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Variation in Young's modulus along the length of a rat vibrissa

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ABSTRACT

Rats use specialized tactile hairs on their snout, called vibrissae (whiskers), to explore their surroundings. Vibrissae have no sensors along their length, but instead transmit mechanical information to receptors embedded in the follicle at the vibrissa base. The transmission of mechanical information along the vibrissa, and thus the tactile information ultimately received by the nervous system, depends critically on the mechanical properties of the vibrissa. In particular, transmission depends on the bending stiffness of the vibrissa, defined as the product of the area moment of inertia and Young's modulus. To date, Young's modulus of the rat vibrissa has not been measured in a uniaxial tensile test. We performed tensile tests on 22 vibrissae cut into two halves: a tip-segment and a base-segment. The average Young's modulus across all segments was 3.34 ± 1.48 GPa. The average modulus of a tip-segment was 3.96 ± 1.60 GPa, and the average modulus of a base-segment was 2.90 ± 1.25 GPa. Thus, on average, tip-segments had a higher Young's modulus than base-segments. High-resolution images of vibrissae were taken to seek structural correlates of this trend. The fraction of the cross-sectional area occupied by the vibrissa cuticle was found to increase along the vibrissa length, and may be responsible for the increase in Young's modulus near the tip.

1. Introduction

The rat vibrissal (whisker) system is an increasingly important model in the field of neuroscience for the study of the sense of touch (Diamond et al., 2008). Rats actively tap and sweep their vibrissae against objects to extract detailed spatial features such as orientation (Polley et al., 2005) and texture (Jadhav and Feldman, 2010).

Unlike the antennae of insects (Staudacher et al., 2005), vibrissae have no sensors along their length. Instead, all mechanical information must be transmitted along the vibrissa length to the receptors located in the follicle at the vibrissa base. Thus, the mechanical properties of the vibrissa determine how the contact with the environment is transmitted to the nervous system.

The transmission of mechanosensory information will depend critically on the bending stiffness of the vibrissa (Birdwell et al., 2007; Solomon and Hartmann, 2006), defined as the product of the area moment of inertia and Young's modulus (Hibbeler, 2011). The area moment of inertia can be found from vibrissa geometry; in contrast, it requires significantly more effort to determine Young's modulus.

Young's modulus of a rat vibrissa was measured previously using nano-indentation techniques (Herzog et al., 2005), but this study was limited to a single sample, and it is difficult to exclude the possibility that the non-uniform strain directly below the indenter caused inelastic deformation. Young's modulus of the vibrissa has also been inferred from matching experimental data with linear elastic models of bending and/or resonance (Birdwell et al. 2007; Hartmann et al. 2003; Neimark et al. 2003). Both of these types of tests, however, require elastic solutions to interpret the results. Resonance experiments additionally rely on measuring dynamic elastic properties, which are often different from static ones.

The tensile test is generally the simplest and most easily interpreted method for determining Young's modulus. The tensile test fundamentally requires only the definition of stress as force/area and strain as a ratio of lengths. To date, however, Young's modulus has not been determined using a uniaxial tensile test.

The present study performs uniaxial tensile tests to quantify Young's modulus of rat vibrissae. We show that Young's modulus is larger near the vibrissa tip than near the base. High-resolution images of vibrissae showed that the area fraction occupied by the vibrissa cuticle increased along the vibrissa length, and therefore is likely to be the physical characteristic that underlies this variation in Young's modulus.

Accurate values of Young's modulus will be important in validating models of vibrissa deformation used to predict sensory input to the vibrissal–trigeminal pathway.

Methods

All procedures were approved in advance by the Northwestern Animal Care and Use Committee. Two different sets of vibrissae were used for mechanical testing and image analysis.

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