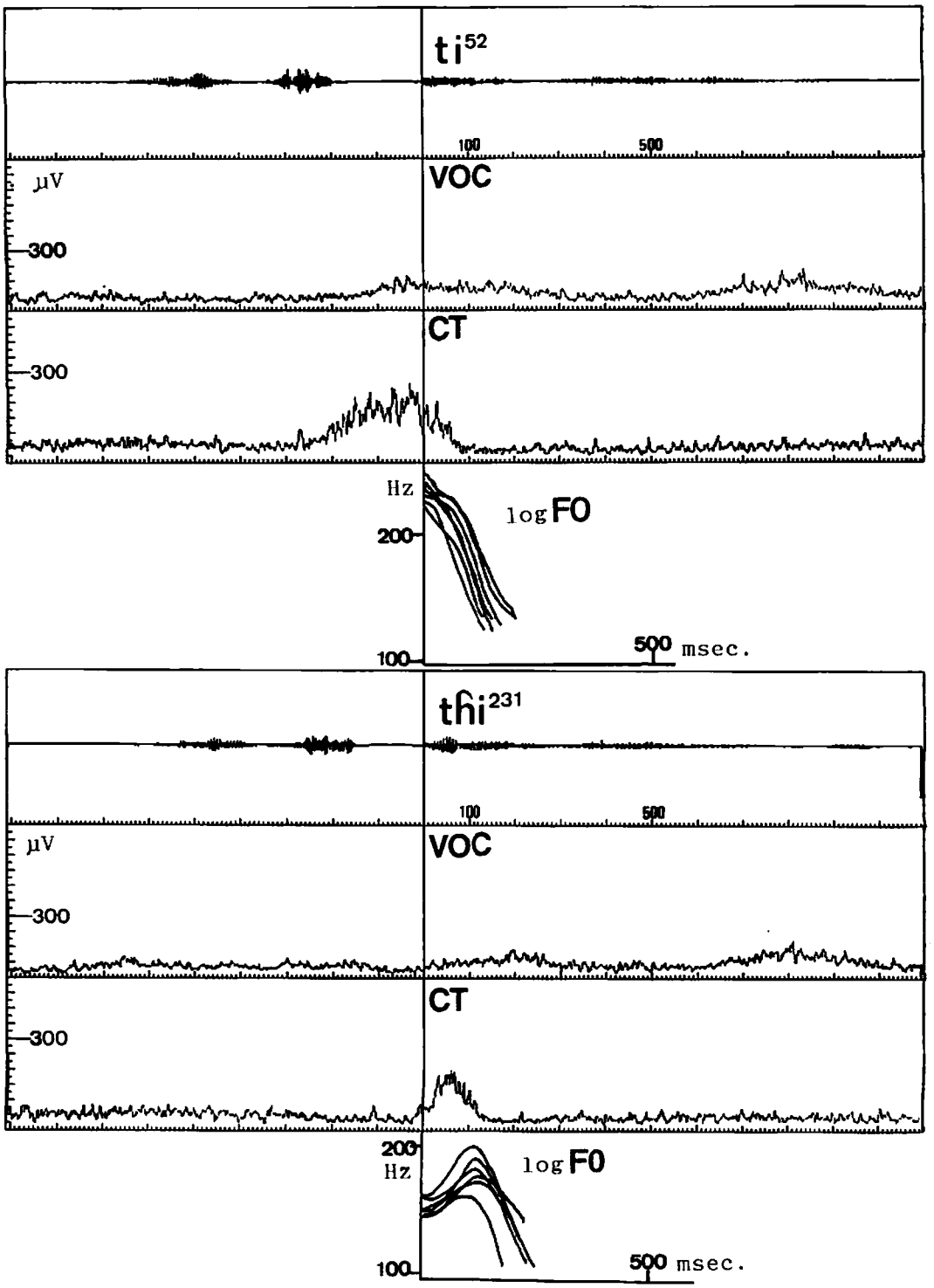

Fig. 8 Averaged EMG signals of CT and VOC for Suzhou(苏州) [ti 52] and [thi231] with the F0 contours and the audio signals.

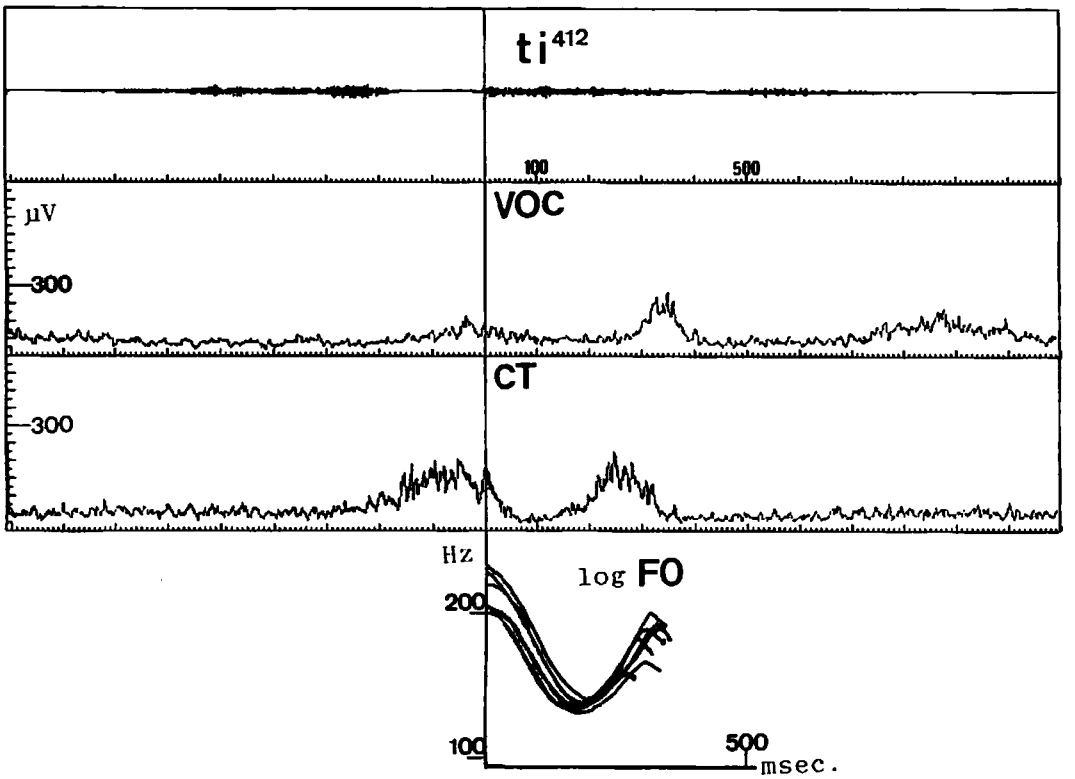

Fig. 9 Averaged EMG signals of CT and VOC for Suzhou(苏州) [ti412] with the F0 contours and audio signals.

open glottis is observed even in the entering tone syllables.

In [ti55],[tĥi24] VOC activity increases at the end of the syllables for all samples except one. On the average the degree of this activity (peak value and the activity interval) is even higher than that in the entering tone syllable [tĥiɪ 223]. In [ti412], an increased activity of VOC is observed at the end portion in four samples out of eight, and it is suppressed throughout the whole syllable in the four other samples. In [ti412], suppressed or less marked activity in VOC appears to be related with shorter voiceless interval after the syllable. In the syllables with falling and low pitch termination([ti52], [tĥi231]), VOC activity does not show any remarkable increase at the end. As stated in section 5-1,2), the supraglottic laryngeal constriction is observed at the end portion in "high level" and "rising" tones, but not in "falling" tones.

6. Discussion

6-1. Physiological mechanism in the production of the glottal stop

In the present study, various aspects of the syllable final "glottal stop" in Chinese dialects, including basic laryngeal features, coarticulatory features and their interactions with tones and vowels, were examined by fiberoptic and electromyographic observations.

It might be a general conception among linguists that the glottal stop is a sound in which the vocal folds are held together resulting in no glottal vibration. This holds true as far as the state of the vocal folds are concerned, but what is often found in the larynx is a supraglottic constriction, particularly the adductive gesture of the false vocal folds (Lindqvist,1969; 1972a,b; Iwata et al., 1979). This type of laryngeal constriction is also observed in the vocal initiation of syllables. For instance in Suzhou [il55],[il52],[il412] and [il25] the adductive gesture of the false vocal folds was observed at initial position in 17 samples out of 40. The false vocal folds were rapidly adducted prior to voice onset up to the beginning of the vowel.

What is of significance for the final glottal stop is that the constricted gesture was initiated in the midst of the vowel periods, not abruptly formed at the very last moment of the syllable as might be generally conceived. The domain of "glottalization" is even the entire part of the vowel-- at least in Suzhou and South Min.

The constriction at the supraglottal level could be controlled by mechanisms or muscles other than those controlling the glottal activities. If the supraglottic constriction is coupled with glottal abduction, "whisper" is produced (Weitzman et al.,1976). Lindqvist (1969,1972a) claimed that the ary-epiglottic sphincter muscles were active in forming the supraglottic constriction. In Lindqvist (1972a,p.5) he mentioned, "The increase in the activity of the ary-epiglottic sphincters results in a shortening and thickening of the vocal folds and if the activity in the vocalis muscles was not increased, this would result in a lowering of the pitch". This type of supraglottic constriction, which we called "ary-epiglottic constriction" in section 5-1,1) above, is typically observed in the so-called "breathy phonation" in Suzhou dialect. What is characteristic of the constriction in breathy sounds, and distinct from that in the glottal stop, is that the false vocal folds are not adducted and that the activity of VOC does not increase.

Adductors such as vocalis and lateralis contribute to the production of the glottal stop, presumably by supplying medial compression to the vocal folds (Hirose and Gay,1973). These intrinsic muscles seem, in some cases, to work independently of the muscles controlling the supraglottal structures. The laryngeal EMGs for Suzhou revealed that the activity of VOC prominently increased in the entering tone syllables followed by the breathy stop [kɦ], while direct observation of the larynx showed that in those syllables the glottis was left open after the voicing cessation accompanied by no supraglottic constriction. In

the present experiment, however, the recordings of the EMG and laryngeal views were not made simultaneously; in EMG the phonetic condition for the target syllable was similar to that uttered in isolation, while in fiberoptic experiment it was similar to that in connected speech (see 5-2). It appears that the level of the VOC activity is related with the following phonetic condition: suppressed or less marked activity of VOC is related with absence of voiceless interval(voicing through) or shorter voiceless interval; increased or marked activity with longer voiceless interval. Further experiments are required in this respect.

As far as the present data are concerned, the laryngeal control at the glottal level and that at the supraglottal level show a remarkable consistency. An interesting finding in Suzhou is that the increased activity of VOC seems to be coupled with the supraglottic constriction at the end of syllables in "high level" and "rising" tones, while no remarkable activity of VOC or supraglottal gesture was observed in "falling" tones. It might be assumed that adductors like VOC and some extrinsic muscles other than SH would, at least in a majority of cases in Chinese dialects, work jointly in producing the glottal stop. The SH (sternohyoid) was found to show no remarkable activity at the end of syllables in Suzhou.

VOC as well as LCA primarily functions as an adductor, but they are also involved in modulating pitch, particularly in pitch raising (Gårding et al.,1970; Simada and Hirose,1971; Atkinson,1978). The present EMG findings on Suzhou appear to contradict the former ones; VOC is pertinent to a F0 fall in a high pitch register at the end of the syllable. There is a general tendency in "high" and "rising" tones that as the constricted gesture goes on and the VOC activity increases, F0 gradually falls within a certain range. This type of pitch lowering, however, is redundant in distinguishing the tone patterns of the dialect. Note that in "falling" tones ([52],[412] and [231]) the pitch is lowered mainly in terms of a decrease in CT activity, VOC showing no prominent activation. Therefore, a F0 fall at the syllable ending should be brought about by mechanisms other than those in normal pitch lowering. What is of interest here is that there is a reciprocity in pattern between the VOC and CT activities. In "high level" or "rising" tones the contraction of CT results in a high pitch by elongating the vocal folds. After a peak, CT activity gradually decreases toward the end of the syllable, but it is not suppressed even at the latest part of the syllable. The contraction of VOC at this moment would counteract the CT presumably by shortening the vocal folds, the inner tension of which being increased, resulting in a certain F0 fall.

The coarticulatory laryngeal feature can be accounted for in terms of assimilation; the constricted gesture disappears and an open glottis is observed exclusively if the entering tone syllable is followed by any voiceless consonant; in a voiced or breathy context where the following segment is either a vowel, voiced consonant or /h/ the constriction is sometimes preserved. The phonetic conditions for determining the coarticulatory features are almost identical with those found in -p,-t,-k in South Min and Cantonese (Iwata et al.,1979,1981, see Iwata,1985 for a more detailed phonetic explanation).

6-2. Contributions of the present study to phonetics and phonology in Chinese dialects

One of the remarkable features, and a matter of controversy, in the phonology of Chinese is the interaction between segments and suprasegments, as is the case with other tone languages in South-East Asia. The syllable final glottal stop, except in some minor cases, usually appears under the entering tone. The present investigation sheds new light on the phonetic reality of this feature and will bring us to a new interpretation of it.

In Chinese linguistics, -2 is generally considered along with -p,-t,-k. The historical change from -p,-t,-k to -2 has been considered a backward movement in "articulatory point". It was revealed, however, that at least in Suzhou and South Min the domain of "glottalization" is even the entire part of the syllable. This would suggest that it is possible to consider the glottalization as a syllabic feature or a type of phonation.

Another contribution of the present study to Chinese phonetics might be that the glottal stop gesture can be observed even in "non-entering" tone syllables which have been believed to have a pure vocalic ending. An extreme case was found in Taigu in which almost every utterance terminated with the glottal stop gesture. Admitting that this is phonologically a redundant feature and that there could be ideolectal or individual variations in laryngeal control on this particular point, the findings clearly show that the glottal stop gesture is not always specific to entering tone syllables.

Finally, it should be pointed out that the supraglottic laryngeal constriction found in isolated forms often disappears when entering tone syllables are uttered at the non-final position of sentences or words. Y-R Chao as early as the 1920's mentioned, "In connected speech, when a syllable in the rusheng(entering tone) is followed by another syllable, its rusheng character is only shown its brevity, there being no glottal stop" (Chao,1928, in his English introduction,xiii)[5]. Though his remark is on Wu dialects as a whole, not specifically on Suzhou, the present study has proved it true as far as the supraglottal features are concerned. Our EMGs showed an increased VOC activity in that carrier sentence where the entering tone syllable was followed by a breathy stop. But the EMG recording tentatively made on some bisyllabic words, in which the entering tone syllable stood at the first syllable, showed no remarkable activities in VOC except in limited tone combinations. As for South Min, it has been reported that syllables with -2 would not only lose -2 but also lose their brevity unless they precede a syntactic/phonetic boundary in sentences. Our observations showed that the constricted gesture often disappeared even when it was followed by a boundary if the sentence was uttered at fast (i.e. normal conversational) tempo with no phonetic pause between the target word and the following syllable, though the brevity of the syllable was preserved in this case. Assimilatory gestures in the larynx were also observed for Taigu.

This evidence would suggest that the primary feature of the entering tone syllable is its brevity, except in the case where the syllable has become longer in duration. The glottal stop is

employed here in order to cease the glottal vibration, and if the voicing cessation is accomplished by another laryngeal control, like the abduction of the vocal folds, it would not be necessary to employ it. The constricted gesture is employed even in non-entering tone syllables just to cease the glottal vibration. Whether the glottal stop is employed or not depends on phonetic circumstances to a considerable degree, and should be considered as a phonetic strategy in the larynx.

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Foot Notes

1) On phonetic details on Taigu dialect we are indebted to Isao Higuchi who is investigating the dialect.
2) The particle [tə23] in Taigu corresponds to "de" in Pekinese. It is pronounced with a neutral tone, i.e. atonic, in Pekinese. According to Yang(1983), there are no atonic variants in Taigu. To our ears, however, [tə23] in Taigu is somewhat weakened in stress and shorter in duration.
3) The glottal views for South Min [ti221] were presented at p.71 in Iwata et al.1979.
4) The breathy initials in Suzhou are realized as fully voiced consonants at the intervocalic position of closely connected syllable sequences. In the fiberoptic experiment there was a general tendency that [kɦi], in this carrier sentence, was voiceless or only partially voiced if the speech tempo was relatively slow and was fully voiced if the speech tempo was faster. While in EMG experiment it was voiceless or only partially voiced except a few samples. The voicing in [kɦi] at this position might be related with its closure duration as well as presence or absence of the phonetic pause preceding it. Measurement of intraoral pressure in the fiberoptic experiment revealed that the closure duration in [kɦi] was 87.9 ms on the average(Max.129.9ms-Min.62.1ms.), while it was much longer in EMG experiment though the exact measurement was unobtainable.
5) We are indebted to Mituaki Endo who brought Chao's remark to our attention.

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