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Folia Phoniatrica
et Logopaedica

Separatum
Folia Phoniatr Logop 1994;46:139–151

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S. Karger
Medical and Scientific
Publishers
Basel · Freiburg
Paris · London
New York · New Delhi
Bangkok · Singapore
Tokyo · Sydney

KARGER

Printed in Switzerland
on acid-free paper by
Thür AG Offsetdruck, Pratteln

Original Paper

Folia Phoniatr Logop 1994;46:139–151

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Abstract

In order to clarify the nature of the physiological adjustment for the production of whispering, physiological studies were conducted on the glottal and supralaryngeal adjustments during whispering. The results indicate that for the production of whispering there is a necessary relationship between glottal adjustment and supralaryngeal adjustment in terms of the coordination between posterior cricoarytenoid muscle (PCA) and thyropharyngeus muscle (TP). Also, there might be a function switch in our brain which enables the speaking mode to change from ordinary to whispering, using the activation of PCA and TP, as a result of human evolution.

Die Rolle des Musculus Cricoarytaenoideus posterior und des Musculus thyropharyngeus beim Flüstern

Zur Klärung der Physiologie des Flüsterns wurden Untersuchungen über die glottalen und supralaryngealen Anpassungen während des Flüsterns durchgeführt. Eine elektromyographische (EMG) Studie der glottalen Anpassung zeigte, dass der Musculus cricoarytaenoideus posterior (PCA) während des Flüsterns eine höhere Hintergrundaktivität als bei normalem Sprechen aufwies. Weiterhin gab es zusätzliche segmentale Aktivitäten des PCA, die anscheinend nicht nur dazu beitragen, dass die Stimmritze offen gehalten wird, sondern auch notwendige Bewegungen für Phoneme durchführen. Es wurde eine faseroptische Studie durchgeführt, um die supralaryngeale Anpassung zu beobachten. Im Vergleich zur normalen Sprache wurde beim Flüstern eine starke Konstriktion der supralaryngealen Struktur festgestellt. Es wurde auch eine EMG-Studie des Musculus thyropharyngeus (TP) durchgeführt. Die Aktivität des TP zeigte einen deutlichen Unterschied zwischen normaler Sprache und Flüstern, wobei der TP bei normaler Sprache inaktiv blieb, während er beim Flüstern kontinuierliche Aktivität zeigte. Der Grad der Aktivität war beim Bühnenflüstern grösser als bei leisem Flüstern. Beim Flüstern gab es keine augenscheinliche segmentale Aktivität des TP. Unsere Ergebnisse lassen sich folgendermassen zusammenfassen: 1) Der PCA-Aktivitätspegel wird höher, um Stimmritzenvibration auf der glottalen Ebene zu verhindern. 2) Der TP-Aktivitätspegel wird höher, um zur Konstriktion der supralaryngealen Struktur beizutragen. 3) Zusätzlich ist am Anfang einer Äusserung eine spezifische Anpassung der PCA- und TP-Aktivitäten erforderlich, um das Flüstern einzuleiten und einen Wechsel der Sprechart zu Flüstern zu bewirken. 4) Weiterhin muss ein Zusammenhang zwischen der glottalen Anpassung und der supralaryngealen Anpassung im Sinne einer Koordination zwischen PCA and TP bestehen, der das für das Flüstern bedeutsame turbulente Geräusch erzeugt.

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1021–7762/94/
0463–0139$5.00/0

Rôles du muscle cricoaryténoïdien postérieur et du muscle thyropharyngien lors du chuchotement

Des études ont été faites sur la nature de l'adaptation de la glotte et des structures supralaryngiennes pendant le chuchotement. Une étude électromyographique (EMG) de l'ajustement glottique a révélé que le muscle cricoaryténoïdien postérieur (PCA) est plus actif pendant les chuchotements que pendant la phonation normale. De plus, on trouva des activités segmentaires supplémentaires du PCA qui semblent contribuer non seulement à maintenir la glotte ouverte, mais aussi à exécuter les gestes nécessaires à l'articulation des phénomènes pertinents. Une étude par fibres optiques fut réalisée pour analyser l'adaptation supralaryngienne. Une forte constriction de la structure supralaryngienne est apparue au moment des chuchotements. Une étude EMG du muscle thyropharyngien (TP) a également été réalisée. Il existe une différence considérable entre l'activité du TP lors de la phonation ordinaire et le chuchotement, car le TP reste inactif pendant le langage ordinaire, et devient actif pendant le chuchotement. Il devient plus actif lors d'un chuchotement fort et moins actif lors d'un chuchotement à voix basse. Aucune activité segmentaire du TP n'a été décelée pendant les chuchotements. Ces résultats permettent de conclure de la manière suivante: 1) Le niveau d'activité du PCA augmente pour éviter les vibrations au niveau glottique. 2) Le niveau d'activité du TP augmente pour faciliter la constriction de la structure supralaryngienne. 3) De plus, au tout début de l'expression, un ajustement spécifique des activités de PCA et de TP est nécessaire pour commencer le chuchotement et passer de la phonation habituelle au chuchotement. 4) De plus, il devrait exister un rapport entre l'ajustement glottique et supralaryngien en termes de coordination entre le PCA et le TP, qui produit le bruit nécessaire au chuchotement.

Introduction

What is whispering? To answer this question, a considerable amount of research has been made by many scientists from various specialities. As one answer, an old textbook of speech science states that 'Whispering is an aphonic laryngeal action' [1]. This means that there is no vocal fold vibration during whispering.

Weitzman et al. [2] performed a fiberoptic observation of the laryngeal gestures in whispering. They observed that an adduction of the false vocal folds took place with a decrease in the size of the anterior-posterior dimension of the laryngeal cavity. They assumed that this particular laryngeal gesture for whispering was to prevent the vocal fold vibration caused by transglottal airflow.

Solomon et al. [3] investigated laryngeal configuration and constriction in whispering. The results suggested that supraglottal constriction, especially by the lateral structures, contributed to the production of high-effort whispering much more than low-effort whispering.

Monoson et al. [4] did an aerodynamic research on whispering; in quiet whispering they found about twice the airflow rate, and three times the requirement for forced whisper as compared to normal phonation.

In past years, the nature of the laryngeal adjustment for speech production has been extensively studied by means of electromyography (EMG). Traditionally, the muscles of the larynx have been divided into two groups, the intrinsic laryngeal muscles and extrinsic laryngeal muscles. Functionally, the intrinsic laryngeal muscles may be divided into three groups with respect to their function: (1) abductor, the posterior cricoarytenoid muscle (PCA); (2) adductor, the interarytenoid muscle (INT), the lateral cricoarytenoid muscle and the thyroarytenoid muscle and (3) tensor, the cricothyroid muscle [5].

The abduction-adduction of the glottis is primarily controlled by the PCA (abductor) and INT (adductor) muscles, respectively [6]. It should be noted that although there are three pairs of adductor muscles, the only abductor is the PCA. These intrinsic laryngeal muscles adjust the laryngeal gesture for speech production.

During ordinary speech, the glottis is closed and the vocal folds vibrate for voiced sounds, whereas for voiceless sound production, the vocal folds are abducted to prevent vocal fold vibration. During the production of voiceless segments, a marked elevation in PCA activity associated with suppression of INT is always observed. On the other hand, PCA activity generally remains suppressed for voiced sound production. Thus, it is reasonable to consider that PCA is activated to prevent vocal fold vibration.

There have been several reports dealing with the activity of the intrinsic laryngeal muscles during whispering. Among these, Faaborg-Andersen [7] performed an EMG study of the cricothyroid and vocalis muscles. He stated that the electrical activities of both muscles appeared to be suppressed for whispering. Sawashima and Hirose [8] reported that PCA activity increased, while INT and the cricothyroid were suppressed during whispering.

It has been reported, based on perceptual studies, that the voiced-voiceless contrast of consonants can be distinguished even in whispered speech [9]. Our preliminary study also revealed an overall accuracy of judgment for the voiced-voiceless contrast in Japanese stops and fricatives of 75 and 95%, respectively [10]. These results would seem to suggest that there might be a difference in laryngeal gestures between the production of voiced and voiceless segments even during whispered speech.

The purpose of the present study was thus to elucidate the nature of the physiological adjustments for whispering with special attention to the laryngeal and supraglottal adjustments. For this purpose, the study was divided into two parts: one for glottal adjustment, and the other for supraglottal adjustment.

Experiments

Experiment 1: An EMG Study of the Glottal Adjustment during Ordinary and Whispered Speech

Method

EMG activity was recorded from the PCA of 2 native speakers (K.T. and S.N.) of the Tokyo dialect of Japanese. For the EMG recordings, hooked wire electrodes were used, since hooked wire electrodes are useful for studying muscle activity with special reference to the kinesthetic function of the larynx or pharynx during speech [11, 12].

The electrodes were inserted perorally into the PCA. For peroral insertion, topical anesthesia (4% Xylocaine) was administered to the pharyngeal mucosa in order to control the gag reflex. After anesthesia, a curved probe bearing a needle at its tip was directed to the point of insertion through the mucosa covering the PCA. Verification was made by having the subject repeat short periods of vowel phonation separated by deep, quick inspiration. The PCA is active for inspiration and suppressed during phonation [6].

For EMG data assessment, an electromyograph was used. It consisted of an amplifier and a recording system equipped with a monitor oscilloscope and loudspeaker. A digital audio tape data recorder (Sony PC108M) with a special modification and with our original amplifier was also in use.

As an indication of the ariculatory gestures, the intraoral pressure (PO) was sensed by a miniature transducer system (Gaeltec F811) inserted through the nose and also recorded on the data recorder with the EMG and speech signals. A block diagram of data assessment and processing is shown in figure 1.

The subjects were required to utter nonsense test words of the form /CVCV/. Each test word was embeded in a carrier sentence /ii CVCV desu/ (It is a good /CVCV/), and uttered more than 10 times in whispered and in ordinary speech. The test words are presented in table 1.

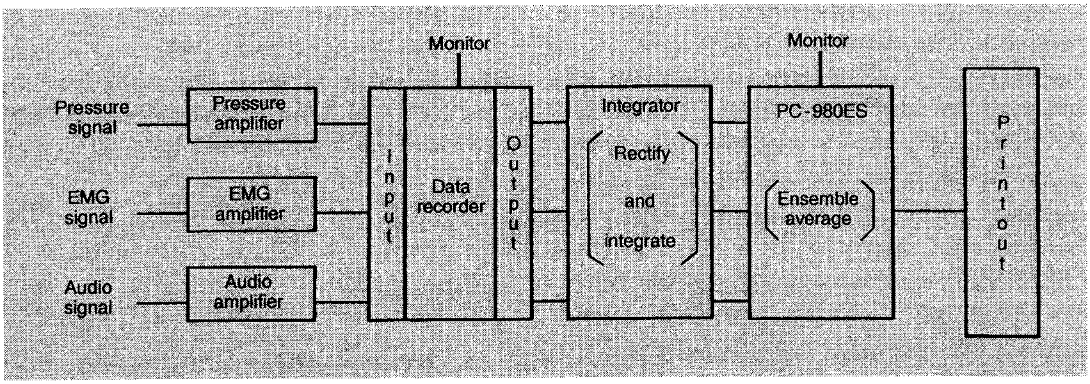

Fig. 1. Data acquisition and processing.

Table 1. List of test utterances

/ii tete desu/	(It is a good tete.)
/ii dede desu/	(It is a good dede.)
/ii sese desu/	(It is a good sese.)
/ii zeze desu/	(It is a good zeze.)

In order to eliminate irrelevant signals, after the recordings, the EMG signals were rectified, smoothed and averaged with a special reference point. As the reference point for averaging the EMG signals, the moment of the abrupt drop of the intraoral pressure was taken as an indication of the oral release of the first consonant.

Results

Ordinary Speech vs. Whispering. Figure 2a shows the averaged EMG patterns (bottom panel) and PO (top panel) for whispering (dotted line) and ordinary speech (solid line) for subject K.T. The ordinate represents the EMG potential, and the abscissa represents time. Zero on the abscissa indicates the lineup point. The lineup was chosen at the release of the first /t/ judged by the abrupt drop in the PO. In ordinary speech, PCA activity (bottom panel of fig. 2a) decreases 700 ms prior to the lineup point for adduction of the vocal folds for phonation from its higher activity level for inspiration. On the other thand, in whispering, there is no suppression of PCA activity. In addition, there is a rather transient increment in the activity at the initiation of the utterance (−550 ms). Furthermore, there is no suppression at all throughout the period of utterance from −550 to +750 ms. In addition to the elevated activity level, PCA showed a segmental pattern related to each phoneme. The EMG peak around the lineup point corresponds to the first /t/ in the test word /tete/; PCA activity for second /t/ is seen at 50 ms after the lineup point (+50 ms) in figure 2a.

Voiced vs. Voiceless. Figure 2b shows the EMG patterns for the production of /tete/ (solid line) and /dede/ (dotted line) in whispered speech. We can see a higher increment rate and peak activity of PCA (bottom panel of fig. 2b) for the voiceless consonant /t/ than for the voiced consonant /d/ just before the lineup point. Figure 3a, b shows the average EMG patterns for subject S.N. In this experiment, the dynamic range of recorded PCA activity was somehow smaller than in the previous experiment. However, we can see the increased activity of the PCA throughout the utterances with an increment at the beginning

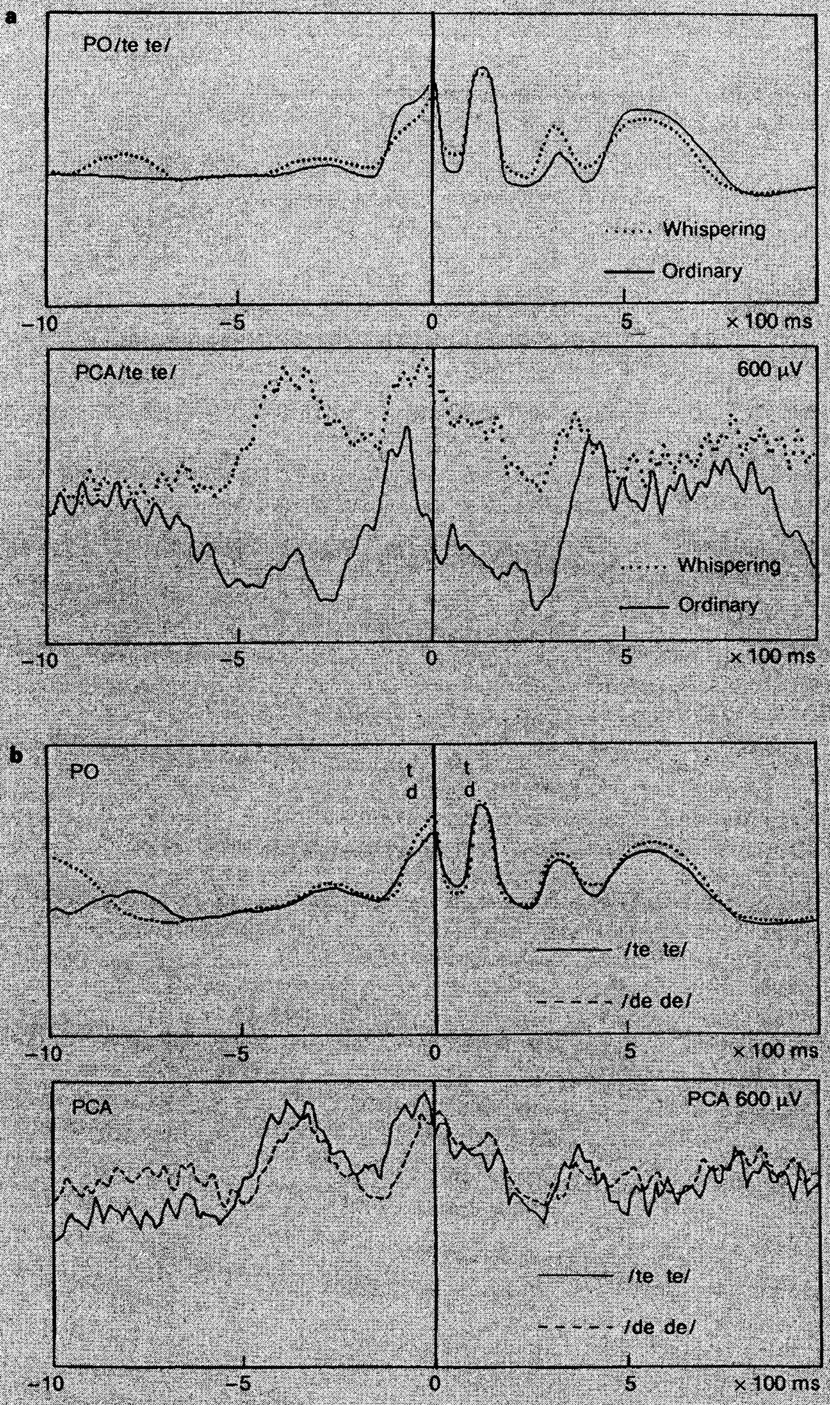

Fig. 2. a Ordinary vs. whispered speech (subject K.T.). **b** 'Voiced' vs. 'voiceless' in whispering (subject K.T.).

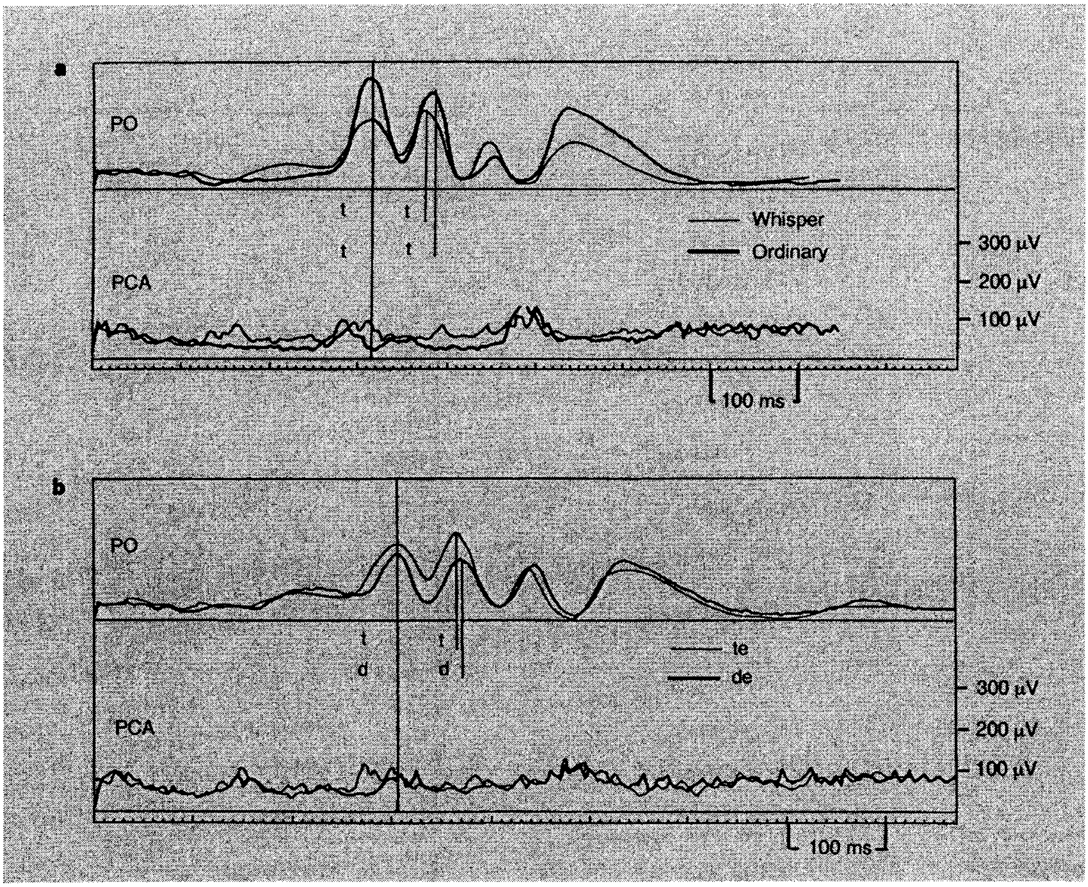

Fig. 3. **a** Ordinary vs. whispered speech (subject S.N.). **b** 'Voiced' vs. 'voiceless' speech in whispering (subject S.N.).

of the utterance and segmental perturbation with a relatively higher activity for the voiceless segment than for the voiced segment. These observed activity patterns are comparable to the results from the former experiment with subject K.T. and are also consistent for the other test words.

Discussion

The results of our EMG experiments showed an increased PCA activity throughout a whispered utterance as the upward shift of the baseline may represent the force applied to open the glottis. This particular higher baseline activity for whispering suggests that oridnary speech and whispering are completely different modes of speech.

Hence, the higher baseline activity of the PCA can be assumed to indicate a change in the speaking mode from ordinary speech to whispered speech. Furthermore, PCA activity showed a segmental pattern which corresponded to each phoneme. In other words, even during whispering, PCA showed EMG patterns compatible with ordinary speech except for its higher baseline activity. Thus,

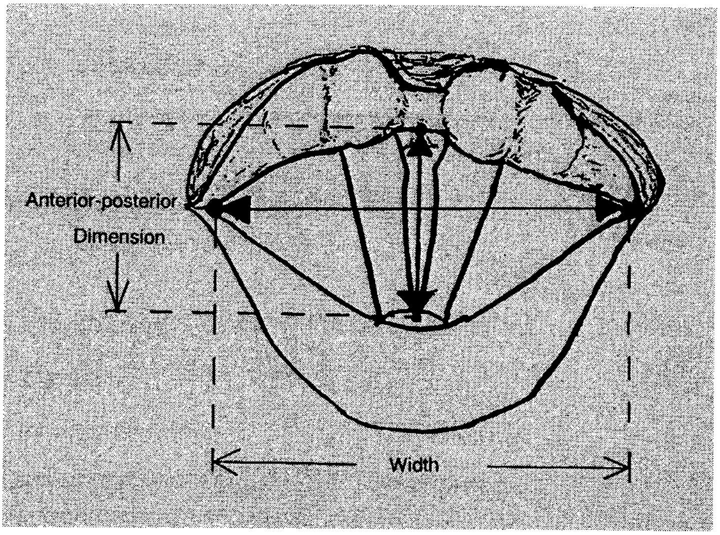

Fig. 4. Measurement landmarks.

even in the whispering mode, the general laryngeal attitude for the voiced vs. voiceless aspect was preserved in this case. This can explain the difference in EMG patterns for the production of 'voiced' and 'voiceless' segments uttered in whispered speech.

It was also observed that there was high PCA activity at the beginning of utterances around 300 ms before the lineup point, which was supposed to be related to the first syllable of the carrier sentence /ii/. This observation seems to be contradictory to the previous finding, that is, PCA becomes more active for 'voiceless' segments and less for 'voiced' segments. To explain this phenomenon, we have to take into consideration that this segment /ii/ is located at the beginning of the utterance. Probably, this particular phonetic condition may cause a laryngeal gesture that is different from that in the whispering mode. We can speculate that the high EMG activity of PCA corresponding to /ii/ in utterance-initial position contributed to a prevention of vocal fold vibration which would have been caused by a high airflow rate.

Experiment 2: Studies on Supralaryngeal Adjustment

A Fiberoptic Study

Method

In order to observe the dynamics of speech production, a laryngeal fiberscope was inserted through the nose of one of the 2 subjects in experiment 1 (K.T.) to get an optimum view of the laryngeal movement. The laryngeal views were recorded on a VTR system with a CCD camera.

The subject was required to utter the same test words in whispered and in ordinary speech as in experiment 1, more than 6 times each. A computer-aided tracing system (NEC PC980ES) was used to analyze the movement data. A tracing was then made for each field of the VTR on a computer monitor. For analysis, the VTR was played back in the field mode. By using the field mode, the time resolution was as fine as 1/60 s.

In order to represent the constriction of the supralaryngeal structures, the distance between the posterior commissure and the petiolus of the epiglottis and the distance between both aryepiglottic holds were measured. The landmarks of the measurement are shown in figure 4. The products of these two distances were calculated to give an indication of the laryngeal aperture.

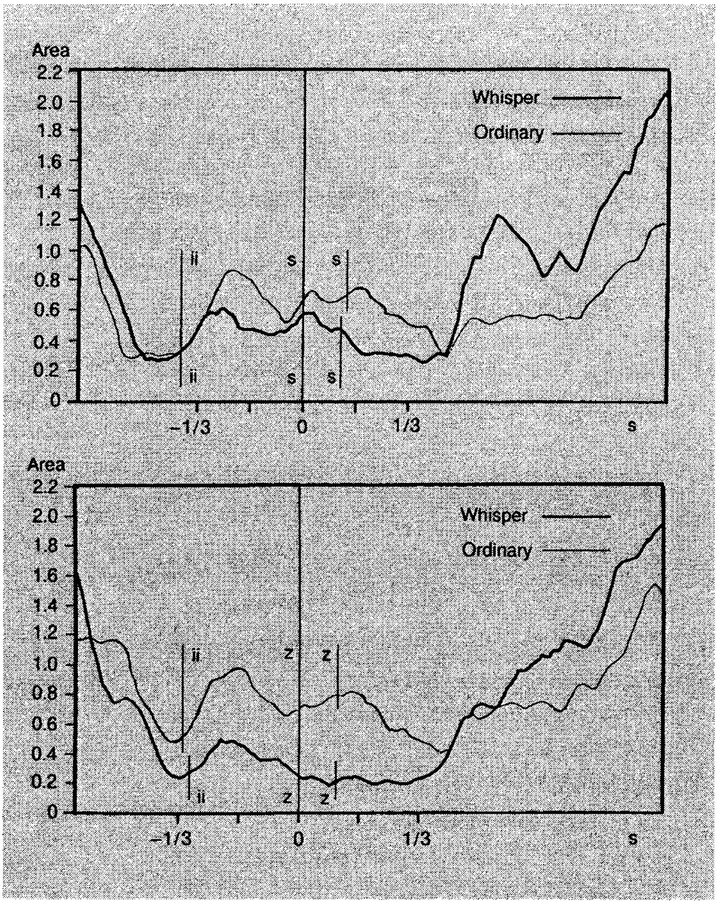

Fig. 5. Area of laryngeal aperture (subject K.T.).

Results

Figure 5 shows the results of the measurement for the utterances /sese/ and /zeze/ in ordinary and whispered speech. The ordinate represents the area of the laryngeal aperture (in arbitrary units) and the abscissa represents time. Zero on the abscissa indicates the release of the consonant. The small vertical lines in the graphs indicate (left) a particular acoustic initial and (right) the release of the second consonant.

Before the initiation of the utterances, the area was large in both ordinary and whispered speech, but during speech, the area decreased. From these figures, it is obvious that the area of the supralaryngeal aperture was larger for ordinary speech than that for whispering throughout the utterances.

Based on this result, in order to generalize the observed tendency, the areas at the release of the first consonant were measured for each utterance. Figure 6 shows the mean value of the area (arbitrary units) for each utterance and the standard deviation. As shown in this figure, it is clear that there was a significant difference ($p < 0.01$) between ordinary and whispered speech. That is, the constriction of the upper structure of the larynx for whispered speech was much tighter than that for ordinary speech. However, there was no significant difference between voiced and voiceless consonants in both ordinary and whispered speech.

Discussion

A large supraglottal area indicates a looser constriction, and a small area means tighter constriction. The present fiberoptic study has supported previous reports on supraglottal constriction during whispering, showing a tighter constriction of the larynx for whispering compared with ordinary speech.

Anatomically, the false vocal cords move with the arytenoid cartilages and are brought together in a forced closure of the glottis to help seal the air passage [13]. During whispering, however, the glottis is kept open to prevent vocal fold vibration, whereas the false vocal cords are adducted at this time. Since there are no particular muscles which simply contribute to the adduction of the false vocal cords, it can be hypothesized that there should be some other adjustment which performs the constriction of the supraglottal structures from the outside of the laryngeal framework.

One possible explanation of the supraglottal adduction is as follows. The inferior constrictor of the pharynx arises from the lateral surface of a thyroid cartilage, then meets the opposite constrictor to form the raphe of the pharynx. It is divided into two muscles: the thyropharyngeus muscle (TP) and the cricopharyngeus muscle. The glottis is located above the cricoid cartilage and inside the thyroid cartilage. The TP attaches to both sides of the posterior edge of the thyroid cartilage directly. So if TP is activated, TP pulls both sides of the thyroid cartilage in the mid-line direction, and consequently the adduction of the supralaryngeal structures occurs. According to the above explanation, it can be hypothesized that TP contributes to the adjustment of the supraglottal constrictions during whispering.

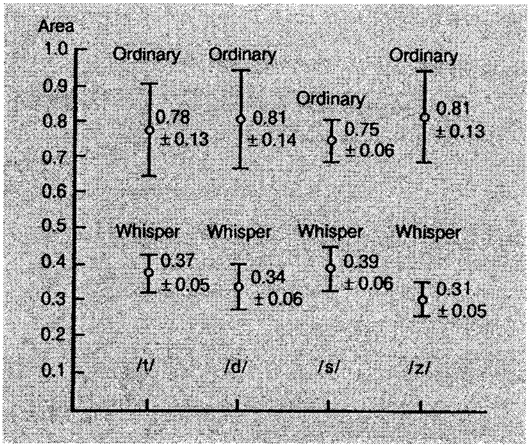

Fig. 6. Area of laryngeal aperture.

EMG Study

In order to test the above hypotheses, an EMG study of the TP was conducted.

Method

The subject was K.T., who served as one of the subjects in experiment 1. EMG activity was recorded from TP. The material, method and analysis were the same as in the PCA study, except that TP was reached percutaneously. At the insertion of the electrodes, the needle was aimed toward the posterior end of the thyroid ala and inserted to touch the thyroid cartilage. Since the TP muscle is in the deepest layer of the muscles which cover the thyroid ala (fig. 7), EMG activity fed from the electrode can only be from the TP muscle. If the activity increased on swallowing, the location of the electrode must be in the TP muscle.

The subject was asked to utter nonsense words of the form /CVCV/ in soft whispering (the kind of whisper used when whispering into someone's ear), stage whispering (that which one would use if the listener were quite a distance away from the speaker) and in ordinary speech. The test words were the same as used in the previous experiment.

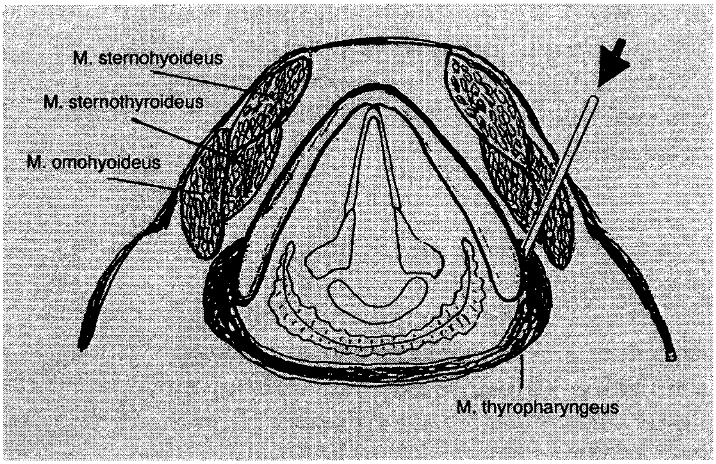

Fig. 7. The route of insertion of the electrode.

Results

Figure 8 shows the averaged EMG patterns of TP for ordinary speech (top panel of each figure), soft whispering (middle panel of each figure) and stage whispering (bottom panel of each figure). The ordinate represents the EMG potential and the abscissa represents time. A perpendicular line at the center of a horizontal line indicates the lineup point. The lineup point was also the same as in the previous experiments.

At rest, the baseline activity was around 40 µV for each condition. In ordinary speech, TP increases its activity only slightly. On the other hand, in soft whispering, there is a greater increment of TP activity, while the increment of EMG activity is more dominant for stage whispering.

However, the general pattern of EMG perturbation was quite similar in soft and stage whispering, except in amplitude. In both modes of whispering, the activity gradually increased before the phonation and reached a peak at around the lineup point, staying at the same level during the utterance, then gradually decreasing to the baseline activity. There was no apparent segmental perturbation pattern related to each phoneme, even in ordinary speech. The period between the onset of the increment of EMG activity and the initiation of the utterance (carrier sentence ii) was between 160 and 180 ms in both modes of whispering.

As shown in figure 8, the amplitude of EMG for stage whispering was almost two times higher than that for soft whispering. But there was no particular difference in TP activities between the voiced and voiceless pairs in whispering.

Discussion of TP Activity

As for TP activity during speech, we could see a higher activity in whispering than in ordinary speech. Furthermore, TP was stronger in stage whispering than in soft whispering. These results would seem to indicate that the contraction of TP is one of the contributing factors in the constriction of the supralaryngeal structures whispering. Being different from PCA, TP did not show any apparent segmental pattern, probably because, in this study, the vowels in the test words were all front vowels which require little activity from the inferior constrictor [14].

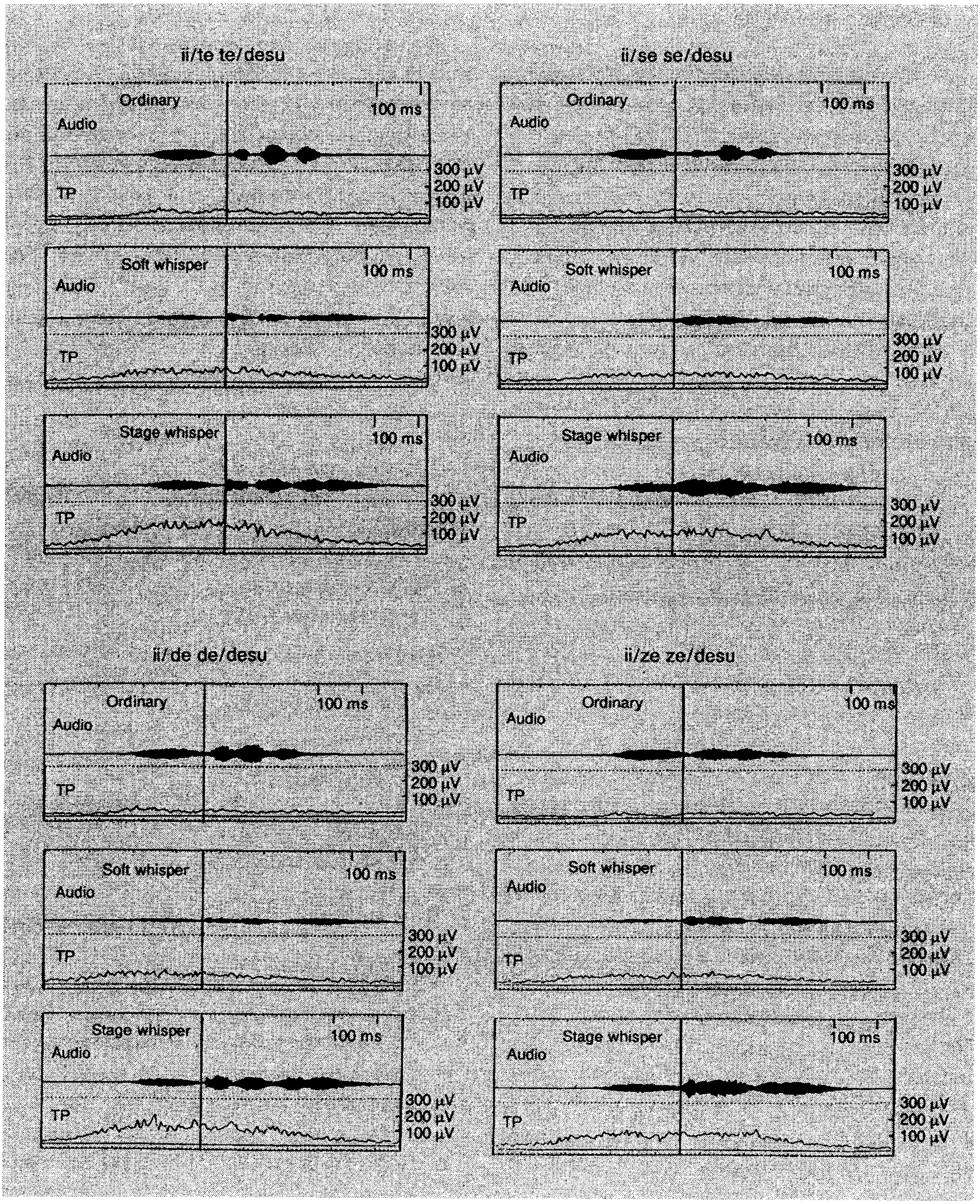

Fig. 8. TP activity.

General Discussion

Whispering has been defined as an 'aphonic laryngeal gesture'. From this point of view, several studies have been conducted to describe the laryngeal gesture during whispering, mainly using fiberscopes [2]. These studies have concluded that during whispering, the glottis is kept open to prevent vocal fold vibration, and that the supraglottal structures are constricted to reduce the transglottal pressure.

According to our results, we have suggested that at least two different adjustments should be made. The first is at the glottal level and the second is at the supraglottal level.

The Role of PCA in Whispering

At the glottal level, the PCA has the most important role for the glottal adjustment in whispering. In mammals, including humans, the primary function of the PCA is to open the glottis for inhalation. In ordinary speech, the PCA should be suppressed throughout an utterance, except in voiceless segments. As a result of our study of whispering, it was suggested that the PCA also adjusts the glottal movements during whispering. In whispering, the PCA is activated resulting in a different laryngeal gesture (whispering mode) even for those segments which are voiced in ordinary speech. Thus, the role of the PCA in whispering could be summarized as follows. The PCA keeps the glottis open to prevent vocal fold vibration and maintain the whispering mode. Its activity remains high above the baseline activity throughout the whispering mode. During whispering, PCA activity showed segmental patterns which corresponded to each phoneme. In other words, after it changed to whispering mode, it remained active for voiceless consonants compared with voiced consonants. This suggests that the PCA may contribute to the distinction between voiced and voiceless consonants during whispering.

The Role of TP in Whispering

According to the observations of Weitzman et al. [2] and Solomon et al. [3] the degree of constriction in the supralaryngeal structures for stage whispering is even more radical than that found in soft whispering. In the present fiberoptic study, the area of the supralaryngeal constrictions was much tighter for whispering than for ordinary speech. The present EMG study showed that TP activity was higher when the supraglottal constriction was tighter. Thus, it is most likely that TP activity contributes to the supraglottic constriction.

The Relation between PCA and TP

Although in general these two muscles have different roles, they become active at the same time and show similar activity patterns during whispering. There seems to be a positive relation between TP activity and supralaryngeal constriction, and there should also be a relationship between glottal adjustment and supralaryngeal adjustment.

The adjustments of PCA and TP activity for whispering seem to be compatible with respect to the increment rate, baseline activity, onset, offset and trajectory of general activity, except that there is no difference in segmental patterns in TP. Thus, it can be assumed that there is a coordination between PCA and TP.

The higher baseline activity of PCA may contribute to changing the speaking mode from ordinary speech to the whispering mode. The higher baseline activity of the TP may also contribute to changing the speaking mode from ordinary speech to the whispering mode, since it is activated almost at the onset of whispering. These simultaneous higher baseline activities in PCA and TP may be the result of a changed speaking mode for whispering from ordinary speech, and this particular condition may cause a different laryngeal gesture in the whispering mode. The increased activities of both muscles indicate that the speaking mode has changed from the ordinary speech mode to the whispering mode.

Whispering is not only an aphonic laryngeal action but also an action making a turbulent noise. For the aphonic gesture, it is clear that the glottis is kept open during whispering, whereas the supraglottal adjustment should contribute to the turbulent noise for whispering. In other words, the turbulent noise should be made between the glottis and the supraglottal constriction. This adjustment is made mainly by TP.

PCA and TP do not primarily relate to phonation. Their primary and primitive functions are related to the respiratory and swallowing control in all mammals. Humans use PCA and TP for speech as a result of animal evolution. It is also impossible for young infants to produce whispering. Thus, the function of PCA and TP for whispering may be regarded as an evidence of human evolution. There might be a function switch in our brain which enables the speaking mode to change from ordinary to whispering, using the activation of PCA and TP.

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