J. Cosmet. Sci., **60,** 637–648 (November/December 2009)

Changes in structure and geometric properties of human hair by aging

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Accepted for publication May 12, 2009.

Synopsis

To clarify hair changes by aging, the effect of age on hair properties was investigated from macro- to microscopic viewpoints. Sensory hair luster tests were performed on 230 Japanese females from 10 to 70 years of age, revealing that hair luster decreases with age. The age dependence of the hair diameter and the ellipticity of the hair cross section could not explain luster reduction by aging. It has been determined that an irregular increase in fiber curvature occurs with age and is a cause of luster reduction with aging. A detailed structural analysis by synchrotron radiation microbeam X-ray diffraction revealed that the inhomogeneity in the lateral distribution of the hair microstructure increased with age and relates to the irregular increase in curvature. Such an increase in curvature is one of the important factors that leads to a poor alignment of hairs and luster reduction, and is related to the appearance of aging hair.

INTRODUCTION

Human hair undertakes important roles, such as protection of the head and displaying an attractive personal appearance. People, especially women, care for their hair day-to-day and have a deep interest in their hair. Most consumers are aware of, and try to minimize, undesirable changes in hair properties. One of the causes of the critical effects on hair properties is aging.

The symptoms of aging appear everywhere in the body. Remarkably, they appear not only within the body, as in the decline in strength, but also in the skin. In the world of health care and cosmetics, a lot of research is aimed at anti-aging. However, studies of hair aging are relatively sparse. It is well known that hair grays and decreases in the number of fibers, and the fibers become finer with age (1–5). Several examinations reported that hair lipids are age-dependent and that some are related to the change from pre- to postmenopause (6–8). However, little is known about hair aging beyond these effects.

It is important to clarify actual hair changes by aging in terms of the physical properties and the structure of hair fibers. It is very difficult to continue research on the same individual for a long period of time. Thus, investigations on a large number of panelists are necessary for statistically significant results. For example, Ootsuka and Nemoto (3) showed the age dependence of hair diameter from research on a large number (18,262) of Japanese females and males even though the individual deviation was large. According to them, the diameter of female hair increased up to the age of 35 and decreased gradually past the age of 40. On the other hand, for males, it decreased with age after puberty.

Recently, Nagase *et al.* (9) presented a study of the variation in hair curvature in Japanese women. According to that study, about 47% of Japanese women have curved hair, from slightly wavy to frizzy, and their curl radius varies widely from 0.6 cm to 16 cm. By TEM observations and amino acid analyses on the convex and concave sides of curls, it was shown that the internal structure and amino acid composition in each side were different and that the trend of the difference had some similarities to highly crimped wool. The changes in hair shape and internal structure with age was, however, not reported.

In this current paper, through investigations on a large number of panelists, changes in hair appearance and macroscopic form, such as hair shape, are shown as they vary with age. To examine the cause of this hair-aging phenomena, the microstructural morphology in hair fibers has also been investigated. Recently, Kajiura *et al.* (10) analyzed the internal nanostructure in micro-areas of curly and nearly straight single human hair fibers of several races by small-angle scattering with an X-ray microbeam of synchrotron radiation. As a result, it was shown that the macroscopic curl shape of human hair is consistent with the inhomogeneous distribution of the internal microstructure. By applying this method, the microstructure of a number of hair fibers of various ages is examined in this study.

EXPERIMENTAL

PANELISTS

Two hundred thirty Japanese female panelists, ranging in age from 10 to 70, and with no permanent wave treatment in the last six months, were selected. The breakdown was: 21 panelists for each five-year period from the age of 10, except for the ranges of ages 20 to 24 (20 panelists) and 60 to 70 (21 panelists for the eleven years). Informed consent was obtained from all of the panelists.

EVALUATION OF HAIR LUSTER

Before the evaluation, a hair stylist shampooed and rinsed the panelists' hair with the same shampoo and conditioner, a simple formula without silicone and cationic polymers, and dried the hair with a hot dryer so as not to impose any tension on the hair. The sensory evaluations of hair luster were performed by a professional hair stylist and two hair researchers. The hair luster was evaluated in five grades from 1 (lusterless) to 5 (lustrous). Photographs of hair on the back of the head were taken with a digital camera (1632×2464 pixels) for each panelist to evaluate hair luster quantitatively. In order to take photos under the same lighting conditions, the two light sources (artificial sunlight, 100 W), the panelist's head and the digital camera were set at the same positions every time. Figure 1a is an example of this type of image. A bright luster belt is seen a little under the top of the head. The brightness (L) was calculated from the values of R, G, and B of RGB data with the equation of $L = 0.299R + 0.587G + 0.114B$, which is used to represent the brightness relating to the sensitivity of human eyes. The L of Figure 1a, from the top toward the hair tip, is shown in Figure 1b. Here this value of L is the average along the width of *ca*. 30% of head width (surrounded by a white rectangle in Figure 1a). The value of ΔL is defined as the hair luster value, where it is the difference in L from the brightest value (171 in Figure 1b) at the luster belt and the value at the baseline (38 in Figure 1b) so that it ties between the upper and lower positions of the luster belt, as in Figure 1b (dashed line).

HAIR SAMPLES AND THEIR CHARACTERIZATION

Hair fibers from the panelists were cut very close to the scalp for the analyses of hair properties and structure. For the measurements of diameter, hair fibers were obtained by cutting from 7-mm × 7-mm areas at the top of the head. Ten fibers were selected randomly around the top of the head for each panelist and were used for the measurement of hair fiber shape.

For 132 panelists from the 230 panelists above, hair diameter was measured with a rotating fiber diameter system equipped with a laser (Kato Tech Co. Ltd., Kyoto, Japan), at 20°C and 65% relative humidity. The shadow of the hair fiber was recorded while it was rotated at intervals of 30 degrees, and the orthogonal projection of the hair was measured. The maximum value was taken as the major axis and the minimum value as the minor axis of the hair fiber. Each fiber was measured at five positions at intervals of 1 mm along the fiber, and the mean values of the minor and major axes were calculated.

Hair curl radius was measured according to the method reported earlier (9). To remove any temporary water set, which is formed while a hair fiber dries and is caused by the

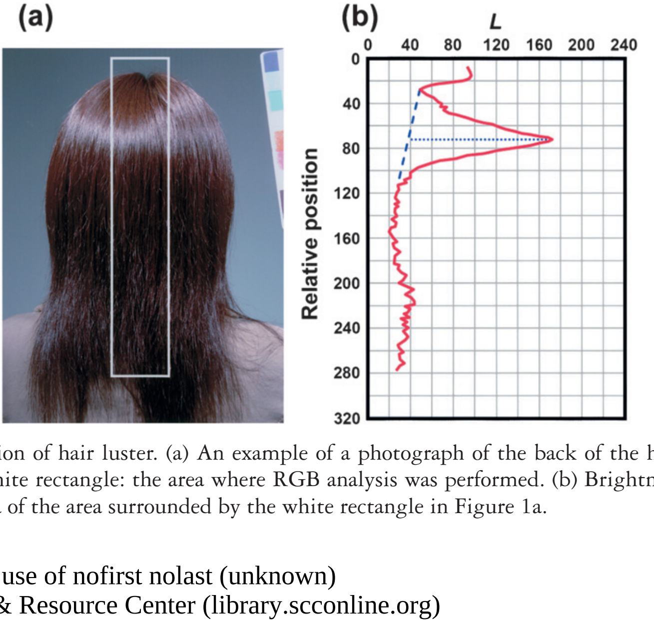

Figure 1. Evaluation of hair luster. (a) An example of a photograph of the back of the head taken with a digital camera. White rectangle: the area where RGB analysis was performed. (b) Brightness (L) calculated from the RGB data of the area surrounded by the white rectangle in Figure 1a.

exchange of hydrogen bonds, the hair fibers were immersed in water for 10 min at 25°C and dried on vibrating filter paper. By drying in this manner, hair does not have any tension that affects hair fiber shape. Hair fibers were put on an image scanner (Epson, Type GT-X800) and sandwiched softly with a bonnet, and then the two-dimensional image of the hair shape was obtained. Through the analysis of the two-dimensional image (9), the curvature at every 1-mm step along the trajectory, from the root along a 15-cm length, was calculated. In the case of the panelists who had had their hair permed, only the hair segment with no history of perming was used for the analysis. On the other hand, hair color hardly affects hair shape, and so the color-treated hairs were used for shape measurements with no distinction. The mean value of the curvature was used as an index of the curliness of the hair fiber.

STRUCTURAL ANALYSIS

For 82 panelists randomly selected from the 230 panelists above, two or three hair fibers were again randomly chosen (total of 187 fibers) to be analyzed for internal structure by microbeam X-ray scattering at beamline BL40XU of the synchrotron facility SPring-8 (Hyogo, Japan). The quasi-monochromated X-ray beam ($\Delta E/E \sim 0.02$; X-ray wavelength = 0.083 nm) from the helical undulator (11) was used in this study. An X-ray microbeam with a diameter of 5 μm was obtained by inserting a pinhole of 3-μm diameter 15 cm up-stream of the sample position. The parasitic scattering was removed by the second pin-hole inserted just before the sample position. The sample-to-detector distance and the X-ray exposure time were 1470 mm and 1.2 s, respectively. A cooled CCD, coupled with an X-ray image intensifier (Hamamatsu Photonics, Shizuoka, Japan), was used as a detector (12). Sample fibers were set out on a slotted mounting plate, at about 1-mm intervals, and then glued on to the plate at both ends such that the fibers were fixed under no tension. The plate was held on the stage so that the fiber's axis was perpendicular to the X-ray beam. The sample position, with respect to the X-ray microbeam, was changed in equal steps (5 μm), in the transverse direction of the fiber. The tilt angle of intermediate filaments against the fiber axis was estimated from the full-width value at half maximum (*FWHM*) of the scattering profile concerning intermediate filaments in the azimuthal direction (10,13). P is defined as the relative position in the transverse direction from the most convex side ($P = 0$) to the most concave side ($P = 1$) of the curl. Scattering data from both regions ($0 < P < 0.2$ and $0.8 < P < 1.0$) are possibly affected by the scattering from the cuticle. Thus, the parameter indicating the internal inhomogeneous distribution, $\eta 2$, is defined as the ratio of the averaged value of *FWHM* in the convex side ($0.2 < P < 0.5$) to that in the concave side ($0.5 < P < 0.8$).

STATISTICS

Statistical analyses were performed using regression analysis or Student's t-test. For scatter plots, regression analysis was used to obtain the correlation coefficient R and the p-value for the linear slope. For comparisons between values of two decennial age groups, Student's t-test was used. In both cases, p-values < 0.05 were considered statistically significant.

RESULTS

CLINICAL INVESTIGATION

From the sensory evaluation of hair luster by three evaluators, it was found that hair is more lustrous in young women than in elder women. Figure 2 shows the sensory hair luster scores of each decennial age group. Hair luster does not change significantly up to the 30s, but decreases afterwards. Figure 3 shows the age dependence of the hair luster value, ΔL. The hair luster value varies widely from panelist to panelist; however, it also decreases with age in general agreement with the sensory luster scores. This relationship is statistically significant at a very high level ($p = 3.0 \times 10^{-11}$), and the index of determination r^2 is 0.176, indicating that 18% of the variation in the hair luster (ΔL) is explained by variation with age.

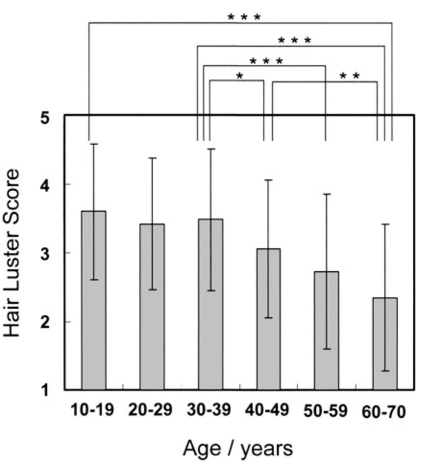

Figure 2. Age dependence of hair luster from sensory evaluations. The hair luster was scored by sensory evaluations on 230 randomly selected Japanese females ranging from age 10 to age 70. All panelists had not had their hair permed in the last six months. Bars with an error bar: mean ± SD of each decennial age group. Asterisks *, **, and *** represent $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively, obtained by Student's *t*-test.

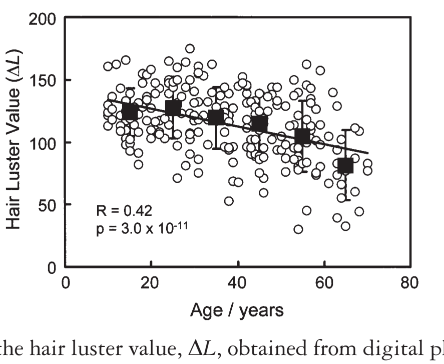

Figure 3. Age dependence of the hair luster value, ΔL, obtained from digital photographs of the back of the head. The panelists are the same as in Figure 2. The definition of ΔL is described in Experimental. Solid line: result of linearization. Filled squares with an error bar: mean ± SD of each decennial age group.

GEOMETRIC PROPERTY CHANGE BY AGING

In Figure 4, the hair diameter (minor axis) is plotted against age. These are the averaged values of all hair fibers sampled from a 7-mm × 7-mm area of the top of the head. Here, the hairs less than 5 cm in length are avoided so as not to count the newborn hairs. The hair diameter increases until the age of around 40, then decreases. This trend is consistent with the previous result on large numbers of Japanese females (3). This consistency suggests that the hair samples of this study are representative ones. In Figure 5, the ellipticity of a cross section, defined by the ratio of the major to the minor axis, is plotted against age, showing that it has no dependence on age. The average value 1.28 indicates that the hairs are relatively round, compared to values for Caucasian and Ethiopian hair (1,14). As shown in Figures 4 and 5, the age dependence of both hair diameter and ellipticity does not correlate with the decrease in hair luster with age, meaning that the luster reduction with age does not arise from the changes in fiber diameter or ellipticity.

Figure 6 displays examples of magnified photographs of the hair of three panelists and several hair fibers randomly sampled from them. For the youngest (25 years old) panelist (a), the appearance looks smooth and the bright luster belt around the top of the head is

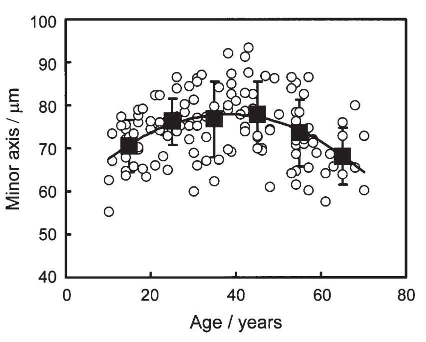

Figure 4. Age dependence of minor axis of a hair cross section measured at 20°C and 65% relative humidity for 132 randomly selected Japanese females. Each point is the average of all the fibers sampled from a 7-mm × 7-mm area of the top of the head for each panelist except for fibers less than 5 cm in length. Solid curve: quadratic approximation. Filled squares with an error bar: mean ± SD of each decennial age group.

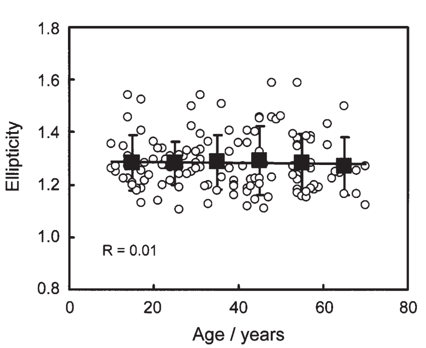

Figure 5. Age dependence of the ellipticity of a hair cross section (major axis/minor axis). The panelists and measured hairs are the same as those in Figure 4. Solid line: result of linearization. Filled squares with an error bar: mean ± SD of each decennial age group.

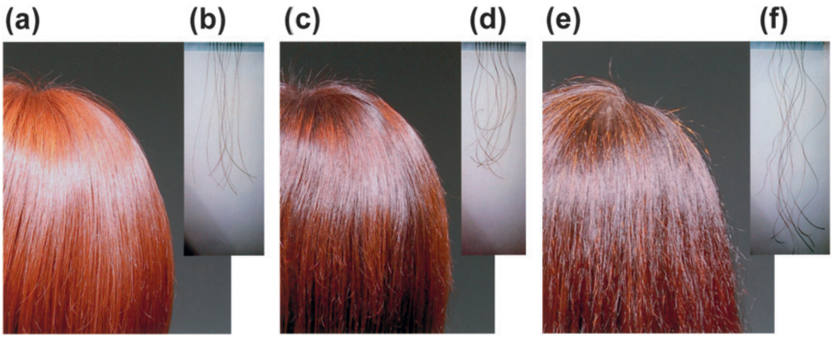

Figure 6. Examples of hair appearance (sensory luster) and hair fiber shape for three panelists. Parts a, c, and e: magnified back-shot images of hair appearance. Parts b, d, and f: hair fibers randomly selected from each panelist. The ages of the panelists are 25 for parts a and b, 40 for parts c and d, and 57 for parts e and f.

clear, but for the oldest (57 years old) panelist (e), the appearance looks dull and the luster belt is diffuse. The hair fibers of the youngest (b) are relatively straight, but the irregular curled shape increases with age (d,f). This shape difference is likely the cause of the uneven alignment of hair fibers that leads to the decrease in the luster of hair.

To clarify the actual change in hair shape with aging, measurements of the curl radius were performed on the hair fibers sampled from the 230 panelists. Figure 7 shows the age dependence of the mean curvature (reciprocal of the curl radius) for each panelist. It is seen that the hair curliness increases with age and that the slope of the line is statistically significant (p-value $= 9.9 \times 10^{-12}$). The index of determination r^2 is 0.185, indicating that 19% of the variation in mean curvature is explained by variation with age.

INTERNAL STRUCTURE OF HAIR

In order to understand the cause of this irregular curl shape of hair fibers with aging, small-angle X-ray scattering measurements were performed. By moving the target position of the X-ray microbeam on a hair fiber from the convex side to the concave side of the curl, it was possible to detect microscopic unevenness of the nanostructure in the

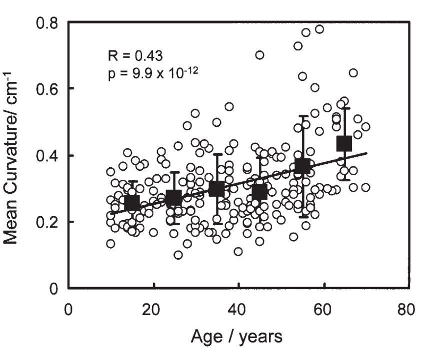

Figure 7. Age dependence of the mean curvature of hair fibers for the same panelists an in Figure 3. These points are the averages of ten fibers randomly selected from the top of the head. Solid line: result of linearization. Filled squares with an error bar: mean ± SD of each decennial age group.

transverse direction. Figure 8 shows the age dependence of $\eta 2$, the degree of inhomogeneity in microstructural distribution. These points are the average value for each panelist. Data points again vary widely, but the linear regression line has a statistically significant positive slope (p-value = 0.030). This means that the internal inhomogeneity becomes larger with increasing age. The index of determination r^2 is only 0.058, indicating that 6% of the variation in the cross-sectional inhomogeneity is explained by variation with age. According to comparisons between the data of two decennial age groups, however, the data of the 10s and 60s and those of the 20s and 60s showed $p = 0.021$ and $p = 0.011$, respectively, indicating significant differences between these age groups.

DISCUSSION

CAUSE OF LUSTER DECREASE WITH AGING

It is well known that the parallel alignment of hair fibers of an assembly contributes greatly to hair luster. It is also well known that increasing fiber curvature interferes with the parallel alignment of hairs and therefore decreases hair luster. Keis *et al.* (15) have also shown that fiber twists and kinks are also important to hair luster. Furthermore, to determine the luster of curly or frizzy hair tresses special techniques are required (16).

The age dependence of hair luster and the mean curvature of hair fibers (Figures 3 and 7) is in agreement with the known relationship between hair luster and hair curvature. This is illustrated in Figure 9. Hair luster is dependent on the mean curvature of hair fibers (p-value = 6.7×10^{-11}), and so it can be said that as the curvature of the fiber increases with age, it causes a reduction in hair luster. The index of determination of this relationship is 0.176, indicating that 18% of the variation in the luster (ΔL) is explained by variation in the mean curvature. The data points in Figure 9 are scattered. This data scatter suggests that other factors are involved in affecting hair luster with age. The lifting up of cuticles at the hair surface, gray or less-pigmented hairs, and a porous medulla are possible reasons (1,17–19). For aged persons, the dull hair appearance may be due to a combination of these factors.

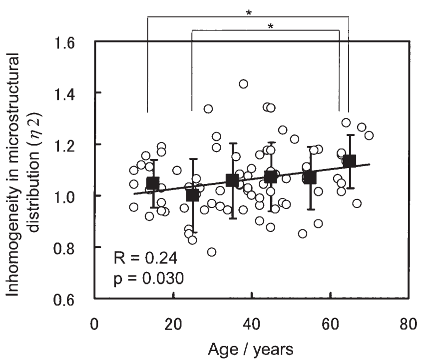

Figure 8. Age dependence of inhomogeneity in microstructural distribution, $\eta 2$, for 82 randomly selected Japanese females. $\eta 2$ is the ratio of the averaged value of *FWHM* that relates to the IF tilt angle in the convex side to that in the concave side (see Experimental). Solid line: result of linearization. Filled squares with an error bar: mean ± SD of each decennial age group. Asterisks * represent $p < 0.05$ obtained by Student's *t*-test.

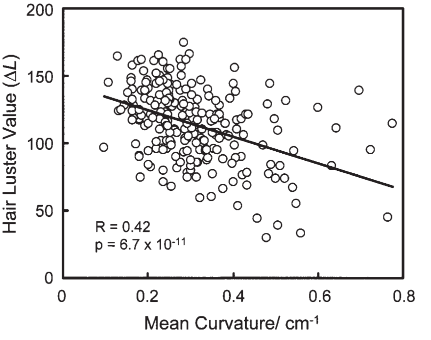

Figure 9. The relationship between the hair luster value and the mean curvature. The measured panelists and the hair fibers are the same as those in Figures 3 and 7. Solid line: result of linearization.

There is some evidence that non-pigmented hairs (gray hairs) are coarser and more wavy (1,20) than heavily pigmented hairs. The ratio of panelists who have gray hairs, as a matter of course, increases with age in this study. According to this consideration, the increase in the hair curvature might come from the increase in gray in heavily pigmented hairs. The curvature values were, therefore, separately evaluated for pigmented hair and gray hairs. Many panelists had had their hair colored, but we could distinguish gray hairs from pigmented hairs by examining the root part of the hair fiber. Thirty-seven panelists had gray hairs in the ten fibers selected from the top of their head for the measurement of curvature. The mean values of curvature for the pigmented hairs (252 fibers) and the gray hairs (107 fibers) were 0.39 ± 0.14 cm^{-1} and 0.33 ± 0.15 cm^{-1}, respectively, and the difference is not statistically significant. This result suggests that the curliness is independent of the existence of pigments in hair. However, it has been shown that hair pigment and hair color increase hair luster (21); therefore, a decrease in pigmentation must account for part of the decrease in luster that we observed upon aging.

CONSIDERATION ABOUT ORIGINALLY CURLY HAIR

In this paper we have examined ordinary Japanese hair, which is characterized by a relatively straight shape. Shape variation on aging, however, seems to occur in the hairs having a more curly shape originally. It is a future research issue to determine fiber shape change on aging in other ethnic groups. The widely ranging longitudinal shape observed in aging Japanese females in this study, as shown in Figure 6, varies from fiber to fiber. With aging, even Caucasian or African hairs are expected to show more variation in shape, although this hypothesis should await further experimentation.

INTERNAL STRUCTURE IN IRREGULARLY CURLED HAIR BY AGING

Figure 10 shows the relationship between the curl radius (= 1/curvature) and the inhomogeneity in microstructural distribution, $\eta 2$. Figure 10 includes the data of three ethnic origins and Merino wool, as has been presented earlier (10). All data points follow one smooth curve, and this suggests that the curliness of human hair fibers is related to the

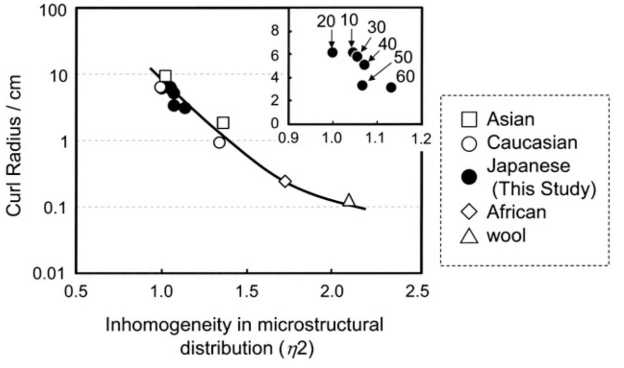

Figure 10. Relationship between the curl radius and inhomogeneity in microstructural distribution, $\eta 2$. Data of African hair (diamond), Caucasian hair (open circle), Asian hair (square), and Merino wool (triangle) are the same as reported by Kajiura *et al*. (10). Filled circles are the average values of each decennial age group in this study. The inset is an expansion of the results of this study in linear scale. Ages are given for each point.

inhomogeneity in microstructural distribution, regardless of the ethnic origin. The results of this current study are displayed by the filled circles in Figure 10. These are the averaged values of each decennial age group. Since the curly shape generated by aging is not very large, the data points are grouped at the upper left of the figure and they follow the currently described relationship. The inset is an expansion of these results in linear scale. It can be seen that the curl radius decreases with age, indicating that the relationship between curliness and age holds, even for the sample group selected for this X-ray study. Clearly the inhomogeneity in microstructural distribution becomes larger as the curl radius decreases. From these results, it is suggested that the widely varying shape of hairs and the curliness increase with age and are consistent with the inhomogeneity of the internal structure.

Nagase *et al*. (9) found morphological differences in the macrofibrils between the convex and concave regions of hair fiber curls, and different amino acid compositions between them also. Bryson *et al*. (22) found this difference in the arrangement of intermediate filaments between the convex side and the concave side by electron tomography. These differences between the convex side and the concave side are similar to those of orthocortical cells and paracortical cells in wool fibers, respectively. Considering that the varying curvature of hair due to aging has an internal structure similar to that of curly hair suggests a similar distribution of ortho-type and para-type cortical cells. The formation and distribution of these cortical cells are controlled in the hair follicles. Although the key factors relating to their formation and distribution have not been revealed, they could be different among different ethnic origins and could also be changed by aging. The mechanism of the inhomogeneous distribution due to aging could be different from the case of curly hairs of different ethnic origins. When the mechanism is clarified and a method to control it is understood in the future, it might provide a means to depress hair aging and might provide the ability to have more lustrous-appearing hair.

CONCLUSIONS

The hair luster of Japanese females decreases with aging. Aging increases the inhomogeneity in the microstructural distribution in hair fibers, and as a result hair curvature increases. This is one of the large factors in the decrease in hair luster with aging, along with other factors such as the graying of hair or reduction of the pigment in some hairs.

ACKNOWLEDGMENTS

A part of the research shown here is a result of the Industrial Application Proposal of SPring-8 (Proposal No.2007A1886). We express our appreciation to Dr. Naoto Yagi, Dr. Katsuaki Inoue, and Dr. Noboru Ohta of JASRI, who supported the experiment. We also thank Ms. Fukuda and Mr. Taguchi of Kao Corporation for their help in collecting 132 panelists and in the sampling of hairs for the measurement of diameter.

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