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Influence of subglottic stenosis on the flow-induced vibration of a computational vocal fold model

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ABSTRACT

The effect of subglottic stenosis on vocal fold vibration is investigated. An idealized stenosis is defined, parameterized, and incorporated into a two-dimensional, fully coupled finite element model of the vocal folds and laryngeal airway. Flow-induced responses of the vocal fold model to varying severities of stenosis are compared. The model vibration was not appreciably affected by stenosis severities of up to 60% occlusion. Model vibration was altered by stenosis severities of 90% or greater, evidenced by decreased superior model displacement, glottal width amplitude, and flow rate amplitude. Predictions of vibration frequency and maximum flow declination rate were also altered by high stenosis severities. The observed changes became more pronounced with increasing stenosis severity and inlet pressure, and the trends correlated well with flow resistance calculations. Flow visualization was used to characterize subglottal flow patterns in the space between the stenosis and the vocal folds. Underlying mechanisms for the observed changes, possible implications for human voice production, and suggestions for future work are discussed.

1. Introduction

Subglottic stenosis (SGS) is a narrowing of the airway within the subglottal region of the larynx or upper trachea (see Fig. 1). In most patients it results from damage to the airway lumen caused by prolonged intubation and/or tracheotomy. It can also occur congenitally, as a result of external trauma, from disease, or idiopathically (George et al., 2005; Giudice et al., 2003; Herrington et al., 2006). Symptoms include respiratory problems such as dyspnea, stridor, and croup (Bailey et al., 2003; Lesperance and Zalzal, 1998; Poetker et al., 2006). It can also be associated with changes in voice quality, in which case it can present as hoarseness and/or dysphonia (Giudice et al., 2003; Poetker et al., 2006). Symptoms generally worsen as the severity (i.e., greater narrowing) of the stenosis increases.

The Myer–Cotton grading scale is used to classify SGS severity according to the percent occlusion of the airway (Grade I: 0–50% occlusion; Grade II: 51–70%; Grade III: 71–99%; Grade IV: 100%) (Myer et al., 1994). Lower grades (Grade I or mild Grade II) may require little to no treatment, but more severe cases require more prompt and extensive treatment. Initial treatment for such cases often involves tracheostomy (placement of a tracheal tube) in order to ease respiration, but when the airway is severely compromised, surgery is required. While simple operations can be performed for Grades II and III, Grades III and IV call for open reconstructive surgeries, with tracheal resection and partial cricotracheal resection being the most effective (Bailey et al., 2003; Herrington et al., 2006). These types of surgeries have been shown to affect voice quality (Smith et al., 1993; Smith et al., 2008).

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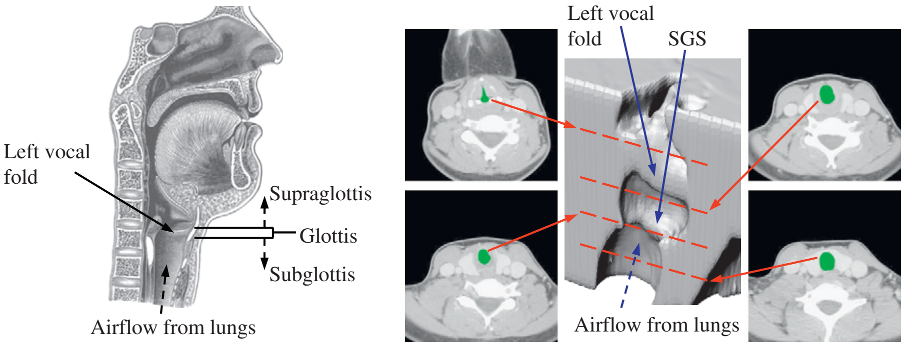

Fig. 1. *Left:* Sagittal view of the human larynx, including the vocal folds and subglottal, glottal, and supraglottal regions (adapted from *Gray's Anatomy of the Human Larynx*, www.bartleby.com, used with permission). *Right:* CT images at four different elevations of a patient with subglottic stenosis (SGS) and corresponding 3D reconstruction. In the CT images the airway is colored green. Red dashed lines overlaid on the 3D reconstruction denote approximate vertical location of each slice. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

Understandably, research related to SGS has focused primarily on treatments that will effectively obtain the goals of restoring airway patency and decannulation (tube removal). A subject less studied in relation to SGS, however, has been the management of laryngeal function, particularly the voice. A number of studies have considered voice quality due to SGS before surgery (Cotton, 1991; Zalzal, 1988; Zalzal et al., 1993), but the purpose of the assessments was for simple comparison with postoperative voice quality, and, therefore, no detailed qualitative or quantitative data about voice quality in the patients were reported. Ettema et al. (2006) sought to quantify voice quality in SGS patients through a perceptual voice analysis. According to their assessment, roughly 50% of their SGS patients had moderately to extremely affected voice quality. However, the majority of these patients had other negative risk factors besides SGS that would contribute to poor voice quality, including multiple stenoses, vocal fold impairment, and previous airway surgery. Thus, it is unknown whether effects on the voice were due to the subglottic stenosis or other factors. Furthermore, some patients with higher grade stenoses retained normal voice quality, suggesting that SGS may affect some voices and not others. Because of the uncertainty about the connection of SGS to voice quality, it is of interest to further study the subject.

While a few studies have focused on airway models with a subglottic stenosis, to the best of the authors' knowledge, none have explored the effect of SGS on vocal fold vibration. In three studies (Brouns et al., 2007; Cebral and Summers, 2004; Mihaescu et al., 2008) the airway with SGS was modeled using three-dimensional geometry from human image data sets. Computational simulations of respiratory airflow were performed. Brouns et al. (2007) parametrically varied the severity of the stenosis. However, these studies focused solely on the effects of SGS on respiration and did not include vocal fold vibration.

Other studies related to subglottal geometry have explored how subglottal shape influences vocal fold motion and other factors related to phonation. It was proposed by Li et al. (2006) that the pre-vibratory inferior vocal fold surface angle has little effect on the intraglottal pressure distributions that provide the driving force for vocal fold oscillation. A follow-up study was recently performed by Smith and Thomson (2012) which showed that inferior vocal fold surface angle does directly affect vocal fold motion. Specifically, it was concluded that changing the angle influenced vocal fold motion by altering vocal fold stiffness and net flow-solid energy transfer. Grisel et al. (2010) recently found that changes in the subglottal shape after medialization thyroplasty surgery can significantly increase turbulence through the glottis, which may cause an abnormal voice, breathiness, and chaotic vocal fold vibrations. They showed that turbulence can be reduced with medialization of the subglottis.

While these prior studies have provided insight into the influence of subglottal geometry on phonation, further exploration is needed to understand this interaction. In the present study, the influence of varying subglottal geometry due to SGS on vocal fold vibration was considered using a two-dimensional, fully coupled finite element model of the vocal folds and laryngeal airway. The model enabled identification of the effects of the stenosis itself, absent other contributing factors. Systematic changes to subglottal geometry were made by varying the severity of a parameterized subglottic stenosis.

2. Methods

2.1. Computational model

A computational model simulating two-dimensional laryngeal air flow and the resulting vocal fold flow-induced vibration was developed. A stenotic region was included in order to simulate an airway with SGS. The model was created and solved using ADINA (ADINA R&D, Inc., Watertown, MA), a commercial finite element software package which specializes in solving systems that involve fluid–structure interactions and which has been employed in previous studies