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Normal cuticle-wear patterns in human hair

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Synopsis

A quantitative study of CUTICLE-WEAR PATTERNS in HUMAN HAIR from six Caucasian subjects whose hair had only been subjected to normal wear—*i.e.*, no chemically reactive cosmetic treatment—is presented. The data was collected by counting the number of cuticle cell layers at different positions along the length of hair fibers. The counting was done on cross-sectional cuts by means of a Scanning Electron Microscope. Results are analyzed in terms of a mathematical model of cuticle wear. The similarity among the cuticle-wear patterns from the different subjects suggests that, under normal wear conditions, there is a common general pattern of cuticle wear in human hair. A theoretical rate of cuticle wear versus distance from the scalp expression was derived. This expression excludes age *per se* as a major factor in cuticle wear, and points instead to a source of hair surface wear which accelerates as we get closer to the hair ends. An analysis of combing forces showed that the type of damage known to be produced by combing can account for the shape of the observed cuticle-wear patterns. It was also found that beyond a certain length human hair should appear to be growing slower due to a cuticle-loss-fracture mechanism, a consequence of this being that, under otherwise equal conditions, the care with which hair is treated and handled directly affects the maximum length that it can attain.

INTRODUCTION

It is well known that the cortex of human hair is surrounded by layers of cuticle cells. These cells, which are flat and very thin, are wrapped around the cortex, building up a system of concentric layers that overlap in telescopic fashion. This assembly of cells is referred to as the cuticle. By virtue of being the outermost section of the hair, the cuticle is subjected to a multitude of environmental influences which cooperate towards its gradual destruction. Many of these, such as exposure to the sun and washing, are the same ones that contribute to the deterioration of the surface of fibers in fabrics. Others, such as combing, brushing, setting and cosmetic chemical treatments, are more unique to hair. Fortunately, the multilayer structure of the cuticle is such that, when under normal mechanical and chemical wear small fractions of the cuticle cells fracture and separate from the hair, they leave behind a fresh uneroded surface belonging to the cell below. This clever scheme of nature allows hair that has been on a living head for two or three years to still have an appealing unworn surface.

From an aesthetic point of view, the importance of the cuticle cannot be overemphasized. Since it serves as the optical surface through which hair interacts with light, the structure and state of preservation of the cuticle determine the extent to which incident light is reflected, scattered, and transmitted, thus determining to a great degree the pleasing appearance of human hair (1,2). As the surface through which hair makes physical contact with other bodies and with itself, its frictional properties determine how hair feels to the touch and how it combs, handles and styles. Structurally, the cuticle contributes critically to the preservation of the physical integrity of hair fibers. Without the radial mechanical constraint of the cuticle, the microfibers in the cortex would rapidly break apart just from the everyday handling of the hair. The potentially important contribution of the cuticle to the mechanical properties of human hair and its effect on the overall rates of chemical treatment of the hair have been brought to our attention by Wolfram and Lindeman (3).

The structure of individual cuticle cells and of the cuticle as a whole has been extensively studied and considerable progress has been made (4–12). In most of these studies, however, with some exceptions [for example, Swift and Brown (14,16), Bottoms, *et al.* (13, 15,17)] the cuticle has been treated as an unchanging structural component of the hair; the subject of its wear receiving little attention. At an average rate of growth of 5 in. per year, the tip ends of the hairs on a female head can typically be two to three years old. During this time, and just due to normal handling, the five to ten cuticle cell layers that hair has when it emerges from the scalp will have gradually been worn away, and we frequently find that very close to its tip the hair shows an exposed cortex with very few or no cuticle cells left. This phenomenon is very likely accelerated if the hair has been subjected to strong chemical treatments.

Because of the important roles of the cuticle, a study of its wear has potential use in understanding and improving the performance of cosmetic hair products. This, coupled with the scant information on the subject, initiated this work in our laboratories. The results of the first step of this investigation, consisting of a study of cuticle-wear patterns on human hair from six female subjects whose hair had only been subjected to normal wear—*i.e.*, no chemically reactive cosmetic treatments—are presented in this paper. Also included is a mathematical analysis of the data which rendered some interesting insights into the phenomena of cuticle wear and its likely connection with combing damage.

EXPERIMENTAL

The experimental work consisted of examining hair fibers longitudinally and cross-sectionally at predetermined distances from their root ends by means of a Scanning Electron Microscope. Hair from six Caucasian subjects was used. The participating females had been letting their hair grow long for at least two or three years prior to our sampling. That is, they had not been cutting their hair with the possible exception of occasional trimmings near the ends to eliminate split ends, etc. The ends of their hair were approximately even. Ten fibers per subject were examined. For each subject, the longer hairs in the scalp were chosen for our work. This normally meant hair with root ends in the uppermost parietal regions of the scalp. The hair samples were obtained by cutting the hair as close as possible (1 to 2 mm) to the scalp. Distances along hair shafts from where this cut was made are indiscriminately referred to in what follows as either distances from root end or distances from the scalp. None of the subjects had treated their hair with chemically reactive cosmetic products (lighteners, permanent waving products, oxidation dyes, etc.) for at least five years prior to sample gathering. The hair had thus only been subjected to what we call normal wear, which includes shampoos, soap, water, sea water, water settings, hair dryers, hot rollers, combing, brushing, sun exposure and exposure to the atmosphere.

Table I contains general information on the subjects participating in this study.

Table I
Subject Summary

Subject	Sex	Age (Years)	Approximate Maximum Hair Length (cm)	Hair Color
1	F	25	60	Blonde
2	F	30	60	Blonde
3	F	15	40	Blonde
4	F	29	40	Brown
5	F	8	30	Brown
6	F	20	30	Brown

After sampling, the hair was shampooed with a commercial shampoo[1], rinsed with distilled water at room temperature for 10 min, allowed to dry at ambient temperature and prepared for examination. The hair fibers that were 30 cm long were sampled at 15-cm intervals, and the fibers 40 and 60 cm long were sampled at 10-cm intervals from the root end. Sample preparation consisted of cutting 1.5-cm-long segments from the fibers at the above intervals and then from each segment cutting $\approx$50-μm-thick cross sections for internal examination, using hand-held, single edge industrial razor blades and aided visually with an American Optical Model 46 stereoscopic microscope. The remaining portion of the segment was used for external examination. The hair specimens were then mounted on aluminum sample stubs 1.4 cm in diameter, using conductive silver paint.

The specimens were metal coated with a 10 to 20 nm layer of Au-Pd (60 per cent Au—40 per cent Pd). This continuous uniform coating suppresses charging of the non-conductive biological specimen and increases electron emission from the sample surface. A JEOLCO Model JEE-4B vacuum evaporator was used to metal coat the specimens at a vacuum of 4×10^{-5} torr.

The specimens were examined by secondary electron emission in a JEOLCO Model JSM U-3 Scanning Electron Microscope at an accelerating voltage of 15 kv. Photomicrographs of the image displayed on the cathode ray tube were taken with Polaroid 4×5 in., Type 52 film using a JEOLCO Model SMU 3-CS1 camera. Using these photomicrographs, the following information was obtained for each of the hair sections examined.

NUMBER OF CUTICLE CELL LAYERS

Cuticle cell layers were counted, using photomicrographs taken at the edge of cross sections at magnifications of the order of 10,000 X. At least five cross-sectional cuts were

[1]Clairol herbal essence shampoo for normal to dry hair.

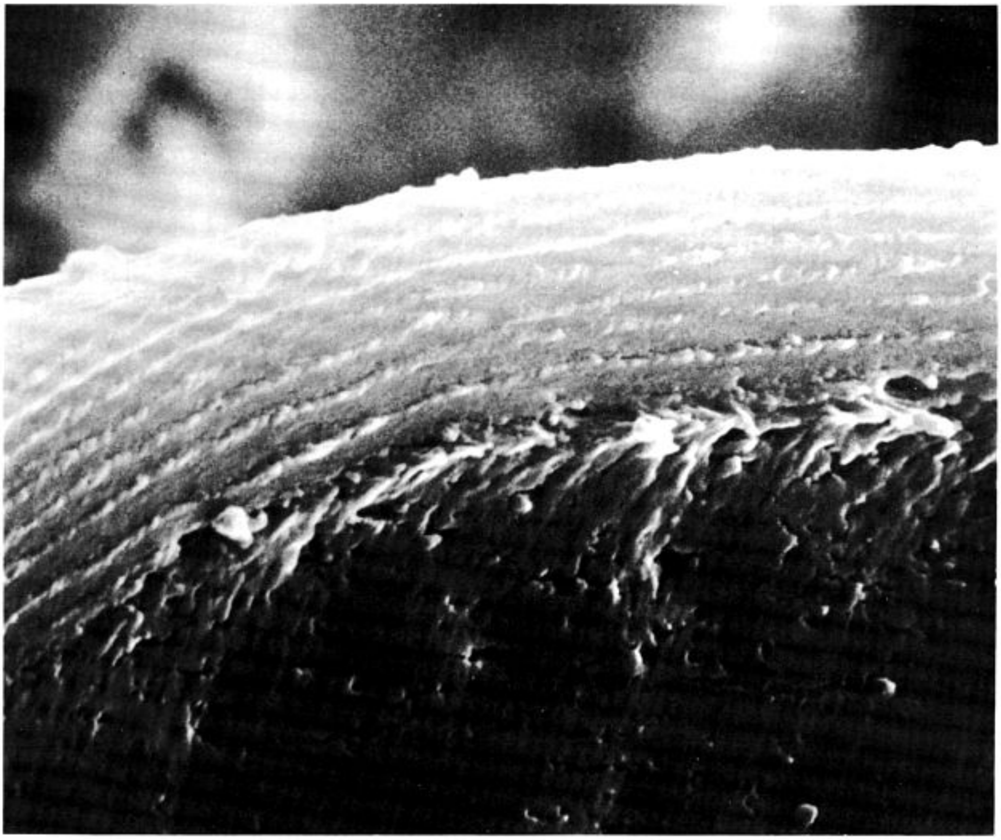

Figure 1. Photomicrograph of edge of a cross-sectional cut of a hair fiber at the root end taken at the magnification (10,000X) that was used to count number of cell layers. Eight cuticle cell layers can be counted

examined at each of the distances from the scalp for each hair. The value recorded as the number of cuticle cell layers for that distance was the maximum number of layers that could be unequivocally counted in any of the cuts among the five examined. Figures 1 and 2 are photomicrographs of the edges of cross-sectional cuts typical of the ones used to count the number of cell layers.

MINOR AND MAJOR AXES, ELLIPTICITY AND CROSS-SECTIONAL AREA

The major axis was determined by measuring the length of the longest possible straight line drawn from one side of the photomicrographed cross section to the other passing through the center of the cortex. The minor axis was determined by measuring the length of a straight line drawn perpendicular to and bisecting the major axis and extending from one side of the photomicrographed cross section to the other. Obviously, the magnification used is taken into account. The ellipticity was calculated by dividing the minor axis by the major axis.

The cross-sectional areas were determined by measuring the areas of the cross-sectional views on the photomicrographs. This was done by cutting the outline of the cross-

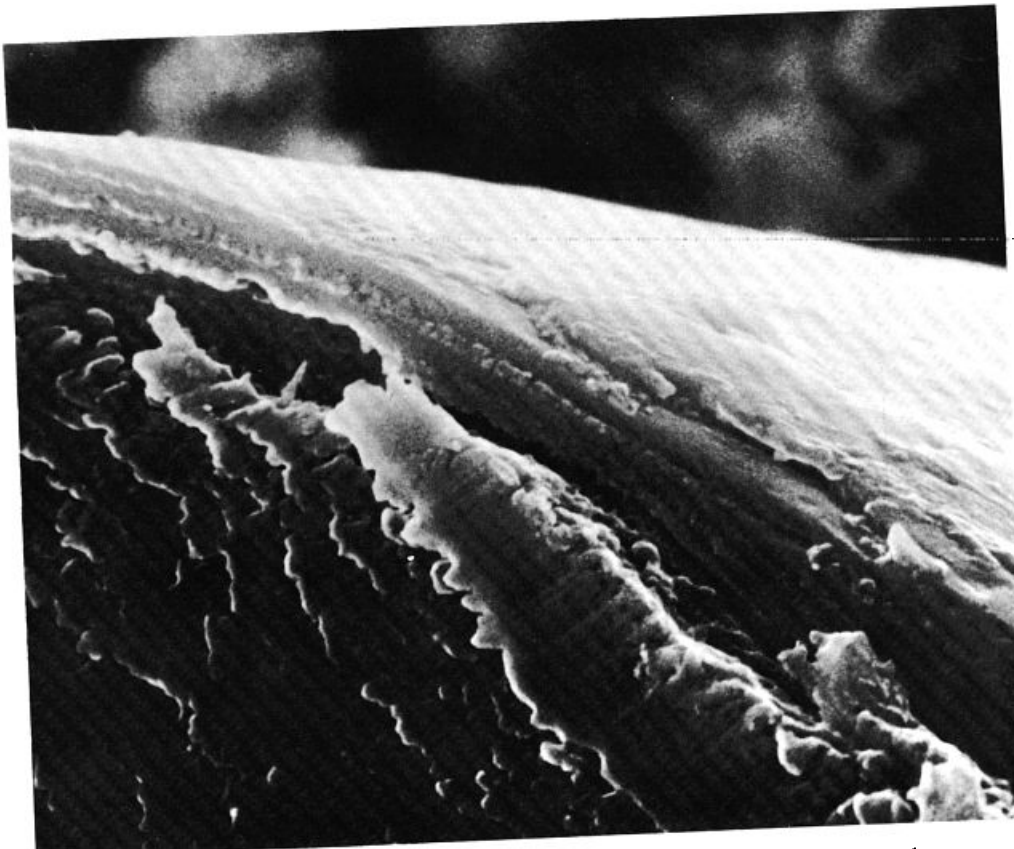

Figure 2. Photomicrograph of edge of a cross-sectional cut of a hair fiber at 40 cm from the root end of a 60-cm-long hair (taken at 10,000X). Four cuticle cell layers can be counted

sectional views and weighing the cutouts with an analytical balance. The actual areas were then calculated, taking into account the magnification used (usually 1,000 X) and the weight per unit area of the Polaroid print paper. This method was chosen because it is more accurate than the one involving the use of the major and minor axes of the cross sections and the formula for the area of an ellipse. The S.E.M. magnification on the photomicrographs was checked using a calibrated grid.

RESULTS

The data in Table II corresponds to three of the ten hairs that were examined from Subject 1. It illustrates the type of natural variability found from hair to hair within a subject. Table III contains the average value for the ten hairs examined for each subject.

CROSS-SECTIONAL AREA AND ELLIPTICITY

The cross-sectional area values are of interest because they do not show a reduction in going from the root to the tip end of the fibers as could be expected due to cuticle loss if the cortex dimensions did not change in the process. Actually, small increases were observed in the hairs of some of the subjects examined.

Table II
Subject 1

Hair	Distance From Root End (cm)	Number of Cuticle Cell Layers	Major Axis Length (μm)	Minor Axis Length (μm)	Ellipticity	Cross-Sectional Area (μm^2)
2	0	8.	99.	63.	0.636	5.15×10^3
	10	8.	102.	81.	0.794	6.49×10^3
	20	6.	96.	66.	0.687	5.09×10^3
	30	5.	97.	67.5	0.696	5.33×10^3
	40	4.	101.	75.	0.743	6.19×10^3
	50	1.	102.	73.3	0.718	6.33×10^3
	60	0.5	97.7	73.3	0.750	5.83×10^3
3	0	7.	93.5	69.5	0.743	5.38×10^3
	10	6.	95.5	73.3	0.767	5.23×10^3
	20	6.	115.	104.	0.904	6.33×10^3
	30	4.	104.3	69.9	0.670	6.02×10^3
	40	2.	95.	74.	0.779	5.70×10^3
	50	2.	86.	54.	0.628	4.34×10^3
	60	0.	83.	70.	0.843	4.66×10^3
5	0	7.	93.	73.	0.784	5.37×10^3
	10	7.	94.	73.	0.776	5.80×10^3
	20	6.	102.	71.	0.696	5.99×10^3
	30	5.	113.	76.6	0.678	7.14×10^3
	40	4.	100.	65.	0.650	5.55×10^3
	50	1.	95.	69.	0.726	5.29×10^3
	60	0.	92.	60.	0.652	4.95×10^3

A calculation was made of the percentage of the hair volume (or cross-sectional area) which corresponds to the cuticle layer at the root end of the hair. This was done by measuring the areas corresponding to the cuticle and cortex on cross section photomicrographs. The average results for the ten hairs for each subject appear in Table IV.

The fact that percentage reductions in cross-sectional area values of the order of magnitude shown in Table IV are not observed shows that the cortex of human hair expands radially during its lifetime on a human head. The reason is likely to be a reduction in radial constraining forces due to cuticle loss, coupled with internal mechanical and chemical damage to the cortex through normal wear. The average percentage increase in the cross-sectional area of the cortex for all our subjects' hairs can be calculated to be approximately 15.0 per cent. This expansion of the cortex should give rise to a reduction in its bulk density of the same order of magnitude. This phenomenon is probably very closely associated with "overporous" behavior towards dyeing and other treatments in human hair.

The cross-sectional area values *vs.* distance from the scalp for each subject appear to follow a pattern characterized by an initial increase in area followed by decreasing values. No simple explanation can be offered for this pattern unless it is due to hair diameter growth variations.

The ellipticity of the hair used in our study was in the range of 0.635 to 0.853. No trends could be seen for the changes in ellipticity along the hair length. Neither were trends detected for the values of the minor and major axes along the length of the fibers.

Table III
Average Results (Ten Hairs per Subject)

Subject	Distance From Root End (cm)	Number of Cuticle Cell Layers*	Major Axis Length (μm)	Minor Axis Length (μm)	Ellipticity**	Cross-Sectional Area (μm^2)
1	0	7.0 ±0.58	97.0	73.3	0.758	5.69×10^3
	10	6.7 ±0.59	97.7	76.8	0.781	5.79×10^3
	20	5.6 ±0.96	104.1	75	0.714	5.95×10^3
	30	5.0 ±0.67	99.8	80.5	0.739	5.96×10^3
	40	3.7 ±0.90	98.5	74.1	0.758	5.87×10^3
	50	2.4 ±0.75	97.6	74.0	0.732	5.58×10^3
	60	0.4 ±0.48	94.1	70.0	0.741	5.33×10^3
2	0	7.1 ±0.79	85.1	53.4	0.635	3.64×10^3
	10	6.5 ±0.51	83.4	53.0	0.683	3.97×10^3
	20	6.0 ±0.34	84.4	54.4	0.653	3.95×10^3
	30	5.5 ±0.61	85.5	55.3	0.647	3.75×10^3
	40	4.5 ±0.77	82.5	54.1	0.656	3.76×10^3
	50	2.6 ±0.96	82.9	52.9	0.647	3.58×10^3
	60	1.2 ±1.25	82.9	54.0	0.661	3.67×10^3
3	0	6.4 ± 0.37	74.3	46.8	0.698	3.12×10^3
	10	5.7 ± 0.59	78.7	51.4	0.654	3.32×10^3
	20	4.8 ± 0.56	73.6	48.3	0.604	3.31×10^3
	30	3.3 ± 0.48	81.2	50.2	0.617	3.40×10^3
	40	0.4 ± 0.33	78.1	49.4	0.632	3.24×10^3
4	0	8.7 ± 0.48	67.3	48.1	0.733	3.01×10^3
	10	7.7 ±0.68	66.1	51.2	0.777	3.13×10^3
	20	6.8 ±0.56	71.5	50.0	0.713	3.32×10^3
	30	5.5 ± 0.61	67.1	54.0	0.816	3.40×10^3
	40	2.5 ± 1.22	63.2	51.9	0.756	3.23×10^3
5	0	6.4 ± 0.50	64.2	53.7	0.853	2.79×10^3
	15	3.5 ± 0.84	69.5	56.1	0.804	3.27×10^3
	30	0.3 ± 0.25	67.7	53.6	0.815	2.93×10^3
6	0	6.0 ± 0.39	76.4	57.9	0.763	4.03×10^3
	15	4.3 ± 1.02	82.0	64.5	0.768	4.30×10^3
	30	1.3 ± 0.93	80.9	59.2	0.711	4.06×10^3

*The ± values correspond to the 95 percent confidence level limits of the averages.
**These values are the average of the individual ellipticity values for each of the ten fibers.

CUTICLE-WEAR PATTERNS (C.W.P.)

External observation of the hair fibers revealed the same findings of previous studies (13, 14); that is, the edges of the cuticle cells which are smooth and rounded close to the root ends gradually become sharp, irregular and jagged as we move toward the tip ends.

Table IV

	Sub. 1	Sub. 2	Sub. 3	Sub. 4	Sub. 5	Sub. 6
Percentage of volume (or of Cross-Sectional Area) corresponding to cuticle layer at root end	13.5	12.1	11.4	19.1	17.1	14.4

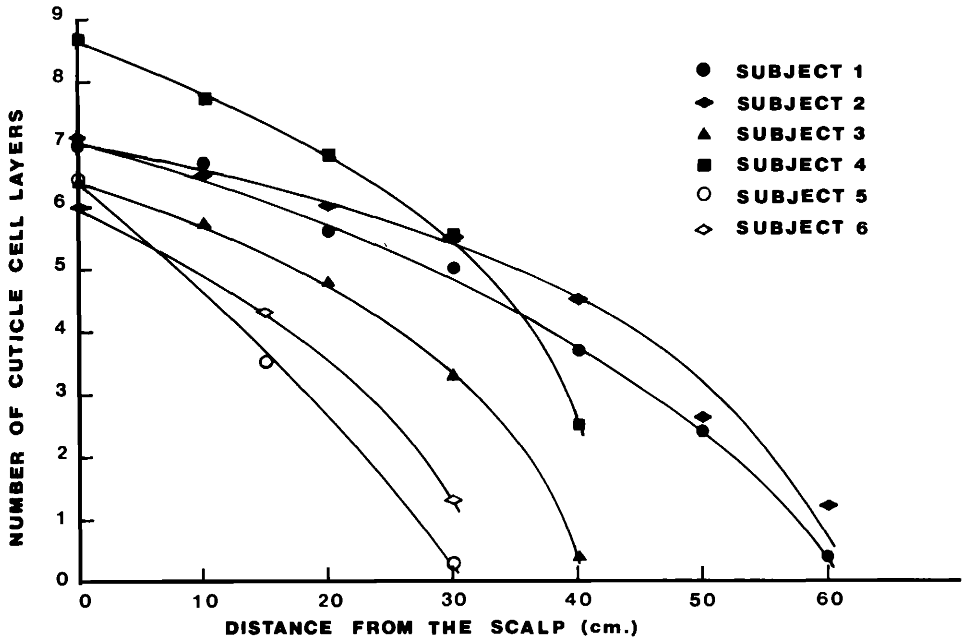

Figure 3. Average number of cuticle cell layers *vs.* distance from the scalp for hair of each of the six subjects. Solid lines were visually fitted to the data points

If we analyze the number of cuticle cell layers (C) *vs.* distance from the scalp (x) data (Table III), we find interesting similarities among the hairs from different subjects (Figure 3). These patterns are the net result of years of cuticle wear. If we assume that there can be something in common among them, the common factor does not appear to be the age of the specific sections of the hair at different distances from the scalp. If this were the case, we would expect that cuticle-wear patterns from different subjects could, if corrected for the different number of cuticle cell layers at the scalp level, fall approximately on top of each other. This, however, is not the case with our data. That is, if cuticle-wear patterns are displaced vertically so that the number of cuticle cell layers at the scalp level are arbitrarily made to coincide for all of the subjects, it can easily be seen, for example, that hairs that are 30 cm long have lost many more cuticle cell layers at their ends than 60-cm-long hairs at a distance of 30 cm from the scalp.

In thinking of ways of analyzing this data, we found that if the number of cuticle cell layers is plotted against the distance from the scalp (x) divided by the length of the hair (L) and if the curves are displaced vertically so that they all start with the same number of cuticle cell layers at the scalp, the similarity among wear patterns for different subjects becomes more apparent (Figure 4). We became interested at this point in determining what type of relationship must exist between rates of cuticle wear and distance from the scalp in order to generate the apparent common cuticle-wear pattern observed in our data. For this purpose, we had to develop a mathematical model for cuticle wear. This was facilitated by fitting an empirical equation to the data from the six female subjects' hair using a least-squares method with the aid of a computer. The curve fitting was done considering the data from the six subjects as belonging to the same population. The result was

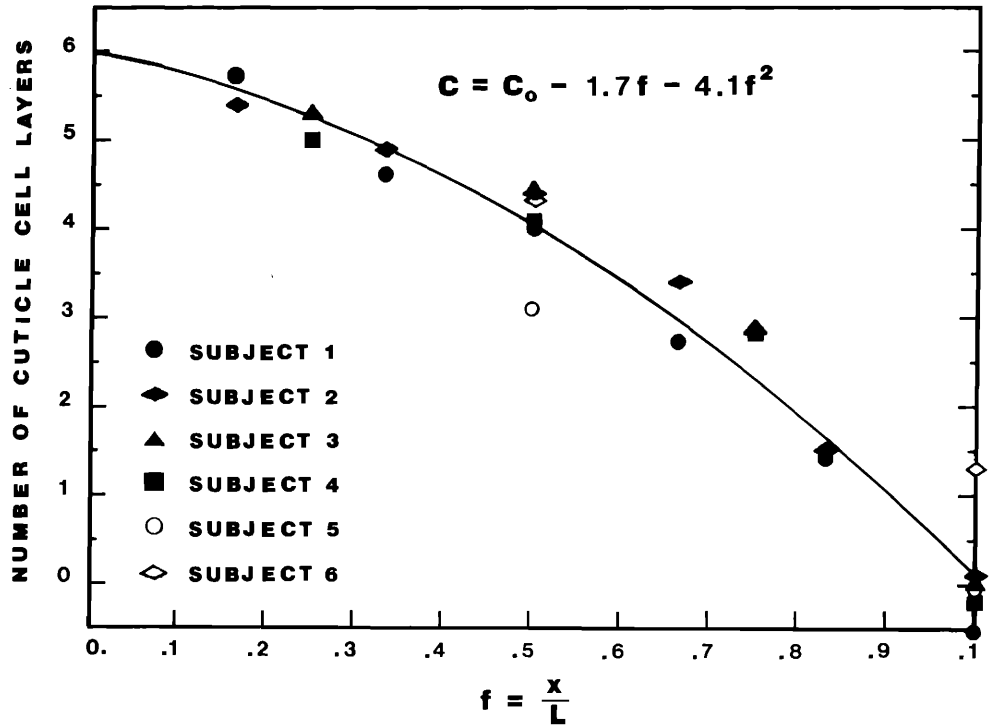

Figure 4. Average number of cuticle cell layers (corrected for the differences in the number of cuticle cell layers at the root end) *vs.* fractional distance from the scalp (f). Solid line is a graph of the empirical equation (shown in figure) statistically fitted to the data from all subjects

$$C = C_0 - 1.7f - 4.1f^2 \qquad [1]$$

where C_0 = number of cuticle cell layers at the scalp

$f = \frac{x}{L}$

L = observed length of the hairs

and 1.7 and 4.1 = empirical parameters.

Equation [1] (solid line, Figure 4) fits the data to within approximately ± 0.5 cuticle cell layers, which is of the order of the uncertainty in the number of cuticle cell layer average values shown in Table III arising from the natural variability of this parameter from hair to hair. It should be emphasized that this is only an empirical equation and that other mathematically different functions can be fitted to this data.

At any specific time, not all of the hairs on a scalp are growing or are being subjected to cuticle wear at the same rate. Differences in rates of hair growth result from the different life cycles of the individual follicles. Variations in the instantaneous rates of cuticle wear result from the different position that each hair occupies on the scalp. Even more important is the variation due to the intrinsically random nature of the wear phenomena of a large number of fibers constantly changing spatial distribution and configuration. However, at any specific time, for any one person, a value will exist for the average rate of growth of all of the fibers on the scalp and also for the average rate of cuticle wear at any distance from the scalp for all of the fibers. The analysis that follows was done by focusing on one hypothetical hair fiber which is assumed to be growing at the average rate and experiencing the average rate of cuticle wear of the large population of fibers to which it belongs. The cuticle-wear dynamics of this hair thus describes that of the parent hair population. The minimal amount of available data on rates of human hair growth as a function of the different stages of the follicle life cycles, hair length, etc., precludes a more detailed analysis that would take those factors into consideration.

If we consider the changes in C taking place simultaneously in an element (H) of this hypothetical hair located within the fixed distances of x and x + Δx from the scalp, and assume that

a) the average rate of hair growth (for all fibers) is constant and
b) the average rate of cuticle loss (for all hairs) at any time t and distance from the scalp x can be treated as varying in a continuous fashion and corresponds to the time averages of all factors affecting cuticle wear,

we can derive the following differential equation describing the dynamics of cuticle wear (see Appendix for details).

$$\left(\frac{dC}{dt}\right)_N = -\frac{dC}{dx} \cdot \frac{dx}{dt} - \left(\frac{dC}{dt}\right)_W \qquad [2]$$

where $\left(\frac{dC}{dt}\right)_N$ = Net rate of change per unit time of number of cuticle cell layers C at time t, and distance x resulting from cuticle wear and hair growth.

$\frac{dC}{dx}$ = Change in C along hair shaft (x) at time t and distance x.

$\frac{dx}{dt}$ = Rate of hair growth.

$\left(\frac{dC}{dt}\right)_W$ = Rate of change per unit time of number of cuticle cell layers C at time t, and distance x, resulting just from cuticle wear.

Rate of Cuticle Wear at Different Positions Along Hair Shaft

The fitness of our data to equation [1] suggests that the C.W.P. for any of the subjects (corrected for C_0) will have the same shape as would be observed for any other subject when the former's length coincides with the latter's at some time t. That is, for example, Subject 1's C.W.P. would become like Subject 5's when the former's hair gets to be that long (see Figure 3). If this assumption is correct, it remains to be explained how, for example, the ends of Subject 1's hair could still retain 0.5 cuticle cell layers during the time that it would take to grow from 30 to 60 cm. An unlikely explanation would be that the ends were practically undamaged during that time. A more logical one, however, is that when the number of cuticle cell layers falls below a critical range (≤ 1.5) the cortex becomes so vulnerable to handling that that section of the hair eventually breaks off. This could explain why we rarely observed any significant length of hair without cuticle, even on hairs which were shorter than the average (perhaps trimmed) length of the bulk of the hairs.

This argument is introduced into our analysis as follows: If L_c (critical length) is the length at which breakage begins to happen, we can write for $L_0 > L_c$:

$$L_n = L_0 + L_L \ (\text{if } L_0 \leq L_c, \text{ then } L_0 = L_n)$$

where L_0 = observed length of hair (previously referred to as L)
L_L = lost length of hair
L_n = natural length of hair if it did not break or was not cut

and equation [1] can then be written

$$C = C_0 - 1.7\frac{x}{L_0} - 4.1\frac{x^2}{L_0^2} \qquad [3]$$

Equation [3] can then be used in conjunction with the differential equation [2] to analyze some aspects of cuticle-wear dynamics. Differentiating [3] with respect to time (x constant)

$$\left(\frac{dC}{dt}\right)_{NET} = \frac{k_0}{L_0}(1.7f + 8.2f^2) \qquad (\text{where } k_0 = dL_0/dt) \qquad [4]$$

Differentiating with respect to x (L_0 constant)

$$\frac{dC}{dx} = \frac{1}{L_0}(-1.7 - 8.2f) \qquad [5]$$

Substituting [4] and [5] in [2] and rearranging

$$-\left(\frac{dC}{dt}\right)_W = (k_0 f - k_n)\frac{(1.7 + 8.2f)}{L_0} \qquad (\text{where } k_n = dx/dt = dL_n/dt) \qquad [6]$$

at the end of the hair f = 1, hence

$$-\dot{C}_{W,1} = (k_0 - k_n)\frac{9.9}{L_0} \qquad \text{where } \dot{C}_{W,1} = \frac{dC}{dt}_{W,(f=1)} \qquad [7]$$

Equation [7] predicts the length at which k_0 will be zero (*i.e.*, no apparent hair growth) for any $\dot{C}_{W,1}$. For example, making $k_0 = 0$ in [7] we obtain:

L_0 = 86. cm for $\dot{C}_{W,1}$ = 0.004 for cuticle cell layers/day (C.C.L./day),
L_0 = 58. cm for $\dot{C}_{W,1}$ = 0.006 C.C.L./day,
L_0 = 43. cm for $\dot{C}_{W,1}$ = 0.008 C.C.L./day
and L_0 = 35. cm for $\dot{C}_{W,1}$ = 0.01 C.C.L./day.

What this means is that for any of the above pairs of L_0, $\dot{C}_{W,1}$ values the hair will not grow any longer unless the rate of cuticle wear (defined by the parameter $\dot{C}_{W,1}$) is reduced. Minimizing cuticle wear is thus essential for growing long hair. Solving for k_0 and substituting in [6] we have

$$-\left(\frac{dC}{dt}\right)_W = \frac{(1.7 + 8.2f)k_n(f - 1)}{L_0} - \dot{C}_{W,1} \cdot \frac{(1.7 + 8.2f)f}{9.9} \qquad [8]$$

Equation [8] gives values for $(dC/dt)_W$ as a function of f and L_0 (which are known) and $\dot{C}_{W,1}$ and K_n which were not measured in our study. Note that if for any subject the rates of hair growth k_n and k_0 were measured, equation [7] would give $\dot{C}_{w,1}$, and [8] would then completely define the rate of cuticle wear at any distance from the scalp for that subject. In addition, any of the infinite number of damage *vs.* x curves generated by this equation for different values of k_n and $\dot{C}_{w,1}$ will result in a C.W.P. pattern given by [3]. In other words, different rates of hair growth and cuticle wear could still produce C.W.P. similar to the ones observed in our study as long as the cuticle wear *vs.* x pattern follows, or is very similar to, any of the curves predicted by [8]. Different k_n and $C_{w,1}$ values will have the effect of influencing the development in time of C.W.P., but not its basic shape. In order to observe the form of [8], a set of values can be given to the parameters in this equation. An accepted average value for k_n is $\approx$ 0.035 cm/day. The order of magnitude of $\dot{C}_{w,1}$ can be estimated with the data for two shorter hair female subjects, 5 and 6. For Subjects 5 and 6, the tip ends of their hair (assuming that $L_0 \approx 30$ cm) have lost an average of $6.2 - 0.8 = 5.4$ cuticle cell layers (Table II) in t = 30/0.035 days. That is, the average rate of cuticle loss was approximately 0.0063 C.C.L./day. Considering that it is likely that when the hair was much shorter the rate of cuticle damage at the hair ends was less than the average value, it is probable that $\dot{C}_{w,1}$ is larger than 0.0063 C.C.L./day for the 30-cm-long hairs.

Figure 5, curves A, B and C, shows the hypothetical rate of cuticle wear versus x pattern predicted by [8] for hairs 30, 45 and 60 cm long respectively, $k_n = 0.03$, and $\dot{C}_{w,1} = 0.008$. Curves D, E and F are similar curves calculated using $\dot{C}_{w,1} = 0.006$. An in-

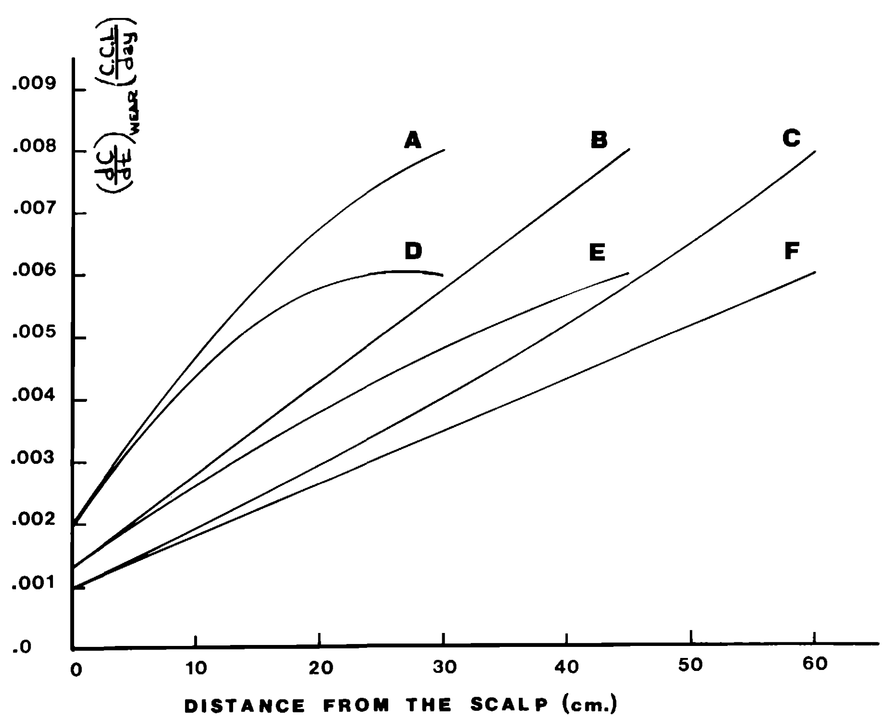

Figure 5. Rates of cuticle wear *vs.* distance from the scalp calculated using equation [8] in text. Curves A, B and C were calculated using k_n (natural rate of hair growth) = 0.03 cm/day, and $\dot{C}_{w,1}$ (rate of cuticle wear at tip end of hair) = 0.008 cuticle cell layers/day. For curves D, E and F, $k_n = 0.03$ cm/day and $\dot{C}_{w,1} = 0.006$ cuticle cell layers/day

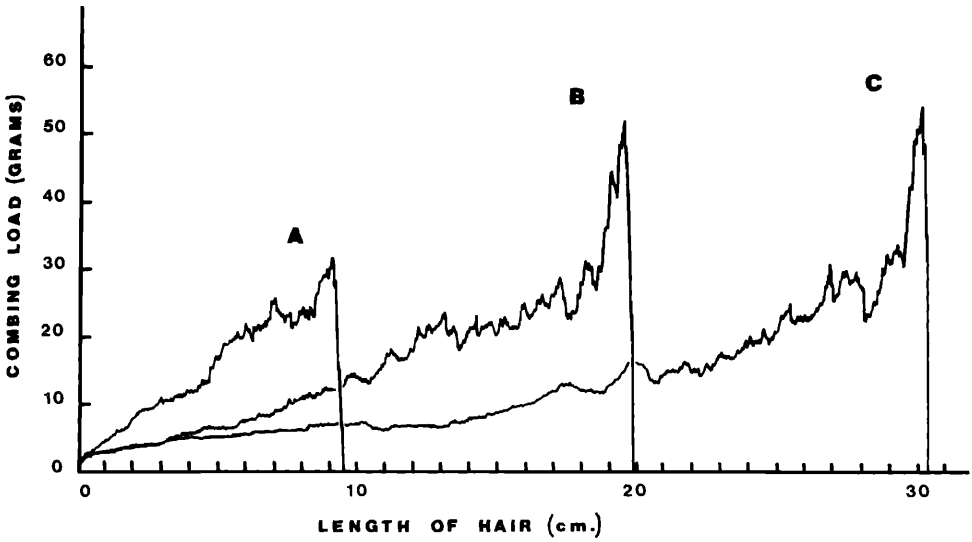

Figure 6. Combing loads *vs.* position of comb (measured in cm from root end) on dry hair swatches 10.(A), 20.(B) and 30.(C) cm long. In looking at the graph, the comb should be considered to have been moving from left to right

teresting characteristic of the curves predicted by [8] is that the rate of cuticle damage is always greater toward the tip ends of the hair, increasing in some cases almost linearly with x. Also, at any fixed distance from the scalp, the longer the hair the lower the rate of damage. This pattern of damage *vs.* distance from the scalp excludes the age of the hair *per se* as a major factor in cuticle wear, and points instead at a source of damage that is related for any one segment of hair to the position (distance from the scalp) of that segment relative to the total length of the hair. The type of damage that is produced during combing appears to fulfill these requirements.

Combing curves recorded in our laboratory with an instrument which allows us to measure the forces encountered by a comb as it moves through a swatch of hair can be seen in Figures 6 and 7 (19). Figure 6 shows such curves for dry hair swatches tangled prior to combing (conditioned and measured at 65 per cent R.H., 70°F); the swatches were of increasing lengths (curve A $\approx$ 10 cm, curve B $\approx$ 20 cm, curve C $\approx$ 30 cm). Figure 7 shows the corresponding curves for the same swatches (also tangled prior to combing) recorded while wet. These curves are plots of the loads (forces) encountered by the comb, against its position along the length of the swatch. In Figures 6 and 7 the comb was moving from left to right.

The recorded combing forces are the sum of all the frictional forces generated at each hair-to-hair and hair-to-comb point of contact by the moving comb. Frictional forces between two sliding surfaces always produce some surface damage, and A. C. Brown and J. A. Swift (16) have convincingly demonstrated the extensive amount of cuticle damage that can be produced during combing, especially when there is some degree of hair tangling (18). Higher combing forces values are the result of more points of contact and/or higher normal loads at each contact point, and can be expected to produce higher levels of surface damage. Cuticle wear during combing should thus be directly related to the magnitude of the combing forces. If combing damage is a major factor in

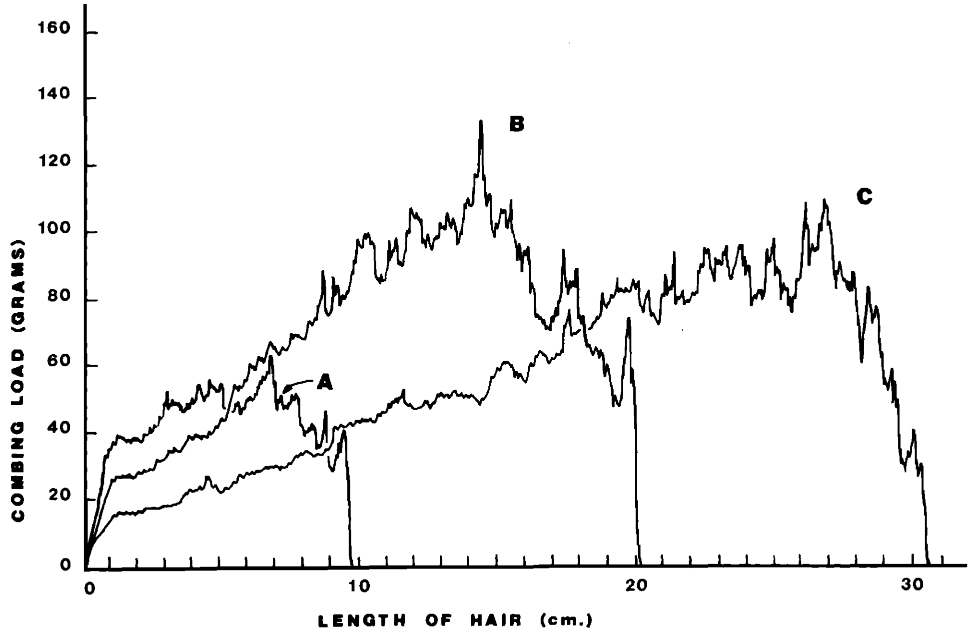

Figure 7. Combing loads *vs.* position of comb (measured in cm from root end) on wet hair swatches 10.(A), 20.(B), and 30.(C) cm long. In looking at the graph, the comb should be considered to have been moving from left to right

cuticle wear, there should be some similarity between the shape of the combing curves (especially the ones for wet hair because hair is then mechanically weaker and more susceptible to damage) and the rate of cuticle wear *vs.* x hypothetical curves predicted by equation [8]. This can be observed to be the case by comparing Figures 6 and 7 with Figure 5. Practically all of the numerous combing curves which we have observed are characterized by initial low combing forces which, on the average, increase as the comb moves towards the tip end of the hair bundles. Even more important is the fact that as the hair gets longer (Figures 6 and 7) combing forces continue to be large closer to the tip ends and diminish near the root ends. This is precisely the general shape of the curves that can be plotted using expression [8] (Figure 5). It can therefore be concluded that the frictional forces *vs.* distance from the scalp pattern characteristic of combing is very likely a major factor in generating C.W.P. of the shape we have observed.

Another source of damage that should be given serious consideration and which, on first sight, appears likely to contribute to the generation of C.W.P. similar to ones observed is exposure to the sun. R. Beyak *et al.* have shown that a correlation exists between the amount of radiation and the mechanical weakening of hair fibers as measured by yield forces at 15 per cent elongation (20). Interestingly, these results show the changes in tensile properties increasing exponentially with increased amounts of radiation. If it is assumed that some weakening of the cuticle is occurring concurrently with the weakening of the fiber as a whole, that such weakening is also accelerated by increased exposure and that weakening leads to cuticle loss, simple exposure to the sun could, in principle, produce C.W.P. such as those observed. However, the evolution in time of C.W.P. produces an increase in C at any distance x as the hair grows longer. In other words, the rate of cuticle damage at any fixed distance x decreases as the hair length increases. This could only occur if sun exposure is gradually reduced as the hair gets longer. Although this situation could occasionally happen in reality, as a general explanation it is arbitrary. Sun damage, however, is a very real effect experienced by beach attendants during the summer and which continues during the rest of the year to a degree depending on sun exposure. Its manifestations, *i.e.*, split-end formation, dull, coarse looking hair, indicates that sun radiation produces and/or accelerates cuticle damage. It can be concluded that although sun damage by itself does not appear likely to generate C.W.P. such as the ones observed, it must contribute to it. Its main role in cuticle wear is probably that of increasing the amount of damage produced by combing (or brushing).

Still another source of damage which could contribute to the generation of C.W.P. of the observed shape is setting the hair in rollers. Although we do not believe that this operation is nearly as damaging as combing, any damage produced by it is likely to be concentrated at the ends of the hair, as is the case in combing. This will occur because (a) the hair ends will be in direct contact with the potentially damaging surface of some roller types, (b) hair ends can easily be sharply bent and twisted when hair is wrapped around rollers and (c) the radius of curvature increases as we move away from the ends of hair wrapped around a roller, *i.e.*, the degree of bending increases towards the end.

Observed Rates of Hair Growth

It was previously mentioned that it appears likely that beyond a certain length, a cuticle-loss, hair-breakage mechanism becomes operative. A direct result of this would be that hair will appear to grow at a rate less than the natural rate of hair growth out of the scalp. Mathematically, this situation can be described as follows. Equation [7] can be written

$$k_0 = \frac{dL_0}{dt} = k_n - \frac{\dot{C}_{W,1} L_0}{9.9}$$

and integrating, assuming that k_n is constant we have

$$L_0 = \frac{9.9}{\dot{C}_{W,1}} \left[k_n - e^{-\frac{\dot{C}_{W,1}(t+A)}{9.9}} \right] \qquad [9]$$

A is an integration constant which should be evaluated considering that [9] is only valid for $t \geq t_c$ where t_c (critical time) is the time at which the hair breakage due to cuticle-loss mechanism starts to operate. We can then write:

for $t < t_c$ $\quad L_0 = k_n t$

for $t = t_c$ $\quad L_0 = k_n t_c = \frac{9.9}{\dot{C}_{W,1}} \left[k_n - e^{-\frac{\dot{C}_{W,1}(t_c+A)}{9.9}} \right]$ $\qquad$ [10]

and for $t > t_c$ $\quad L_0$ is given by [9]

Solving for A in [10] we have:

$$A = -\left[t_c + \frac{9.9}{\dot{C}_{W,1}} \ln \left(k_n - \frac{\dot{C}_{W,1} L_c}{9.9} \right) \right] \quad (\text{where } L_c = k_n t_c) \qquad [11]$$

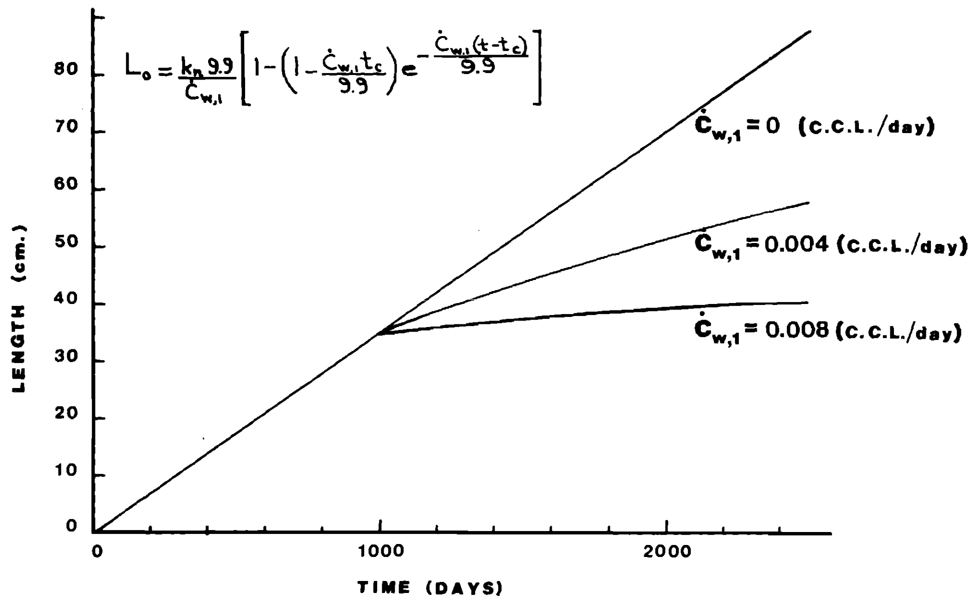

Figure 8. Calculated observed (L_0) length of hair *vs.* time predicted by the equation [12] shown in figure for three different values of $\dot{C}_{w,1}$

Substituting [11] in [9] we obtain

$$L_0 = \frac{k_n 9.9}{\dot{C}_{W,1}}\left[1 - \left(1 \quad \frac{\dot{C}_{W,1}t_c}{9.9}\right) e^{-\frac{\dot{C}_{W,1}t'}{9.9}}\right] \quad (\text{where } t' = t - t_c) \qquad [12]$$

Equation [12] describes the effect of k_n and $\dot{C}_{W,1}$ on L_0 (observed length) with time. Figure 8 shows the effect of time on L_0 predicted by [12] for $k_n = 0.035$ cm/day and three different values of $\dot{C}_{W,1}$. The curves were calculated assuming L_c equal to 35 cm ($t_c = 1000$ days).

Effect of Hair Cutting on Cuticle-Wear Patterns

Our analysis so far has been based on the fact that the subjects participating in our study had not cut their hair for at least three to four years prior to the experiment (with the exception of perhaps occasional trimming to remove split ends). It is of interest to consider what would happen in cases that differ from the above situation.

In the first place, let us consider the case in which hair that has been allowed to grow freely up to a certain length L_0 is then kept at that length by its owner through frequent cuttings. For a hair of length L_0, the rate of damage at any x will be given by [8] for the correct values of $\dot{C}_{W,1}$ and k_n. If k_n does not change and $\dot{C}_{W,1}$, is not significantly changed by any changes in hair treatment and handling habits, the form of [8] will not change. For such a hair prior to cutting, the number of C.C.L. at any distance from the scalp was continuously increasing as the hair grew longer. This occurred because the rate of supply of hair with a larger number of C.C.L. (given by the first term on the right of [2] was bigger than $(dC/dt)_W$ at any x. After cutting, however, this increase in the number of C.C.L. will continue only until in [2]

$$\frac{dC}{dx} \cdot \frac{dx}{dt} = \left(-\frac{dC}{dt}\right)_W \qquad [13]$$

which will eventually occur due to the decrease in (dC/dx) produced by a positive $(dC/dt)_{NET}$ at any x. At this point, a steady state is achieved and the C.W.P. will not change with time. Steady state cuticle-wear patterns can be calculated for any value of k_n and $\dot{C}_{W,1}$, by means of [13]. Thus, combining [13] with [8]

$$\frac{dC}{dx} = \frac{(1.7 + 8.2f)(f - 1)}{L_0} \llcorner \frac{\dot{C}_{W,1}}{9.9\,k_n}(1.7 + 8.2f)f$$

and integrating (for constant L_0)

$$C = C_0 - 1.7f - \left(3.2 + 0.1\frac{\dot{C}_{W,1}L_0}{k_n}\right)f^2 + \left(2.8 - 0.3\frac{\dot{C}_{W,1}L_0}{k_n}\right)f^3 \qquad [14]$$

Figure 9 shows two steady state cuticle-wear patterns for k_n = 0.035 cm/day, L_0 = 60 cm, C_0 = 6 C.C.L. and $\dot{C}_{W,1}$ = 0.002 and 0.004 C.C.L./day, compared to the normal C.W.P. of a growing hair. It illustrates the interesting result that hair kept at a constant length by cutting will be in better condition than would be that same hair arriving at the same length by growing freely.

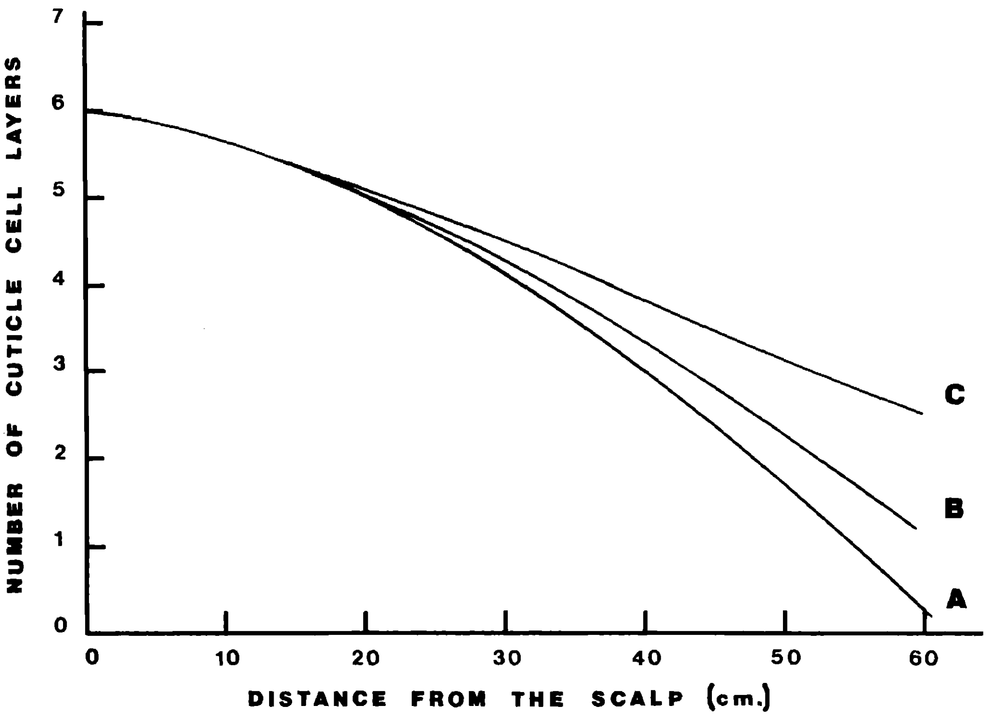

Figure 9. *Curve A:* cuticle-wear pattern of 60-cm-long hair that has arrived at this length by growing freely. *Curve B:* steady state cuticle-wear pattern for hair kept at a length of 60.cm by frequent cutting, calculated using equation [14] in text, $\dot{C}_{w,1}$ = 0.004 C.C.L./day. *Curve C:* same as Curve B but $\dot{C}_{w,1}$ = 0.002 C.C.L./day

CONCLUSIONS

1. Determining the number of cuticle cell layers at different positions along the hair shaft by means of Scanning (or Transmission) Electron Microscopy is a good method for quantitating and analyzing the degree and type of wear that hair has been subjected to. We believe that this approach will prove more productive than previous ones which have been based on the qualitative description of observations of changes in the appearance of the outermost cuticle cell layers along the hair shaft.
2. Although well aware that the number of subjects included in our study was very small, the similarity of the cuticle-wear patterns among subjects and the fact that all of the data can be reasonably well superimposed by plotting the number of cuticle cell layers versus the fractional distance from the scalp suggest that, under normal wear conditions, there is a common, general pattern for cuticle wear in human hair. An empirical equation describing this pattern was presented.
3. An expression for the rate of cuticle wear versus distance from the scalp, which would generate the type of cuticle-wear patterns shown by our data, was mathematically derived. This expression excludes age *per se* as a major factor in cuticle wear and points instead to a source of hair surface wear which accelerates as we move closer to the hair ends. An analysis of combing curves shows that the type of damage known to be produced by combing (or brushing) can very well be responsible for the shape of cuticle-wear patterns that our data reveals.
4. The rate of cuticle wear *vs.* x function [8] will have a different shape depending on the value of its parameters k_n and $\dot{C}_{w,1}$. Any member of this family of curves will, however, satisfy the differential equation [2] thus producing a C.W.P. described by [3]. It is therefore possible to have different rates of damage *vs.* x patterns for different subjects and still end up with C.W.P. which have the same shape.
5. Our data shows that, at any common distance from the scalp x, the state of preservation of the cuticle is better for a long-hair subject than for a short-hair one.
6. As the cuticle wears during hair growth, the cortex appears to gradually expand, reaching an expansion of the order of 15 per cent in its cross-sectional area as we approach the tip ends.
7. It was found reasonable to assume that beyond a certain length, which we refer to as the critical length (L_c), human hair will appear to be growing slower due to a cuticle-loss-fracture mechanism. If the hair is cut, it will then appear to be growing faster. This apparent faster growth will continue until a new L_c is reached.
8. Hair that is kept at a constant length will be in better condition in regard to its cuticle than hair of the same length which is growing freely.
9. Last, but most important, the care with which hair is treated and handled directly affects the maximum length that it can attain. The use of products which reduce combing damage should effectively enable a person to grow longer hair. Faster rates of hair growth, more cuticle cell layers on the hair at the follicle and longer follicle growth cycles will also contribute to increasing the maximum attainable length.

The authors are well aware that the number of subjects participating in our study was relatively small. Our assumptions and results should therefore be tested further by gathering more extensive data of the type presented in this paper. It is hoped, however, that our conclusions, some of the questions they pose, and the mathematical tools proposed for their analysis will stimulate additional research on the subject of cuticle wear and, what is even more important, on its prevention.

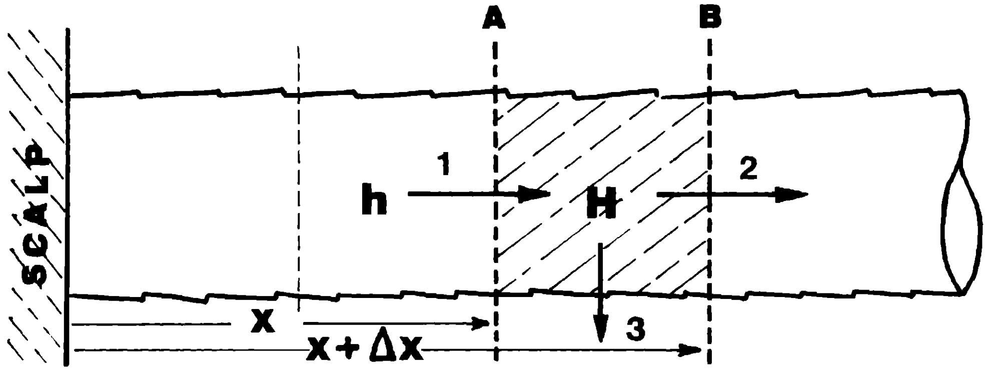

Figure 10. Flow diagram of cuticle into and out of a hypothetical hair element H located within the fixed distances of x and x + Δx from the scalp

APPENDIX

Let H be an element of a hypothetical hair located within the fixed distances of x and x + Δx from the scalp (Figure 10). Let C′ (proportional to C) stand for mass of cuticle (in grams). Let [C′] be the concentration of cuticle, expressed as mass of cuticle per unit volume of hair. Assume that (a) the average rate of hair growth (for all fibers) is constant and (b) the average rate of cuticle loss (for all hairs) at any time t and distance from the scalp x can be treated as varying in a continuous fashion, and corresponds to the time averages of all factors affecting cuticle wear. Then, during a time interval Δt, the following changes in C′ will be taking place:

$$\begin{bmatrix}\text{Change in C}' \text{ per unit time due to} \\ \text{cuticle entering H through boundary} \\ \text{A due to hair growth (Flow ① Figure 10)}\end{bmatrix} = \left[\frac{\Delta C'}{\Delta t}\right]_{G.I.} = \overline{[C'_h]} \cdot A \cdot \frac{\Delta x}{\Delta t}$$

where $\overline{[C'_h]}$ = Average concentration (during Δt) of C′ in element h (adjacent to H) which moves into position H during Δt

A = Cross-sectional area of hair (assumed constant)

Δx = Length of elements h and H

G.I. = Stands for growth of hair into H

If Δt approaches 0 (*i.e.*, dt) and Δx approaches 0 (*i.e.*, dx), then $\overline{[C'_h]}$ approaches $[C'_x]$ (*i.e.*, concentration of C′ at x), and the above expression becomes

$$\left(\frac{dC'}{dt}\right)_{G.I.} = [C'_x] \cdot A \cdot \frac{dx}{dt} \qquad [15]$$

In the same manner:

$$\begin{bmatrix}\text{Change in C}' \text{ per unit time due to} \\ \text{cuticle leaving H through boundary} \\ \text{B due to hair growth (Flow ② Figure 10)}\end{bmatrix} = \left[\frac{\Delta C'}{\Delta t}\right]_{G.O.} = \overline{[C'_H]} \cdot A \cdot \frac{\Delta x}{\Delta t}$$

As before, if $\Delta t \rightarrow 0$ and $\Delta x \rightarrow 0$ then $\overline{[C'_H]} \rightarrow [C'_{(x+dx)}]$, and:

$$\left(\frac{dC'}{dt}\right)_{G.O.} = [C'_{(x+dx)}] \cdot A \cdot \frac{dx}{dt} \qquad [16]$$

where G.O. stands for growth of hair out of H. The change in C′ within H due to cuticle wear can be expressed as

$$\left[\begin{array}{l}\text{Change in } C' \text{ per unit time due to}\\ \text{cuticle leaving H due to wear}\\ \text{(Flow ③ Figure 10)}\end{array}\right] = \left[\frac{\Delta C'}{\Delta t}\right]_W = \left(\frac{dC}{dt}\right)_W \qquad [17]$$

where W stands for wear. The net change in C′ within H per unit time can then be expressed as:

$$\left(\frac{dC'}{dt}\right)_{NET} = ① - [② + ③]$$

or

$$\left(\frac{dC'}{dt}\right)_{NET} = \left(\frac{dC'}{dt}\right)_{G.I.} - \left[\left(\frac{dC'}{dt}\right)_{G.O.} + \left(\frac{dC'}{dt}\right)_{W}\right] \qquad [18]$$

Substituting [15] and [16] in [18] we have:

$$\left(\frac{dC'}{dt}\right)_{NET} = [C'_x]\cdot A \cdot \frac{dx}{dt} - [C'_{(x+dx)}]\cdot A \cdot \frac{dx}{dt} - \left(\frac{dC'}{dt}\right)_W \qquad [19]$$

noting that

$$[C'_x] = \frac{C'_{(x)}}{A \cdot dx}, [C'_{(x+dx)}] = \frac{C'_{(x+dx)}}{A \cdot dx}$$

[19] becomes

$$\left(\frac{dC'}{dt}\right)_{NET} = \frac{C'_x \quad C'_{(x+dx)}}{dx} \cdot \frac{dx}{dt} - \left(\frac{dC'}{dt}\right)_W$$

or

$$\left(\frac{dC'}{dt}\right)_{NET} = - \frac{dC'}{dx} \cdot \frac{dx}{dt} - \left(\frac{dC'}{dt}\right)_W$$

C′ is (to a good approximation) proportional to C; therefore, dC′ = KdC hence

$$\left(\frac{dC}{dt}\right)_{NET} = - \frac{dC}{dx} \cdot \frac{dx}{dt} - \left(\frac{dC}{dt}\right)_W$$

which is equation [2] in the text of the paper.

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