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# Human hair: A unique physicochemical composite

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All hair is ethnic. Categorizing diverse hair types into 3 major groups—African, Asian, and Caucasian—makes it easier to recognize characteristics specific to each hair type, such as curliness, color, and cross-sectional parameters. All hair, however, regardless of its ethnic origin, exhibits common characteristics of morphology, chemical makeup, and molecular structure. This article provides a brief review of the salient elements of hair structure, chemistry, and the fundamental interplay that contributes to the properties of the hair fiber and its response to treatments. (*J Am Acad Dermatol* 2003;48:S106-14.)

**H**air follicles, tens of thousands of which are deeply invaginated in the scalp tissue, are the essential growth structures of hair. At the base of each follicle, cells proliferate, and as they stream upward, the complex and intertwined processes of protein synthesis, structural alignment, and keratinization transform the cytoplasm into the fibrous material known as hair. The development of hair is a dynamic, cyclic process in which the duration of growth cycles depends not only on where the hair is growing but also on such issues as the individual's age, nutritional habits, and hormonal factors.

In the scalp, each hair grows steadily, approximately 1 cm per month, and continuously for 3 to 5 years (anagen phase). Growth then stops and is followed by a brief transient stage (catagen) and a 2- to 4-month resting stage (telogen), during which old hair is shed. With the onset of the anagen stage, new hair starts to grow from the same follicle. The growth process functions independently in each follicle; therefore, hairs are not shed simultaneously as they are in many animals. At any given time, some hairs are growing, some are resting, and some are being shed. Normally, of approximately 150,000 scalp hairs, 90% are in the anagen phase, and the remaining 10% are in the catagen and telogen phases, with 50 to 100 hairs being shed daily.

Scalp hair is a fiber 60 to 80  $\mu\text{m}$  in diameter, and its exterior consists of a layer of flat, imbricated scales pointing outward from root to tip. Enveloped

by the protective layers of the cuticle is the fibrous hair cortex, which constitutes the bulk of the fiber (Fig 1). During the process of keratinization, the plasma membranes of cortical cells are modified and form a strongly adhesive layer between the adjacent cells, known as the cell membrane complex (CMC). This is the only continuous phase in the hair fiber, fusing the cortical cells and providing adhesion to cuticle cells. Dispersed throughout the structure of the cortex are the melanin pigment particles. The number, chemical characteristics, and distribution pattern of these cells determine the color of the hair. In many (but not all) hairs, vacuolated medulla cells are present in the central region of the fiber.

## THE CUTICLE

In fully formed hair, the cuticle cells are in the form of flat, square sheets 0.5  $\mu\text{m}$  thick and 50  $\mu\text{m}$  in length. Their proximal portions are firmly attached to the cortex, and the distal free edges protrude toward the tip of the fiber (Fig 2). Extensive overlapping of the cells (up to 5% of their length) and a slight tilt away from the fiber axis give the hair surface a racheted appearance. These imbrications are highly functional. By interlocking with the pointing downward cuticle cells of the inner root sheath, they contribute to the follicular anchorage of the growing hair. The firmness of this interlock is demonstrated by the fact that pulling out hair forcefully causes extensive dislodgment of individual cuticle cells, which then coil on themselves (Fig 3). The imbricated surface also serves as a self-cleansing fixture. As the hairs grow and move relative to one another, the outward pointing cuticular edges facilitate removal of trapped dirt particles and desquamated cells from the scalp.

In the course of the process of maturation and keratinization, a stratified structure develops within each cuticle cell. A cross section of a cuticle (Fig 4) displays layers of distinctive texture, and chemical analysis reveals an intertwined mosaic of proteins,

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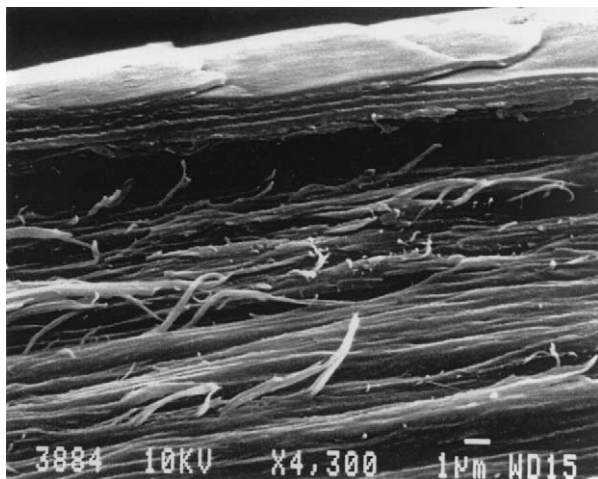
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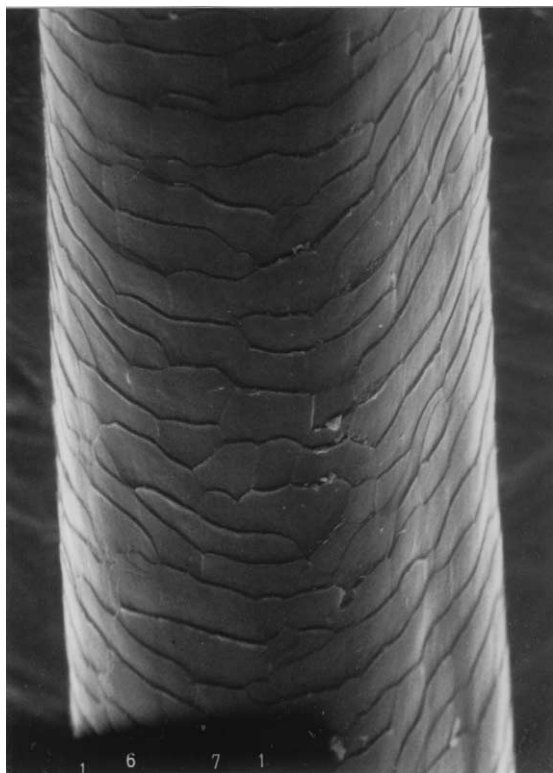
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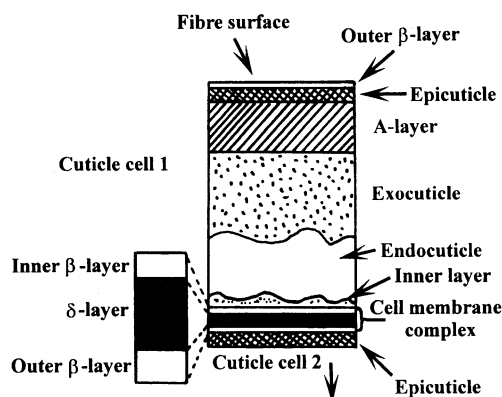
**Fig 1.** Scanning electron micrograph of longitudinal hair section (courtesy of Mr. J. Epps).



**Fig 3.** Transmission electron micrograph of the longitudinal section of hair pulled out of the follicle (courtesy of Mr. D. Cobble).



**Fig 2.** Scanning electron micrograph of hair surface (courtesy of Mr. J. Epps).



**Fig 4.** Cross section of a hair cuticle (courtesy of Dr. A. Swift).

lipids, and carbohydrates. Each cuticle cell is surrounded, and thus separated from its neighbors, by the CMC. The CMC consists of a central core ( $\delta$  layer) bound on both sides by 2 lipid-endowed  $\beta$  layers. As yet, the composition of the  $\delta$  layer is not fully determined, but it contains little protein and seems to be polysaccharidic in nature. On the outer

“environmental” side of the cell, the cystine-rich A layer abuts the major component of the cuticle—the exocuticle. The proteins of the exocuticle are densely cross-linked by disulfide bonds of cystine, but not as extensively as the proteins of the A layer. In contrast, the adjacent layer of endocuticle is poor in cystine and contains much of the nonkeratinous cellular debris and a high content of basic and acidic proteins.

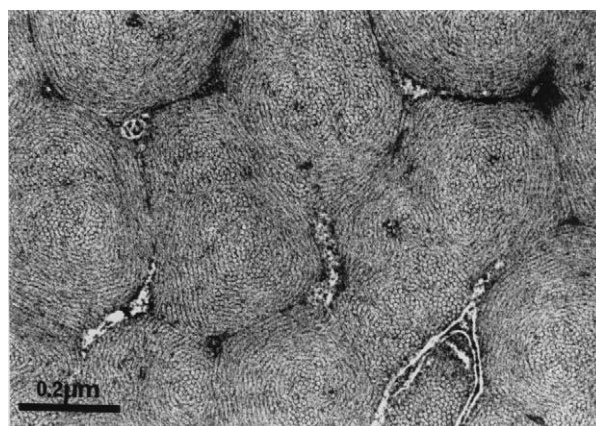
The layer of epicuticle, shown in Fig 4, has been a matter of controversy since von Allworden<sup>1</sup> deduced its existence by observing the membrane-bound sacs on mammalian hairs treated with chlorine water. As recently as 1995, an assertion was made that the membrane is not a histologically identified component of the cuticle cell, but rather a by-product of the reactive modification of other sub-components of the cuticle.<sup>2</sup> Atomic force micros-

copy tentatively identified the epicuticle as a continuous layer 13 nm thick, covering the entire outwardly facing intracellular surface of every cuticle cell.<sup>3</sup>

The description of the structural elements of the cuticle would be incomplete without mentioning the 18-methyleicosanoic acid (18-MEA). An important lipid constituent of the cuticular CMC, 18-MEA is covalently linked to its protein components.<sup>4</sup> It also has been ascertained that a thin layer of 18-MEA is grafted onto the outer surface of each cuticle (upper layer).<sup>5</sup> The presence of such a lipid film confers to the hair surface the attribute of low friction with concomitant hydrophobic character. It is noteworthy how well the cuticle sheath has adapted to meet the environmental challenge. A water-repellant surface facilitates drying of hair, and the cuticular imbrications keep the fibers and scalp clean. The densely cross-linked outer layers provide stability and a measure of protection against mechanical assault, cushioning the effects of physical impacts with a soft stratum of the endocuticle. The layers of overlapping cells also constitute a formidable diffusion barrier that must be considered when devising processes for chemical modification of hair. Because most reactive treatments are performed in an aqueous environment, it is fortuitous that a potentially easy passage can be channeled through the endocuticle, whose low cross-link density combined with its hydrophilic character make it highly water swellable.

## THE CORTEX

This morphologically dominant component of hair is made up of elongated, interdigitated, spindle-like cells approximately 100  $\mu\text{m}$  long and 5  $\mu\text{m}$  across at the maximum width. The cells are fused tightly and oriented parallel to the axis of the fiber. Each cell is packed with fine, axially oriented filaments (microfibrils) that consist of highly organized helical proteins responsible for the diagnostic x-ray diffraction pattern of  $\alpha$  keratins. The microfibrils are approximately 7 nm in diameter and are grouped into larger units called macrofibrils. By using specific staining techniques of electron microscopy, the structural resolution of these fibrillar assemblies has been accomplished. The results indicate that each macrofibril represents a structural composite consisting of rods of microfibrils embedded in cystine-rich matrix (Fig 5). The macrofibrils represent approximately 50% to 60% of the cortex material (by mass). There is some variation in the packing mode within the macrofibrils and in the macrofibrillar arrangements within the cortical cells. The 2 different packing dispositions have been designated as para-



**Fig 5.** Transmission electron micrograph of hair macrofibrils (courtesy of Dr. J. Sikorski).

cortex and orthocortex, and their structural difference has been detected by differential staining techniques.<sup>6</sup> It is well known that the crimp in wool is associated with the asymmetric disposition of the orthocortex and paracortex along the length of the fiber, with the paracomponent always on the inside of the crimp wave and the orthocortex on the outside. Recently, Swift reported a similar bilateral disposition of orthocells and paracells in curly hair, both African and Caucasian.<sup>7</sup> This author has examined samples of highly curled albino African hair with the methylene blue-staining technique but could not find evidence of regular bilateral disposition of the orthocells and paracells (unpublished observation, 1979). Thus, it is unlikely that the curliness in African hair is the result of the same factor responsible for the crimp in merino wool.

Although the cause of the geometry of African hair is unknown, the results of examination of scalp biopsies taken from African Americans indicate that highly cured hair follicles may be a strong contributing factor.

## CHEMICAL COMPOSITION AND REACTIVITY

The pattern of reactivity of hair is complex because it depends not only on the presence of reactive moieties in the fiber but also on their availability. The latter is significantly affected by fiber morphology and molecular structure. The bulk of hair is proteinaceous in nature, with the structural lipids and other materials representing only a minor fraction. The amino acid makeup of the protein components is given in Table I.<sup>8</sup> Viewed from the perspective of biologic variability, dietary habits, sampling techniques, environmental effects, and diversity of texture, it is remarkable how uniformly the data cut across ethnic groups. Although there is

**Table I.** Amino acid composition of human hair of various ethnic origins ( $\mu\text{M/g}$ )

Amino acid	Hair type		
	African	Brown/Caucasian	Asian
Alanine	370-509	345-475	370-415
Arginine	482-540	466-534	492-510
Aspartic acid	436-452	407-455	456-500
Cysteic acid	10-30	22-58	35-41
1/2 Cystine	1310-1420	1268-1608	1175-1357
Glutamic acid	915-1017	868-1053	1026-1082
Glycine	467-542	450-544	454-498
Histidine	60-85	56-70	57-63
Isoleucine	224-282	188-255	205-244
Leucine	484-573	442-558	515-546
Lysine	198-236	178-220	182-196
Methionine	6-42	8-54	21-37
Phenylalanine	139-181	124-150	129-143
Proline	642-697	588-753	615-683
Serine	672-1130	851-1076	986-1101
Threonine	580-618	542-654	568-593
Tyrosine	179-202	126-194	131-170
Valine	442-573	405-542	421-493

considerable variation within each set of data, the ranges overlap and there are clearly no significant contrasts in the amino acid composition of hair of different ethnicity.<sup>8</sup>

The macromolecular structure of keratin derives its stability from a variety of intrachain and inter-chain interactions holding the protein chains together. The interactions range from covalent bonds to weaker interactions, such as hydrogen bonds, coulombic interactions (salt links), van der Waals interactions, and, in the presence of water, hydrophobic bonds.

Although relatively weak and readily broken by water, the hydrogen bonds are the most numerous (approximately 4.6 mM/g). The interchain hydrogen bonding between the amide groups along the polypeptide design is an essential element in the stability of  $\alpha$ -helical structure. The high content of acidic and basic side chains (1.6 mM/g total) gives rise to coulombic interactions that are relatively stable in aqueous environments but are readily broken by acids and alkalis. Central to the stability of keratin structure, however, is the disulfide bond of cystine. The high incidence of these cross-links (0.8 mM/g), which display both inertness and selective reactivity, is key to most of the chemical modifications of hair. The susceptibility of the disulfide bonds, both to reduction and oxidation, allows for solubilization of keratin and identification of its components, laying the groundwork for the resolution of its molecular texture.

Two major protein fractions have been isolated:

**Table II.** Keratose fractions of solubilized hair (wt %)

Hair type	Keratose fraction (%)		
	$\alpha$	$\beta$	$\gamma$
Caucasian	43	15	33
Asian	42	14	34
African	43	15	33

one with low sulfur content and high molecular weight and the other with high sulfur content and low molecular weight. The low-sulfur proteins yield an  $\alpha$ -pattern that is not found in the sulfur-rich fractions. The differences in the chemical composition and physical character of the proteins were major factors in assigning them as integral elements of the filament and matrix structure put forward by Birbeck and Mercer.<sup>9</sup> Thus, the filaments have low sulfur content, high molecular weight, and helical proteins, whereas high-sulfur proteins with no defined orientation or crystallographic pattern form the matrix.

Two general approaches to solubilization have been developed. One relies on the reductive cleavage of disulfide bonds, the other on oxidative fission. On the whole, the fractionation of the solubilized keratin into the component fractions yields similar results. The oxidatively generated proteins have been termed  $\alpha$ ,  $\beta$ , and  $\delta$  keratoses, corresponding to low-sulfur, membrane-derived, and high-sulfur proteins, respectively.

Table II lists the results of oxidative solubilization and fractionation of hair of different ethnic origins. It is evident that the fractionation pattern of the different hair types is similar, and that there is no indication of significant differences in the filament and matrix texture of keratins.<sup>10</sup>

Because of the strategic importance of disulfide cross-links, researchers must be aware of the extent of their modification resulting from environmental or chemical treatments. In some cases, the involvement of the disulfide bonds is directly associated with the nature of the process, as is the case with waving or straightening. In other cases, involvement of the disulfide bonds may be described as that of an "active" bystander (oxidative hair coloring, bleaching, and weathering). In either case, the physicochemical properties of hair are affected.

Chemical waving and straightening are 2 important hair-care treatments that require involvement of almost every aspect of hair structure to accomplish their goals. The objective of both processes is to impart to hair a durable configuration that is different from what hair exhibits in its native form. Each hair has a geometry that is the result of the processes

of keratinization and follicular extrusion, transforming a viscous mixture of proteins into strong, resilient, and rigid fiber. In principle, waving and straightening can be viewed as a combination of reversal and stepwise restaging of these processes, entailing softening of keratin, molding it into the desired shape, and annealing the newly conferred geometry. Thus, the underlying mechanism of waving and straightening is essentially molecular and involves manipulation of physicochemical interactions that stabilize the keratin structure.

It might be useful at this point to emphasize the essential difference between these processes and setting of hair, whether by water or hot comb. Although waving and straightening involve giving new geometry to hair, only water-labile bonds of hair are manipulated in setting, and thus, the newly acquired geometry is moisture sensitive and is lost on shampooing or exposure to high humidity. In waving and straightening, both the covalent and secondary bonds are involved, and the new geometry is stable for repeated washing cycles. The covalent bonds that are essential to achieve the permanence of the effect are derived from the disulfide cross-links.

Three classes of nucleophilic agents are commonly used to accomplish these reactions: mercaptans, sulfites, and hydroxyl ions. The first 2 selectively cleave the disulfide bonds in such a manner that they can be recombined at the end of the process. The alkaline-relaxing cleavage, on the other hand, is much less selective. A permanent fission of disulfide bonds takes place, and although some of them are converted into monosulfide cross-links (lanthionine), significant impairment of fiber integrity results. The straightening efficacy of alkaline relaxers, however, is superior to that of mercaptans and sulfites.

## PHYSICAL PROPERTIES

The perception of hair appearance provides an almost instant recognition of the interplay of diverse physical parameters. The obvious attributes, such as hair geometry, color, and luster, intertwine with the spatial arrangement of fiber arrays, yielding a judgment on its aesthetics.

There has been a tendency, based on both the testing methodology and comparison purposes, to group the physical attributes of hair into 2 general categories. The first category deals with the properties that are material specific, such as fiber diameter, tensile strength, bending and torsion, swelling, friction, and luster. The second category focuses on the behavior of hair assemblies and entails the evaluation of combability, style retention, and body. Although the intrinsic properties of single fibers are

**Table III.** Cross-sectional parameters of hair

Hair type	Ellipticity (range)	Equivalent diameter ( $\mu\text{m}$ )	
		range	mean
Caucasian	1.43-1.56	67-78	72
Asian	1.21-1.36	69-86	77
African	1.67-2.01	54-85	66

likely to have a dominant effect on the performance of hair assemblies, these attributes can be modulated perceptibly by the hair mass.

## Fiber diameter

This attribute is of major significance in the behavior of hair assemblies, although its importance has a different impact on consumers from different ethnic origins. "Body" is a term widely used by consumers and hair-product manufacturers to describe a highly desirable attribute of hair. It conveys bulk, liveliness, and resilience. It is a result of an interplay between the single fiber parameters, such as diameter, stiffness, geometry, and the disposition of the individual fibers within the hair mass. Thus, for Caucasian consumers, the perception and value of hair body (closely tied to hair diameter) ranks supreme, whereas that particular factor is of much lesser concern to both Asian and African consumers, for whom different aspects of hair appearance are more meaningful. Nevertheless, the hair diameter has been extensively evaluated, with the general finding that, at least in the case of Caucasian and Asian hair, it follows a Gaussian distribution with a relatively narrow maximum of 66 to 75  $\mu\text{m}$ . Hair well to the left of the maximum is considered fine; hair to the right of the maximum is considered coarse. It has been very instructive to learn that consumers without any measurement aids to classify their hair as fine, normal, or coarse closely follow these diameter distinctions. Their judgment is usually based on the tactile perception of their hair and assessment of its wearing characteristics, such as body and style retention.

Because hair fibers are seldom round, the descriptor of "hair diameter" is somewhat misleading until accompanied by information on fiber ellipticity. Table III lists the results of such combined measurements obtained on Caucasian, Asian, and African hair (J. Quadfleig, F. J. Wortmann, L. J. Wolfram, unpublished observations, 2002). The fibers, clipped closely to the scalp, were donated by individuals (20 in each case) and were measured at 65% relative humidity. The "equivalent diameter" descriptor ( $d$ ) was calculated from  $d = \sqrt{A \times B}$ , where A stands for the long axis of the fiber diameter and B stands

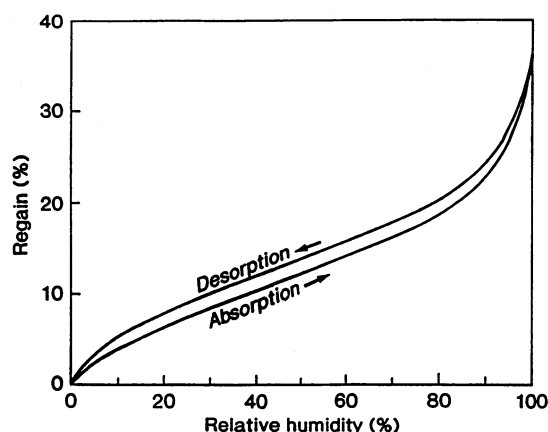


Fig 6. Moisture absorption isotherm of human hair.

for the short axis of the fiber diameter. The “ellipticity factor” (E) was determined from  $E = A/B$ .

The trait that distinguishes the African hair fibers is not only the high ellipticity factor but also the broad ranges, particularly when compared with highly uniform Asian hair. Although there was no apparent relationship between fiber diameter and ellipticity, the latter seems to go hand in hand with the degree of hair curliness (a subjective assessment only).

### Water absorption and swelling

To put in perspective the nature of keratin-water interactions, it is important to keep in mind that the biosynthesis of hair occurs in an aqueous environment, and that the final keratinized structure is in mechanical equilibrium while in a wet state. As the swollen fiber dries on emerging from the follicle, that equilibrium “memory” is retained and then restored on wetting. This hydration–dehydration process is highly anisotropic and accompanied by a 15% diametric swelling with only 1% change in length. This phenomenon can be well accounted for by the 2-phase composite model of the keratin structure in which the radial expansion and contraction of the hydrophilic matrix in the hydration–dehydration cycle cause only a small change in the axially oriented microfibrils.

Keratin’s high affinity for water extends over the whole range of relative humidities (Fig 6). Although water vapor permeates hair readily, there is some binding selectivity within the molecular structure and accessibility restraints in the filament and matrix texture.

Available data on moisture binding by hair of different ethnic origin reveal no significant differences in uptake, either at intermediate humidities or at the saturation point.

Reactive cosmetic treatments of hair (waving,

**Table IV.** Effect of hair treatment on moisture uptake by hair (wt %)

Treatment	Moisture regain (%) at		
	65% RH	95% RH	Liquid water
Intact	15	32	34
Dyed	15	32	36
Bleached	16	35	50
Waved	15	33	41
Relaxed	15	34	57

RH, relative humidity.

straightening, bleaching, and coloring) usually result in some disruption of the fiber structure. Such damage usually has little effect on the water absorption by hair at ambient humidities but causes a significant increase in swelling or liquid retention on wetting (Table IV).

The selectivity of water absorption may lead to some significant changes in fiber response. Thus, high swelling of the endocuticle layer raises the free edges of cuticle cells, resulting not only in an increase in friction but also in a decrease of the diffusion barrier.

### Tensile properties

All animal fibers with  $\alpha$ -keratin structure have developed as an outer covering to protect animals during exposure to a wide range of environmental conditions. Such fibers are durable, water insoluble, and chemically inert. They are pliable and resilient, and recover from repeated mechanical deformations with little loss of their physical properties. Vestigial as it is, human scalp hair has retained all these valuable characteristics. The thick layer of cuticle cells diminishes mechanical impacts, whereas the fibrous cortex contributes to mechanical stability. In the area of fiber evaluation, tensile and longitudinal testing play an important role by providing information not only on the strength and extensibility of the fiber but also on the molecular mechanism involved in such mechanical deformations. This testing mode is relatively well comprehended by the public, for whom fiber strength is tantamount to the index of hair “wellness.”

In intact hair, the tensile properties are primarily a function of the integrity of the corticular structure in general and of the filament and matrix composite in particular. The high sensitivity of the composite to absorbed water underscores the necessity of making the measurements under well-controlled conditions of humidity. Clearly, any imperfections of the hair structure—whether innate or environmentally induced—are likely to affect the results.

**Table V.** Mechanical properties of hair\*

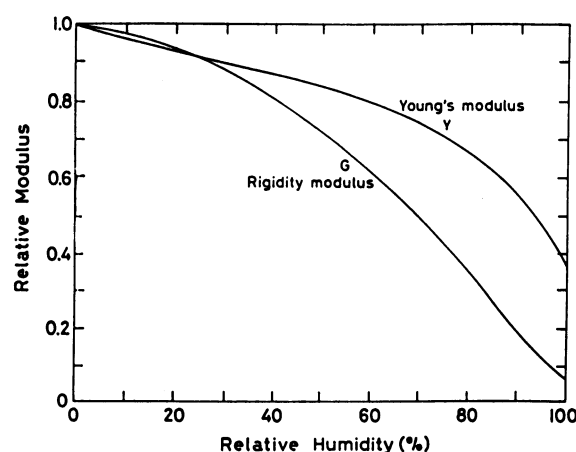
Hair type	Breaking stress (MPa)								Breaking extension (%)							
	Dry (65% RH)				In H <sub>2</sub> O				Dry (65% RH)				In H <sub>2</sub> O			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
Caucasian	188	178	184	180	165	155	162	—	44	46	49	38	62	49	61	—
Asian	190	185	—	—	158	165	—	—	46	47	—	—	62	48	—	—
African	191	180	148	112	156	160	94	—	42	41	39	29	54	48	42	—

\*A, B, C, and D denote different locations where the tests were conducted.

Table V presents the results of tensile testing on Caucasian, Asian, and African hair conducted at different laboratories (data compiled by the author from information obtained at Wollforschungsinstitut, Aachen, Germany; Gillette Research Institute, Rockville, MD; Avlon Industries Inc., Chicago, IL; and Textile Research Institute, Princeton NJ, 2001). The obvious discrepancies are striking. Although the tensile properties of the Asian and Caucasian hair are similar and matched in this respect by 2 samples of the African hair, the other 2 are considerably weaker and more brittle. This raises an important question: Which samples are truly representative of the African hair or are all samples representative? It is important to note that the testing of both Asian and Caucasian hair is usually conducted with commercial samples provided by hair traders. The low supply of African hair forces researchers to sample the hair from individuals. Although care is taken to ensure "harvesting" of hair with no cosmetic history, this cannot always be verified. In the testing of African hair, this author has often encountered fibers with an axial twist resulting in narrow segments. Such segments proved to be weak points, and the fiber extension invariably broke in those locations.

### Torsion

Torsional properties are important in both creating and maintaining hair style; therefore, it is important to explore the role of filament and matrix texture in different modes of hair deformation and to extrapolate data on cuticular structure. In dry hair, the mechanical properties of both the filaments and matrix are similar. The fiber acts as a homogeneous, isotropic material, in which either tensile or torsional deformations are resisted by the total structure. When hair is exposed to increasing levels of humidity, the absorbed water progressively softens the matrix, thus lowering its mechanical modulus, whereas the water-impenetrable microfibrillar phase remains relatively unchanged and resistant. Thus, the water brings to the fore the mechanical anisotropy of the fiber. In the tensile mode of deformation,



**Fig 7.** Effect of moisture on changes in tensile (y) and torsion (G) module of hair.

the filaments are the primary load-bearing elements of the fiber because the water-softened matrix contributes little to overall resistance. The reverse occurs in torsion. In this deformation mode, the water-penetrated matrix phase takes up virtually all shear stress imparted on the fiber, with the filaments merely tilting as the matrix deforms. This dichotomy of behavior is demonstrated in the changes of respective moduli (Fig 7). Thus, the tensile modulus of hair decreases on wetting by a factor of 2.7, whereas the rigidity modulus (torsion) decreases by a factor of 15.

Because cuticle cells do not have any fibrous proteins and thus show no filament and matrix texture, it was of interest to ascertain the effect of water on their resistance to deformation. Advantage was taken of the fact that the thickness of cuticular layer is invariant with hair diameter, which means that the cuticle to cortex ratio increases with the decrease in hair diameter. The torsional experiments were conducted on fibers of varying diameter under both wet and dry conditions.<sup>11</sup> The results showed that although the loss modulus was diameter invariant in dry fibers, a 50% increase in the wet fibers was noted

for the diameter range tested (100-70  $\mu\text{m}$ ). The diameter range is given in reverse order to reflect the fact that the increase in the loss modulus was observed as the hair diameter decreased. The data permitted computation of the torsional modulus of the cuticle layer. The value obtained was even lower than that ascribed to the hydrated matrix. This was unanticipated because the cuticle cells contain densely cross-linked exocuticle, which should be much less water sensitive than the cortical matrix. However, it is likely that the deformation stress was taken up primarily by the highly water-swollen endocuticle layer.

### Combability

It takes no more than a touch or a gentle squeeze of hair strands and a pass of a comb. In that instant, the interplay of tactile sensation and the awareness of the mechanical effort fuse together into a firm perception of hair "condition." It is this remarkable coincidence that the tactile attributes and combing effort undergo directionally parallel changes that made the combability a significant element in the area of objective techniques of claim support for efficacy of hair conditioners and shampoos.

The combability test entails simply attaching a tress of hair to a strain gauge and measuring the force required to pull the comb through the tress. Fig 8 depicts combing curves of African hair and Caucasian hair. The tresses were identical in weight and length. Not only is African hair more difficult to comb, its combing pattern is qualitatively different. In the case of straight Caucasian hair, the engagement of the comb causes some parallelism of individual hair strands and results in a clear pathway ahead of the teeth of the comb. The comb moves through the hair mass with relatively little effort; it is only at the tip of the tress that the resistance of a multitude of individual hair crossovers has to be overcome and the combing force sharply increased. On the contrary, insertion of a comb into a tress of highly curled African hair does not induce hair parallelism and thus creates no clear pathway. The engagement and motion of the comb lead to a displacement and intensification of individual curl entanglements, which are reflected in an immediate and progressive rise in the combing force. A lesser contribution to the overall work required to comb African hair may come from the effort necessary to unbend individual curls that are unable to twist their way through the teeth of the comb.

The curly geometry of African hair has an interesting consequence in the case of wet combing. Unlike Caucasian hair, which is more difficult to

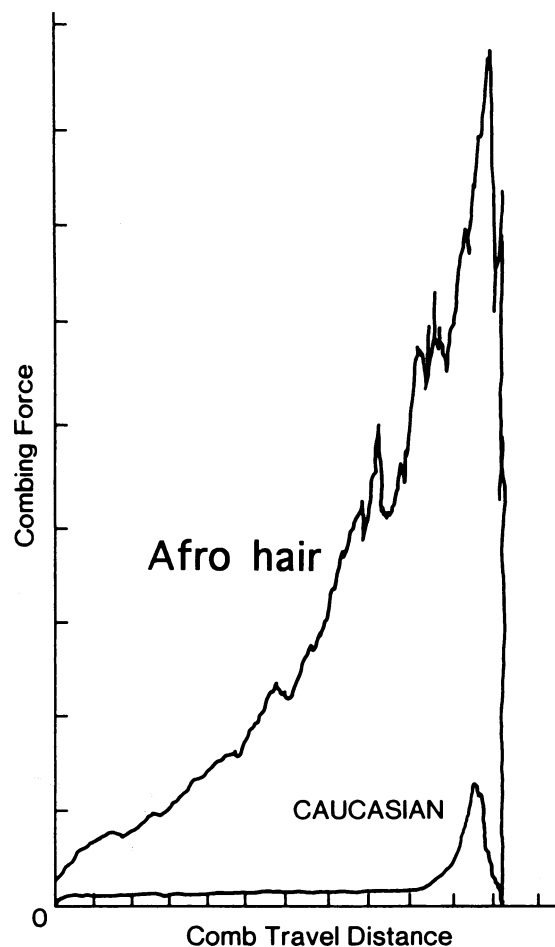


Fig 8. Dry combing of intact African and Caucasian hair.

Table VI. Dry and wet combing of Caucasian and African Hair

Hair type	Work of combing (gcm)	
	Dry	Wet
Caucasian	50	130
African	575	225

comb wet than dry, wet combing of African hair is easier than dry combing (Table VI).

Caucasian hair, fluffy while dry, acquires a stringy and compact form on wetting. Initially driven by the surface tension of the water, the individual hairs adhere strongly to each other along much of their length, forming a cohesive and densely packed assembly. The disentanglement of this assembly by the moving comb is difficult because of reduced fiber stiffness, whereas the increased interfiber and fiber-comb friction further magnify the work of combing. Wetting of African hair causes little change in the tress configuration because the curly geometry of



individual hairs is able to resist fiber adhesion and clumping. There is slight relaxation of the curl, which lessens the extent of individual entanglement. Both the torsion and bending moduli decrease on wetting, further aiding the unbending of curls and their twist passage between the teeth of the comb.

Straightening of African hair, whether by chemical relaxers or physical hot combing, results in hair whose assembly behavior in combing is indistinguishable from Caucasian hair.

## CONCLUSION

This brief review sought to increase awareness of the wealth of information developed on the structure of the physicochemical properties of hair. There is a wide gap in our understanding of the structure of ethnic and, in particular, African hair, and this dilemma should be seriously addressed if novel and consumer-friendly hair processes are to be developed.

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