J. Soc. Cosmet. Chem., **22,** 667–678 (September 17, 1971)

Elasticity and Tensile Properties of Human Hair. II. Light Radiation Effects

RICHARD BEYAK, M.S., G. S. KASS, B.S.,
and C. F. MEYER, M.S., M.B.A.*

Synopsis—The effects on the TENSILE PROPERTIES of HAIR by LIGHT RADIATION in the form of ULTRAVIOLET and SUNLIGHT are reported. These effects are interpreted from the stress-strain measurements made on single fiber tests and the index used is the force at 15% elongation. The ultraviolet light effects were studied by exposing hair samples to a carbon-arc lamp for increasing periods of time, while the solar effects were examined by exposing hair to natural daylight for periods of ten weeks. The daylight exposures were made throughout the year to study seasonal variation in the solar radiation. Effects of other environmental factors such as temperature and humidity were monitored by testing unexposed control sample groups.

Results indicate a correlation between the total light radiation on the hair and the loss of tensile properties as expressed by the yield point at 15% elongation. In addition, the correlation appears to be the same for UV and sunlight suggesting the effects are due to the total incident radiation and not the character of the light.

INTRODUCTION

There is a growing interest in the field of physicomechanical testing of hair and wool. These studies may be classified into three categories: chemical and morphological characterization of keratin (1–3), chemical and environmental effects on the fiber (4–9), and diagnostic interpretations in the medical literature (10–12). Sunlight and ultraviolet light have long been known to affect the mechanical properties of hair (6, 7, 13), but very little quantitative data are available in the literature. The purpose of this study is to determine the environmental effects of sunlight and ultraviolet radiation on the tensile properties of human hair.

---

* Alberto-Culver Co., Melrose Park, Ill. 60160.

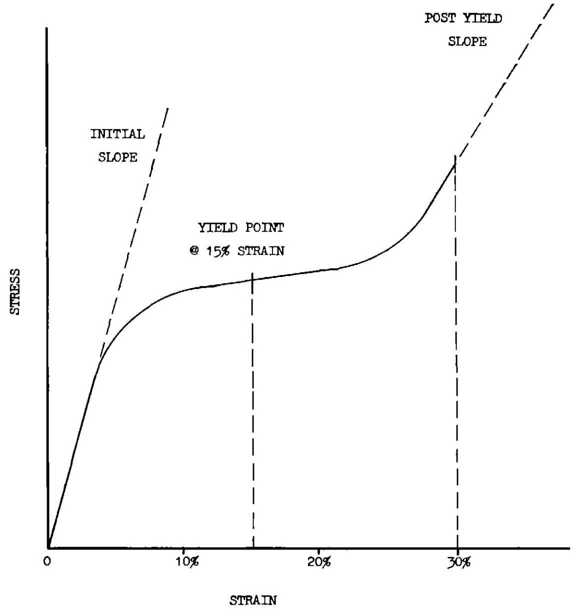

Figure 1. Typical stress-strain curve of a hair fiber

Interpretations of tensile and mechanical changes to the hair fiber are based upon changes in the stress-strain curve. A typical stress-strain curve is shown in Fig. 1. The yield region of the curve has been reported to represent the unfolding of the α-helices of keratin (2), while the major restoring forces to the extension when performed in water are the disulfide linkages (1). The yield point at 15% elongation was shown to be independent of cross-sectional aberrations (3) and responsive to chemical effects (14); thus, it serves as a convenient reference point for detecting tensile changes to the hair as a result of disulfide rupture.

EXPERIMENTAL

Apparatus

The Instron Tensile Tester,* Model TM, with a Model A load cell and a 50-g full scale chart response was used. The gage length taken was 2.5 in. with a 0.2-in./min or 8%/min rate of elongation. The total elongation was 0.5 in. and a 2-in./min rate of unloading. All extensions were run in deionized water at 20° ± 2°C. Instron Model G-51-1A sample mount was used to mount the hair fibers which were wound around the

---

* The Instron Corp., Canton, Mass.

Figure 2. Two shielded and four exposed sample hair groups in sunlight exposure box

jaw post once and secured firmly with a rubber-faced screw clamp. This arrangement did not show evidence of hair damage at the jaw face.

The sunlight exposure box (Fig. 2) was fabricated of wood and Penn-Vernon, single-strength sheet glass with provisions for cross-ventilation according to ASTM standards (15). The glass absorbed all radiation below 310 nm and transmitted a minimum of 77% of the solar ultraviolet light and 85% of the total solar radiation. The box was placed at a 40° position facing southward. The sunlight exposure was recorded as total incident radiation with measurements supplied by U. S. Weather Bureau Reports (16). The pretested hair samples were mounted in Atlas specimen holders No. SL-LSR* (Fig. 3) and placed in the box at a distance of 3 in. below the glass for the 10-week exposure period.

The exposures to ultraviolet light were conducted in an Atlas Fade-Ometer,* Model 18FT, with an enclosed carbon arc. The hair samples were placed in the No. SL-LSR specimen holders at a distance of 10 in. from the arc. The temperature was maintained at 37°C and the relative humidity was controlled at 65% during the exposure period. The car-

---

* **Atlas Electric Devices Company, Chicago, Ill.**

Figure 3. Sample hair group mounted in Atlas SL-LSR specimen holder

bon arc was designed to simulate the effect of sunlight in the visible and UV regions of the spectrum with a radiation output of 155 g-cal/cm^2/hr.

Procedures

Preparation of Hair Samples

The hair samples were obtained from a private source and certified to be untreated virgin hair. That is, they were free of cold wave treatments, bleaches, and permanent hair colors. A 2.5-in. section of the hair sample was tested from a central portion of an 8-in. strand and precautions were taken to retest the same section of hair on the second elongation test. In addition to exposing untreated virgin hair, groups of bleached hair were also exposed to irradiation sources. The bleach treatments were performed in open Petri dishes at 25°C for 30 min with a commercial hair bleach formula based upon 20 vol % hydrogen peroxide.

Strands of hair (8 in. each) were selected at random and were tagged individually before being placed in sample groups containing 25 specimens. The sample groups were immersed in deionized water overnight at 25° prior to the first Instron test to record the yield point at 15% elongation.

Sunlight Exposure Tests

After the initial elongation test, the sample groups were mounted in Atlas specimen holders No. SL-LSR and placed in the exposure box. An unexposed control sample group, covered with aluminum foil, was also placed in the box to monitor the effects of temperature and humidity during the 10-week test period. The exposure was recorded as total radiation (in langleys*) incident in the region. At the end of the exposure period, the sample groups were placed in water overnight and a second elongation test was made to record the yield point at 15% strain.

Ultraviolet Exposure Test

After the initial elongation test the sample groups were mounted in the Atlas specimen holders and placed in the Fade-Ometer. A 5-in. section of the hair was exposed to the carbon arc at a distance of 10 in. from the enclosed source. When the exposure period was over, the sample groups were removed from the holders and retested as in the sunlight tests. The UV radiation level during the test period was 155 langleys/hr as determined from instrument specifications and performance data supplied by the manufacturer.

RESULTS AND DISCUSSION

The sunlight studies were continued throughout the year to determine seasonal variations in the level of effects on hair. These results are summarized in Tables I and II. The total radiation levels were obtained from the Climatological Data reports of the U. S. Weather Bureau, and consist of "sun plus sky" measurements which correct for the absorption interference of water vapor and other atmospheric contaminants. These measurements are reported in langley units or gram calories per square centimeter. Due to the time lag of the Climatological Reports, sometimes as much as five months, current radiation levels were also obtained from the Argonne National Laboratory. The average per cent

---

* 1 langley = 1 g-cal/cm^2.

Table I

Effect of Sunlight on Virgin Hair

Group No.	Test Period	Total Radiation (langleys $\times 10^4$)	Change in Yield Point[a] (%)	Std. Dev. (±)
1	9-26-68 to 12-4-68	1.60	−9.58	2.40
2	9-26-68 to 12-4-68	1.60	−10.84	4.54
3	2-6-69 to 4-17-69	2.30	−16.9	3.12
4	4-17-69 to 6-27-69	3.53	−23.8	2.49
5	7-1-69 to 9-9-69	3.60	−32.7	2.38
6	7-1-69 to 9-9-69	3.60	−32.3	2.29
7	4-20-70 to 6-29-70	3.31	−27.8	2.41
8	4-20-70 to 6-29-70	3.31	−28.9	2.42
9	4-20-70 to 6-29-70	3.31	−29.9	1.99
10	4-20-70 to 6-29-70	Shielded	−2.7	1.17
11	6-29-70 to 9-8-70	3.52	−45.1	3.85
12	6-29-70 to 9-8-70	3.52	−41.4	4.07
13	6-29-70 to 9-8-70	Shielded	−3.0	0.60
14	9-8-70 to 11-17-70	1.76	−22.0	1.99
15	9-8-70 to 11-17-70	1.76	−21.5	2.07
16	9-8-70 to 11-17-70	Shielded	−1.9	0.27
17	11-24-70 to 2-2-71	1.02	−7.3	0.89
18	11-24-70 to 2-2-71	1.02	−7.4	1.18
19	11-24-70 to 2-2-71	Shielded	−0.76	0.79

[a] Average of 25 hair fibers per group.

Table II

Effect of Sunlight on Bleach-Damaged Hair

Group No.	Test Period	Change in Yield Point After Bleach[a] (%)	Total Radiation (langleys $\times 10^4$)	Change in Yield Point After Exposure (%)	Net Change in Yield Point[b] (%)
1	9-26-68 to 12-4-68	−5.20	1.60	−17.0	−11.8
2	2-6-69 to 4-17-69	−5.50	2.30	−19.1	−13.6
3	7-1-69 to 9-9-69	−4.70	3.60	−36.7	−32.0
4	7-1-69 to 9-9-69	−4.40	3.60	−36.1	−31.7
5	4-20-70 to 6-29-70	−6.60	3.31	−36.1	−29.5
6	4-20-70 to 6-29-70	−6.49	3.31	−35.4	−28.9
7	11-24-70 to 2-2-71	−6.19	1.02	−11.7	−5.5
8	11-24-70 to 2-2-71	−4.90	1.02	−11.1	−6.2

[a] Average of 25 hair fibers per group.

[b] Due to solar radiation.

change in the yield point at 15% strain for each group was obtained as the difference between the yield point measurements taken before and after the exposure period. The standard deviation for each average is included.

Table III
Shielded Control Group
Exposure Period: 6-29-70 to 9-8-70

Hair No.	Yield Point at 15% Strain (g) 1st Test	2nd Test	% Change[a]
1	29.0	27.8	−4.13
2	27.4	26.7	−2.55
3	31.0	30.0	−3.22
4	25.6	24.9	−2.73
5	36.0	34.9	−3.05
6	38.0	36.7	−3.42
7	30.0	29.1	−3.00
8	30.7	30.0	−2.28
9	28.4	27.5	−3.16
10	20.3	19.9	−1.97
11	28.6	27.8	−2.79
12	33.2	32.3	−2.71
13	29.3	28.7	−2.04
14	29.5	28.7	−2.71
15	32.3	31.2	−3.40
16	37.6	36.1	−3.98
17	37.4	36.2	−3.20
18	25.2	24.6	−2.38
19	28.1	27.1	−3.55
20	32.9	32.2	−2.12
21	36.0	35.0	−2.77
22	28.7	27.6	−3.83
23	35.9	34.9	−2.78
24	35.0	33.8	−3.42
25	34.5	33.7	−2.31

[a] Average, −2.95%; std. dev., ±0.60.

These yield point data indicate the tensile effect of summer solar radiation to be five times greater than that which was experienced during the winter months. While the differences in the seasonal radiation levels were expected, the pronounced tensile alteration and the effect on the disulfide linkages in the hair keratin were not anticipated. The shielded sample groups experienced minimal changes during the test period and were probably due to residual infrared scattering or thermal radiation. The bleach-damaged hair, with fewer disulfide linkages (17), was included in this study to determine whether or not the additional radiation damage was additive or potentiated. These results indicate an additive effect at these low levels of bleach damage. The data in Tables III and IV illustrate the yield point measurements, as grams of force at 15% strain, of an exposed and shielded sample group of hair from a summer test.

Table IV
Exposed Sample Group
Exposure Period: 6-29-70 to 9-8-70

Hair No.	Yield Point at 15% Strain (g) 1st Test	2nd Test	% Change[a]
1	30.8	16.5	−46.42
2	28.0	14.7	−47.50
3	35.0	20.5	−41.42
4	27.7	14.0	−49.45
5	32.6	19.2	−41.10
6	25.1	12.4	−50.59
7	22.2	12.0	−45.94
8	24.2	12.1	−50.00
9	29.6	16.0	−45.94
10	38.5	22.8	−40.77
11	31.7	18.4	−41.95
12	28.4	15.4	−45.77
13	35.7	21.1	−40.89
14	30.0	17.4	−42.00
15	34.0	20.2	−40.58
16	29.7	16.5	−44.44
17	33.7	20.6	−38.87
18	28.6	15.6	−45.45
19	28.2	15.2	−46.09
20	31.6	18.3	−42.08
21	25.1	11.6	−53.78
22	27.5	14.6	−46.90
23	25.1	12.4	−50.59
24	31.2	16.6	−46.79
25	34.2	19.6	−42.69

[a] Average, −45.13%; std. dev., ±3.85.

The changes in the tensile properties of hair are also apparent in the UV irradiation experiments whose data are reported in Tables V and VI. As in the sunlight experiments, the change in the yield point at 15% elongation is reported as the average for a 25-specimen sample group. The shielded sample groups also exhibited minimal changes in the tensile properties of the hair while the results of the bleached-damaged hair indicated additive damage as in the sunlight tests.

The increased effect on the tensile properties with increased amounts of radiation disclosed an exponential relationship which is illustrated in Fig. 4. Previous work with radiation-induced damage to macromolecules revealed a logarithmic function (18–20). This relationship was explained by the decreasing probability of radiation striking the disulfide bonds as the dose increased. However, our test results suggest the

Table V
Effect of Ultraviolet Light on Virgin Hair

Group No.	Exposure Time (hr)	Total Radiation (langleys × 10^4)	Change in Yield Point[a] (%)	Std. Dev. (±)
1	0	0	−1.42	1.49
2	50	0.77	−4.03	1.40
3	50	0.77	−4.35	0.69
4	75	1.16	−5.47	2.41
5	75	1.16	−4.70	1.62
6	100	1.55	−7.16	1.24
7	100	1.55	−6.82	1.34
8	125	1.93	−7.64	0.81
9	125	1.93	−7.97	1.75
10	150	2.32	−10.2	1.69
11	150	2.32	−12.0	1.29
12	150	0 (shielded)	−1.55	0.99
13	150	0 (shielded)	−1.30	0.74

[a] Average of 25 hair fibers per group.

Table VI
Effect of Ultraviolet Light on Bleach-Damaged Hair

Group No.	Change in Yield Point After Bleach[a] (%)	Exposure Time (hr)	Total Radiation (langleys × 10^4)	Change in Yield Point After Exposure (%)	Net Change[b] in Yield Point
1	−9.50	50	0.77	−13.8	−4.3
2	−9.05	100	1.55	−14.2	−5.2
3	−7.65	150	2.32	−18.4	−10.8
4	−8.88	150	2.32	−19.4	−10.5

[a] Average of 25 hair fibers per group.
[b] Due to ultraviolet radiation.

exponential relationship as shown in Fig. 4, i.e., as the radiation dose increased the effect on the tensile property became more pronounced. This behavior can be compared to that of severing individual strands of a yarn, wherein each successive rupture places a greater load on the remaining strands. A progression of this type would amplify the tensile effect as our test results indicate with radiation-induced disulfide rupture of hair keratin.

The UV carbon-arc source in this experiment emitted 33.9 W/ft^2 of radiation below 400 nm or 20% of its total radiation compared to an average of 6.1 W/ft^2 or 5.9% of the total solar radiation in June. The

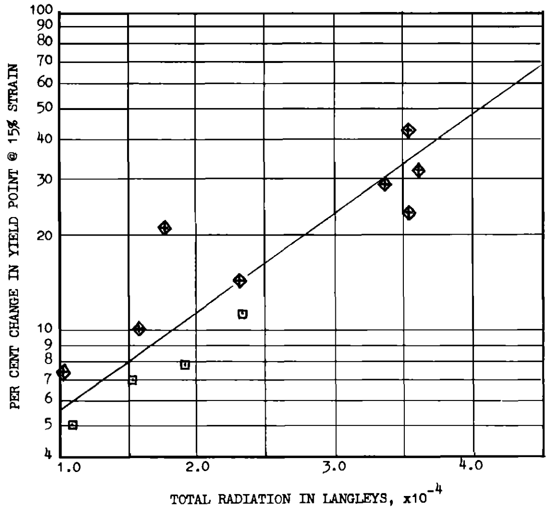

Figure 4. Average change in yield point at 15% elongation as a function of total light radiation

◈ Solar radiation data
⊡ Ultraviolet light data

greater UV intensity of the carbon-arc source, and its agreements with the sunlight effects represented in Fig. 4, suggests the radiation effects on hair are independent of wavelength character but dependent upon the total absorbed radiation (19).

This study along with other examinations into the photochemical reaction of hair and wool keratin (21–24) strongly suggests the important role of disulfide bonds in the light radiation effects on the tensile properties of hair. While our *in vitro* measurements were centered upon the disulfide linkage and its effect on the tensile properties, there are other moieties that are sensitive to radiation. For example, the deamination or decarboxylation of amino acids (25), the disorientation of the hydrogen bonds, and the chemical alteration of the aromatic nuclei in tyrosine and phenylalanine (19). These additional factors must also be considered when attempts are made to ascertain the total effects of light radiation on the physical properties of human hair.

ACKNOWLEDGMENT

The authors wish to express their gratitude to Mrs. Tessie Wiegand for her meticulous and devoted work which has been a key to the success of this program. The authors would also like to thank the Meteorology Department of the Argonne National Laboratory, Lemont, Ill., for the solar radiation data.

(Received March 22, 1971)

REFERENCES

(1) Speakman, J. B., Mechano-chemical methods for use with animal fibers, *J. Text. Inst., Trans.,* **38,** 102–26 (1947).

(2) Feughelman, M., and Reis, P. J., The longitudinal mechanical properties of wool fibers and their relationship to the low sulfur keratin fraction, *Text. Res. J.,* **37,** 334–6 (1967).

(3) Collins, J. D., and Chaikin, M., The stress-strain behavior of dimensionally and structurally, non-uniform wool fibers in water, *Ibid.,* **35,** 777–87 (1965).

(4) Rebenfeld, L., Weigmann, H. D., and Dansizer, C., Temperature dependence of the mechanical properties of human hair in relation to structure, *J. Soc. Cosmet. Chem.,* **17,** 525–38 (1966).

(5) Bogaty, H., Torsional properties of hair in relation to permanent waving and setting, *Ibid.,* **18,** 575–89 (1967).

(6) O'Connell, R. A., and Walden, M. K., Influence of ionizing radiations on wool fiber properties, *Text. Res. J.,* **27,** 516–18 (1957).

(7) Berth, P., and Reese, G., Alteration of hair keratin by cosmetic processing and natural environmental influences, *J. Soc. Cosmet. Chem.,* **15,** 659–66 (1964).

(8) Zahn, H., Stein, W., and Blankenburg, G., Influence of surfactants on the physical properties of keratin fibers, *Fette, Seifen, Antrichm.,* **70,** 756–60 (1968).

(9) Deem, D. E., and Rieger, M. M., Mechanical hysteresis of chemically modified hair, *J. Soc. Cosmet. Chem.,* **19,** 395–410 (1968).

(10) Korostoff, E., Rawnsley, H. M., and Shelley, W. B., Normalized stress-strain relationship in human hair perturbation by hypothyroidism, *Brit. J. Dermatol.,* **83,** 27–36 (1970).

(11) Swanbeck, G., Nyren, J., and Juhlin, L., Mechanical properties of hairs from patients with different types of hair diseases, *J. Invest. Dermatol.,* **54,** 248–51 (1970).

(12) Price, V. H., and Menefee, E., On the effect of dimethyl sulfoxide on hair keratin, *Ibid.,* **49,** 297–301 (1967).

(13) Speakman, J. B., and McMahon, P. R., The action of light on wool and related fibers, *N. Z. J. Sci. Technol.,* **20,** 248B–264B (1939).

(14) Beyak, R., Meyer, C. F., and Kass, G. S., Elasticity and tensile properties of human hair. I. Single fiber test method, *J. Soc. Cosmet. Chem.,* **20,** 615–26 (1969).

(15) *Book of ASTM Standards,* Part 30, ASTM designation E187-63T, "Conducting natural light (sunlight and daylight) exposures under glass," Philadelphia, 1964, p. 526.

(16) Climatological Data, National Summary, U. S. Department of Commerce, Environmental Data Service, Asheville, N. C., 1970.

(17) Wolfram, L. J., Hall, K., and Hui, I., The mechanism of hair bleaching, *J. Soc. Cosmet. Chem.,* **21,** 875–900 (1970).

(18) Setlow, J. K., *The Effects of Ultraviolet Radiation and Photoreactivation,* in Florkin, M., and Slotz, E. H., *Comprehensive Biochemistry,* Vol. 27, *Photobiology, Ionizing Radiation,* American Elsevier, New York, N. Y., 1967, pp. 157–209.

(19) Alexander, P., and Lett, J. T., *Effects of Ionizing Radiations on Biological Macromolecules, Ibid.,* pp. 267–356.

(20) Marzona, M., and Dimodica, G., Effects of ionizing radiations on wool. Part 1: Solubility in alkalis, acids, urea, and urea-bisulfite solutions, *Text. Res. J.,* **38,** 974–76 (1968).

(21) Joubert, F. J., Botes, D. P., and Haylett, T., The action of ultraviolet light on wool, *J. Afr. Chem. Inst.*, **17,** 44–54 (1964).

(22) Dunlop, J. I., and Nicholls, C. H., Electron spin resonance studies of UV irradiated keratin and related proteins, *Photochem. Photobiol.*, **4,** 891–90 (1965).

(23) Shatkay, A., and Michaeli, I., Electron paramagnetic resonance study of wool irradiated by ultra-violet and visible light, *Radiat. Res.*, **43,** 485–98 (1970).

(24) Bhan, M. M., and Sule, A. D., The effect of sunlight on canary-stained wools, *J. Text. Inst., Trans.*, **58,** 46–8 (1967).

(25) Luse, R. A., and McLaren, A. D., Mechanism of enzyme inactivation by ultraviolet light and the photochemistry of amino acids (at 2537 Å), *Photochem. Photobiol.*, **2,** 343–60 (1963).