Chapter 10
Definitions of Consumer Relevant Hair Assembly Properties and How These are Controlled by Single Fiber Properties

Abstract Herein is an attempt to bridge the gap between consumer and scientist by defining the more important consumer hair assembly properties (heads of hair, tresses, or wigs) describing how these properties are affected by changes from cosmetic treatments to fundamental single fiber properties. The effects of changes in single fiber properties by chronological age for five different stages of one's life is also described in terms of how these fiber properties relate to and affect the important consumer hair assembly properties. The literature on hair breakage is also summarized as a multifactorial phenomenon involving tangle formation with hairs looped over other hairs, severe bending deformations, highly localized stresses, and the amount of water in the fibers. The effects of hair curvature, fiber twists, knots, hair damage and abrasive wear on hair breakage are also described. A new unpublished section describing split hairs found on the heads of consumers is described along with preferred mechanisms for the formation of these different types of split hairs.

10.1 Introduction

This new Chapter defines and summarizes the literature on the more important cosmetic hair assembly properties (CHAP) of human hair including, hair conditioning, hair strength, hair breakage, split ends, flyaway hair, luster or shine, combing ease, hair body, style retention, manageability and hair handle or feel. Hair feel assessments include dryness-oiliness, clean-feel, conditioned-feel, softness and smoothness, etc. are important assessments that are currently being addressed and is summarized in the section entitled *Hair Handle or Feel*.

Over the past several years these elusive cosmetic terms, hair conditioning, hair damage, hair strength, hair body, manageability and moisturization have been defined in ways that have permitted progress to be made in terms of understanding these properties and in stimulating new methods for their measurement. Therefore,

C.R. Robbins, *Chemical and Physical Behavior of Human Hair*, DOI 10.1007/978-3-642-25611-0_10, © Springer-Verlag Berlin Heidelberg 2012

I decided to define these and other important CHAP all together in this Chapter. Some of these definitions are new; however, several have been taken or slightly modified from the cosmetic literature including the following references [1–7] and sections of Chap. 8 in previous editions.

This Chapter also contains a summary of the hair literature on hair breakage and some new information on the splitting of hairs that actually occurs on live heads. This information shows that splitting of hairs is accelerated by cosmetic treatments and sunlight exposure that involve free radical reactions on the cortex cell membrane complex of hair.

Some of the more important cosmetic terms are defined below including:

Combing ease: the ease of aligning hair fibers of a tress or hair assembly with a comb so the fibers are essentially parallel [1, 2].

Frizziness: when the curvature of neighboring hairs of an assembly are not synchronized (parallel) producing the appearance of disorder or disarray near the ends [3].

Hair body: is primarily the apparent volume of an assembly of hair fibers [1], but it is defined in more detail on the next few pages.

Relative scalp coverage or "Amount of Hair": a new metric for the manner in which hair provides coverage to the scalp [7].

Style retention: the ability of an assembly of hair fibers to retain a style that it is placed in for several hours after grooming (time limit is arbitrary, but longer than grooming operations) [1].

Manageability: the ease of putting hair into place and its temporary ability to remain in place during styling operations. See additional details below [4].

Flyaway hair: the static ballooning of a hair assembly at a specific RH by controlled combing, brushing[1] or rubbing.

Luster: a scientific term to measure consumers' assessment of hair shine.

Hair breakage: is only relevant as it relates to and explains breakage that occurs on the head of consumers. The most relevant tests for breakage are those that count or weigh the hairs that are broken in hair combing or brushing tests or those that correlate closely with that type of test.

In addition to the definitions above, definitions for Hair Conditioning, Hair damage, Hair Strength, Hair Body, Moisturization and additional details for Manageability are provided below:

A good working definition for **Hair Conditioning** is based on the action or function expected by consumers for this type of product. Thus, a hair conditioner is an ingredient or a product, that when applied to hair in its recommended use procedure and concentration improves the combability relative to appropriate controls. For testing an ingredient in a product, the control should be a product containing all ingredients except the potential active. In the case of a product, the control should be a cleansing medium such as 12% sodium lauryl sulfate or sodium laureth-2 sulfate in water.

This definition does not say that combability is the only property of a hair conditioner, but it defines combability as the "acid test" or the "price of entry" for a hair conditioner. Different combing tests to assess hair conditioning are described in the section entitled, *Combing Ease*. Market research studies with consumers and current scientific literature are consistent with the above definition. The advantage of this definition is that it permits ease of combing a method that can be used for reproducible measurement to be used to study and to improve hair products for conditioning.

Hair Damage is defined and described in detail in Chap. 6 in the section entitled, *Damage to Hair from Shampoos, Grooming and Weathering*. **Hair Strength** may be defined as the ability to resist hair breakage by grooming actions and is defined further in the section entitled, *Breakage of Hair during Grooming Actions* in this Chapter. Methods to assess these important properties are also described in these same sections.

Hair Body has been defined by Robbins [1] as thickness or apparent volume of a hair assembly, involving sight and touch for assessment. This definition does not lend itself to one simple method for measurement, however, it does help to improve our understanding of this important hair property and it has permitted several scientific tests to be proposed that correlate with hair body. For a more complete discussion on the utility of this definition, see the section on *Hair Body* in this Chapter.

Manageability [4] involves the ease of arranging hair in place and its temporary ability to stay in place during the grooming process; that is while arranging hair in place. Long-term effects on hair behavior (after one is finished arranging the hair in place) are actually style retention and not manageability. Manageability is an even more complex consumer assessment than hair body. It is such an inclusive term that it cannot be measured by one single procedure. Robbins et al. [4] recommended considering this important cosmetic property in terms of its component fiber assembly properties, such as different types of manageability that can be more readily visualized and measured. Manageability is concerned with:

Arranging hair in place (combing/brushing),
Keeping hair in place (style retention during styling), and
Flyaway hair.

Therefore, the suggestion was made [4] to consider these three types of manageability to permit measurement and scientific evaluation, rather than the single elusive term manageability. The section on manageability (later in this chapter) explains how to prioritize and use methods relevant to these three types of manageability.

Moisturization of hair is another important cosmetic term that has been misunderstood in the past. Because this word is derived from moisture, some jump to the conclusion that moisturization should relate to the water content of the fibers. Actually moisture in hair is a scientific or technical term determined by the amount or percentage of water in hair and it can be measured, see the section in Chap. 9 entitled, "*Water (RH), pH and Solvents and the Dimensions of Hair*". On the other hand, moisturization is a consumer (ist) term not a scientific term. Davis and Stofel [5] described the consumers' perception of moisturized hair vs. the actual water content. These scientists [5] demonstrated that the consumers' perception of moisturized hair does not correlate positively with the amount of water in hair, but it does correlate with consumers' perception of smoothness of hair. For example, trained panelists were asked to rate hair tresses for moisturized hair equilibrated at 15% RH vs. the same type tresses at 80% RH when the tresses were brought together rapidly at 45% RH. The hair tresses that had been equilibrated at 80% RH were judged to be less moisturized even though they were found to contain higher water content at the time of evaluation. The apparent discrepancy here is that the hair with the higher water content has a higher friction coefficient and feels rougher.

These scientists also asked panelists to rate shampooed hair vs. hair treated with shampoo plus conditioner for% moisturization. The conditioner treated hair was judged as more moisturized by a large margin even though the samples had identical water content at the time of evaluation. Additional related experiments were run demonstrating conclusively that the consumers' perception of moisturization is not at all related to the water content of the hair but to smoothness and softness. Therefore, the hair feel involving smoothness or fiber friction is clearly a more reliable estimate of the consumers' perception of moisturization or moisturized hair than the actual water content of the fibers.

The above definitions of hair conditioning, hair damage, hair strength, hair body, manageability and moisturization, in all cases, do not provide a single method to measure these properties; however, they do permit a better understanding between scientist and consumer and a better overall understanding of these important consumer hair assembly properties. Therefore, these definitions will permit science to move forward to improve these important hair properties for consumers.

10.2 Combing Ease

As indicated earlier, combing ease may be defined as the ease of aligning fibers of an assembly with a comb so that they are essentially or more parallel. Combing ease may be considered in terms of a combination of single-fiber properties or treated as an assembly property. Robbins and Reich [2] conducted a very large study relating quantitative combing behavior to the single-fiber properties of curvature, friction, stiffness, and diameter for straight, wavy, and very curly hair. These different hair types were each treated with a shampoo detergent (sodium lauryl sulfate), a long-chain quaternary ammonium compound (stearalkonium chloride), a commercial pomade (from mineral oil and petrolatum), and a hair bleach (peroxide/persulfate system).

In their analysis of combing ease, Robbins and Reich [2] demonstrated that combing forces can be quantitatively defined by the square of the fiber curvature while considering only linear terms for friction and fiber stiffness as in this equation for 3 g tresses of 10 in. hair:

$$\log PCL = 0.0057\ C^2 + 1.48\ F - 0.05\ S + 1.66$$
$$PCL = \text{Peak combing load};\ C = \text{curvature};\ F = \text{friction};\ S = \text{stiffness}$$
$$r^2 = 0.96;\ p<0.0001$$

Fiber diameter did not provide a significant contribution to combing forces (because diameter correlates with stiffness). Fiber friction was determined by a capstan method measuring friction of hair fibers over a hard rubber mandrel at a high load of 1 g per fiber [2].

The above quantitative combing expression suggests that when hair is curly to highly coiled as for curly African American hair or hair permanent waved on small rollers, curvature tends to dominate combing behavior and changes in friction and stiffness play only a minor role leading to the C^2 hypothesis of Robbins. However, when curvature is low as for wavy to straight hair of all types, for example, Curl types I, II and III (by the STAM system, see Chap. 9) such as most Caucasian or Asian hair or even wavy to straightened African hair, friction plays the major role with only a small contribution from fiber stiffness. This conclusion was confirmed by regression analysis of the data for only wavy and straight hair showing that curvature effects are not significant with hair of low curvature as in average Asian or Caucasian hair or straightened African American hair.

In an unpublished part of this same project naturally curly African American hair from several female panelists was examined. This hair was cut directly at the scalp, and tresses were made from it. Its combing behavior compared to the combing behavior of curly to highly coiled steam set Caucasian hair (two different lots of differing curvatures). Both types of hair were reasonably close to the combing values predicted by a combing equation involving the square of the fiber curvature.

The results of this latter study are in agreement with what is essentially the reverse experiment by Epps and Wolfram [8]. These scientists concluded that, “straightening of Black hair whether by chemical (relaxers) or physical (hot combing), results in hair whose assembly behavior is indistinguishable from Caucasian hair”. Robbins actually straightened some of the naturally curly African American hair using a commercial alkaline straightener and confirmed that the combing forces for hair tresses from this hair were similar to that of tresses made from wavy Caucasian hair and in agreement with values predicted by a combing equation.

The work from these two different laboratories confirms that using very curly highly elliptical hair from African Americans (ellipticity = 1.76) and very curly hair of Caucasians of low ellipticity (ellipticity = 1.38) that the longitudinal shape (hair fiber curvature or curliness) is the primary factor governing combing forces and not the elliptical cross-sectional shape of the fibers.

Robbins and Reich also demonstrated that the primary reason the combing forces are lower for wet curly hair vs. dry curly hair is an effect on fiber curvature. Wetting out the hair in a tress or an assembly actually uncurls the fibers to some degree decreasing the fiber curvature. This water straightening in high curvature hair is sufficient to provide a significant decrease in combing forces in agreement with the values found by quantitative combing.

Table 10.1 How single fiber properties relate to combing ease [2]

Increase in these fiber properties makes combing easier	Increase in these fiber properties makes combing more difficult
Stiffness	Curvature[a]
Diameter[b]	Friction
Cohesion	Length
	Static charge (chargeability)[c]

Note: Fiber length is not changed by cosmetic treatments
[a]A relatively large effect, and the effect increases with increasing curliness
[b]Relatively small effect
[c]A relatively small effect is predicted

Table 10.1 describes how "changes" in the more important fiber properties affect combing ease. This table suggests that increasing fiber curvature, friction or static charge will each make hair more difficult to comb. Fiber length cannot be changed by cosmetic treatments. On the other hand, increasing fiber stiffness, diameter, or cohesive forces will make hair easier to comb as confirmed by the study of Robbins and Reich [2].

Table 10.1 indicates that curvature has the most impact on combing forces. When the curvature changes are relatively small and the fibers are straight to wavy, the curvature effect on combing forces is small, but at higher curvatures the effect on combing forces increases until it becomes dominant. Fiber friction and stiffness also contribute to combing behavior. The effect of these two variables becomes more important as curvature decreases and they are most important when the hair is relatively straight. Fiber diameter was not significant in the quantitative study by Robbins and Reich [2] because it is collinear with and contained in stiffness.

Increasing fiber curvature or fiber friction makes combing more difficult as expected (see Table 10.1). However, increasing fiber stiffness results in lower combing forces. Pomades and other oily or wax-containing conditioning products are used in leave on products and large amounts of these materials, are left on the hair surface. These low level cohesive forces serve to lower combing loads. This effect occurs because these ingredients' inhibit the reformation of entanglements as the comb traverses through the hair. Thus, cohesive ingredients facilitate combing by helping to keep the fibers more parallel.

10.2.1 Methods to Evaluate Combing Ease

Qualitative combing of tresses in replicate and evaluation of the data by nonparametric statistics can be a powerful tool when properly applied. This procedure provides a fast, sensitive, and reproducible method for the development of products. However, quantitative instrumental methods have also been useful [9–12]. Basically, these methods consist of attaching a tress or swatch of hair to a strain gauge such as the load cell of an Instron tensile tester and measuring the forces and/or work required to move a comb through the tress under controlled conditions.

Fig. 10.1 Schematic of wet and dry combing force curves for hair from tresses of low curvature Caucasian hair (curl type II)

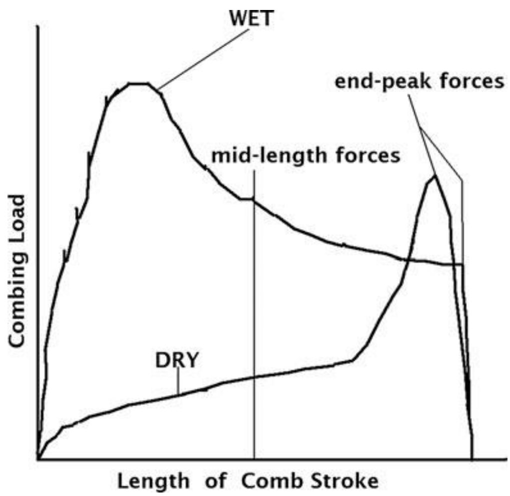

Figure 10.1 represents a schematic of typical wet and dry combing force curves for a single comb system with relatively straight hair such as Curl types I, II or III. Note the high end peak force for the dry combing vs. the wet combing and the relatively high mid-length force for wet vs. dry combing. Analysis of combing force curves tells us that dry combing reveals tip end conditioning, and tip damage, along with short segment breakage better than wet combing. However, wet combing is better for revealing longer segment breakage and conditioning over the mid-length portion of the fiber.

Figure 10.2 represents a schematic of typical dry combing force curves for very curly hair; for example, Curl type VI or higher vs. relatively straight hair, such as Curl type I or II. Note the extremely large differences in the relative combing forces. The curves for Fig. 10.2 were drawn to represent combing forces where the same type comb is used with both hair types. In practice, this would not be the case because the person with Curl type VI or higher will use a comb with wider spaces between the teeth or a pick.

An interesting modified version of this test is the one by Kamath and Weigmann [12] that involved a double comb system wherein the combs are about 100 mm apart. With this system, the first comb helps to remove snags while the second comb measures the hair on hair plus hair on comb rubbing forces. Figure 10.3 is a schematic representing the combing forces for a double comb system. In a single or double comb system, the mid-length combing loads or the forces or work of combing (total area under the curve) are related to long segment breakage. On the other hand, the end peak force is related more to short segment breakage.

An alternative approach to the determination of combing forces is the raspiness method of Waggoner and Scott [11]. This method utilized an electronic comb designed to pick up vibration frequencies emitted as the comb teeth rub along the hair scales.

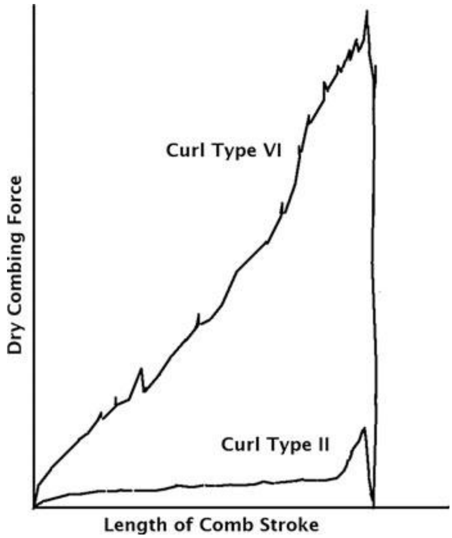

Fig. 10.2 Schematic of dry combing force curves for a hair tress of low curl (curl type II) compared with a hair switch made of high curvature hair (curl type VI)

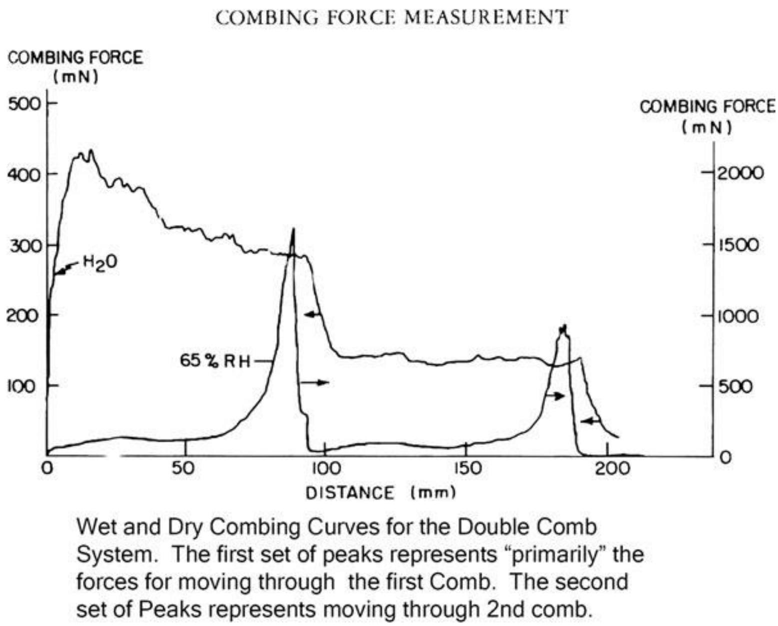

Fig. 10.3 Schematic of wet and dry combing force curves for the double comb system of Kamath and Weigmann [12] for Caucasian hair of low curvature (Reprinted with permission of the Journal of Cosmetic Science)

10.2.2 Treatment Effects on Combing Ease

Both permanent waving and bleaching make hair more difficult to comb [2, 10]. Permanent waving increases both fiber curvature and inter-fiber friction [2], primary factors that make hair more difficult to comb (see Table 10.1).

In the case of bleaching, the primary factor is the friction increase [2, 13]. There is no measurable curvature change in bleaching [2]. Stiffness [2] and diameter [2] changes are also negligible from bleaching. In contrast to permanent waves and bleaches, conditioners [9, 10, 13] and some conditioner sets make hair comb easier by providing a decrease in inter-fiber friction. Chargeability [13, 14] may also decrease, thus helping to improve dry combing. Pomades decrease fiber friction and increase low-level cohesive forces between hairs. This cohesive effect helps to inhibit the formation of entanglements beneath the comb as it travels through the hair. At the same time it helps to keep the fibers parallel after each comb stroke. Thus, cohesive forces from oily ingredients make hair comb easier.

Shampoos are a category with wide variability because these products can make hair either easier or more difficult to comb (Ross, private communication). High-cleaning shampoos with anionic surfactants remove surface oils, increasing inter-fiber friction (Chap. 9) and thereby make clean hair more difficult to comb than greasy hair. However, certain conditioning shampoos deposit ingredients onto the hair surface and decrease fiber friction, making hair easier to comb.

Shampoo ingredients [13, 14] can also alter the chargeability of the hair. For example, high-cleaning shampoos remove surface oils and deposit small amounts of anionic surfactant onto the hair, thus increasing chargeability. On the other hand, some conditioning shampoos lubricate the hair surface, providing easier combing and at the same time decreasing chargeability, leading to less flyaway and easier dry combing. Other conditioning shampoos deposit conditioners that improve wet combing, but they increase flyaway hair demonstrating that the nature of the deposit is critical to chargeability and to static charge. Changes in fiber stiffness, curvature, and diameter by current shampoos are negligible. Therefore, changes in these properties are not relevant to combing effects by current shampoos.

10.3 Breakage of Hair During Grooming Actions

Research shows that methods such as combing hair and collecting the broken fragments and either counting or weighing the broken hairs [15–20] is the best approach to measuring or estimating hair strength. Abrasion to break [17] which has also been called flex-abrasion by Leroy et al. [18] and impact loading [19] are more relevant than tensile testing to hair breakage during grooming because they relate more to the actual strength of hair fibers under the stresses of abrasion, bending and/or impact actions. These methods will be considered in this section.

Abrasion resistance and the resistance to break under abrasive stresses (flex-abrasion) are methods that should receive more attention in the future because of their closer relationship to some, but not all of the stresses that actually damage hair and ultimately lead to hair breakage during grooming actions. The apparatus built by Textile Research Institute of Princeton, NJ under the guidance of Sandhu and Robbins [17] illustrates this type of test procedure, see Fig. 10.4. Rubbing hair fibers to break on this apparatus is capable of differentiating between some conditioning shampoos.

Furthermore, work by Swift et al. [20] suggested improvement in the sensitivity of this method beyond this earlier work. This system merits further investigation, because of the relevance of rubbing, bending and compressive actions to everyday hair grooming/hair wear and fiber breakage. The protein loss method measures cuticle and cortical fragmentation damage and is a measure of abrasion resistance and dissolution; however, it is not a measure of catastrophic failure of hair fibers.

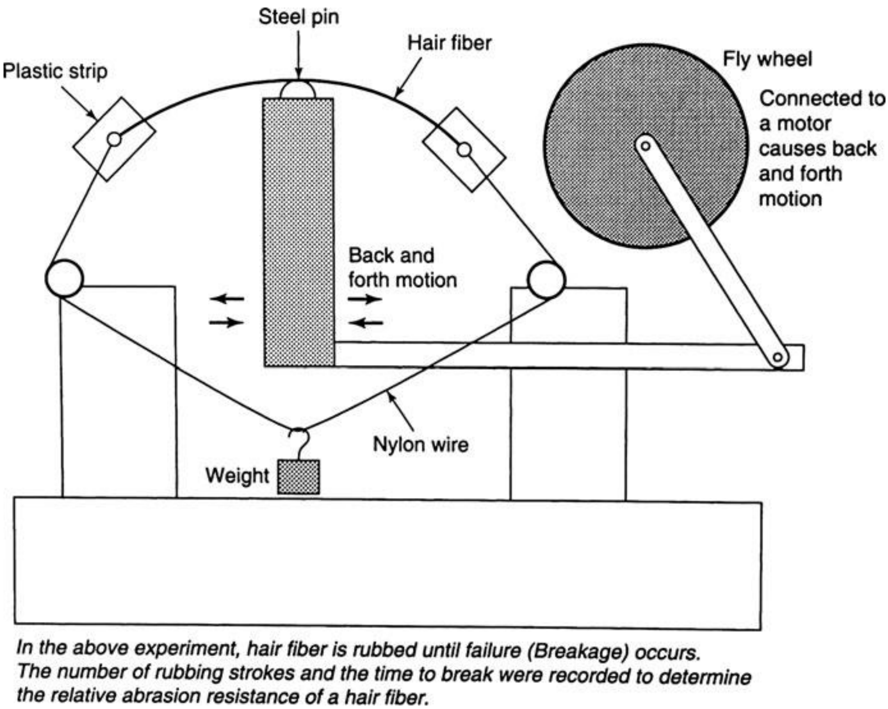

Fig. 10.4 Schematic illustrating an instrument developed by TRI Princeton and S. Sandhu to study abrasion to break

10.3.1 Evidence that Hairs Don't Break from Tensile Elongation by Combing or Brushing

There are several important papers in the scientific literature on the fracturing and breakage of human hair fibers [15, 19–29]. However, there is relevant literature that raises questions as to how relevant tensile test conditions are for simulating or for predicting hair breakage on live heads [21, 22, 25, 28, 29] or from combing or brushing human hair tresses in the laboratory.

Contrary to a superficial assessment, most hair fiber breakage that occurs during combing or brushing does not result from simple tensile elongation. Hamburger, Morgan and Platt in 1950 [21] demonstrated that the load to pull Caucasian hairs out of the scalp was about 45% of the load required to break hair fibers at 65% RH. Subsequently, Berthiaume et al. [22] published results that the pullout load for Caucasian hair is about 40–45 g (slightly higher than that of Hamburger et al. [21]), for African hair 30–35 g and for Asian hair 60–65 g. Back calculating the average load to break at 65% RH from the breaking stress for these three different types of hair provides breaking loads for average Caucasian hair at about 76 g, for average African hair at 73 g, while average Asian hair should be more than 100 g because of its larger area of cross-section. Therefore hairs must be damaged extensively or they will pull out before breaking by tensile elongation; however, an alternative is that hairs must break by another mechanism.

An equally important factor to consider is the percentage extension to break for hair fibers at 65% RH which is about 50% for Caucasian and Asian hair and about 40% for African type hair at 65% RH (discounting premature failure) and even greater at higher humidity. Hair on the head just does not stretch to this extent before breaking.

10.3.2 Hair Fibers Bend and Loop Around Other Hairs Forming Tangles Which Break Hairs by High Localized Forces from Pulling a Comb or Brush Through a Tangle

Combing and brushing hair of Curl types I–III (by the STAM procedure) have been studied more systematically than higher Curl types and have been shown to provide two types of breakage, short segment breaks (less than 2.54 cm) and longer segment breaks. Brown and Swift [29] examined the arrangements of hair fibers in snags while combing tresses in a scanning electron microscope to try to understand more fully how hair fibers break during combing. These scientists concluded that hair fibers loop over other hairs (see Fig. 10.5) and that hair on hair interactions with severe bending actions are involved in hair breakage during grooming.

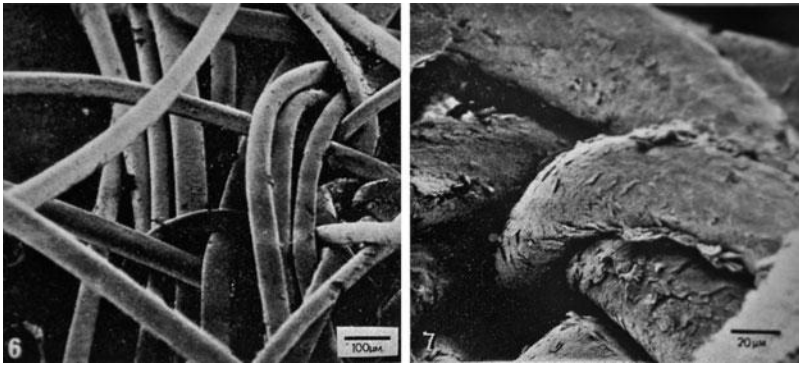

Fig. 10.5 Small tress combed in the SEM showing hairs looped around other hairs by Brown and Swift [29] (Reprinted with permission of the Journal of the Society of Cosmetic Chemists)

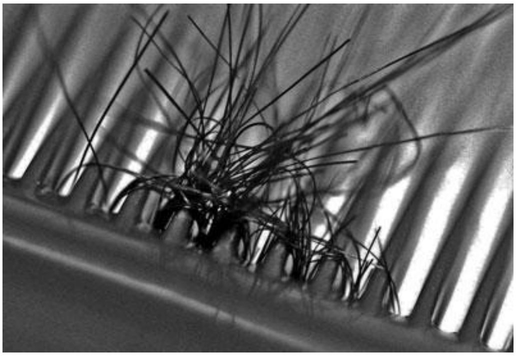

Fig. 10.6 Hairs wrapped around comb teeth and other hairs in a snag [27] (Reprinted with permission of the Journal of the Society of Cosmetic Chemists)

Robbins [19, 26] studied hair breakage by combing hair tresses and examining photographs of snags of hair fibers in combs. The resultant hair fiber arrangements provided support to the evidence and the conclusions of Brown and Swift that breakage involves hair on hair interactions (see Fig. 10.6) where hairs loop and bend over comb teeth and over other hairs to provide sites for hair on hair breakage through highly localized forces on impact while pulling through a tangle. Furthermore, in combing experiments broken fragment size related to the site of higher combing forces in combing force curves suggesting that breakage occurs primarily at or near the hair to comb interface.

Even though these experiments were on Curl types I–III, it is likely that Curl types IV–VIII break similarly because the more highly coiled the hair the more looping and entanglements and higher combing forces and as we shall see breakage increases with combing forces. In addition, Robbins and Kamath [28] demonstrated an increase in breakage with hair fiber curvature corresponding to higher combing forces with higher curvature.

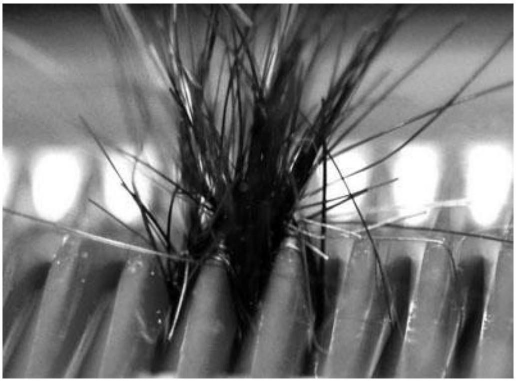

Fig. 10.7 Ends of hair fibers wrapped around comb teeth in a snag [28] (Reprinted with permission of the Journal of the Society of Cosmetic Chemists)

10.3.3 Hair Fibers by Combing or Brushing Break into Short and Longer Segments

Evidence suggests that longer segment breaks (generally longer than 2.54 cm) occur primarily by one hair fiber bending over or wrapping around another hair (as illustrated in Fig. 10.6) and impact loading [19]. Furthermore, breakage by bending and impact loading occurs at a hair to hair contact point with essentially no increase in hair length (strain) as compared to normal tensile loading which requires large strain increases [19, 28–30]. On the other hand, short segment breaks (less than 2.54 cm) involve end wrapping of the distal ends of hairs about comb teeth or brush bristles [19, 26–28], see Fig. 10.7. This action at the fiber ends (especially in the dry state) increases the end peak force and with continued abrasive damage to the ends produces an increasing number of short segment breaks [26–28]. The formation of entanglements is a critical determinant for both long and short segment breaks including hair on hair and hair on comb entanglements and abrasion is more important to short segment breaks than long segment breaks.

10.3.4 Hair Breakage Increases with Hair Fiber Curvature

Combing forces increase with the second power of hair fiber curvature as shown by Robbins and Reich [2]. The middle portion of the combing curve and the work of combing relate more to long segment breaks, while the end peak force relates more to short segment breaks.

Robbins and Kamath [28] compared the number of short and long segment breaks by combing hair tresses that had been permanent waved into Curl type II and Curl type III configurations. These scientists found large increases in both the number of short and long segment breaks with increasing curvature. The increase in the long segment breaks are due to more snags that occur from entanglements higher up in the tress produced by higher curvature. Even though the number of long and short segment breaks increased with curvature, the number of long segment breaks increased more than the number of short breaks.

The effect of hair fiber curvature on fiber breakage is well known among consumers, because grooming devices were developed centuries ago to help compensate for curvature effects. For example, combs with small teeth and narrow spacing are normally used for short straight hair, while combs with larger teeth and wider spacing are normally used for hair of medium curvature. On the other hand, combs with very wide spacing called picks are used with hair of high curvature such as Curl types V through VIII or even for some persons with Curl type IV.

10.3.5 Curly Hair Forms Knots Which Also Break on Impact at the Site of the Knot

Khumalo et al. [31] examined a large number of broken and pulled out hair fibers from two Africans (from South Africa). This hair was most likely one of the higher Curl types between V and VIII. Two Asian and two Caucasian volunteers were also on this panel. These panelists had never used chemical treatments on their hair. The volunteers shampooed and combed their hair (using their usual combs or picks) for 4 days in a row and collected the hairs each day from the combings. At the beginning of the experiment, the average hair length of the African hair was 5 cm, for the Caucasians 22 cm and for the Asians 25 cm. Since the two Africans had not cut their hair for more than 1 year and since the growth rate is about 13 cm per year, these facts testify to the high rate of breakage from high stresses, the fragility and the deformations imposed on highly coiled African hair by grooming actions.

The total number of hairs collected was, 1,163 from the Africans, 464 from the Caucasians and 200 from the Asians. Random samples of 100 hairs (or the total number of hairs) from each person for each day were examined visually, by light microscopy and by SEM. For the Africans, 35% of the hairs had bulbs. Therefore, these hairs were pulled out of the scalp by grooming actions leaving 65% broken hairs. For the Caucasians, 85% of the hairs were pulled out and 15% broken. Ninety two percent of the hairs from the Asians were pulled out, providing only 8% broken hairs from the Asians. These scientists also observed that 13.3% of the African hairs examined had knots. This average was relatively consistent each day providing 106 knots in 800 hairs over the 4 day period. This knot formation contrasted to only one knot found in the hair of 464 Caucasian hairs and no knots in 200 Asian hairs.

These scientists proposed that knot formation in the highly coiled African hair is involved in breakage of some curly to highly coiled hairs. Robbins [26] demonstrated that hairs in a knot under light impact loads break much more readily than unknotted hairs and the break forms at the knot. The severe bending in the knot produces extensive elongation and compression over a very short segment of the fiber making it more susceptible to breaking. These results confirm once again the importance of bending actions to hair breakage described by Swift and Brown [29]. So, highly coiled hair fibers such as Curl types IV–VIII tend to form knots and many break through this mechanism [19, 31]. And, the more highly coiled the hair the higher the propensity for knot formation. So, some curly hairs do form knots and break by impact at the site of the knot, however, knots generally account for a small percentage (probably a maximum of about 13–26%) of the broken hairs.

10.3.6 Hair Chemically or Physically Damaged Breaks Easier than Non-Damaged Hair

Chemical damage by perms (Chap. 4), bleaches (Chap. 5), permanent dyes Chap. 5 [32], straighteners (Chap. 4) [33] and sunlight exposure (Chap. 5) [34] weaken hair and increase inter-fiber friction leading to more tangle formation and more breakage. On the other hand, hair conditioners make hair comb and brush easier and have been shown to produce less breakage [27] (see Table 10.3 in Section 10.4.2 entitled Causes of Split Hairs and Split Ends).

Relative humidity or the amount of water in the fibers also affects combing forces and hair breakage [27]. Epps and Wolfram [8] demonstrated that the work of combing of highly coiled African hair is lower wet than dry, but the reverse holds for wavy to straight Caucasians hair where the combing forces are higher wet than dry [27, 35].

Physical damage or wear by abrasion [22, 27] occurs from grooming devices such as combs, picks or brushes and to some extent a fatiguing action. Wear by abrasion occurs over the entire fiber but more near the fiber tip ends because of a longer residence time, but even more so by high end peak forces when combing or brushing hair dry [22] as evidenced by examination of many of the smaller fragments of short segment breaks [22, 27].

10.3.7 Hair Fibers with Twists Contain Flaws and Can Break Prematurely

As indicated earlier, the work of Kamath, Hornby and Weigmann [24] showed “premature failure” (breakage occurring at 20% extension or less) on 22% of the hair fibers from one African American male. In addition, 17% of the fibers broke within 8% extension at 65% RH. These scientists concluded that premature failure generally occurred in a region of twist. Interestingly, premature failure virtually disappeared when the African American fibers were wet with only about 2%

breakage within 33% extension [24]. So, premature failure for African type hair is primarily a dry state phenomenon.

This particular African hair examined by Kamath et al. [24] had a very high ellipticity (1.89) suggesting it is of Curl type VII–VIII. In addition, the load to break for this type of hair in the 3–20% strain area (the yield region) would be one-half or less of the average load to break at 65% RH and very close to the pull out load. Nevertheless, it is still likely that this type of hair breaks more frequently from bending than stretching stresses as suggested by Brown and Swift [29], that is, it would more likely break by bending and impacting over another hair [19, 26–28] or by severe bending and deformation in a knot [18, 31] rather than by tensile loading. In a few instances it is possible that tensile breakage could occur with this type of hair. The wet breaking stress is lower for curly hair, therefore, dry breakage for highly coiled African type hair should be more severe than wet breakage because of the higher grooming forces in the dry state [2, 35]. The fact that premature failure occurs in the dry state and it is virtually eliminated in the wet state and the fibers are more extensible when wet [36] are other reasons favoring dry state breakage for highly coiled hair.

10.3.8 Hair Breakage Correlates with Combing and Brushing Forces and the Location of the Break on the Fiber Corresponds to Where the Higher Combing Forces Occur

Accumulated data from conditioned vs. shampooed hair [27], bleached vs. unbleached Caucasian hair [27] and comb stroke length comparing broken hairs vs. combing loads (Crawford, private communication) shows that hair breakage increases with combing forces. Pearsons's non-parametric correlation test of these data provides a significant correlation for this effect. Furthermore, Kamath and Weigmann [12] observed that wetting and combing Caucasian hair tresses provides a large increase in the mid-length force and at the same time a decrease in the end peak force compared with combing hair dry (65% RH). A few years later, Robbins and Kamath [27] observed more short segment breaks in dry vs. wet combing for Caucasian hair, but more long segment breaks in wet combing. Furthermore, we have shown in our own laboratories that cross cutting hair and combing it dry vs. a tapered cut provides even higher end peak forces and more short segment breaks (see Table 10.4 in section 10.4.2 entitled Causes of split hairs and split ends). These results confirm that combing forces correlate with hair breakage but more importantly the location on the fiber where breaks occur during combing actually corresponds to where higher combing forces occur in combing force curves. In other words, mid-length combing forces correspond to long segment breakage and the end peak force corresponds to short segment breakage. This relationship suggests that hairs break near the hair to comb interface in tangles.

10.3.9 Fatiguing and Hair Breakage

Evans and Park [37] suggested that fatiguing is the primary reason for hair breakage. On the other hand, Kamath and Robbins [15] considered the prior literature on hair breakage and suggested that hair breakage is a multifactorial phenomenon as described above involving looping, bending and breakage by highly localized stresses generated from impact during combing or brushing through a tangle.

Fatiguing occurs primarily between the root section of the fiber and the brush or comb when the combing device encounters a snag, but only on the fibers under tension in that snag and when the same fibers are under tension on thousands of repeat cycles because low cycle fatiguing is defined as less than 50,000 cycles. If we consider fatiguing as two to millions of cycles of highly variable stresses then it covers virtually every event. But, thousands of fatiguing cycles in exactly the same spot on the same fiber happens to only a low percentage of the fibers in the comb or the brush. So, fatiguing is a lower probability process than for a single hair under high tension to be impacted once or even a few times and broken. It is likely that in many cases hairs are damaged or even weakened by a fatiguing action (especially near the tips), however in most cases catastrophic failure occurs from a high localized impact of one hair bent over another in the damaged or undamaged region of the fiber.

Evans and Park [203] used Weibull statistics to calculate the shape parameter and the characteristic life for virgin and bleach damaged hair, and hair treated with conditioners. The definition of the characteristic life for hair breakage in their experiment is the number of brush strokes necessary to break 63.2% of the fibers. For virgin hair, the characteristic life is 55.2 million brush strokes. But, for the same hair after conditioning it increases to 1.04 billion brush strokes. But the data for these huge numbers are based on only 10,000 brush strokes when only 1.6% of the fibers broke (326 of 20,000) as compared to 12,640 fibers corresponding to their definition of characteristic life. These characteristic life values are so large relative to the actual data that they are of questionable reliability. For additional concerns about the application of Weibull statistics to hair breakage data, see the paper by Kamath and Robbins [15].

Therefore, the fracture mechanism based on flaw propagation by fatiguing in real brushing and combing situations requires thousands of cycles. So, fatiguing actions on the same region of the same fiber may occur with a few fibers, but it cannot be the primary cause of hair breakage especially for long segment breaks as shown above and in the following section.

10.3.10 Where Hair Fibers Break Favors a Mechanism Involving High Localized Stresses

Where hair fibers break (along the length of each fiber) during combing and brushing corresponds very closely to the higher combing forces in combing force curves as described above. This fact supports the mechanism of Robbins and Kamath [15] that involves high localized stresses and a few impacts rather than thousands of cyclic stresses for the fatigue mechanism of Evans and Park [37].

In the fatiguing process (primarily in the elastic and/or plastic regions) a crack is likely to initiate anywhere between the snag and the root section of the fiber, but not primarily near the same location and in fatiguing the snag must always be at the same spot on the same hairs. Furthermore, once initiated, the crack is propagated and terminated by thousands of fatiguing actions at exactly the same spot. Therefore, fatiguing would not be expected to show such a close relationship between the location on the fiber where catastrophic failure occurs and the hair to comb interface in tangles as has been found.

This rationale holds especially for long segment breaks. Some short segment breaks likely involve a fatiguing action, but even most short segment breaks will ultimately require a final high localized stress to produce catastrophic failure. Furthermore, short segment breaks are not easily detected by consumers (most of which are less than 1 cm) and often fall unnoticed into the sink. But, long segment breaks (along with pulled out hairs) end up in the comb or brush and those are the hairs that bother consumers.

Tress combing experiments when snags produce high combing forces, show that broken hairs can be collected in tens of comb strokes [27, 28] rather than in thousands of comb strokes necessary for fatigue breakage. These combing force facts have been demonstrated in various ways and they clearly demonstrate that high localized stresses created by tangles are the primary cause of hair breakage by impact more so than by fatiguing actions.

10.3.11 Summary of Hair Breakage as a Complex Multifactorial Phenomenon

- Tangle formation is involved with hair fibers looped over other hairs and severe bending deformations as suggested by Brown and Swift [29].
- Hairs are broken by impact [19] generated by pulling a brush or a comb through a tangle producing high localized forces where one or more hairs are looped over another hair or hairs [26, 29].
- The complexity of snags increases with hair fiber curvature [8, 27] producing very high combing forces in both the mid-length and end peak regions.
- The amount of water in the fibers affects combing forces and hair breakage [27]. Straight to wavy hair when combed dry produces higher end peak forces than mid-length forces, but when wet produces higher mid-length combing forces [12] corresponding to where hairs break and to the amount of breakage.
- The work of combing of highly coiled hair is lower wet than dry, but the reverse holds for wavy to straight hair [8, 27] producing more breakage for coiled hair

when it is dry and more breakage for straight to wavy hair when it is wet, corresponding to combing forces.

– Chemical damage by perms, bleaches, permanent dyes [32], straighteners [33] and sunlight exposure [34] weaken hair and increase inter-fiber friction leading to more tangle formation and more breakage. Once again breakage corresponds to combing forces.
– Conditioners reduce combing and brushing forces and have been shown to produce less hair breakage [27] consistent with combing forces.
– Wear by abrasion for straight to wavy hair occurs from combing over the entire fiber, but more near the fiber tips because of a longer residence time, but even more so by high end peak forces when dry [12] as evidenced by an increase in the number of short segment breaks [12, 27].
– Combs or brushes with more space between the teeth or bristles lead to fewer and less complex tangles and therefore to lower combing forces, to less abrasion and fewer broken hairs. Most brushes provide more long segment breaks and fewer short segment breaks than combs [28].

The literature on hair breakage clearly shows that the primary factors involved in hair breakage are the occurrence of tangles created by combing or brushing where at least one or more hair fibers are severely bent around at least one other hair [12, 26, 29]. Furthermore, hair breakage correlates with combing forces. In addition, combing force curves vs. breakage shows that where the break occurs along the fiber corresponds to the higher combing forces in combing force curves. Therefore, highly localized stresses are created by hair on hair impact when one pulls a comb or a brush through a tangle [29]. As a result, one or more hairs break, either with or without flaws, under this condition. Other variables (described above) are clearly involved to determine the actual number of broken hairs and the type of fractures. These variables are described in detail above and include hair type (primarily curvature) [2, 8, 27], hair condition (treatments and wear) and wet vs. dry combing or brushing of the hair and the specific grooming device as explained in the discussion above. Brushing and combing and fatiguing certainly play a role in weakening hair especially for short segment breaks but it is unlikely to lead to a high percentage of fatigue breaks as claimed by Evans and Park [37] unless one broadens the fatigue definition to include anywhere from two cycles to more than millions, but low cycle fatiguing starts at 50,000 cycles and goes down.

10.4 Split Ends, Types, Their Occurrence and Formation

This author carried out a project to identify the different types of split hairs that form on live heads under "normal" usage conditions by consumers. An arrangement was made with a local hair dresser to collect hair clippings from his customers that he judged would likely have split hairs. A questionnaire was completed by the hair dresser in collaboration with the client to provide an idea of the type of hair and the

Table 10.2 Types of split hairs formed on live heads by consumers (in use)

Type of split	Initials of subjects providing hairs for examination								Totals
	DR[a]	LR	LRR[b]	LJR[c]	DC	HD	MB	QC[d]	
Simple small	4	1	8	19	7	5	5	27	76 (27.9%)
Simple large	9	4	8	34	10	9	2	47	123 (45.2%)
Complex	1	0	0	4	9	0	0	10	24 (8.8%)
Split (not at end)	2	1	2	2[e]	4	3	0	20	34 (12.5%)
Split (off step)	1	1[f]	0	4	1	0	0	0	7 (2.6%)
Split (in middle)	1	0	1	4[g]	0	0	0	2	8 (2.9%)
	18	7	19	67	31	17	7	106	272 (99.9%)
Weight hair (g)	2	2	3	10	6	12	1.5	5	
No. splits/g	9	3.5	6.3	6.7	5.2	1.4	4.7	21.2	

[a]Used frosting system on hair periodically for 2 years
[b]Permanent dyed and in sun frequently and for long times
[c]Permanent dyed and once used persulfate system also sunworshipper
[d]Permanent dyed (blonde-white) and sunbleached
[e]One is a complex split
[f]From simple long step of DR hair that broke between photo and micrograph (count step)
[g]One complex split through a knot

different types of treatments and conditions that the hair had been exposed to. Hair cuttings were collected from eight different consumers and the hairs examined initially under a magnifying lens with a light to separate out the split hairs. The splits were then photographed and classified according to the types summarized in Table 10.2.

Figures 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19, 10.20 and 10.21 depict the different types of split hairs described in Table 10.2. Figure 10.8 is a magnified photograph of two split ends; the one nearest the lower left corner is a simple small split end while the other is a simple large split end. The legs of the split in each case are nearly equal in length and width; therefore these are called simple split ends. The distinction between the large and the small simple split end is when the length of the legs of the split is about 10 times the width of the hair fiber or longer it is called a large split end. Large split ends can be of three different types: One type is when the two legs of the split are essentially equal in width (Figs. 10.8 and also see 10.9 for an extreme case of a large simple split end). Another type is when the two legs are unequal in width (see Fig. 10.10). A third type is when the two legs are unequal in length and the short leg does not appear to be broken off or when the two legs of the split are unequal and the short leg is broken off (this split is sometimes not distinguishable from a split end off of a step fracture (Fig. 10.11)).

A split end off of a step fracture is illustrated in Fig. 10.11. Kamath and Weigmann [23] described this type of split end in their paper on fractography of human hair. The split end of Fig. 10.12 also appears to be a split end off of a step fracture, although it may have been a simple large split end in which a part of one of the legs broke off. The weakened fibrillated part of the longer leg of the split

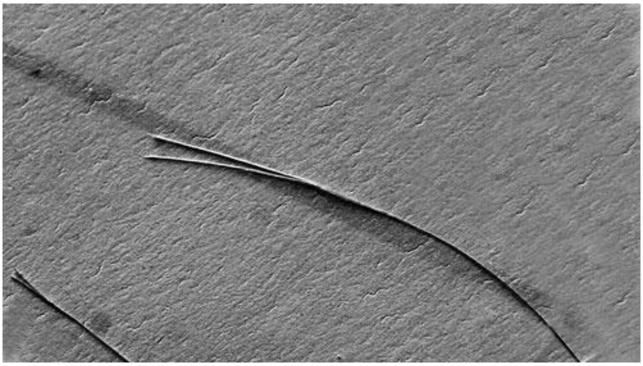

Fig. 10.8 A simple small split end (*lower left*) and a simple large split end

Fig. 10.9 A very large simple large split end

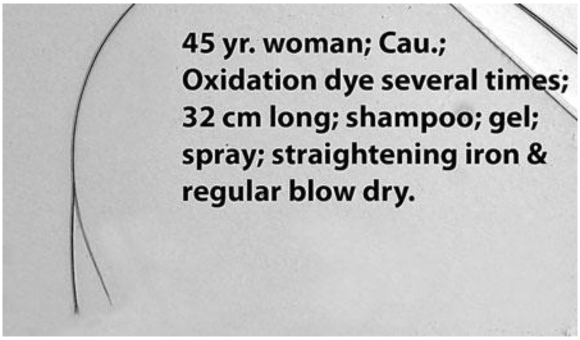

Fig. 10.10 A simple large split end with legs of unequal width

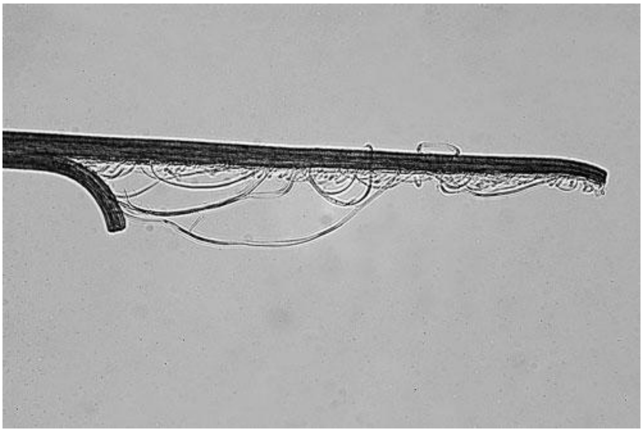

Fig. 10.11 A split end off of a step fracture

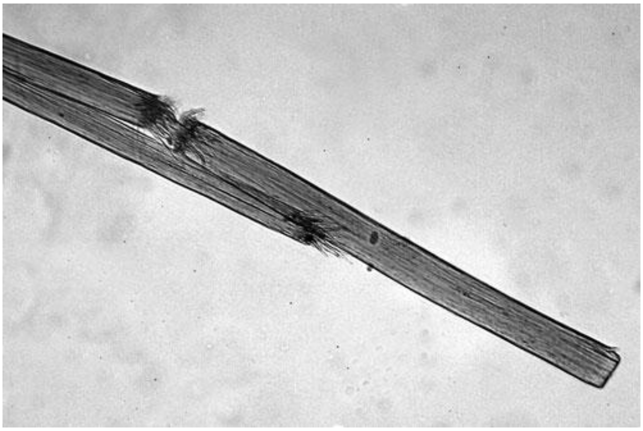

Fig. 10.12 A simple large split end with unequal legs. Note the one leg that is hanging together by fibrils

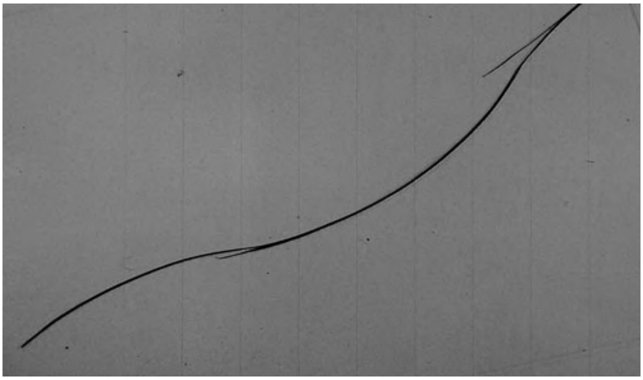

Fig. 10.13 A compound split hair where the splits appear to be independent of each other

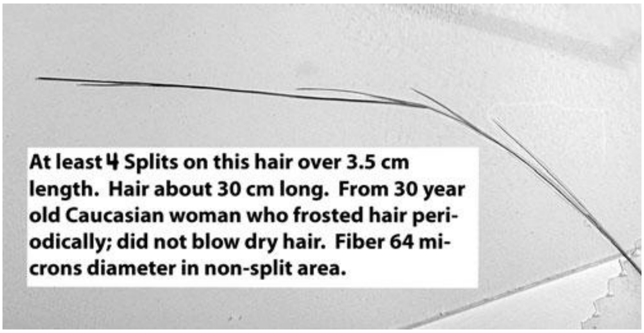

Fig. 10.14 A compound split hair with multiple splits over a 3.5 cm length of the fiber. This hair fiber was taken from the head of a 30 year old Caucasian woman who used peroxide-persulfate bleach on her hair periodically for a period of about 2 years. Her hair was down to her shoulder blades

Fig. 10.15 A very large compound split end cut from the head of a Caucasian woman. This woman used permanent dye on her hair periodically and she was a frequent sun bather

appears to be ready to break off. This split resembles the break found in the genetic abnormality Trichorrhexis nodosa described in Chap. 1. It is remarkable that such hairs can still exist on human heads, but all these split ends came from live heads of consumers who used normal consumer or salon hair products on their hair.

Figure 10.13 depicts a complex split end. I define a complex split end as one that has either two or more splits at different parts of the fiber or three or more legs off of a single split end. Figure 10.13 illustrates a hair fiber that contains two different splits that are far enough apart that they appear to be independent of each other. Figure 10.14 is a complex split hair that contains four splits over a 3.5 cm length of hair. Three of these splits appear to be independent of each other. This fiber was found on the head of a 30 year old Caucasian female with shoulder length hair who applied frosting treatment (persulfate-peroxide) to her whole head of hair

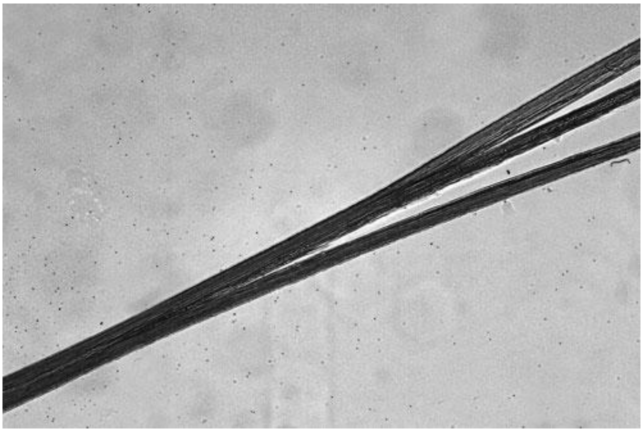

Fig. 10.16 A compound split end with three legs near the origin of the split

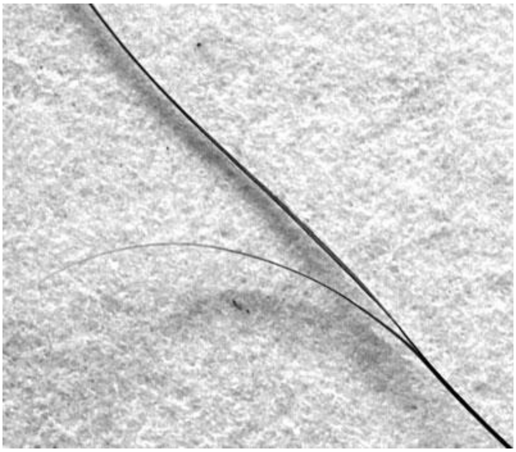

Fig. 10.17 A split hair not a split end. This split was found about 4 cm from the distal end of the fiber

periodically for 2 years. This damaged hair fiber remained on her head and the legs of the splits remained intact without breaking off.

Figure 10.15 is another complex split hair that was found on the head of a Caucasian female with shoulder length hair who had used permanent dye periodically on her hair. This woman was also a frequent sun bather and used a straightening iron on her hair regularly. These three treatments involve free radical reactions. This fiber is another example that I would have expected to have broken off and not be found on the head of a person. Figure 10.16 is another complex split hair in which the three legs of this split originate from or near the split origin.

Figure 10.17 is an example of a split hair that is not at the distal end of the hair fiber. In this case the split occurred about 4 cm from the tip end of the fiber. I have seen cases of this type of split hair in which the distal end of the split is at least 6 cm from the distal end of a hair fiber. In this particular case the origin of the split

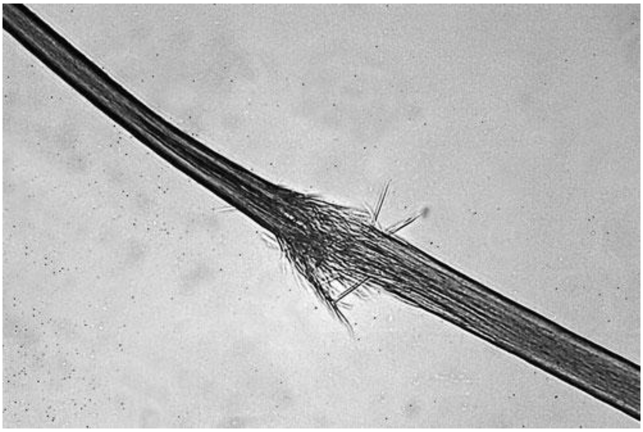

Fig. 10.18 A split hair not a split end where the fiber is held together by fibrils a few centimeters from the distal end

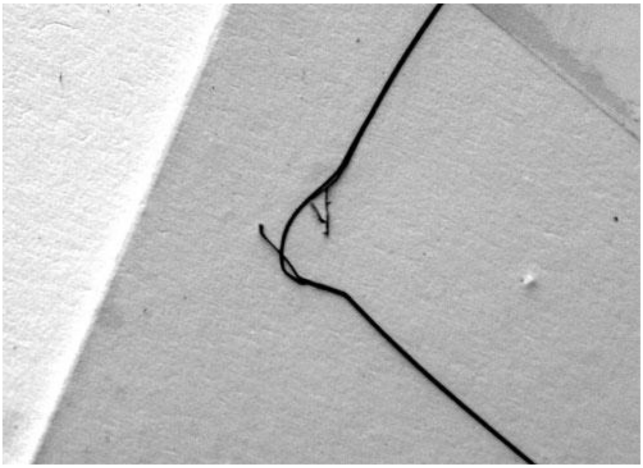

Fig. 10.19 Another split hair not at the end. In this case one end of the split is broken

appears to be close to a twist. This hair was taken from the head of a Caucasian female who treated her hair periodically with oxidation dye. About 1 year prior to cutting, she had a cosmetologist apply a peroxide-persulfate bleach to her hair. She also spent considerable time sun bathing in the Florida sun and regularly used a hot iron straightener and a blow drier on her hair. The oxidation dye, bleach, sunbathing and hot iron all involve free radical reactions.

Figure 10.18 is a split hair (found from the hair of the same woman) in which the fracture site is not at the end. In this case, the fiber has fractured but remains connected by fibrils that resemble the broom-like fractures at the nodes of

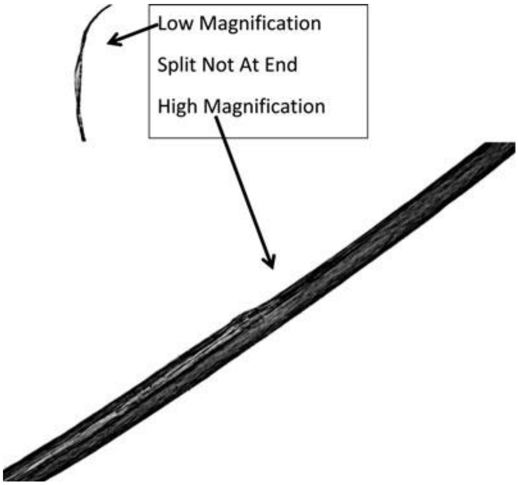

Fig. 10.20 Another split hair not at the end where the split is a slit in the hair. This slit-split was found a few centimeters from the tip end of the hair fiber

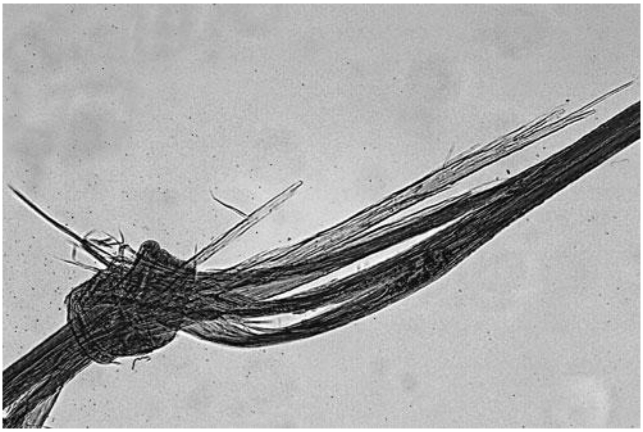

Fig. 10.21 A split fiber at a knot

Trichorrhexis nodosa, see Chap. 3. But in this case the effect is caused by cosmetic treatments and grooming actions, not by a genetic abnormality.

Figure 10.19 is another case of a partially broken hair fiber in which the fracture site is far from the distal end. This woman periodically used permanent dye on her hair and she regularly used a straightening iron on it but indicated she did not sunbathe (two free radical treatments).

The hair fiber depicted in Fig. 10.20 contains a slit far from the distal end. This figure shows the slit at two different magnifications. This split goes completely through the fiber but does not continue to the distal end. This hair fiber was found on a Caucasian woman with shoulder length hair who used permanent dye on her hair, she sunbathed frequently and regularly used a straightening iron on her hair; once again three free radical treatments.

Figure 10.21 is an example of a split hair at a knot. Several knots were found in the hair of this Caucasian woman who had curly hair (curl type III by the STAM procedure). This woman regularly used a straightening iron on her hair and periodically used permanent hair dye and a peroxide-persulfate bleach system had been applied to her hair by a hair dresser. She also occasionally sunbathed. In each case where I examined knots under the light microscope I could see varying amounts of fibrillation at or near the site of the knot. Figure 10.21 depicts the most extensive fibrillation that I observed at a knot.

10.4.1 Hair Treated with Free Radical Cosmetics and Sunlight are Susceptible to Splitting

The data of Table 10.2 shows that the highest incidence of splits (splits per gram of hair) and the most severe splits occurred on the hair that had received both a bleaching treatment (oxidation dyed or bleached) and frequent sunlight exposure. The one exception is the hair that was treated with a peroxide-persulfate frosting treatment (another free radical system) multiple times over a 2 year period. All hair samples were shoulder length or longer. So, a common factor in the hair with the most severe and most splits involved extensive free radical attack on the hair.

Robbins [38] described the cortex-cortex cell membrane complex as the area of the fiber that is most sensitive to free radical attack, because of its multiplicity of double bonds (allylic groups) and tertiary hydrogen atoms. This conclusion is consistent with the conclusion of Kamath and Weigmann [23] in their paper on fracturing of human hair and with the paper by Swift [39] on split end formation. Kamath and Weigmann [23] observed that the cortex-cortex cell membrane complex serves as an area for the axial propagation of cracks which can ultimately lead to split hairs.

Zimmerman and Hocker [40] in their studies on radiation of wool fibers showed that wool fibers that were not irradiated, when fractured, provided mainly smooth or cut fractures. Wool fibers that received short and intermediate term exposures to simulated sunlight when fractured provided mainly step and split fractures. However, after long times of irradiation (approaching unrealistic exposures for hair on heads) when fractured the fibers provided amorphous fractures. Therefore, the cortex-cortex cell membrane complex after it has been damaged by exposure to free radical reactions is prone to crack formation and the splitting of hairs.

The types of free radical reactions that commonly occur on live heads are in sun exposure, bleaching with either peroxide-persulfate or peroxide where copper or iron is present (including permanent dyeing) and/or hair that has undergone a large number of exposures to heat treatments such as hot curling or straightening irons. These effects have been confirmed by the types of hair most prone to split end formation on live heads described in Table 10.2.

10.4.2 Causes of Split Hairs and Split Ends

Among the more important scientific papers with regard to splitting of hairs are the hair fracturing studies by Kamath and Weigmann [23, 24], the paper describing a mechanism for split end formation by Swift [39], the hair breakage study by Brown and Swift [29], the study of irradiation of wool fiber by Zimmerman and Hocker [40] and the hair breakage studies by Robbins [19, 26] and by Robbins and Kamath [27, 28].

The literature provides the following conclusions with regard to split end formation:

1. Split hairs form more readily in the dry state than the wet state, particularly from 30% to 65% RH [23]. In addition, this author has shown in unpublished work that split ends are formed more readily from dry combing than from wet combing.
2. Splits form more readily on oxidized hair (see Table 10.3) and on damaged hair in general [29, 39, 40]; also see Table 10.3. The use of conditioners decrease split end formation, see Table 10.3. The evaluation of split hairs taken from heads shows that fibers that have been exposed to photochemical and chemical bleaching and in some cases also treated with straightening irons (free radical type exposures) are susceptible to split end formation.
3. Paragraph 2 supports this conclusion that the cortex-cortex cell membrane complex serves as a route for the propagation of axial splits in the fiber and for the formation of split ends [23, 38].
4. Splits form more readily on abraded [19, 23] and or weathered hair [29, 39], that is, hairs in which large sections of cuticle have been removed [23].
5. There is a stronger association between short segment breaks and split ends than long segment breaks and split ends (see Table 10.4).

Table 10.3 Effect of chemical bleaching and conditioning on split end formation and on long and short segment breaks after combing at 50% RH

Hair type and treatment	Split ends[a]	Short breaks[a]	Long breaks[a]
Bleached + shampoo + conditioner	2	112.7	18.7
Unaltered control + shampoo	16.3	186.7	27
Bleached + shampoo	24.3	328	102

[a]Means of three tresses; all three means in each column are significantly different from each other

Table 10.4 Cross-cutting vs. taper cutting and split end formation (60% RH)

Type cut	Split ends[a]	Plus splits[b]	End peak force[c]	Short segment breaks[a]
Cross-cut	47.5	3.5	130	799
Taper cut	18	1.5	23	253

[a]This is the number of split hairs that are not split ends at 100 comb strokes
[b]In grams load for 17.8 cm comb stroke and 3 g tresses for Caucasian hair
[c]This end peak force of cross cut hair is about five times that of taper cut hair

6. Split hairs form more from bending [29, 39] or impact loading [19] than from extension actions [29, 39].
7. Cross-cutting hair tresses or a switch so that all of the fibers are essentially of the same length increases the number and severity of splits, see Table 10.4.

The data of Table 10.4 shows that cross cutting the hair so that the ends of the hair are nearly equal in length vs. taper cutting the hair (ends are of different lengths) increases the number of split ends nearly threefold. As expected, the end peak force in quantitative combing also increases by cross cutting the hair. In this case the increase was by a factor of about 4. In another study the end peak force was found to correlate with short segment breaks and the data of Table 10.4 shows a directional effect between split ends and short segment breaks. The split end data of Table 10.3 was obtained on hair tresses that had been used in a breakage study where short and long segment breaks were also counted. These data were analyzed by analysis of variance providing a significant relationship between short segment breaks and the number of split ends; however, the relationship between long segment breaks and split ends was not significant. This analysis suggests a relationship or a connection between short segment breakage and split end formation. In addition, previous data on similar types of hair and similar tresses shows that the end peak force increases by a factor of about 5 (Table 10.4) by cross-cutting hair vs. taper cutting.

These results (Table 10.4) suggest that the end wrapping mechanism described by Robbins and Kamath [27] for formation of short segment breaks is likely involved in the formation of split ends. Before combing, hairs exist in complex interwoven patterns and the curlier and longer the hairs the more complex the interweaving. As the comb descends through the hair, sections of hair above the comb are made parallel. Those hair fibers beneath the comb are either made parallel or entangled. Entanglements occur by hairs looping around other hairs, or hairs looping around comb teeth and other hairs between the comb and the distal tips of the fibers.

As the comb continues to advance through the looped/entangled hairs long segment breaks occur. As the comb approaches the tips (when the hair is dry) wrapped ends result. End wrapping of hairs around comb teeth and other hairs occurs by inertia and possibly static charge. End wrapping produces a high end peak force resulting in high abrasion and severe bending deformations along with impacting and fatiguing all resulting in short segment breaks ($<$2.5 cm). Short segment breaks are more numerous if the hair is cross cut compared with a tapered cut or if the hair is damaged wherein inter-fiber and hair on comb friction is higher.

Split ends form from a crack in the cortex-cortex cell membrane complex as a result of severe bending deformations [39] and hair on hair impacting [19, 28] in wrapped ends. The crack propagates to the end of the hair particularly on highly abraded hair wherein some cuticle has been worn away. Two schemes [23, 39] described in the literature for split end formation are described below.

10.4.3 Mechanisms for Formation of Splits

The formation of split hairs has been either directly or indirectly studied by several different scientists. Since so many different types of split hairs have been identified (Figs. 10.8, 10.9, 10.10, 10.11, 10.12, 10.13, 10.14, 10.15, 10.16, 10.17, 10.18, 10.19, 10.20, 10.21), more than one mechanism is likely to be involved to account for the different types of splits.

The literature suggests that split hairs can form from bending [39] and from stretching actions [23] although Swift suggests that bending actions are more important than stretching on heads. From an examination of the hair literature and the seven factors above that promote or lead to increased split formation, I conclude that split hairs form more readily from abrasion in combination with impact loading involving bending and or torsional deformations.

Swift [39] provided the following mechanism for the formation of split hairs. He explained that snags form as the comb approaches the distal ends of the hair. When this occurs hairs become increasingly bent over each other and comb teeth (end wrapping occurs). Swift explained that since most hairs are elliptical they will bend about the plane of the major elliptic diameter. Upon bending, shear stresses will be parabolic and distributed across the minor axial diameter with a maximum at the plane containing the major axial diameter. Shear fracture then occurs which tends to propagate toward the tip end by the continued bending and straightening of the hair. This author believes that Swifts mechanism does occur with highly elliptical hairs that are damaged, but other mechanisms are operable under other conditions.

Kamath and Weigmann [23] also offered a mechanism for split end formation in their paper on hair fracturing. This mechanism does not favor or preclude any fiber shape from the formation of split ends. Kamath calls this mechanism “shock-wave” splitting. I discussed this mechanism with Kamath while we were working together on hair breakage. According to the mechanism of Kamath, “shock-wave” splitting occurs at low humidity when the fiber is impacted and deformed in a snag and when the cuticle is damaged and weakened.

The following mechanism is what I have taken from these discussions and I have merged Swift’s and Kamath’s mechanisms in the following manner. When the comb approaches the distal ends of the hair, end wrapping occurs and relatively high forces are applied to move the hair through the ends. This likely involves bending actions and as Swift proposed since most hair fibers are elliptical bending will occur about the plane of the major axial diameter. At that instant primarily through impact loading and severe bending deformations a crack is formed in the cortex. Residual elastic energy then dissipates like a shock wave in a radial plane at the fracture faces. The shock wave is then propagated axially through the damaged cortex-cortex cell membrane complex forming the split hair or split end. Furthermore, splitting is most prone to occur at low RH and when the fiber is damaged (both in the cuticle and in the cortex-cortex cell membrane complex). When the cuticle is damaged and weakened that is highly abraded with badly worn tip ends so that there are too few cuticle layers to strongly hold the ends together and the cortex cell membrane complex has been highly oxidized by free radical chemistry the "shock wave" propagates rapidly to the end of the fiber. Thus, this phenomenon is associated with short segment hair breakage explaining the correlation of short segment breaks with split ends.

10.5 Flyaway Hair

10.5.1 Static Charge and Flyaway

When a comb is brought into contact with hair at low RH, charges of opposite sign but equal magnitude are generated on both the comb and the hair surface. The charges are generated because of the difference in the affinity of each of these materials for electrons (electrochemical potential). The repulsive forces of static electricity on the hair cause the fibers to separate producing Flyaway Hair [1]. Static electricity consists of electrons or ions that are not moving. It results from rubbing and pressure during combing and brushing between two poorly conducting surfaces. An electric charge from friction is called triboelectricity; that from pressure is called piezoelectricity.

After combing or after separation of the comb from the hair, the dissipation of the static charge is governed by the conductivity (reciprocal of resistivity) of the fibers or their electrical resistance. In general, materials with a high electrical resistance such as human hair, wool, silk, or nylon are more prone to static buildup than are lower-resistance materials like cotton and rayon [41]. Therefore, the phenomenon of static flyaway is concerned with three conditions:

– Static charge generation on the fibers,
– Conductivity or the removal of static charge from the hair, and
– Hair type.

The primary factors involved in static charge generation are (1) the difference in electrochemical potentials of the two surfaces, and (2) the rubbing forces involved. For example, the use of lubricants can reduce rubbing forces and in that manner provide less charge generation [6]. Jachowicz et al. [14] determined that the conductivity of the hair surface is also important to static flyaway. These scientists demonstrated that long-chain quaternary ammonium salts increase the conductivity of the hair surface in addition to decreasing hair fiber friction. For these two reasons, long-chain quaternary ammonium compounds are excellent antistatic agents.

Hair type is also relevant to the condition of flyaway hair. For example, hair fiber curvature is critical to flyaway. Robbins [6, 42] proposed that by the C^2 hypothesis, at high curvature (for example, Curl types IV–VIII), flyaway hair would be minimal or nonexistent. This lack of flyaway is because the entanglements created by high curvature hair will dominate over the ability of the fibers to separate from static charge. He demonstrated that tresses of Caucasian hair steam set to Curl type V had no flyaway in spite of a high static charge build-up. On the other hand, hair tresses of Curl type II with the same static charge generated extreme flyaway. Furthermore, when the two hair tresses were brought together, the flyaway fibers of Curl type II were repelled by the entangled hairs of the Curl type V tress. This effect proves that the higher curvature hair did have static charge build-up capable of producing flyaway, but not on highly coiled hair. This experiment also supports the hypothesis [6, 42] that at high degrees of curvature, curvature dominates the hair assembly property of flyaway hair as it does for so many consumer hair assembly properties.

10.5.2 Methods Relevant to Static Flyaway

Mills et al. [43] described two techniques for estimating static charge on human hair. The "ballooning method" actually estimates static flyaway. This method consists of acclimating tresses at a desired low humidity in a chamber (generally for 24 h) and then combing the hair in a controlled manner. The relative amount of static charge is then estimated by the amount of ballooning or separation of the fibers of the tress (see Fig. 10.22). The second method of Mills et al. [43] consists of first acclimating tresses, then combing them in a controlled manner with a special comb containing a bare copper wire in its back. The copper wire leads through an insulated holder to an oscillograph. The charge on the comb is measured, and theoretically it is equal and opposite to that on the hair.

Barber and Posner [44], Lunn and Evans [13], and Jachowicz et al. [14] have all described similar yet more sophisticated approaches. Lunn and Evans [13] described methods for measuring charge generation on hair tresses, charge mobility on the hair, and charge distribution along the hair fibers. These methods involve

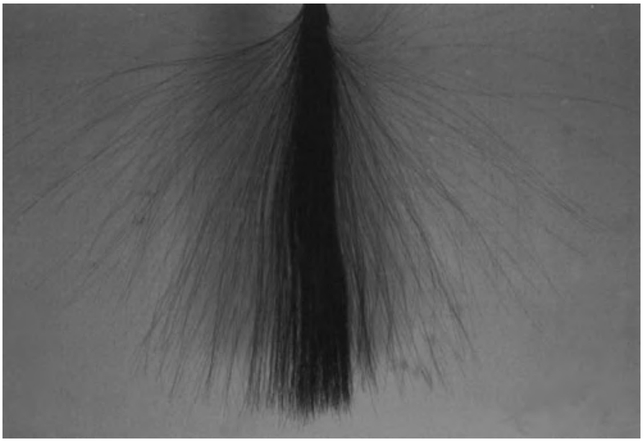

Fig. 10.22 Static ballooning of hairs in a tress due to static charge build-up

combing hair tresses to induce the charge. Jachowicz et al. [14] developed a useful method to measure both charge generation and charge decay by rubbing hair fibers against different elements under controlled conditions. Jachowicz et al. also measured charge density along the length of tresses and showed that the electrical field that concentrates near the fiber tips causes flyaway hair.

The measurement of static charge on textile fibers, fabrics, and yarns has also received a considerable amount of scientific attention and is relevant to this same subject on human hair. The book by Meredith and Hearle [45] provides a good introduction into this subject. Electrical resistance (reciprocal of conductance) of fibers is also fundamental to their static electrification and is described by Hersh [46] for human hair and other fibers and by Meredith and Hearle [45] for textile fibers.

10.5.3 Triboelectric Series

Attempts have been made [47, 48] to classify materials according to "triboelectric series" which lists materials in an order so that the higher one on the list will be positively charged and the lower one negatively charged when any two of the materials are rubbed together. In theory, triboelectric classifications should be useful, because the relative affinity for electrons of each of the materials in contact (electrochemical potential) is very important to the charge developed [13]. However, such series are generally not very consistent.

10.5.4 Moisture Content and Resistance

The moisture content of human hair provides a large influence on static charge. Increasing moisture in hair decreases its electrical resistance [46]. Therefore, increasing moisture increases the conductivity of the fiber surface so that it is less prone to develop a static charge because the electrons distribute more evenly over the entire hair surface.

The electrical resistances of wool and human hair have been shown to be very similar at 85% RH (see Table 10.5), and their resistances are similar from 52% to 85% RH [49]. Since the moisture binding-RH relationships of wool and human hair from 0% to 100% RH are virtually identical (see Table 9.33), their resistance-RH relationships from 0% to 100% RH must also be very similar. Morton and Hearle

Table 10.5 Electrical resistance of wool and human hair at 85% RH [46]

Wool	$4.2–7.4 \times 10^{12}\ \Omega$
Human hair	$10.0–17.0 \times 10^{12}\ \Omega$

Table 10.6 Effect of RH on the static charge developed on human hair for a shampoo and a crème rinse conditioner[a] [43]

	% Relative humidity		
Treatment	27% RH	51% RH	76.5% RH
Experimental shampoo	14.3[a]	10.8[a]	3.3[a]
Creme rinse	2.5[a]	1.5[a]	0.4[a]

[a]Data are relative pip heights from oscillograph recordings of the charge developed on the comb

[41] described the resistance of wool fiber to vary by a factor of approximately 10^5 from 10% to 90% RH and by a much larger factor from 0% to 100% RH.

Confirming this relationship of resistance-RH and static charge for human hair is the effect of RH on static charge shown by Mills et al. [43] (see Table 10.6). These data show a progressive decrease in the static charge developed on the hair with increasing RH, for each of two different types of treatment. For both treatments, the principal effect of RH is to increase the water content of the hair. Increasing the water in the hair surface decreases its electrical resistance, making the fiber a better conducting system and therefore less capable of retaining a static charge.

10.5.5 Temperature and Static Charge

The resistance of keratin fibers generally decreases as temperature increases. An increase of 10°C will produce approximately a fivefold decrease in resistance [43]. Therefore, the perceived effect of temperature on conductivity does not appear to be the cause of greater flyaway from hot combing as compared to room temperature combing.

10.5.6 Impurities on the Fiber Surface can Influence Static Charge

For hygroscopic fibers like wool fiber and human hair, the resistance can be influenced by electrolyte content. For example, the addition of potassium chloride lowers the resistance of wool, whereas washing in distilled water can increase wool's resistance [43] by removal of electrolyte from the hair surface layers.

10.5.7 The Amount of Static Generated is Virtually Independent of Rubbing Velocity

Hersh's [46, 48] studies with textile fibers suggest that the amount of static charge generation is virtually independent of rubbing speed, when rubbing one high-resistance fiber against another high-resistance fiber. However, Cunningham and Montgomery [50] have shown an increase in static charge with increasing rubbing velocity when rubbing high-resistance fibers against metal fibers. Rubbing velocities in both these studies were approximately 1–30 cm/s.

10.5.8 Decreasing Rubbing or Combing Forces Decreases Static Charge

After tresses are shampooed and combed, the amount of static ballooning also depends on the amount of combing. As already indicated, Lunn and Evans [13] concluded that the primary way that long-chain quaternary ammonium salts reduce static buildup is by decreasing inter-fiber friction which in turn reduces the work of combing. Therefore, one way to reduce static buildup is to reduce the work of combing, which is to make the hair comb easier [44].

10.5.9 The Sign of the Charge is Related to the Direction of Rubbing

The sign of the static charge that develops on both human hair and wool when rubbed against similar fibers has been shown to be related to the direction of rubbing [14, 46, 51]. If the fibers are oriented in the same direction and one fiber is removed from the bundle by pulling it out by its root end, a positive charge develops on this fiber. If a fiber is removed from the bundle by pulling it by its tip end, a negative charge develops on the fiber. If the fiber that is removed is oriented opposite to the other fibers of the bundle, or if it contains no scales, no charge develops on it. Although this effect is not fully understood, it has been attributed to the heterogeneity of the scales. The points of the scale edges have been suggested to have a different triboelectric nature from the main scale surfaces. Therefore, rubbing a fiber root to tip rubs primarily against scale surfaces, whereas rubbing tip to root rubs mainly against scale edges [46].

An equally interesting effect on the sign of the static charge on hair has also been found to relate to the nature of surface deposits or treatments [14, 41]. Washing hair tresses with an anionic shampoo and drying at low relative humidity and then combing produces a large amount of static ballooning. Flyaway was considerably less for tresses treated with a cationic creme rinse followed by water rinsing and drying. However, if tresses were treated with a cationic creme rinse and not rinsed or only lightly rinsed with water, a relatively large amount of ballooning was apparent. Furthermore, the charged fibers from this treatment were attracted to (not repelled from) charged fibers from the anionic shampoo treatment, indicating opposite signs of static electricity. This different sign for the charge was confirmed by oscillographic measurements. Jachowicz et al. [14] described related effects.

For discussion and theoretical explanations and controversies on the static electrification of fibers, see the book by Morton and Hearle [41], the thesis by Hersh [46], and the paper by Jachowicz et al. [14].

10.5.10 Effect of Ingredients on the Static Charge

Table 10.6 describes the effects of shampoos (high cleaning) compared with creme rinses on the development of static charge on hair. The amount of charge developed by combing or brushing hair tresses (straight to wavy hair) is related to the amount of flyaway. The amount of flyaway generated is related to both the chargeability (charge generation and conductivity combined) of the hair fibers and to the work of combing. The lower static values (see Table 10.6) for both creme rinse and shampoo treatments as a function of RH are due primarily to a decrease in the electrical resistance of the hair, and the lower work of combing, as well as the increased moisture content (see Table 9.32). When the resistance drops below a certain value near 10^8 Ω-g/cm^2, the charge can apparently spread more readily over the entire hair to adjacent surfaces and dissipate into the air. In this manner, the charge density required to cause noticeable flyaway is not exceeded.

Jachowicz et al. [14] found that the adsorption of long chain quaternary ammonium compounds, cationic polymers, and some specific polymer-detergent complexes decreased the electrochemical potential and increased the conductivity of hair. Of course, long-chain quaternary ammonium compounds also decrease the rubbing forces by a lubricating action. This lubrication decreased the charge generated, and Lunn and Evans [13] suggested that lubrication is the major reason for the antistatic effect of creme rinses. Jachowicz et al. [14] suggested that the increase in surface conductivity by quats in creme rinses is also important to the effectiveness of these ingredients as antistats. Therefore, the lower static charge for creme rinse vs. shampoo treatments (Table 10.6) is a result of lower frictional drag during combing as well as an increase in the conductivity of the hair. The change in resistance (of keratin fibers) from 10^{12} to 10^8 Ω-g/cm^2 that occurs between 22% and 77% RH (Table 10.7) approximates the required decrease in resistance for a creme rinse effect at 27–76% RH (Table 10.8), assuming that a large part of the antistatic effect by creme rinses is due to an increase in conductivity.

Table 10.7 Effect of relative humidity on electrical resistance of hair

% RH	Approximate R_s for wool[a] [46]
27	10^{12}
77	10^8

[a]R_s = resistance in ohms between the ends of a specimen 1 cm long and of mass 1 g (ohm-g/cm^2)

Table 10.8 Effect of creme rinse and RH on static charge in hair [43]

	27% RH	76% RH
Shampoo	11.5–14.3	2.2–3.3
Rinses	2.0–3.8	0.4–0.5

[a]Data are relative pip heights from oscillographic recordings of charge on the comb

Jachowicz et al. [14] modified hair fibers by reduction, bleaching, and oxidation dyes and found only a small difference in triboelectric charge vs. chemically unaltered hair and no increase in surface conductivity by these treatments.

10.6 Hair Shine or Luster

Consumer research suggests that hair shine is a more meaningful cosmetic term to consumers than luster. The word luster is used more frequently in scientific works on textile materials. In most of our work on this important cosmetic property, the objective was to develop methods to correlate with the consumers' subjective assessment of hair shine. The words shine and luster are used interchangeably in this discussion.

When hair is illuminated, the incident light may be reflected at the surface or refracted (bent) (see Fig. 10.23). It may enter the fiber and be absorbed (by pigment), or it may reemerge, usually after hitting the rear wall of the fiber, where it is partly reflected and refracted again. The phenomenon of light scattering is a major subject of this section, and we shall see how reflection of light may either enhance or reduce hair shine, how refraction of light can reduce hair shine, and how absorption of light can enhance it.

10.6.1 The Scale Angle and the Specular to Diffuse Reflectance Ratio

Light striking hair in a root-to-tip direction at an incident angle of 30°, provides a specular reflection of 24° (large peak of Fig. 10.24), rather than 30°. The specular reflectance may be estimated from light-scattering curves (Fig. 10.24), primarily from the specular peak height. If the axis of the hair is 30° relative to the incident light, then the scale angle must be 3° (30–2 $\times$ scale angle $=$ 24°). The second peak (lower peak) of Fig. 10.24 occurs at approximately 40°, and represents light that has entered the fiber and is reflected from the back wall of the hair. This second peak is much larger for blond hair (dashed line) than for dark brown hair (solid line) because of the greater absorption of light in the cortex by the additional pigment granules of the darker hair.

When incident light strikes a surface, it may be reflected specularly (S), when the angle of reflectance equals the incident angle (which increases shine), or it may be

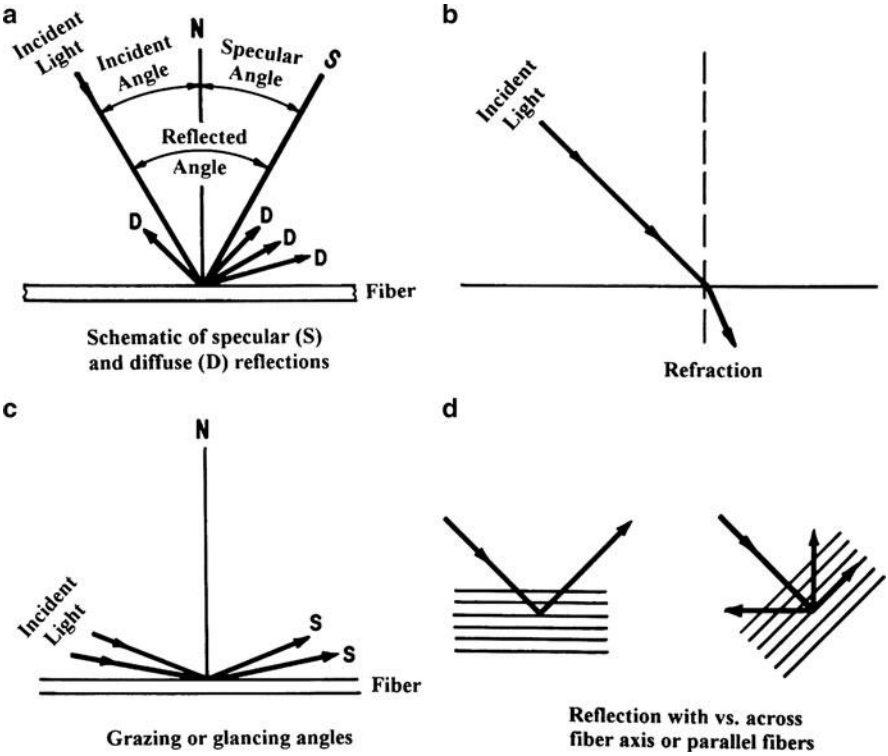

Fig. 10.23 Some parameters important to hair luster

reflected diffusely (D), at angles other than the incident angle (scattered light decreases shine) (see Fig. 10.24). Unless one examines a perfect mirror, a combination of both specular and diffuse reflection takes place.

Diffuse scattering may be estimated from light-scattering curves by drawing a line between the light intensities (voltages of Fig. 10.24) at 0–75° and measuring the area under the line. A light scattering curve with an incident light of 30° striking the fiber in a tip to root direction, shows the back wall reflection near 15° and the specular reflection at 36°, once again suggesting a 3° scale angle.

Some ratio of specular to diffuse reflectance is generally accepted as a measure of luster for fibers and yarns [52–54]. Ward and Benerito [52] determined that the ratio of specular to diffuse reflectance for cotton fibers correlates with visual luster assessments. Fourt [53] suggested a contrast ratio for evaluating luster of wool fabric, using a ratio of specular reflectance at a 45° angle of incidence to diffuse reflectance at 0°. Stamm et al. [55] suggested the function:

$$\text{Hair shine} = (S - D)/S$$

where S = specular reflectance and D = diffuse reflectance.

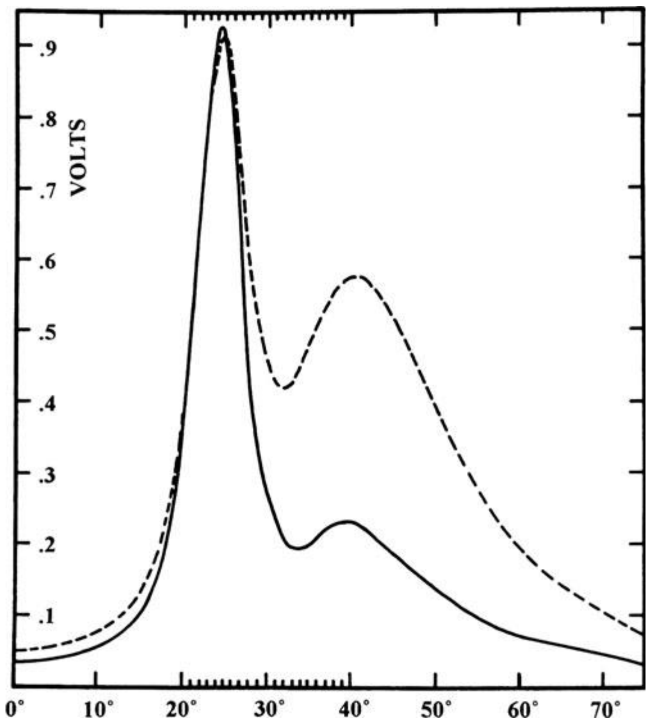

Fig. 10.24 Light-scattering curves from dark brown hair (*solid line*) and blonde hair (*dashed line*) [58] (Reprinted with permission of the Journal of the Society of Cosmetic Chemists)

10.6.2 Hair Shine Methods

Hair shine may be evaluated subjectively on tresses or on heads of hair (preferably on half heads), or it may be evaluated instrumentally. The subjective evaluation of hair shine on tresses can be very consistent and reliable, provided care is taken to consistently align the fibers of the tresses, to control lighting, to use multiple observers to evaluate tresses, and to use replication. Figure 10.25 is a photograph of a board constructed to help align the fibers of a tress consistently and to orient the tresses with respect to the lighting. This board also helps to keep the tresses aligned during the evaluation period. Six tresses seem optimal for any single test. Therefore, only two to three treatments can be evaluated at a time. The data should be analyzed by a nonparametric procedure such as the Friedman or Kruskal Wallis test [56].

Similar care should be taken for subjective analysis of shine on live heads. The primary variables to control for evaluating shine on live heads are lighting and hair alignment [57]. Alignment can be controlled to a limited degree by parting the hair in the center of the head and blow-drying the hair while combing it straight after

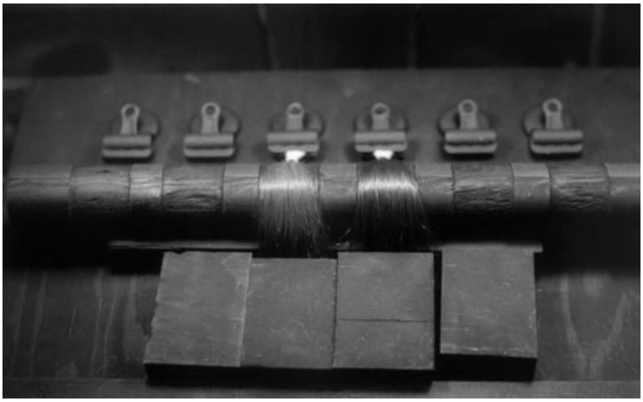

Fig. 10.25 Tress holder developed for panelists assessment of hair shine

treatment. A useful system is to treat hair on heads and to take 30–40 fibers per side after treatment and to evaluate the fibers instrumentally for shine by light scattering.

Several different instrumental methods and approaches have been used to evaluate the shine of human hair [45, 54–62] (Schebece and Scott, private communication). The method of Thompson and Mills [54] measures reflectance from an assembly of hair fibers; the methods of Stamm et al. [55] and Reich and Robbins [58] measure light scattered from either single hairs or from a parallel array of taut hair fibers. The method of Schebece and Scott (private communication) measures light reflected from single hair fibers alone. The method of McMullen and Jachowicz [60] takes digital images of tresses and analyzes the data with special software.

The method of Thompson and Mills [54] illuminates a small tress of hair after the fibers have been carefully aligned over a cylinder 4 in. in diameter. A photocell is placed at an angle of 160° to the incident beam, and at varying distances from the hair sample. The hair is rotated to give a maximum reading. The light source is at a fixed distance (10 in.) from the hair sample. From these parameters, both the specular (S) and diffuse (D) reflectance can be calculated using the following expression, after taking readings at more than one sample to photocell distance (X). In this case, Cos C is the cosine of 80°.

$$\text{Intensity of light reflected} = \mathrm{S}\,\frac{\mathrm{D}\cos \mathrm{C}}{\mathrm{X}^2}$$

The limitations of fiber alignment—the inability to vary incident angle or to scan all reflected light from the surface—with the Thompson and Mills method are solved by the goniophotometric methods of Stamm et al. [55], Schebece and Scott (private communication), and Reich and Robbins [58]. From a strip chart recording of intensity of reflected light vs. angle of observation (see Fig. 10.24), the specular reflectance and diffuse reflectance are obtained. Currently the best function for hair shine is this one by Reich and Robbins [58]:

$$L = S/DW(1/2)$$

where S is the specular reflection, D is the diffuse reflection and W(1/2) is the width of the specular peak at half-height.

Most quantitative methods to measure hair luster have relied on goniophotometric measurements of either single hairs or an array of parallel hairs using some function of the ratio of specular to diffuse reflection [55, 58]. Although tresses have been employed for measurement of luster [54] no one had successfully adapted this method to measure luster on curly African type hair tresses. However, McMullen and Jachowicz [60] described a novel luster method that shows promise for measuring luster on curly African hair as well as on curly Caucasian and Asian hair. In this method, the authors recorded digital images of hair tresses with a digital camera coupled to a macro lens. They then analyzed the photographs using special software (Image Tool 2.0 from the University of Texas Health Science School) that took into account the number of reflection sites and their shapes. This method was capable of showing that sebum dulls African hair and it appears to show promise as a means for measuring luster on many types of hair even curly hair. Even though I have a concern about potentially large variances in measuring luster in curly hair or whole heads of hair (because of variable hair alignment), this approach appears to offer promise for a solution to this difficult problem.

10.6.3 Fiber Alignment, Orientation, and Hair Shine

When hair fibers of an assembly are aligned parallel, maximum specular (mirror) reflectance can be obtained with minimum scattering [54]. The problem of consistently aligning the fibers of a tress or hair on the head the same repeatedly or sufficiently parallel perhaps produces the largest variance in shine evaluations. As a result, alignment interferes with the ability to see small changes in hair shine, thus, the obvious advantage of the instrumental methods that evaluate either single hairs or a parallel array of hairs [55–59].

Keis et al. [59] described the effects of hair fiber curvature on hair luster and on hair of different populations. They explained that high curvature hair in an assembly generally displays low luster because it interferes with a uniform parallel alignment of fibers and thereby increases the amount of scattered light. This light scattering effect suggests that luster will generally decrease with increasing fiber curvature unless the curls are broad and synchronized in alignment as often occurs in Curl types II and III.

10.6.4 Shine Increases with Ellipticity but Decreases with Curvature and Twists

Keis et al. [59] worked with African American hair with an ellipticity index of 1.6 frequently found in curl class IV. Keis, Ram and Kamath also concluded that in addition to curvature, twists and kinks decreased luster because twists increase light scattering. Keis et al. [59] found that by comparing single hair fibers that were straightened in the goniophotometer (to eliminate curvature) that luster increased with fiber ellipticity and with increasing pigmentation. They further demonstrated with an 80 μm nylon fiber with an ellipticity index of 1.0 that when it was mechanically flattened to increase the ellipticity from 1.0 to 1.35 to 7.0 that luster increased because the amount of scattered light decreased. This luster effect occurs because specular light is reflected from the surface of the fiber and light that enters the fiber is scattered by reflecting off of irregularities on the fiber interior.

Apparently this effect of ellipticity on improving luster is smaller at higher curvatures than the misalignment effect at higher curvatures, because assemblies of such hair fibers (Curl type IV–VIII) are generally less shiny than well aligned wavy or straight assemblies of hairs (Curl types I–III) of lower ellipticity. Therefore, Keis et al. [59] agreed with Robbins C^2 hypothesis [6, 42] that when curvature is high, it dominates luster as it does with other physical properties in its influence on hair assembly behavior.

In a single hair method or in an assembly, shine is always more apparent along the fiber axis than across it (Fig. 10.23). When the incident light is in the scale direction, reflectance is at a maximum, and scattering is less than it is in the "against scale" direction [55]. The shine of the surface may appear different when illuminated and viewed from grazing angles as opposed to larger angles where highlights are more prominent (see Fig. 10.23).

10.6.5 Dark Hair (Natural or Dyed) is Shinier than Lighter or Gray Hair

Dark hair often appears shinier than lighter hair. This is because part of the light is reflected at the fiber surface, and part enters the fiber and is scattered by reflecting off irregularities of the interior. When that light reemerges, the diffuse component is increased. If the fiber is colored or dyed, some of this diffuse component is absorbed before reemerging, thus reducing it and making the fiber appear shinier [45]. This effect is depicted in Fig. 10.24, comparing light-scattering curves for a dark Brown hair and a blond hair fiber, and has already been described.

Keis et al. [61] studied the effect of natural hair pigmentation on hair luster using a goniophotometer. This study confirmed that increasing hair color reduces light scattering and increases luster. These same scientists examined dyed hair and found a similar but more complicated picture. Dye composition, concentration and penetration depth must be taken into consideration to account for the results. In addition, the luster of hair of different colors is perceived differently by the human eye adding further complications.

There is less pigment in gray hair than in dark hair. Most likely the pigment granules of gray hair are also smaller in size, both actions a result of changes in the

Table 10.9 Effects of shampoos on hair shine (specular/diffuse scattering)[a]

Step 1: Oily hair from scalp containing only sebaceous soil	0.411
Step 2: Wash with commercial soap containing shampoo	0.466
Step 3: Wash with commercial TEALS based shampoo	0.538

[a]Washing and rinsing in 100-ppm hardness water. Data provided in private communication by F. Schebecewe

melanization process with ageing. Nagase et al. [62] found that hair with a porous medulla gives a whitish appearance with less luster. These air spaces increase the scattering of light due to a change in refractive index at the hair to air interface creating a gray or whitish appearance. This effect is analogous to the one in the genetic abnormality of pili annulati or ringed hair. Pili annulati appears as bands or rings of silver or gray and dark regions along the axis. Musso [63] working with guidance from RDB Fraser observed that ringed hair contains bands or areas with air spaces in the cortex along the axis. These air spaces correspond to the silver or gray bands. The air spaces are believed to be caused by a defect in the synthesis of the microfibril-matrix complex in the cortex with less of it being produced. Therefore, cavities or air spaces are created in the hair [63]. So, gray hair with a porous medulla appears whiter than the same hair without a medulla.

10.6.6 Shampoos, Sebum, and Hair Shine

Schebece and Scott (private communication), using a light-scattering technique demonstrated that sebum de-lusters hair and soap-containing shampoos diminish hair shine. The soap effect can only be seen when hardness is present, but it can be detected in hardness as low as 100-ppm and lower (Table 10.9). Thompson and Mills [54] found a similar effect with soap-containing shampoos at 300-ppm hardness. More recently we found such effects with soap-containing shampoos at 60–80-ppm hardness.

The data of Table 10.9 show that sebum dulls hair and that soap deposits from shampoos also de-luster hair. Similar dulling effects may be observed after shampooing hair with a shampoo containing cationic polymer ingredients (Schebece and Scott, private communication). These deposits are often not uniform on the hair surface. Therefore, they can increase diffuse scattering; however, decreases in the specular component may also be seen with increasing deposition of some conditioning ingredients.

10.6.7 Hair Sprays Decrease the Shine of Single Hairs

Schebece and Scott (private communication) examined several commercial hair sprays for hair luster before and after soaking fibers in different concentrations of the product concentrates. In all cases, the specular/diffuse reflectance ratios decreased (from 2% to 14%) depending on the concentration and type of resin used. Combing and other physical manipulations of the resin on the hair produced cracks in the hair spray resins, increasing the diffuse scattering and further dulling the hair. A method for hair assemblies is required to determine if the additional improvement in hair alignment by hair spray deposits will compensate for the increase in diffuse scattering.

10.6.8 Permanent Waves and Visual Assessment of Hair Shine

Dark brown hair tresses were treated with a commercial home wave and then visually assessed by panelists as slightly less shiny than the untreated control. A color shift to a slightly lighter shade was also noted. This shine change is believed to be due to an actual dulling of the fibers rather than to curvature or alignment changes.

10.6.9 Oxidation of Hair and Visual Assessment of Hair Shine

A group of five subjects were treated half-head-style with a surface oxidative treatment (diperisophthalic acid described in Chap. 5). This treatment oxidized the hair surface but did not penetrate to the cortex. Therefore, no pigment was oxidized and no color change occurred. Both subjects and independent observers through 1 month after treatment made shine evaluations. Independent observers all agreed that the treated side was less shiny than the untreated side. However, only one subject could detect this de-lustering effect on her own hair. These results suggest that oxidative treatments, including hair bleaches, dull hair. In addition, independent observers are more sensitive to hair shine changes on heads than self-evaluation of hair shine. Oxidative treatments that lighten the hair will decrease hair shine.

10.6.10 Abrasion of Hair Decreases Hair Shine

Schebece and Scott (private communication) abraded hair fibers against a smooth Bakelite surface in one experiment (Fig. 10.26) and against a 50-µm tungsten wire in another. The data show that surface abrasion decreases hair shine (specular/diffuse reflectance). This dulling effect increased with increasing abrasion. In certain instances, the total amount of reflected light and the specular component both increased. The specular/diffuse ratio always decreased. These results suggest that teasing (back-combing) hair and other abrasive actions such as vigorous

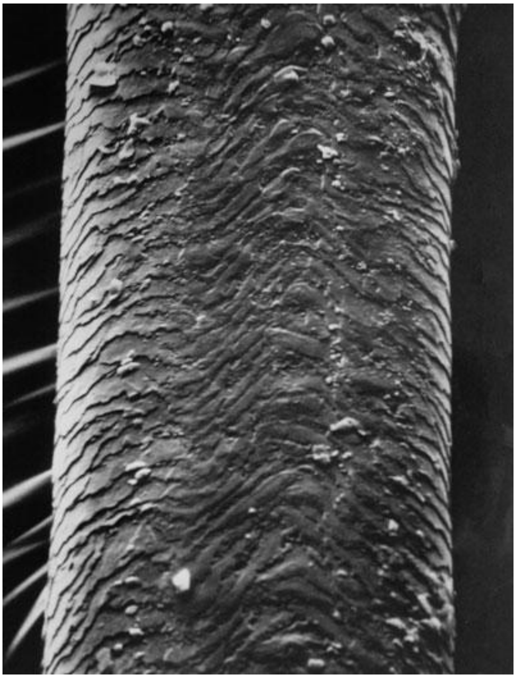

Fig. 10.26 Electron micrograph of a hair fiber mechanically abraded by rubbing against another hair. Note cuticle abrasion and hair fragments on the hair surface

combing or brushing can de-luster the hair by breaking scale edges and creating more irregularities on the fiber surface. These actions dull hair by increasing diffuse scattering.

10.7 Hair Body

10.7.1 Body Definition and its Relationship to Single Fiber Properties

Hair body is defined in the textile trade as that compact, soft, or firm-feel of textile stock or fabric [64]. It is a tactile property. With regard to human hair, body may be defined as thickness or apparent volume of a hair assembly, involving sight and touch for assessment [1]. The quality of liveliness or springiness [65] is also associated with hair body. Hough et al. [36] defined body as the structural strength and resiliency of a hair mass, which is consistent with the above definitions.

Body is a complex characteristic involving several single-fiber properties, including friction, stiffness, curvature, cross-sectional area or diameter, weight, and length (Table 10.10). If we consider changes instead of absolute values for hair body, it permits us to neglect properties that are not changed by cosmetic treatment

Table 10.10 How single fiber properties of hair relate to hair body [1, 2]

Increase in these fiber properties produces an increase in hair body	Increase in these fiber properties produces a decrease in hair body
Curvature[a]	Cohesion[a]
Friction	Weight
Stiffness	
Diameter	

Note: Fiber length is not considered, since it is not changed by cosmetic treatments
[a]Relatively large effect predicted

such as hair density on the scalp and fiber length. Thus considering changes by treatments simplifies the analysis. This approach suggests that if one makes the fibers stiffer, increases their diameter or curvature, or increases the frictional forces between the fibers, hair body will increase.

Hough et al. [36] used a slightly different approach and concluded that five groups of fundamental parameters govern hair body:

1. Hair density on the scalp
2. Stiffness
3. Diameter
4. Fiber interactions
5. Curvature

Thus, increasing hair density on the scalp, stiffness, diameter, or curvature increases hair body. For fiber interactions, the effects depend on the nature of the interactions. Obviously, these two independent approaches are related, and both lead to the conclusion that hair body can be studied systematically through single-fiber properties. However, if we consider only the changes that can be made to hair fibers by cosmetic treatments, then curvature has the greatest impact on hair body. Furthermore, if curvature is high it can dominate changes in hair body as it can for most consumer hair assembly properties as predicted by the C^2 hypothesis.

10.7.2 Methods to Evaluate Hair Body

Several laboratory methods have been described to characterize hair body [37, 67–76]. The Tolgyesi omega loop method [66] examines structural strength of a hair assembly, emphasizing the bending properties of an assembly more than the frictional properties of the fibers. One method that emphasizes frictional behavior but attempts to measure the bulk of hair fibers is the cylinder method of Scott and Robbins [69]. This method involves randomly dropping 1–2 in. hair fibers into a graduated cylinder. Fibers with higher inter-fiber friction tend to provide a larger volume and therefore more body.

The method of Clarke, Robbins and Reich uses image analysis to approximate the volume of hair tresses [72]. This is probably the best of all current hair body methods. The Textile Research Institute's (TRI) method [68] involves transverse compression of a bundle of fibers to determine the compressibility and recovery behavior of hair tresses. Garcia and Wolfram [70] considered the force or work necessary to pull hair tresses through a Teflon ring. Here the net force is a combination of fiber bending and fiber-fiber and fiber-ring friction. But it is not clear with either of these two methods which parameter or combination of parameters correlates best with hair body. TRI suggests that their method is intended to measure the "tactile component of hair body as it is reflected in the resistance that hair offers to compression."

Another approach, by Robbins and Crawford [73], is a modification of the Garcia-Wolfram method. In this system, the bulk of a hair assembly is assessed by measuring the work required to pull the tress through a succession of very thin (0.076 cm) circular templates of decreasing diameter. A plot of work values vs. circle diameter is extrapolated to zero work to obtain the "maximum tress diameter." This parameter appears to be a measure of the bulk of hair assemblies. Dr. G. Blankenburg et al. (private communication) of the German Wool Research Institute has independently developed a similar method using this principle.

The Robbins and Crawford [73] method estimates the visual or volume component of hair body with some contribution from springiness or compressibility and resilience of the hair assembly. This measure of hair body shows that body increases with increasing amounts of hair, with increasing fiber curvature and with increasing inter-fiber friction.

Robbins and Crawford [73] examined hair of different curvatures by water setting Curl type II Caucasian hair in different configurations by curling hair tresses on glass rods and also by braiding hair tresses. They used the ratio of the coiled length of the hair to its extended length (Lc/Lt) as a measure of hair curvature. This ratio is the reciprocal of the natural to straight length described by Hardy [48] as a measure of hair curvature. As the number of braids increased the size of the braid pattern decreased providing a curlier-kinkier tress. The results showed that the larger number of smaller curls (curly to kinky hair) was more effective in producing hair body by this method than the larger curls.

Clarke, Robbins and Reich [72], questioned 150 panelists (Caucasian women and men) and found that only 15% of these consumers use the word stiff to describe hair body, but volume, bounce and thickness were used by 90 some percent of the panelists. This consumer research suggested that both visual and texture analysis are involved in hair body and that hair assembly volume is the primary factor in visual analysis by consumers.

To measure the visual component of hair body, Clarke et al. [72] evaluated four images of each tress by rotating the tress 90° for each image and comparing the results with images from a standard hair tress. Three types of hair were used, Asian, Caucasian and African American. All hair was made into tresses (1–6 g). The Asian and Caucasian hair was permanent waved to different degrees to provide a wide range of visually different tress volumes ranging from Curl type I to Curl type V. The initial results of measured tress volumes were compared with evaluations by panelists who visually estimated hair body.

The highly coiled African American hair (Curl type V) caused confusion among the Caucasian panelists, some judging these tresses to represent very little body while others rated them with very high body. Nevertheless, there was still a highly significant rank correlation (Rho = 0.865 and $p < 0.001$) between hair volume by image analysis and panelists visual rankings of hair body. However, when the data for the African American hair was excluded the correlation improved to Rho = 0.975 and $p < 0.001$. Unfortunately, a panel of African Americans was not assembled to determine if their perceptions would provide the same or a different result from that of the Caucasian panelists. Nevertheless, these experiments show that the volume component of hair body does increase with hair fiber curvature from Curl type I–IV when Caucasian perceptions are involved. Furthermore, the volume component of hair body increases with actual hair fiber curvature over the entire curvature scale.

Robbins [42] demonstrated that the cohesive effects of oils such as synthetic sebum have a "much greater impact" by substantially decreasing hair volume for wavy Curl type II hair than for high curvature Curl type V hair. The effect was relatively small for this curly type hair. From these experiments with cohesive oils on hair volume vs. curvature, Robbins concluded that at high curvatures the effect of fiber curvature on hair volume is dominant. It clearly has a greater impact than changes in other fiber properties such as cohesive forces, fiber friction or stiffness. Such dominance likely begins in Curl types IV and increases through curl Type VIII and is consistent with the C^2 hypothesis.

Dr. Hans Dietrich Weigmann (private communication) suggested from his work on compressibility and body of hair assemblies [68] that fiber curvature was the most important controlling property to their measurement of hair body. In addition, Dr. Mario Garcia (private communication) offered privately from his body method on hair compressibility and resiliency of tresses [70] that fiber curvature was clearly the most important fiber property to these important aspects of hair body. This work reinforces the hypothesis [6, 42] that at a high degree of curvature (curl type IV through VIII), curvature dominates most hair assembly properties, but at low curvatures it displays lesser effects.

10.7.3 Treatment Effects and Hair Body

Permanent waves and hair bleaches are known to increase hair body; however, the mechanisms of action of these products are different. Permanent waving increases hair body by increasing both fiber curvature and fiber friction [74, 75]. Both of these effects increase hair body (see Table 10.10). Bleaching hair does not increase hair fiber curvature, but it increases inter-fiber friction [75, 76].

On the other hand, creme rinses are purported to make curly to straight hair limp. Pomades are heavy leave-on oils that aid in combing and managing African type hair, but they do not make highly coiled African type hair limp. Limpness is the inverse of hair body. This effect is probably due to the fact that creme rinse ingredients decrease inter-fiber friction [74, 75]. Some crème rinses display mild cohesive effects too, especially on low curvature, fine hair.

Conditioner sets are an interesting category, because some of these products increase hair body. At the same time, conditioner sets make hair comb easier. Such effects probably arise because these products reduce high-load friction when the hair is being combed wet (or even when dry). Upon drying, some conditioner sets increase low-load friction and or adhesive forces between fibers. Certain hair sprays behave in this same manner. Increases to the “apparent” fiber diameter are also possible for conditioner sets and hair sprays when they are well distributed throughout the hair.

Shampoos vary in their effects on hair body. High-cleaning shampoos increase the body of dirty (greasy) hair by removing oily soils. These effects decrease cohesive forces between fibers and increase inter-fiber friction. On the other hand, continued use of conditioning shampoos can lead to limp hair by reducing inter-fiber friction and increasing cohesive effects between hairs. These effects are similar to the action of creme rinses. This limpness effect is greatest for straight, fine hair and least for very curly to kinky hair.

10.8 Relative Scalp Coverage or Hair Amount

Robbins and Dawson et al. [7] described the effects of diameter and hair density (hair counts) on age and proposed a new metric “relative scalp coverage” for the perception of the amount of hair. This parameter or modification of it may ultimately find use for quantitation of the perception of the onset or different stages of female pattern alopecia and male pattern alopecia.

When considering only diameter and density this metric is defined as a two dimensional parameter as the average fiber cross-sectional area times the number of hair fibers per square centimeter. In its simplest form, when considering only diameter and density for female Caucasians, relative scalp coverage peaks at about age 35 [7]. This peak age is produced because hair diameter increases until about age 45 but density peaks in the late twenties. So, when these two important contributors to scalp coverage are combined, they provide a maximum for relative scalp coverage for Caucasian females at age 35. The average age for relative scalp coverage for males would be lower, likely in the twenties, since hair diameter for males peaks at about twenty and hair density if it is similar to females peaks in the late twenties.

Robbins and Dawson et al. proposed that when other important fiber parameters are considered for relative scalp coverage, it will have to be considered as a multi dimensional system involving diameter, density, fiber curvature, fiber length, color (hair and scalp) and style and it can relate very much to a hair body metric. Since Mirmirami and Dawson [77] have shown scalp site produces different effects on diameter and density, scalp site will also have to be considered for a more complete model.

10.9 Style Retention

10.9.1 Style Retention Definition and its Relationship to Single Fiber Properties

Style retention may be defined as the ability of hair to stay in place after styling [1]. It is time-dependent and includes curl retention, wave retention, and straightness retention. Style retention may be described in terms of single-fiber properties or it may be treated as an assembly property. Style retention is most important to many hair products including permanent waves and hair sprays as well as to conditioner sets or wave sets, setting gels and to mousses.

When a hair fiber is thoroughly wet with water and allowed to dry it will gradually revert to its natural curvature. For example, a curly hair will assume a curly or coiled configuration, whereas a straight hair fiber will assume a straight configuration. This property of hair fibers to assume their natural curvature is central to the STAM method for curvature assignment [35, 78, 79]. If hair is wet with water and held and dried in a pattern different than its natural curvature it will tend to remain in that configuration until rewet or exposed to a different relative humidity. This type of action is the basis of water setting human hair.

Some heating devices such as blow dryers or hot air straighteners or curling devices are sometimes used to speed up the drying process and to facilitate styling by way of a water set. These devices provide only temporary effects because the primary bonds that help hold the hair in this type of water set configuration are hydrogen bonds and they can be broken by water or exposure to changes in humidity whereupon the hair fiber reverts to its natural curvature.

It has been known for years that exposing water set hair to higher humidity causes the hair to revert to its natural curvature and the water set decreases. Diaz et al. [80] demonstrated that exposure of a tress of water set hair to a lower humidity can also produce a loss of water set. Robbins and Reich [81] showed that water setting single hair fibers into a coiled configuration at 60% RH and then exposure to 10% RH produces a greater loss in style retention than similar single hairs water set and held at 60% RH. The use of single hairs in this experiment demonstrates that this effect is solely an effect of water on the curvature (internal bonding) of the hair fibers and does not involve inter-fiber friction. These results show that *changes in RH* are detrimental to water set in human hair fibers and it is not just exposure to higher humidity.

Therefore the transfer of water into (higher RH) or out (lower RH) of the hair fiber results in breaking hydrogen bonds that are involved in a water set and such an action produces a loss in the water set. As with other hair assembly properties, style retention can be dominated by hair fiber curvature [6, 42]. Confirmation of this conclusion is the fact if a person with high curvature hair (Curl type IV–VIII) wishes to wear a straight type hair style that type of style is difficult to achieve with a water set. However, if a person with straight hair, for example, Curl type I or II wishes to wear a curly hair style, to a limited degree, this can be done with a water set supplemented by hair sprays.

Table 10.11 How single fiber properties of hair relate to style retention [1]

Increase in these fiber properties produces a decrease in style retention	Increase in these fiber properties produces an increase in style retention
Curvature[a]	Friction (low load)
Stiffness	Cohesion
Weight[b]	Curvature[a]

[a]A curvature increase can increase or decrease style retention (see text)
[b]Only for curly to wavy hair styles. For straight styles increasing weight increases style retention

However, making the natural curvature consistent with the optimum curvature for the desired style is the best way to achieve these effects. There are permanent, semi-permanent and short term treatments to achieve this type of goal. For curly hair styles reductive permanent waves are semi-permanent treatments. With the proper size and shape curlers these treatments can provide coiled hair from relatively straight hair in a semi-permanent manner. Furthermore, a permanent wave provides better style retention for a highly coiled style from straight hair than by water setting because for such a style the most important property is hair fiber curvature. The same applies for providing a relatively straight hair style from highly coiled hair. Furthermore, providing for straight hair styles from highly coiled hair, the only permanent treatments are alkaline straighteners. The more important fiber properties that are related to style retention are curvature, friction, stiffness, cohesion, and weight [1, 2]. Table 10.11 suggests that increasing fiber stiffness and weight will decrease style retention. However, for straight hair styles, increasing weight improves style retention. The role of weight is straightforward; that of stiffness is more subtle. Hair fibers are generally water-set to produce an optimum curvature for the desired style. The desired style sometimes differs from the natural curvature of the hair. Changes in humidity promote deterioration of the water set and a gradual change toward the hair's natural curvature [81]. Only friction and cohesive forces tend to hold the assembly in the desired style preventing the hair from reverting to its natural curvature. The stiffer the fibers, the more readily they tend to overcome these frictional forces and the desired style. Thus, increasing fiber stiffness decreases style retention for water set hair.

The maximum fiber curvature consistent with the desired style will produce the optimum number of entanglements and the optimum fiber-fiber interactions and thus the maximum style retention. Generally, an increase in fiber curvature increases style retention. However, if the desired style is considerably straighter than the natural curvature, then a decrease in fiber curvature will be necessary to improve style retention (hair straighteners or relaxers). The converse holds for styles that are curlier than the natural curvature of the hair.

10.9.2 Methods Relevant to Style Retention

Most companies involved in hair products have developed their own procedures for evaluating curl or wave retention of hair assemblies (tresses, wigs, or heads).

Laboratory procedures also vary, depending on the type of product to be evaluated. Differences in application of hair sprays and permanent waves and the difference in performance characteristics require different procedures. The extent of quantitation may also vary. For example, Reed [82] described the evaluation of permanent-waving agents by simply treating tresses wound on curlers and qualitative evaluation of the hair for "curl strength" after removal from the curlers. Other, more quantitative approaches involve calculation of percent curl retention [83] or percent waving efficiency or measuring curl strength [84–86].

Basically, curl retention procedures involve treatment of a tress of known length, winding it on a mandrel or a rod or around pegs, and drying or conditioning it. After removing the hair from the rod, either length measurements vs. time (under controlled humidity) are taken to arrive at percent curl retention. Alternatively, the hair is placed on water and the change in elongation provides a means to obtain percent waving efficiency for cold wave lotions [84, 85].

The curl strength method of Stravrakas et al. [86] is an interesting option. This method involves treating hair, curling it on rods, conditioning it at high humidity. The researcher then determines the resistance to the deformation of curls and waves by the hair treatment using an Instron tensile tester or another strain gauge device. This method provides a large variance; however, it can distinguish between cold waves, hair sprays, and water-set hair.

For hair sprays or hair fixatives, several techniques have been described to evaluate curl-holding ability under conditions of controlled humidity [87, 88]. One novel approach [88] involves the rate of untwisting of tresses treated with the hair fixative. This method correlates with curl retention tests, yet it allows for faster evaluation of treatments.

Robbins [89] used a single fiber method for determining curl retention or straightening. This method offers advantages when used in conjunction with a fiber assembly method (tress method), since it eliminates fiber-fiber interactions from curvature and stiffness changes. It consists of uniformly winding a single hair fiber of known length onto a glass rod, treating it with water or product, and conditioning the hair at a controlled humidity (generally 50–65% RH). The fiber is then removed from the rod and conditioned at different RH's. Changes in length with time are measured with a cathetometer. See Chap. 4 for a discussion of some of the results with this method regarding water setting hair.

10.9.3 Style Retention and Hair Treatments

Permanent waving or relaxing of hair improve style retention when the degree of curl is made more consistent with the desired hair style. Obviously, the type and size of rollers (curlers) in permanent waving are important in determining the final result. The roller dimensions should be consistent with the curvature required by the desired hairstyle. Permanent waving increases inter-fiber friction [75] which also contributes to improve style retention, especially low load friction.

Bleaching increases inter-fiber friction [75, 76] which helps to improve style retention. Most conditioner or creme rinse ingredients [76], in contrast to bleaches, provide a decrease in inter-fiber friction. Except for some straight hair styles, many hair conditioners decrease style retention.

Conditioner sets, setting lotions, mousses, and hair sprays all increase low load inter-fiber attractive forces that help to improve style retention. These effects are greater than that of the weight increase by these ingredients which in some cases tend to decrease style retention.

Cleaning shampoos, when used on hair containing sebaceous soil, remove the surface oils and thereby reduce the cohesive bonding between fibers. These products thus provide an improvement in style retention for "dry look" hair styles. Certain conditioning shampoos provide a decrease in fiber friction and an increase in cohesive bonding. In that manner, they provide for a limp look and a decrease in style retention for many hair styles.

10.10 Hair Manageability

10.10.1 Hair Manageability Definition and Single Fiber Properties

As defined earlier, manageability is the ease of arranging hair in place and its temporary ability to stay in place; long-term effects on hair fiber assemblies are not considered for this property. Manageability is such an inclusive term that it cannot be measured by one single procedure.

As indicated earlier, Robbins et al. [4] concluded that three properties were strongly and significantly associated with manageability: easier combing, reducing static flyaway and keeping hair in place during styling operations. Garcia and Diaz [9] even earlier pointed out that "combability is closely associated with manageability" and Mills, Ester and Henkin [43] referred to the importance of static charge and flyaway hair to manageability.

Robbins et al. [4] found that manageability was perceived differently by different persons and by different hair types. They proposed that hair type and the desired hair style were critically important to the manageability properties expected by consumers. Furthermore, the "curvature of a hair type is obviously associated with the degree of curliness of a hair style and is perhaps the most important of these" three properties. They suggested that when the hair type, curvature, length and texture of the hair match the desired hair style, manageability problems are minimized. However, when the hair type does not match the desired hair style then manageability problems are maximized.

Since combing ease, flyaway hair and style retention (short term, i.e. during styling) are all components of hair manageability and because these three hair assembly properties are all dominated by curvature the logical conclusion is that fiber curvature dominates many manageability issues. For example, when curvature is high and it matches the desired hair style then manageability will be concerned primarily with combing or picking the hair to the desired style. In that situation, style retention concerns will be minimized, and flyaway hair will be of concern primarily for straight to wavy hair but not for very curly hair. However, when the curvature is low and a high curvature hair style is desired then style retention concerns will be higher. So, the further the natural curvature of the hair is from the optimum curvature of the desired style the greater the issues with style retention manageability. The closer the natural curvature is to the desired style the fewer issues with style retention and the more issues with combing/brushing/picking or with flyaway hair; however, flyaway hair is not an issue with high curvature hair such as Curl types IV–VIII, but becomes more of an issue as the natural curvature of the hair decreases.

Therefore to enable a quantitative approach to manageability, Robbins et al. [4] recommended considering this important cosmetic property in terms of its component assembly properties that can be readily visualized and measured. So, manageability is concerned with:

Arranging hair in place (combing/brushing),
Keeping hair in place (style retention during styling), and
Flyaway hair.

Therefore, the suggestion was made [4] to consider these three types of manageability to permit measurement and scientific evaluation, rather than the single elusive term manageability:

Style arrangement manageability (combing/brushing/picking),
Style retention manageability (style retention when styling), and
Flyaway hair manageability.

Existing tests to evaluate hair-combing ease, style retention, and flyaway hair or static charge may then be used to evaluate these different types of manageability. Furthermore, each type of manageability may be expressed in terms of a ratio of control/treatment values.

Using this approach, those single fiber properties defined in Table 10.11 that improve combing ease will also improve style arrangement manageability, while those properties of Table 10.11 that improve style retention will improve style retention manageability. Similarly, those parameters described in the previous section, which decrease static charge on hair, will improve flyaway hair manageability and thereby decrease static ballooning.

Therefore, increasing fiber curvature, static charge, or high-load friction will decrease style arrangement manageability. On the other hand, increasing low-load friction or cohesive forces between fibers will improve style retention manageability. This means that a change in fiber curvature can either increase or decrease style retention manageability. For example, if the treatment changes the curvature so that it is either too straight or too curly for the desired style, it will make the hair less manageable. However, if the treatment makes the hair curvature more consistent with the desired style, then that type of change will improve style retention manageability. Since fiber length is not changed by cosmetic treatments, length is not relevant for this type of analysis which considers changes by cosmetic treatments.

10.10.2 Treatment Effects and Hair Manageability

Since style arrangement manageability and style retention manageability often oppose each other, the decision as to whether a given effect will improve manageability for any particular person's hair depends on which of these two components of manageability is desired more. Since different persons will attach different values to the three different types of manageability, it is very difficult to predict overall manageability. Moreover, it is preferable to discuss each of the three types of manageability separately rather than to try to arrive at a composite for this important cosmetic property.

Permanent waving can increase style retention manageability when it provides an amount of fiber curvature that is more consistent with the desired hair style. Permanent waving also increases low-load friction, thus improving style retention manageability. Permanent waves are generally used to increase fiber curvature, thereby increasing the number of possible entanglements and decreasing style arrangement manageability. Increasing fiber friction also decreases style arrangement ease. Most satisfied users of permanent waves are more concerned with the staying in place component of style retention manageability. Therefore, they feel that after a permanent wave, their hair is more manageable. Those dissatisfied with the style arrangement manageability of a permanent wave can decrease fiber friction with a conditioner and thereby improve style arrangement manageability.

Most conditioner ingredients decrease high-load friction [50, 76], thus making the hair comb easier thereby improving style arrangement manageability. At the same time, quaternary conditioner ingredients decrease fiber chargeability. This latter effect, in combination with combing ease, decreases the propensity of the fibers to fly away and thus improves flyaway manageability. Most satisfied users of conditioners are more concerned with style arrangement and flyaway manageability than with style retention manageability. Therefore, they conclude that their hair is more manageable after using a conditioner. Pomades provide a decrease in high load friction and an increase in cohesive forces between fibers. Those satisfied users of pomades generally have high curvature hair and are satisfied with high curvature hair styles. Therefore, these consumers do not have concerns with style retention manageability, but are more concerned with style arrangement manageability which is delivered better with pomade products than with ordinary rinse-off hair conditioners.

Satisfied users of conditioner sets, setting lotions, pomades, and hair sprays are generally more concerned with style retention manageability. Therefore, the increase in inter-fiber cohesive forces from these products more than offsets any decrease in style arrangement manageability concerns.

High-cleaning shampoos remove sebaceous oils and decrease cohesive forces between the fibers, thereby making the hair more conducive to “dry look” hair styles. These products increase frictional forces relative to dirty hair. These effects aid style retention manageability for “dry look” styles. Satisfied users of these shampoos, who do not use other hair products, are generally more concerned with these factors (related to how hair stays in place) than with style arrangement manageability. Users of high-cleaning shampoos plus conditioners or high-conditioning shampoos are generally very concerned with improving style arrangement manageability and flyaway manageability for a “dry look” type of hair style.

10.11 Hair Handle or Feel

Tactile properties of hair fiber assemblies such as softness, smoothness and moisturization are important to advertising of hair products. But tactile properties provide difficulty in assessment in and between different laboratories. Boucsein et al. [90] described that the use of psycho-physiological techniques aided discrimination of sensory assessments. For example measurement of peripheral blood volume and facial muscular activity were found to be more sensitive and discriminating than ordinary sensory assessment to effects and interactions between emotional and technical responses to three different hair samples including two different shampoos and one untreated control.

Wortmann and Schwan-Jonczyk [91] working with a European Hair Products Group conducted a study to determine how single fiber and hair collective properties contribute to hair feel or handle. From a study on 4 hair types of European hair braids, the bending properties of single fibers interacting in the tress as a fiber collective and fiber friction were found to be the most important fiber properties related to handle. Single fiber friction was determined by a capstan method on root, middle and tip sections of hairs. Significant differences between hair types were found for diameters, ellipticity, bending stiffness and friction. Handle or feel was perceived as inferior when the hair was coarse and the bending stiffness was high. Friction was also important to feel especially in the tip regions of the hair. Hair perceived as fine was soft and friction appeared to play less of a role than in hair perceived as coarse.

Kawasoe et al. [92] added to these findings by showing that an increase in hair fiber friction produces the perception of a more coarse texture for hair. Alteration of the hair surface by damaging treatments generally produces an increase in hair fiber friction resulting in what is perceived as a more coarse texture for hair. Kawasoe et al. determined that hair damage is perceived as a more irregular or more varied scale pattern (as opposed to uniform but different scale heights and widths). This conclusion came from having consumers feel simulated cuticle structures on an artificial hair surface of engraved images of different scale patterns on polyimide plates. A highly varied or irregular scale pattern produced what is perceived as a coarse texture for hair.

This conclusion is related to results of unpublished work where we bleached hair to different extents and had blindfolded female panelists evaluate hair tresses. The hair was rated for coarseness and tested for friction. The greater the degree of bleach damage, the higher the friction and the more coarse the ratings.

We know that African type hair is elliptical, highly coiled, and larger in diameter than Caucasian hair. It is also generally perceived and described as coarse hair. Asian hair on the other hand is the largest in diameter of the three major geo-racial groups and it is the least coiled, the most circular and is usually characterized as straight and coarse. However, quantitative studies by Nagase et al. [3] on the curvature of hair fibers from 230 Japanese women showed that about 53% of Japanese women have straight hair and 47% have hair that varies from slightly wavy to what is perceived as frizzy. As indicated earlier, the peak in the distribution for curvature was at Curl type II and extended to Curl type IV on the STAM curvature scale. Frizzy Japanese hair is distinguished from curly hair by neighboring hairs not being parallel or synchronized [3].

These scientists concluded that there should be a positive correlation between hair fiber curvature and the perception of coarse hair, a reasonable conclusion. However, I could not find data in the literature to either support or deny this conclusion. This is an area that requires additional research.

10.12 How Consumer Hair Assembly Properties Change with Age

Considering one variable at a time, it is easy to qualitatively predict the changes in Consumer Hair Assembly Properties (CHAP) with respect to age; however, unfortunately changes in hair properties with age do not happen one variable at a time. In this section, we will discuss different stages of life considering the aggregate and/or individual changes in hair fiber properties and how these affect the CHAP in terms of the following five stages in the life of hair fibers:

Infancy to childhood: approximately the first year of life.
Childhood to puberty: about age 1–12.
Puberty to young adult: about age 13–30.
Young adult to middle age: about 31–45.
Middle age to and including advanced age: approximately 45 and upward.

10.12.1 Infancy to Childhood: Approximately the First Year of Life

Infants hair is very fine [93–95] (about 30 μm in diameter for infants, about 60 μm for children and somewhat larger but highly variable for adult Caucasians). These average fiber diameters tell us that the time-span of anagen (growth period) for infants' hair is shortest compared with children or adults until about age 20 (for males) and middle to advanced age (about 45 for females) when anagen starts to become shorter once again. Infants' hair was found to be less elliptical (1.26 vs. about 1.37) in one study of Caucasian infants vs. children's hair and about 1.38 for adult Caucasians. So, the hair of infant Caucasians is more round than children's [93] or adults hair.

The fine hair of infants is lost by about the seventh month and is replaced by a coarser and longer hair which is generally replaced by an even coarser hair at about 2–3 years of age [95]. The loss of hair tends to be randomly dispersed over the scalp; however, during infancy, Pecoraro et al. [94] suggested that the initial hair loss may occur in waves. Infants' hair grows to only about 15 cm long compared with the final stage of children's hair that can grow to about 60 cm and adults hair can grow even longer to about 100 cm see Chap. 1.

Hair lipids are produced by two sources, the sebaceous glands, located in each hair follicle and the hair matrix cells that produce the growing hair fiber. The cholesterol level of forehead skin is low at birth, but it reaches a maximum at about age 6. It then declines to near adult levels by age 9 [96]. Cholesterol is produced primarily by the hair matrix cells and since sebum production is low in infants and children, the cholesterol level in human hair fibers is high during infancy and childhood when sebaceous lipids are low. Therefore, fine hair of Caucasian children tends to provide low hair body and is generally easy to comb unless it is curly.

I could not find data on hair density of infants, but sources state that follicle density is highest in the fetus and it decreases with increasing skin surface accompanying growth of the head. Estimates of the scalp surface area of adults are about 350–400 cm^2, while that of infants at birth would be approximately 200–225 cm^2. These scalp areas are approximate dimensions of the head of infants vs. adults calculated from head dimensions found in the Merck Manuals Online Medical Library [97]. Assuming a follicle density of about 321 follicles/cm^2 for Caucasian adults [98] and assuming the only change is the surface area of skin by growth, provides a scalp follicle density for Caucasians of 565/cm^2 at birth. Based on data by Sperling [98] for African Americans the follicle densities would be lower for that group and even lower for Asians from data by Tajima et al. [99].

10.12.2 Childhood to Puberty: Approximately Age 1–12

During childhood, scalp hair fiber diameter nearly doubles and the maximum length that the hair can grow to increases nearly fourfold from infancy to the first few years of childhood. However, fiber ellipticity increases only a small amount in Caucasians from infancy to childhood [93]. This ellipticity effect is likely not meaningful in terms of CHAP. I could find no literature on the hair curvature changes during this time period. There may be changes in hair color during this time period.

The large increase in hair fiber diameter from infancy will increase tensile and bending stiffness but torsional resistance of hair fibers will decrease. Unless there is a noticeable increase in hair fiber curvature, the stiffness increase will add body to the hair, making it fuller. The stiffness factor alone will tend to make the hair comb easier. The hair fiber diameter and length increases are due to longer anagen periods and are clearly the most important changes (unless there is a large curvature change) in terms of hair body, style retention, etc.

Hair tends to be relatively dry during childhood because of the low sebaceous output [100, 101] with the composition of the hair lipids being high in cholesterol [102] and its esters while the percentages of squalene [102] and fatty acids [103] are lower than in the hair of teenagers or adults.

10.12.3 Puberty to Young Adult: Approximately Age 12–30

During this stage there is approximately a 25% increase in scalp hair diameter and an increase of about 60% in the maximum length that the scalp hair fiber can achieve. The anagen period is frequently as long as 6 years during this phase of life compared to about 2–4 years in the previous stage. The diameter increase for males tends to peak near the late teenage years, however, for females it continues through this stage and into the next. Once again the most important missing information in terms of hair behavior is the lack of data on changes in hair fiber curvature. Nevertheless, an increase in curvature of the hair of Japanese females has been shown to occur from age 10 to 70 [104], but it appears to be a small and gradual increase that appears to be a bit larger in advanced years. However, we cannot even speculate as to whether this effect is sufficient to affect the CHAP, therefore this is a major gap in the hair fiber literature. I would expect a similar change in Caucasians hair too, although there is currently no evidence to support this conclusion at this time.

The beginnings of male pattern alopecia (MPA) can initiate during the middle part of this stage (about ages 19 or 20) for some Caucasian males, but it is normally a few years later for some Asians [105] and those of African descent, see Chap. 1. Female pattern alopecia (FPA) can initiate during the last part (late 20s) of this period (see Chap. 1 and references [108, 109]) and it tends to begin earlier for Caucasians than for Asians. Both of these conditions produce a decrease in the hair density (hair counts), but in spite of the decrease in hair density the average hair diameters continue to increase for females, but decreases for males during this stage [108–110]. By about age 30, MPA affects about 25% of Caucasian males see Chap. 1 and reference [105], but only about 5% of Asian males and most of those Asians are in the early stages of MPA.

During this stage, FPA affects only about 8% of Caucasian women, but it affects virtually no Asian women as shown by Norwood [106] and Birch et al. [107] for Caucasians and Chap. 1 for Caucasians and Asians. FPA occurs more in the top central part of the scalp and is more diffuse than MPA which initiates and tends to concentrate more in the frontal and crown areas. The increase in hair fiber diameter during this stage will increase tensile and bending stiffness, but it will decrease torsional resistance of hair fibers. These diameter and stiffness changes will tend to increase hair body and to make the hair comb easier [2].

There is a noticeable increase in hair greasiness for most persons during this stage [100, 101]. The greasiness effect is caused by both an increase in the amount and the composition of hair lipids. For example, the sebaceous lipids including squalene [102] and most fatty acids [103] and wax esters [101] increase in the hair while those lipids that are produced in the matrix cells in the hair follicle including cholesterol [102] and its esters decrease on and in the fiber.

These lipid changes (alone) at the hair surface tend to decrease hair body and require more frequent shampooing to improve the overall appearance of the hair in terms of hair matting and luster. For those with little or no MPA or FPA, the effects of hair diameter, stiffness and surface lipid deposits are the most important changes that occur during the first few years of this stage. This conclusion assumes that there are no changes in hair fiber curvature during this stage. Increases in hair fiber diameter and stiffness will tend to increase hair body and combing ease. For those with noticeable MPA or FPA, regional changes in hair density and fiber diameter especially during the latter part of this stage will tend to decrease hair body and combing forces.

The graying process initiates for some especially during the last decade of this period. Therefore, hair color can change during the last 10 years of this period. A few gray hairs are noticed at about age 21–22 for dark haired Caucasians, at about age 25 for Caucasians with medium colored hair and at about age 26 for fair haired Caucasians. By the age of 30 about one fourth of all Caucasians will have a small amount of gray hairs [111, 112], while about 20% of Asians and 15% of African descent will have begun graying [113].

10.12.4 Young Adult to Middle Age: Approximately 31–45

Hair density per unit area tends to gradually decrease during this stage [7, 77, 107] even for those with no noticeable MPA or FPA. This decrease in hair density should be more rapid and more scalp-region specific for MPA than for FPA and it occurs at a faster rate in the frontal and crown sites for males. Nevertheless this effect is still region specificity with regard to hair count decreases with age for women [77] and most likely for men too.

At the beginning of this period, only about 8% of female Caucasians have clinically observable hair loss, but at the end of this time period that number nearly doubles [106, 107]. The average hair density decrease for women not suffering from FPA is about 26 hair fibers/cm^2 per decade or approximately 15% hair loss during this period which is generally not detectable. Data from Birch et al. [107] on two groups of women one group concerned about FPA and the other group not concerned with FPA suggests that a 30% hair density decrease is borderline detectable. Therefore, it would appear that the hair loss in FPA must be about two times this rate of hair loss over this same time period for some persons to be concerned about FPA. This effect is likely due to the increase in hair diameter during this stage for women.

The subjective impression of alopecia among females is multi-factorial involving hair density, hair fiber diameter and the often overlooked property of fiber curvature. A 25–30% decrease in hair density is borderline detectable. If most of the fibers are fine and straight the hair loss will likely be more noticeable than if the fibers are coarse and curly. The use of the new metric for relative hair coverage by Robbins and Dawson et al. [7] should become useful in improving our understanding of the perception of alopecia.

At the beginning of this life period our data suggest that about one-fourth of Caucasian men have Type II–VII (see Chap. 1, Table 1.5 and Fig. 1.12) hair loss, while only about 6% have Type V–VII (see Chap. 1, Table 1.5 and Fig. 1.12) hair loss. At the end of this stage about 46% of Caucasian men have Type III–VII hair loss and about 14% have type V–VII hair loss see Chap. 1 and references [107, 114–116]. On the other hand, less than 5% of Asian men have Type III–VII hair loss at the beginning of this period and about 12% have this same amount of hair loss at the end of this stage [115, 116]. I could not find data for those of African descent.

Approximately 5% of all Caucasians will be totally gray at the end of this period while virtually no Asians or those of African descent will be totally gray during this stage [111, 112]. A little more than three fourth of all Caucasians, about two-third of all Asians and by deduction about ½ of African descent will have some gray hair by the end of this period [111–113].

According to our sources on hair diameters vs. age, for females diameters gradually increase up to the end of this stage [108–110], but for males diameters continue to decrease [110]. Based on graphical data of smaller numbers of Caucasians [108, 109] I assume that a similar effect occurs for Caucasians and likely for those of African descent; however, I could not find sufficient data to estimate quantitatively the extent of those changes for these geo-racial groups.

The decrease in hair fiber diameter from the late teenage years upward for males will decrease tensile and bending stiffness but increase torsional resistance of hairs, while the continued increase in diameter for females will increase tensile and bending stiffness. Males will also suffer larger regional decreases in hair density/unit area and therefore will suffer a greater loss in hair coverage and hair volume and other evaluations of hair body from the diametric decrease. It is unfortunate that we know so little about hair fiber curvature changes with respect to age, however, there is one study that shows that the hair of Japanese women increases in curvature from age 10 through 70. However, there is no data for Caucasians or Asians on hair curvature vs. age. Lipid levels do not appear to change to a large degree for most Caucasians during this stage [100, 101].

10.12.5 Middle Age to and Including Advanced Age: Approximately 45 and Up

The primary effects of a decrease in hair density and in fiber diameter over multiple regions of the scalp in MPA will continue from the previous stage [117] and will worsen during this stage. The percentage of male Caucasians suffering from MPA increases during this time period from about 46% to about 70% see Chap. 1 and reference [105]. Related effects will occur with those suffering from FPA during this stage because both hair density and diameter decrease during this stage. The incidence of FPA in Caucasians is approximately 16% of women at the beginning of this stage and that percentage will double by age 75 see Chap. 1 and these references [106, 107].

Graying will further increase during this stage. Approximately 21% of Caucasians will go from little gray to moderate gray and about 35–40% more Caucasians will become totally gray during this time period see Chap. 1 and these two references [111, 112]. Using the Tobin and Paus approximation [116]; approximately 15% Asians and 10% of African descent will go from little gray to moderate gray, about 30% Asians will become totally gray and about 25% of African descent will go totally gray during this time period.

Major effects occur during and a few years prior to Menopause to the scalp hair of women including lower frontal scalp hair density [77] (on the frontal but not occipital scalp), lower growth rates [77], lower hair fiber diameters [77] and changes in the composition of hair lipids on and in the fibers [100–102, 118]. Lower total sebum in post-menopausal women vs. pre-menopausal women also occurs [100, 101].

These changes in hair effects translate collectively into lower hair greasiness and less softness and smoothness for post-menopausal women [118], and although there is a decline in lipid levels for males it is substantially less than for females [100, 101]. The hair of post-menopausal women has also been shown to be less shiny than the hair of pre-menopausal women [118]. Whether this decrease in hair shine is due to a decrease in fiber alignment from an increase in hair fiber curvature as occurs with age in the hair of Japanese women [104] or to another factor is not known. I would expect an increase in fiber curvature would also produce less synchronized waves or curl patterns with the end result being an increase in hair frizziness [104].

For males, the major effect during this stage appears to be a decrease both in hair fiber diameter and density. We know that this effect occurs in all geo-racial populations, but the relative quantitative effects need to be determined. The decrease in hair fiber diameter will decrease tensile and bending stiffness and increase torsional resistance of hair fibers. The effects on fiber diameter in combination with hair density produces a decrease in relative hair coverage in the frontal, parietal and crown areas of Caucasians and should produce changes in important consumer assessments such as a decrease in hair body and a reduction in combing forces which should be more apparent for men than for women.

For women the regional decreases in fiber diameter and hair density is generally less than for men, however there can be a meaningful decrease in hair density for women in the frontal and top central region of the scalp. In addition, the decrease in hair greasiness that would appear after a day or two or longer will tend to partly offset the decrease in hair body from a decrease in fiber diameter and stiffness for women except for the everyday shampooer. I would anticipate related effects on combing ease, that is, the decrease in stiffness will tend to make the hair more difficult to comb [2]; however the decrease in hair density will tend to make the hair comb easier. I would guess that the hair density effect would be larger, however which effect is stronger is too difficult to say without additional data.

References

1. Robbins CR, Scott GV (1978) Prediction of hair assembly characteristics from single fiber properties. J Soc Cosmet Chem 29:783–792
2. Robbins CR, Reich C (1986) Prediction of hair assembly characteristics from single fiber properties. Part II: the relationship of fiber curvature, friction, stiffness and diameter to combing behavior. J Soc Cosmet Chem 37:141–158
3. Nagase S et al (2008) Characterization of curved hair of Japanese women with reference to internal structures and amino acid composition. J Cosmet Sci 59:317–332
4. Robbins CR, Clarke J, Reich C (1986) Hair manageability. J Soc Cosmet Chem 37:489–500
5. Davis M, Stofel SW (2009) Measurement of hair moisture content utilizing novel analytical and real time techniques. J Cosmet Sci 60:80–81
6. Robbins CR (1988) Chemical & physical behavior of human hair, 2nd edn. Springer, Berlin, pp 251–265, 3rd and 4th Edition also
7. Robbins CR, Dawson TL et al What women want—a new more perception relevant model of scalp hair, hair amount. Variation in scalp hair diameter and density with age in Caucasian women. Br J Dermatol, in press
8. Epps J, Wolfram LJ (1983) Letter to the editor. J Soc Cosmet Chem 34:213–214
9. Garcia M, Diaz J (1976) Combability measurements on human hair. J Soc Cosmet Chem 27:379–398
10. Newman W et al (1973) A quantitative characterization of combing force. J Soc Cosmet Chem 24:773–782
11. Waggoner W, Scott GV (1966) Instrumental method for the determination of hair raspiness. J Soc Cosmet Chem 17:171–179
12. Kamath YK, Weigmann H-D (1986) Measurement of combing forces. J Soc Cosmet Chem 37:111–124
13. Lunn A, Evans R (1977) The electrostatic properties of human hair. J Soc Cosmet Chem 28:549–569
14. Jachowicz J et al (1985) Relationship between triboelectric charging and surface modifications of human hair. J Soc Cosmet Chem 36:189–212
15. Kamath YK, Robbins CR Hair breakage by combing and brushing—A comment on the paper. In: Evans TA, Park K (eds) A statistical analysis of hair breakage–II. J Cosmet Sci (in press)
16. Cooper N, Short J, Szodwiski J, Turek B (1986). In: Proceedings of the 14th congress international federal social cosmetics chemistry, vol 2, Barcelona, p 1125
17. Robbins C (2002) Chemical & physical behavior of human hair, 4th edn. Springer, New York, pp 445–446

18. Leroy F et al (1995) Poster presented at the 1st Transcontinental meeting of hair research society, Brussels, Oct 8–10 1995
19. Robbins C (2006) Hair breakage during combing. II. Impact loading and hair breakage. J Cosmet Sci 57:245–257
20. Swift JA et al (2001) Flexabrasion-a method for evaluating hair strength. Cosmet Toiletries 116(12):53–60
21. Hamburger W, Morgan HM, Platt MM (1950) Some aspects of the mechanical behavior of hair. Proc Sci Sect TGA 14:10–16
22. Berthiaume MD, Riccio DA, Merrifield JH (1994) Silicone based products for damaged hair in various ethnic groups. Drug Cosmet Ind 155(6):24–32
23. Kamath Y, Weigmann H-D (1982) Fractography of human hair. J Appl Poly Sci 27:3809–3833
24. Kamath Y, Hornby S, Weigmann H-D (1984) Mechanical and fractographic behavior of Negroid hair. J Soc Cosmet Chem 35:21–43
25. Robbins C (1979) Chemical and physical behavior of human hair, 1st edn. Van Nostrand Reinhold Co., New York, NY, pp 155–156
26. Robbins C (2006) Hair breakage during combing. I: pathways of breakage. J Cosmet Sci 57:233–243
27. Robbins CR, Kamath YK (2007) Hair breakage during combing. III: the effects of bleaching and conditioning on short and long segment breakage by wet and dry combing of tresses. J Cosmet Sci 58:477–484
28. Robbins CR, Kamath YK (2007) Hair breakage during combing. IV: brushing and combing of hair. J Cosmet Sci 58:629–636
29. Brown C, Swift JA (1975) Hair breakage: the scanning electron microscope as a diagnostic tool. J Soc Cosmet Chem 26:289–297
30. Swift JA (1999) The mechanics of fracture of human hair. Int J Cosmet Sci 21:227–239
31. Khumalo NP et al (2000) What is normal black African hair? a light and scanning electron microscopic study. J Am Acad Dermatol 43:814–820
32. Pande CM, Albrecht L, Yang B (2001) Hair photoprotection by dyes. J Cosmet Sci 52:377–390
33. Kamath YK, Hornby S, Weigmann H-D (1985) Effect of chemical and humectants treatments on the mechanical and fractographic behavior of Negroid hair. J Soc Cosmet Chem 36:39–52
34. Beyak R et al (1971) Elasticity and tensile properties of human hair. II: light radiation effects. J Soc Cosmet Chem 22:667–678
35. Porter C et al (2009) The behavior of hair from different countries. J Cosmet Sci 60:97–109
36. Hough PS, Huey JE, Tolgyesi WS (1976) Hair body. J Soc Cosmet Chem 27:571–578
37. Evans TA, Park K (2010) A statistical analysis of hair breakage. II. Repeated grooming experiments. J Cosmet Sci 61:439–456
38. Robbins C (2009) The cell membrane complex: three related but different cellular cohesion components of mammalian hair fibers. J Cosmet Sci 60:437–465
39. Swift JA (1997) Mechanism of split end formation in human head hair. J Soc Cosmet Chem 48:123–126
40. Zimmerman M, Hocker H (1996) Typical fracture appearance of broken wool fibers after simulated sunlight irradiation. Text Res J 66:657–666
41. Morton W, Hearle JWS (1962) Physical properties of textile fibers, vol Ch. 21. Butterworths, London
42. Robbins CR The importance of single fiber properties for hair assembly behavior. In: Human hair/cosmetic interactions: fundamentals and methodology, study book and lectures, TRI/Princeton, Continuing Professional Education (1997 to 2007)
43. Mills C, Ester VC, Henkin H (1956) Measurement of static charge on hair. J Soc Cosmet Chem 7:466–475
44. Barber R, Posner A (1959) A method for studying the static electricity produced on hair by combing. J Soc Cosmet Chem 10:236–246

45. Meredith R, Hearle JWS (1959) Physical methods of investigating textiles, vol Ch. 13.3. Interscience, New York
46. Hersh S (1954) Static electrification of fibrous materials. Ph.D. Thesis, Princeton University, Princeton, NJ
47. Henry PSH (1953) The role of asymmetric rubbing in the generation of static electricity. Br J Appl Phys 4(2):S31–S35
48. Hersh S, Montgomery D (1955) Static electrification of filaments: experimental techniques and results. Text Res J 25:279–295
49. Alexander P et al (1963) Wool, its chemistry and physics, 2nd edn. Franklin Publishing Co., New Jersey, pp 25–46
50. Cunningham R, Montgomery D (1958) Studies in the static electrification of filaments. Tex Res J 28:971–979
51. Martin AJP (1944) Observations on the theory of felting. J Soc Dyers Col 60:325–328
52. Ward T, Benerito R (1965) Correlation of visual luster with measured reflectance of cotton fabrics. Text Res J 35:271–279
53. Fourt L (1966) Scale angles for wool and mohair. Text Res J 36:915–924
54. Thompson W, Mills CM (1951) An instrument for measuring the luster of hair. Proc Sci Sect TGA 15:12–15
55. Stamm RF et al (1977) The optical properties of human hair. I: fundamental considerations and goniophotometer curves. J Soc Cosmet Chem 28:571–599
56. Conover WJ (1980) Practical nonparametric statistics. Wiley, New York, pp 299–308
57. Rennie JHS, Bedford SE, Hague JD (1997) A model for the shine of hair arrays. Int J Cosmet Sci 19:131–140
58. Reich C, Robbins C (1993) Light scattering and shine measurements of human hair: a sensitive probe of the hair surface. J Soc Cosmet Chem 44:221–234
59. Keis K, Ramaprasad ER, Kamath YK (2004) Studies of light scattering from ethnic hair fibers. J Cosmet Sci 55:49–63
60. McMullen R, Jachowicz J (2004) Optical properties of hair—detailed examination of specular reflection patterns in various hair types. J Cosmet Sci 55:29–47
61. Keis K, Ramaprasad ER, Kamath YK (2004) Effects of hair color on luster. J Cosmet Sci 55:423–436
62. Nagase S et al (2002) Influence of internal structures of hair fibers on hair appearance. I: light scattering from the porous structure of the medulla of human hair. J Cosmet Sci 53:89–100
63. Musso LA (1970) Pili annulati. Aust J Derm 11:67–75
64. Harris M (1954) Handbook of textile fibers, 1st edn. Harris Research Labs, Washington, DC
65. Modern Beauty Shop Magazine (December 1957)
66. Yin N et al (1977) The effect of fiber diameter on the cosmetic aspects of hair. J Soc Cosmet Chem 28:139–150
67. Gao T, Bedell A (2001) Ultraviolet damage on natural gray hair and its photoprotection. J Cosmet Sci 52:103–118
68. Studies of the modification of human hair properties by surface treatments, phase II—hair assembly behavior. Progress Report No. 7, Textile Research Institute, Princeton, NJ (March 15, 1978)
69. Robbins CR (1979) Chemical and physical behavior of human hair, 1st edn. Van Nostrand Reinhold Co., New York, NY, p 199
70. Garcia ML, Wolfram LJ (1978) 10th IFSCC congress. Sydney, Australia
71. Wedderburn DL, Prall JK (1973) Hair product evaluation from bench to consumer and back again. J Soc Cosmet Chem 24:561–576
72. Clarke J, Robbins CR, Reich C (1991) Influence of hair volume and texture on hair body of tresses. J Soc Cosmet Chem 42:341–350
73. Robbins C, Crawford RJ (1984) A method to evaluate hair body. J Soc Cosmet Chem 35:369–377
74. Robbins CR (1984) 3rd International hair science symposium of DWI, Syburg, Germany (1984) and described in detail at TRI/Princeton, Continuing Professional Education in Lectures and in the Course Book from 1997 to 2006

75. Schwartz A, Knowles D (1963) Frictional effects in human hair. J Soc Cosmet Chem 14:455–463
76. Scott GV, Robbins CR (1980) Effects of surfactant solutions on hair fiber friction. J Soc Cosmet Chem 31:179–200
77. Mirmirani P, Dawson TL Jr et al (2010) Hair growth parameters in pre- and post-menopausal women. In: Treub R, Tobin D (eds) Hair aging. Springer-Verlag, Berlin
78. De La Mettrie R et al (2006) Shape variability and classification of human hair: a worldwide approach. Hum Biol 79(3):265–281
79. Loussouarn G et al (2007) Worldwide diversity of hair curliness: a new method of assessment. Int J Dermatol 46(suppl 1):2–6
80. Diaz P (1984) 4th International hair science symposium, Syburg, Germany
81. Robbins CR, Reich C (1998) Chemical and physical behavior of human hair, 2nd edn. Springer Verlag, Berlin, pp 89–91
82. Reed RE (1956) A new home permanent waving process. J Soc Cosmet Chem 7:475–480
83. Scott GV (1967) Colgate palmolive curl retention methods
84. Cortekar HW, Oberkobusch D (2000) US Patent 6,146,619 Process and agents for permanently shaping keratin fibers
85. Cortekar HW (2000) Process and agents for permanently shaping keratin fibers. US Patent 6,146,619
86. Stavrakas EJ et al (1959) Determination of curl strength of tresses treated with water, hair spray and waving lotion. Proc Sci Sect TGA 31:36
87. Ganslow S, Koehler FT (1978) Evaluation of hair fixatives—a new technique utilizing torsional measurements. J Soc Cosmet Chem 29:65–78
88. Reed AB Jr, Bronfein I (1964) Curl retention with hair sprays. Drug Cosmet Ind 94:178
89. Robbins CR (1983) Load elongation of single hair fiber coils. J Soc Cosmet Chem 34:227–239
90. Boucsein W et al (2002) Objective emotional assessment of tactile hair properties and their modulation by different product worlds. Int J Cosmet Sci 24:135–150
91. Wortmann F-J, Schwan-Jonczyk A (2006) Investigating hair properties relevant for hair handle. Part I: hair diameter, bending and frictional properties. Int J Cosmet Sci 28:61–68
92. Kawasoe T et al (2008) Tribiology in the hair surface and tactile properties. Tribiol Online 3(2):127–130
93. Trotter M, Duggins OH (1930) Age changes in head hair from birth to maturity: index and size of hair of children. Am J Phys Anthropol 6:489–506
94. Pecoraro V et al (1964) Cycle of the scalp hair of the new born child. J Invest Dermatol 43:145–147
95. Furdon SA, Clark DA (2003) Scalp hair characteristics in the newborn infant. Adv Neonatal Care 3(6):286–296
96. Ramastastry P et al (1970) Chemical composition of human skin surface lipids from birth to puberty. J Invest Dermatol 54:139–144
97. The Merck Manuals Online Medical Library, www.merck.com.mmpe/sec19/ch269/ch269b.html#
98. Sperling LC (1999) Hair density in African-Americans. Arch Dermatol 135:656–658
99. Tajima M et al (2007) Characteristic features of Japanese women's hair with aging and with progressing hair loss. J Dermatol Sci 45:93–103
100. Pochi PE, Strauss JS (1974) Endochrinologic control of the development and activity of the human sebaceous gland. J Invest Dermatol 62:191–201
101. Pochi PE, Strauss JS, Downing DT (1979) Age related changes in sebaceous gland activity. J Invest Dermatol 73:108–111
102. Nicolaides N, Rothman S (1952) Studies on the chemical composition of human hair fat. I. The squalene-cholesterol relationship in children and adults. J Invest Dermatol 19:389–391
103. Nicolaides N, Rothman S (1953) Studies on the chemical composition of human hair fat. II. The overall composition with regard to age, sex and race. J Invest Dermatol 21:9–14

104. Nagase S et al (2009) Changes in structure and geometric properties of human hair by aging. J Cosmet Sci 60:637–648
105. Norwood OT (1975) Male pattern baldness: classification and incidence. Southern Med J 68(11):1359–1365
106. Norwood OT (2001) Incidence of female androgenetic alopecia (female pattern alopecia). Dermatol Surg 27:53–54
107. Birch MP, Messenger JF, Messenger AG (2001) Hair density, hair diameter and the prevalence of female pattern hair loss. Br J Dermatol 144:297–304
108. Trotter M (1930) The form and color of head hair in American whites. Am J Phys Anthropol 14:433–445
109. Trotter M, Dawson HL (1934) The hair of French Canadians. Am J Phys Anthropol 18:443–456
110. Otsuka H, Nemoto T (1988) Study on Japanese hair, Koshokaishi. J Cosmet Assoc Japan 12:192–197
111. Keogh EV, Walsh RJ (1965) Rate of graying of human hair. Nature 207:877–880
112. Schnohr P et al (1995) Gray hair, baldness and wrinkles in relation to myocardial infarction: the Copenhagen city heart study. Am Heart J 130:1003–1010
113. Tobin DJ, Paus R (2001) Graying: gerontobiology of the hair follicle pigmentary unit. Exp Gerontol 36:29–54
114. Hamilton JB (1951) Pattern loss of hair in man: types and incidence. NY Acad Sci 53:708–728
115. Paik JH et al (2001) The prevalence and types of androgenetic alopecia in Korean men and women. Br J Dermatol 145:95–99
116. Xu F et al (2009) Prevalence and types of androgenetic alopecia in shanghai, china: a community based study. Br J Dermatol 160:629–632
117. Courtois M et al (1995) Aging and hair cycles. Br J Derm 132:86–93
118. Wills T et al (2004) Free internal lipids in hair from pre- and post-menopausal women. IFSCC Mag 7(4):293–297