Acta Biomaterialia 76 (2018) 108–115

Contents lists available at ScienceDirect

Acta Biomaterialia

journal homepage: www.elsevier.com/locate/actabiomat

Full length article

On the correlation between the curvature of the human eyelash and its geometrical features

Hironori Tohmyoh [a,*], Mitsuharu Ishihara [a], Kaori Ikuta [b], Tomoko Watanabe [b]

[a] Department of Finemechanics, Tohoku University, Sendai 980-8579, Japan
[b] Shiseido Global Innovation Center, Yokohama 224-8558, Japan

ARTICLE INFO

Article history:
Received 6 February 2018
Received in revised form 26 June 2018
Accepted 2 July 2018
Available online 4 July 2018

Keywords:
Human eyelash
Curvature
Structural elasticity
Cuticle
Neutral axis for bending

ABSTRACT

Although human eyelashes are generally curved, the cause of the natural curvature of eyelashes has not yet to be clarified elsewhere. Related with this, this paper reports our discovery of a correlation between the curvature of the eyelash and its geometrical features. Eyelashes can be divided into root, middle and tip sections. Because the curvature at the root is larger than that at the tip, we expected that the root section could be more easily deformed by bending compared with the tip section. However, the structural elasticity in bending, which is the flexural rigidity without depending on the external dimensions, at the root was found to be greater than that at the tip, contrary to our initial expectations. Next we examined the internal dimensions of cross sections of the eyelashes, and found that the thicknesses of the cuticle layer at the root were different for the convex and concave sides of the curved eyelash, although these were almost the same at the tip. Theoretical analysis of this variation in thickness of the outer cuticle layer shows that this displaces the neutral axis. Finally, we found that there is a good correlation between the displacement of the neutral axis and the curvature of the eyelash.

Statement of Significance

Why are human eyelashes naturally curved? To find a hint for this question, the mechanical and geometrical properties of human eyelash were investigated. Although the curvature at the root of the eyelash was larger than that at the tip, this was not related to the deformability of the eyelash by bending. From the cross-sectional observation of eyelash, we noticed that the thickness of the outer cuticle layer was non-uniform depending on the position, and this brought the displacement of the neutral axis of the eyelash for bending. Finally, a good correlation between the curvature and the change in the neutral axis was discovered. With practically using this findings, the curvature of the eyelash might be controlled artificially in the future.

1. Introduction

Human and animal hair plays an important role not only for protecting the body from external shock or from ultraviolet light but also for gathering external information. Moreover, hair can give us other kinds of information, such as information about aging [1], etc., and therefore, understanding the physical properties and origin of the geometrical features of hair is a very important issue in biology. With respect to the biological function of hair, Quist *et al.* used a tensile test to measure the elasticity of a rat's vibrissae and discussed how mechanical information is transmitted along the vibrissae [2]. Angelo *et al.* reported that the hairs on a bat's wings work as sensors to support its flight control [3]. Moreover, from the view point of health and cosmetics, understanding the mechanical properties of hair, such as the elasticity [4–9], viscoelasticity [10,11], friction and wear properties [12], failure behavior [13], etc., is vital. For example, the elasticity and the shape of individual hairs play important roles in deciding the hairstyle. Goldstein *et al.* treated hair fiber bundles consisting of elastic hair fibers having random intrinsic curvature based on statistical physics, and predicted the ponytail shape [14]. Moreover, the elasticity of hair is sensitive to moisture [15] and temperature [16], and the absorption of elements such as zinc, copper, etc. [17]. The elemental composition of hair, which holds geographic information [18], is also extensively analyzed [19,20].

* Corresponding author.
E-mail address: tohmyoh@ism.mech.tohoku.ac.jp (H. Tohmyoh).

https://doi.org/10.1016/j.actbio.2018.07.005
1742-7061/

So far, eyelashes are generally curved. It has been reported that the eyelashes of Westerners are much more curved than those of East Asians [21]. The difference in the curvature of eyelashes is a very important topic in human ecology. Moreover, the origin of the curvature of eyelashes is of great interest in beauty and cosmetic science because it affects the personal impression one gives. Xu and Chen performed the finite element analysis for a curly human hair, where the hair's mechanical properties are assumed to be homogenous and isotropic for simplicity, and reported that the mechanical stress strongly influences the formation of a curly pattern of human hair [22]. Thibaut *et al.* investigated the growth and morphology of curly hair follicles, and concluded that the human hair shape is programmed from the bulb [23]. Nagase *et al.* reported that there is an inhomogenous internal structure between the outer and inner regions of the curved hair fiber, and in relation to the inhomogeneous structure, different amino acid composition of the hair keratin was observed between the outer and inner regions [24]. Although the various research works on the curved hair, especially from view point of biology, are reported [23–26], to the best of our knowledge, the physical mechanisms giving rise to the natural curvature of human eyelashes have yet to be fully understand elsewhere. Is the elasticity of the eyelash related to its curvature? The structural elasticity of human hair was defined and measured by the bending tests [27]. Although the unit of the structural elasticity in bending is matched with that of Young's modulus, the physical meaning of the structural elasticity in bending is the flexural rigidity without depending on the external dimensions.

In this paper, we investigate the reason why human eyelashes are curved. Because we suspect that the deformability of eyelashes is related to the curvature, the structural elasticity in bending of the eyelash was accurately measured by a small-span three-point bending test. Surprisingly, although the curvature of the root section was larger than that of the tip section, the structural elasticity in bending of the root was greater than that of the tip. From detailed observations of the structure of cross sections of the examined eyelashes with a transmission electron microscope, we observed that the thickness of the cuticle layer on the inner side with respect to the curvature was thinner than that on the outer side. Based on this knowledge, we theoretically calculated the displacement of the neutral axis of the eyelash for bending due to the ununiformity of its cross section, and finally, found out that displacement of the neutral axis of the eyelash for bending highly correlated with the curvature of the eyelash.

2. Materials and methods

2.1. Eyelash samples

Three eyelashes were selected from a Caucasian female aged 30 s. She didn't use an eyelash curler, so that they were not damaged. Fig. 1 shows a photograph of the eyelash investigated in this study. The eyelash has curvature, and the curvature varies depending on the position in the axial direction. In the present study, 3 eyelashes were collected from the same person, and each eyelash was divided into 3 sections, i.e., root (R), middle (M) and tip (T). Thus a total of 9 samples were examined. Each sample was cut out from each section into about 1.5 mm long and their cross sectional profiles were measured by direct observation with a digital microscope.

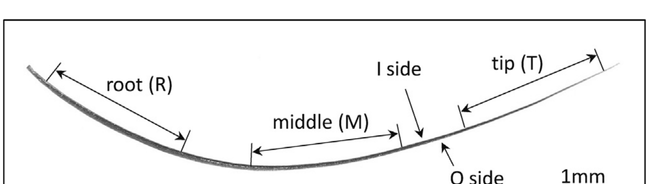

Fig. 1. Photograph of the tested eyelash.

2.2. Small-span, three-point bending test

Generally, human hair has a multi-walled structure, and the ability to deform hair depends on its internal structure [28–30]. To quantitatively express the ability to deform human hair by bending, we have defined the structural elasticity (SE), which we can measure by a bending test [27]. Here, the values of SE in bending for the root, middle and tip sections were obtained using a small-span, three-point bending test.

A schematic illustration of the test is shown in Fig. 2a. The eyelashes under test are three-layered structures and assumed to have elliptical cross sections as illustrated in Fig. 2a. Each end of the sample is simply supported and the span length is s. Because the length s is small compared to the length of the whole eyelash, the pieces under test could be considered to be straight. A load P is applied at the center of the span and in the direction of the short axis in the cross sectional profile of each section. The displacement at the loading point δ is given by the following equation provided that the flexural rigidity of the sample A is constant within the interval s.

$$\delta = \frac{Ps^3}{48A} \quad (1)$$

where A is flexural rigidity of the hair sample. For simplicity, we assumed that each layer is uniform. In this case, A is given by

$$A = \sum_{i=1}^{3} E_i I_i \quad (2)$$

where E is Young's modulus and I is the area moment of inertia. The subscripts 1, 2 and 3 are for the inner, middle, and outer layers of the hair sample. SE in bending of the hair sample is defined as [27]:

$$\mathrm{SE} = \frac{A}{I} \quad (3)$$

where $I = \pi ab^3/4$ for loading in the direction of the short axis. The load-displacement curve is obtained by the small-span three-point bending test with the test apparatus (Fig. 2b and c). The slope of the load-displacement curve matches with $48A/s^3$, and from this, we determine A. The area moment of inertia I is determined form external dimensions (a, b), and from Eq. (3), we get SE.

2.3. Test apparatus

The small-span three-point bending test was conducted using test equipment consisting of a force sensor [31], a stage with a piezoelectric drive, etc., see Fig. 2b. The force acting on the tip of the force sensor is given by $P = k\,\delta_C$, where δ_C is the deflection of the cantilever beam. k is the spring constant of the cantilever, and was selected to be in the range 19.1–74.2 μN/μm depending on the sample in order to generate sufficient deformation during testing. The jig was used to simply support an eyelash sample (Fig. 2c). This jig consists of 2 pairs of sharp-edged metal plates, one facing vertically toward the load direction which works as a simple support in the three-point bending test and the other facing horizontally toward the load direction which prevents the sample from falling. The eyelash sample was set on this pair of horizontal sharp-edged metal plates where weights (Al wire with diameter 100 μm and length about 1 mm) were fixed to each end of the eye-