Elastography of vocal folds

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Abstract. The diagnosis of changes in the structure of the vocal folds is an important clinical task. There is no approach available, which is capable of getting synchronous spatial and biomechanical properties of them. Whereas biomechanical changes, particularly the elasticity, are a good maker for malignant and benign conditions. To gain the elastic characteristics of the vocal folds we are proposing an endoscopic approach using ultrasound elastography.

1. Introduction

The voice is one of the most important ways of communication in everyday life. Consequently, disorders of the voice forming organs cause a big impact on patients. Approximately 10% to 30% of the population are affected by problems of their voice in their lifetime, professional speakers or singers up to 50% [1, 2]. Voice disorders have many reasons: the most common ones are vocal strain/excessive tension, reflux, vocal fold paralysis, functional dysphonia, nodules, cysts, presbyphonia and Reinke’s edema [1, 3]. Diagnosing and assessing those pathologies is a wide clinical- and research-field. Especially imaging techniques to gain qualitative data have been studied recently.

A fundamental part of voice production are the vocal folds (VFs). The biomechanical properties of the VFs change if pathologies occur [4]. To separate the nondysphonic cases from dysphonic, it was shown that the measurement of VFs stiffness is highly sensitive [5]. Different methods are used in vivo to determine the stiffness of the VFs: aspiration method [6], tension meter, optical measurements and ultrasound [7].

But so far only one group [8, 9] used (transcutaneous) ultrasound elastography to assess the VFs. We are proposing a laryngoscopic, semi-static-elastography approach to examine the stiffness of the VFs.

2. Anatomical and biomechanical basics of the vocal folds

The true vocal folds are located in the larynx. They are surrounded by the false vocal folds, also called the vestibular fold (Figure 1a).

The oscillation of the true VFs is responsible for a major part of phonation, whereas the vestibular folds play a minor role in the phonation process. The VFs are 3-10 mm thick and measure 10-20 mm anterior-posterior and 8-12 mm in the medial-lateral direction [7].

The human VFs (Figure 1b) are formed by five different layers: epithelium, lamina propria and the vocalis muscle. The lamina is divided into three sublayers (superficial, intermediate and deep lamina...
Vocal folds

Transducer
Vocal folds
Vestibular folds

Epithelium
Superficial l. p.
Intermediate l. p.
Deep l. p.
M. vocalis

(a) Porcine vocal folds.

(b) Layers of the human VFs: Epithelium, lamina propria (l.p.) and Musculus vocalis [7].

**Figure 1.** Anatomical properties of the vocal folds.

The outer layers primarily consist of an extracellular matrix, whereas the inner layers consist mainly of cells [7]. Likewise, they fulfill different tasks: the epithelium maintains the shape and protects the underlying tissue whereas the lamina propria mainly keeps the elastic properties. The muscle has two functions: passive as a stiff rubber band and active as a muscle [10].

Due to the complex structure of the VFs it is clear that their elastic behavior is nonlinear [7]. The VFs are primarily responsible for the phonation process. They oscillate self-sustained with a high frequency and small amplitude [7]. Different models have been developed to describe the biomechanical properties and the oscillation of the VFs [11].

3. State-of-the-art methods

3.1. Diagnosing vocal fold disorders

For a clinical assessment of voice disorders endoscopic imaging techniques are widely used, mostly videostroboscopy or high-speed videoendoscopy [12]. Stroboscopy still remains the standard examination because it is cost-efficient, easy to use and it provides synchronized audio and visual data. The stroboscopic approach is limited by its relatively low sample rate. If the dysphonia exceeds a moderate level, the stroboscopy cannot visualize the changes because it does not capture cycle-to-cycle changes [13].

To differentiate between malignant and benign it is necessary to take a biopsy of the affected tissue [14]. Like every invasive examination a biopsy does have some risk and potentially leaves scars on the VFs, which could lead to a decrease in the patient’s voice quality [15]. New endoscopic techniques - like narrow band imaging, optical coherence tomography (OCT), three-dimensional imaging and iScan technology - are being examined and show promising results [15, 16, 17]. The narrow band imaging and iScan cannot detect the depth of the infiltration that limits it to superficial lesions [16]. Whereas the OCT can visualize the tissue in depth [15]. The three-dimensional laser imaging is capable of imaging the surface of the VFs in three dimension during phonation [17].

Other medical imaging techniques like ultrasound, computer tomography and magnetic resonance imaging [18] are also used to examine the larynx and the vocal folds. Those approaches are capable of gaining spatial information. New approaches - especially using ultrasound [19] - are being developed, but still barely used.
An elastographic approach could combine the spatial image and biomechanical information, which possibly leads to a higher sensitivity in discovering lesions.

3.2. Measuring the elastic properties of the vocal folds
Pathologies of the VF\(\text{s}\) affect the biomechanical properties \[20\]. For example, previous studies indicate that healthy VF\(\text{s}\) are stiffer, compared to the ones with polyps \[21\]. Measuring the biomechanical properties of the VF\(\text{s}\) has always been a challenge because of not only their size but also their anatomical accessibility, their anisotropies and their broad range of elasticity. It is desirable to measure the elasticity of human VF\(\text{s} \text{ in vivo, but for an approximation also ex- and in-situ and animal studies have been made} \[7\]. To mechanically measure the elasticity of a tissue it is necessary to apply known stress and measure the displacement (e.g. aspiration technique) \[12\]. Other approaches observe shear wave propagation in the tissue and measure their group velocity (e.g. shear-wave-elastography) \[22\].

The \textit{in vivo} approaches can be separated into three groups: mechanical, optical and medical imaging techniques \[7\]. One approach to mechanically examining the elastic properties is an aspiration tool, which sucks the tissue into a tube and measures the largest displacement \[23\]. Other aspiration tools excite the tissue, using air-pressure oscillations and determine the vibration \[24\]. All mechanical approaches need direct contact to the VF\(\text{s}\), which could lead to tampering with the results.

Optical methods, like stroboscopic or high-speed imaging, focus on observing the mucosal waves and gain qualitative information about the movement of the VF\(\text{s}\). Using high-speed images, quantitative methods have been developed. Those are capable of visualizing the time dependent distances between the VF\(\text{s}\). Variations in mucosal wave propagation indicate biomechanical changes \[21\].

In addition, an optical method, but here summarized with the medical image techniques, is the OCT. It was shown that OCT is a proper approach to measure the histological layers of the vocal folds \[21\]. The optical coherence elastography was successfully used to assess the biomechanical properties of porcine trachea \[25\].

Another medical imaging technique is the ultrasound. Two approaches are known: transcutaneous and direct imaging. Ultrasound imaging of the VF\(\text{s}\) has been tested and it showed usable results \[26\]. The transcutaneous access is easy to use because a common clinical ultrasound device is used. Identifying the VF\(\text{s}\) on the ultrasound image could be challenging for the examiner. Especially the true vocal folds are hard to find \[27\].

Various ultrasound methods have been proposed examining the VF\(\text{s}\): B-mode- \[28\], Doppler- \[29\], Nakagami-imaging \[26\] and elastography \[8, 9\]. Except B-mode-imaging, all of them are capable of measuring the biomechanical properties. Ultrasound elastography is a widely used assessment method to examine the elasticity of tissues \[22\]. All the transcutaneous approaches have the limitation that identifying the VF\(\text{s}\) is difficult. This limitation could be resolved by a direct measurement on the VF\(\text{s}\).

4. Methods
To overcome the discussed limitations, a semi-static-elastography approach to examine the stiffness of the VF\(\text{s}\) is proposed here. The measurement directly on the VF\(\text{s}\) enables the examiner to gain results that are more exact. It is difficult to identify the VF\(\text{s}\) with transcutaneous approaches and the overlying tissues could distort the measurement. To show the feasibility, porcine larynxes are examined with a 8-17 MHz intraparative transducer. The ultrasound transducer is directly placed on the VF\(\text{s}\). Establishing a small displacement, an internal strain is applied. The elastography package of Alpinion E-CUBE 15 EX is used to get qualitative results. To quantify the results the B-Mode images are registered with a Bspline-registration with \texttt{elastix} \[30, 31\]. \texttt{elastix} is an established tool for image registration in medicine. The strain in the tissue was determined according to Lai et al. \[32\].
5. Results
The two measurements, which are shown in figure 2 & 3, were done on the same porcine VFs. The transducer was placed on the position shown in figure 1a. In both measurements, the results were comparable.

![Fig 2. Displacement field in the tissue of a porcine VF](image1)

![Fig 3. Absolute value of the strain field](image2)

The visualization of the internal strains is a new assessment method. Therefore, no comparable data was found. Different studies were made to examine the surface strains of the VFs [33, 34]. The strain in material depends on its elastic properties. The stiffer a material under constant stress the lower the strain and vice versa. The tissue of the vocal folds has different layers that have different elastic properties. In the evaluated porcine larynx, it was not yet possible to distinguish between those layers. The image registration process needs to be refined to differentiate them.

6. Conclusion & Outlook
We showed an assessment method, which is capable of displaying the strain distribution in the VFs. Our approach is based on a conventional ultrasound and image registration. The strain distribution gives us an idea of the elasticity in the tissue.
To get quantitative results it is necessary to measure the applied forces. To determine the applied force field, we are using a stress sensor fixed on the transducer (Figure 4). The stress sensor has well known elastic properties. Measuring the deformation of the sensor, it is possible to determine the force field on the surface [35]. This approach is still under development.

![Figure 4. Measurement set up to determine the surface forces on the tissue.](image)

To evaluate the registration process and get quantitative material results a finite-element body-cover-model [4] should be implemented in COMSOL. The simulation results are used to update the material properties [36].

The advantages of our approach is the direct measurement on the VFVs, which should provide better results than transcutaneous approaches. Disadvantages are that the patient needs to be anesthetized and possible irritations of the VFVs. For a clinical use, it would be necessary to develop a new transducer, which has the required size and properties.

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