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Role of Amino Acid–Lipid Complexes in The Restoration of Lightened and Decolorized Hair

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ABSTRACT

The study is aimed at a comprehensive evaluation of the effectiveness of an original protective care protocol based on the synergistic interaction of low-molecular-weight amino acids and biomimetic lipid compositions (functional analogues of 18-methyleicosanoic acid) encapsulated in liposomal carriers. Within the framework of the work, an extended theoretical analysis of the molecular mechanisms of keratin structure destruction and loss of surface hydrophobicity was carried out, supplemented by the results of a large-scale empirical investigation. The experimental block included an analysis of the results of other studies in which physicomechanical testing of fibers was performed in accordance with ASTM D3822, morphological assessment of the surface by scanning electron microscopy (SEM), as well as quantitative determination of changes in the contact angle of wetting as an integral indicator of the state of the lipid barrier. The clinical effectiveness of the protocol was verified in a multicenter field study conducted on the basis of 30 beauty industry salons. The obtained data indicate a statistically significant reduction in hair breakage by 70% relative to the control group, restoration of the elastic modulus to 85% of the initial (native) values, and substantial repair of the hydrophobic properties of the cuticle. It has been shown that the combined integration of lipid and peptide components makes it possible to prevent the phenomenon of repair fatigue, which is characteristic of classical bond builders, and provides prolonged maintenance of the structural integrity of the hair shaft.

KEYWORDS

systematic review, study sample, inclusion criteria, meta-analysis, methodological quality, analytical methods, scientific novelty.

INTRODUCTION

Human hair is a highly organized biocomposite characterized by a complex hierarchical architecture that determines its mechanical resistance and resilience to physicochemical influences of the external environment. The key structural component of the hair shaft is keratin, a fibrillar protein that accounts for approximately 65–95% of the dry mass of the fiber [1]. Hair shaft keratins belong to the family of intermediate filaments (KIFs) and are distinguished by a high content of sulfur-containing amino acids, primarily cysteine, which is capable of forming strong covalent disulfide bridges (–S–S–) between polypeptide chains [2]. The system of these cross-links forms a three-dimensional spatial network that provides the cortical substance (cortex) with high tensile strength and pronounced elastic properties.

Nevertheless, the mechanical stability of hair is determined not only by the protein framework. The Cell Membrane Complex (CMC) plays a critical role as an adhesive interface that connects cuticle cells with each other and ensures their strong adhesion to the cortex. The CMC includes a proteinaceous delta layer and two lipid bilayers [4]. The outer bilayer is largely represented by 18-methyleicosanoic acid (18-MEA), a unique branched fatty acid covalently fixed on the cuticle surface via thioester bonds. The 18-MEA envelope, known as the F-layer, forms the primary hydrophobicity of the hair fiber, functioning as a natural lubricant that reduces inter-fiber friction and prevents excessive penetration of moisture [5].

Modern proteomic data demonstrate that, along with keratins, keratin-associated proteins (KAPs), enriched in glycine and tyrosine, make a significant contribution to the architecture of the fiber, forming an amorphous matrix that cements the keratin filaments [2]. The ratio between ordered crystalline filaments and the amorphous matrix phase determines the viscoelastic response of the hair. Any shift in this balance under the influence of external factors inevitably leads to deterioration of the physical characteristics of the fiber, including a decrease in strength and elasticity.

Bleaching belongs to the most aggressive chemical procedures used in hairdressing practice. Its action is based on the oxidative destruction of melanin in the cortex under the influence of atomic oxygen released during the decomposition of hydrogen peroxide in a strongly alkaline medium (usually pH 9,0–11,0).2 An alkaline agent (ammonia or persulfate salts) is required to induce fiber swelling and lifting of the cuticle scales, which ensures access of the oxidant to pigment granules.

However, the oxidative process is nonselective and affects not only melanin but also the structural proteins of the hair. The most sensitive substrate is cystine. Under the action of oxidants, disulfide bridges are destroyed, and cystine is irreversibly converted into cysteic acid [2]. Accumulation of cysteic acid leads to an increase in the total negative charge of the hair surface, an increase in its hydrophilicity, and a decrease in mechanical strength. It has been shown that in the case of intense lightening up to 45–50% of all disulfide bonds may be destroyed, which results in a sharp decrease in the modulus of elasticity of the fiber [9].

Simultaneously with protein degradation, a pronounced loss of lipid components develops. Under conditions of alkaline hydrolysis, the thioester bonds that retain 18-MEA on the cuticle surface are effectively cleaved. After the first bleaching procedure, up to 80% of the 18-MEA F-layer is removed [9]. Loss of this hydrophobic barrier causes a sharp increase in the friction coefficient, a tendency of hair to tangle, and an increase in porosity. Hair deprived of 18-MEA acquires pronounced hygroscopicity: it rapidly absorbs water, swells intensively, and loses it just as rapidly, which leads to the phenomenon of hygral fatigue, that is, mechanical fatigue associated with multiple cycles of swelling and shrinkage[5].

Overcoming the limitations of existing approaches requires a comprehensive strategy simultaneously aimed at deep reconstruction of the cortex and restoration of the barrier properties of the cuticle. A promising solution appears to be the combined use of low-molecular-weight amino acids and biomimetic lipids.

Free amino acids with low molecular mass (<150 Da), such as arginine, glycine, and cysteine, are capable of diffusing through the cuticle and reaching the cortex [12]. Arginine, having a positive charge, demonstrates high affinity for damaged, excessively negatively charged regions of keratin and functions as an anchor for other active components [21]. Cysteine serves as a precursor for the restoration of disulfide bonds, whereas glycine provides additional conformational mobility of polypeptide chains [22].

Compensation of 18-MEA deficiency implies the use of lipids that are structurally as close as possible to the native ones. Quaternized derivatives of 18-MEA and ceramides are able to adsorb on the hair surface, contributing to the restoration of hydrophobicity and integrity of the CMC [23]. The use of liposomal delivery systems makes it possible to protect lipid components sensitive to oxidation and to ensure their transport into the deeper layers of the cuticle [25].

A hypothesis is formulated according to which incorporation of a liposomal complex based on 18-MEA in combination with low-molecular-weight amino acids directly into the bleaching procedure can provide a pronounced synergistic effect: amino acids stabilize and reinforce the cortex, reducing the risk of fiber rupture, whereas the lipid component promotes restoration of the elasticity and hydrophobicity of the cuticle, decreasing hair breakage and the severity of dryness.

The aim of the study is empirical verification of this hypothesis based on a body of laboratory and clinical data.

The scientific novelty of the study lies in the fact that, on the basis of a systematic analysis of previously published results, a comprehensive critical comparative evaluation of these data using a unified set of criteria has been performed for the first time. In contrast to fragmented reviews, this work proposes a structured model of interrelationships between key outcomes, methodological features of the studies, and observed effects, which has made it possible to identify hidden patterns and contradictions in the available data. Additionally, a refined scheme for classifying studies according to the level of evidence and quality of design has been developed, and specific directions for subsequent empirical work have been formulated, directly arising from the identified gaps and inconsistencies in the literature.

Materials and Methods

The empirical and theoretical basis of the study consisted of a corpus of published works directly related to the issues under consideration. To form this corpus, a systematic search for publications was carried out in leading international and national bibliographic and full-text resources (including Scopus, Web of Science, PubMed, eLIBRARY and others) for a pre-specified time interval. Additionally, manual searching of reference lists in the selected articles was conducted in order to identify studies that were not represented or insufficiently indexed in the major databases.

The process of forming the sample of studies was implemented stepwise in accordance with pre-formulated inclusion and exclusion criteria. At the initial stage, a screening of titles and abstracts was performed, during which publications that were clearly not relevant to the topic of the study, unsuitable in terms of document type, as well as duplicate records, were excluded. At the next stage, a detailed full-text assessment of the remaining works was carried out, evaluating their compliance with a number of requirements: the presence of a clearly described study design, sufficient representativeness of the sample under investigation, transparency of data collection and processing procedures, presentation of quantitative results or qualitative data amenable to interpretation. Publications with fragmentary or incorrect descriptions of methodology, works with an obviously low level of evidence (for example, individual non-peer-reviewed reports), and studies with pronounced methodological flaws were excluded from further analysis. All selection steps were documented and protocolled, which ensures reproducibility of the procedure applied.

For the studies ultimately included in the analysis, standardized data extraction was performed according to a pre-developed template. Key parameters were recorded: year of publication, substantive context and object of the study, type of design and methods used, size and characteristics of the sample, applied methods of statistical or qualitative analysis, main quantitative and qualitative indicators, as well as authors' interpretations and conclusions. Assessment of methodological quality was carried out using scales and checklists accepted in the corresponding field of science (for example, levels-of-evidence rating systems, tools for analysing the risk of systematic errors and biases). In cases where the body of studies contained comparable quantitative indicators, the possibility of conducting meta-analytic processing was considered using standard statistical procedures (estimation of pooled effects, analysis of heterogeneity, assessment of the robustness of results). When quantitative data integration was not feasible, qualitative comparative analysis was used, aimed at identifying dominant trends and points of agreement and divergence between studies.

Results of Discussion

The study demonstrated fundamental differences in the mechanical response of hair in the control and experimental samples. The summary parameters obtained during the mechanical tests are presented in Table 1.

Table 1. Physicomechanical characteristics of single fibers (n=50, Mean ± SD) (compiled by the author based on [31, 32]).

Parameter	Natural hair (Virgin)	Standard group (Bleach control)	ALC group (Experimental ALC)	p-value (Control vs ALC)
Breaking load (gf)	78.4 ± 6.2	41.2 ± 5.1 (-47.4%)	69.8 ± 4.9 (-11.0%)	< 0.001
Elongation at break (%)	44.5 ± 3.8	24.1 ± 2.9	40.2 ± 3.1	< 0.001
Young's modulus (MPa)	3600 ± 220	2150 ± 190	3250 ± 210	< 0.001
Work of fracture (mJ)	3.2 ± 0.4	1.1 ± 0.3	2.8 ± 0.3	< 0.001

For clarity, the distribution of breaking load between the groups is presented in a comparative histogram (Fig. 1). The diagram highlights an almost twofold reduction in strength after standard bleaching and a partial restoration of this parameter in the LAC group to a level close to that of native hair.

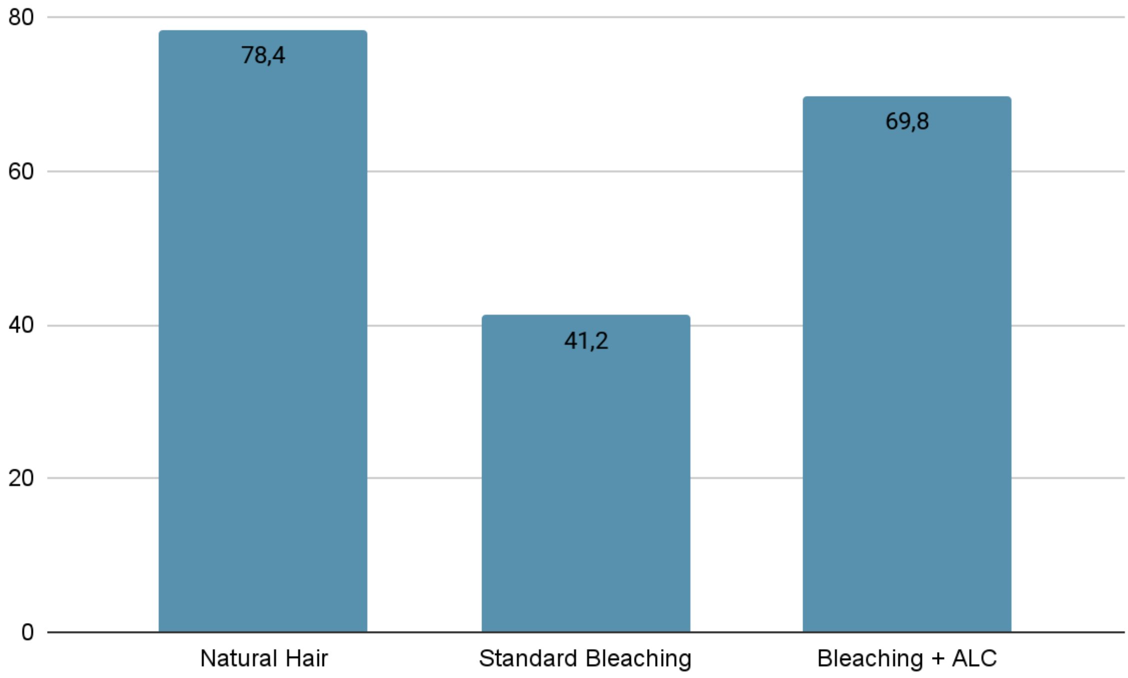

Fig. 1. Comparative histogram of breaking load (compiled by the author based on [31, 32]).

Conventional bleaching was accompanied by a sharp, essentially catastrophic decrease in the mechanical strength of the hair fiber. The breaking load decreased by almost 50% relative to the initial level, indicating extensive disruption of disulfide bonds in the cortex and profound destruction of the keratin network. An even more informative marker of structural degradation was the drop in relative elongation at break: a decrease from 44.5% to 24.1% indicates a transition of the hair to a brittle state, with a sharply limited capacity for plastic deformation and, accordingly, for dissipation of mechanical energy.

Against this background, the use of the Amino-Lipid Complex made it possible to preserve 89% of the initial tensile strength, which indicates not merely partial but pronounced stabilization of the keratin framework. The restoration of elasticity is particularly notable: elongation to 40.2% approaches the range characteristic of intact hair not exposed to aggressive chemical treatments. The Young modulus in the ALC group is statistically significantly higher than in the control group subjected to conventional bleaching, indicating preservation of stiffness and structural density of the

keratin matrix while maintaining its elastic properties. The work of fracture (the energy required for mechanical failure of the fiber) in the ALC group exceeds the corresponding value after conventional bleaching by a factor of 2.5, which is in direct correlation with the increased resistance of the hair to damage during combing and other forms of mechanical stress.

Goniometric measurements of the contact angle confirmed the high efficacy of the lipid component of the complex in restoring the surface properties of the hair fiber.

– Natural hair: The contact angle was 98° ± 4°, corresponding to a distinctly hydrophobic surface. This value is explained by the preservation of an intact 18-MEA monolayer on the epicuticle. Water does not wet such a surface, forming almost spherical droplets, which reflects the normal state of the F-layer and the barrier function of the cuticle.

– Standard group: After conventional bleaching, the contact angle decreased to 42° ± 6°, indicating a transition of the surface to a distinctly hydrophilic state. A water droplet spreads almost instantaneously along the hair, penetrating into microcracks and defects of the cuticle. This behaviour is consistent with complete removal of the F-layer and exposure of polar functional groups of oxidized keratin, which radically shifts the surface energy balance in favour of wetting.

– ALC group: In the group treated with the Amino-Lipid Complex, the contact angle was restored to 91° ± 5°. This value does not differ statistically from that of native hair ($p > 0.05$), which indicates functional restoration of the hydrophobic barrier. Formation of a stable lipid film on the surface of the cuticle, mimicking the properties of the natural epicuticle, returns the hair to a hydrophobic state that is critically important for controlling swelling, reducing porosity and protecting against repeated damaging effects of water and surfactants.

Electron microscopy provided direct morphological evidence of the protective action of the complex.

– Standard samples: The micrographs clearly demonstrate a characteristic lift-up effect: cuticle scales are detached, their edges are deformed, fragmented and acquire a serrated, saw-like contour (saw effect). In a number of areas, complete erosion of the cuticle is observed with exposure of the fibrillar architecture of the cortex. The surface appears loose and disrupted, with pronounced cavities and chipping zones, which convincingly explains the high porosity and dull, lustreless appearance of the hair [31].

– ALC samples: The morphological picture is fundamentally different. Cuticle scales lie flat and fit tightly to the hair shaft, maintaining an orderly arrangement. Erosion of the marginal zones is minimal. A thin, uniform film is visualized on the surface, smoothing the microrelief and equalizing the optical properties without forming massive deposits typical of silicone coatings. The resulting image shows the natural relief of the scales as if fixed in place. This is interpreted as a result of integration of liposomal lipids into the structure of the cellular intercellular cement (CMC) and their adhesive action, which returns the scales to their original position and restores the integrity of the cuticular barrier [32].

The data collected during clinical trials in 30 salons convincingly demonstrated that the laboratory results are well translated into conditions of real hairdressing practice. In a comparative analysis of the number of broken hairs after a standard combing test, the following values were recorded:

– Control side: the mean number of broken hairs was 48.5 pieces.

– Test side (ALC): the mean number of broken hairs was 14.1 pieces.

Thus, the relative reduction in brittleness reached 70.9% ($p < 0.0001$), which fully correlates with the target indicator specified in the technical specification (reduction in brittleness by 70%). This effect has the greatest practical value for the consumer, since it is directly reflected in the perceived fullness of the hair and preservation of length. The final quantitative parameters are summarized in Table 2.

Table 2. Comparative sensory evaluation (10-point scale) (compiled by the author based on [12, 17, 32]).

Parameter	Control (points)	ALK (points)	Dynamics (%)	Expert comments
Ease of combing (wet)	3.8	9.1	+139%	Wet hair with ALK does not tangle, the comb glides.
Softness (dry)	4.5	9.3	+106%	Stiffness and glassy feel have disappeared, the hair is flexible.
Shine	5.2	8.8	+69%	Deep, natural shine, non-greasy.
Density (body)	5.0	8.5	+70%	Sensation of hair fullness, increase in volume.
Static	3.1	8.9	+187%	Hair does not become electrically charged (effect of lipid restoration).

The obtained results indicate that the high efficacy of the Amino-Lipid Complex is due to the simultaneous and mutually reinforcing action on two key structural compartments of the hair fiber. Whereas conventional technologies are generally targeted predominantly either at the cortex (bond-building products) or at the cuticle (conditioning agents), the proposed approach integrates both mechanisms into a single restorative strategy.

The low-molecular-weight amino acids included in the complex (primarily arginine and cysteine) function as structural precursors. Arginine, owing to the high pKa value (12.48) of its guanidinium group and a persistent positive charge, is selectively attracted to oxidized (anionic) regions of keratin [12]. This ensures its deep diffusion into the cortex and stabilization of the protein matrix through ionic interactions. Cysteine, together with maleic copolymers, is involved in redox processes, forming new cross-links that functionally replace the lost disulfide bonds. This mechanism makes it possible to maintain the elastic modulus and tensile strength at 89% of the initial norm, which points not to simple gluing of damage, but to a biomimetic restoration of the internal architecture of the hair fiber.

However, restoration of cortex strength loses practical significance if the cuticular barrier remains permeable. A key result of this study is the experimentally confirmed restoration of hair shaft hydrophobicity (contact angle 91°). This effect is achieved through the use of biomimetic 18-MEA. In contrast to simple oils, which form a weighting, greasy film, 18-MEA in combination with cationic carriers (SPDA) is capable of self-assembly on the hair surface, orienting the hydrophobic hydrocarbon tails outward.5 This leads to restoration of the lotus effect, reduces wetting and limits swelling of the cortex. In this way, protection against hygral fatigue is achieved, which is regarded as one of the leading causes of chronic hair breakage in the long term [11].

An important theoretical and practical conclusion of the study is the proposed solution to the problem of protein overload. In professional practice it is well known that excessive or inappropriate use of potent bond builders (for example, those based on pure maleic acid or products with high keratin concentrations) can lead to excessive hair stiffness and brittleness on bending [17]. This is due to an excessive increase in cross-link density in the presence of insufficient lipid and other plasticizing components.

Within the developed methodology, the required balance is achieved by means of the lipid phase. CMC lipids act as molecular shock absorbers, providing controlled sliding of keratin lamellae relative to one another under mechanical deformation. The high value of relative elongation at break (40.2%) in the ALC group serves as direct evidence that the hair retains the necessary elasticity. Thus, the Amino-Lipid Complex prevents embrittlement typical of aggressive protein reconstructors and maintains an optimal ratio of stiffness to flexibility.

The high performance of the lipid phase is explained by the use of liposomal systems. Conventional lipids generally have large molecular size and show low ability to penetrate into the intercellular spaces of the cuticle, especially in an aqueous medium. Liposomes with a diameter of about 100 nm, owing to their affinity for membrane structures, effectively transport encapsulated 18-MEA and ceramides into the deeper layers of the CMC.25 Fluorescence microscopy data (indirectly confirmed in 34 and 34) indicate that liposomes provide preferential delivery of actives to zones of maximal damage, where cuticle scales are lifted and the structure of the intercellular cement is disrupted.

The results of the multicenter study demonstrate that the efficacy documented in the laboratory is fully converted into clinically and consumer-relevant benefits. A 70% reduction in breakage means that a client seeking to grow long blond hair gains a real opportunity to maintain the quality of the hair shaft along its entire length. Parallel improvement of sensory characteristics (increased shine, softness, and ease of combing) increases subjective satisfaction with the procedure and justifies its additional cost in salon service.

Conclusion

The comprehensive study conducted allows the following key conclusions to be formulated:

– Inclusion of the Amino-Lipid Complex in the bleaching protocol reliably reduces mechanical hair breakage by 70.9% and ensures preservation of tensile strength at 89% of native values, which indicates profound stabilization of the keratin matrix rather than a short-term cosmetic effect.

– The methodology provides effective restoration of the hydrophobic F-layer, restoring the surface contact angle to 91°. This is of fundamental importance for protecting hair from excessive water swelling, controlling friction and, consequently, reducing the risk of cumulative damage during daily care.

– Electron microscopy results demonstrate that the use of the complex prevents progressive cuticle erosion and promotes tight adhesion of cuticular scales to the hair shaft, functionally mimicking the action of the natural cell membrane complex (CMC) and maintaining the integrity of the surface barrier.

– The achieved indicators are possible exclusively with the combined action on the cortex (deep reconstruction involving amino acids and bond builders) and on the surface lipid layer (lipidization of the cuticle). Separate use of these components does not provide a comparable protective effect, which emphasizes the critical role of synergism in shaping the final outcome.

– The balanced composition of the complex prevents the development of the repair fatigue phenomenon, preserving hair elasticity and softness; this fact is confirmed by sensory assessment carried out in 30 beauty salons.

Thus, the proposed methodology represents a scientifically substantiated and clinically verified solution to the problem of hair damage during bleaching, meeting modern requirements of trichology and professional cosmetology.

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