Wetting Properties of Human Hair by Means of Dynamic Contact Angle Measurement

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ABSTRACT: The interaction between human hair and water occurs continuously in atmospheric air, and even more so, during application of shampoo and conditioner. For this reason the wettability of hair, and how hair care products affect the wetting properties, is of interest to hair care science. In this study, the Wilhelmy balance method is used to measure dynamic contact angle of both conditioner-treated hairs and those left untreated to study the interaction of hair with water. The method uses a microbalance to measure the force exerted on a single fiber when it is immersed into the wetting liquid of interest. This measured force is related to the wetting force of the liquid on the fiber, and the dynamic contact angle can be calculated. The contact angles of chemically damaged, mechanically damaged, virgin (undamaged) as well as conditioner-treated hairs and those left untreated are measured and compared. These samples were measured dry, and then also allowed to soak in water before being measured to determine whether a wet environment affects the wetting properties of the hair surface. Additionally, wettability of hairs from subjects of different ethnicities are measured and compared. Further, the mechanisms driving a significant directionality dependence are studied and discussed. The results are also used to explain tribological properties found in previous studies. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 102: 5255–5265, 2006

Key words: wetting; human hair; conditioner; Wilhelmy balance method; dynamic contact angle

INTRODUCTION

The desire for products that improve the look and feel of hair has created a huge industry for hair care. The ways in which common hair care products, such as conditioner, deposit onto and change hair properties are of interest in beauty care science, since these properties are closely tied to product performance. Conditioner is one hair care product which most people use on a daily basis. Conditioner thinly coats hair and can cause drastic changes in the surface properties of hair. The layer of conditioner creates a softer, smoother feel for the consumer and provides a protective coating on the hair surface for prevention of future damage. Conditioner consists of a gel network chassis (cationic surfactant, fatty alcohols, and water) for superior wet feel and a combination of conditioning actives (silicones, fatty alcohols, and cationic surfactant) for superior dry feel. Cationic surfactants are critical to the forming of the lamellar gel network in conditioner, and also act as a lubricant and static control agent, since their positive charge aids in counteracting the negative charge of the hair fibers. The cationic surfactants in the conditioners used in this study are quaternary amine-based surfactants. They have low-energy alkyl chain on one end of the molecule and relatively higher-energy cationic group on the other. Fatty alcohols are used to lubricate and moisturize the hair surface, along with forming the gel network. Among all the components of conditioner, silicones are the main source of lubrication in the conditioner formulation.

Figure 1(a) shows the schematic structure of a human hair fiber with its various cellular structures.[1–4] Hair fiber (about 50–100 μm in diameter) consists of cuticle and cortex cells which run longitudinally along hair fiber. The cortex takes up the majority of hair fiber composition and the cuticle is the outermost region that protects the cortex. The cuticle consists of flat overlapping cells (scales). The cuticle cells are attached at the root end and they point forward toward the tip end of hair fiber, like tiles on a roof. Each cuticle cell is ∼ 0.3 to 0.5-μm thick and the visible length of each cuticle cell is ∼ 5–10 μm. The cuticle in human hair is generally 5–10 scales thick. Each cuticle cell consists of various sublamellar layers: the A-layer, the exocuticle, the endocuticle, and the cell membrane complex (also referred to as the epicuticle). The cell membrane complex consists of a protein matrix and a lipid layer, [Fig. 1(b)]. The lipid layer consists of fatty acids, primarily 18-methyleicosanoic acid (18-MEA),

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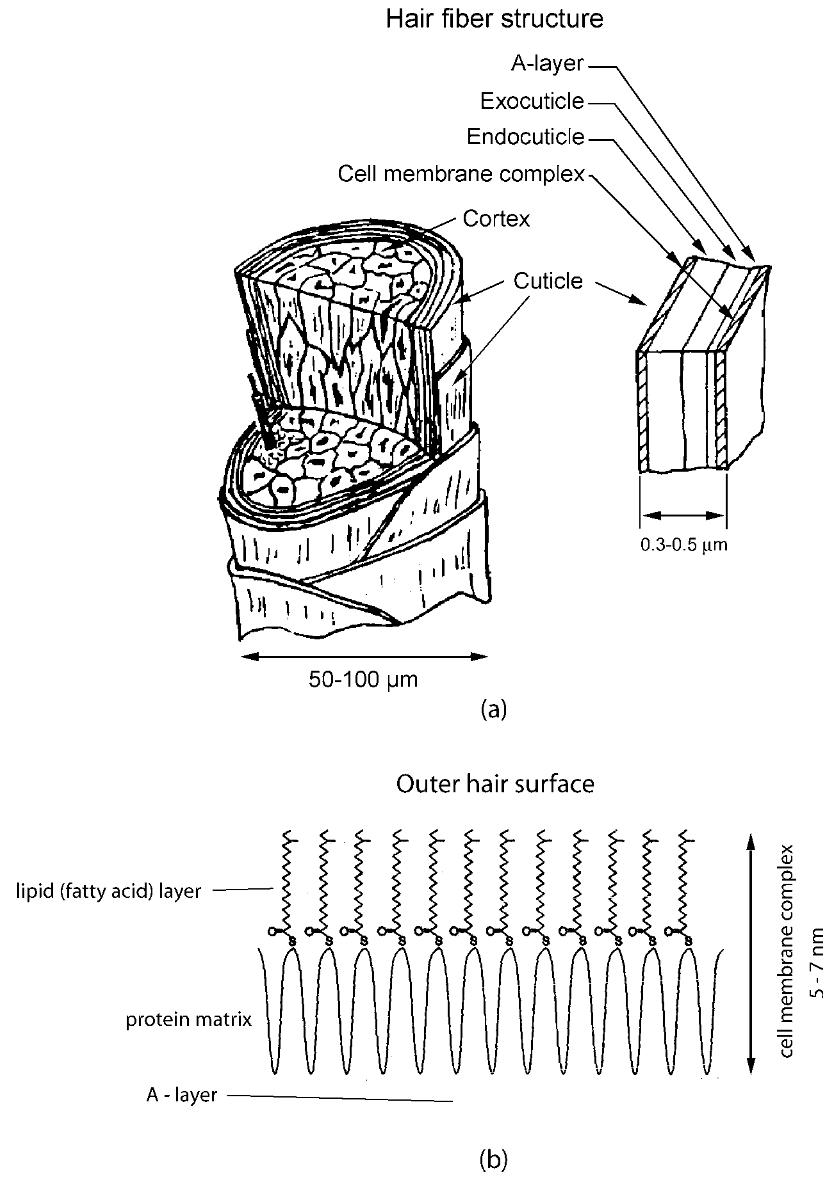


Figure 1 (a) Schematic structure of human hair.[3] (b) Schematic of outermost surface of hair showing 18-MEA location.[6]

which strongly contributes to the hydrophobicity and lubricity of virgin hair. This fatty acid is intact in virgin hair, but is removed during chemical treatment, causing a slightly hydrophilic and less lubricious surface for chemically damaged hair.[5–7] This is also the case for mechanically damaged hair, where the mechanical damage physically removes the top, hydrophobic layer of the hair.

Because that water is prevalent in the air, and conditioner and other hair products are applied in a wet environment, the wetting properties of hair are of interest. It has also been shown that the contact angle of water on an atomic force microscope (AFM) tip significantly affects the measured values of friction and adhesion using that tip,[8] as does the contact angle of water on the measured surface itself. Similarly, the way in which damage and conditioner treatment affects the wetting properties of hair is also important in understanding the tribological properties of hair. However, the size and geometry of a hair fiber make static contact angle measurement with a goniometer difficult and unreliable. For this reason, dynamic contact angles are measured using the Wilhelmy balance method[9] in which a microbalance is used to measure the wetting force. This method is often used to measure wetting properties of thin fibers.[10] Ecke et al.[11] used an atomic force microscope (AFM) to study wetting of individual particles. AFM has also more recently been used to measure the dynamic contact angle of carbon nanotubes.[12] In addition, the Wilhelmy balance technique has been employed to study hair fibers,[5,7] although the effect of conditioner treatment has not been previously studied to the authors' knowledge.

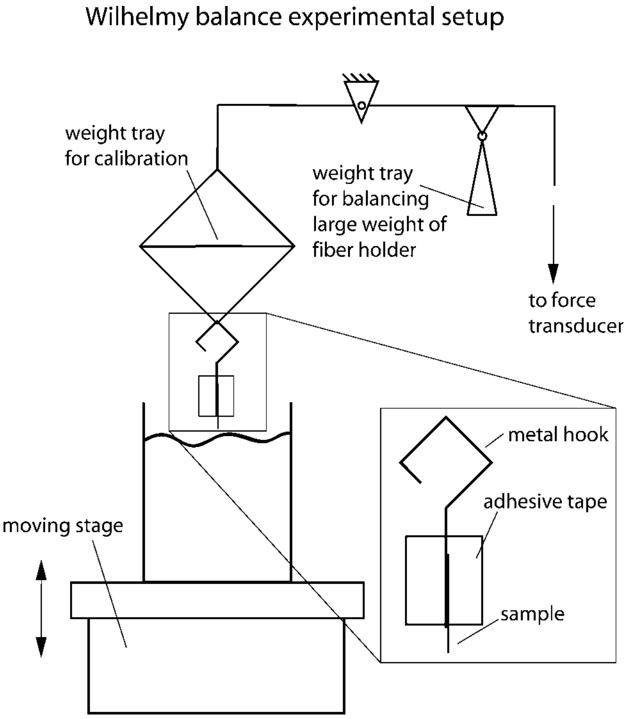


Figure 2 Schematic diagram of Wilhelmy balance technique measurement setup and zoomed view of sample mounting.

In the Wilhelmy balance method a single fiber is suspended from a microbalance, shown in Figure 2. A beaker of the wetting liquid sits on a stage below the fiber sample to be measured. The liquid moves toward the fiber at a constant velocity (advancing mode) until the sample contacts the liquid surface. The liquid then continues in the same direction, submerging the fiber to a specified depth (1 mm in this study), and then moves away from the fiber (receding mode) until the fiber is completely out of the wetting liquid. The force exerted on the hair fiber is related to the contact angle of the fiber surface by the following equation:

$$F = \gamma P \cos\theta + W - \rho g y A \tag{1}$$

where F, measured force; γ, surface tension of wetting liquid; P, wetted perimeter of fiber at liquid/air interface; θ, contact angle of fiber surface; W, weight of fiber; ρ, density of wetting liquid; y, immersion depth; and A, cross-sectional area of fiber.

The first term in eq. (1) is the wetting force acting on the fiber, the second is the weight of the fiber, and the third represents the buoyancy force on the fiber. The weight of the fiber is tared prior to measurement, and the buoyancy is neglected as it is several orders of magnitude smaller than the measured force. With the preceding assumptions, the relation reduces to:

$$F = \gamma P \cos\theta \tag{1a}$$

In this study, chemically damaged, mechanically damaged as well as virgin (undamaged) samples are studied. Additionally, samples treated with commercial conditioner and those left untreated are used.

EXPERIMENTAL

Hair samples

Hair samples were received from Procter & Gamble (Cincinnati, OH) and prepared per Appendix A. Four main categories of hair samples were studied: virgin, chemically damaged, mechanically damaged and treated. Virgin samples are considered to be baseline specimens and are absent of chemical damage. Chemically damaged hair fibers have been exposed to two cycles of permanent wave treatment, washing, and drying, which are representative of common hair management and alteration. Mechanically damaged samples were not specially treated to cause mechanical damage, but were observed under an optical microscope at 100× and found to exhibit a high degree of cuticle damage, indicative of mechanical rather than chemical damage. Treated samples have been treated with one cycle or three cycles of a Procter & Gamble commercial conditioner. All hair samples had undergone two rinse/wash cycles of commercial shampoo treatment (in the case of treated samples, prior to conditioner treatments). The samples of interest in this study are Caucasian virgin, Caucasian virgin treated, Caucasian chemically damaged, Caucasian chemically damaged treated (one cycle), Caucasian chemically damaged treated (three cycles), Caucasian mechanically damaged, Asian virgin, and African virgin.

The samples arrived as hair swatches $\sim$ 0.3 m long. Although the exact location from the root is unknown, it is estimated that hair samples used for testing were between 0.1 and 0.2 m from the scalp. The tests were conducted on the middle parts of hair samples. Hair specimens were mounted alongside a straight metal hanger to a piece of adhesive tape. The metal hanger served as a guide to align the hair sample normal to the surface of the liquid as best as possible. This arrangement is shown in Figure 2.

Wilhelmy balance method

A Cahn DCA-322 (Dynamic Contact Angle Analyzer) was used in this study. This device employs a microbalance to measure the wetting force as described earlier and is shown in Figure 2. Tests were carried out in a 50–60% relative humidity and 22°C ± 1°C environment. Samples were exposed to this environment for a minimum of 30 min prior to measurement to allow them to equilibrate. All contact angle measurements were taken using deionized water.

As previously mentioned, the force measured by the microbalance is related to the contact angle of the sample surface by [eq. 1(a)]. However, this relation makes assumptions which must be discussed. The fiber is assumed to be normal to the liquid surface, but due to the natural curl of most hairs, mounting the hair exactly normal to the liquid surface is nearly impossible. An off-normal fiber has the effect of producing a larger actual wetted perimeter than one calculated using the nominal diameter of the hair. To deal with this issue, the wetting perimeter is measured by employing the same technique with a liquid of known contact angle. In this study, octane was used, as it is believed to completely wet the solid surface due to its low surface tension and apolarity, and thus a contact angle of zero is assumed. The octane used in this study was reagent grade (95% pure, minimum) octane supplied by Fisher Scientific. This technique is employed with a similar liquid, decane, by Molina et al.[7] Error analysis indicates that even if these liquids do not have a contact angle of zero, the error that results is acceptable. The largest error would arise for measured contact angle closest to 45°. For this study, this corresponds to an angle of around 70°, with a cosine of 0.342. If the actual contact angle of this sample with octane is 30°, then the actual contact angle with water is 66.7°, giving slightly less than 5% error in the calculated contact angle. The other extreme found in this study, 103° (contact angle of virgin hair with water), gives an error of only 2% for the conditions stated above. This error is considered acceptable by the authors and thus measuring perimeter by immersion in octane is used throughout the study. With the only unknown left in [eq. 1(a)] being the wetted perimeter, this value can be calculated. In this study hair fibers were tested in water first, then in octane to obtain perimeter data. It should be noted that it is also possible that an off-normal fiber will flex during immersion bringing it normal to the liquid surface, thus negating any issues that arise with an off-normal fiber. Though this behavior was not monitored and can not be confirmed, the use of octane to measure perimeter and the possibility of fiber flexure make off-normal effects negligible.

Similarly, if the force is large enough to cause the hair fiber to buckle, an off-normal effect will exist. Only hydrophobic fibers will have this problem as the wetting force will be compressive, whereas it is tensile for hydrophilic fibers. The use of octane to alleviate this issue is not sufficient since the buckling in water does not necessarily imply buckling in octane, thus the wetted perimeter measured in octane would be different than in water. Therefore the experiment was designed to ensure buckling did not occur. The buckling issue is analyzed by using the Euler buckling equation:[13]

$$P_{\mathrm{cr}} = \pi^2 EI/L_e^2$$

where P_{cr}, critical buckling load; E, tensile elastic modulus of hair fiber; I, area moment of inertia of circular cross section; and L_e, unsupported length of hair.

To design the experiment so that buckling does not occur, a maximum unsupported fiber length was calculated. The modulus of elasticity used was 3 GPa, which is a conservative estimate based on the 3.89 GPa reported by Robbins.[3] The maximum compressive force measured in this study was $\sim 4\ \mu$N. Finally, a conservative fiber radius of 15 μm was used to calculate the moment of inertia, as this is the minimum radius observed. Using these values the critical unsupported fiber length at which buckling would occur is $\sim$ 17 mm. To prevent buckling and to obtain the straightest fiber possible, an unsupported length of 5 mm or less was used.

Additionally, significant hysteresis is observed for the advancing and receding modes. Figure 3 shows a typical force plot for virgin hair. It should be noted that a negative value of force indicates an upward (compressive) force on the fiber, indicating the fiber is hydrophobic. A positive force indicates a downward (tensile) force on the fiber, indicating it is hydrophilic. The hysteresis is quite obvious here as the advancing mode shows a much lower force than does the receding mode. The reason for this is shown in the cartoon of Figure 3. During advancing mode, the wetted perimeter is that of the general surface of the cuticle scales, away from the scale edges. During receding mode, the opposite is true, and the wetted perimeter tends to exist at the scale edges. Due to the fact that the scale edges are more prone to mechanical damage from handling, they are more likely to have the hydrophobic top layer removed exposing the hydrophilic underlayers. Likewise, the scale edge surfaces are very far from normal to the liquid surface, often times they are almost parallel, whereas the hair surface away from the edges is very close to normal. Because the fiber surface must be normal to the liquid surface to employ the Wilhelmy technique, measurements which are heavily influenced by the scale edges are not accurate and are therefore not used in this study. Similar arguments for this hysteresis are given by Kamath et al.[5] and Molina et al.[7] Additionally, a study by Lam et al.[14] suggests that receding contact angles are influenced by wetting liquid properties, and are not a function of the solid surface alone. For these reasons, only advancing contact angles are used as they more accurately reflect the wetting properties of the hair surface.

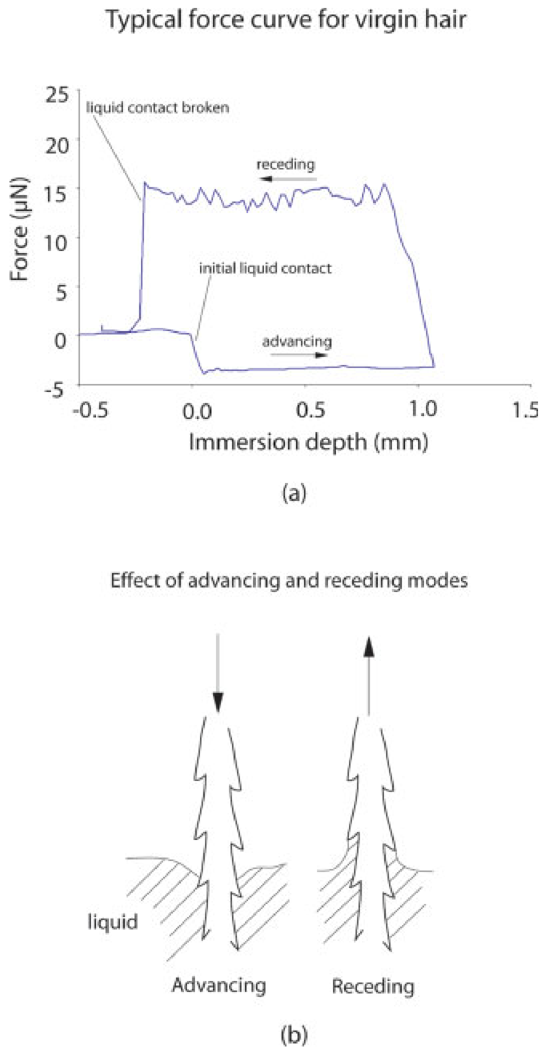


Figure 3 (a) A typical force curve for virgin hair showing advancing and receding regions. (b) Schematic of liquid/hair interaction during measurement process. Advancing direction correlates to contact angle values of the hair surface away from the scale edge. Receding direction correlates to values that are heavily influenced by scale edge contributions. Receding direction also influenced by liquid properties.[14] [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

The following values for surface tension were used:[15]

$$\gamma_{\text{water}} = 72.2 \text{ dyne/cm}$$

$$\gamma_{\text{octane}} = 22.0 \text{ dyne/cm}$$

Soaking experiments

For the soaking portion of this study, hair fibers were mounted as usual. The hair fiber was then immersed in deionized water just past the 1 mm mark over which the contact angle is measured. The advancing stage was then stopped and the hair allowed to soak in this position for 5 min. At the end of the soaking time, the stage was returned to its original position, and the contact angle measurement in water immediately carried out. The test was then run in octane as usual to calculate perimeter.

RESULTS AND DISCUSSIONS

Directionality dependence

There are two significant directionality effects using this measurement technique. The first is the contrast between forces measured in the advancing direction and those measured in the receding direction. This issue has been discussed in the earlier section, and will not be discussed further here. The other involves the orientation of the hair fiber in the measurement setup. Caucasian virgin samples were measured in both fiber orientations and compared, as shown in Figure 4. It is evident here that fibers oriented in the with scale (WS) orientation exhibit lower advancing contact angles than those in the against scale (AS) orientation. The reason for this is shown in Figure 4. Here it is shown that for the advancing direction, the AS orientation creates a situation in which the liquid does not come in contact with the scale edges at the liquid/air interface. However, for the WS orientation, the scale edges are fully wetted at the liquid/air interface as the hair pushes through the liquid surface. Being that the scale edges are far more prone to mechanical damage than the cuticle surface away from the edges, and all hair samples will exhibit some degree of mechanical damage which is unavoidable due to handling, the scale edges tend to be more hydrophilic than the rest of the hair surface. This being the case, the WS orientation exhibits a lower contact angle than the AS orientation because the scale edges are more easily wetted in the WS orientation. This result is in contrast to that reported by Molina where it was determined there was no effect of scale orientation on advancing contact angle. Molina did report, however, that the receding mode was affected in the same manner that was found in the present study. However, the data presented in Figure 4 shows an obvious advancing mode force dependence on scale orientation, and the argument given here and shown in Figure 4 explains this dependence. It is possible the hair fibers used in this study exhibited thicker cuticle scales for any variety of reasons, which would make the effect more noticeable. Thinner cuticle scales would cause less of an effect, perhaps making it unnoticeable, indicating no difference as reported by Molina. Because the AS orientation relates to wetting properties of the scale surface instead of the scale edge, all further data is given for fibers in the AS orientation.

Conditioner-treated hairs and environmental effect

The five samples of interest in this section are Caucasian virgin, virgin treated, chemically damaged,

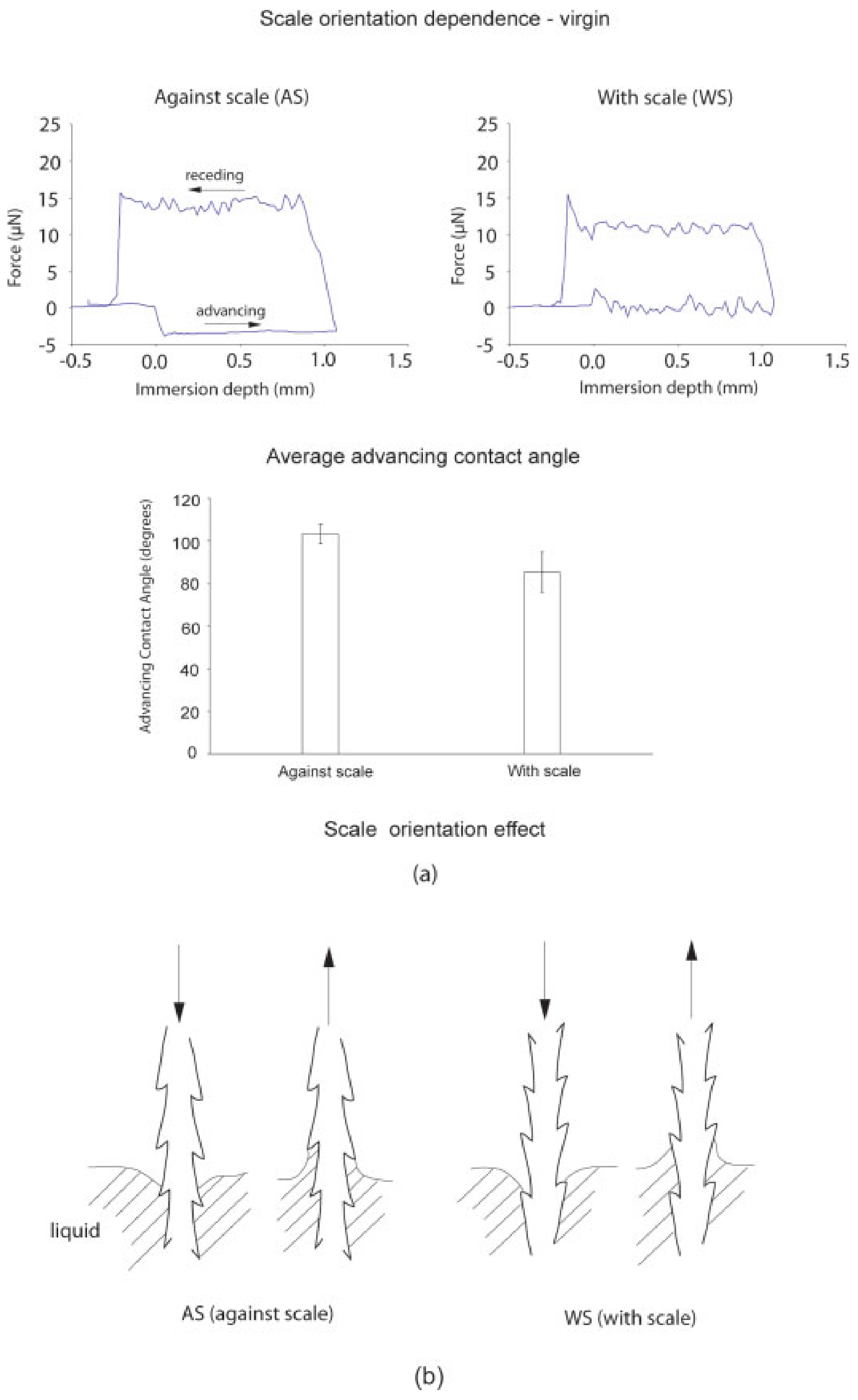
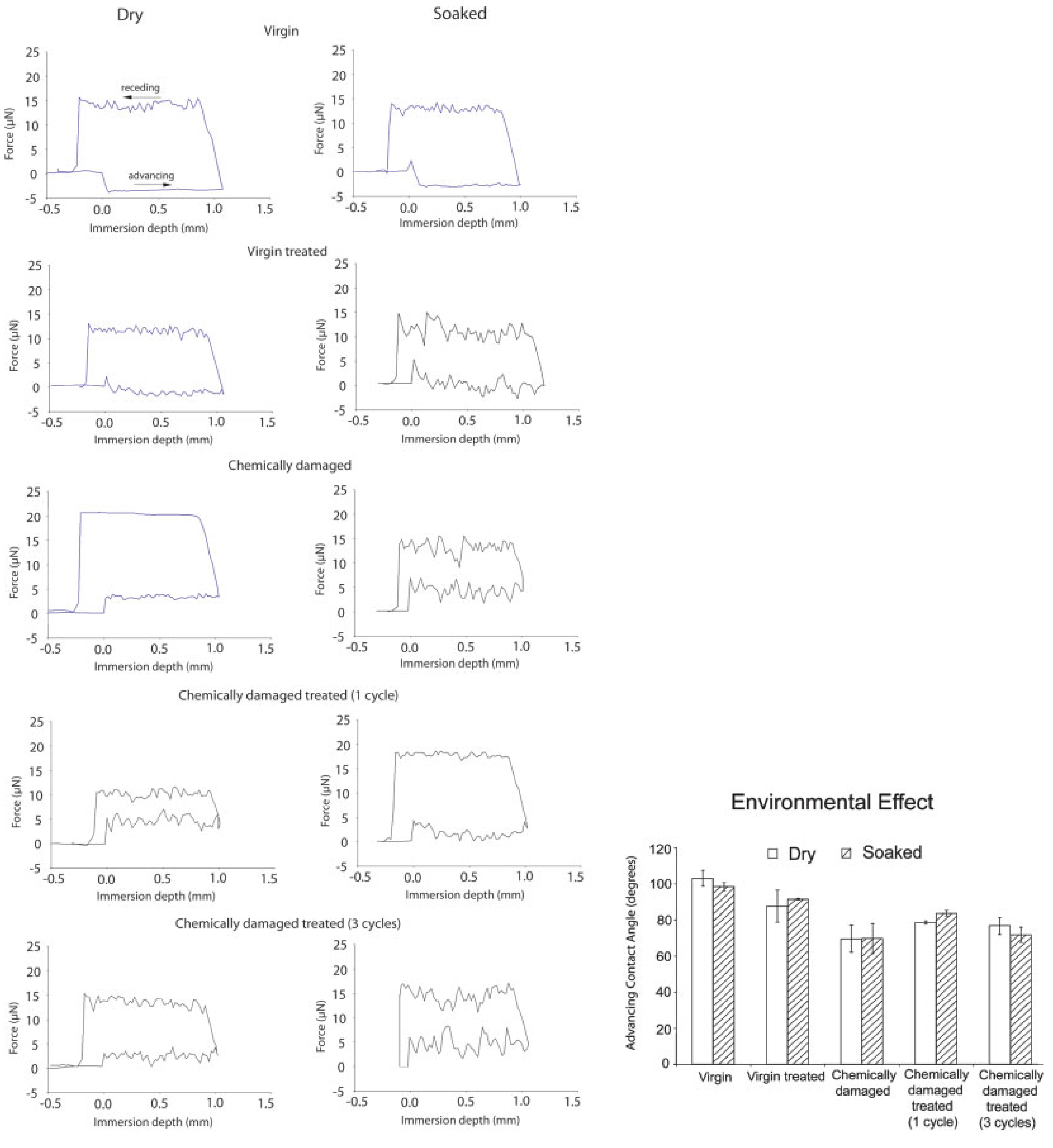


Figure 4 (a) Force curves and average advancing contact angle values for virgin hair in both against scale (AS) and with scale (WS) orientations. Contact angle value is observed to be lower for the WS direction. (b) Schematic showing mechanism for result shown in (a). WS advancing direction correlates to contact angle values heavily influenced by scale edge contributions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

chemically damaged treated (one cycle), and chemically damaged treated (three cycles). Five samples were measured for each type of hair. The results are shown in Figure 5 and Table I. Virgin hair was measured first, and a value of 103° was obtained. This agrees well with values measured by Molina et al. It was found that chemically damaged hairs exhibit a much lower contact angle than do virgin hairs. In this study P-values were used to determine if the variations in contact angle value for different samples were statistically significant. A P-value is the probability that significance is found where there really is none ($P = 0.05$, 5% chance significance is declared where it does not exist). A P-value of 0.00005



(a) (b)

Figure 5 (a) Force curves for five Caucasian samples for both dry and wet scenarios. (b) Average advancing contact angle values for five Caucasian samples for both dry and wet conditions.

was found for the difference between virgin and chemically damaged hairs. This is a strong evidence that the difference is real, as it indicates only a 0.005% chance that the difference is not real. This trend is also the same as in previous studies.[16,17] The reason for this, as mentioned earlier, is that the hydrophobic outermost layer of virgin hair, the cell membrane complex, is partially removed during damage, exposing hydrophilic underlayers. A schematic of this surface structure is shown in Figure 1. Additionally, conditioner treatment was found to lower the contact angle of virgin hair (*P*-value of

TABLE I
Summary of Average Advancing Contact Angle Values

Sample	Contact angle (°)	
	Dry	Soaked
Virgin	103 ± 4	98 ± 2
Virgin treated	88 ± 9	92 ± 1
Chemically damaged	70 ± 7	70 ± 8
Chemically damaged treated (one cycle)	79 ± 1	84 ± 2
Chemically damaged treated (three cycles)	77 ± 5	72 ± 4
Asian	95 ± 4	–
African	92 ± 11	–
Mechanically damaged	80 ± 14	–
Virgin—with scale (WS) orientation	85 ± 10	–

0.0075) and increase the contact angle of chemically damaged hair (*P*-value for chemically damaged and chemically damaged treated (one cycle) is 0.024. These results explain previous findings that virgin hair exhibits a lower coefficient of friction than chemically damaged hair.[8,16,17] The *P*-value for the difference between chemically damaged treated (one cycle) and chemically damaged treated (three cycles) was found to be 0.36. This indicates multiple conditioner applications may not affect the wetting properties of the hair. Because the damaged surface is hydrophilic, meniscus forces may contribute a significant portion to the total friction force, whereas this is not the case for the hydrophobic virgin hair surface. For the case of conditioner treated samples two things are altered: contact angle of the surface and shearing force required. For virgin hair, treatment reduces the contact angle slightly, but it tends to remain very near 90°, so meniscus forces will not likely be significant. Also, because the virgin hair surface is already rather lubricious due to the lipid layer that is present, the addition of conditioner does not significantly add to the lubricity of the surface on the nanoscale. For these reasons, the coefficient of friction does not change much in virgin hair with conditioner treatment.[8,16,17] This, however, is not the case for chemically damaged hair. Addition of conditioner to chemically damaged hair raises the contact angle, so less meniscus forces are present. It also creates a lubricious layer that does not exist on damaged hair, since the natural lipid layer has been removed due to the damage. The combination of these effects significantly decreases the coefficient of friction.[8,16,17]

It is observed that conditioner treatment has opposite effects on virgin and damaged hairs. One explanation for this is that on virgin hair, a low energy surface is intact due to the lipid layer present. Therefore, when the conditioner deposits the cationic surfactants will orient such that the alkyl chains are toward the hair surface and the cationic groups are out. The higher energy cationic groups cause a decrease in contact angle. However, for chemically damaged hair, the cationic groups will tend to orient toward the hair, leaving the alkyl chains away from hair surface, causing a decrease in surface energy and an increase in contact angle. However, the chemical interactions just proposed cannot be proven without separating each component and testing them individually, which is difficult. Another possible explanation for the effect of conditioner treatment is that if the conditioner material dominates the wetting properties of the fiber, treatment will not necessarily increase or decrease the surface contact angle, but rather cause a convergence to an angle representative of the conditioner used in the treatment. Therefore, it may be that the contact angle of the conditioner material coincidentally lies between that of virgin and damaged hair, and with treatment, contact angles converge to this value. To further understand this converging behavior, chemically damaged hair that was treated with a conditioner containing an amino silicone was also measured. Amino silicone conditioner is known to bind to the hair surface and does not redistribute.[17] This is in contrast to commercial conditioner which is mobile on the hair surface. Therefore, amino silicone treated hair will be less affected by immersion in the wetting liquid. The contact angle of the amino silicone treated hair was found to be 75° ± 1°, which is similar to chemically damaged hair treated with commercial conditioner. This suggests that the contact angle of treated hair is indeed representative of the wetting properties of the conditioner itself.

Additionally, the force plots shown in Figure 5 for the dry samples indicate the probable location of conditioner deposits. As previously discussed, the receding portion of the force plot is strongly influenced by scale edge contributions, which likely have significant hydrophilic regions. This affects the force plots by giving a large hysteresis. If the scale edges are covered or hidden from proper wetting, however, this hysteresis should be smaller as the hydrophilic edges then contribute less to the receding force. It can be observed from Figure 5 that the untreated samples have significantly greater hysteresis than do the treated samples. This is an indication that the conditioner remains at the scale edge bases, hiding the edges from proper wetting. This agrees well with previous claims.[8]

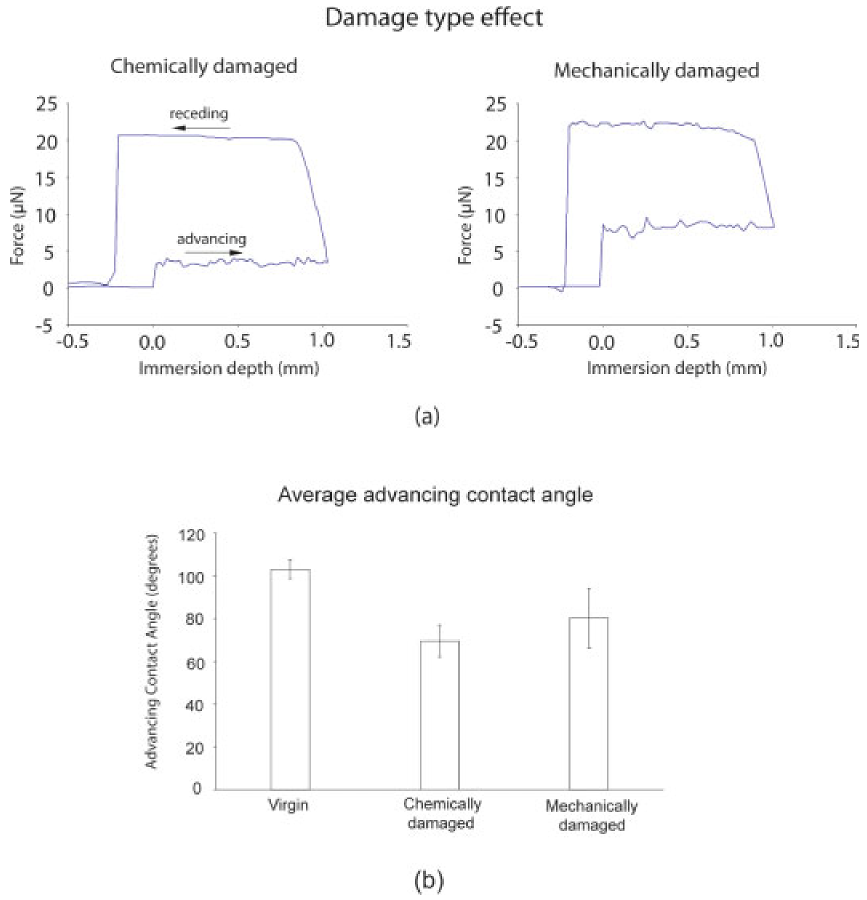
These hair samples were also soaked in deionized water for 5 min, and then measured to determine the effect of a wet environment on contact angle. This data is also shown in Figure 5. The figure shows that the contact angle values after the samples had been soaked are nearly identical to those that were measured on dry samples. This suggests that even when subjected to a liquid water environment, the wetting properties of hair do not change with time. That is, after having been exposed to liquid water, the water still wets the surface with the same contact angle that it did before the hair was exposed to liquid water. This also shows that soaking for 5 min does not remove a significant amount of the conditioner layer on treated hairs, as the contact angle does not return to the untreated value after having been soaked. It should be noted that single hair fibers exhibit a high rate of drying and thus may be changing during the experiment.

Dependence on type of damage

In addition to chemical damage, samples affected with mechanical damage were also studied to compare the effects of various types of damaging treatments. The results of this experiment are shown in Figure 6. These results show that chemically damaged hair tends to be more hydrophilic than mechanically damaged hair. However, the mechanical damage occurs primarily at the scale edges. Due to the orientation of the hair fiber (AS), the contributions to the contact angle measurement from surface material around the scale edges is very low due to the way the fiber interacts with the wetting liquid as it pushes into the liquid (shown in Fig. 3 and discussed earlier). Due to the geometry of the hair fiber, the majority of the contact at the liquid/air interface is on the general surface of a cuticle scale, away from scale edges. Therefore, even though the mechanical damage exposes hydrophilic underlayers, this effect is only observed when the damage extends well beyond the scale edge. In contrast, the chemical damage occurs over every part of the hair surface, so its effect is more pronounced using this measurement technique. A method to mechanically damage the hair surface away from the scale edges, or a different measurement technique, would have to be used to more appropriately compare damaging treatments.

Ethnicity dependence

Virgin samples of Caucasian, African, and Asian hair were measured and compared. Results are shown in Figure 7. No significant difference was found, although African and Asian hairs do exhibit a



(a)

(b)

Figure 6 (a) Force curves comparing chemical and mechanical damage effects. (b) Average advancing contact angle comparing chemical and mechanical damage effects. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

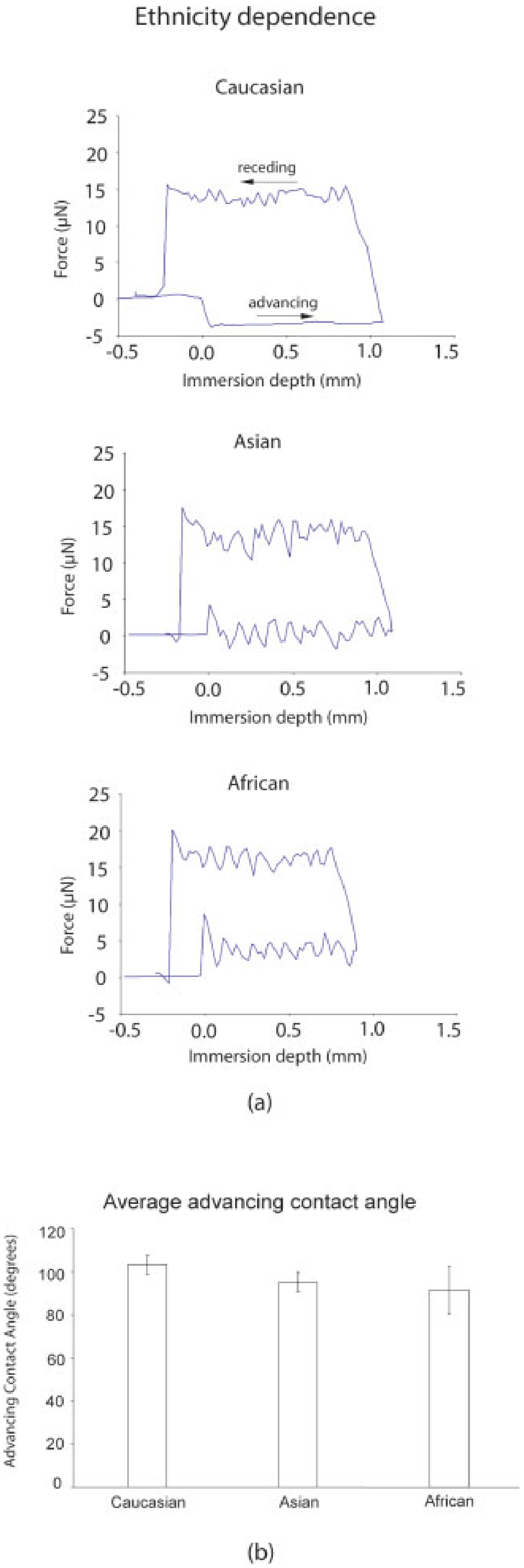


Figure 7 (a) Force curves showing ethnicity dependence. (b) Average advancing contact angle values showing ethnicity dependence. No significant dependence on ethnicity was found for advancing contact angle values. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

slightly lower contact angle that Caucasian hair on average. Further study would have to be done to investigate whether this difference was real or simply a result of the low number of samples measured.

CONCLUSIONS

In this study dynamic contact angle of human hair was studied. The conclusions from this study are as follows:

1. The Wilhelmy balance technique is a powerful tool in analyzing the wetting properties of thin fibers such as human hair. To study the contact angle of the surface of human hair away from cuticle scale edges where mechanical damage may alter results, the advancing direction using the against scale orientation is the most appropriate.
2. Virgin hair was found to be hydrophobic as a result of the outer lipid layer coating its surface. Hair that has been damaged chemically or mechanically was found to be hydrophilic as a result of this outermost layer being at least partially removed during the damaging process. Conditioner treatment was found to lower the contact angle of virgin hair, and raise the contact angle of damaged hair.
3. The effect of conditioner on the contact angle of the hair surface was found to explain the drastic drop in friction of damaged hair after conditioner treatment.
4. The large hysteresis values found in untreated samples is in contrast with a smaller hysteresis for treated samples. This indicates the presence of conditioner at the cuticle scale edge bases, which agrees with previous claims.

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APPENDIX: SHAMPOO AND CONDITIONER TREATMENT PROCEDURE

This appendix section outlines the steps involved in washing hair switches with shampoo and/or conditioner.

Shampoo treatments

Shampoo treatments consisted of applying a commercial shampoo evenly down a hair switch with a syringe. Hair was lathered for 30 s, rinsed with tap water for 30 s, and then repeated. The amount of shampoo used for each hair switch was 0.1 cm^3 shampoo per gram of hair. Switches were hanged to dry in an environmentally controlled laboratory, and then wrapped in aluminum foil.

Conditioner treatments

A commercial conditioner was applied 0.1 cm^3 of conditioner per gram of hair. The conditioner was applied in a downward direction (scalp to tip) thoroughly throughout hair switch for 30 s, and then allowed to sit on hair for another 30 s. The switch was then rinsed thoroughly for 30 s. Switches were hanged to dry in an environmentally controlled laboratory, and then wrapped in aluminum foil.

References

1. Feughelman, A. Mechanical Properties and Structure of α-Keratin Fibres: Wool, Human Hair and Related Fibres; University of South Wales Press: Sydney, 1997.
2. Morioka, K. Hair Follicle—Differentiation Under the Electron Microscope; Springer-Verlag: Tokyo, 2005.
3. Robbins, C. Chemical and Physical Behavior of Human Hair, 3rd ed.; Springer-Verlag: New York, 1994.
4. Zviak, C., Ed. The Science of Hair Care; Marcel Dekker: New York, 1986.
5. Kamath, Y. K.; Dansizer, C. J.; Weigman, H. D. J Appl Polym Sci 1978, 22, 2295.
6. Negri, A. P.; Cornell, H. J. Textile Res J 1993, 63, 109.
7. Molina, R.; Comelles, F.; Julia, M. R.; Erra, P. J Colloid Interface Sci 2001, 237, 40.
8. Lodge, R. A.; Bhushan, B. J Vac Sci Technol A 2006, 24, 1258.
9. Wilhelmy, L. Ann Phys 1863, 119, 177.
10. Hoecker, F. Karger-Kocsis, J. J Appl Polym Sci 1996, 59, 139.
11. Ecke, S.; Preuss, M.; Butt, H. J Adhesion Sci Technol 1999, 13, 1181.
12. Barber, A. H.; Cohen, S. R.; Wagner, H. D. Phys Rev B 2005, 71, 115443.
13. Timoshenko, S. Strength of Materials Part 1 and Part 2, 3rd ed.; Krieger: Melbourne, FL, 1983.
14. Lam, C. N. C.; Kim, N.; Hui, D.; Kwok, D. Y.; Hair, M. L.; Neumann, A. W. Colloids Surf A 2001, 189, 265.
15. Lide, D. R., Ed. The CRC Handbook of Chemistry and Physics, 85th ed.; CRC Press: Boca Raton, 2004.
16. LaTorre, C.; Bhushan, B. Ultramicroscopy 2005, 105, 155.
17. LaTorre, C.; Bhushan, B.; Yang, J. Z.; Torgerson, P. M. J Cosmetic Sci 2006, 57, 37.