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Vocal Fold Vibration and The Speech Waveform in Diplophonia

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Diplophonia can be considered to be produced through quasi-periodic variations in the vocal fold vibration. Ward and Moore[1] have reported on the pattern of vocal fold vibration during the voluntary production of diplophonia. They found that the left and right vocal folds were vibrated at different frequencies in this condition. Hirano[2] et al have also reported an interesting case of unilateral recurrent nerve palsy in which they observed a difference in the vibratory frequency between the left and right vocal folds. However, in both of these reports, a detailed description on the relationship between the pattern of the vocal fold vibration and the speech waveform was not given.

In the present study, a simultaneous recording of the vocal fold vibration and the speech signal was performed on three patients with diplophonia using a high-speed digital imaging technique recently developed at our Institute. All three cases exhibited vocal fold vibration similar to that in the above two reports. Furthermore, by the use of the high-speed digital imaging technique, the observation of the relationship between the vocal fold vibration and the speech waveform could be performed quite easily. The present analysis revealed the specific nature of the cause of the quasi-periodic variations in the speech wave. In the following, the results of this analysis will be presented.

Method

Simultaneous recording of the vocal fold vibration and the speech signal was performed with three patients having diplophonia. The recordings were conducted using a high-speed digital image recording system developed by the present authors. The system consists of an obliquely-angled solid endoscope, an image sensor and a digital image memory. The glottal image obtained through the endoscope is focused on the image sensor. The video signal from the sensor is digitized through a high-speed A/D converter and stored in the image memory. The stored data are then reproduced in a form of slow motion display. In order to realize a high frame rate for the recording of vocal fold vibrations, only a part of the picture elements in the image sensor is sampled. In the present experiment, the frame rate was 2000/second with the number of picture element at 100x36. The image memory was 1M byte which enabled storage of approximately 270 image frames.

All three cases examined in this study showed temporal variations in the pattern of their vocal fold vibrations and, correspondingly, in their glottal area waveform. In order to obtain clear information on the pattern of these temporal variations, a measure of glottal width was defined as follows, and its temporal course was displayed by the computer. Namely, in the glottal images, the area where the brightness was darker than a selected threshold was taken as the glottal opening. Then, a horizontal scan line at an appropriate position on the glottal opening was selected and, on this scan line, the width of the glottal opening was measured. Figure 1 shows an example of the computer display of the time sequence of this measure obtained from a normal vocal cord vibration.

Results

Case 1 Female aged 50. Unilateral paralysis of therecurrent laryngeal nerve (Figure 2)

The speech signal shows quasi-periodic variations in the amplitude and waveform which repeat at about 11 vibratory cycles. Display of the time sequence of the glottal width measure reveals that the left and the right vocal folds vibrate apparently at different frequencies and that the phase difference between the movements of the two vocal folds varies with time. At around A in the figure, the movements of the vocal folds are nearly in phase, and the glottis shows a period of complete closure. At around cycle No.6 indicated in the figure, the phase difference is larger, and the glottal closure becomes incomplete. At cycle No.9, the phase difference is nearly 180 degrees, and the left and right vocal folds move almost in parallel.

In this cycle, the inward movement of the right vocal fold is incomplete, and during the period of both cycle No.10, the right vocal fold stays at an outer position. Then cycle No.11 of the right vocal fold starts with a slight outward movement followed by a clear closing movement which is nearly synchronous with that of the left vocal fold. At this point, the left and right vocal folds resume synchrony, and the vibration shows a period of glottal closure. Thus, in this case, the 10th vibratory cycle of the right vocal fold almost disappears and is apparently fused with the preceding and following cycles. This process cancels and resets the phase difference between both vocal folds which is brought about through a difference in the vibratory frequencies of the vocal folds. Between the points A and A' in the figure, the left vocal fold has 11 vibratory cycles and the right vocal fold has 10 vibratory cycles plus one additional incomplete vibration.

The temporal change in the pattern of the vocal fold vibration described above explains the pattern of the temporal change in the speech waveform. At around A where the vocal fold vibration exhibits complete closure, there is a strong excitation pattern in the speech waveform. The amplitude is large, and the formant oscillations are very clear. When the glottal closure become incomplete, the excitation gets weak. The waveform is noisy and its amplitude becomes smaller.

Case 2 Female aged 42. Unilateral paralysis ofthe external branch of the superior laryngeal nerve

The speech signal shows the temporal variation in a period of 6 cycles. This case also shows a difference in the vibratory frequencies between the left and right vocal folds. The degree of phase difference also varies with time. At around cycle No.1, the phase difference is small, and there is glottal closure. However, at around cycle No.4, the phase difference is nearly 180 degrees, and there is no glottal closure. Then, in cycle No.5, the inward movement of the right vocal fold appears as if it is truncated, and in cycle No.6, the left and right vocal folds resume synchrony. In this case, phase resetting is brought about through a shortening of vibratory cycle No.5 of the left vocal fold. Both vocal folds show 6 vibratory cycles between A and A'. There are corresponding variations in the speech waveform which are similar to those in Case 1.

Case 3 Female aged 54. Unilateral paralysis of the external branch of the superior laryngeal nerve.

Temporal variation in the speech waveform occurs in a period of 7 cycles. In this case, the difference between the natural frequencies of the left and right vocal folds appears to be larger than in the other cases. This difference can be discerned as differences in the velocity of the movement and the timing of the maximum outer displacement even at around point A, where the movement of the two vocal folds are most in phase. Between points A and A', the left and the right vocal folds show 6 and 7 vibratory cycles, respectively. At point A, the vibration shows glottal closure, and in later cycles, glottal closure become incomplete. There is a corresponding variation in the waveform, which is essentially similar to that in the preceding two cases.

Concluding remarks

All three cases studied(unilateral paralysis of the recurrent nerve(1) and the external branch of the superior laryngeal nerve(2)) showed a difference in the vibratory frequency between the left and right vocal folds. During successive cycles, the phase difference became progressively larger. At a point where it exceeded a certain threshold, the phase difference was reset and the vocal cord movements resumed synchrony. This pattern is in good agreement with that described by Moore[7]. In other words, when the movements of the vocal cords are in phase, glottal closure is complete and the excitation pattern in the speech waveform is strong, whereas when the movements are out of phase, glottal closure is incomplete and the excitation pattern is weak. This quasi-periodic variation in speech waveform appears to be related to the diplophonic voice quality of our cases.

Although the present paper is a case report based on only three subjects, it is still noteworthy that all the three cases have common characteristics in the temporal variation of the vibratory pattern of their vocal folds, that is, an alternation between vibrations with and without glottal closure. From an acoustical point of view, the presence or absence of glottal closure brings about a large difference in the generated speech waves. The present subjects were selected for high-speed laryngeal imaging because they had diplophonia with perceptually prominent low frequency modulations in the speech wave. Thus, it might be the case that such voices result, to a large extent, from the kind of vibratory pattern observed in the present study.

Concerning the physiological conditions underlying irregular vocal fold vibration, there are a series of papers by Tanabe, Isshiki et al[3], and Ishizaka et al[4]. These authors have investigated the effect of asymmetrical vocal fold tension on the pattern of their vibration through high-speed motion pictures of the excised larynx as well as through computer simulations based on Ishizaka-Flangan's two-mass model[5]. They have reported that the pattern of abnormal vibration varies depending on the glottal area at rest, and that irregular vibrations are brought about only when the glottal area at rest is set at some intermediate value.

Of relation to our experimental results, Tanabe[6] noted the interesting fact that, in the excised larynx experiment, a simple tension imbalance did not cause a difference in the vibratory frequency between the vocal folds. He noted that an additional perturbation of the laryngeal conditions such as a difference in the level of the vocal folds was necessary to bring about the frequency difference. However, the results of the computer simulation in Ishizaka et al's paper[4] appear to show that a tension imbalance can cause a frequency difference under certain conditions of the glottal area at rest and the subglottal pressure. Thus, another possibility is that the difference in the vibratory frequency between the vocal folds emerges only within a very narrow range of physical/physiological conditions of the larynx which might be too difficult to manipulate experimentally. In fact, as is pointed out in the above papers, the vibratory frequencies of the left and right vocal folds tend to be kept the same when the glottal area at rest is narrow and sufficient glottal closure is formed during vibration even when there is a considerable difference in the inherent natural frequencies, presumably due to the coupling between the movements of the vocal folds through mechanical contact. One of the necessary conditions for a frequency difference to be brought about is , as stated above, that the glottal area at rest has an intermediate value. Such a condition may correspond to a slight contact of the vocal folds during the closure period, and a small perturbation in the vibratory pattern may easily cause incomplete glottal closure. Thus, it can be expected that the frequency difference between the vocal folds and the temporal alternation between the vibratory patterns with and without a closure period are concomitant results originating from a given physical/physiological condition.

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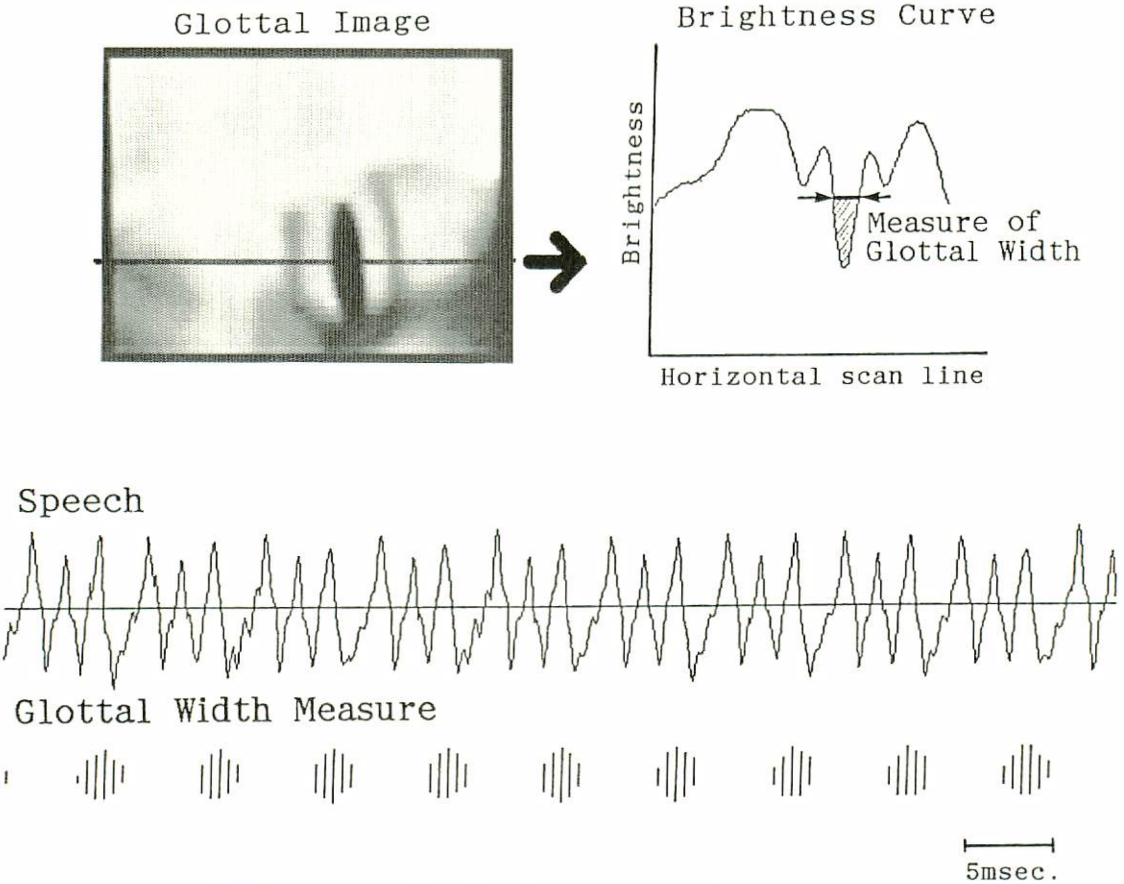

Fig.1 An example of the time sequence of the glottal width measure obtained for the normal vocal fold vibration.

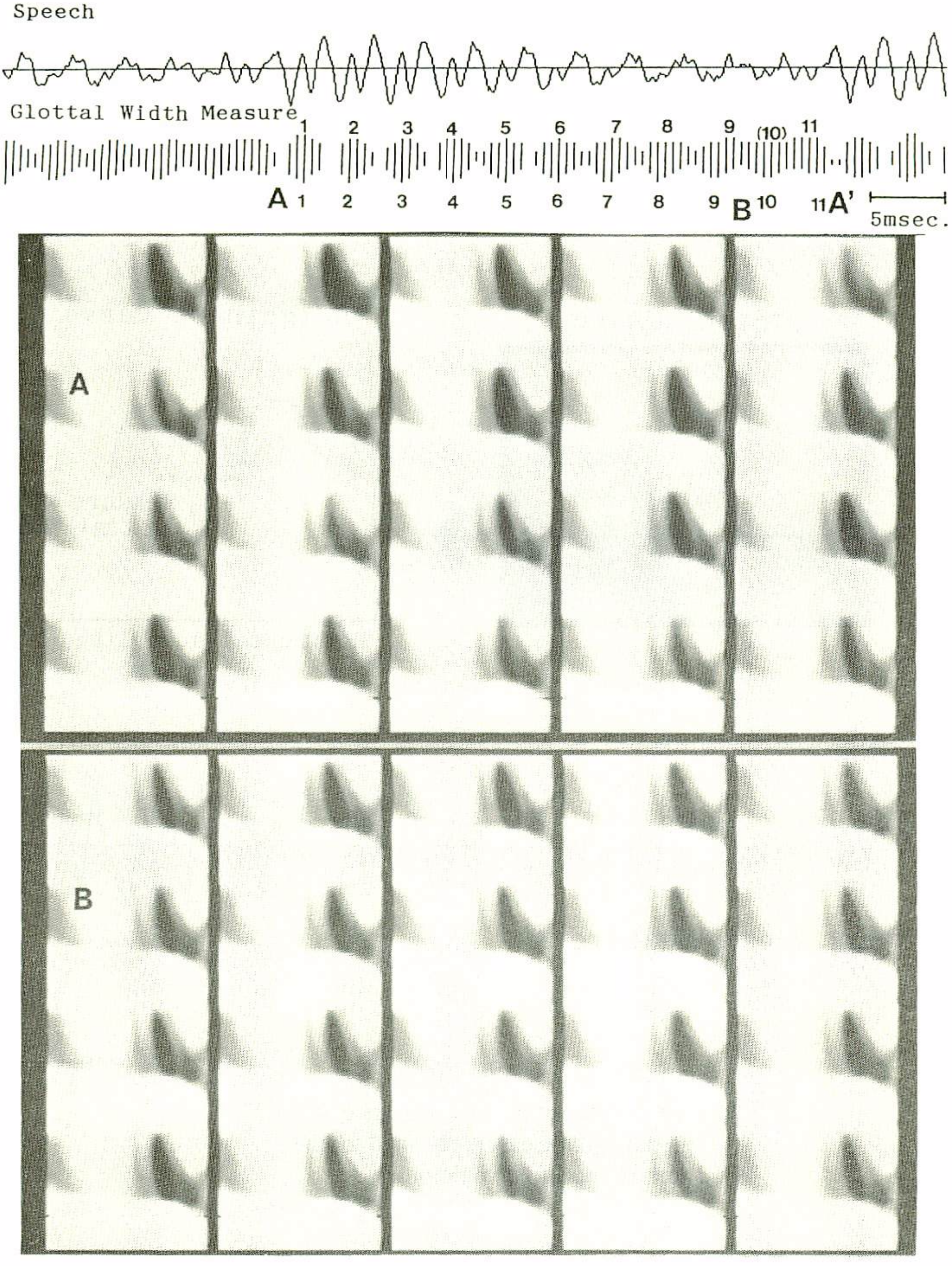

Fig.2 Case 1. Unilateral paralysis of the recurrent nerve.

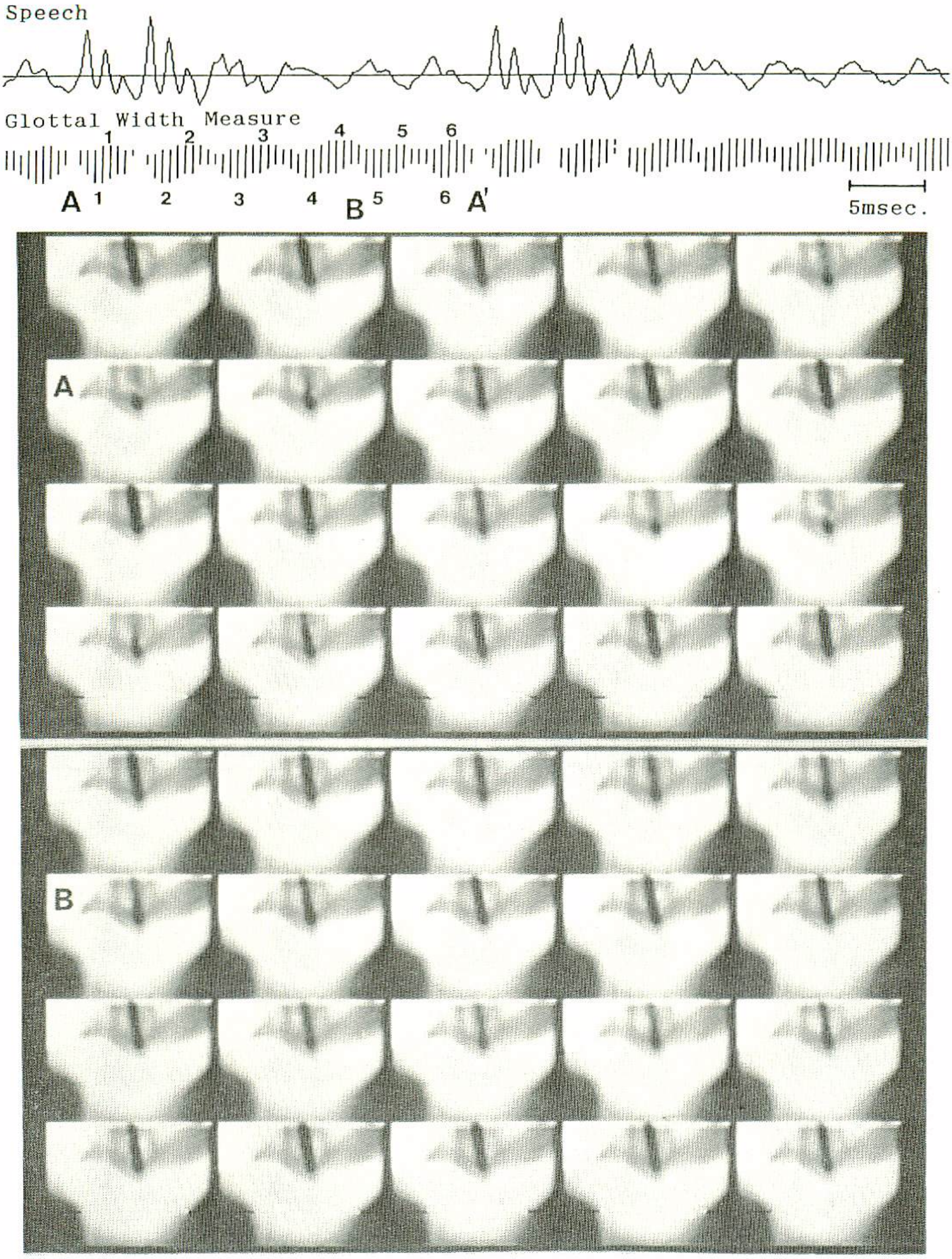

Fig.3 Case 2. Unilateral paralysis of the external branch of the superior laryngeal nerve.

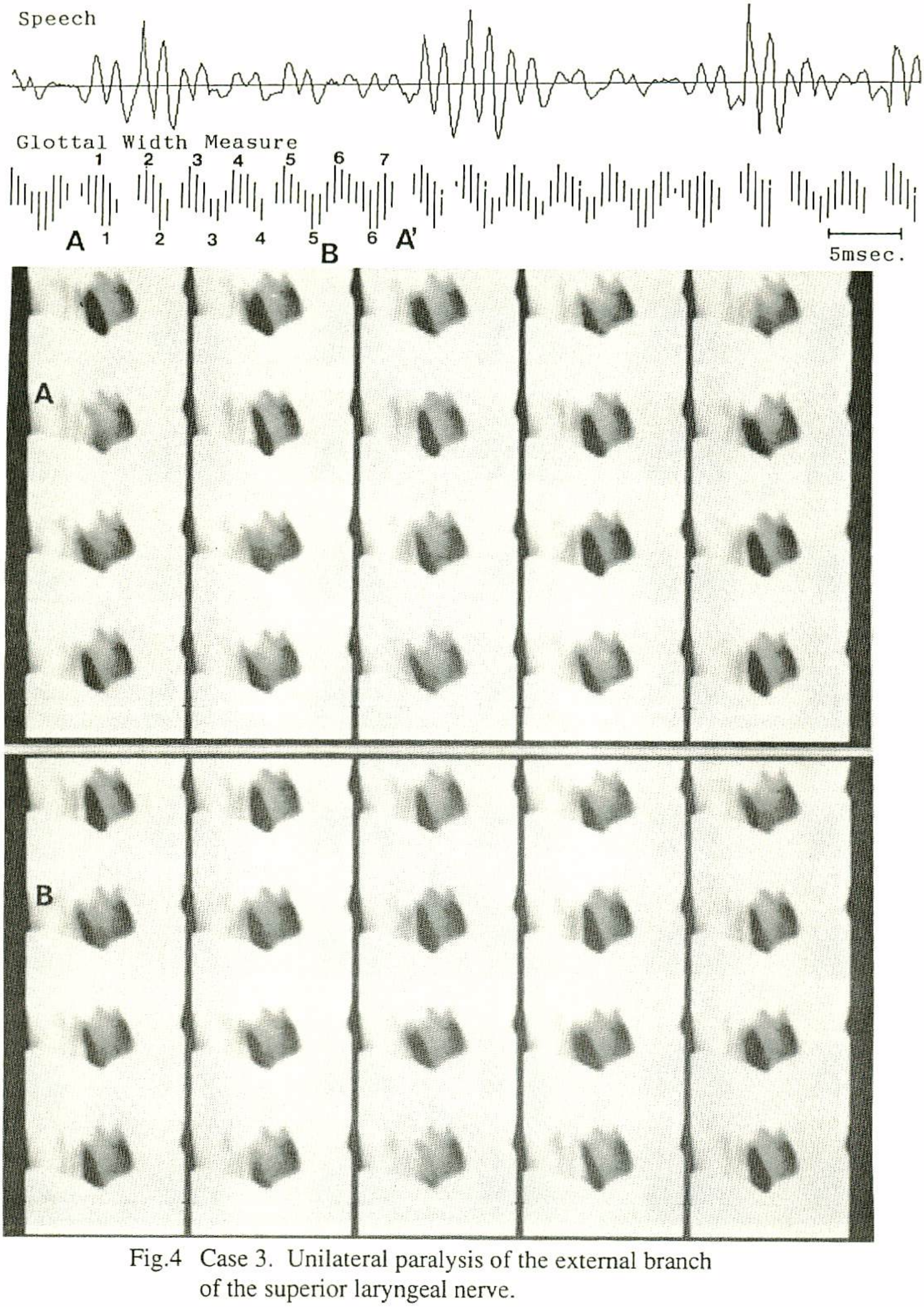

Fig.4 Case 3. Unilateral paralysis of the external branch of the superior laryngeal nerve.