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Optical measurements of vocal fold tensile properties: Implications for phonatory mechanics

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ABSTRACT

In voice research, *in vitro* tensile stretch experiments of vocal fold tissues are commonly employed to determine the tissue biomechanical properties. In the standard stretch-release protocol, tissue deformation is computed from displacements applied to sutures inserted through the thyroid and arytenoid cartilages, with the cartilages assumed to be rigid. Here, a non-contact optical method was employed to determine the actual tissue deformation of vocal fold lamina propria specimens from three excised human larynges in uniaxial tensile tests. Specimen deformation was found to consist not only of deformation of the tissue itself, but also deformation of the cartilages, as well as suture alignment and tightening. Stress–stretch curves of a representative load cycle were characterized by an incompressible Ogden model. The initial longitudinal elastic modulus was found to be considerably higher if determined based on optical displacement measurements than typical values reported in the literature. The present findings could change the understanding of the mechanics underlying vocal fold vibration. Given the high longitudinal elastic modulus the lamina propria appeared to demonstrate a substantial level of anisotropy. Consequently, transverse shear could play a significant role in vocal fold vibration, and fundamental frequencies of phonation should be predicted by beam theories accounting for such effects.

1. Introduction

The importance of image-based deformation measurements of soft tissues in order to avoid local stress concentrations and local deformations has long been recognized (Yin et al., 1972; Lanir and Fung, 1974). Protocols in the cardiac biomechanics field routinely employ optical deformation measurements (Fronek et al., 1976). However, such an approach has not yet been applied in the characterization of vocal fold tissues. In our recent work, the digital image correlation method was applied to characterize tissue deformation at one time point in a tensile stretch-relaxation experiment (Kelleher et al., 2010). This study indicated that the applied tensile deformation was significantly larger than the deformation of the tissue itself. How such discrepancies might affect the mechanical characteristics of the tissue under a sequence of stretch cycles remains unknown. Therefore, we hypothesized that the true deformation of a vocal fold tissue specimen would differ from the deformation applied by the stretch-release apparatus; hence, the tissue biomechanical properties would be different from what has been reported in the past.

Biomechanical experiments of vocal fold tissues began by simply hanging weights on specimens and measuring the displacements visually (Kakita et al., 1981). This technique was unable to produce a stress–stretch curve accounting for nonlinearity and only order-of-magnitude estimations of the elastic modulus were obtained. A more precise *in vitro* experimental apparatus was developed using servo-motors to apply displacements to specimens held in a physiological solution (Perlman and Titze, 1988). Throughout the past 20 years, this method has been followed by many studies on various laryngeal tissues (Perlman et al., 1984; Alipour-Haghighi and Titze, 1985, 1987, 1991, 1999; Perlman and Titze, 1988; Perlman and Alipour-Haghighi, 1988; Alipour-Haghighi et al., 1989, 2011, Min et al., 1995; Zhang et al., 2006, 2007, 2009; Chan et al., 2007; Hunter and Titze, 2007; Riede et al., 2010).

In vivo indentation-type loading was applied by Berke and Smith (1992) and Tran et al. (1993). A force gage was brought into slight contact with the vocal fold; the recurrent laryngeal nerve was stimulated with electric current causing vocal fold adduction and deflecting the gage. From force-deflection data and known areas of contact, the elastic modulus was estimated. In a laryngeal

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