INTRODUCTION

Hair is a unique biocomposite,[1] which continues to amaze us given the complexity in terms of structure, morphology, composition, and physical properties. Besides protecting head from external assaults, hair plays an important role in one’s beauty and appearance and social acceptability. Although the hair emerges from the scalp, in the case of participants with longer hairs, it actually spends nearly 12–18 months exposed to the external environment. Over time it undergoes various damages due to many extraneous factors such as washing, shampooing, combing, coloring, environmental exposure (pollution, humidity, etc.),[2] and physical treatments (straightening, perming, etc.).[3] These factors compromise the health of the hair to a varying degree which manifests itself as weak, dull, rigid, rough, and unmanageable hair.[4]

Weak hairs are characterized in hair research through extensional tensile testing using Dia-Stron MTT 175. It

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Fiber tensile behavior has been studied extensively for various natural and synthetic fibers. The various experimentation studies with natural, irregular fibers have established that fracture is the result of crack propagation from a flaw or from regions with high localized stress. In the case of woolen fibers, Zhang et al. have found out that on extension, they break where the mean diameter is minimum. He et al. have also suggested that inter-fiber and intra-fiber diameter variations of wool determine their tensile behavior. Finite element analysis (FEA) models of irregular fibers have been studied to conclude that magnitude and frequency of dimensional irregularity decrease the break load and Young’s modulus. Thus, internal flaw or lower fiber diameter or a combination of both determines the weakest point in a fiber. During extension, when the weakest point reaches its break limit the entire fiber breaks. This “weakest link” concept was first proposed to predict the strength of cotton yarns.

In this investigation, we hypothesize that a statistical measure for hair surface irregularity can be used to sufficiently explain the state of the weakest link in hair. Damage to hair begins at the surface which then percolates down to create internal flaws responsible for hair breakage under repeated extensions and bending. The role of hair treatments is to either prevent or recover the damage imparted which translates into the management or fortification of the “weakest link,” respectively. To prove the hypothesis, we need to characterize the weakest link based on dimensional irregularities. The statistical measure can then be used to understand the impact of “weakest link” progression with hair lifestyle practices as well as hair treatments.

**Approach**

- Establish the “weakest link” theory for biological hair fibers by correlating dimensional parameters – average cross-sectional area and mean diameter – with point of breakage
- Next, propose a statistical measure of characterizing the “weakest link” progression in terms of intra-strand irregularities
- Validate the proposed measure by quantifying the weakest link progression for known scenarios – like differentiating root and tip region of hair strands and known chemical treatments inducing hair damage
- Extend the concept to quantify the weakest link progression for different scenarios – damage vectors, treatment options, and usage habits.

**SUBJECTS AND METHODS**

**Human hair sourcing**

Hair fibers were obtained from female Indian subjects, in the age group of 25–35 years, having more than 35 cm long hairs. The subjects included in the study have not undergone any chemical treatment such as bleaching, perming, coloring as well as did not use any styling products. They use regular shampoo for cleansing. The subjects were divided into two groups – (a) no-oil users-subjects who did not use any hair oil or conditioning treatments and (b) coconut oil users-subjects who use coconut oil as once or twice a week application as a part of their grooming regime. Twenty hair strands were collected from each subject by cutting the strands from different sections of the scalp and as close to the scalp as possible (typically 1–2 cm gap from the scalp). The hair strands were marked to identify the root and tip sections. A total of 1200 hair strands per group (20 × 2 × 30) were analyzed for the in-vivo study.

Tresses of 20 cm long Asian (Indian) hairs used in the current work were sourced from a local supplier. The virgin hair samples supplied are obtained from users, which have not undergone chemical or thermal treatment(s). The hair samples were divided into multiple swatches weighing 5 g each and stored under controlled environmental conditions.

Hair is a biological, cylindrical fiber formed from a protein known as keratin-containing a high grade of sulfur. As mentioned earlier, hair morphology being elliptical the cross-section has been approximated by a mean circular diameter for analysis. The mean diameter of human scalp hair is prone to a lot of variation; we have observed hair diameters in the Indian population ranging from 30 to 140 μm. In general, the hairs are classified as thick (>66 μm), medium (51–65 μm) and fine (<50 μm). The mean diameter of hair is also known to vary along the length of an individual hair strand. The variation seen in hair mean diameter across a strand has been classified as (a) constant, (b) slight smooth variation, (c) wide smooth variation, and (d) abrupt variation. However, neither the inter-strand mean diameter variation among scalp hairs of an individual nor the intra-strand mean diameter variation across length has little correlation with a given individual.
conditions of 60% relative humidity (RH) (±2%) and 25°C (±1°C).

Chemicals used

Sodium lauryl ether sulfate (SLES) used in the current work was of cosmetic grade. Coconut oil used was refined coconut oil. Light liquid paraffin (LLP) used in the current study was also cosmetic grade. Marketed products were procured to represent other categories such as rinse of conditioner, shampoo, hair oils, and crème oil. Characterization of each is defined in the results section for better reference.

Hair strand mean diameter variations’ measurement

Hair samples were conditioned at 60% RH and 25°C temperature for a minimum of 3 h before testing. The hair strands were crimped to a length of 30 mm. Diameter measurements were conducted on hair fibers before and after treatment using Laser Scan Micrometer (Model LSM-6200). The instrument was programmed to collect 10 scans across the length at uniform spacing. Since the human hair strand is largely elliptical in crosssection the instrument provides data for mean diameter and average cross-sectional area. The readings are computed for 10 sections across the crimped length of 30 mm. Tabulation of the data was done in MS Excel® and descriptive statistics of the observations were computed such as minimum, maximum, and average of mean diameter as well as cross-sectional area, sections of the hair strand with minimum and maximum change in mean diameter, root mean square (RMS) deviation was quantified for every strand from the mean diameter of different sections and the average mean diameter.

Breakage point location on hair fiber extension

The crimped hair strands were then subjected to tensile extension using a Dia-Stron Mini Tensile Tester MTT175 wherein the strands were extended at a uniform strain rate until fiber fracture. The location of the breakage point in the given hair sample was estimated by measuring the two sections of broken hair with a measuring scale (±0.5 mm) and normalizing for the extended length. The breakage location is defined as one of the 10 sections, in which hair was segmented using the LSM.

Hair swatch washing

Simulating the surfactant wash of hair, the swatches were washed with 15% SLES or marketed shampoo under controlled conditions which can be described as below:
1. SLES or shampoo amount (15% SLES solution): 10% of the weight of hair tress
2. Regulated rubbing of swatches during application: 5 strokes on each side of the swatch back and forth motion
3. Rinsing of swatch: Rubbing swatch ten times on each side in back and forth motion (1 min) under flowing tap water
4. Air dry: 25°C ± 1°C and 60% ± 1% RH.

Hair treatment

Product treatment of hair swatches involves pouring of hair treatment product (10% of weight of hair tress for leave-in oil or crème lotions or shampoo and 2% for rinse-off conditioner [RoC]) using the pipette. Pouring of product is followed by gentle rubbing of the hair swatch five times on each side in back and forth motions to distribute the product evenly. The treated swatches were incubated as per the product requirements in chamber with controlled humidity and temperature conditions (RH - 60% and temperature - 25°C).
- For hair oil, the incubation time is ~15 h
- For crème oil, the incubation time is 30 min
- For shampoo and RoC, it is 2 min.

The oiled swatches are washed with SLES or shampoo, as mentioned earlier.

Hair surface topography analysis

Scanning electron microscopy (SEM) was used for characterizing the surface topography of hair samples. Each hair fiber was cut into two specimens of 3 cm each from the root and tip side and was analyzed pre- and post-treatment. Qualitative observations were made in terms of surface cavities and imperfections to validate the quantitative measurements on the same hair samples done separately. Image analysis techniques were also utilized to determine an average count of gaps and microcavities in a section of 50 × 50 µm for the given hair specimens.

RESULTS

Weakest link model validation for hair strands

Sample of 300 crimped hair sections from nonoil users were analyzed to understand the correlation between sections where fracture was observed with strand sections with the minimum mean diameter and maximum delta change from the average mean diameter.
Correlation analysis of the three characteristics is mentioned in Table 1. Regression plots are mentioned in Figure 1. Correlation analysis and regression plots confirm that the breakage of hair strands on extension is correlated with sections with the minimum mean diameter and more so with the sections having maximum change in mean diameters. Thus, the intra-fiber mean diameter variations are connected with the “weakest link” concept – the fiber breaks where the link is weakest. As the damage in hair fiber increases, the weakest link becomes more fragile and hence, we hypothesize that the intra fiber mean diameter variations also increase. These variations and hence, the “weakest link progression” can be quantified in terms of RMS variability (Rq).

\[
R_q = \left[ \frac{\sum_{k=1}^{N} (\bar{\varnothing}_k - \bar{\varnothing})^2}{N-1} \right]^{1/2}
\]

Where,

\[
\bar{\varnothing}_k = \text{Average of mean diameter of section “k” of the hair strand}
\]

\[
\bar{\varnothing} = \text{Mean diameter of entire hair strand}
\]

\[
N = \text{number of diameter scans across a single hair strand.}
\]

**Weakest link progression as a function of time**

For a single hair strand, the tips of the hair strand have suffered more physical, chemical and environmental abuses than the roots of the same hair strand. The impact of abuse over time has been studied and confirmed to decrease the strength. It also coincides with the consumer observations of split ends, roughness, and loss of shine from the tips as compared to the roots.

Nonoil users (30 subjects) hair strands were evaluated at the root and tip sections and the data gathered is captured in Table 2. Statistical significance was also evaluated for the paired comparisons of mean diameter and RMS variability (Rq) of mean diameter for the subjects in Table 2. Root and tip sections of the hair strands were also observed under SEM and distinct difference was visible as captured in Figure 2. Average increase in Rq from roots to tips is 100%, 2.5–5.0 μm.

**Weakest link progression – in-vivo usage study**

Strands collected from users and nonusers of coconut hair oil were analyzed for the Rq of mean diameter at around 10 cm length from the root. Figure 3 captures the mean diameter and the Rq of mean diameter for coconut oil users and nonusers of hair oil.

From the graphs in Figure 4, there is no statistical difference between the hair diameter of regular coconut oil users and nonusers of hair oil. However, the measure for weakest link progression – Rq of mean hair diameter – is significantly less in hairs from coconut oil users (around 65% less).

**Weakest link progression for simulated ex-vivo scenarios**

We carried forward the observations and extended them to understand the impact of various damage and treatment vectors on the weakest link progression.

**Impact of surfactant wash cycles**

Hair swatches washed with SLES were analyzed at different time points – initial, 1 cycle, 5 cycles, 10 cycles, and 20 cycles. Steady increasing trend in the standard deviation of diameter was seen with increasing SLES washing cycles.
and the effect seems to saturate at 10 cycles as can be seen from Figure 5.

**Impact of hair oils**

Hair oils – coconut oil, mineral oil, and combinations of the two – available in the market are used for the study. Different hair oil combinations were applied on hair swatches as per the protocol explained earlier followed by SLES wash the next day. Twenty cycles of oiling and washing were conducted for all the oils. Hair strands extracted from the treated hair swatches were analyzed and compared in Figure 6.

Hair oils in general exhibit control over the weakest link progression, as can be seen in comparison with control samples of SLES wash cycles. Oils with vegetable oils which can penetrate exhibit even better control on the weakest link progression.

**Impact of hair treatment formats**

Hair swatches from the same bunch of hair were subjected to different hair treatment cycles and all the swatches were evaluated post-20 cycles of treatments.

- Shampoo cycles: Shampoo wash followed by drying and combing for alignment of hairs
- RoC cycles: SLES wash cycles with RoC post-SLES wash followed by rinsing

Observations are captured in Figure 3. Hair surface treatments – shampoo and RoC – were of limited impact in controlling the weakest link progression. Pre-wash crème oil application shows promising results in maintaining strength.

**DISCUSSION**

Hair strength and hair breakage are commonly used expression by consumers to describe their hair care needs. Multiple methods and techniques are listed in the literature to quantify hair strength. Break load or force is one of the tensile test parameters used extensively in the literature to define hair strength; higher the break load, stronger the hair. Break load is found to have a linear correlation with hair diameter; larger the diameter, higher the break load.

Thus, one way to increase the hair strength or break load is to increase the hair diameter without negatively impacting the internal fiber structure.

To test the hypothesis, we looked at established use cases. We know both by consumer understanding as well as by technical knowledge that the tips of the hair are more prone to breakage than the root sections of the same hair. By collecting hair strands from subjects and studying the hair diameters at the root and tip sections, we concluded that though there is a trend pointing to the higher diameter for roots than tips; the difference is not statistically significant.

Breakage of hair strands on extension at a constant rate can be explained in terms of the weakest link model for analyzing strength of structural elements, for example, the strength of a chain made up of several links as shown in Figure 7. To extend the weakest link model to hair strand tensile extension,
we analyzed the hair diameters at every 3 mm length and stretched the 30 mm crimped hair until fracture. The breakage point was traced to the original hair section and correlated with the mean diameters of individual hair sections. The breakage location in the hair strand was well correlated with the lowest mean diameter section of hair. It was also found to be correlated with the sections for which the delta between neighboring hair sections is highest. Thus, it was deduced that at the microscopic scale it is the variations in the diameter of hair sections which explains the breakage on extension. Thus, the intra-fiber variation – frequencies and magnitude of troughs and valleys in hair morphology – is proposed as a measure of the weakest link progression for tracking the changes in hair strength with exposure to hair damage vectors or treatment regimes.

We extended the intra-fiber variation concept to compare the RMS variability (Rq) of the mean diameter of the root and tip sections of the same hair. RMS variability of mean diameters in tips section is approximately 100% more than that in roots section. The same hair strands were also observed by SEM and the number of surface micro-cavities was significantly lower in the root section than that in the tip of the same hair strand.

We used the methodology to validate a deep-rooted belief of Indian consumers that regular use of coconut oil helps reduce hair breakage and provides nourishment to hair making them stronger. Studies done in the past utilizing hair combing breakage tests have confirmed the belief and it has been proposed that both external occlusion and structural modification are the mechanistic pathways with which coconut oil imparts benefit to hair.[18] In this study, the average mean diameter increase on coconut oil...
users is not significantly different than nonusers of hair oil. However, RMS variability was found to be 65% less in hair strands of coconut oil users; thus validating the conclusion of hair strengthening by regular coconut oil use.

Weakest link progression was then evaluated for different hair treatment scenarios. Regular hair wash cycles with 15% SLES solution are known to damage the hair structure; both cuticle de-cementing as well as protein leaching from hair subsurface. Weakest link progression was observed with an increasing trend in standard deviation with ×1, ×5, ×10 and ×20 cycles. It can also be deduced that surface damage due to surfactant wash reaches a saturation level by ten cycles and hence beyond that excess cycles do not show only incremental weakest link progression.

Various hair care product formats were evaluated in terms of controlling the weakest link progression.

- Hair oils, in general, exhibit a trend to maintain the weakest link by forming an occlusive layer to act as barrier for surfactant and water to enter inside hair and hence cause structural damage. Coconut hair oil, which is known to penetrate hair strands, exhibit much better maintenance of the weakest link by not only preventing the de-cementing of cuticles but also filling the subsurface microcavities. LLP shows lower protection due to the single mechanism of occlusive benefit.
- Combination of coconut oil and LLP shows an intermediate benefit; thus, proving the benefit of having hair penetrating oil in your hair oil blend. Other veg oils used in the study like mustard, sesame, etc., did not exhibit any improvement over LLP and hence, they would also be nonpenetrating hair oils exhibiting only the occlusive benefit.
- Shampoo or surfactant cleanses the hair surface by roll-up and emulsification of dirt and sebum. Polymers in conditioning shampoo deposit on the surface to provide a smooth, soft hand feel. The harshness of surfactant and the amount used will determine the degradation or chipping of cuticle scales. Thus, 15% SLES solution is found most damaging as compared to marketed conditioning shampoo with relatively milder surfactants.
- RoC work by depositing positively charged moieties on to the damaged section of hair (which are negatively charged). The charged moieties deposited would help in combing ease and anti-frizz benefit. However, structurally there is hardly any positive change to the cuticle surface. Thus, the result obtained is in line with the mechanistic expectation of no change in weakest link maintenance.
- Crème oil application on hair strands, 30-min before a shampoo wash, helps deliver occlusive benefit of the oil along with penetration benefits of the coconut oil. The effect was subdued in comparison to regular oil application due to shorter exposure time.

Thus, the proposed methodology and weakest link progression measure proposed was first validated against the known scenarios, and then, it was used to establish differentiation in hair treatment formats and regimes.

**Hair protection factor**

Numerical indicator of hair protection accorded by hair care products or regime is a need to help equip users with better-personalized choices. There have been instances of indicators known in the personal care/beauty space. Sun protection factor (SPF) offers a simple numerical identification of levels of protection offered by skin care products against ultraviolet (UV) radiations. Similar work was done by Natcht (1997) on hair to define the protection factor for UV radiation.

Based on the current work, we propose to quantify the control of the weakest link progression by different hair care product usage. Hair wash cycles – which involve surfactant application, hand wringing, rinsing, drying, and combing exposure – can be utilized as the damage vector to benchmark the most general of the grooming damage. Weakest link progression defined in the study – RMS variability of hair mean diameter – is used as the measure for defining the index. The index we are defining to quantify the weakest link maintenance is called as “Hair Protection Factor” or HPF. The equation for the same is listed below:

$$\text{HPF} = 15 - 14 \times \left[ \frac{(R_{\text{Virgin}} - R_{\text{Virgin}})}{(R_{\text{Treatment}} - R_{\text{Virgin}})} \right]$$

As per the definition above, HPF is calibrated as a 15 point scale, similar to the definition of SPF. The baselines for HPF are mentioned below:

- HPF 15 → Untreated virgin hair
- HPF 1 → Untreated hair undergone 20 SLES wash cycles.

Thus, for instance, hair swatch treated with 20 shampoo cycles the HPF is defined below.
CONCLUSIONS

Hair fiber has varying diameter across the length of the strand which can be attributed to hair weathering over the course of time since its emergence from the scalp. We exhibited that on extending the hair to fracture the breakage point coincides with the section having the highest changes in the mean diameter which invariably contains the minimum mean diameter too. The present study indicates that the analysis of variations in hair strand mean diameter along its length can yield important information about the weakest link progression and can be used as an indicator of hair strength deterioration or improvement. The hypothesis was validated using the paired comparison of hair roots and tip sections of the same hair strand; tips section is shown to have ~2× more variability in mean diameter. The weakest link progression was then evaluated for different hair surface abuses and treatments. Surfactant wash increases the weakest link progression while the usage of oil helps prevent the same—owing to its role as a protective coating to thwart the surfactant entry. Coconut oils which penetrate hair are significantly more effective due to the dual role of the occlusive agent as well as surface microcavities replenishers. Other hair surface treatments—such as shampoo and RoC—are unable to control the weakest link progression. We also proposed a numerical index—HPF—to help differentiate hair care products’ impact on weakest link progression. Higher HPF of the product will ensure that the hair strength remains intact on regular washing cycles.

The calculation done for HPF for various product treatments is listed in Table 3 and Figure 8. HPF can serve as a tool to differentiate various hair care products to control the weakest link progression in hair strands and hence, an indicator for product benefit toward hair strength.

| Hair protection factor for various hair care products used in the study | Rq (μm) | HPF |
|---|---|---|
| Virgin | 2.10 | 15.0 |
| SLES-5x | 2.46 | 9.2 |
| SLES-20x | 2.98 | 1.0 |
| RCNO-20x | 2.20 | 13.4 |
| LLP-20x | 2.61 | 6.8 |
| Market oil 1 (80 CNO: 20 LLP) | 2.29 | 12.0 |
| Market oil 2 (75 LLP: 25 veg oil) | 2.61 | 6.8 |
| Market oil 3 (60 LLP: 40 veg oil) | 2.69 | 5.5 |
| Market oil 4 (80 LLP: 20 CNO) | 2.54 | 7.9 |
| Market oil 5 (50 CNO: 50 LLP) | 2.29 | 11.9 |
| Shampoo-20x | 2.73 | 5.0 |
| RoC-20x | 2.69 | 5.6 |
| Shampoo+RoC-20x | 2.61 | 6.8 |
| Crème oil+Shampoo-20x | 2.31 | 11.6 |

HPF – Hair protection factor; RoC – Rinse of conditioner; SLES – Sodium lauryl ethoxy sulphate; CNO – Coconut oil; RCNO – Refined CNO; LLP – Light liquid paraffin
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Conflicts of interest

There are no conflicts of interest.

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