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Disulfide Bond Protection Systems Vs Amino Acid Protector: Comparative Analysis in Real Salon Practice

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Abstract

In the context of contemporary aesthetic trichology and cosmetology, the task of preserving the structural integrity of keratin fibers under exposure to aggressive chemical factors is acquiring a fundamentally critical character. In the present work, a comparative analysis was carried out of the effectiveness of classical plex systems and an innovative proprietary technology of amino acid–lipid protection. The methodological basis of the study consisted in the use of a combination of biomimetic peptides and low-molecular-weight lipids aimed at compensating for the deficit of 18-methyleicosanoic acid (18-MEA). The results obtained in the course of the analysis indicate that the integrative approach not only maintains tensile strength at the level of leading bond-building systems but also significantly surpasses them in terms of the restoration of elasticity and hydrophobicity, as well as improvements in the sensory characteristics of the hair fiber.

Keywords: disulfide bonds, bond-building systems, amino acid–lipid protection, biomimetic peptides, hair lipid barrier, hair lightening, salon practice.

Introduction

The professional hair care industry is entering a phase of radical transformation of technological approaches. If the interval 2014–2020 can be described as the era of plexes (bond builders), initiated by the introduction of Olaplex and its numerous analogues, the current development cycle (2024–2025) is increasingly characterized by the concept of skinnification [2]. Within this paradigm, hair is considered not as an isolated appendage of the skin, but as its functional extension, requiring a comparable level of dermatologically oriented care with the use of highly active ingredients such as peptides, hyaluronic acid, lipid complexes, and antioxidants.

According to analytical reports, the hair care segment in the Middle East and Africa region, where a historically high standard of salon procedures has been established, demonstrated growth of 17% in the period 2024–2025 [4]. In the global market, there is a stable shift in demand towards personalized and scientifically validated products. The modern consumer is becoming more informed and critical, insisting on demonstrable efficacy, which forces manufacturers and technologists to shift the emphasis from purely marketing narratives to rigorous biochemical and trichological argumentation [5]. Under these conditions, classical protection protocols during bleaching, based on the action of a single key molecule (for example, maleic acid), are perceived as methodologically limited and insufficiently systemic.

For correct interpretation of the mechanisms of protective action, it is necessary to characterize in detail the substrate of impact. Human hair is a highly organized biocomposite that includes three main morphological zones: cuticle, cortex, and medulla.

The cortex, which forms up to 90% of the mass of the hair shaft, is constructed from keratin intermediate filaments (KIF) integrated into an amorphous matrix of keratin-associated proteins (KAP). The mechanical strength and functional stability of this system are ensured by a complex hierarchy of chemical interactions:

Disulfide (covalent) bonds (S–S): formed between sulfur atoms in the side chains of cysteine residues. These are the strongest bonds that determine the shape of the hair and its resistance to breakage; they are the primary target of oxidative stress during bleaching procedures [6].

Ionic (salt) interactions: arise between positively charged amino groups (NH_3^+) and negatively charged carboxyl groups (COO^-); their stability depends significantly on the pH of the medium.

Hydrogen bonds: numerous but energetically weak interactions that are easily disrupted by water and spontaneously restored during the drying of the hair [7].

Exposure to alkaline agents (ammonia, ethanolamine) in combination with oxidizing agents (hydrogen peroxide, persulfates) leads to cleavage of S–S bonds. Part of the disulfide bridges is subsequently reformed; however, a significant proportion undergoes further oxidation to cysteic acid (cysteic acid, SO_3H). This process is irreversible and is accompanied by progressive loss of structural integrity of the hair shaft [8].

For a long time, the contribution of the lipid component to hair quality and health was underestimated; however, current data indicate its critically important role. Although lipids account for only 1–9% of hair mass, they perform the function of intercellular cement. The cell membrane complex (CMC) provides adhesion between cortical cells and fixation of the cuticular plates relative to the cortex.

CMC is structured into the following elements:

– Beta-layers, lipid layers of oriented packing with a thickness of about 5 nm;

– Delta-layer, a protein layer between the beta-layers with a thickness of about 15 nm [9].

Particular importance is attributed to 18-methyleicosanoic acid (18-MEA), a unique lipid covalently bound to the epicuticle. It is 18-MEA that provides pronounced hydrophobicity of the hair surface, reduces friction and tangling, and determines the characteristic healthy shine. Under the influence of an alkaline environment (pH > 9), the ester bond that anchors 18-MEA is hydrolyzed, as a result of which the hair becomes more hydrophilic, porous, and visually dull [11].

The revolutionary shift initiated by the launch of Olaplex in 2014 was associated with the introduction of technologies based on bifunctional molecules (bis-aminopropyl diglycol dimaleate) capable of reorganizing broken disulfide bridges. The mechanism of action of such systems is based on the Michael addition reaction, in the course of which the active component crosslinks free thiol groups, blocking their further irreversible oxidation [13].

Despite the high efficacy in preserving tensile strength, the unilateral focus on restoring S–S networks revealed a number of limitations. Practicing hairdressers and clients began to observe a phenomenon of overloaded structure: hair objectively demonstrated high tensile strength, but subjectively and under bending was perceived as rigid, dry, and brittle. This condition, referred to as repair fatigue, is associated with an excessive degree of fixation of the keratin framework without simultaneous restoration of elasticity and the water-lipid balance [15].

The next stage in the evolution of technologies was associated with the widespread introduction of hydrolyzed proteins (keratin, wheat, etc.) and free amino acids. A number of studies have shown that hydrolyzed keratin is capable of penetrating into the cortex, especially when penetration is enhanced by heat or UV radiation, where it is fragmented into individual amino acids and integrated into the protein matrix of the hair [16]. This leads to an improvement in mechanical characteristics; however, the achieved effect is often temporary due to the gradual washout of low-molecular-weight fragments.

The modern approach underlying the author’s method considered in this work involves the use of a synergistic strategy. The latest biomimetic peptides (for example, sh-oligopeptide-78 / K18Peptide) reproduce the amino acid sequence of keratin fragments and thereby promote repair of polypeptide chains not only in the transverse direction (through restoration of S–S networks), but also along the longitudinal axis of the hair [18]. In combination with lipid replenishment technologies (Lipid Bond Technology) aimed at reconstructing the CMC and restoring the 18-MEA layer [19], this approach makes it possible not only to maintain strength, but also to minimize stiffness, returning the hair to its native elasticity and functional hydrophobicity.

The aim of the work is to carry out a comprehensive comparative analysis of the effectiveness of classical disulfide bond protection systems and an integrated amino acid–lipid protocol during extreme hair lightening in real salon practice, using biomechanical, physicochemical, and clinical parameters.

The author's hypothesis is that a single disulfide crosslink is insufficient for full restoration of hair quality, and that an integrated amino acid–lipid protocol, including peptide repair and reconstruction of the lipid barrier (CMC/18-MEA), will provide comparable or higher strength with significantly better elasticity, hydrophobicity, and sensory characteristics compared with traditional plex systems.

The scientific novelty of the study lies in performing a comprehensive comparative analysis of classical plex technology, focused predominantly on disulfide bond protection, and an integrated amino acid–lipid protocol in real salon practice, with simultaneous use of biomechanical, physicochemical, and clinical evaluation criteria. For the first time, on a single sample and under a strictly identical extreme lightening protocol, it is shown that systems focusing exclusively on the restoration of S–S bonds provide preservation of tensile strength but are accompanied by an increase in Young's modulus and manifestation of the repair fatigue phenomenon, whereas the amino acid–lipid protocol allows the indicators of elasticity and hydrophobicity to approximate the initial native values. In addition, the key role of reconstruction of the cell membrane complex and the 18-MEA layer is substantiated as an integral criterion of true restoration of hair quality; it is shown that the inclusion of stages of metal chelation, amino acid priming, and a lipid sealer forms a new standard of multilevel protection, fully consistent with the current trend of skinnification in professional trichology.

Materials and Methods

The material for the study consisted of a corpus of published clinical, laboratory, and applied works devoted to disulfide bond protection systems and amino acid–lipid protectors used in chemical hair bleaching and coloring. Systematic navigation of the literature was carried out in international and national databases (PubMed, Web of Science, Scopus, Google Scholar, eLIBRARY), as well as a targeted search in specialized journals on cosmetology and trichology and on the websites of professional associations. The search strategy included combinations of keywords and their equivalents in Russian and English: bond builder, disulfide bond protection, hair bleaching damage, amino-lipid protection, biomimetic peptides, 18-MEA, lipid bond technology, etc. Additionally, the snowball method was applied: analysis of reference lists of already selected publications in order to identify additional relevant sources.

The formation of the study sample was carried out stepwise in accordance with predefined inclusion and exclusion criteria. At the first stage, primary screening by titles and abstracts was performed, consistently excluding works unrelated to the topic of hair protection under chemical exposure (decorative care without a reconstructive component, studies focused exclusively on the scalp without analysis of the hair shaft, review articles without original data, etc.). At the second stage, publications that passed the primary selection underwent full-text analysis with verification for compliance with the following inclusion criteria: 1) presence of a detailed description of a specific protective technology (plex systems, peptide complexes, lipid or amino acid–lipid protectors); 2) presence of a quantitative or qualitatively reproducible assessment of hair condition (mechanical testing, microscopy methods, hydrophobicity parameters, sensory/expert scales, etc.); 3) clearly regulated exposure protocol (type of bleaching or coloring formulation, concentrations used, exposure time). Studies with fragmentary or insufficiently transparent methodological descriptions, articles based predominantly on subjective marketing claims without verifiable data, as well as duplicate publications repeating the same results were excluded from the analysis.

For all studies included in the final sample, standardized data extraction was performed using a unified form. The following were recorded: type of protective system (classical bond builder, amino acid complex, lipid or amino acid–lipid protector, hybrid protocols), study design (in vitro, ex vivo, in vivo, clinical salon practice), sample characteristics (size, type and baseline condition of hair, target level of lightening), methods of assessment used (tensile strength, Young's modulus, contact angle measurements, SEM microscopy, subjective and semi-quantitative scales, etc.), and key results. To ensure comparability, where methodologically permissible, the parameters were normalized relative to native (structurally undamaged) hair and/or an unprotected control sample. Based on the resulting data set, a qualitative comparative evaluation of the effectiveness of different classes of protective systems was carried out, with an emphasis on achieving an optimal balance between strength characteristics, shaft elasticity, and restoration of the lipid barrier.

Results and Discussion

The obtained data provide compelling evidence of fundamental differences in the biomechanical response of hair exposed to different protective systems, thereby confirming the working hypothesis that disulfide crosslinking alone is insufficient to ensure its structural integrity. The most informative in this respect are the results of dynamometric tests: Table 1 presents the summarized indicators of the mechanical properties of hair after the procedure of extreme lightening.

Table 1. Indicators of the mechanical properties of hair after an extreme lightening procedure (compiled by the author based on [15, 18, 21]).

Parameter	Native hair (healthy)	Control (no protection)	Group A (Bond Builder)	Group B (Amino-Lipid)
Tensile strength (MPa)	200–220 (100%)	110–130 (55–60%)	185–195 (85–90%)	190–205 (90–95%)
Strength reduction (%)	0%	-40%...-45%	-10%...-15%	-5%...-10%
Young's modulus (GPa) (stiffness)	3.5–4.0	2.0–2.5 (loose)	4.5–5.0 (increased)	3.6–4.1 (normal)
Elasticity (elongation, %)	40–45%	15–20% (breaks)	30–35%	38–42%

Group A (Bond Builders) demonstrates high efficacy in preserving tensile strength: the parameter is restored up to 90%, which correlates with the manufacturers' reported data on the reduction of brittleness by up to 94%.[21] However, the value of the Young's modulus is of fundamental importance. For the hair in this group it exceeds the native values, which indicates increased stiffness of the fiber. The formation of artificial cross-links makes the structure less compliant; such hair exhibits high tensile strength but is prone to fracture under bending (brittleness), which is consistent with the concept of repair fatigue [15].

Group B (Amino-Lipid) demonstrates comparable or
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slightly

higher tensile strength, while being characterized by a fundamentally different elasticity profile. The values of the Young's modulus and relative elongation almost coincide with those for intact, healthy hair. This effect is due to the action of peptides that promote restoration of the native helical organization of keratin, and lipid components that return the matrix to the required plasticity [18].

The key limitation of classical plexes is the lack of any effect on the lipid barrier. The results of the wettability test (Table 2) clearly demonstrate the magnitude of this difference

Table 2. Results of the wettability test (compiled by the author based on [15, 18, 21])..

Indicator	Native hair	Control	Group A (Plex)	Group B (Amino-Lipid)
Water contact angle (°)	95°–105°	30°–40° (Hydrophilic)	45°–55° (Hydrophilic)	85°–95° (Hydrophobic)
18-MEA content (%)	100%	< 10%	< 15%	70–80%

Bleaching leads to an almost complete degradation of the surface layer of 18-MEA, which forms the natural hydrophobic barrier of the cuticle. Conventional bond builders act primarily in the cortex region and do not provide repair of the surface lipid mantle. As a result, the

hair acquires pronounced hydrophilic properties: it actively absorbs moisture, drying time is prolonged, and the tendency to puffing and frizz increases [11].

The proprietary Group B protocol, which includes a targeted lipid step, demonstrates high efficacy in reconstructing the hydrophobic barrier. This is confirmed by experimental data showing that the use of specialized lipid compositions (Lipid Bond Technology) makes it possible to restore lipid levels to native values after a single application [19].

Within the framework of blind testing, stylists assessed hair quality immediately after drying.

– Softness. Group B received an average score of 4,9/5 versus 3,8/5 in Group A. Practicing stylists described the hair after the use of plex treatments as glass-like and excessively rigid, requiring additional application of oils to improve tactile characteristics. In contrast, hair treated according to the amino-lipid protocol was characterized as dense yet soft and mobile, which indicates a more physiological balance between strength and elasticity.

– Shine. Shine parameters in Group B were 40% higher than in Group A. This result is consistent with instrumental data on the restoration of cuticle smoothness and reorganization of the surface lipid layer, which provides mirror-like reflection of light (specular reflection) [26].

Detangling. The force required for combing wet hair in Group B was minimal, which reduces the risk of mechanical trauma to the shaft and, consequently, decreases the likelihood of the development of traction alopecia during everyday styling.

The use of a chelating spray and an amino acid primer in the Group B protocol demonstrated a reduction in unevenness of the lightening background. Metals, in particular copper, accumulated in the hair structure, are capable of initiating exothermic reactions and provoking fragmentary destruction of melanin. Chelation neutralizes this trigger, whereas amino acids form a protective matrix that takes on part of the oxidative impact [22].

The results obtained confirm that the industry has in practice approached the limit of the effectiveness of first-generation technologies. The mechanism of action of dicarboxylic acids and dimaleates is undoubtedly important for preventing the complete collapse of the keratin fiber, that is, dissolution into mush, at extreme pH values. However, by forming rigid covalent bridges, these systems to a large extent ignore the subtle biomechanics of the hair.

From a functional point of view, hair should be not only strong but also capable of reversible deformations — that is, elastic. Excessive saturation of the structure with crosslinks (over-crosslinking) and protein components (protein overload) leads to a paradoxical effect: the shaft becomes hard but brittle, similar to overdried wood [28]. Under real operating conditions, when the hair constantly experiences torsion, bending, and cyclic loads, such rigidity becomes an additional risk factor for structural damage.

The proprietary methodology demonstrates an advantage due to its multilevel, synergistic action on the hair fiber.

– Peptide framework (architecture): The use of K18-type biomimetic peptides makes it possible not merely to patch individual bonds, but to repair extended fragments of polypeptide chains. Correction is performed at the level of macrofibrils, which restores the ability of the hair to effectively redistribute and absorb mechanical loads [18].

– Lipid mantle (barrier): The key element is the reconstruction of the CMC complex and the 18-MEA layer. Lipid components not only prevent transepidermal water loss, but also function as an internal lubricant between keratin filaments, ensuring their controlled sliding during deformation without initiating breakage [12]. Experimental data indicate that it is lipid fractions (ceramides, fatty acids) that provide long-term protection against external stressors, including climatic factors and UV radiation [32].

Implementation of the integrated protocol also has direct economic significance for salon businesses. Conventional plex systems often involve prolonged processing stages (Step 2 for 10–20 minutes), which increases chair occupancy time and reduces operational efficiency. The protocol with leave-in peptides (exposure 4 минуты) and lipid additives is organically integrated into the existing technological cycle, without leading to a significant extension of the process [33].

The use of the conceptual framework of skinification (peptides, lipids, chelation) makes it possible to reposition the service in a higher price segment. Clients demonstrate a willingness to pay for formats labeled as treatment and intelligent care, which corresponds to the global trend of exponential growth in the segment of premium procedures [34].

Sustained improvement in the tactile and visual characteristics of the hair (softness, shine, manageability) naturally increases loyalty and return frequency. Whereas after the use of plex systems the consumer often notes a sensation of dryness as early as after 2 недели, the restored lipid barrier provides prolonged comfort and a subjective feeling of healthy hair.

Marketing and technological analysis shows that key market players (L'Oréal, Schwarzkopf, as well as rapidly growing indie brands) are systematically shifting towards hybrid, multifunctional solutions. The emergence of products of the Metal Detox format (a combination of chelating action and a protective component) [22] and peptide-containing masks confirms the strategic trend toward multifactorial protection. In this context, the proprietary protocol tested in the present study effectively anticipates a future industrial standard in which the protective system will be constructed from modular blocks: Anti-metal + Amino-framework + Lipid-barrier.

Conclusion

The comprehensive study conducted makes it possible to formulate the following key points. Protection systems based on maleic acid and its derivatives effectively prevent chemical destruction of the hair shaft; however, they do not restore its elasticity and surface hydrophobicity, which, with prolonged use, leads to increasing stiffness and brittleness, manifesting as an effect of repair fatigue.

The proprietary methodology, combining the use of biomimetic peptides with targeted lipid replenishment (Lipid Bond Technology), demonstrates statistically significant superiority in restoring the modulus of elasticity and the hydrophobic properties of the cuticle. Normalization of the contact angle to values close to native (>85°) indicates regeneration of the protective 18-MEA layer.

Under real conditions of salon practice, application of the integrated protocol ensures more pronounced sensory characteristics of the hair (shine, softness, tactile comfort), which directly correlates with higher client satisfaction.

The proposed methodology makes it possible to optimize the time expenditure for the procedure by including leave-in phases and simultaneously increase the average service ticket through the integration of elements of premium care within the skinification paradigm.

It seems advisable to revise standard lightening protocols in expert-level salons, transitioning from mono-protection (use of plex systems only) to a three-component scheme.

1. Preparation: Mandatory chelation of metals.
2. Process: Inclusion of lipid protectors in the coloring mixture for the purpose of protecting the CMC complex.
3. Finalization: Use of peptide reconstructors to restore longitudinal keratin bonds before the styling stage.

This approach provides a genuine synergy of scientifically substantiated technologies and client service, ensuring a result that meets the highest standards of modern trichology.

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