Yonago Acta medica 2016;59:241–247

Patient Report

Analysis of Direct Simultaneous Measurement of Glottal Airflow Velocity, Subglottal Pressure, and High-Speed Imaging Using Flexible Transnasal Endoscope in a Human Subject

Hideyuki Kataoka,*† Shiro Arii,‡ Takahiro Fukuhara,† Kazunori Fujiwara,† Yasuomi Kunimoto,† Kensaku Hasegawa§ and Hiromi Takeuchi†

**Department of Adult and Elderly Nursing, School of Health Science, Tottori University Faculty of Medicine, Yonago 683-8503, Japan, †Division of Otolaryngology, Head and Neck Surgery, Department of Medicine of Sensory and Motor Organs, School of Medicine, Tottori University Faculty of Medicine, Yonago 683-8503, Japan, ‡Department of Information and Knowledge Engineering, Graduate School of Engineering, Tottori University, Tottori 680-8550, Japan and §Department of Otolaryngology-Head and Neck Surgery, Nippon Medical School Chiba Hokusoh Hospital, Inzai 270-1694, Japan*

ABSTRACT

It is difficult to directly observe glottal airflow velocity just above the glottis due to sensor size requirements and limited accessibility. We developed a miniature hot-wire probe and flexible fiberscopic high-speed imaging system for human examinations. Simultaneous direct measurement of glottal airflow velocity, subglottal pressure, and vocal fold vibration was achieved in a patient who was treated with a T-tube for tracheal stenosis. Airflow velocity changes at the anterior midline of the vocal folds were synchronized with subglottal pressure changes during each phonation cycle. The velocity at the anterior midline of the vocal folds showed a rhythmic pattern of sharp, high peaks. The result of fast Fourier transform analysis indicated that glottal velocity at the anterior midline of the vocal folds had abundant high-frequency components that were not affected by resonance of the vocal tract. Airflow velocity was variable and diminished except at the anterior midline of the vocal folds.

Key words glottal velocity; high-speed imaging; subglottal pressure; transnasal endoscope

Laryngeal aerodynamic parameters represent valuable information about the mechanical characteristics of human phonation. Simultaneous analysis of multiple parameters is important to evaluate the relationships between glottal flow, subglottal pressure, and vocal fold vibration.[1] Alipour et al. reported that it is conceivable that measuring airflow velocity at the laryngeal level in humans will be feasible in the future when accessibility and sensor size requirements are met.[2] Currently, studying the human vocal folds is significantly complicated by the fact that their movements are difficult to observe directly. Thus computer simulation models[3] and experiments with excised canine larynges[4, 5] can be powerful tools in lieu of direct in vivo human study.

To the knowledge of the authors, no studies have combined measures of subglottal pressure and glottal airflow velocity with simultaneous high-speed recording of vocal fold movements in human phonation. Vocal fold movements are likely to have an impact on the relationship between subglottal pressure and glottal airflow velocity. Such laryngeal aerodynamic studies are necessary for a basic understanding of the mechanics of phonation. We developed an extremely small, flexible hot-wire probe that is inserted into a flexible transnasal endoscope.[6] Glottal velocities were measured in a single subject after expansion of subglottic stenosis and before stomal closure. We demonstrated the realistic evaluation of glottal velocity in a human in different phases of the phonation cycle. Subglottal pressure and glottal velocity were recorded concurrently with the observation of vocal fold vibrations using a high-speed imaging system.

PATIENT REPORT

Patient

A 53-year-old man was treated with a silicone T-tube for tracheal stenosis. He suffered from life-threatening heat stroke on a very hot summer day and was therefore intubated. After he recovered from heat stroke–induced brain damage, he was referred to Tottori University Hospital for the treatment of post intubation tracheal stenosis. We removed endotracheal granulation and scarred tissue using an XPS microdebrider (Medtronic Xomed, Jacksonville, FL) and a silicone T-tube stent was placed for tracheal expansion in the area of tracheal stenosis. The patient was evaluated 3 months after the expansion. Endoscopic evaluation found that vocal focal fold movements were normal and endotracheal stenosis was thought to be cured. He provided informed consent using a procedure approved by the ethics committee of

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Corresponding author: Hideyuki Kataoka, MD, PhD
hkataoka@med.tottori-u.ac.jp
Received 2016 May 30
Accepted 2016 June 20
Abbreviation: FFT, fast Fourier transform

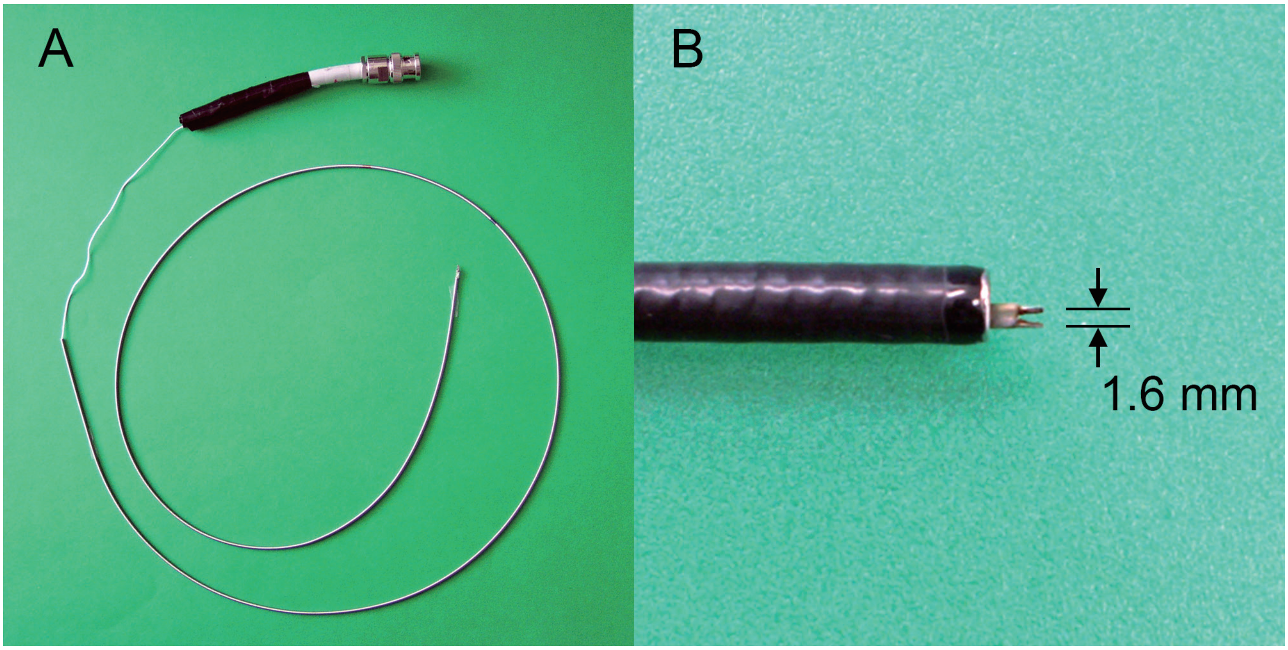

Fig. 1. A miniature hot-wire probe. **A**: A hot-wire tip was connected to a coaxial cable, which passed through the wire commonly used for clinical biopsy. **B**: The hot-wire tip was inserted into the channel of the flexible transnasal endoscope. The tip of the probe had an active length of 1.6 mm.

Tottori University (Record Number 2614). The examination was performed a few days before the operation of the T-tube removal and stomal closure.

Velocity measurement system

Glottal airflow velocity was measured with a miniature hot-wire anemometer that was attached to the tip of the wire commonly used for clinical biopsy (Fig. 1A). The hot-wire tip was inserted into the channel of a flexible transnasal endoscope ENF Type3 (Olympus, Tokyo, Japan) (Fig. 1B). Calibration curves were obtained for all hot-wire probes. The high-speed camera system was run at a frame rate of 1000 images per second with an image resolution of 512 × 512 pixels. In previous articles, we described a method for calibrating the hot-wire probe and high-speed recording system.[6] A flexible transnasal endoscope was inserted into the nose and the sensor probe remained inside the channel until it crossed over the epiglottis. The sensor probe then protruded from the endoscope channel and the position of the tip was carefully checked on a monitor. Glottal airflow velocity was measured at different positions as the probe approached the vocal folds.

Pressure measurement system

In order to obtain the waveform of the pressure below the vocal folds, pressure recording should be performed in the trachea. A pressure transducer was placed inside the silicone T-tube. A schematic diagram is shown in Fig. 2.

This procedure had a barely obvious influence on phonation, as normal spontaneous phonation was possible even with the T-tube in place because tracheal stenosis had been fully treated on the day of the examination. The pressure transducer was placed in the subject’s trachea about half an hour in advance; this minimized temperature and moisture differences between the transducer and the environment and therefore increased the accuracy of detecting pressure changes.

Data analysis

Transnasal fiberscopic examination was performed to enable observation of vocal fold vibrations. The subject was asked to produce steady phonation of the vowel /e/ within the modal register and in a comfortable manner.

The signal from the pressure converter was input to a control unit (TCB-500, Millar, Houston, TX), and the output from the control unit was displayed on an oscilloscope (SS -7602, Iwatsu, Tokyo, Japan) and synchronized with the glottal velocity measurement results using a 4-track, 16-bit analog to digital conversion board (CBI-320416, Interface Corporation, Hiroshima, Japan) in a personal computer.

The glottal velocity was measured by means of the hot-wire probe while the patient maintained continuous phonation of /e/ in a comfortable manner. The tip of the

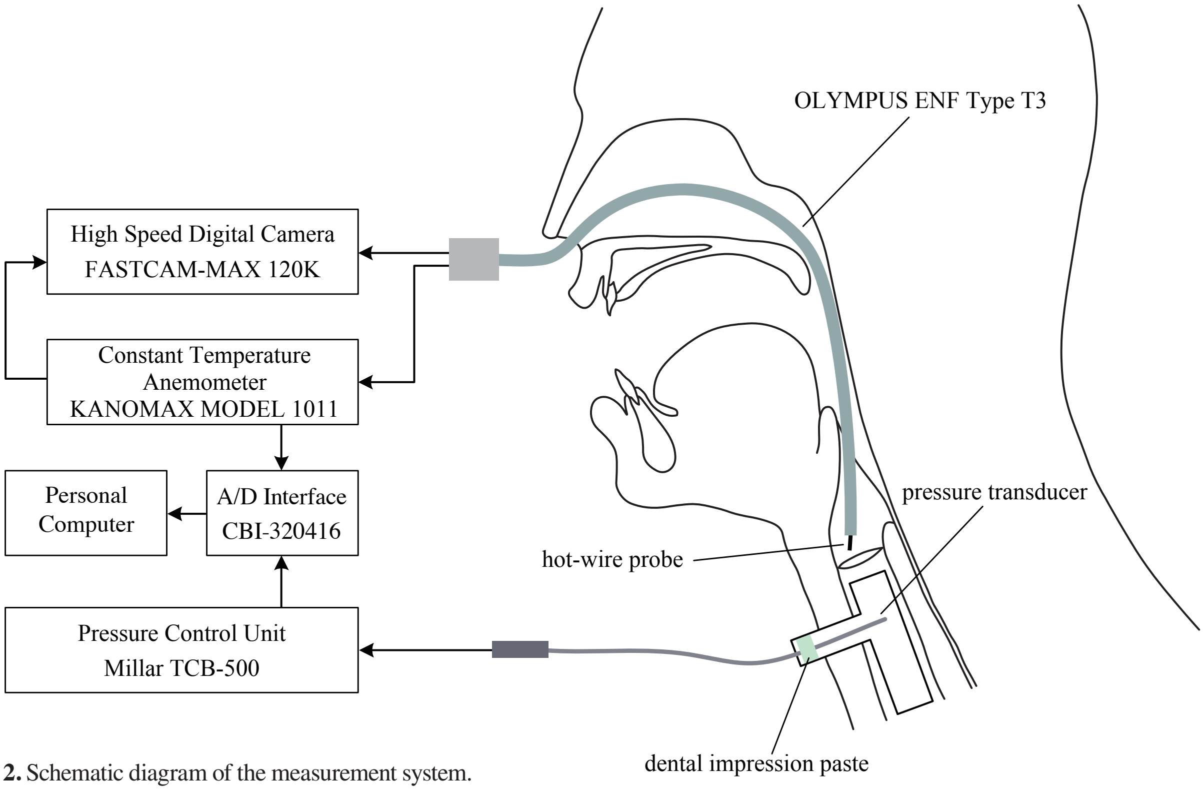

Fig. 2. Schematic diagram of the measurement system.

probe was gradually advanced toward the vocal folds during a single sustained vowel sound, then gradually slid over the vocal fold surface to the false vocal fold surface.

Figure 3 shows examples of airflow velocity at different sensor positions; inside the upper edge of the epiglottis (about 20 mm above the glottis) in the top graph A, at the anterior midline of the vocal folds (about 10 mm above the glottis) in the second graph B, and at the lateral shift on the false vocal folds in the third graph C. In graphs A and C, the airflow velocity fluctuates irregularly with no discernible peaks, and is diminished overall. In graph B, the velocity at the anterior midline of the vocal folds shows a rhythmic pattern of sharp, high peaks.

Figure 4 shows subglottal pressure (dotted line) and airflow velocity (solid line) measured at the anterior midline about 10 mm above the glottis. Maximum airflow velocity higher than 30 m/s was found at the anterior midline of the vocal folds. The airflow velocity showed sharp fluctuations corresponding with the phonation cycle. Subglottal pressure was measured relative to atmospheric pressure, and thus 0 kPa in Fig. 4 is equivalent to atmospheric pressure. The fundamental frequency was almost 155 Hz. Glottal velocity changes at the anterior midline of the vocal folds were synchronized with subglottal pressure changes during each phonation cycle. Peak glottal airflow velocities seemed to occur slightly earlier than peak subglottal pressures.

The glottal airflow velocity at the anterior midline of the vocal folds was analyzed by fast Fourier transform (FFT) algorithm (Fig. 5). The waveform had abundant high-frequency components, but otherwise did not demonstrate the typical amplitude reduction of the consecutive harmonic components throughout the tract. These results suggest that the glottal airflow velocity at the anterior midline just above the glottis was not affected by vocal tract resonance filters.

Figure 6 shows a detailed analysis of the vibration during a single phonation cycle, and illustrates eight sequential high-speed images during the open and closing phases of the vocal folds. The upper portion of the figure shows subglottal pressure (dotted line) and airflow velocity (solid line) measured at the anterior midline of the vocal folds. The lower portion shows high-speed images captured at 1000 frames per second during the phonation cycle phase, and illustrations of vocal fold movements at each downward-pointing arrow on the solid line indicating airflow velocity.

The highest subglottal pressure was almost 3 kPa (between phases 4 and 5), and the maximum glottal velocity profiles were highest during the late closing phase (phase 4). Maximum velocities occurred slightly earlier than maximum subglottal pressures.

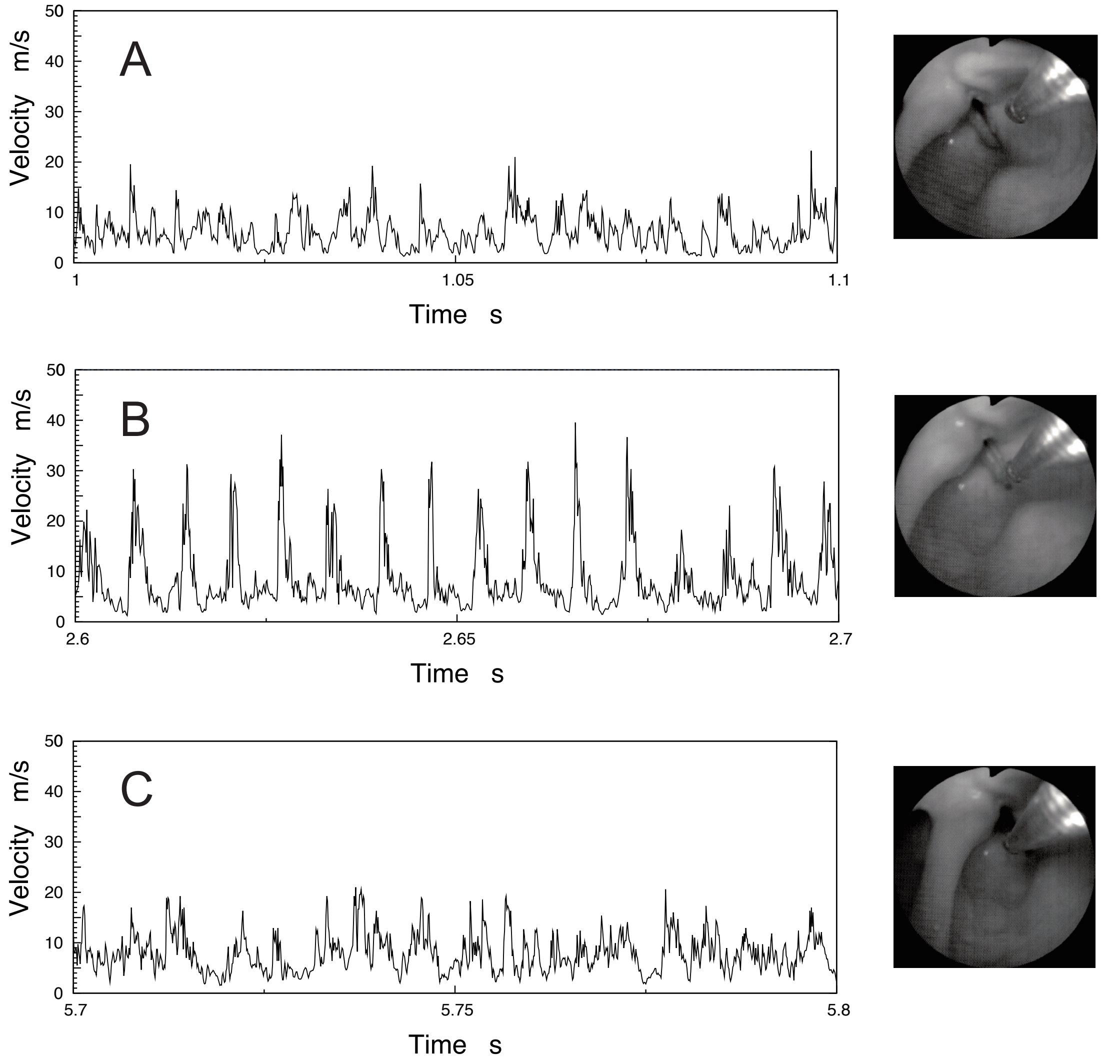

Fig. 3. Airflow velocity recorded at different positions. **A**: inside the upper edge of the epiglottis. **B**: at the anterior midline of the vocal folds. **C**: lateral to the false vocal folds.

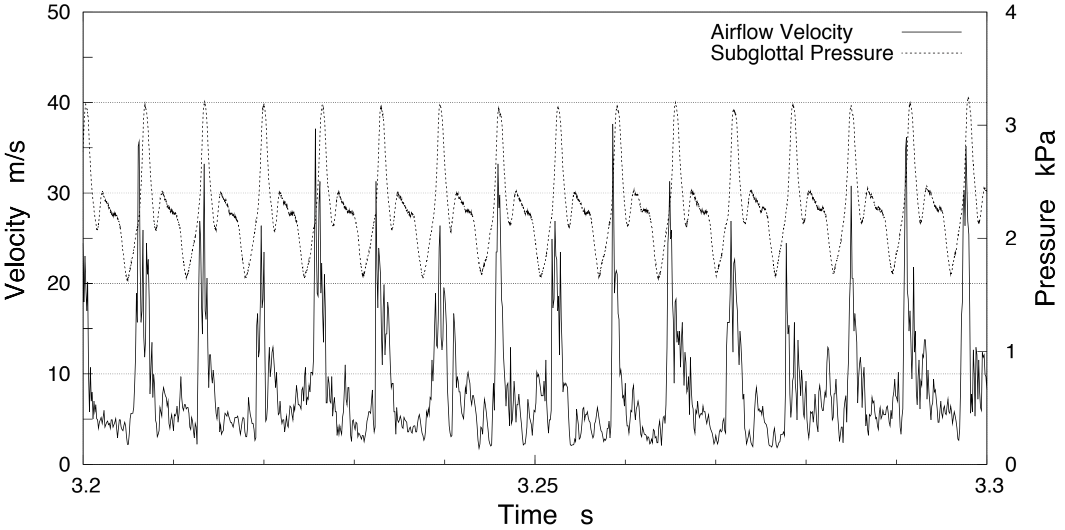

Fig. 4. Typical subglottal pressure and glottal airflow velocity signal recordings at the anterior midline of the vocal folds.

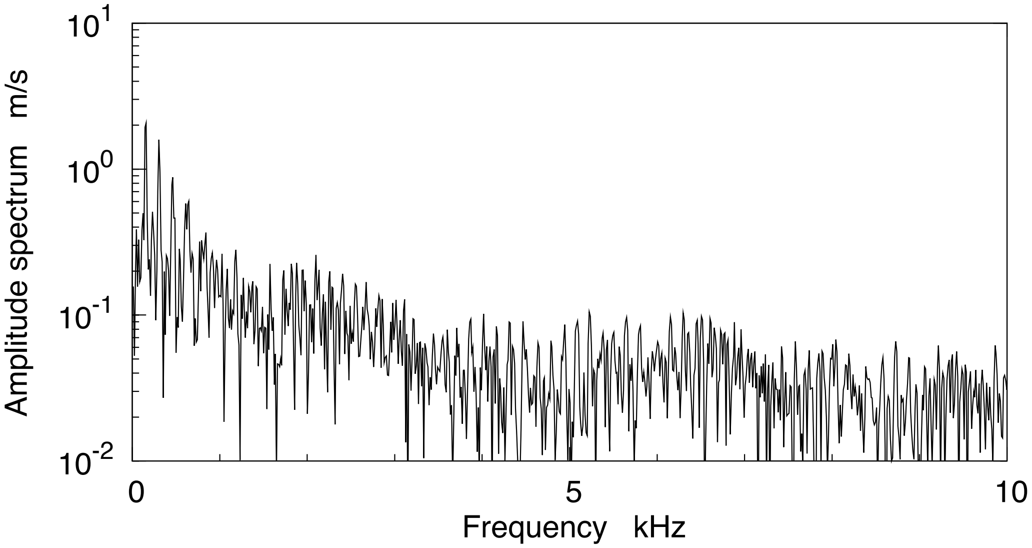

Fig. 5. FFT amplitude spectrum of glottal airflow velocity at the anterior midline of the vocal folds. FFT, fast Fourier transform.

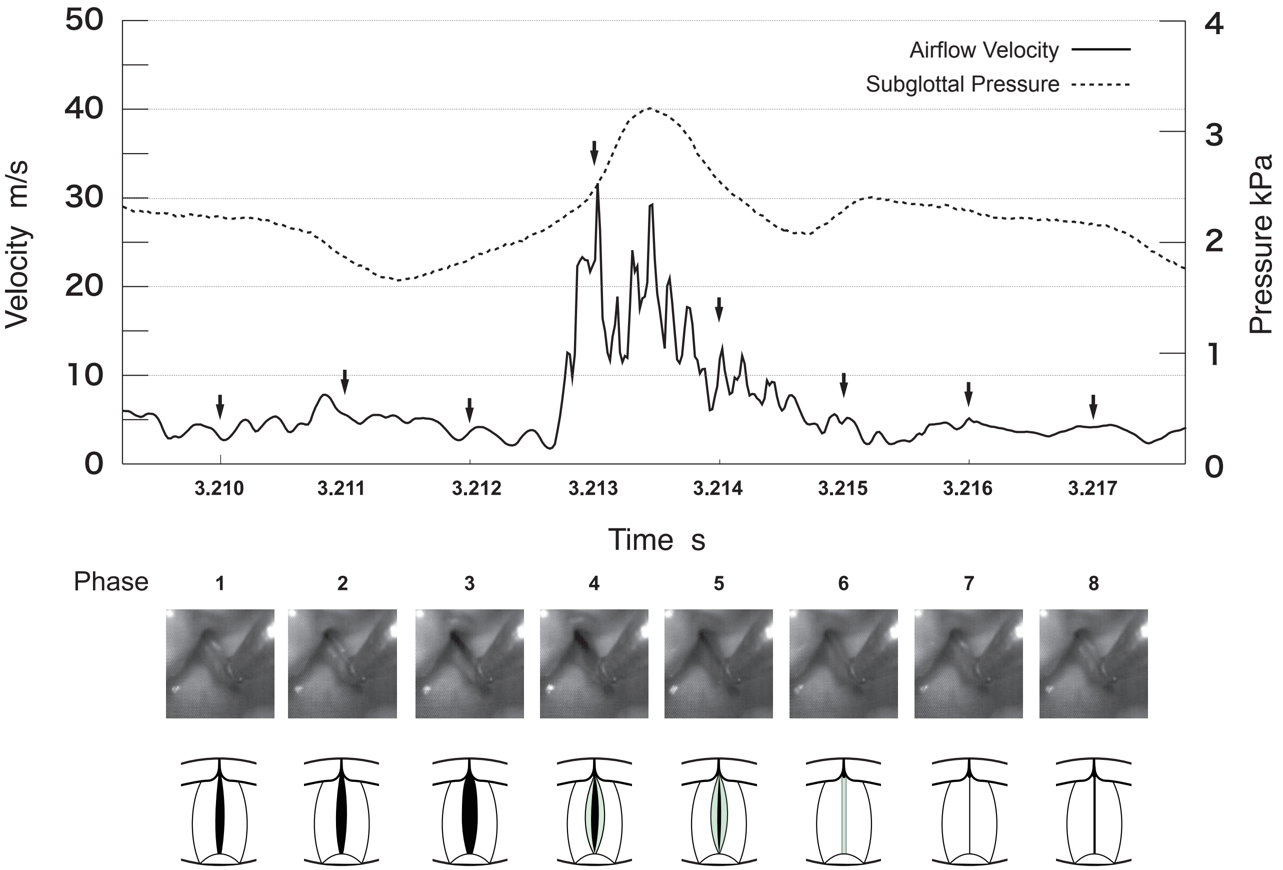

Fig. 6. The correlations among vocal fold movement, glottal airflow velocity, and subglottal pressure. Dotted line: subglottal pressure; solid line: glottal airflow velocity measured at the midline immediately above the glottis. The lower photographs and illustrations show the phases of the phonation cycle at each downward-pointing arrow on the solid line (glottal airflow velocity).

DISCUSSION

In this report we present an evaluation of glottal airflow velocity above the glottis in a single subject who had undergone expansion for subglottal stenosis and was treated with a T-tube. The subject's phonation was performed in natural manner during high-speed image recording performed via insertion of a flexible transnasal endoscope.

The flexible transnasal endoscope appears to offer better potential than the rigid transoral endoscope in terms of simultaneously acquiring additional vocal function measures, because the insertion path of the transnasal endoscope results in less interference with the normal function of the vocal tract during voice production. In a transoral rigid telescope study, phonation was unnatural due to the common practice of protruding and holding the tongue outside of the mouth during the examination.[7]

Hot-wire anemometer measurements have become accepted for use in phonation studies.[8, 9] Experimental characterization of glottal jet velocity measurements above the glottis has been reported in canine models. Velocities obtained from hot-wire anemometry during phonation have been described in the in vivo canine larynx[10, 11] and the excised canine larynx.[2] Teager[12] reported the first direct flow measurements of the vocal tract using a hot-wire anemometer, but the probe was inserted through the mouth and positioned near the tongue and below the hard palate.

In this report we measured glottal airflow velocity above the glottis using a miniature hot-wire probe that was advanced as closely as possible to the vocal folds. A detailed analysis of the vocal fold vibration of the phonation cycle showed that glottal airflow velocity was maximum just before closure of the vocal folds, and subglottal pressure substantially increased at the moment of closure of the lower edges of the vocal folds. The amplitude of the velocity fluctuated sharply.

Several reports have suggested that airflow through the vocal folds may produce additional sound sources due to the rotational motion of the flow.[13–15] Khosla et al.[16] suggested that intraglottal vortices, occurring during the latter phase of vocal fold closing, play an important role in rapid vocal fold closing and flow reduction. Triep et al.[17] constructed a mechanical glottal cam model that simulated glottal motion with silicone membranes, and visualized the fluid dynamics that are relevant for glottal jet flow.

In our report, airflow velocity was lower and more variable lateral to the midline than at the midline itself. It is possible that variable airflow indicates the formation of vortices. Our report also found that glottal airflow velocity may consist of high frequency components and may include vortices around the vocal fold vibration. Our results do not contradict those of a variety of canine larynx experiments or computer models. The laryngeal aerodynamic parameters discussed in this study showed that direct measurements of subglottal pressure and glottal airflow velocity above the glottis, with simultaneous recording of vocal fold movement, are feasible and contribute to understanding the energy source of voice production.

The authors declare no conflicts of interest.

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