

Biocompatibility and Safety of Solid-State Gel Systems in Nail Services: A Comprehensive Analysis of Materials and Application Techniques

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Abstract: *The article examines the safety problem of solid gel systems in nail services, driven by the dual nature of risks: chemical, associated with the sensitizing action of (meth) acrylate monomers and the provocation of contact dermatitis, and biomechanical, arising from incorrect e-file techniques and leading to injuries, including onycholysis. The aim of the study is to provide theoretical and empirical justification for the hypothesis that safety is the result of synergy between chemically modified biocompatible materials and minimally invasive techniques. The research methodology is interdisciplinary and combines a systematic review of scientific literature, a comparative analysis of modeling systems (hard gel, acrylic, dip system), and a qualitative case study of the author's E-File Dry Manicure protocol. As a result, it was established that the key factors in risk minimization are the transition to HEMA-free formulations with low allergenic potential and the application of biomechanically calibrated protocols using safe instrumentation, in particular a rounded cone bit that prevents trauma. The conclusions confirm that the safety of hard gel is not an immanent property of the product but is achieved within an integrated system of material – technique – specialist, which is empirically demonstrated by the example of a commercially successful and globally recognized author's method oriented toward nail restoration. The presented data will be of interest to practicing nail technicians, instructors, curriculum developers, and judges of professional championships.*

Keywords: hard gel, nail safety, e-file manicure, E-File Dry Manicure, biocompatibility, (meth) acrylates, HEMA-free, contact dermatitis, onycholysis, bit biomechanics

1. Introduction

The global nail service sector continues to expand steadily, consistent with the worldwide shift toward prioritizing personal care and aesthetic comfort. According to analytical data for 2024, the industry's global revenue is estimated at 24.56 billion, and the projected compound annual growth rate (CAGR) through 2032 is 5.01%. The professional salon segment contributes the most to this dynamic: by 2029, an additional increase of 9.47 billion is expected [1]. The economic acceleration is accompanied by heightened attention to the regulatory and scientific agenda concerning the safety of technologies and materials employed [2].

Against the backdrop of rising demand for nail modeling and strengthening, including the use of hard gel systems, a methodological paradox emerges: the pursuit of flawless aesthetics and coating durability may conflict with preserving the health of the client and the practitioner. Risks consolidate along two dimensions: chemical exposure associated with the development of allergic contact dermatitis (ACD), and damage to the nail apparatus of mechanical or thermal nature arising from violations of technique, especially when working with electric filing devices (e-files) [3, 4]. The scientific corpus describes in detail cases of ACD induced by (meth) acrylate monomers widely present in polymerizable coatings, and documents the threats of nail plate thinning, burns, and microtraumas during device-based treatment [5, 6].

At the same time, despite the presence of studies in individual areas ranging from toxicological assessment of components to the biomechanics of processing, the current research paradigm continues to lack an integral perspective. There is no holistic model that treats safety as a unified system

comprising two interdependent blocks: material (chemical architecture and biocompatibility) and technique (standardized application and processing protocol). The isolated investigation of these components prevails, which hinders the formation of a comprehensive picture of the factors that determine the safe execution of the procedure.

The scientific novelty of the study consists in integrating three methodological contours: in-depth chemical profiling of current gel systems; biomechanical quantification of hardware manicure procedures; empirical verification through the analysis of a real case study. As the empirical foundation, an authorial technology is used that has proven its effectiveness in the highly competitive US market and has undergone international approbation.

The author's hypothesis is formulated as follows: the safety and biocompatibility of solid-state gels for nail modeling are not characteristics inherently embedded in the material by default; they are achieved as the result of the synergy between chemically modified compositions with reduced sensitizing potential (including HEMA-free formulas) and biomechanically optimized, minimally invasive application techniques, provided that the procedures are performed by a highly qualified specialist.

The aim of the study is to theoretically and empirically confirm this hypothesis by accomplishing the following tasks:

- 1) Carry out a critical analysis of the chemical parameters and associated risks of modern hard gels;
- 2) Conduct an assessment of the biomechanics and safety metrics of hardware manicure techniques;
- 3) Present empirical evidence of the efficacy and safety of the integrated material—technique system based on the selected case study.

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2. Materials and Methods

The present study has a pronounced interdisciplinary orientation and relies on an integral methodology that synthesizes several complementary analytical approaches for a comprehensive examination of the stated problem. The methodological architecture includes a systematic literature review, procedures of comparative analysis, and a qualitative case study.

The systematic review of scientific sources was oriented toward identifying data on chemical composition, indicators of biocompatibility, and dermatological risks associated with nail modeling products. Search strategies were implemented in the scientometric databases Scopus, Web of Science, and PubMed using the key queries hard gel composition, (meth) acrylate allergy, contact dermatitis nail cosmetics, e-file manicure safety, nail biomechanics. The inclusion criteria covered thematic relevance, publication in peer-reviewed outlets, and a temporal restriction.

Comparative analysis was applied to juxtapose various nail modeling technologies (hard gel, acrylic system, dip system) according to key safety parameters and effects on the nail apparatus. Additionally, this approach was used to assess the biomechanical advantages of different types of bits employed in e-file manicure. Analytical conclusions were based on data from manufacturers technical documentation, publications in dermatology, and materials science.

The qualitative case study was employed for the analysis and contextualization of the authors method E-File Dry Manicure. The primary empirical material was obtained from an expert narrative that includes a description of the technique, characteristics of professional experience, outcomes of clients and students, as well as achievements in market and competitive environments. The indicated narrative was treated as a model of expert practice subject to scientific interpretation and verification in comparison with data from other sources.

3. Results and Discussion

Hard gels are highly organized composite systems based on the chemistry of UV-curable (meth) acrylate monomers and oligomers [8]. Polymerization initiated by photoinitiators under UV/LED irradiation forms a robust three-dimensional crosslinked network that imparts the coating with the required hardness and service durability [10]. A significant parameter determining the biocompatibility and toxicological safety of the material is the degree of conversion of monomers into polymer: if it is insufficient, residual unreacted monomers remain in the coating and constitute a key risk factor for the development of allergic contact dermatitis [8].

In comparison with more elastic soak-off gels, hard gels are characterized by an increased crosslink density achieved through the introduction of multifunctional monomers (di-, tri-, and tetrafunctional) [10]. This architecture provides high mechanical strength but predetermines the need to remove the coating by filing rather than dissolution.

ACD induced by components of nail cosmetics is a

dermatological problem: according to various estimates, from 1% to 3% of the population is sensitized to at least one ingredient used in nail products [6]. In recent years, there has been a marked increase in the prevalence of sensitization to (meth) acrylates [6]. The most significant allergen in this group is 2-hydroxyethyl methacrylate (HEMA), identified in more than half of ACD cases associated with nail coatings [12]. The clinical presentation ranges from local inflammation on the fingers and periungual folds to eczematous eruptions at distant sites (face, eyelids, neck) due to transfer of the allergen by the hands [3].

Under the conditions of a rising incidence of ACD, the professional nail cosmetics industry is rapidly transitioning to HEMA-free compositions by developing and implementing HEMA-free formulas. The key to the toxicological profile of HEMA is its low molecular weight: the small molecule readily traverses the skin barrier, reaches immunocompetent cells, and initiates an immune cascade culminating in sensitization [23]. Once established, sensitization is lifelong: clinical reactivity may occur even upon contact with trace amounts of the allergen [24].

As HEMA-free alternatives, 2-hydroxypropyl methacrylate (HPMA) and isobornyl acrylate (IBOA) are used, with a preference for monomers of higher molecular weight and different spatial configuration. The increased size and configuration of the molecules impair their transepidermal penetration, thereby reducing sensitizing potential and improving material biocompatibility. It has been shown that HPMA exhibits more favorable biocompatibility and a lower propensity to induce allergic reactions compared with HEMA [25].

At the same time, the designation HEMA-free should not be construed as an absolute guarantee of hypoallergenicity: a proportion of patients may be sensitive to other (meth) acrylates present in the composition [28]. Nevertheless, the shift to HEMA-free systems is a fundamentally important step toward enhancing the chemical safety of professional nail materials, while contemporary HEMA-free formulas are comparable to traditional ones in performance metrics—adhesion, strength, and durability [23].

When selecting a system for nail modeling, one should analyze not only the chemical nature of the materials but also the technological protocols for application and removal, as these determine the subsequent condition of the nail plate. Acrylic systems, despite their sustained popularity and leading market position among types of artificial coatings by material (see Fig.1), are associated with an elevated level of risk [17].

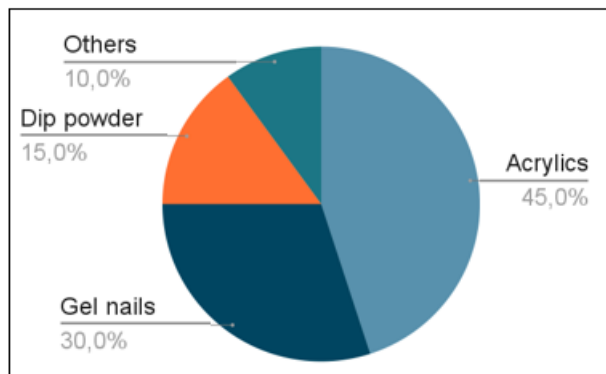


Figure 1: Distribution of market shares of artificial nail systems by type of material (compiled by the author based on [16-18; 23, 24]).

The preparatory stage when working with acrylics often includes intensive mechanical abrasion (filing) to create surface roughness, which predictably leads to thinning and reduced mechanical strength of the nail plate. An additional unfavorable factor is the pungent odor of the liquid monomer and the possible presence of aggressive chemical constituents in it.

Dip systems, often presented as a so-called healthier alternative, also have vulnerabilities. Repeated immersion of the finger into the powder when sanitary standards are not observed (using a single container for different clients) creates prerequisites for cross bacterial and fungal contamination. In addition, the preparation and removal

stages of such coatings require mechanical processing, which increases the likelihood of trauma to the nail plate [7, 9, 11].

One of the most frequent adverse outcomes with incorrect application of modeling systems is onycholysis, the separation of the nail plate from the nail bed. The pathogenesis can be induced by mechanical factors (excessive pressure during filing; wearing excessively long and rigid artificial nails that act as a lever) as well as by chemical exposures (allergic reactions; the action of aggressive solvents during removal). It has been shown that traumatic onycholysis is more frequently recorded in wearers of acrylic coatings due to their high rigidity and the strength of the adhesive contact with the nail plate, which exceeds the natural adhesion of the plate to the bed [13, 14].

In this context, hard gels, when applied with correct technique, represent a gentler option. Their application usually requires less aggressive surface preparation, and the absence of toxic monomers and pungent odor in modern formulations increases the comfort and safety profile of the procedure. Controlled removal of hard gel by filing, performed by an experienced specialist, allows titration of the intervention and minimizes trauma to the natural nail, whereas complete soaking in acetone markedly dehydrates the nail plate and perionychium. Consequently, the predominance of acrylic systems on the market is associated with a higher prevalence of certain types of nail damage, thereby shaping a clinical demand and a market niche for safer, restorative approaches [14, 15]. Table 1 presents a comparative analysis of nail modeling systems.

Table 1: Comparative analysis of nail modeling systems (compiled by the author based on [8, 14, 15]).

Characteristic	Acrylic system	Dip powder system (Dip Powder)	Hard gel system
Primary chemistry	Polymerization of acrylic monomer and polymer	Cyanoacrylate adhesive and acrylic powder	UV/LED polymerization of (meth) acrylate oligomers
Primary sensitizers	(meth) acrylate monomers, benzoyl peroxide	Cyanoacrylates, acrylic powder	(meth) acrylate monomers (including HEMA in older systems)
Nail preparation	Aggressive mechanical filing	Light mechanical filing	Minimal mechanical filing (buffing)
Application risks	Sharp chemical odor, risk of ACD	Risk of cross-contamination, risk of ACD	Risk of incomplete polymerization, risk of ACD (minimized in HEMA-free)
Removal method	Soaking in acetone, mechanical filing	Soaking in acetone, mechanical filing	Mechanical filing
Removal risks	Mechanical damage, severe dehydration	Mechanical damage, dehydration	Risk of mechanical damage with improper technique
Common pathologies	Traumatic onycholysis, ACD, nail plate thinning	Nail plate thinning, bacterial/fungal infections	ACD (with skin contact), thermal burns (with incorrect polymerization)

The use of an electric device (e-file) in manicure and pedicure today essentially serves as an industry standard, as it enables substantial acceleration of processing and increases the reproducibility of outcomes. At the same time, the safety level is entirely determined by the specialist's competence and their understanding of the physics of interaction between a rotating bur and biological tissues [4]. The key risk groups reduce to two types of impacts: tribological (mechanical) and thermal.

Mechanical injury forms under excessive pressure, selection of overly aggressive abrasiveness, or incorrect positioning of the working angle. Consequences include thinning of the nail plate, formation of longitudinal and transverse grooves, irregularities (file-throughs), and in severe cases — injury to the matrix (the nail growth zone) with subsequent irreversible

distortion of nail shape [4].

Thermal injury is caused by friction of the bur against the surface of the nail or skin: the generated heat under incorrect technique (excessive revolutions per minute, prolonged holding of the instrument at one point, working with a worn bur) provokes a burning sensation and may lead to a thermal burn of the nail bed. In professional practice this phenomenon is known as ring of fire and can initiate onycholysis. Any of the specified injuries disrupts the integrity of the nail apparatus, creating a portal of entry for subsequent bacterial or fungal infection [5].

The safety of device-based processing is structured as a controllable system, in which the outcome is determined by

the combination of three parameters: rotational speed, magnitude of applied pressure, and the operational characteristics of the selected bur.

Rotational speed (RPM — rotations per minute). The parameter is selected strictly according to the task. When working on the natural nail plate and the cuticle, low values are advisable — approximately 3 000–8 000 RPM — to prevent overfiling and thermal injury to tissues. For removal of artificial coatings (gel, acrylic), substantially higher speeds are required — approximately 14 000–16 000 RPM and above, which ensures efficient removal without excessive pressure. The use of unjustifiably high frequency on the natural nail is one of the most common and injury-prone errors.

Pressure. The applied force should be minimal. Work is performed essentially with the weight of the handpiece, where the abrasive capacity of the bit, not the operator's force, plays the main role [4]. Smooth, gliding passes reduce the contact area and time, thereby decreasing friction and consequently heat generation.

Geometry and abrasiveness of the bit. The configuration, material, and grit of the attachment are key determinants of safety and efficiency. Coarse-grit bits are used exclusively for rapid removal of massive layers of artificial material. For work on the natural nail and for final finishing, fine-grit attachments are used. The structural shape of the attachment defines its functional purpose and determines the risk profile

upon contact with tissues [19, 20].

Bit selection is not a matter of preference but a key engineering and technological decision that shapes the safety contours of the entire procedure. In practice, a Flame bit with a thin, sharply tapered apex is widely used; it allows lifting the cuticle and working in the lateral sinuses. However, the very geometry of the tip underlies its main drawback from a biomechanical standpoint: localization of force on a minimal contact area multiplies the likelihood of pinpoint skin perforation, trauma to the matrix, and formation of deep linear defects of the nail plate even with a slight deviation by the operator from the optimal mode [19, 21].

In contrast, the Rounded Cone bit shape illustrates the principle of design for safety. Its defining biomechanical advantage is the absence of a sharp apex. The spheroidally rounded tip eliminates pinpoint perforation: the load is distributed over a larger contact area, ensuring delicate displacement and exfoliation of the pterygium and dry tissues without critical peaks of mechanical stress. In practical terms, this makes work with such a bit substantially safer, since it is structurally designed to neutralize the most hazardous operational errors — an improperly selected angle of attack and excessive compressive force, typical of sharp-tipped attachments. Consequently, a preference for the rounded cone is a deliberate choice aimed at reducing the influence of the human factor and driving procedural risks down to a negligibly low level [21, 22] (fig.2).

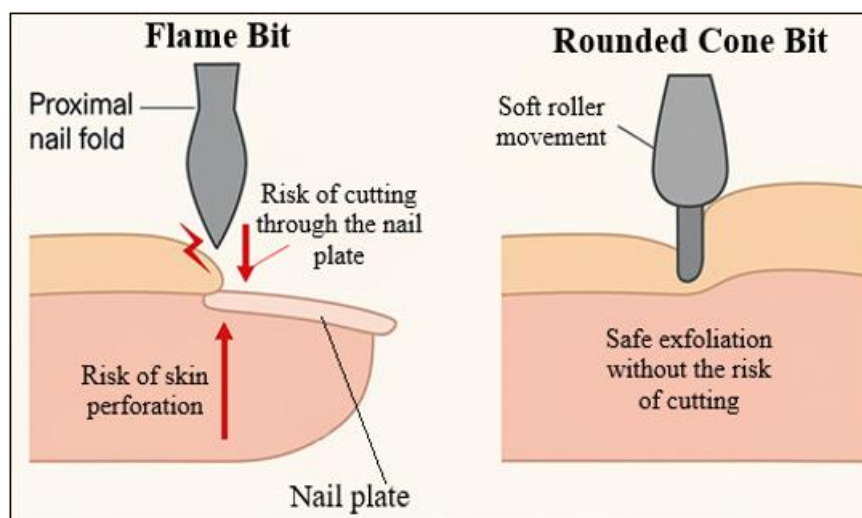


Figure 2: Comparative biomechanics of the “Flame” and “Rounded Cone” cutters (compiled by the author based on [19-22]).

Analysis of an empirical case makes it possible to test the applicability of the theoretical assumptions formulated earlier. The method proposed by the author E-File Dry Manicure describes an integrated protocol aimed at systematic management of chemical and mechanical risks. The technique is of a combined nature: preliminary device-based treatment is performed with a safe rounded cone bit to prepare the nail plate and periungual folds, after which classical cuticle removal with a cutting instrument (nippers) follows.

Such hybridization provides a key advantage — high adaptability. Unlike exclusively device-based approaches that

demonstrate unstable efficacy when working with moist or elastic cuticle, and unlike strictly classical techniques that do not always guarantee impeccable cleaning of the sinuses, the combined protocol allows the procedure to be variably adjusted taking into account the individual morphofunctional characteristics of the client.

The methodology is positioned not as a procedure oriented solely toward an aesthetic result, but as a restorative protocol. Its goal is targeted work with a problem widespread in the US market: a large group of clients with nail damage resulting from aggressive interventions based on acrylic and dip systems, as well as from incorrect device-based treatment.

Thus, the methodology occupies an intermediate niche between standard manicure and podiatric care, offering a safe aesthetic option for clients with a weakened or traumatized nail plate.

The effectiveness and demand of the proposed methodology are corroborated by a set of empirical indicators that are best examined along several validation trajectories.

Attaining the status of the highest-paid specialist within the niche (e-file dry manicure) in the state of Arizona while simultaneously maintaining a stable client flow indicates a high perceived value of the service. Consumers' willingness to pay a price premium for safety, predictable quality, and a clinically meaningful outcome is particularly evident in cases related to nail health restoration. The pronounced demand for training in this technique points to a structural competence gap among practicing technicians. Fully sold-out master classes in Portland and strong interest at the largest industry trade show, America's Beauty Show, in Chicago demonstrate

the professional community's recognition of the novelty and importance of a safety-oriented approach [23, 24].

The highest marker of recognition of mastery and technique effectiveness is the victory at the Organisation Mondiale Coiffure (OMC) World Championship in Paris in the salon manicure category. OMC is one of the most authoritative institutions in the global beauty industry; its championship is rightly regarded as the functional analogue of the Olympic Games for professionals. This result confirms the methodology's compliance with the highest international standards of quality and aesthetics.

The practical achievements of graduates who completed the training provide direct evidence of the economic efficiency of the method: according to available data, the average income growth of technicians is 50–100%. This effect is driven by higher service prices, an expanded client base (including an audience oriented toward safe procedures), and overall improvements in the service component (see fig.3).

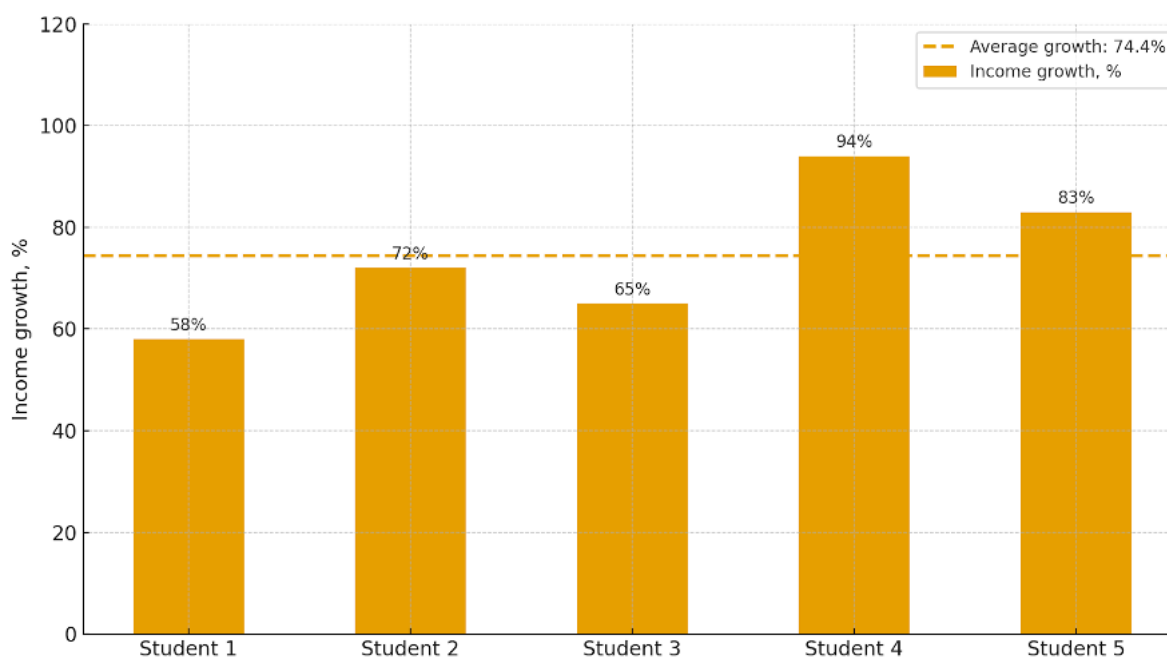


Figure 3: Average increase in income of specialists after mastering the “E-File Dry Manicure” technique

The results of implementing this methodology underscore the need to revise existing standards of professional training in the nail industry. Typical licensing curricula for nail technicians in the United States are generally limited to basic modules in sanitation, anatomy, and core techniques, but most often do not provide in-depth study of materials chemistry and the biomechanics of working with modern equipment, including electric filing (e-file) [19]. Although licensing regulations vary by state, they very rarely establish mandatory requirements for advanced e-file training [18, 26].

As a result, licensed practitioners enter the market whose competencies are insufficient for the safe performance of complex procedures. Consequently, the primary cause of nail plate damage when using an e-file is not a technical defect of the instrument but the practitioner's lack of professional training [4].

grounded in the primacy of safety, a robust scientific foundation, and the principle of continuous learning is both ethically impeccable and exceptionally effective commercially. It contrasts with the paradigm in which speed and low price prevail at the expense of client health, and reveals a persistent premium demand for guaranteed safety and expertise (fig.4).

The presented case study demonstrates that a business model

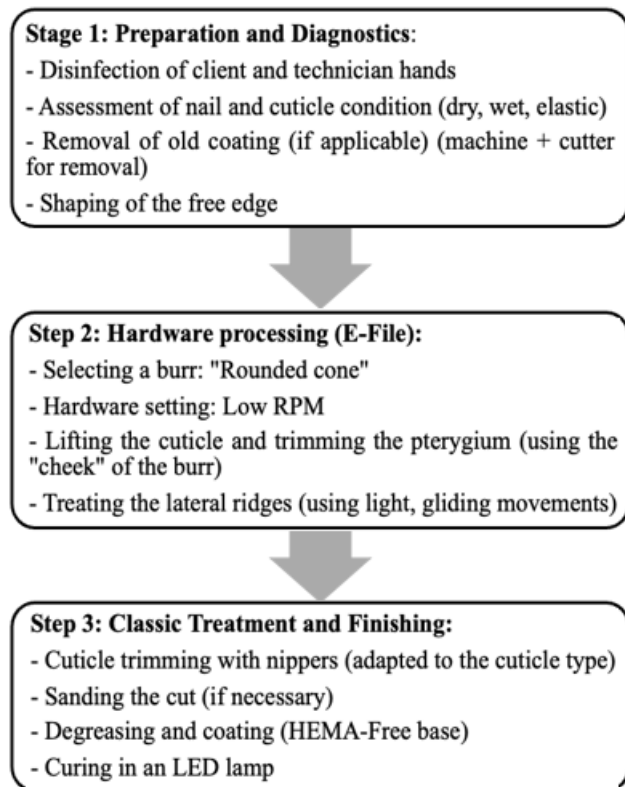


Figure 4: Block diagram of the protocol of the combined technique "E-File Dry Manicure" (compiled by the author based on [4, 19, 27, 29]).

This, in turn, creates an economic incentive for professionals to invest in high-quality education and to raise industry standards from within. Educational programs structured according to this methodology can serve as prototypes of advanced continuing education courses intended to become an integral element of the professional development of the modern nail technician.

4. Conclusion

The study provided a comprehensive assessment of the determinants influencing the safety of hard gel systems in nail services and made it possible to formulate a set of scientifically grounded conclusions.

First, it was established that the risk profile of nail modeling procedures has a dual nature — chemical and biomechanical. The chemical component is driven by the sensitizing effect of residual (meth) acrylate monomers, primarily HEMA, which underlies the increasing frequency of allergic contact dermatitis. The biomechanical component is associated with incorrect use of hardware techniques and manifests as mechanical and thermal injuries to the nail unit, including thinning of the nail plate, burns, and onycholysis.

Second, it was demonstrated that these risks are amenable to effective minimization through the implementation of a systems approach with two key links. At the materials level, this entails the selection of chemically refined, biocompatible formulations, in particular HEMA-free hard gels characterized by a substantially lower allergenic potential. At the technique level, this entails the application of biomechanically verified protocols using safe instrumentation

(for example, rounded cone bits) and strict standardization of processing parameters (speed, pressure).

Third, empirical verification in a case study format confirmed the central hypothesis. It was shown that an integrated system combining safe materials and expert technique (E-File Dry Manicure) not only ensures a high level of safety and promotes the restoration of damaged nails, but also demonstrates commercial effectiveness, demand in the educational environment, and recognition at the highest professional level. Thus, it is convincingly shown that nail health and safety are not a compromise, but a competitive advantage and the foundation for forming the premium segment of the industry.

As a result, the goal was achieved: it was scientifically substantiated that the safety of hard gel is not an inherent property of the product, but represents the outcome of the functioning of an integrated system — material — technique — practitioner. The practical significance of the work lies in creating an evidence base for revising and improving professional training standards, as well as for clarifying the criteria for assessing the quality and safety of nail services. The results obtained can be directly used by practitioners to optimize practice, by instructors when developing advanced training courses, and by championship judges when forming stricter and more objective evaluation criteria.

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