Structural Analysis of Curly and Straight Human Hair Fibers by Scanning Microbeam SAXS

Human hair is one of many keratinous fibers and has a structure similar to that of wool. Figure 1 illustrates the structure of hair. The surface of a hair fiber is covered with thin scale-like cells (cuticles) and beneath the cuticle layers are the cortex and the medulla, which exists at the center of hair. The cortex dominates (*ca.* 80%) and is comprised of cortical cells. Figure 1 also shows the hierarchy structure of a cortical cell. It is filled with macrofibrils, which are composed of intermediate filaments (IFs) surrounded by matrix proteins.

Most wool fibers contain two (sometimes three) types of cortical cells, namely, orthocortex and paracortex (and mesocortex), and the bilateral distribution of these has been associated with the crimped structure of wool. It has been found by transmission electron microscope (TEM) observations that there are obvious differences in the geometrical arrangement of the IFs in these cortical cells. IFs seem to be oriented more parallel to the fiber axis in the para- and mesocortex, whereas they are twisted helically in the orthocortex [1]. The shape of wool fiber is curly, but that of human hair varies from curly to straight. There are some reports on cortical cell types for human hairs [2] but no information on their distributions or the relationship with the macroscopic hair shape. The purpose of this study is to analyze the IF arrangement of curly and straight hairs, in the intact condition, to elucidate the difference in macroscopic curl shape from the viewpoint of the internal nanostructure. Measurements have been performed for Asian, Caucasian and African hairs having various curl strengths, ranging from strong curly to nearly straight.

Small angle X-ray scattering (SAXS) experiments were carried out at beamline **BL40XU** of SPring-8 and BL-4A of Photon Factory (Tsukuba) [3,4]. Two-dimensional (2D) SAXS from different positions in the transverse direction of a fiber was measured. The diameters of measured hairs were larger than 50 µm, so the size of the microbeam used (less than 6 µm) was small enough to analyze the inner and outer sides of the curl separately. In this study, only the scattering patterns from the cortex have been analyzed.

Figure 2 shows typical 2D SAXS patterns of a curly human hair fiber. Major intensity maxima, which are observed along the equator (short arrows), are attributed to the lateral packing between IFs. A clear difference in these IF peaks is seen between the outer side (a) and the inner side (b) of the curl. The IF peaks of the inner side are strong and sharp but those of the outer side are weak and broad. This means the IF arrangements are different between the outer side and the inner side of the curl, suggesting the inhomogeneity of IF arrangement in the transverse direction. This inhomogeneity was observed for Merino wool, curly African, Caucasian and Asian hairs, but not for nearly straight Caucasian and Asian hairs.

Through analyses of equatorial scattering profiles with a model having closed packing of infinite cylinders [5], values of the IF diameter and the mean IF-IF distance are estimated. The degree of IF tilt against the fiber axis is also analyzed on the basis of the full-width at half maximum (FWHM) of the IF peak profile in the azimuthal direction. As a result, it has been found for curly hairs that the IF diameter is almost constant, but that the mean IF-IF distance decreases while the IF tilt angle increases from the inner side toward the outer side of the curl. These tendencies are consistent with those of wool fibers, which were speculated only qualitatively on the basis of TEM observation. In contrast, if the curl strength is very weak, not only the IF diameter but also the mean IF-IF distance and IF tilt angle are almost constant from the inner side to the outer side of the curl.

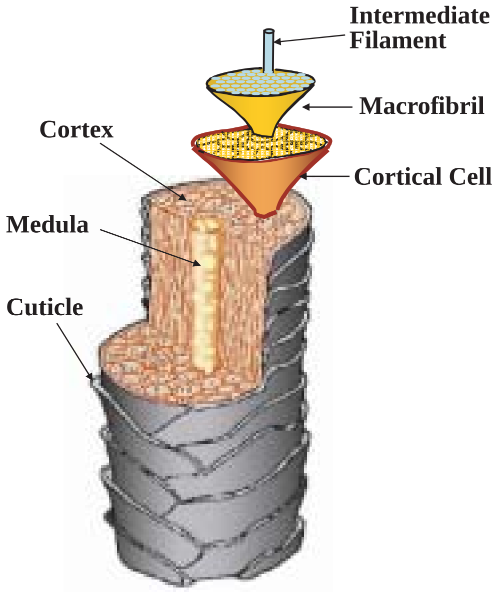

Fig. 1. Internal structure of human hair fiber.

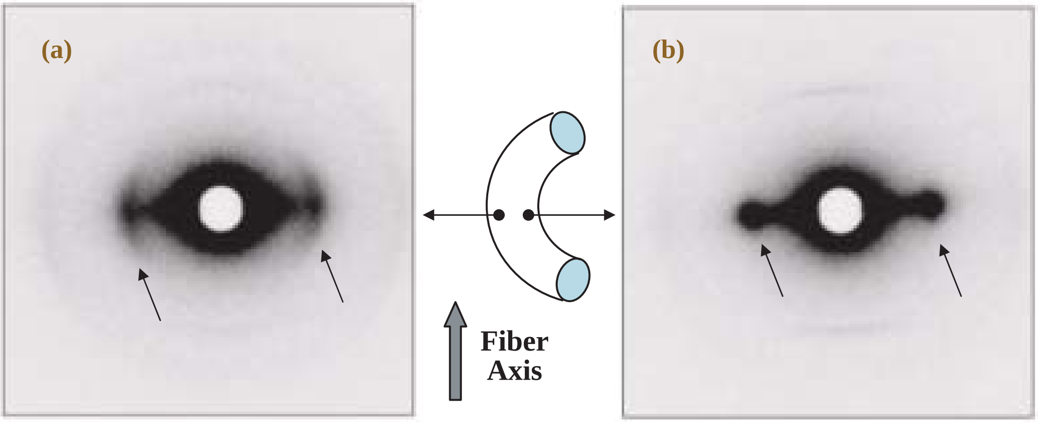

Fig. 2. SAXS patterns from outer side **(a)** and inner side **(b)** of strong-curl African hair.

In order to quantify the inhomogeneity in the transverse direction, we have introduced the index η, which represents the nanostructural difference based on the difference in the IF tilt angle between the inner side and the outer side of the curl. η is defined as the ratio of the averaged FWHM of the IF profile in the azimuthal direction in the outer side ($0.2 < P < 0.4$) to that in the inner side ($0.6 < P < 0.8$), where P is the relative position in the transverse direction from the outermost side ($P = 0$) to the innermost side ($P = 1$) of the curl. Data within the ranges 0.2 to 0.4 and 0.6 to 0.8 are likely to be a result of scattering from the cortex and will have no contribution from the cuticle or medulla.

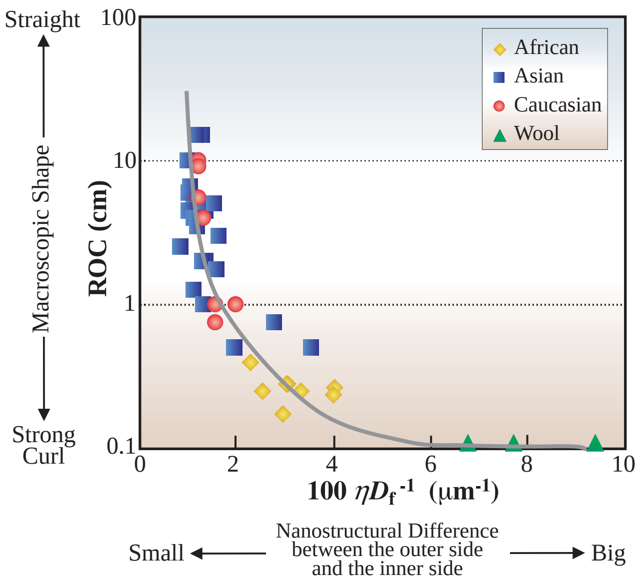

Fig. 3. Relationship between macroscopic curl strength (radius of curvature: ROC) and normalized η for microscopic inhomogeneity in transverse direction of fiber. ◆: African hair; ●: Caucasian hair; ■: Asian hair; ▲: Merino wool.

Figure 3 shows the relationship of macroscopic curl strength (radius of curvature: ROC) *vs.* η normalized by the fiber diameter D_f. The Caucasian and Asian hairs used in this study have a wide variety in their curl strength and overlap. The curls of African hairs are stronger than those of Caucasian and Asian hairs and Fig. 3 also includes the results for Merino wool fibers as an extreme case. It can be seen that the larger the nanostructural difference between the inner side and the outer side of the curl, the higher the macroscopic curl strength. Moreover, all the data points follow one smooth curve. This strongly suggests that the macroscopic curl strength depends on the microscopic inhomogeneity in the transverse direction of fibers, and that this relationship holds over all ethnic origins, including wool.

Takashi Itou[a,*], Yoshio Kajiura[a] and Yoshiyuki Amemiya[b]

[a] Hair Care Research Laboratories, Kao Corporation
[b] Department of Advanced Materials Science, The University of Tokyo

*E-mail: itou.takashi1@kao.co.jp

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