Journal of Biomechanics 44 (2011) 1936–1940

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Elasticity and stress relaxation of a very small vocal fold

Tobias Riede [a,*], Alexander York [b,c], Stephen Furst [b,c], Rolf Müller [d], Stefan Seelecke [b,c]

[a] Department of Biology and National Center for Voice and Speech, University of Utah, Salt Lake City, UT 84112, USA
[b] Department of Mechatronics, University of Saarland, Saarbrücken, Germany
[c] Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695-7910, USA
[d] Department of Mechanical Engineering, Virginia Tech, IALR, Danville, VA 24540, USA

ARTICLE INFO

Article history:
Accepted 19 April 2011

Keywords:
Larynx
Viscoelastic properties
Bioacoustics
Anisotropy

ABSTRACT

Across mammals many vocal sounds are produced by airflow induced vocal fold oscillation. We tested the hypothesis that stress–strain and stress-relaxation behavior of rat vocal folds can be used to predict the fundamental frequency range of the species' vocal repertoire. In a first approximation vocal fold oscillation has been modeled by the string model but it is not known whether this concept equally applies to large and small species. The shorter the vocal fold, the more the ideal string law may underestimate normal mode frequencies. To accommodate the very small size of the tissue specimen, a custom-built miniaturized tensile test apparatus was developed. Tissue properties of 6 male rat vocal folds were measured. Rat vocal folds demonstrated the typical linear stress–strain behavior in the low strain region and an exponential stress response at strains larger than about 40%. Approximating the rat's vocal fold oscillation with the string model suggests that fundamental frequencies up to about 6 kHz can be produced, which agrees with frequencies reported for audible rat vocalization. Individual differences and time-dependent changes in the tissue properties parallel findings in other species, and are interpreted as universal features of the laryngeal sound source.

1. Introduction

The voice of most terrestrial mammals is produced in the larynx by flow-induced vibrations of the vocal folds. The vibrations modulate the glottal airflow, thus creating pressure fluctuations which can be perceived as sound. The basic rate of vibrations is determining the fundamental frequency (F_0) of the perceived sound. F_0 depends on the driving lung pressure, the size/length of the vocal folds and, most importantly, on the tension of the vocal folds (Titze, 1988). Length changes of a vocal fold lead to dramatic changes in tension, which is the main mechanism to regulate F_0 in humans (Hollien and Moore, 1960; Hirano et al., 1969) and in non-human mammals (e.g. Brown et al., 2003). Vocal fold tissue responds differently to dorso-ventral elongation between individuals, sexes, as well as species (Haji, 1990; Min et al., 1995; Chan et al., 2007; Hunter and Titze, 2007; Zhang et al., 2009; Riede et al., 2010; Alipour et al., 2011) contributing to vocal differences at all three levels. Tensile data exist for a range of large and medium sized vocal folds (Min et al., 1995; Chan et al., 2007; Riede and Titze, 2008; Riede et al., 2010; Riede, 2010) but not for very small species. There are at least two reasons why elastic moduli of vocal fold tissue in small mammals could be very different from those found in larger mammals. First, boundary effects may affect bending properties in small vocal folds more than in large vocal folds (Titze and Hunter, 2007). The greater stiffness at the dorsal and ventral anchor point of a vocal fold may reduce effective length more dramatically if overall length is small. Second, a number of small mammals (rodents, primates, microchiropteran bats) produce sound in the ultrasonic range. If the string model would be applicable in the same way as suggested for the human vocal fold (Titze, 1988), huge elastic moduli would be necessary to achieve those large oscillation rates, and those moduli would have to be accommodated by specialized tissue designs. This study investigated the tensile properties in a very small vocal fold using a custom-built tensile testing apparatus. Data allow a direct comparison with studies in large mammals, in order to assist in the understanding of the functional morphology of laryngeal sound production across the wide range of more than 5000 mammal species, most of which use their vocal folds to produce acoustic signals relevant in communication.

The challenge for collecting stress data from very small samples is to control and quantify the force transmission from the mounting apparatus to the tissue as well as the determination of the changing tissue geometry (Sharpe, 2003). Some tests have been suggested to measure stress in small samples (e.g. Dailey et al., 2009; Hertegard et al., 2009; Zörner et al., 2010). However, these techniques are not designed to measure tensile strain and

---

[*] Corresponding author. Tel.: +1 801 5859590.
E-mail address: t.riede@utah.edu (T. Riede).

0021-9290/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jbiomech.2011.04.024