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Hair Follicle Biology and Shaft Structure

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Abstract:

Background: Hair follicle biology and hair shaft structure are essential for maintaining normal hair integrity, growth, and resistance to external damage. The hair follicle is a complex mini-organ composed of distinct anatomical regions that regulate hair formation and cycling. The hair shaft itself consists of the cuticle, cortex, and medulla, each contributing specific structural and functional properties. Variations in hair composition and morphology occur among different ethnic groups and influence susceptibility to mechanical and chemical damage. Cosmetic procedures such as bleaching, coloring, and hair straightening can disrupt the protective cuticle layer, alter the biochemical composition of hair fibers, and impair hair strength and biomechanical properties. Understanding the anatomy, composition, and growth cycle of hair provides a scientific basis for recognizing the mechanisms of hair shaft damage and the effects of cosmetic interventions on hair health.

Keywords: Hair follicle, Hair shaft, Cuticle, Cortex, Medulla, Hair growth cycle, Hair damage, Hair biology, Ethnic hair variations, Hair structure.

Introduction:

Hair breakage is a multifactorial condition associated with intrinsic and extrinsic factors. The integrity of healthy hair depends largely on an intact cuticle composed of overlapping scales that protect and maintain the cohesion of the hair shaft. Damage to the cuticle disrupts this protective barrier, resulting in increased hair dryness, split ends, frizz, and hair shaft breakage. Hair straightening procedures are recognized as significant contributors to hair damage and may also predispose individuals to hair loss. The primary mechanisms involved include excessive heat exposure, inappropriate hair straightening techniques, and the application of chemical agents during the process. Nevertheless, many of these adverse effects may be reduced through proper hair straightening practices and avoidance of common damaging behaviors **(1).** This chapter provides an overview of normal hair follicle anatomy, hair shaft structure, ethnic variations in hair characteristics, and the hair growth cycle, thereby establishing a foundation for understanding straightening-induced hair damage, which is discussed in subsequent chapters.

In addition, the biochemical composition of hair plays a critical role in determining its mechanical strength, elasticity, and resistance to environmental and cosmetic damage. Human hair is composed primarily of keratins and keratin-associated proteins (KAPs), which form a highly organized structural network stabilized by multiple disulfide bonds. Variations in lipid and protein composition among different ethnic hair types may influence susceptibility to dryness, fragility, and chemical injury. African hair, for example, contains higher levels of apolar lipids, whereas Asian hair demonstrates greater resistance to ultraviolet-induced damage because of its higher integral lipid content**.** Furthermore, alterations in protein integrity and lipid distribution following cosmetic procedures may contribute to impaired biomechanical properties and increased hair shaft fragility **(2).**

The normal hair follicle undergoes a continuous cyclic process consisting of anagen, catagen, and telogen phases, which regulate hair production, regression, and shedding. Under physiological conditions, approximately 85–90% of scalp hairs remain in the anagen phase, allowing continuous hair growth at an average rate of nearly 1 cm per month **(3).** Disturbances in this tightly regulated cycle may lead to excessive shedding or impaired hair regeneration. Multiple signaling pathways originating from the dermal papilla and epithelial stem cells within the bulge region are involved in initiating and maintaining the growth phase of the follicle **(4).** Therefore, understanding the molecular and structural biology of the hair cycle is essential for interpreting the pathogenesis of hair disorders and evaluating the effects of therapeutic and cosmetic interventions on hair health.

Hair Follicle Anatomy

The hair follicle, also referred to as the pilosebaceous unit, consists of the hair follicle, sebaceous gland, and arrector pili muscle. Hair follicles that produce terminal hairs are larger and extend deep into the dermis, occasionally reaching the subcutaneous tissue. In contrast, the follicles responsible for vellus hair are much smaller and are usually confined to the upper reticular dermis.

The scalp hair follicle is structurally divided into three main parts: the infundibulum, isthmus, and lower segment, which includes the hair bulb **(5)**. The bulge region, located within the isthmus, is particularly important because it serves as a reservoir of epithelial stem cells and expresses markers such as CK19, CK15, and CD200. Extending from the bulge to the base of the follicle, the lower segment plays a major role in hair formation and the hair growth cycle **(6).**

The hair shaft comprises three main layers. The medulla, which forms the inner core of the hair, lies at the center. The cortex, the thickest layer that constitutes most of the hair shaft and provides strength and structure, surrounds the medulla. Covering the cortex is The cuticle, a single outer layer of overlapping cells, protects the hair shaft.

The cuticle is surrounded by the inner root sheath, which consists of three layers and plays an essential role in molding and guiding the growing hair shaft as it emerges from the hair matrix. As the hair grows upward, the inner root sheath undergoes keratinization from the outer layer inward and eventually breaks down at the isthmus level. The outer root sheath encloses all these structures, surrounding the hair follicle and undergoing trichilemmal keratinization near the isthmus region **(7)**

Sebaceous glands are holocrine glands closely connected to hair follicles, particularly in the facial skin. These glands empty their secretions directly into hair follicles. Under the influence of hormones, especially androgens, sebaceous glands produce sebum, a lipid-rich substance that helps lubricate and protect the hair while also contributing to the skin hydrophobic protective barrier **(7).**

Hair Shaft Structure

The hair shaft is composed of three concentric layers: the cuticle, cortex, and medulla.

The cuticle is the outermost protective layer of the hair shaft. It is composed of flattened, overlapping cells that shield the inner cortex from physical and chemical damage. Structurally, the cuticle is mainly composed of keratin and keratin-associated proteins (KAPs), particularly those rich in cysteine and glycine**.** During differentiation, cuticle cells accumulate cysteine-rich granules and express ultra-high sulfur (UHS) keratin proteins**.** In addition, the cuticle contains S100A3, a calcium-binding protein with a high cysteine content **(8).**

The surface of the hair cuticle is covered by a thin fatty acid layer that helps maintain hair smoothness and protects against external damage. The main fatty acid present is 18-methyleicosanoic acid (C21a), which is firmly bound to the underlying protein membrane through covalent bonds **(9).**

The cortex forms the largest portion of the hair shaft and is mainly responsible for hair strength and durability**.** It is composed of keratin filaments and melanin granules, which give hair its characteristic color**.** These keratin filaments are embedded within a protein matrix rich in cystine, an amino acid that forms multiple disulfide bonds between keratin molecules, contributing to hair strength and stability**.** Based on their structural characteristics, cortical cells in human hair are classified into orthocortex, paracortex, and mesocortex **(10).**

The medulla forms the innermost core of the hair fiber and is not simply an empty space within the hair fiber. Recent studies have shown that it contains fibrillar structures similar to those found in cortical cells, as well as spherical vacuoles**.** Medullary cells exhibit unique keratin expression patterns, including both hair-specific and epithelial keratins. The medulla also contains citrulline-rich proteins with epsilon-(gamma-glutamyl) lysine cross-links and structural proteins that are resistant to chemical treatments **(11).**

Considerable variation exists in the structure of the medulla among different hair fibers of the same individual. Some hairs possess a narrow medulla, whereas others possess a broader medulla**.** In zigzag hairs, the medullary structure appears to be closely related to the regions where the hair bends are formed **(12).**

Damage to the Hair Shaft

The integrity of the hair shaft can be affected by various factors, including genetic susceptibility, environmental exposure, and cosmetic practices. Trichoscopic examination may reveal characteristic hair abnormalities, such as exclamation mark, comma, corkscrew, coiled, flame, and tulip hairs **(13).** These patterns are often observed in conditions such as alopecia areata, trichotillomania, and tinea capitis.

Cosmetic interventions, including hair coloring, bleaching, and straightening, can cause significant structural damage to the hair shaft. Studies using scanning electron microscopy (SEM) have shown that repeated use of these procedures may produce subtle ultrastructural changes that are not always detectable by routine clinical or light microscopic examinations**.** In addition, chemical treatments can alter both the physical architecture and chemical composition of hair fibers, ultimately leading to structural weakening and impaired biomechanical properties **(14).**

Ethnic Variations in Hair Composition

African hair shows less radial swelling when exposed to water than Asian and Caucasian hair, which is thought to reflect differences in lipid composition among ethnic groups. Hair lipids can be divided into two categories: internal lipids, which are produced within the hair matrix cells, and external lipids, which originate primarily from sebaceous gland secretions. Internal lipids include free fatty acids (FFA), cholesterol, ceramides, cholesterol esters, and cholesterol sulfate, whereas external lipids primarily consist of sterol esters and squalene **(15).**

African hair contains the highest level of total extractable lipids, followed by Caucasian and Asian hair**.** In African hair, most lipids are derived from sebaceous secretions, whereas in Asian and Caucasian hair, lipids are mainly of internal origin **(2)**. In addition, African hair has approximately 1.7 times more internal lipids than the other two hair types **(16)**.

The lipid composition also differs in quality: African hair is richer in apolar lipids, whereas Asian and Caucasian hair contain relatively higher amounts of free fatty acids and polar lipids. The greater proportion of apolar lipids in African hair helps to reduce water absorption and limit fiber swelling. Across all ethnic groups, lipid levels are lower in the cortex than in the cuticle **(15).** Furthermore, Asian hair, owing to its higher content of integral lipids, tends to be less susceptible to ultraviolet-induced damage.

Protein Composition of Hair

Human hair is mainly composed of proteins, particularly keratins and keratin-associated proteins (KAPs), which together create a complex structural network that gives hair its strength and mechanical properties **(17).** The protein composition also varies depending on the pigmentation of the hair. In black hair, eumelanosomes contain approximately 14.6 ± 0.5% amino acids, mainly due to proteins trapped within the melanosome granules. In contrast, red hair melanosomes show a much higher amino acid content, exceeding 44%, even after extensive enzymatic digestion, suggesting that some proteins may be tightly or covalently bound to the melanin structures**.**

Human hair proteins are highly diverse in nature. Using two-dimensional gel electrophoresis combined with mass spectrometry (2-DE gel MS), researchers have identified a wide range of keratin forms, including fragmented keratin proteins **(18)**. Several histone proteins with antimicrobial activity have also been detected in human hair **(17).** This wide protein diversity contributes to the complexity of the hair proteome and supports multiple biological roles, including stress response, innate immune defense, and epidermal development **(17)**.

The Hair Growth Cycle

The hair follicle cycles through three phases: anagen, catagen, and telogen.

Anagen phase: is the active growth stage of the hair cycle, during which a new hair shaft forms. In scalp hair, this phase typically lasts between 2 and 6 years, whereas in eyebrows and eyelashes, it is much shorter, lasting only a few months.

The initiation of anagen is regulated by signaling from the dermal papilla, which activates multipotent epithelial stem cells in the bulge region. Once these cells are stimulated, the inferior segment of the follicle begins to extend downward and forms a bulb-like structure surrounding the dermal papilla. In turn, the dermal papilla stimulates the matrix cells within the bulb to proliferate, differentiate, and move upward, ultimately producing a new hair shaft **(4).**

Catagen phase: also known as the transitional or regression stage, is the shortest phase of the hair cycle, lasting only a few weeks. During this period, cell proliferation in the hair matrix stops, and the lower segment of the follicle begins to shrink and regress. As a result, club hair is formed, characterized by a white, hardened bulb at its base **(19).**

Telogen phase : is the resting stage of the hair cycle, during which club hairs (non-growing, dead hairs) remain anchored to the scalp for approximately 100 days. After this period, the hair is naturally shed, making way for the initiation of a new anagen phase and the growth of a new hair shaft **(20).**

Hair grows in a cycle, and not all hairs grow at the same time. At birth, many hairs are in the growth phase, but not all of them. The human scalp has about 100,000 hairs, and most of them (around 85–90%) are actively growing at any time. Hair grows about 1 cm per month. It is normal to lose around 50–100 hairs every day. When washing hair, more hairs may seem to fall out, but this is usually because already shed hairs are being removed, not because more hair is actually being lost **(3).**

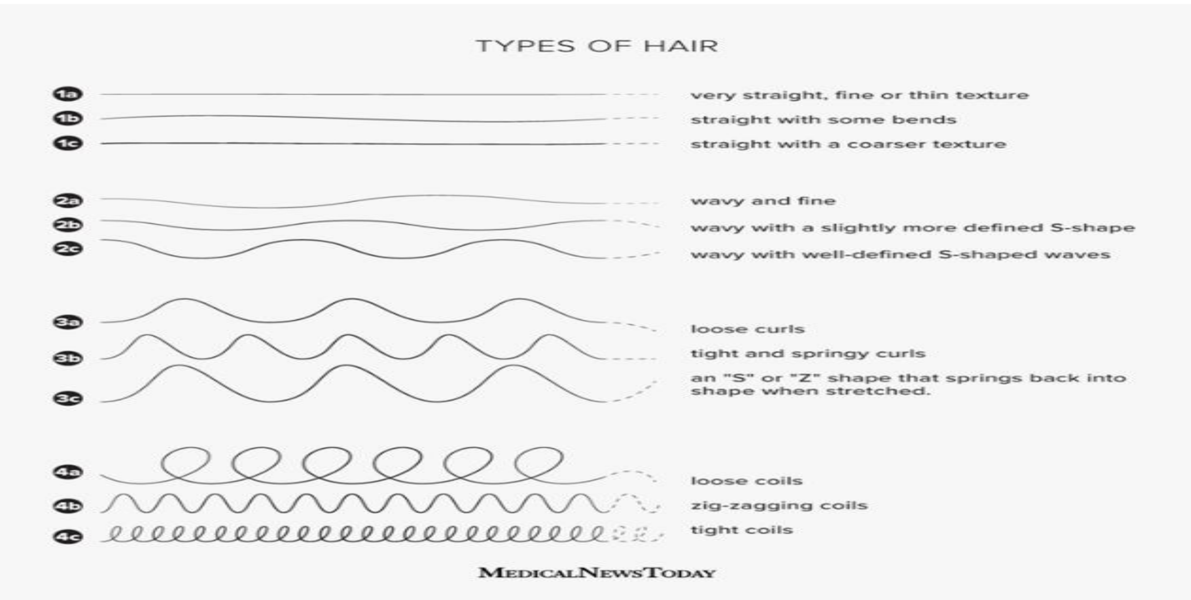

Figure 1: Different hair types **(21).**

References:

1. Barreto, T., Weffort, F., Frattini, S., Pinto, G., Damasco, P., & Melo, D. (2021a). Straight to the Point: What Do We Know So Far on Hair Straightening? Skin Appendage Disorders, 7(4), 265–271. https://doi.org/10.1159/000514367
2. Martí, M., Barba, C., Manich, A. M., Rubio, L., Alonso, C., & Coderch, L. (2016). The influence of hair lipids in ethnic hair properties. International journal of cosmetic science, 38(1), 77-84.

3. Chen, R., Miao, Y., & Hu, Z. (2019). Dynamic Nestin expression during hair follicle maturation and the normal hair cycle. Molecular Medicine Reports, 19(1), 549–554. https://doi.org/10.3892/MMR.2018.9691
4. Hoover, E., Alhajj, M., & Flores, J. L. (2023). Physiology, Hair. StatPearls.
5. Martel, J. L., Miao, J. H., & Badri, T. (2023). Anatomy, Hair Follicle. In StatPearls. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK470321/
6. Flores, A. F., Varela-Vazquez, A., Mayan, M. D., & Fonseca, E. (2018). Expression of connexin 43 in the human hair follicle: Emphasis on the connexin 43 protein levels in the bulge and through the keratinization process. Journal of Cutaneous Pathology, 45(1), 8–15. https://doi.org/10.1111/cup.13050
7. Paniagua Gonzalez, L. M., Tschen, J. A., & Cohen, P. R. (2018). Ectopic Sebaceous Glands in the Hair Follicle Matrix: Case Reports and Literature Review of this Embryogenic Anomaly. Cureus, 10(11). https://doi.org/10.7759/CUREUS.3605
8. Kizawa, K., Uchiwa, H., & Murakami, U. (1996). Highly-expressed S100A3, a calcium-binding protein, in human hair cuticle. Biochimica et Biophysica Acta (BBA)-Molecular Cell Research, 1312(2), 94-98.
9. Jones, L. N. (2001). Hair structure anatomy and comparative anatomy1. Clinics in dermatology, 19(2), 95-103.
10. Yang, F. C., Zhang, Y., & Rheinstädter, M. C. (2014). The structure of people's hair. PeerJ, 2, e619.
11. Piérard-Franchimont, C., Paquet, P., Quatresooz, P., & Piérard, G. E. (2011). Mechanobiology and cell tensegrity: the root of ethnic hair curling?. Journal of Cosmetic Dermatology, 10(2), 163-167.
12. Schlake, T. (2005). Segmental Igfbp5 expression is specifically associated with the bent structure of zigzag hairs. Mechanisms of development, 122(9), 988-997.
13. Rudnicka, L., Rakowska, A., Kurzeja, M., & Olszewska, M. (2013). Hair shafts in trichoscopy: clues for diagnosis of hair and scalp diseases. Dermatologic clinics, 31(4), 695-708.
14. Kaliyadan, F., Gosai, B. B., Al Melhim, W. N., Feroze, K., Qureshi, H. A., Ibrahim, S., & Kuruvilla, J. (2016). Scanning electron microscopy study of hair shaft damage secondary to cosmetic treatments of the hair. International journal of trichology, 8(2), 94-98.
15. Coderch, L., Oliver, M. A., Carrer, V., Manich, A. M., & Martí, M. (2019). External lipid function in ethnic hairs. Journal of Cosmetic Dermatology, 18(6), 1912-1920.
16. Cruz, C. F., Costa, C., Gomes, A. C., Matamá, T., & Cavaco-Paulo, A. (2016). Human hair and the impact of cosmetic procedures: a review on cleansing and shape-modulating cosmetics. Cosmetics, 3(3), 26.
17. Adav, S. S., Subbaiaih, R. S., Kerk, S. K., Lee, A. Y., Lai, H. Y., Ng, K. W., ... & Schmidtchen, A. (2018). Studies on the proteome of human hair-identification of histones and deamidated keratins. Scientific reports, 8(1), 1599.
18. Barthélemy, N. R., Bednarczyk, A., Schaeffer-Reiss, C., Jullien, D., Van Dorsselaer, A., & Cavusoglu, N. (2012). Proteomic tools for the investigation of human hair structural proteins and evidence of weakness sites on hair keratin coil segments. Analytical biochemistry, 421(1), 43-55.
19. Welle, M. M. (2023). Basic principles of hair follicle structure, morphogenesis, and regeneration. Https://Doi.Org/10.1177/03009858231176561. https://doi.org/10.1177/03009858231176561
20. Oh, J. W., Kloepper, J., Langan, E. A., Kim, Y., Yeo, J., Kim, M. J., Hsi, T. C., Rose, C., Yoon, G. S., Lee, S. J., Seykora, J., Kim, J. C., Sung, Y. K., Kim, M., Paus, R., & Plikus, M. V. (2016). A guide to studying human Hair follicle cycling in vivo. Journal of Investigative Dermatology, 136(1), 34–44. https://doi.org/10.1038/JID.2015.354
21. Westgate, G. E., Ginger, R. S., & Green, M. R. (2017). The biology and genetics of curly hair. Experimental Dermatology, 26(6), 483–490. https://doi.org/10.1111/EXD.13347