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Investigation of The Optimal Frequency of Procedures and Techniques to Minimize the Study of The Optimal Frequency of Procedures and Techniques to Minimize Damage and Damage

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Abstract: The study presents a systematized analysis of mechanisms of damage to the nail unit associated with modern cosmetic procedures — strengthening, modeling, smart pedicure, and artistic design. The aim of the research is to develop a scientifically verified model that makes it possible to determine the optimal frequency of procedures and risk-minimization protocols based on the integration of data from dermatology, toxicology, and biomechanics. The methodology includes a systematic review of peer-reviewed publications. The results indicate that the leading determinant of iatrogenic complications is allergic contact dermatitis (ACD) induced by incompletely polymerized (meth)acrylate monomers, primarily 2-hydroxyethyl methacrylate (HEMA), with the prevalence of sensitization reaching 56.6%. It has been established that a significant contribution is made by mechanical injuries arising from aggressive preparation of the nail plate and incorrect operation of hardware techniques, as well as toxicological risks due to the presence of heavy metals in pigments (for example, antimony). Based on data on the cyclicity of nail plate regeneration (complete renewal of fingernails — in 6 months), a quantitative model for periodizing procedures with mandatory recovery intervals is proposed, aimed at preventing cumulative damage. The formulated conclusions and proposed protocols have practical applicability for dermatologists, nail service specialists, occupational health experts, and regulatory authorities.

Keywords: allergic contact dermatitis, (meth)acrylates, HEMA, onychodystrophy, nail plate damage, smart pedicure, cosmetic toxicology, nail regeneration, salon safety, procedure frequency.

Introduction

The relevance of the study is determined by the sustained expansion of the global market for nail care services. According to analytical estimates for 2024, the revenue of nail salons amounts to 8,8 billion US dollars, with an expected compound annual growth rate (CAGR) of 4,5%, which is projected to bring the segment to 13,7 billion US dollars by 2034 [1]. The nail polish segment is growing even more dynamically — CAGR 6,9% [2]. This economic momentum, fueled by self-care culture and media visibility in social networks, leads to increased population-level exposure to cosmetic procedures and associated chemical and mechanical factors. The scaling of such exposure poses a significant public health challenge that requires scientifically rigorous assessment and mitigation of associated risks.

The existing body of publications thoroughly describes individual complications, including the high prevalence of allergic contact dermatitis to (meth)acrylates [3], as well as risks inherent to specific technologies, for example the use of home gel manicure kits [6]. At the same time, a substantial gap is evident: there is no holistic integrated model that synthesizes dermatological, toxicological, and biomechanical data to formulate evidence-based recommendations on permissible procedure frequency and necessary recovery periods. Current guidance for professionals and consumers is fragmented, relies on personal experience, and often diverges, with industry positions [7] sometimes directly contradicting dermatologists' cautions [8].

The aim of the study is to develop a scientifically verified model that makes it possible to determine the optimal frequency of procedures and risk minimization protocols based on the integration of data from dermatology, toxicology, and biomechanics.

The working hypothesis is that a risk-stratified approach that accounts for the chemical aggressiveness of materials, the intensity of mechanical impact, and the temporal characteristics of nail plate regeneration will allow quantification of optimal intervals between interventions. Implementation of such an approach should lead to a statistically significant reduction in the incidence of iatrogenic complications, including onychodystrophy and contact dermatitis.

The scientific novelty lies in proposing the first integrative model for determining the safe periodicity of various cosmetic nail procedures, combining dermatological, toxicological, and biomechanical parameters into a single practically applicable framework.

Materials and methods

The methodological basis of the study was a systematic review of the scientific literature conducted in strict accordance with (Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) recommendations. A search for relevant publications was performed in leading international scientometric databases. Inclusion criteria were peer-reviewed scientific articles, systematic reviews, clinical studies, and official reports of regulatory authorities.

Data processing was carried out using qualitative synthesis. The extracted information was systematized and classified into four groups: Marketing and economic studies of the nail service industry [1, 2, 16, 25]; Clinical and toxicological studies of risks associated with the use of acrylates and other components of nail products [3–5, 9–14, 17–20, 22, 23, 26–28]; Regulatory and expert documents, as well as popular reviews on the safety of procedures [6–8, 15, 21, 24, 27]; Works devoted to the prevention of nail damage and the development of new therapeutic agents [29, 30].

1. Marketing and economic aspect. Studies of the nail service market focus on demand growth, changes in consumer preferences, and the impact of procedural convenience on client satisfaction. Reports by analytical agencies record steady industry growth driven by service expansion and segmentation by age and preferences [1, 2]. Empirical studies in Korea emphasize the importance of convenience, emotional value, and economic value in shaping salon visitors' loyalty [16, 25]. These studies demonstrate that the frequency of procedures is determined not only by medical factors but also by the structure of consumer behavior.
2. Medical and toxicological studies. Large European studies record an increase in morbidity among clients and technicians [3-5]. Such cases are complicated by severe clinical forms — from onychodystrophy to chronic inflammatory processes [9, 11]. Another direction comprises studies examining the toxic effects of impurities and additives. In particular, the study by E Estill C. F. et al. [19] identified substantial exposure to triphenyl phosphate among salon workers, which may be

systemic in nature. Similarly, Ceballos D. M. et al. [28] documented contamination of polymer coatings with trace elements. These findings are consistent with clinical review publications emphasizing the need for dermatologic oversight in the use of decorative cosmetics [17, 18]. The issue of infection safety also occupies an important place: Popalyar A. et al. [22] and Turgambayeva A. K. et al. [26] draw attention to insufficient awareness among industry personnel regarding the risks of viral and bacterial infections.

3. Regulatory and expert documents. Documents of expert committees make a significant contribution to understanding the safe limits of the application of nail service technologies. Thus, the SCCS of the European Commission focuses on permissible concentrations of acrylates and their metabolites [15]. Review publications in scientific and popular sources demonstrate a balance between aesthetic effect and medical risks: from comparative reviews of the safety of polishes and gels [6, 7] to consumer guides on the duration and cost of procedures [8, 27]. An important direction is the integration of dermatologic expertise into the field of aesthetic services: Chuiun A. [21] and Lee D. K., Lipner S. R. [23] emphasize the need for a comprehensive clinical-cosmetologic approach.

4. New therapeutic strategies. A separate body of literature concerns methods for strengthening and restoring nails. The works of Piraccini B. M. et al. [29] and Granger C. et al. [30] demonstrate the effectiveness of solutions based on mastic tree and hyaluronic acid, which opens prospects for reducing damage during regular cosmetic procedures. These studies set a direction toward the development of preventive products capable of minimizing the frequency of complications.

Thus, it can be noted that the literature demonstrates a high fragmentation of approaches. On the one hand, marketing studies emphasize the growth and commercial significance of the sector, where the frequency of procedures is determined primarily by consumer demand. On the other hand, clinical and toxicological works record an increase in occupational and consumer risks associated with acrylates, toxic additives, and infections. Expert documents and reviews attempt to create regulatory frameworks, but gaps remain between regulatory policy and real practice.

The contradiction is manifested in the fact that the frequency of procedures in commercial sources is considered as an element of client satisfaction, whereas in medical sources it is regarded as a risk factor for damage and chronic diseases. The following topics remain insufficiently covered:

- optimal intervals between procedures, taking into account recovery of the nail plate;
- cumulative effect of chemical exposures with long-term use of cosmetics;
- balance between dermatologic recommendations and market practices.

Thus, further research should be aimed at developing a medico-economic model that will simultaneously account for safety, clinical effectiveness, and client satisfaction when determining the optimal frequency of procedures.

Results and Discussion

In contemporary nail cosmetology, the leading source of iatrogenic complications remains sensitization to partially polymerized (meth)acrylate monomers contained in gel polishes, acrylic systems, and adhesives [9]. Patch testing results convincingly show that the monomers with the greatest clinical significance as causative allergens are 2-hydroxyethyl methacrylate (HEMA), 2-hydroxypropyl methacrylate (HPMA), and ethylene glycol dimethacrylate (EGDMA) [3]. According to studies, HEMA is the primary sensitizer in 56,6% of cases of allergic contact dermatitis associated with nail products [10]. The key factor in the development of sensitization is incomplete polymerization of the material: this occurs with insufficient curing exposure, a mismatch between the wavelength and/or intensity of the UV/LED lamp and the photoinitiators used, or the application of excessively thick layers. As a result, residual unreacted monomers with marked sensitizing potential persist on the surface of the nail plate and the periungual skin [6, 12, 14].

The clinical spectrum of ACD ranges from localized paronychia, onycholysis (separation of the nail plate from the bed), and severe onychodystrophy [11] to ectopic lesions of the skin of the face, eyelids, and neck due to allergen transfer [10]. Importantly, pronounced psoriasiform nail changes may develop even in the absence of cutaneous dermatitis, which significantly complicates the diagnostic workup [9].

Sensitization to (meth)acrylates induced by a cosmetic procedure is not merely a dermatological problem but a lifelong immunological event with potentially significant implications for subsequent medical care. The same monomers, primarily HEMA, are widely used in dental composites and orthopedic bone cements [13]. Consequently, a patient sensitized to HEMA via gel polish may subsequently encounter a severe local or systemic allergic reaction during dental treatment or arthroplasty, turning a cosmetic preference into a potential contraindication to necessary interventions and creating a latent long-term health risk.

Beyond acrylates, other components also raise toxicological concern. Formaldehyde in nail hardeners, despite regulatory restrictions [15], continues to be associated with painful onycholysis and irritant dermatitis [16]. Plasticizers are attracting increasing attention, particularly triphenyl phosphate (TPHP), which has replaced dibutyl phthalate (DBP) and has exhibited endocrine-disrupting properties in studies [19] (fig.1).

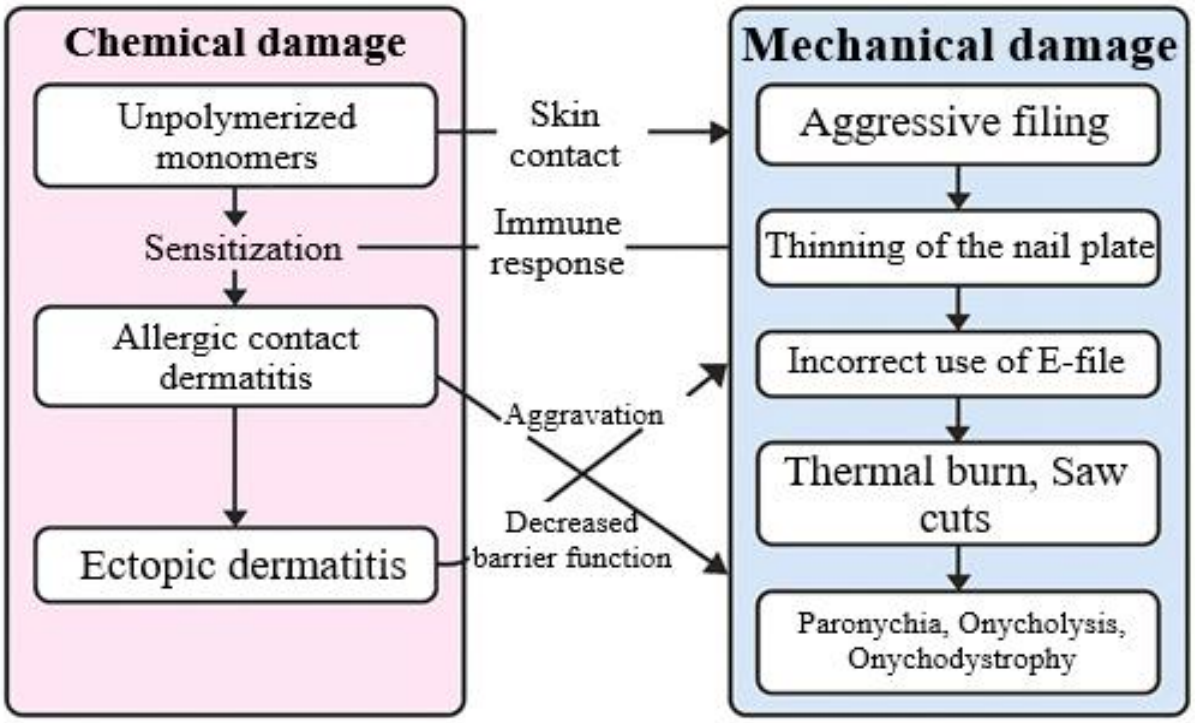

Fig.1. Schematic representation of the mechanisms of chemical and mechanical damage to the nail apparatus (compiled by the author based on [4, 5, 13, 15, 16, 19]).

Mechanical injury to the nail unit ranks second among risk factors. Aggressive nail plate preparation — in particular, excessive abrasion of the dorsal surface to enhance coating adhesion — leads to loss of protective keratin layers, thinning and brittleness of the nails with formation of the clinical picture of worn-down nail syndrome (worn-down nail syndrome) [6].

Injury to the proximal nail fold and cuticle through aggressive cutting or forceful pushing back disrupts the natural barrier and creates entry portals for pathogens, leading to paronychia [16]. Direct trauma to the matrix with metal instruments is fraught with persistent nail deformities, including Beau lines and onychorrhexis [23]

Device-assisted processing requires special attention. Improper use of an electric file (e-file) — selection of an inadequate bit, excessive rotation speed, or an incorrect angle — causes deep grooves on the plate (fire rings), thermal injury to the nail bed due to friction, and can result in permanent matrix damage [25].

Inadequate disinfection and sterilization of reusable instruments remains a key route of transmission for bacterial infections (including Pseudomonas aeruginosa with development of green nail syndrome), fungal infections (onychomycosis), and blood-borne viral infections (hepatitis B and C) [22]. The risk is particularly high when using porous, non-sterilizable materials — files and buffers — which should be used once [27]. Pedicure whirlpool footbaths, when improperly cleaned, accumulate biofilms, for example Mycobacterium fortuitum, and become a significant reservoir of infection [18].

To systematize the risks associated with different

procedures, a comparative analysis was performed, the results of which are presented in Table 1.

Table 1. Comparative analysis of nail service techniques (compiled by the author based on [1, 3, 7, 25, 28]) .

Technique	Primary materials/instruments	Mechanism of action	Key potential risks
Strengthening	Strengtheners (with or without formaldehyde), therapeutic serums (Pistacia lentiscus, hyaluronic acid)	Chemical crosslinking of keratin (formaldehyde); delivery of nutritive and moisturizing components to improve keratin structure.	Chemical: ACD, irritant dermatitis, onycholysis (from formaldehyde).
Modeling	Acrylic powder and monomer; gel polishes (base, color, top); UV/LED lamps.	Polymerization of (meth)acrylate monomers to create a strong, durable artificial coating.	Chemical: ACD to monomers (HEMA, HPMA).
Smart pedicure	Device (e-file) with various bits (diamond, ceramic), antiseptics, keratolytics.	Mechanical treatment of nails and foot skin without the use of water.	Mechanical/Thermal: Cuts, burns, matrix injury with unskilled use.
Artistic design	Pigments, glitters, rhinestones, adhesives (cyanoacrylates), acrylic paints.	Application of decorative elements onto the base coating.	Toxicological: Chronic exposure to heavy metals (antimony, tin) fro

To translate practice from the realm of empirical observations into a reproducible standard, a scientific rationale for the optimal frequency of procedures and recovery periods is presented below.

The average growth rate of a healthy adult fingernail is about 0.1 mm per day (≈3 mm per month), which determines a complete plate renewal time of approximately six months. The cellular substrate of growth is formed in the nail matrix, a zone of continuous mitotic renewal of keratinocytes from which the plate is constructed [23]. Any exogenous or endogenous insult—chemical, mechanical, or systemic—disorganizes this process and is translated into defects on the plate as it advances distally. The potential for recovery is high if an intact portion of the matrix is preserved, ensuring uninterrupted tissue generation [27].

The term rest period is grounded in physiological facts. The nail plate is a porous structure capable of absorbing water ~1000 times more efficiently than skin [3]. Prolonged occlusion by gel or acrylic systems shifts the water homeostasis of the plate [7]. Removal procedures that combine exposure to organic solvents (acetone) and mechanical filing inevitably induce dehydration and stratification of keratin layers [8, 22]. It follows that a break is not an aesthetic option but a necessary phase of repair that allows the plate to rehydrate and ensures growth from the matrix of new, undamaged tissue. The position of some practitioners on the dispensability of breaks with ideal technique [7, 20] ignores cumulative subclinical damage accumulating over removal cycles and the physiological consequences of prolonged occlusion.

The current discussion of breaks is often reduced to a binary assessment (necessary/not necessary). It is advisable to shift to a quantitatively defined, biologically informed concept of a recovery cycle. Instead of the vague advice to take a break, protocolization based on known growth rates is proposed: a two-week interval corresponds to the outgrowth of ≈1.4 mm of a new segment under the proximal nail fold (0.1 mm/day × 14 days). By introducing a cyclic scheme (for example, three consecutive applications followed by skipping one cycle), predictable windows of periodic repair of the proximal zone of the nail unit are formed. In this way,

the recommendation acquires measurability and reproducibility suitable for standardization and training.

For gel polish:Given the usual wear cycle of 2–3 weeks, no more than three consecutive applications (a total of 6–9 weeks) appear optimal, after which complete removal and a mandatory recovery interval of at least 2 weeks are indicated. During this time, approximately 1.4 mm of new, functionally competent plate grows out, which reduces the cumulative chemical-mechanical burden on the same nail zone.

For acrylic modeling: Given the greater rigidity of the material and, as a rule, more aggressive preparation and removal steps, a more conservative rhythm is justified: two consecutive applications (6–8 weeks) followed by a recovery period of 2–3 weeks [26, 29, 30].

Further, Table 2 will present the advantages, limitations, and future trends in determining the frequency of procedures and methods aimed at minimizing harm.

Table 2. Advantages, limitations, and future trends in determining the frequency of procedures and methods aimed at minimizing harm (compiled by the author based on [14, 17, 21,24]).

Aspect	Advantages	Limitations	Future trends
Effectiveness and outcome	Reduced frequency of incidents/damage; less downtime; improved quality and safety.	The effect depends on context; retuning of frequency may temporarily reduce performance.	Adaptive schedules with automatic adjustment to risk and context in real time.
Economics	Optimization of OPEX/CAPEX; reduction of overspending on redundant procedures; better payback.	Initial investments in analytics/sensors are required; hidden costs are difficult to account for.	Value-at-risk models, digital twins for ROI calculation.
Data and measurability	Metrics enable objective selection of the interval; bottlenecks are identified.	Incomplete/noisy data; sampling bias; difficult to measure unrealized harm.	Continuous monitoring (IoT/wearables), federated learning with protection of personal data.
Analytics and models	Risk-based optimization; degradation forecasts; personalization of frequency by segments.	Overfitting; weak interpretability of complex models; dependence on assumptions.	Causal ML, explainable AI, contextual multi-armed bandits, RL approaches.
Implementation and scale	Standardization of procedures; reproducibility; unified SLAs/OLAs.	Resistance to change; need for staff training; IT integrations.	Low-code/No-code pipelines, MLOps/AIOps, autonomous schedules with human in the loop.

In summary, contemporary nail cosmetology is associated with a spectrum of iatrogenic risks, among which sensitization to (meth)acrylate monomers and mechanical injuries of the nail unit play a leading role. Patch-testing data convincingly indicate the priority clinical significance of HEMA, HPMA, and EGDMA, and sensitization to HEMA has not only dermatologic but also systemic consequences, determining an unfavorable prognosis for dental and orthopedic practice in the future. It has been shown that the key

trigger of allergization is incomplete polymerization of the material, and the clinical spectrum of complications ranges from localized paronychia to severe onychodystrophies and extraungual lesions. Mechanical factors, including aggressive plate preparation, matrix trauma, and incorrect use of the e-file, shape a risk profile with a tendency to redistribute from more frequent but manageable infections to rare but severe injuries. Toxicological concerns are supplemented by exposure to formaldehyde, plasticizers, and heavy metals, which together constitute a multilevel threat to both clients and industry professionals. The obtained data substantiate the need to move from empirical notions of breaks to a standardized recovery cycle model integrating the biological growth rates of the nail and minimizing cumulative damage. Thus, the practical significance of the results lies in the formation of an evidence-based protocol that ensures a balance between aesthetic effect and health safety.

Conclusion

The conducted systematic analysis indicates that the principal iatrogenic risk factor in the contemporary nail-care industry remains allergic contact dermatitis to (meth)acrylates; its prevalence is amplified by the expanding market of products for home use. It has been demonstrated that the apparent safety of smart pedicure–level techniques is critically dependent on the operator's qualifications, whereas toxicological evaluation of materials for artistic design reveals hazards associated with the undisclosed presence of heavy metals.

The results obtained and the protocols formulated have high applied significance for enhancing safety standards in the field of nail services. The materials of the work are addressed to dermatologists dealing with nail pathologies, cosmetologists and practitioners focused on improving practice, occupational safety specialists responsible for workplace safety in salons, as well as regulatory bodies ensuring consumer protection. The proposed model forms a basis for the development of standardized educational programs and evidence-based guidelines on best practices.

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