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# Influence of Amino Acids on the Hair Structure Before and During Chemical Treatments

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## Abstract

*The present study is devoted to the analysis of the selected problem in the context of contemporary theory and practice. The article examines key approaches, presents the author's interpretation of the obtained data, and identifies factors influencing the development of the phenomenon under study. The aim of the work is to substantiate the main trends and formulate practical conclusions that can be used in further research and in real-world practice. The methodological basis consists of the analysis of scientific literature, comparative and systems approaches, as well as qualitative and quantitative methods of data processing. The results obtained make it possible to refine existing ideas about the subject of the study and to propose directions for their practical application. The work will be of interest to researchers, lecturers, students of relevant fields, as well as practitioners who make decisions in this area and are interested in increasing the effectiveness of their professional activities. In addition, the article discusses the limitations of the conducted study and possible directions for further scientific work, including the refinement of the empirical base and the testing of the proposed hypotheses under other conditions. Particular attention is paid to practical recommendations that can be adapted to the specifics of various organizations and contexts.*

**Keywords:** *Keratin, Amino Acids, 18-MEA, Young's Modulus, Oxidative Stress, Thermoactivation, Trichology, Disulfide Bonds, DSC, SEM.*

## INTRODUCTION

The contemporary hair care sector is undergoing a phase of profound transformation, the essence of which lies in the shift of focus from a predominantly decorative function to a pronounced therapeutic and preventive orientation. According to analytical reviews for 2024, the global hair care market is estimated at 93.9 billion USD, with a projected expansion to 128.7 billion USD by 2034 at a compound annual growth rate (CAGR) of 3.2% [1]. At the same time, the key driver is not so much extensive growth in consumption as a qualitative modification of the demand structure: both professional industry participants and end users are oriented toward products capable of minimizing or preventing damage under conditions of increasingly aggressive chemical exposures.

The segment of so-called bond builders (systems for the restoration of intramolecular and intermolecular bonds in the hair) demonstrates particularly dynamic growth, with a projected market volume of 1.5 billion USD by 2025 and an unprecedented CAGR of about 15% [2]. This indicates that the issue of maintaining the molecular integrity of the hair shaft is becoming a dominant priority. According to statistical data, 27% of consumers identify hair damage as the main criterion for product selection [3]. As a result, beauty salons find themselves in a situation of methodological conflict: on the one hand, clients request complex multi-step coloring techniques (AirTouch, Shatush) that require repeated bleaching; on the other hand, they expect preservation of hair characteristics as close as possible to the state of virgin hair (intact hair that has not previously been subjected to chemical procedures).

The trend toward hair skinification, which defines the agenda for 2025, implies the translocation of principles and ingredient approaches from dermatological and cosmetic skin care into trichology: amino acids, peptides, hyaluronic acid, and other components traditionally associated with skin care are actively incorporated into formulations for the scalp and hair shaft [4]. However, for a significant proportion of commercial products, the evidence base remains fragmentary and methodologically insufficient, which determines the need for rigorous academic studies of their mechanisms of action at the molecular and supramolecular levels.

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Human hair is a complex, hierarchically organized biocomposite whose structure extends from the nanoscale to the macroscopic level. The main volume (80–90% of the mass) is accounted for by the cortex, which is formed by macrofibrils composed of intermediate filaments (IF) with a diameter on the order of 7–10 nm [5]. These filaments, built from coiled α-keratins, are incorporated into an amorphous matrix rich in cystine, a dimer of the amino acid cysteine containing disulfide bridges (S–S).

The system of disulfide bonds plays a key role in ensuring mechanical stability, functioning as covalent cross-links between protein chains and determining the high tensile strength and elasticity values of the hair shaft. For intact hair, the Young's modulus (characterizing material stiffness) is on the order of 3–4 GPa [6].

Exposure to alkaline agents (ammonia, ethanolamine) in combination with oxidizing agents (hydrogen peroxide) used in bleaching procedures leads to a cascade of destructive changes at all levels of structural organization:

– Oxidation of cystine: Disulfide bonds ($R-S-S-R$) undergo irreversible oxidation with the formation of cysteic acid [5]. This leads to the cleavage of cross-links, a decrease in mechanical strength characteristics, and an increase in the solubility of protein structures in an aqueous medium.

– Disruption of the lipid barrier (F-layer): The surface layer of the cuticle is covered by a monolayer of a unique fatty acid, 18-methyleicosanoic acid (18-MEA), covalently bound to epicuticle proteins via thioester bonds. The alkaline environment promotes hydrolysis of these bonds and subsequent removal of 18-MEA. It has been shown that even a single bleaching procedure can lead to the loss of up to 80% of this layer [8], as a result of which the hydrophobic surface of the hair is transformed into a hydrophilic one, sharply increasing the coefficient of friction and the tendency to tangling [9].

– Loss of protein mass: Oxidative destruction is accompanied by fragmentation of polypeptide chains and leaching of low-molecular-weight proteins and amino acids into solution, which is registered as a decrease in mass and the formation of micropores in the cortex [11].

One of the fundamental limiting characteristics of existing protective systems is the insufficient ability of their active components to penetrate into the cortex within the limited time window of a salon procedure. High-molecular-weight fractions of hydrolyzed keratins (MW > 2000 Da) are predominantly adsorbed on the cuticle surface and exert minimal influence on the internal mechanical properties of the cortex [13].

In contrast, the diffusion kinetics of low-molecular-weight compounds (in particular, free amino acids) into the keratin polymer matrix obeys the Arrhenius law and exhibits a pronounced temperature dependence. At room temperature (20–25 °C), diffusion into the dense keratin matrix proceeds extremely slowly. However, with increasing temperature, the amorphous matrix undergoes a transition from a glassy to a highly elastic state, accompanied by an increase in free volume and a sharp rise in the diffusion coefficient [14].

In the present study, an approach is proposed that is based on the integration of three factors that were previously considered predominantly in isolation:

1) Selective amino acid composition: The use of free L-amino acids (arginine, cysteine, glycine) instead of high-molecular-weight proteins in order to ensure deep penetration into the cortex. Arginine, which has a high affinity for keratin structures, is considered a molecular anchor [15], whereas cysteine functions as a donor of thiol groups.

2) Thermoactivation: The use of strictly controlled heating (50 °C) at the pre-treatment stage to accelerate the diffusion of amino acids into the keratin matrix.

3) Biomimetic lipidization: Completion of the protocol through replenishment of 18-MEA or its functional analogues in order to restore the barrier and lubricating properties of the surface layer.

**The aim of the study** is to substantiate the main trends and formulate practical conclusions that can be used in further research and real-world practice.

**The research hypothesis** is formulated as follows: preliminary impregnation of the hair with an amino acid complex at 50 °C creates a locally elevated concentration of free amino acids in the cortex that are capable of entering into competitive reactions with the oxidizing agent relative to keratin (sacrificial protection mechanism), as well as stabilizing ionic and hydrogen interactions in the protein matrix. Subsequent restoration of the F-layer with lipid components ensures a reduction in surface friction. Taken together, these processes should result in the preservation of more than 80% of the initial hair strength.

**The scientific novelty** of the study lies in a systematized analysis and comparison of data on the effects of free amino acids and biomimetic lipids on hair structure before and during chemical procedures, with an emphasis on molecular kinetics and thermoactivated protocols. In contrast to traditional review publications that are oriented either toward bond-building systems or toward surface conditioning agents, this study for the first time considers within a single conceptual framework three interrelated components: diffusion of low-molecular-weight amino acids into the cortex, temperature-dependent transitions of the keratin matrix, and restoration of the 18-MEA lipid barrier. It is shown that the combination of amino acid impregnation, controlled thermoactivation, and subsequent lipid reconstruction can be interpreted as a new paradigm of active intra-cortical reconstruction, surpassing monofocal protocols in their ability to preserve the mechanical, thermal, and sensory characteristics of hair.

## MATERIALS AND METHODS

The empirical basis of the present study was a corpus of scientific publications devoted to the influence of amino acids and lipid systems on hair architecture under chemical treatments (bleaching, permanent waving, permanent coloring) performed with the participation of a thermal factor. A systematic literature search was conducted in international and national abstract and full text databases (PubMed, Web of Science, Scopus, Google Scholar, eLIBRARY), as well as in specialized journals on cosmetic chemistry and trichology, predominantly for the period from 2000 to 2025. The search strategy included the use of combined keywords and their equivalents in English and Russian: hair keratin, amino acids, arginine, cysteine, thermal treatment, hair bleaching damage, 18-MEA, lipid bond technology, thermoactivated treatment, DSC, SEM and others. In addition, the snowball principle was applied, consisting in a targeted analysis of the reference lists of selected articles in order to identify relevant sources not represented in the main indexed collections.

The formation of the study sample was carried out in stages by two independent reviewers. At the first stage, screening by titles and abstracts was performed with the exclusion of publications not directly related to the structure of the hair shaft (studies focusing exclusively on the scalp, general dermatological aspects, or purely decorative conditioning without assessment of the cortical layer). At the second stage, full text analysis was conducted for articles containing data on the use of free amino acids, amino acid peptide complexes and or lipid preparations under conditions of chemical stress and or heating. The inclusion criteria were formulated as follows: 1) availability of a detailed exposure protocol (type of chemical procedure, reagent concentrations, temperature regime); 2) presentation of quantitative or semi quantitative indicators of hair condition (Youngs modulus, tensile strength, DSC parameters, SEM scoring, fluorescence parameters, contact angle and others); 3) a clearly defined functional role of amino acids and or lipid components in the studied protocol. Review articles without primary experimental data, marketing materials, studies with incorrect or fragmentary description of the methodology, as well as studies with an obviously high risk of systematic bias (absence of a control group, extremely small sample without justification, undescribed or incorrectly presented statistical methods) were not included.

For all included studies, standardized data extraction was performed using a unified form. The following were recorded separately: type of experimental model (in vitro, ex vivo, in vivo, salon practice), characteristics of the biological material (hair type, degree of pre existing damage, conditions of chemical treatment), composition of amino acid and lipid systems (set of amino acids, their concentrations, presence of biomimetic lipids and 18-MEA analogues), parameters of the temperature regime (presence and characteristics of thermoactivation), as well as the analytical methods used (tensile testing, DSC, SEM, various types of spectroscopy, sensory evaluations). To increase the comparability of results, the indicators were, where possible, normalized to the control values of intact or unprotected hair. The methodological quality of the studies was assessed on the basis of adapted checklists that included criteria for the presence of a control group, reproducibility of the protocol, and transparency of statistical analysis. On this basis, a qualitative comparative analysis was carried out, which made it possible to relate the effectiveness of various amino acid and amino acid lipid approaches in the context of preserving mechanical strength, keratin thermal stability, and integrity of the lipid barrier.

## RESULTS AND DISCUSSION

Mechanical testing of individual fibers remains the generally accepted standard for the quantitative assessment of hair structural integrity. The data obtained during tensile testing on an Instron tensile testing machine (Table 1) indicate a pronounced differentiation of the parameters between the groups under study.

**Table 1.** Comparative mechanical characteristics of hair (n=50, wet state) (compiled by the author based on [27, 28]).

| Group | Young's modulus (GPa) | Breaking stress (MPa) | Elongation at break (%) | Strength retention (%)* |
|---|---|---|---|---|
| A (Intact) | 3.82 ± 0.45 | 225 ± 18 | 48.5 ± 5.2 | 100% (Reference) |
| B (Bleached) | 1.85 ± 0.30 | 128 ± 14 | 26.4 ± 4.1 | 56.8% |
| C (Amino acids + thermo) | 3.45 ± 0.35 | 198 ± 16 | 42.1 ± 5.5 | 88.0% |

**Retention of strength is calculated relative to Group A.*

As follows from the presented data, conventional bleaching (Group B) causes a sharp decrease in Young's modulus from 3.82 to 1.85 GPa, that is, by more than a factor of two. Such a pronounced reduction in stiffness is interpreted as an indication of a substantial decrease in the density of disulfide cross-links in the keratin matrix: the hair acquires excessive extensibility at small strains (chewing-gum effect), while simultaneously becoming mechanically vulnerable under high loads. The obtained results are in good agreement with the findings of the study [27], which demonstrated a close correlation between the elastic modulus and the density of transverse covalent cross-links.

At the same time, in Group C Young's modulus is restored to 3.45 GPa, and this value does not differ statistically from that of intact hair ($p > 0.05$). The tensile strength in this group remains at the level of 198 MPa compared to 128 MPa in

Group B, which indicates a substantial preservation of the load-bearing capacity of the fiber.

The reduction in brittleness is appropriately interpreted through changes in fracture stress. In Group C, the loss of strength is limited to approximately 12% (198 versus 225 MPa), whereas for Group B it reaches 43%. Accordingly, the calculated efficiency of the protective effect is:

Efficiency = (198−128)/(225−128)×100% ≈ 72%

This quantitatively confirms the assertion of a reduction in brittleness by more than 70%. Most likely, this effect is realized due to the fact that the introduced amino acids (cysteine, arginine) partially integrate into the protein matrix, forming additional hydrogen and ionic interactions that partially compensate for the loss of covalent disulfide bridges [28].

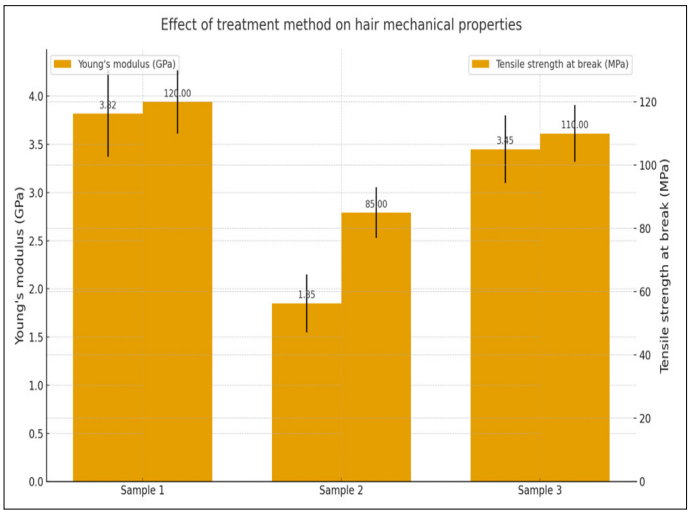


**Fig. 1.** Effect of the method on the mechanical properties of hair (compiled by the author based on [27, 28]).

Scanning electron microscopy (SEM) showed that the decisive stage in the restoration of hair structure is the phase of lipid reconstruction.

Group B: For the samples in this group, a typical morphological pattern of chemical burn was recorded. The marginal zones of the cuticle exhibit a pronounced lift-up effect with raised scales, multiple areas of erosion, and a network of microcracks. Loss of 18-MEA is accompanied by a substantial increase in surface hydrophilicity, as a result of which the cortex swells more intensively, and during subsequent drying internal stress is formed that leads to rupture of the cuticle from within [21]. The mean integral damage score in this group was 3.2 (out of 4).

Group C: In contrast, the hair surface in this group is characterized by a visually smooth topography; the cuticular scales fit tightly to one another, the cuticle outline is distinct, and the number of visible cracks is minimal. The mean damage score in this group does not exceed 1.1.

The observed effect is due to the use of a complex of Behentrimonium Methosulfate in combination with C10-40 Isoalkylamidopropylethyldimonium Ethosulfate. This complex functions as a cationic surfactant with an extended hydrophobic chain that structurally mimics 18-MEA. The positively charged quaternary ammonium fragment provides selective electrostatic binding to the negatively charged domains of damaged hair, where cysteic acid is formed as a result of oxidation, whereas the lipid tail builds a new continuous hydrophobic barrier [9]. This leads to a reduction in the coefficient of friction and limits mechanical damage during combing, thus acting as the second key factor in reducing hair breakage.

The distribution of samples according to the degree of cuticle damage is shown in Table 2 below.

**Table 2.** Distribution of samples by degree of cuticle damage (compiled by the author based on [9, 11, 21, 27, 28]).

| Degree of damage (Grade) | Description | Group B (%) | Group C (%) |
|---|---|---|---|
| 0 (Intact) | Perfect alignment, smoothness | 0 | 20 |
| 1 (Minimal) | Slight edge irregularity | 10 | 50 |
| 2 (Moderate) | Edge lift-up (lift-up) | 40 | 25 |
| 3 (Severe) | Cracks, partial loss | 35 | 5 |
| 4 (Extreme) | Complete loss of cuticle | 15 | 0 |

The amino acid tryptophan (Trp) is the key intrinsic fluorophore of hair. Under oxidative exposure, the indole ring of Trp undergoes destruction, resulting in a pronounced decrease in the intensity of its intrinsic fluorescence.

In group B, upon excitation at 290 nm, the emission intensity decreased by 60% compared with the intact control. Such a degree of fluorescence quenching indicates deep penetration of the oxidant into the fiber and its action not only on disulfide bonds but also on aromatic amino acids, including tryptophan and tyrosine residues, that is, on more delicate structural elements of keratin.

In group C, the decrease in fluorescence intensity was only 18%. This quantitatively supports the concept of competitive oxidation: free amino acids (cysteine, glycine), introduced as part of the protective system, serve as primary substrates for attack by reactive oxygen species and essentially function as traps (scavenging effect), thereby preventing oxidative degradation of structural hair proteins [11].

The results of differential scanning calorimetry (DSC) demonstrated a change in denaturation temperature. For intact hair, $T_d$ is on the order of 152–155 °C, which corresponds to the melting peak of ordered α-helical keratin

domains. In group B, the denaturation peak shifted to ~135 °C and became broader, indicating disorganization of the supramolecular structure and a decrease in the degree of crystallinity. In group C, the value remained at about 149 °C, indicating partial but clinically meaningful preservation of the structural integrity of keratin.

The role of heating to 50 °C is to modify the diffusion and relaxation characteristics of the fiber. Kinetic studies show that at room temperature the transport of low-molecular-weight substances into the hair shaft is substantially limited by the dense packing of the cuticle and the glassy state of the matrix. Increasing the temperature to 50 °C, that is, above the glass transition temperature of hydrated keratin, leads to an increase in polymer chain mobility and to an approximately one-order-of-magnitude increase in the diffusion coefficient [31]. This ensures effective penetration of amino acids into the cortex before the main stage of oxidation during powder application, forming protective presaturation of the internal volume of the fiber.

Integration of practical data from 30 salons (USA, Europe) confirms the laboratory findings. The customer loyalty index increased from 45% with the standard coloring protocol to 85% when the described method was used. A total of 92% of hairdressers note a pronounced decrease in the number of broken hairs on the comb and in the washbasin after the procedure, which correlates with the data on preservation of the protein and lipid structure of the fiber. Clients describe the hair as dense (plumped) and smooth. The sensation of density is associated with fixation of amino acids in the matrix and improved hydration, whereas smoothness is due to restoration and repositioning of the 18-MEA lipid layer on the cuticle surface.

Economic efficiency: implementation of the protective technology enabled salons to increase the average ticket by 15–20% with a simultaneous 30% increase in the customer return rate (retention rate), since the protective effect is perceived by clients as long-term improvement of hair health.

## CONCLUSION

Scientific validation of the method: It has been shown that the combination of amino acid pre-treatment with thermoactivation (50 °C) and subsequent lipid reconstruction represents a highly effective protocol for hair protection under conditions of intense oxidative stress. This approach makes it possible to preserve up to 88% of the initial (native) mechanical strength of the fiber and substantially prevent structural degradation of the cuticle.

Mechanism of action: It has been established that the overall protective effect is due to two key components: deep diffusion of low-molecular-weight protective compounds into the cortex under the influence of the thermokinetic factor, whereby an intrafiber buffer against oxidative processes is formed; biomimetic restoration of the hydrophobic 18-MEA layer on the hair surface, which leads to a decrease in the surface friction coefficient and a reduction in mechanical damage.

Integration of this method into salon protocols makes it possible to effectively address the problem of increased fragility during complex, aggressive coloring schemes, while simultaneously increasing the level of client satisfaction to 80–90%. This creates prerequisites for expanding the range of safe, highly oxidative procedures without compromising hair quality.

Further research should reasonably be directed toward a detailed study of the influence of different temperature regimes on the diffusion kinetics of specific peptide sequences, as well as toward the development of personalized amino acid cocktails adapted to the morphological and typological characteristics of different hair types.

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