3D measurement of vocal fold elasticity using the linear skin rheometer

Mario Otten[1], Frank Müller[2], Anna-Katharina Rohlfs[2], Andreas Gömmel[3], Markus Hess[2], Malte Kob[1]
[1] *Erich-Thienhaus-Institut, Hochschule für Musik Detmold, Email: otten@hfm-detmold.de*
[2] *Poliklinik für Hör-, Stimm- und Sprachheilkunde, Universitätsklinikum Hamburg-Eppendorf*
[3] *Lehrstuhl für Baustatik und Baudynamik, RWTH Aachen*

Introduction

Human phonation results from the vibration of the vocal folds. To simulate this vibration, the elastic properties of the vocal folds are essential. It is common to assume an isotropic tissue, so that a single value for the elasticity of the vocal folds is used from which all other parameters can be derived by the Poisson's ratio. In the FE-model by Gömmel et al. [1] and the multiple mass model Vox by Kob et al. [2] the tissue of the vocal fold is divided into two layers as proposed by Story and Titze [3]: A body layer representing the muscular tissue responsible for the tensioning of the vocal fold and a cover layer representing the mucosa. It is assumed that the cover layer is an isotropic tissue, as stated by Berry and Titze [4], with a transversal shear modulus of 4.5 kPa.

The present study investigates the validity of this assumption by measuring the elasticity of human vocal folds in all three dimensions and at different positions on the vocal fold, in the proximate tissue and in the underlying muscle tissue. To construct a valid model with stable vibrations the elastic parameters and the geometry of the vocal folds need to be known.

Measuring the elasticity of tissue

To measure the elasticity of the oscillating tissue, the "Linear Skin Rheometer" (LSR) was used. This device, constructed by Matts and Goodyer [5], is able to measure elongation vs. applied force.

To measure the tissue properties, a mount was constructed which did not deform the tissue in any unintentional way. It was decided to mold the larynx. A material was found that enclosed the larynx tightly without deforming it. The constructed mount furthermore provided the possibility to grab the arytenoid cartilages and turn them to tension the vocal chords using a defined force. To measure the elastic properties with respect to all directions, the larynx needed to be split. A grid of three measuring points in three rows was established. Figure 1 shows the split larynx with the measuring points indicated by black dots. In the course of the text the measuring points are described by a pair of a letter and a number.

Every point was measured in three axes: The axis parallel to the vocal fold and both axes normal to this axis. Every point in every direction was measured 10 times and the probe was loosened and afresh fixed to the tissue several times.

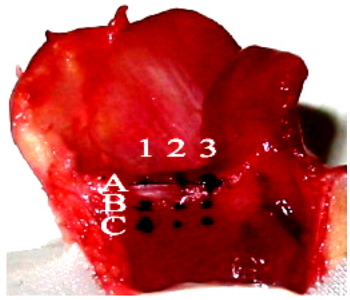

Figure 1: Split larynx with markers

After the first set of measurements the mucosa was incised along the vocal fold edge. Microsurgical instruments were used to detach the mucosa and the ligamentum vocale from the underlying muscle tissue in the area where the measurements took place. To keep the tissue in its anatomical context, the mucosa was not removed completely. The probe was attached to the muscle tissue through the incision.

Results

Three larynges were examined: Larynx 1 was dissected from a 56 year old male, the vocal folds were 15 mm long. Larynx 2 was dissected from a 39 year old male, the vocal folds were 16 mm long. The third larynx was dissected from an 28 year old female, the length of the vocal folds was 12 mm.

Table 1 gives an outline of the collected data, point A2 was chosen as a reference point with cranial-caudal excitation as this point is investigated in most studies.

Table 1: Shear modulus for left and right vocal fold at point A2 in cranial-caudal direction, standard deviation for 10 measurements in brackets

Larynx	Shear modulus in Pa	
	Left	Right
1	555 (17%)	1005 (3%)
2	654 (6%)	495 (5%)
3	854 (7%)	676 (9%)

The results of the present study show that elasticity of the vocal fold measured on the mucosa is not isotropic. Especially with respect to the difference between cranial-caudal and anterior-posterior displacement the results differ by far more than 100% near the edge of the vocal fold, caudal to it the difference decreases. Table 2 shows an excerpt from the measurements from the 3 larynges.

Table 2: Difference between elasticity in cranial-caudal and anterior-posterior direction in column 2

Larynx	Location		
	Row A	Row B	Row C
1	194%	174%	119%
2	220%	100%	64%
3	362%	102%	90%

The values from different points along the cranial-caudal axis (rows A-C) reveals a coherence with respect to the location: With increasing distance to the vocal fold edge the difference between the directions decreased. The measuring point farthest from the vocal fold was only 4 mm away, it is anticipated that this tendency will continue when moving further caudal until no difference is observable, as beyond the vocal folds the mucosa of the trachea is expected to show isotropic behavior.

Regarding the same direction of excitation but different measuring points along the vocal fold edge respectively parallel to it one can detect a change of elasticity. This difference is by far not as dramatic as the gap between different directions, but differences between 10 and 50 % are detectable.

The measurements of the muscle tissue revealed that the differences between directions and differences between measuring points are well below 10 %, so an isotropic behavior can be assumed.

In the next step the arytenoid cartilages were turned as described above using a torque of 0,001 Nm. With this torque applied to the tissue the shear modulus changed significantly but the change can not be related to the position of the measuring point and the direction of excitement. When observing larynx 1 in cranial-caudal direction, the highest difference between relaxed and strained vocal fold can be regarded in Point A3, observing larynx 2 the highest difference occurs in B3 and regarding larynx 3 the highest difference occurs in Point A1.

The shear modulus of the muscle tissue was not altered by more than 10 % when tensioned.

Discussion

When measuring normal to the vocal fold the values are mostly in between values with respect to the cranial-caudal respectively the anterior-posterior axes, but the measurement method in this direction needs to be reconsidered, as during measurement the effective area of the probe changes if the tissue is attached by suction.

The results differ from the data taken from literature. The data for the cover layer collected by Story and Titze [3] were taken from a dissected mucosa and measured using a parallel plate rheometer, in the present study the mucosa was measured in its anatomical context, so that the results may be altered by the underlying muscle tissue. It could be asserted that the mucosa showed anisotropic behavior rather than isotropic.

The small change of shear modulus of the muscle tissue when tensioned is possibly due to the fact that most of the additional force is absorbed by the not entirely removed mucosa and that the dissected ligamentum vocale can not transmit the force to the muscle.

Further this study shows like previous studies, e.g. [6], that the differences between larynges are huge, so that a general assumption of the elasticity is difficult. The simulation of the vocal fold needs reliable data to base the models on. The difference between the measured values in this study and corresponding values in literature may relate to the different measurement techniques. It was anticipated that the first measurements with an intact mucosa would only affect the mucosa itself, the differences to other studies suggests that the underlying tissue and the boundary conditions evoked by the geometry of the larynx alters the measurements. The measurements revealed an isotropic behavior of the muscle tissue beneath the mucosa, the measured anisotropic characteristics of the vocal fold have to relate to the combination of both tissues, the vocal ligament and the geometry of the vocal fold. The FE-model of the vocal folds needs to take this fact into account. To elucidate the difference between measurements of the sole mucosa tissue in literature and the measured values in anatomical context, optimization calculations are planed to be performed including geometry data. This way the gap between data from literature and the data measured during this study will be closed and the FE-simulation of vocal folds will take a huge step forward.

References

[1] Gmmel, A., Butenweg, Ch., Kob, M.: A fluid-structure interaction model of vocal fold osciallation, Proceedings 5th Int. Workshop on Models and Analysis of Vocal Emissions for Biomedical Applications (MAVEBA) in Florence, Italy 2007, pp. 127-128.

[2] Dejonckere, P.H., Kob, M.: Pathogenesis of Vocal Fold Nodules: New Insights from a Modelling Approach. Folia Phoniatrica et Logopaedica 2009, 61, 171-179.

[3] Story, B.H., Titze, I.R.: Voice Simulation with a body cover model of the vocal folds, J. Acoust. Soc. Am. 1995, 97, 1249-1260

[4] Berry, D.A., Titze, I.R.: Normal modes in a continuum model of vocal fold tissues, J. Acoust. Soc. Am. 1996, 100, 3345-3354

[5] Matts, P.G., Goodyer E.: A new instrument to measure the mechanical properties of the human stratum corneum. J. Cosmet. Sci. 1998;49:321-323

[6] Goodyer, E., Hemmerich, S., Müller, F., Kobler, J.B., Hess, M.: The shear modulus of the human vocal fold, preliminary results from 20 larynxes. Eur. Arch. Otorhinolaryngol 2007; 264:45-50