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Measurements of hair volume by laser stereometry

ROGER McMULLEN, FRANCO ZISA, and
JANUSZ JACHOWICZ,* *International Specialty Products, Wayne, NJ.*

Synopsis

A three-dimensional laser stereometer was constructed utilizing an x-y two-dimensional translational stage and a laser device, which provides distance information in the z-direction. The distance data is obtained by triangulation of the reflecting red laser beam from the surface of the measured object, in this case hair. Since hair fiber assemblies do not have a continuous solid surface, each z-dimension reading is obtained as an average of measurements obtained from multiple reflections corresponding to fibers at various depths below the outermost hair surface. We demonstrate the utility of this technique to perform the analysis of either an entire hair tress or relatively short sections of tresses prepared from straight, curly, and frizzy hair and subjected to cosmetic treatments such as washing, conditioning, dyeing, etc. An interpretation is provided for the three-dimensional images of hair assemblies as well as for the calculated volume of space occupied by a hair tress. In addition, we investigated various strategies for testing the volume retention of styling polymers.

INTRODUCTION

Hair body is one of the most important attributes for the hair care consumer. It is a complex phenomenon that describes the three-dimensional state of one's hair and often alludes to the overall mechanical properties of the hair fiber assembly. Several single fiber properties are thought to be responsible for hair body and include curvature, friction, stiffness, diameter, cohesion, or weight of the individual fibers that comprise the hair fiber assembly (1–3). Based on consumer research in conjunction with principal component analysis (a statistical technique), it was found that three words, together, describe body: volume (bulk, thickness), springiness (bounce), and stiffness (of the hair-set, not soft) (4). Other studies have emphasized the structural strength and resiliency of a hair mass as the predominant characteristics responsible for consumer-perceivable body (5). These studies were followed by the development of techniques to evaluate hair body based on the amount of work required to pull a hair tress through a specially designed template or utilizing a radial compressibility apparatus (6–9). Hair volume is recognized as a key component of hair body, and several attempts have been made to measure the three-dimensional volume of a hair-fiber assembly (10,11). In this account, we describe a technique to measure hair volume by three-dimensional laser stereometry and demonstrate how physical properties of the hair fiber assembly influence the volume.

*The current address of Janusz Jachowicz is International Specialty Products, LLC, Bethel, CT.

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MATERIALS AND METHODS

DESIGN AND CONSTRUCTION OF A THREE-DIMENSIONAL LASER STEREOMETER

A three-dimensional laser stereometer was constructed based on laser triangulation technology, allowing for measurement of three-dimensional surface plots. Utilizing a reflective laser in conjunction with a two-dimensional translation stage, an instrument was constructed that was capable of scanning a substrate in the x- and y-direction while at the same time measuring the distance from the laser to the surface of the substrate. The laser component of the instrument, referred to as Smart Sensor unit, consisted of a diffuse reflective measurement sensor head (ZX-LD100L), series communications interface (ZX-SF11), and a laser measurement amplifier (ZX-LDA11), all manufactured by Omron Corporation, Kyoto, Japan. The measurement sensor head has a measurement range of 6–14 mm and beam dimensions of 1 mm in width by 4 mm in length. The two-dimensional translation stage was constructed utilizing two NLS4 Series Precision Linear Stages manufactured by Newmark Systems, Mission Viejo, CA, U.S. (Model NLS4-12-25). As shown in Figure 1, the two-dimensional translation stage and the laser system are mounted on a black anodized optical board with dimensions of 36 in. × 24 in. × ½ in.—purchased from Edmund Optics, Barrington, NJ, U.S. (Model A03-680). In order to coordinate data collection from the laser component with movement of the two-dimensional stage, a software program was written using Visual Basic 6.0 (Microsoft, Redmond, WA, U.S.) allowing for automated control of the three-dimensional laser stereometer.

PRINCIPLE OF LASER TRIANGULATION

The laser device utilized in this work operates based on the principle of laser triangulation. Light is sent from the laser diode, located in the laser sensor head, and is reflected by the surface of the substrate under study, thereby sending the light back to the sensor where it is focused via lenses onto a charge-coupled device (CCD). The resulting path length of the light forms a triangle with the distance between the laser diode and CCD

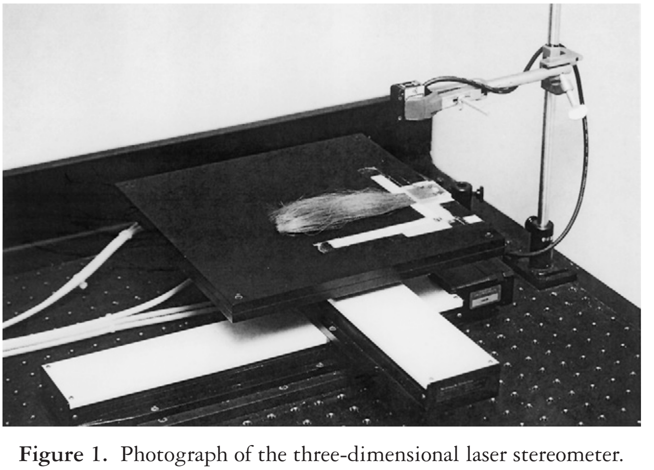

Figure 1. Photograph of the three-dimensional laser stereometer.

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comprising one leg, while the distance between both components and the surface of the substrate forming the other two legs. Based on set angles and distance of the CCD and laser diode devices, the distance from the sensor to an object may be calculated. Depending on the distance of the laser to the substrate, the reflected light will strike the surface of the CCD in a different position allowing for measurement of distance.

HAIR SUBSTRATES

A variety of hair types were examined, which consisted of European dark brown straight hair as well as dark brown European hair characterized by various degrees of curvature, such as straight, very curly, and frizzy hair. Measurements were also performed on Natural African Kinky hair. All hair was purchased from International Hair Importers & Products, Inc., Glendale, NY, U.S. Straight hair tresses were constructed by gluing 2 g of fibers to a 1.5 in. × 1.5 in. Plexiglas tab with Duco cement. The resulting dimensions of straight hair tresses were 6.5 in. in length and 1.25 in. in width. The masses of the straight, very curly, and frizzy hair were variable and are indicated in the Results and Discussion section of this report. We also examined the effect of a bleaching process on the measured topographical plot and volume of hair. To bleach hair, 120 g of commercial bleaching powder (BW 2 – Clairol Professional, Procter & Gamble Company, Cincinnati, OH, U.S.) was mixed with 147 mL of 20 volume clear developer (Emiliani Brothers, Union, NJ, U.S.). After thorough mixing with a spatula, European dark brown hair was treated with this mixture and allowed to react for 30 minutes. The hair was then shampooed with 3% (w/w) ammonium lauryl sulfate (ALS) followed by rinsing. To examine the effect of bleaching on the fiber assembly properties of hair, we utilized an atypical drying technique. After wetting, excess water was removed from the tress by sliding two fingers (index and middle) along the length of the hair tress allowing all of the fibers to remain together. The hair tress was then allowed to air-dry overnight at ambient temperature and humidity (25°C and 50% RH).

INVESTIGATED MOLECULES

The effect of various polymers were tested in order to evaluate their ability to either increase volume for bleached hair or retain volume for hair subjected to stress stimuli such as high humidity or external forces. The following polymers, manufactured by ISP (Wayne, NJ), were utilized and their respective commercial names are provided: VCL/VP/DMAEMA (Advantage LCA), VP/acrylates/lauryl methacrylate copolymer (Styleze 2000), Polyimide-1 (Aquaflex XL-30), Polyquaternium-55 (Styleze W-20), VP/DMAPA acrylates copolymer (Styleze CC-10), Polyquaternium-11 (Gafquat 755N), Polyquaternium-69 (AquaStyle 300), isobutylene/ethylmaleimide/hydroxyethylmaleimide copolymer (Aquaflex FX-64), and VP/VCL/DMAPA acrylates copolymer (Aquaflex SF-40). The acronyms VCL, VP, DMAEMA, and DMAPA are used to represent the monomer units vinyl caprolactam, vinyl pyrrolidone, dimethylaminoethyl methacrylate, and dimethylaminopropyl methacrylate. Polyimide-1 may more specifically be described as isobutylene/dimethylaminopropyl maleimide/ethoxylated maleimide/maleic acid copolymer. We examined the commercially available polymer as well as a high molecular weight analog. Several samples of PVP (supplied by ISP, Wayne, NJ) were tested and consisted of PVP K30 (M_w = 60,000 Da), PVP K90 (M_w = 1,300,000 Da), and PVP K120

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(M_w = 3,000,000 Da). Unless otherwise indicated, all samples were prepared as 1% solutions (w/w) and applied to hair with a pipette or a hairspray pump applicator.

HIGH HUMIDITY AND FORCE DEFORMATION

All experiments were conducted in a laboratory with humidity and temperature control (25°C and 50% RH). For high humidity experiments, hair samples were placed in a humidity chamber at 90% RH. Force deformation of hair samples was carried out with a texture analyzer (Model TA-XT2, Texture Technologies Corporation), Which was located inside the humidity chamber. The texture analyzer has a load sensitivity of 0.1 g and was operated using XTRA dimension 3.7 software from Stable Micro Systems.

RESULTS AND DISCUSSION

Hair volume measurements were carried out utilizing an in-house designed laser stereometer. As already stated, the stereometer was constructed utilizing a laser device, based on the principle of laser triangulation, in conjunction with a two-dimensional translation stage. The laser device sensor head is capable of measuring the distance from the laser source to an object of interest. Therefore, by placing an object such as hair on the translation stage, we were able to obtain z-data for each x- and y-coordinate of a scan. Utilizing this approach, a hair tress may be positioned on the platform of the translation stage and a surface plot corresponding to the three-dimensional volume occupied by the hair assembly may be constructed. In addition, data are also presented in the form of contour plots or cross-sectional representations of the hair tress allowing one to view the tress along its primary axis. In an attempt to differentiate the shape between hair samples, we analyzed hair of varying degrees of curvature (straight, very curly, and frizzy) to determine the occupied volume of each hair type. We also investigated the effect of bleaching and subsequent treatment on the fiber assembly properties of European dark brown hair. Further, we studied the effects of various polymeric treatments on the volume of hair fiber assemblies. This was accomplished by employing several different techniques to build volume into the hair fiber assembly, then to subject hair to challenge tests, such as high humidity or external forces, and measure how well the hair fiber-polymer assembly performs to induced stress.

MEASUREMENT OF HAIR ASSEMBLIES WITH DIFFERENT GEOMETRIC ARRANGEMENTS

Traditionally, straight hair tresses have been utilized for research and development work in the personal care industry, mostly European dark brown hair. In more recent years, hair suppliers have begun to offer hair types with various fibers assembly properties. Some examples of these hair types are shown in Figure 2 and are classified as straight, very curly, and frizzy hair. The three-dimensional geometric arrangements in these hair types are dramatically different from each other and from traditional straight hair tresses. As a result, the occupied volume by such a fiber assembly is also very different. For the hair types shown in Figure 2, we also provide a corresponding surface plot for a section of each tress (See Figure 3). The calculated volume for each tress section is: straight–123.04, very curly–276.32, and frizzy–514.97 (values reported as cm^3). The corresponding weights of

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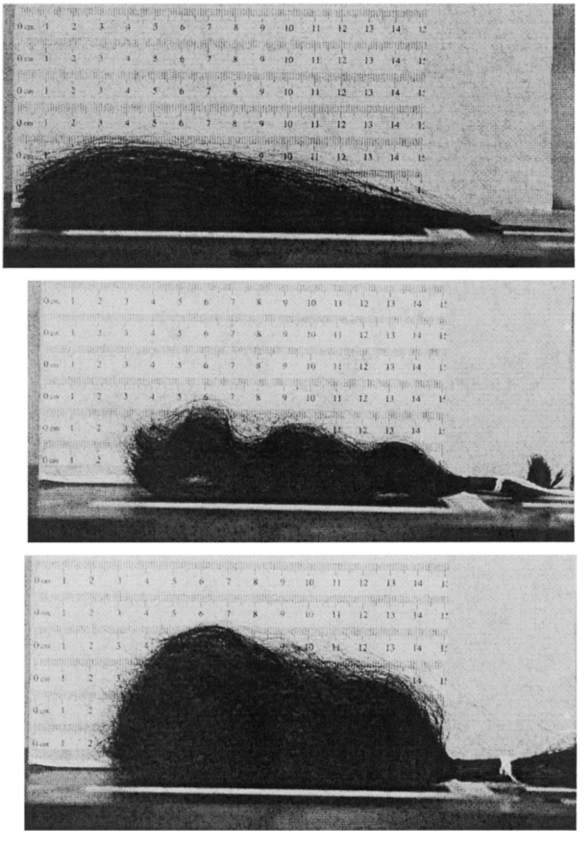

(a)

(b)

(c)

Figure 2. Photograph of various hair tress geometries with numeric scale.

the entire tresses were: straight–2.0 g, very curly–1.9 g, and frizzy–4.8 g. It is important to note that while mass is reported for the entire tress, volume is provided only for a 40 mm × 80 mm section.

EFFECT OF BLEACHING ON FIBER ARRANGEMENT

Bleaching is generally thought to increase the body of hair. Most likely, this is due to increased friction or adhesion between the fibers as a result of bleaching in which spot welds are formed between multiple fibers on a human head of hair. As a result, a three-dimensional structure is produced that contains voids of air due to the random nature of the spot welds and lends to an overall increase in volume. Utilizing the technique outlined in the Methods and Materials section, the effect of bleaching on fiber assembly behavior may be monitored with the three-dimensional laser stereometer.

A comparison was made between virgin dark brown hair and the same hair type that had undergone bleaching. The virgin hair was washed twice with 3% ALS followed by thorough rinsing. While still in the wet state, two fingers (middle and index) were run along the hair tress removing excess water and maintaining the fibers bound together in a mat arrangement. The hair was then allowed to dry overnight on a hanging rack without

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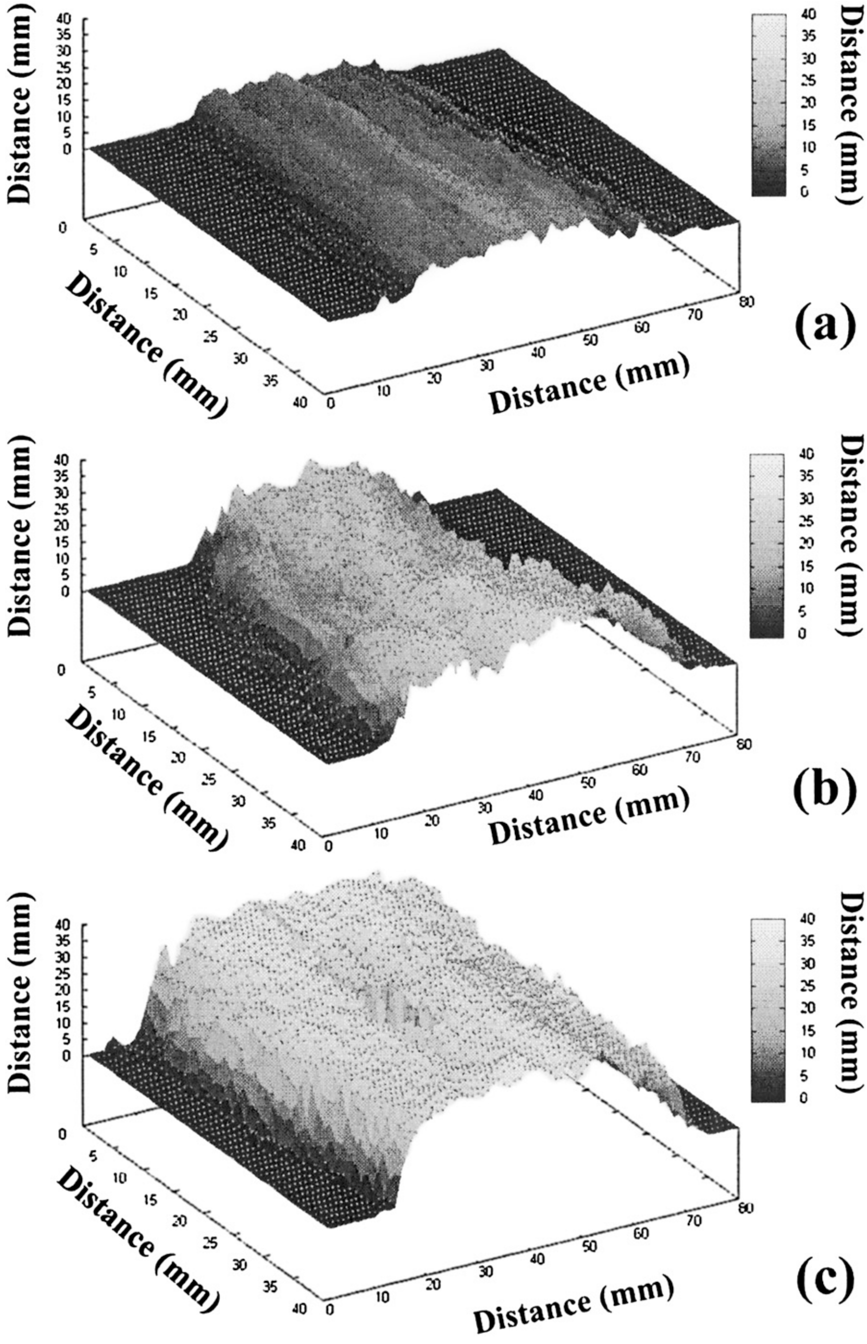

Figure 3. Three-dimensional surface plots of hair types shown in Figure 2.

disruption. As seen in Figure 4a, virgin dark brown hair appears in its normal (fluffy) state after following this procedure. We followed the same procedure for bleached hair, which after drying resulted in a matted bundle of fibers with less apparent volume (Figure 4b). In addition, the effect of treatment with a cationic polymer is also shown in

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(a) **(b)** **(c)**

Figure 4. Images of (a) dark and (b) bleached hair. Bleached hair was then treated with (c) Polyquaternium-55.

Figure 4c in which case we observe the fibers returning to a less matted state, similar to the original hair tress. This was verified by performing scans with the three-dimensional laser stereometer and subsequent surface plotting, which is provided in Figure 5. We also calculated the corresponding volumes of each tress section scanned to obtain the values provided in Table I, which include virgin hair, the same hair after bleach treatment, and bleached hair treated with indicated ingredient.

Each average value in the chart represents the average of three measurements. In all cases we observe a decrease in volume when comparing the virgin dark brown hair to the same hair that underwent the bleach treatment. Subsequent treatment of the bleached hair with a conventional commercial conditioner, or with some of the tested polymers (Polyquaternium-55 and Polyimide-1), results in an increase in volume. Thus, the visually perceptible loss or increase in volume is confirmed by a formal quantitative analysis of hair geometry).

METHODS TO INVESTIGATE THE VOLUME RETENTION OF HAIR STYLING AGENTS

Consumers often seek products, which deliver and maintain hair volume. Typically, they build volume in a hair fiber assembly through the combined action of treatment with a hair styling agent and mechanical manipulation of the fibers. Once the three-dimensional fiber assembly is set, it is desirable to maintain the created or formed volume. It may be often desired to monitor the volume-building capability of a treatment. However, this would require a mechanical robot or instrument to manipulate the fibers in a very reproducible manner. In the studies presented in this section we examine the ability of treatments to maintain volume of hair. To accomplish this, we first build volume in a fiber assembly, and then subject it to external stresses such as high humidity (90% RH) or small force deformations analogous to an action of a person touching his or her hair. Thus, we can provide a detailed analysis of the ability of various styling agents to retain volume under mechanical or environmental stress.

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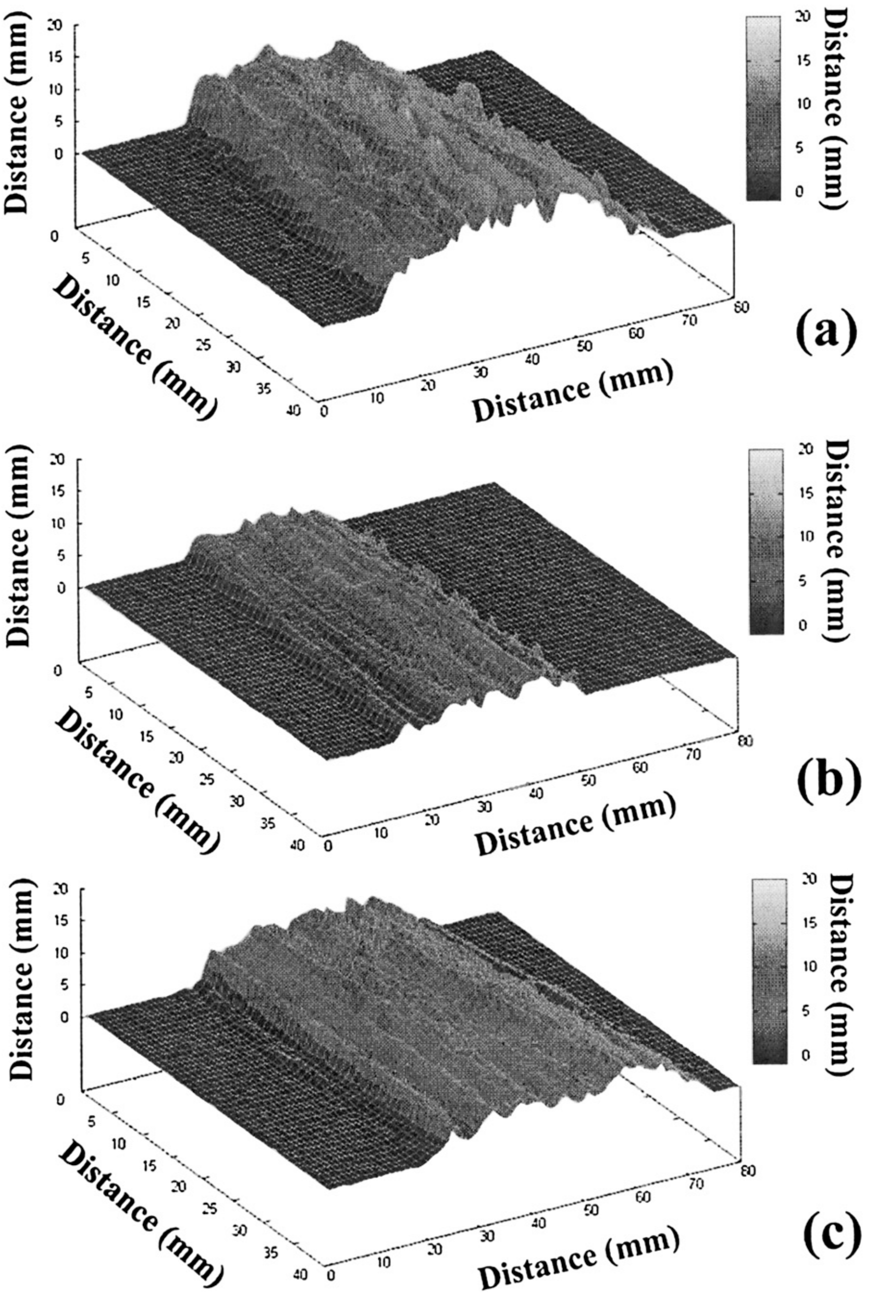

Figure 5. Three-dimensional surface plots corresponding to the images in Figure 4.

Three different techniques were employed to measure volume retention, which we will refer to as (1) frizzy hair, (2) root-lift, and (3) straight hair techniques. In the frizzy hair technique, a hair tress is treated with a 1% solution of the ingredient; then we mechanically mainpulate the fibers while blow-drying to build an expanded three-dimensional fiber assembly. The hair tress is then placed in a wooden frame, as shown in Figure 6, and

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Table I
Volume Data for Bleached Hair Treated with Various Polymers

	Volume (virgin hair)	Volume (after bleaching)	Volume (after treatment)
VCL/VP/DMAEMA	83.35 ± 1.55	35.98 ± 6.17	28.15 ± 5.18
VP/acrylates/lauryl methacrylate copolymer	100.34 ± 17.07	42.16 ± 1.45	45.45 ± 7.69
Polyimide-1	100.47 ± 12.31	19.53 ± 2.25	38.93 ± 3.16
Polyquaternium-55	99.18 ± 12.48	21.07 ± 3.73	41.84 ± 11.64
Commercial conditioner	100.47 ± 12.31	23.06 ± 0.54	85.14 ± 6.68

Each value is the average of three measurements (three different tresses) and is reported with standard deviation. Data are provided in units of cm^3.

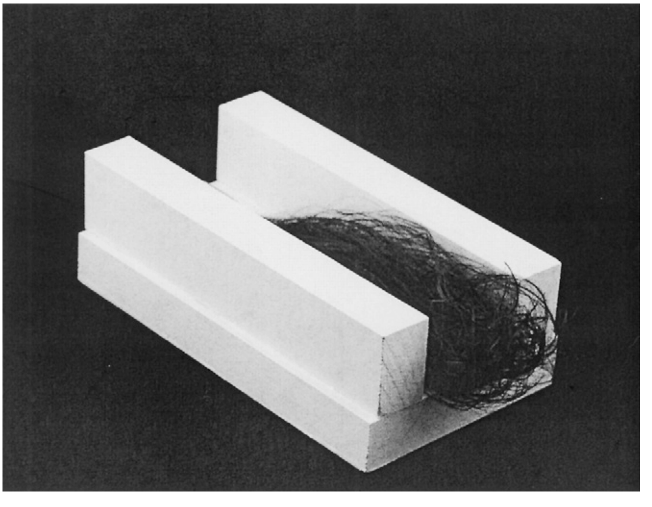

Figure 6. Frizzy hair technique. A frizzy hair tress is shown situated in a wooden frame.

readings are obtained with the laser stereometer. The wooden frame, with the tress inside, is carefully placed in a humidity chamber and subjected to high humidity (90% RH) and/or mechanical deformation. After stressing the sample (with high humidity or mechanical forces) for a given period of time subsequent laser stereometer measurements are performed in order to acquire the values of volume before and after the stressing procedures. We explored several different protocols to conduct these tests, which included (1) placing the sample in a 90% RH environment for 4 hours or (2) subjecting the sample to 90% RH for 30 minutes followed by compression deformation employing a Texture Analyzer with the maximum forces of 3, 5, 7, or 9 grams. Using the frizzy hair technique, we were able to observe a loss in volume after the applied stress (see Figure 7). However, we were not able to differentiate between the various treatments. This may be attributed to an excessive variability of experimental conditions. First, frizzy hair is probably not the most ideal choice of substrate for a hair volume test, especially one that involves high humidity. Typically, frizzy hair becomes frizzier upon exposure to high humidity. Secondly, probe penetration by the Texture Analyzer is not always limited to the contact area of the probe. Often, the probe forces large areas of the tress to undergo deformation. This may lead to

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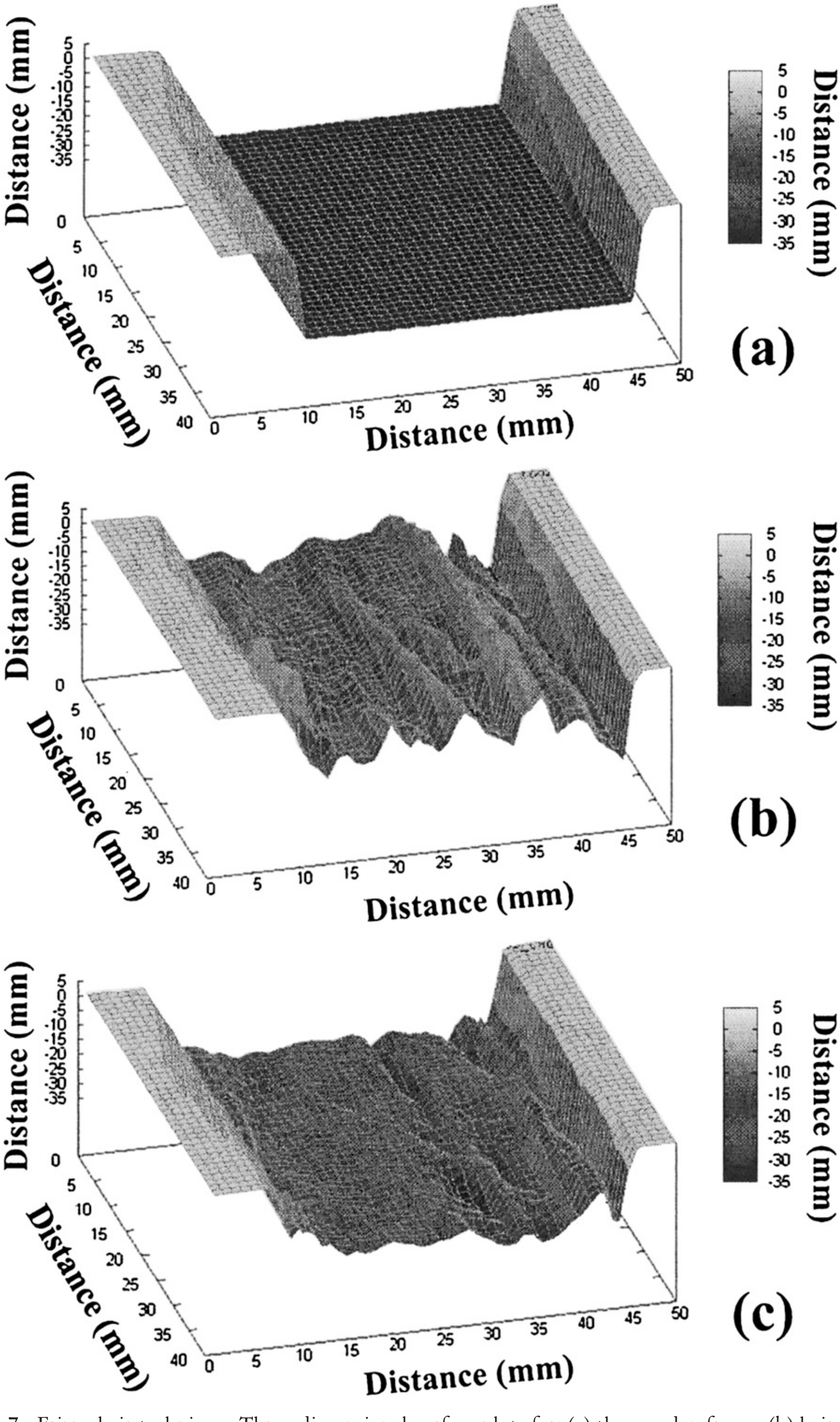

Figure 7. Frizzy hair technique. Three-dimensional surface plots for: (a) the wooden frame, (b) hair treated with Polyquaternium-55 then placed in the frame, and (c) the Polyquaternium-55 treated hair after exposure to 90% RH.

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erroneous readings, overestimating the amount of lost volume. Thirdly, choosing the correct force, humidity exposure conditions, and the number of times that the probe comes in contact with the hair sample are key parameters in this experiment.

The root-lift technique consists of forming the hair into an almost u-shaped arrangement in the treated state resulting in all of the fibers bonded together. An illustration of a tress prepared for the root-lift technique is provided in Figure 8. This technique corresponds to a method commonly employed by beauticians and consumers in which they heavily treat the root portion of the hair in order to enhance volume. Often, it is accompanied by blow-drying. An example of the root-lift technique is shown in Figure 9 for hair that was treated with PVP K30. After 4 hours of exposure to 90% RH, we found that the height of the loop decreased, resulting in less volume underneath the hair. Several different polymers were tested in this manner and a summary of these results is given in Table II.

In general, we find that polymers with the highest humidity resistance perform the best in this test. To examine concentration and molecular weight dependence, we studied Polyimide-1. These data are given in Table III and clearly demonstrate that increasing the polymer concentration or molecular weight increases the amount of retained volume.

The third method for investigating volume retention of styling agents, the straight hair technique, consisted of utilizing conventional hair tresses and building tress volume by treatment and subsequent mechanical manipulation and blow-drying. This method is very similar to the frizzy hair technique. It does, however, utilize a different mass (4 g) of straight European dark brown hair and the wooden frame for these samples does not have walls as the one discussed above. Also, we only subjected the treated tresses to 2 hours of 90% RH without any force deformations. As in the other tests, before and after stress readings were obtained with the laser stereometer. A pictorial view of a hair tress treated with PVP K15 is provided in Figure 10. The scale in the photograph allows us to discern the difference in the sample before and after humidity exposure. As an example, a three-dimensional surface plot, corresponding to before and after 90% RH exposure, is provided in Figure 11. Further, we subjected other polymers to a similar test and the obtained results are shown in Table IV.

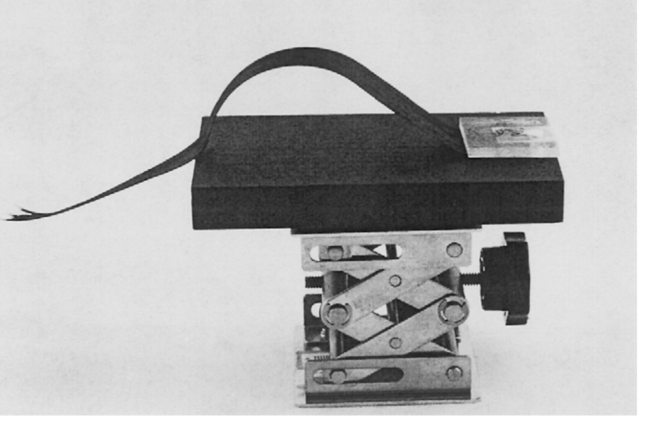

Figure 8. Root-lift technique. Photograph of hair treated and shaped into a particular arrangement.

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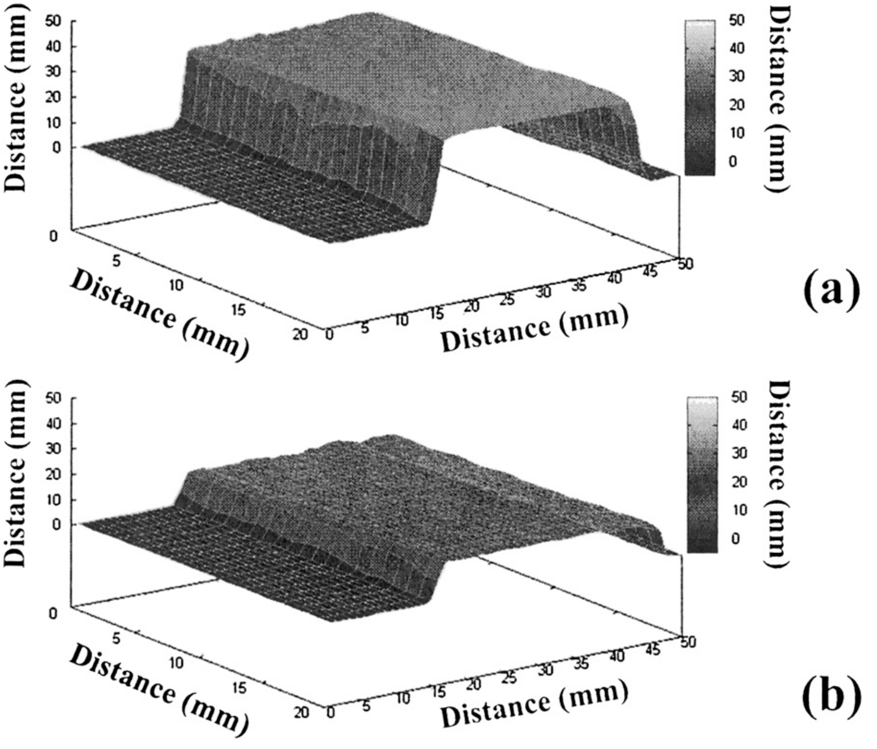

Figure 9. Root-lift technique. Three-dimensional surface plots for hair treated with PVP K30 (a) before and (b) after exposure to 90% RH.

Table II
Volume Difference Data for Hair Treated with Various Polymers

	ΔV (cm^3)
Polyquaternium-55	1.07 ± 9.03
VP/DMAPA acrylates copolymer	42.57 ± 39.55
Polyquaternium-11	69.94 ± 22.90
VP/acrylates/lauryl methacrylate copolymer	16.93 ± 3.18
VCL/VP/DMAEMA copolymer	26.00 ± 6.02
Polyquaternium-69	46.93 ± 9.94
Isobutylene/ethylmaleimide/hydroxyethylmaleimide copolymer	3.93 ± 2.20
VP/VCL/DMAPA acrylates copolymer	25.57 ± 10.49
PVP K120	87.40 ± 5.09
PVP K90	92.81 ± 8.30
PVP K30	104.26 ± 16.9

Tests were conducted using the root-lift technique. ΔV represents the difference in volume before and after humidity exposure. Each value represents the average of three measurements and is reported with standard deviation.

CONCLUSIONS

A laser stereometer was constructed in order to take measurements of hair fiber assemblies allowing for the generation of surface plots and the subsequent calculation of volume

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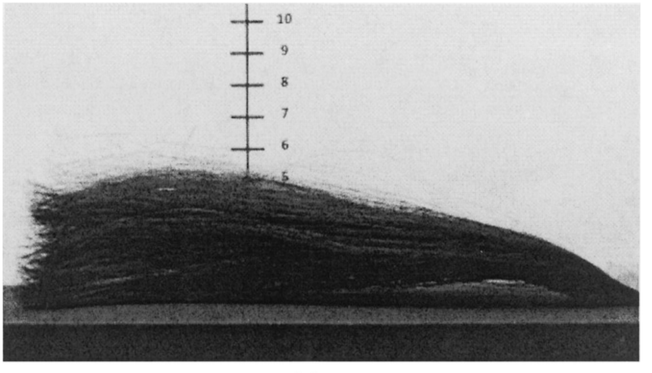
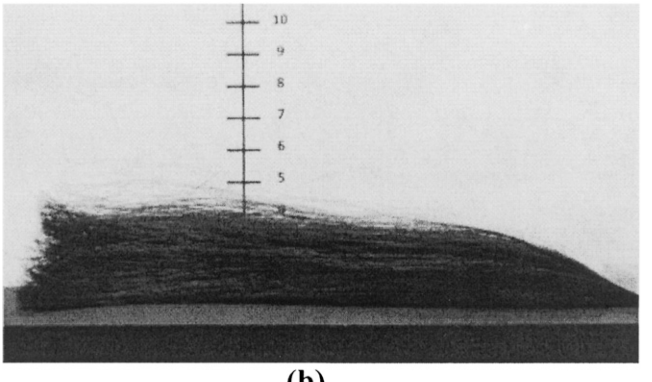
Table III
Volume Difference Data for Hair Treated with Various Concentrations of Polyimide-1 and a High-Molecular-Weight Version of the Polymer

	ΔV (cm^3)
1% Polyimide-1	79.08 ± 10.92
2% Polyimide-1	29.03 ± 7.44
4% Polyimide-1	10.80 ± 5.36
1% High MW Polyimide-1	50.14 ± 7.94

Tests were conducted using the root-lift technique. ΔV represents the difference in volume before and after humidity exposure. Each value represents the average of three measurements and is reported with standard deviation.



(a)



(b)

Figure 10. Straight hair technique. Photograph of conventional hair tresses treated with PVP K30 (a) before and (b) after exposure to 90% RH.

occupied by a hair tress section. Three types of hair (straight, very curly, and frizzy) with visually noticeable volume differences were analyzed and found to produce surface plots and volume data corresponding to their visual appearance. In addition, the effect of a bleaching process on the volume of straight hair tresses was also examined and found to produce effects perceptible to the human eye and measurable by the instrument. Several

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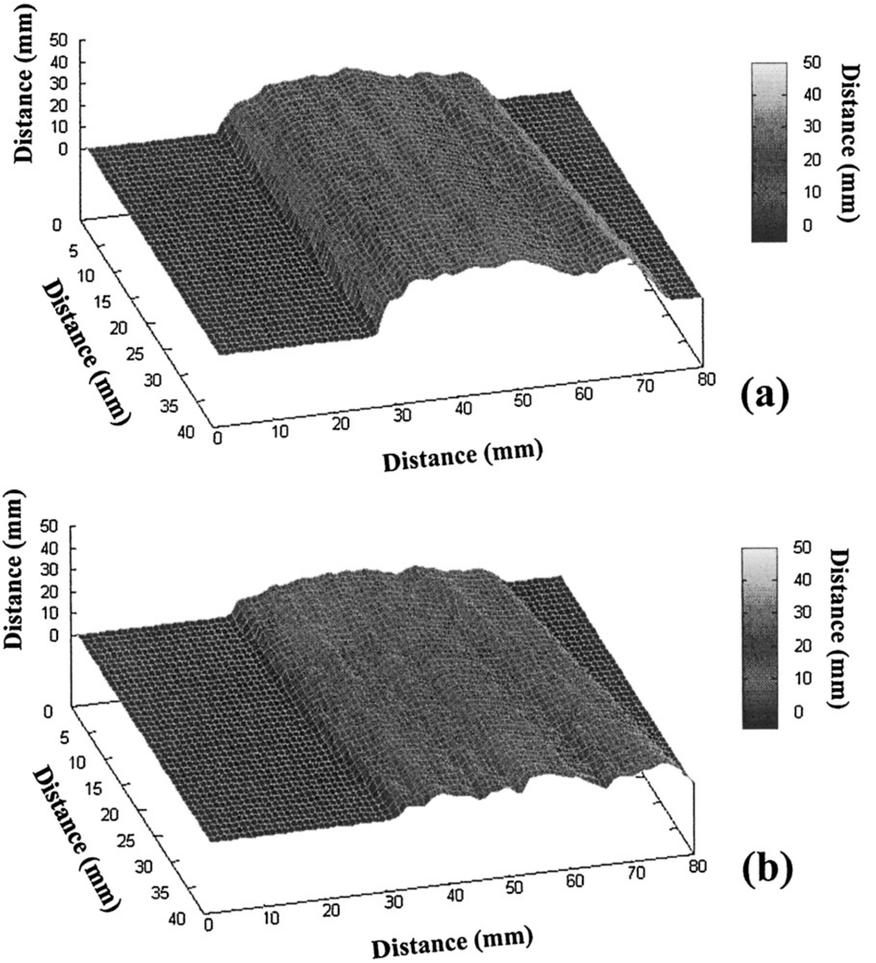

Figure 11. Straight hair technique. Three-dimensional surface plots for hair treated with PVP K30 (a) before and (b) after exposure to 90% RH.

Table IV
Volume Difference Data for Hair Treated with Various Polymers

	ΔV (cm^3)
VP/acrylates/lauryl methacrylate copolymer	22.67 ± 3.52
VCL/VP/DMAEMA copolymer	40.10 ± 6.36
Polyquaternium-69	25.07 ± 5.72
Isobutylene/ethylmaleimide/hydroxyethylmalemide copolymer	33.67 ± 17.36
VP/VCL/DMAPA acrylates copolymer	40.33 ± 16.30
High MW Polyimide-1	22.37 ± 13.54
Polyimide-1	56.93 ± 16.62
PVP K90	81.17 ± 16.60
PVP K30	154.30 ± 12.38

Tests were conducted using the conventional hair tress technique. ΔV represents the difference in volume before and after humidity exposure. Each value represents the average of three measurements and is reported with standard deviation.

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methods were investigated to determine the style retention of polymers used as fixatives. Volume was introduced to the hair fiber assembly by mechanical manipulation. Then the ability of a given treatment to maintain the induced volume was tested by stressing the hair sample with either force or high humidity. Future testing should include methods, which differentiate the ability of treatments to build volume. This would, however, require the use of a mechanical device capable of manipulating a hair fiber assembly similar in manner to that exercised by consumers.

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