

Photopolymer Transdermal Patches and Conformal Drug-Delivery Interfaces: Skin Contact, Diffusion, Adhesion and Dose Control

Translational medical manufacturing

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Abstract

Photopolymer-enabled transdermal systems range from printed patch structures to microneedle arrays and conformal interfaces. Their engineering problem is coupled: the manufactured geometry controls skin contact; material and microstructure influence diffusion and drug loading; adhesion or retention governs residence; and the delivered dose depends on both device state and biological transport. This review treats dose as a system output rather than as a direct consequence of nominal drug loading. The evidence base is centred on 3D-printed transdermal and microneedle reviews, including vat-photopolymerisation routes. Adhesive chemistry itself is reserved to ER-467, while wound-contact dressings are reserved to ER-468. A proposed mass balance separates device loading, surface recovery, barrier retention and transport, with a synthetic example showing why disappearance from an array is not a delivered dose.

Keywords: photopolymer transdermal patches · conformal drug-delivery interfaces · skin contact · diffusion · adhesion · dose control

1. Scope and boundaries

ER-464 owns drug-delivery interfaces whose primary function is controlled transdermal delivery through a printed photopolymer-enabled structure. It does not own tissue-adhesive chemistry, sealants or wound-dressing qualification. The numbered bibliography contains six entries of differing evidentiary scope. Their inclusion does not imply full-text verification of every study or equivalent evidentiary weight across manufacturing routes.

2. Geometry and skin contact

The designed contact area is not necessarily the realised contact area. Curvature, stiffness, surface roughness, adhesive layer behaviour and skin motion determine contact continuity. In microneedle systems, insertion depth and feature integrity add another geometric state. A patch therefore needs both dimensional qualification and interface verification.

3. Diffusion and release

Drug transport can be governed by diffusion through a matrix, dissolution from a coating, partitioning into skin, or release from a reservoir. Printed geometry can alter path length and exposed area, but no universal geometry-to-flux relation exists across materials and drugs. Release testing must therefore preserve formulation, loading, temperature, medium, device geometry and time.

4. Microneedle-specific coupling

The transdermal reviews by Economidou et al. and Elahpour et al. describe 3D-printing approaches for microneedle-based transdermal delivery; Economidou et al. explicitly includes direct and indirect microneedle manufacture and drug-containing coatings [1,2]. Vat photopolymerisation offers fine geometry but introduces material-selection and residual-species questions that must be separated from geometric success. A sharp, dimensionally correct array is not automatically a safe or dose-controlled device.

5. Adhesion and residence

For ER-464, adhesion is treated as residence and contact retention of the delivery interface. The chemistry and translational barriers of photocurable tissue adhesives and sealants belong to ER-467. This boundary prevents a patch-retention question from becoming a general adhesive-material review.

6. Dose control

Nominal loading, released mass and delivered dose are different quantities. Dose control requires an accounting chain from incorporated drug to releasable fraction, released fraction, skin transport and systemic or local delivery endpoint. Manufacturing variation can alter each stage through dimensions, porosity, cure state or coating uniformity.

7. Conformal interfaces

Conformal patches must maintain function during flexion, perspiration and local deformation. A flat coupon can overstate contact quality on a moving anatomical surface. Qualification should therefore include representative curvature and motion where these affect residence or transport.

8. Minimum verification set

Report material and print route; feature geometry; post-processing; drug identity and loading method; release medium and conditions; release profile; skin or surrogate model; contact area or insertion verification; residence or detachment criterion; and the calculation that converts measured release into the claimed dose metric.

9. Boundary with wound dressings

ER-468 owns wound-contact dressings whose principal functions include moisture balance, removal and wound-healing performance. A transdermal patch may contact skin for extended periods, but it remains in ER-464 only when the primary engineering endpoint is drug delivery rather than wound management.

10. A mass balance for the delivery claim

The following analytical scheme distinguishes manufacture of a microneedle from delivery of an active substance. The location and timing of loading should be explicit: incorporation before curing, loading after manufacture, surface coating and use of a printed mould create different exposure histories for the active substance. A photopolymerised geometry alone does not identify which route was used.

A proposed mass balance would begin with the measured amount on or in the finished device, not the amount originally added to a formulation vessel. After use, the investigator would separately measure material remaining in the device, recovered at the surface, retained in the tested barrier and detected in the receiving compartment. Analytical recovery and degradation would be evaluated with their own controls. An unaccounted fraction should remain unaccounted; assigning it automatically to successful delivery would bias the result.

For illustration only, suppose a finished array contains 100 arbitrary mass units. Following a test, 35 remain on the array, 20 are recovered in a surface wash, 15 in the barrier and 20 in the receiving compartment. The balance accounts for 90 units and leaves 10 unresolved. Calling the disappearance of 65 units from the array the delivered dose would confound several destinations. Calling the receiving-compartment amount systemic bioavailability would add a further inference that this experiment did not measure.

11. Connect geometry with function through distinct tests

The proposed evidence chain would link manufactured geometry to mechanical integrity, insertion, release, transport and biological activity. Each link needs an observable endpoint. A penetration image could show access to a barrier without quantifying transported mass. A release test in a liquid could characterise release without representing insertion or tissue transport. An analytical assay could detect the active substance without establishing retained biological activity.

Controls should match the question. A blank manufactured device could help identify a matrix contribution to the assay. Recovery controls could test whether the analytical procedure loses material. A relevant reference delivery route could support a bounded comparison, provided the amounts and observation periods are compatible. These are proposed study-design elements, not a dosing protocol or a claim that the same controls suffice for every active substance.

The final claim should name the tested model and destination of delivery. This makes a successful manufacturing demonstration useful without allowing it to substitute for an unmeasured pharmacological or clinical outcome.

12. Critical evidence synthesis: manufacturing routes are not interchangeable

The 2024 review by Graça and colleagues focuses specifically on vat-photopolymerisation routes for topical and transdermal applications. Its central translational limitation is not a lack of printable shapes, but restricted availability of materials suitable for pharmaceutical and skin-contact contexts [3]. This distinction matters: an array manufactured with excellent dimensional fidelity may still contain process-derived species, have inappropriate long-term contact behaviour, or be incompatible with the intended active substance. The review by Elahpour et al. surveys a broader mix of microneedle technologies and therefore cannot be interpreted as proof that any particular photocurable formulation is clinically suitable [2].

Three production chains need independent evidence. In direct printing, the final drug-delivery structure is the photopolymerised object and its material state must be qualified. In indirect printing, a photopolymerised master or mould is a manufacturing aid, while the dose-contacting microneedle may be made from another material. In post-print coating, the exposure history of the drug may be different from that of the structural array; coating mass and uniformity then become separate variables. Chanabodeechalermrung et al. (2024) explicitly studied vat-photopolymerisation parameters for mould fabrication followed by HPMC/PVP dissolving microneedles [4]. Results from that route should not be transferred directly to drug-containing cured resin.

For each paper, the evidence table should therefore encode the manufacturing route, the actual skin-contact material, when the active ingredient is introduced, and which physical object was tested. The distinction prevents the misleading pooling of micro-mould geometrical fidelity with direct-contact polymer biocompatibility or in-vivo delivery outcomes.

13. Transport interpretation and model comparability

A measured release curve describes mass leaving a device into the chosen receiving environment; it does not by itself quantify transport across viable skin. Permeation studies require the sampled membrane or skin preparation, its integrity, donor concentration, receptor phase, exposed area, temperature, sampling correction and analytical recovery to be reported. Differences in those parameters may exceed apparent differences between printed designs. Results should therefore be compared conditionally rather than combined as an unconditional ranking of formulations.

For a planar model under appropriate steady-state assumptions, flux may be expressed as $J = (1/A)(dM/dt)$, where M is cumulative receptor-side mass and A is the exposed area. Insertion-based delivery may violate the uniform, constant-area assumption because pathways and tissue recovery change with time. Such equations are analysis tools, not evidence that the conditions apply to a particular printed array. A reported enhancement factor is meaningful only when the reference patch, test skin, loading, observation interval and sampling method are compatible.

An apparently rapid depletion of the printed array can reflect release into surrounding fluid, deposition in tissue, adsorption on test components, chemical degradation, or true receptor-side transport. Direct chemical assay and mass-balance recovery are consequently needed to interpret the compartments. Biological activity or pharmacokinetics, where relevant, require independent endpoints and cannot be substituted with the receptor-side concentration in an ex-vivo cell.

14. Mechanical integrity, insertion and contact as coupled states

Microneedle height, tip radius, taper, base dimensions and spacing contribute to contact mechanics, but print orientation, curing, washing and conditioning determine the actual as-used state. Compression or fracture force reported on an isolated array is not synonymous with successful skin insertion. A representative qualification approach would combine dimensional metrology, force-displacement data,

imaging after application and a barrier-specific insertion measure. Fractured fragments and repeated application warrant distinct assessment where the intended use creates those hazards.

Conformal interfaces introduce a second mechanical problem: retention under curvature, sweat, shear and body movement. The design should separate in-plane extensibility of a backing from stiffness and failure of the individual delivery features. Testing a flat, stationary substrate cannot establish performance across a moving anatomical location. The recent microneedle literature emphasises that materials and printing resolution are influential, while translation additionally requires assessment of evaluation methods and manufacturing consistency [5,6].

In reports combining insertion and flux, chronological ordering is important. Insertion success should be confirmed before or alongside permeation testing, and the effect of application force, dwell time and removal should be recorded. Otherwise two arrays that differ in delivered mass may differ primarily in insertion efficiency rather than drug release behaviour.

15. Curing, post-processing and pharmaceutical compatibility

Photopolymer conversion, extractable residues and solvent/post-cure history can change a device independently of its CAD geometry. A material advertised as biocompatible for one use does not thereby establish acceptability for a different skin-contact duration, damaged skin, or co-formulation with a drug. The intended contact scenario and relevant toxicological endpoints must govern evaluation; safety cannot be concluded from a generic material label.

Where an active pharmaceutical ingredient is present during exposure, potential photochemical or thermal stress should be assessed with stability-indicating analytical methods and process-representative controls. Where the active is added after manufacturing, cleaning and curing must still be evaluated for possible migration of residues into the loaded layer. For indirect mould routes, the validation question includes whether residues are transferred from mould to the actual microneedle. None of these routes warrants a universal acceptance number from the review literature alone [3,4].

Batch comparability should cover raw-material lot, printing exposure strategy, process temperature, washing, post-curing, conditioning, feature integrity, and drug loading at the finished-device stage. Any statistical process capability assessment needs enough representative lots and a clinically or functionally justified specification; a single successful laboratory demonstration is insufficient.

16. Hierarchy of claims, gaps and translational interpretation

The evidence hierarchy should proceed through distinct questions: Can the structure be fabricated reproducibly? Does it retain mechanical function in the intended state? Is material exposure acceptable for the specific application? Does it release a characterised active substance? Does the substance cross the intended barrier in a validated model? And does the system achieve the desired pharmacological or clinical outcome? Positive answers to earlier questions do not settle later ones.

The cited literature provides useful manufacturing and preclinical foundations, but reviews vary in device class, material chemistry, skin model and definition of delivery success [1–6]. Consequently, pooled numerical targets for penetration depth, universal drug flux, adhesive residence or systemic bioavailability are not justified here. A defensible Engineering Review should instead identify comparable subsets of evidence and record which endpoints remain missing for each route.

Priority gaps are route-specific extractables and contact safety, standardised geometric and insertion testing under representative conditions, stability-indicating drug assays, complete mass-balance recovery, scalable lot control and evidence connecting ex-vivo transport with clinically relevant exposure. Closing those gaps is more informative than increasing the number of print demonstrations without harmonised endpoints.

17. Coupled exposure, transport and device verification

The phrase photopolymer transdermal device covers different causal architectures. A photopolymerised mold may never contact tissue, while a directly printed array or adhesive patch may remain in intimate contact with skin and deliver material-associated extractables. These exposure pathways must not be merged in safety interpretation. A useful review records the function of each polymer component, its final cure and extraction history, and whether the drug is incorporated during or after fabrication.

Release profiles are meaningful only when the relevant mass balance is identifiable. The initial loaded amount, residual drug, released fraction, retained fraction and analytical recovery should be independently reported where feasible. A fitted diffusion equation alone does not prove a mechanism: swelling, polymer erosion, barrier transport and imperfect sink conditions can generate superficially similar curves. The review should separate observations from mechanistic attribution and examine whether models remain valid across the measured time range.

Functional acceptance couples mechanical integrity and dose. A microneedle may show acceptable insertion in a synthetic membrane but a different response in hydrated biological skin; a patch may adhere adequately while producing variable contact area and delivery. The strongest comparison uses route-matched controls, measured material state, appropriate skin models and a dose-related endpoint with uncertainty, rather than solely printability or geometric fidelity.

Critical synthesis: design-space boundaries for skin-contact delivery systems

Three manufacturing routes must not be treated as interchangeable: direct printing of a drug-containing feature, printing of a tool or mould subsequently used to form the drug product, and printing of a structural substrate followed by coating or loading. They create distinct risks for photoinitiator exposure, drug degradation, dose uniformity and residual extractables. A literature table should identify the route for each reported outcome before drawing mechanistic conclusions.

For a transdermal interface, permeability results depend on skin source, anatomical region, integrity, temperature, receptor medium, sink conditions and duration. A reported increase in flux does not by itself demonstrate dose accuracy or safety. A critical synthesis separates drug release from a construct, transport across a membrane and systemic exposure, with mass-balance accounting at each step when the original study permits it.

Conformal attachment introduces a coupled mechanical and transport problem: local bending may change seal pressure, contact area, microneedle insertion or path length. Qualification should pair mechanical adhesion and skin integrity with measured transport after relevant deformation. The proposed testing architecture is an engineering interpretation rather than evidence of clinical effectiveness.

18. Limitations

The controlling sources are reviews, not a single harmonised qualification standard. They cover multiple printing and formulation strategies. No universal dose, insertion depth, adhesion strength or release acceptance limit is inferred.

19. Conclusions

Photopolymer transdermal systems should be qualified as coupled geometry-material-transport interfaces. The correct chain is not nominal loading to dose, but manufacturing state to contact, release, skin transport and measured delivery. Boundaries with tissue adhesives and wound dressings must remain explicit.

Competing interests

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. The company develops and supplies photoresins and related process materials. No proprietary formulation, manufacturing sequence, process window or comparative product recommendation is disclosed.

Data availability

No new experimental dataset was generated.

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