Fracture Toughness of Vocal Fold Tissue: A Preliminary Study

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Summary: A customized mechanical tester that slices thin, soft samples was used to measure the fracture toughness of vocal fold tissue. Porcine vocal fold lamina propria was subjected to quasi-static, guillotine-like tests at three equally distanced regions along the anterior-posterior direction. The central one-third where high-velocity collisions between vocal folds occur was found to have the maximum fracture toughness. In contrast, the anterior one-third featured a lower toughness. Fracture toughness can be indicative of the risk of benign and malignant lesions in vocal fold tissue.
Key Words: Vocal folds–Fracture toughness–Benign lesions.

INTRODUCTION

Phonotrauma is believed to be a result of high-impact stresses between colliding vocal fold membranes.[1] Large stress concentration can cause localized tissue rupture in the mucosal layer, leading to avascular lesions or bleeding. A good understanding of the mechanisms associated with tissue rupture is needed for the etiology of voice disorders. Computational simulations, such as finite element models,[1,2] have been used to assess stresses and strains within vocal folds undergoing idealized mechanical vibrations. Conventional mechanical testing methods have been implemented to characterize the elastic properties of vocal fold tissue.[3] However, its fracture toughness has not yet been investigated. Fracture toughness measures the ability of materials against the propagation of cut or tear, known as "crack" in classical fracture mechanics.[4] Fracture toughness has been measured for biological hard tissues such as bone; however, few attempts have been made to measure this property for soft tissues (eg, Chu et al[5]).

There are two common approaches in classical fracture mechanics to study crack propagation in elastic materials, including the stress intensity factor and the energy release rate.[4] The stress intensity factor has been defined for linear elastic materials; thus, it is unsuitable for very soft tissues, such as vocal fold tissue which undergoes large deformations. The energy release approach that considers the required mechanical energy input for damage growth has been used for soft materials, in which a cutting device slices the specimen.[5] In the present study, the latter approach was used to measure the fracture toughness of porcine vocal fold lamina propria at three distinct locations along the anterior-posterior direction, in an attempt to identify injury-prone regions. The mechanical toughness can also be a useful parameter for the assessment of biomaterials used for vocal fold regeneration.[6]

METHODS

Sample preparation

Fresh porcine larynges were harvested and their vocal fold tissues were dissected following the protocol used for mechanical testing in Miri et al.[7] The lamina propria was gently separated from the glottal wall and the muscle. Within a 3-hour postmortem, the samples were snap frozen while submerged in normal phosphate saline buffer. On the day of the experiment, they were thawed at room temperature. Three distinct regions along the anterior-posterior direction were extracted: one-third anterior (ie, location A), one-third center (ie, location B), and one-third posterior (ie, location C), as shown in Figure 1. These regions were sliced along the coronal plane. In addition, the central region was sliced along the transverse direction. Care was taken to obtain thin, uniform samples.[5]

Experiments

Figure 2 shows a schematic of the test apparatus, which was mounted on a commercial mechanical tester (ElectroForce ELF3200; Bose Inc., Eden Prairie, MN). A polished preconditioned razor blade (0.228 mm thickness; Personna American Safety Razor Company, Cedar Knolls, NJ) was installed into the blade holder, while lubricated to reduce frictions between the blade and the sample. The measurements consisted of two successive loading cycles, as schematically shown in Figure 3. The blade velocity was 0.1 mm/s to enforce quasi-static conditions (the total time was <5 minutes for each sample). In the first cycle, the moving blade cut the tissue, and then a second cycle was performed to estimate the friction force between the blade and the tissue sample. The difference of the projection areas under the two curves yielded the fracture toughness, as highlighted in Figure 3. The tissue hydration was maintained by adding water drops to the sample surface because the testing apparatus did not allow submerging samples in a bath solution. The blade lubrication was also preserved using oil droplets. The blade position was adjusted to make a 4- to 6-mm deep cut in tissue samples to ensure the estimation of the fracture properties (see the following and Taylor et al[4]). The beginning of the cut (up to 1 mm in most cases) is probably dominated by elastic deformation; hence, a longer cut is needed to reduce the contribution of elastic deformation. In the present study, the error associated with elastic deformation was deemed <10%.

Data analysis

The lubricated, guillotine-like, cutting system provided controlled crack propagation, under mode I,[4] and eased the use of small-sized samples. Figure 3 displays the possible deformation mechanisms occurring within small tissue samples under contact with the blade. After the first contact between the

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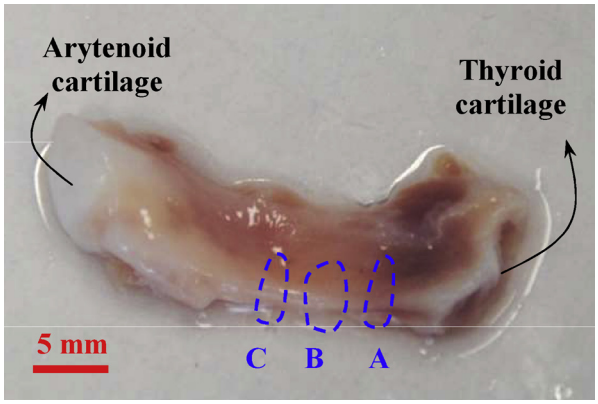

FIGURE 1. Locations A, B, and C are depicted in a porcine vocal fold sample.

blade and sample, the tissue undergoes nearly elastic deformation and the blade tip acts like a conical indenter. The stress concentration leads to the first cut, which reduces the tissue resistance against further cuts. The load-time history consists of a series of elastic deformation, cutting, and force relaxation. The fracture toughness is determined from the mechanical energy, *W,* consumed by the blade tip. The mechanical energy calculated from the area under the displacement-force curves yields the fracture toughness, that is,

$$J = \int F\,\mathrm{d}x/(hL) \tag{1}$$

where F denotes the normal force at the crack tip, h is the tissue thickness, and L is the crack length. The parameter J that represents the energy absorbance of the tissue for high stress concentrations is defined as fracture toughness. Comparisons within each group were performed using two-tailed, paired t tests.

To present the empirical relation in Equation (1), one may extend the energy balance between the blade and the tissue as (in the form of differentials)

$$J\,h\,\mathrm{d}x + \mathrm{d}(\delta u) + F_f\,\mathrm{d}x = F_r\,\mathrm{d}x + \mathrm{d}U, \tag{2}$$

where F_r denotes resistance force imposed by tissue on the blade, F_f represents friction force on the blade, U represents internal strain energy in the tissue, and δu is the change in the stored internal recoverable strain energy potential (Equation 2). The strain energy changes are mainly associated with the elastic deformation at the beginning of the cut. Ignoring the minimal changes in the internal strain energy, one may write the energy balance between the blade and the tissue as

$$J\,h\,\mathrm{d}x = \left(F_r - F_f\right)\mathrm{d}x, \tag{3}$$

in which the fracture toughness J is defined as a constant (ie, mean) value for each case, and the net force in Equation (3) is equal by F in Equation (1).

RESULTS

Physical model

The possible dependency of the fracture toughness on sample thickness was investigated using silicone rubber samples that were cured by mixing equal ratios of Dragon Skin constituents (model 10 medium; Smooth-On Inc., PA) and Silicone Thinner (Smooth-On Inc.). This composition exhibited a similar Young's modulus as that of porcine vocal fold lamina propria.[7] The fracture toughness values of the silicone rubber were consistent (420–440 J/m^2) when the sample thickness was varied between 0.3 and 1 mm. The toughness values significantly reduced for greater thicknesses (eg, 300 J/m^2 for 2 mm). The tissue samples used in this study ranged in thickness from 0.3 to 0.6 mm, typical of porcine lamina propria. The results in each group (Table 1) had smaller standard deviations than those of other mechanical properties, such as Young's modulus.[7] The samples were mounted with minimal pretensions to ensure they were flat.

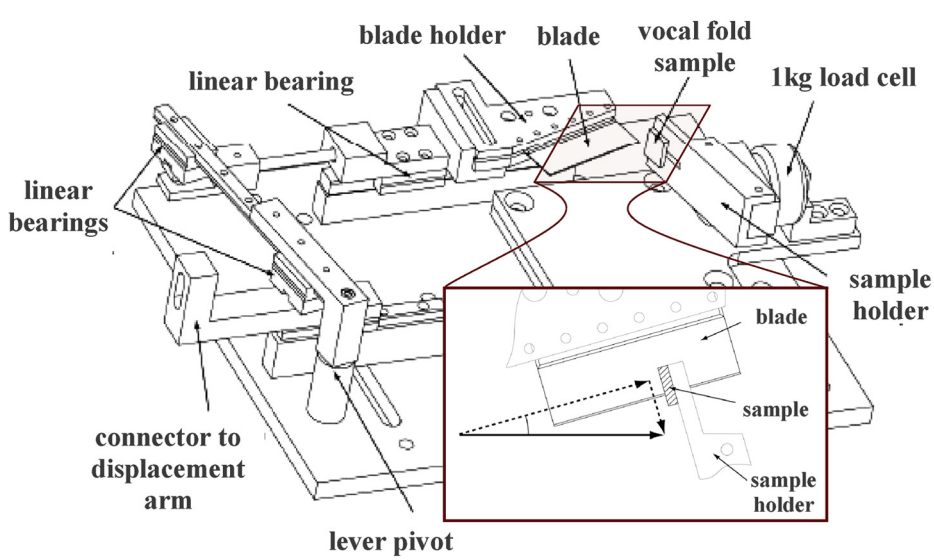

FIGURE 2. Schematics of the fracture toughness setup. Adopted from Chu et al.[5]