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Nanomechanical properties of human skin and introduction of a novel hair indenter

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ABSTRACT

The mechanical resistance of the stratum corneum, the outermost layer of skin, to deformation has been evaluated at different length scales using Atomic Force Microscopy. Nanomechanical surface mapping was first conducted using a sharp silicon tip and revealed that Young's modulus of the stratum corneum varied over the surface with a mean value of about 0.4 GPa. Force indentation measurements showed permanent deformation of the skin surface only at high applied loads (above 4 μN). The latter effect was further demonstrated using nanomechanical imaging in which the obtained depth profiles clearly illustrate the effects of increased normal force on the elastic/plastic surface deformation. Force measurements utilizing the single hair fiber probe supported the nanoindentation results of the stratum corneum being highly elastic at the nanoscale, but revealed that the lateral scale of the deformation determines the effective elastic modulus.This result resolves the fact that the reported values in the literature vary greatly and will help to understand the biophysics of the interaction of razor cut hairs that curl back during growth and interact with the skin.

1. Introduction

Skin, the largest human organ, protects the body from the surrounding environment and regulates its temperature. It is built up of different layers comprising the subcutis, dermis and epidermis. The outer layer of the epidermis, the stratum corneum (SC), is composed of keratinized cells (corneocytes), which are embedded in lipid cement oriented parallel to the corneocyte surface. As the

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outermost layer of skin, the stratum corneum (SC) acts as a photoprotective and physical barrier, regulates water loss, and is the contact surface for tactile perception (Yuan and Verma, 2006; Potter et al., 2009; Tang and Bhushan, 2010; Norlén, 2006).

The human hair consists of a layered fiber structure comprising the cuticle, cortex and a central medulla, a structure not always present (Luengo et al., 2014). The cuticle is the outer protective layer of the hair fiber and determines the surface properties of the hair. The cortex is the main structural component providing the hair fiber its characteristic mechanical properties. Both skin and hair are layered composite materials, of which an improved biomechanical understanding is essential for many applications (Potter et al., 2009; Luengo et al., 2014) and in the fields of nanomechanics and biomimetics (Tang and Bhushan, 2010; Luengo et al., 2014). The mechanical properties of the SC and its contribution to the overall properties of skin are of great interest but only limited data are available on these aspects (Yuan and Verma, 2006; Potter et al., 2009; Tang and Bhushan, 2010). The majority of studies of the elastic properties of the SC are tensile measurements, where the material is stretched, until it gives way (Geerligs, 2006; Xu and Lu, 2011). These studies clearly show that the SC has a very strong dependence on the relative humidity, and the modulus can change by several orders of magnitude over the range of 20–100% RH, where the modulus is higher at low humidity (Wildnauer et al., 1971; Park and Baddiel, 1972). The temperature at which the experiments are performed is also very important and the tensile measurements indicate that the modulus can change by more than a factor of 10 between 37 °C (2.6 GPa) and 60 °C (0.11 GPa) at 32% RH (of course this also corresponds to an increase in the absolute humidity). The results are broadly in agreement, irrespective of the source of the SC, whether it be human, rat or pigs ear (Geerligs, 2006; Xu and Lu, 2011). Given the composite nature of the SC, and the possibility that the response to deformation may not be isotropic, it would be instructive to study the contact mechanics in response to a penetrative deformation. This would mimic the deformation experienced by the skin during active touch, or in response to the prickling by hairs or garments. Surface indentation measurements may be performed to achieve a better understanding of the SC mechanical properties and such measurements performed by Yuan (Yuan and Verma, 2006) indicate a slightly lower value than for the tensile measurements, though these studies are limited to the cases of "wet" (0.026 GPa) and "dry" (0.12 GPa.) Scanning acoustic measurements, performed at 650 MHz also probe the normal deformation, but the much higher frequency appears to lead to a higher value (around 3 GPa). This dependence of the value on the measurement technique, warrants studies where the modulus is extracted from experiments using probes which mimic the interaction of interest. Nanoindentation can be conducted using Atomic Force Microscopy (AFM) by pressing either a sharp tip or small probe against the surface and measuring the resulting force versus displacement with or without surface damage and at different rates (Ralston et al., 2005; Crichton et al., 2011; Chen and Bhushan, 2013). Intermolecular and surface forces as well as frictional properties for various systems have previously been studied at the nanoscale by the authors, employing the colloidal probe technique (Ducker et al., 1991) in both air and liquid environment (Nordgren and Rutland, 2009; Álvarez-Asencio et al., 2012; Olszewska et al., 2013). In addition, the more recently developed technique utilizing crossed fiber configuration allows the direct interaction between biofibers to be studied (Mizuno et al., 2010, 2006). Moreover, recent advances in AFM have also driven the development of PeakForce® QNM (Quantitative Nanomechanical Property Mapping). The technique allows surface imaging to be recorded while, at the same time, providing quantitative surface material properties (Duner et al., 2012; Sweers et al., 2011; Foster, 2012; Rico et al., 2011; Ankerfors et al., 2012).

Up to now, some studies on nanoindentation of skin have been reported using different types of probe (Yuan and Verma, 2006; Xu and Lu, 2011; Chen and Bhushan, 2013; Kendall et al., 2007; Geerligs et al., 2011; Pailler-Mattei et al., 2007). The trends follow the same response to relative humidity as the tension methods above, but micron size penetration leads to significantly lower values of Young's modulus, once again suggesting that the dimensions affect the magnitude of the result. Furthermore, the indenter material was normally limited to a narrow selection of inorganics such as diamond, sapphire, silicon, silica and silicon nitride. To the authors' knowledge, no nanoindentation study has yet used a biocomposite material, such as a single hair fiber.

The choice of hair is not arbitrary. When a hair fiber grows, it may tend to curl and interact with the skin producing in some cases damage and irritation, or possibly a local infection of the hair follicle (folliculitis). This interaction depends on hair condition, local pressure and hair fiber contact geometry which all contribute to the tactile perception of hair. Therefore, a new nanoindentation technology using a hair fiber as an indenter will allow for a deeper understanding of the mechanical properties of hair interacting directly with skin, but could also help to elucidate the key parameters governing tactile perception at the nanoscale.

This study investigates the nanomechanical properties of the outermost surface of skin (SC) and the magnitude of the force needed to induce elastic/plastic deformation using a combination of AFM imaging and force measurements. This includes measurements using AFM cantilevers bearing sharp silicon tips as well as the design and utilization of an indenter probe comprising a single hair fiber.

2. Materials and methods

Force measurements (Ralston et al., 2005) and PeakForce® QNM (Pittenger et al., 2010) (Quantitative Nanomechanical Property Mapping) imaging were carried out on a Multimode 8 AFM equipped with a Nanoscope V controller (Bruker®, Santa Barbara, CA, USA). The cantilevers (NSC12) were purchased from MikroMasch (Tallinn, Estonia). When the spring constant of the cantilever is known, quantitative forces between the tip and a lower substrate can be measured. The normal spring constants of the cantilevers were accurately determined using the calibration software AFM TuneIT v2.5 (ForceIT, Stockholm, Sweden) based on hydrodynamic damping (Sader et al., 1999; Pettersson et al., 2007). Force measurements were otherwise performed and analyzed according to the procedures described in an IUPAC report