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Commentary

Beyond millijoules: a six-dimensional tissue-dose model for fractional ablative carbon dioxide laser therapy

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ABSTRACT

Fractional ablative carbon dioxide (CO_2) laser treatment is commonly documented with displayed parameters such as pulse energy, power, pulse duration, density level and number of passes. These settings are device-specific inputs, not a portable description of the tissue dose. This perspective proposes a six-dimensional tissue-dose model that represents treatment as a state vector comprising ablation geometry, coagulation geometry, treated fraction, spatial distribution, heat accumulation and healing reserve. The framework was developed through a targeted narrative synthesis of foundational fractional photothermolysis studies, histologic and computational dosimetry work, wound-healing investigations, clinical consensus statements and complication literature. A targeted PubMed, Crossref, journal-archive and web search through 19 August 2026 did not identify a previously published framework integrating the same six dimensions. The model separates the delivered tissue insult from device settings and treats healing reserve as a biological and anatomical constraint on the acceptable exposure. It explains why equal millijoules, equal nominal density or equal total energy can produce different lesion geometry, local overlap, thermal burden and recovery. The framework is intended for treatment planning, cross-platform reporting, education and prospective data collection; it is not a validated dose calculator and does not support universal presets. Validation should combine expert content assessment, platform-specific histology or optical imaging, a common clinical data dictionary and prospective prediction of efficacy, delayed healing, postinflammatory hyperpigmentation and scarring. A shared six-dimensional vocabulary may improve reproducibility while preserving the site-and patient-specific judgment required for safe fractional ablative laser therapy.

Keywords: Ablative fractional laser, Carbon dioxide laser, Dosimetry, Microscopic treatment zone, Tissue response, Wound healing

INTRODUCTION

Fractional photothermolysis changed cutaneous laser treatment by distributing microscopic zones of injury among reservoirs of viable tissue.[1] Ablative fractional CO_2 systems extend this concept by removing a microscopic tissue column and surrounding it with a thermally altered envelope. Histology therefore describes at least two vertical tissue effects-ablation and coagulation-rather than a single depth.[2,3]

Clinical documentation, however, remains dominated by device inputs: millijoules per microbeam, watts, pulse duration, density levels, scanner patterns, passes and proprietary mode names. These variables are indispensable for operating a specific platform but cannot be assumed to be biologically equivalent across systems. Spot size, beam profile, pulse shape, peak power, scanner geometry and tissue hydration can alter the microscopic lesion generated by the same displayed energy. Histologic and computational studies support relationships between pulse energy and lesion

dimensions, but the relationships are platform- and context-dependent.[2-7]

This gap matters clinically. A treatment can be vertically deep but horizontally sparse, superficially dense but individually shallow, or modest in nominal settings yet locally aggressive because of overlap, stacking or rapid repeated passes. Anatomical sites also differ in skin thickness, adnexal density, vascularity and tolerance of thermal injury. Consensus recommendations emphasize individualized parameter selection, whereas reports of hypertrophic neck scarring demonstrate that a fractional pattern does not eliminate the consequences of excessive local tissue burden.[8-10]

The objective of this Perspective is to propose a device-independent six-dimensional tissue-dose model for fractional ablative laser therapy. The model is intended to improve planning, reporting, teaching and hypothesis generation. It is not a validated calculator, does not convert settings between manufacturers and does not define universal presets.

FRAMEWORK DEVELOPMENT AND NOVELTY ASSESSMENT

The framework was developed by conceptually synthesizing four evidence domains: (1) foundational fractional photothermolysis and histologic dosimetry studies; (2) computational and imaging studies linking inputs to microscopic tissue effects; (3) wound-healing, safety and complication literature; and (4) contemporary clinical consensus and guideline statements.[1-20] The synthesis was deliberately mechanistic and clinically oriented; it was not designed as a systematic review or meta-analysis.

A targeted novelty search was completed on 19 August 2026 using PubMed, Crossref, the International Journal of Research in Dermatology archive and targeted web searches. Search concepts combined fractional CO2 or ablative fractional laser with dosimetry, tissue dose, framework, model, six-dimensional and six-axis. Related publications described lesion geometry, probabilistic coverage, heat-transfer simulation, pulse stacking, consensus-based parameter selection or site-specific complications. No identifiable publication combined the same six dimensions into one named, device-independent clinical tissue-dose framework. Because a targeted search cannot prove absolute absence, novelty is stated as 'to our knowledge' rather than as an exhaustive priority claim.

THE SIX-DIMENSIONAL TISSUE-DOSE MODEL

The proposed representation is the state vector D6=(A, C, F, S, H and R), where A is ablation geometry, C coagulation geometry, F treated fraction, S spatial distribution, H heat accumulation and R healing reserve. The expected biological effect is expressed conceptually as E=f (A, C, F, S and H | R). The vertical bar emphasizes that healing reserve constrains the acceptable delivered insult. The expression is not a multiplication formula: the dimensions are partly correlated, some are measurable and others require structured clinical estimation.

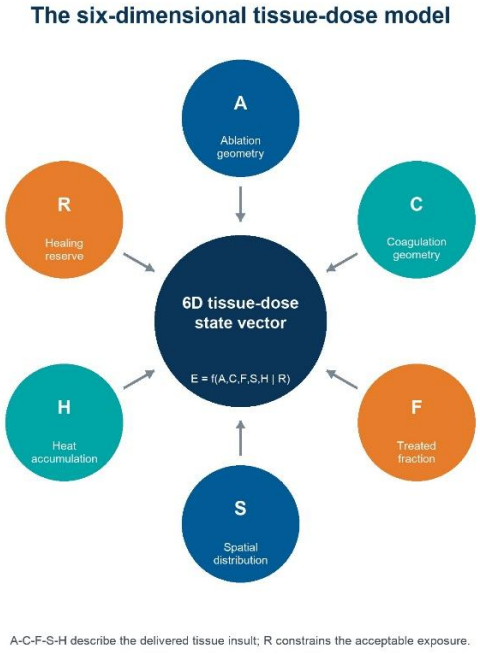


Figure 1: The six-dimensional tissue-dose model.

*Treatment is represented as the state vector D6=(A, C, F, S, H and R): ablation geometry, coagulation geometry, treated fraction, spatial distribution, heat accumulation and healing reserve. The expected biological effect is expressed conceptually as E=f (A, C, F, S and H | R). Healing reserve constrains the acceptable exposure; the expression is not a multiplicative dose equation.

Dimension 1: ablation geometry

Ablation geometry describes the width, depth, volume and shape of removed tissue in each microscopic treatment zone. Depth is clinically intuitive but incomplete: a narrow tapering cavity and a wider cylindrical cavity can reach the same depth while removing different volumes. Energy per microbeam contributes to ablation, but the translation is modified by spot diameter, pulse duration, pulse profile, peak power and tissue water content.

The *ex vivo* prototype study by Hantash et al illustrates both the value and the limitation of a numeric relationship. When pulse energy increased from 9.2 to 23.3 mJ, reconstructed mean ablation depth increased from 280±10 to 760±10 micrometers, while total lesion depth increased from 480±10 to 1,000±10 micrometers.[2] These values are mechanistic anchors, not a cross-platform lookup table.

Dimension 2: coagulation geometry

Coagulation geometry describes thermally denatured but non-vaporized tissue around and below the ablation cavity. It includes thickness, depth, volume and the ablation-to-coagulation relationship. Coagulation influences hemostasis, inflammatory signaling, extracellular-matrix remodeling, channel patency for laser-assisted drug delivery and the burden that must be cleared during healing.[2,3,14,17-19] Similar ablation depths can coexist with different coagulation envelopes when temporal pulse structure or power differs. Consequently, 'depth' alone cannot define tissue dose.

Dimension 3: treated fraction

Treated fraction is the proportion of the target surface or volume exposed during a session. It should distinguish nominal scanner density from effective coverage. In the Hantash coverage formulation, the probability of surface treatment depended on single-lesion area, density per pass and number of passes; pulse energy therefore changed coverage even when spot count remained fixed.[2] A reported density level without spot geometry and pass information is not a complete horizontal dose descriptor.

Dimension 4: spatial distribution

Spatial distribution describes where microcolumns are placed and how evenly they are separated. Relevant features include regularity, clustering, field-edge crossings, intentional or inadvertent overlap, stacking, treatment across concave folds and the relation between focal scar passes and surrounding field treatment. Two exposures with identical average coverage may have different maximum local coverage. This distinction is important because biological failure often begins at a hotspot rather than at the mean field dose. Neck scarring reports specifically implicate aggressive exposure and overlap in a site with limited tolerance.[9,10]

Dimension 5: heat accumulation

Heat accumulation is the temporal dimension of delivered injury. It reflects pulse repetition, dwell time, pulse stacking, adjacent scan timing, scan speed, repeated passes, cooling and the interval available for thermal relaxation. Total energy delivered to a field cannot reconstruct these temporal relationships. Numerical simulations and histologic models show that pulse timing and energy influence the extent of microscopic thermal damage.[4,6,7] Heat accumulation should therefore be documented separately from lesion geometry and treated fraction.

Dimension 6: healing reserve

Healing reserve is the capacity of the treated unit to re-epithelialize, clear thermally altered tissue and remodel without clinically important dyspigmentation, infection or scarring. It integrates anatomical site, skin thickness, adnexal density, vascularity, phototype, baseline inflammation, scar tendency, relevant disease and medication, recent procedures, infection risk, aftercare capability and adherence. It is not a laser output. It is a constraint on the other five dimensions.

Evidence supporting a reserve concept is distributed rather than labeled as such. Human neck studies show that histologic remodeling can continue after apparent clinical closure and that excessive thermal damage may outlast visible recovery.[5] Case reports document hypertrophic scarring after fractional CO_2 treatment of the neck.[9,10] PIH risk and prevention evidence also supports adjusting treatment planning to patient susceptibility rather than treating phototype as an afterthought.[11-13] Current evidence no longer supports a universal six-month delay for every procedure after isotretinoin, but fully ablative procedures remain a separate risk category; medication history therefore belongs in a structured reserve assessment rather than a binary folklore rule.[20]

WHY THE DIMENSIONS MUST REMAIN SEPARATE

The model resists the temptation to compress all exposure into a scalar. Consider three patterns. First, deep sparse columns and shallow dense columns may produce similar total energy yet address different tissue targets and create different healing demands. Second, a moderate nominal density can become locally confluent when scanner fields cross at margins or folds. Third, a device can generate relatively narrow coagulation with one pulse shape and a broader coagulation envelope with another, despite similar visible ablation. The dimensions interact, but preserving them makes the interaction explicit.

This structure also distinguishes delivered insult from observed response. Erythema, edema, frosting, punctate bleeding and pain can help close the procedural feedback loop, but they are not themselves dose dimensions and may vary with anesthesia, vascularity, recent injectables, cooling and observation timing. A response endpoint should therefore modify the plan, not replace the tissue-dose description.

CLINICAL USE: PLAN TISSUE EFFECT BEFORE DEVICE SETTINGS

A practical sequence begins with the clinical target. The operator defines whether the intended effect is superficial texture change, dermal remodeling, focal scar disruption, contracture release or creation of channels for drug delivery. That target determines the desired vertical geometry (A and C). The operator then chooses the horizontal and temporal distribution (F, S and H) and constrains the combined plan by healing reserve (R). Only after this tissue-level plan is explicit should it be translated into platform-specific settings.

This sequence does not require every dimension to be quantified at the point of care. A structured ordinal profile - for example low, moderate or high - is preferable to an undocumented intuition, provided the terms are locally calibrated. Device-specific histology, optical coherence tomography, line-field confocal optical coherence tomography or other imaging may gradually convert qualitative categories into measurable ranges.[15,16] In an exploratory single-investigator OCT plausibility assessment reported in an ahead-of-print multicenter study, identical displayed settings produced mean estimated microcolumn depths of 611 micrometers at the lower eyelid, 578 micrometers at the neck and 625 micrometers at the décolleté.[16] The assessment could not quantify coagulation and was not a participant-level endpoint; it illustrates why one measured axis is informative but not sufficient.

Anatomical translation is especially important. Periocular treatment requires spatial precision and conservative thermal burden near a delicate functional organ.

Robust midfacial skin may tolerate a different profile, particularly when focal scar morphology is the target. Neck and décolleté treatment should reflect limited appendage density, repetitive folding and the published scarring signal. The model therefore supports site-specific profiles without pretending that qualitative profiles are manufacturer-independent presets.

REPORTING AND A COMMON DATA DICTIONARY

A minimum report should record the clinical target and anatomical subsite; device, wavelength, handpiece and mode; displayed pulse energy or power and pulse duration; spot or microbeam diameter when available; scanner density and pattern; passes; overlap or stacking; cooling and inter-pass timing; immediate endpoint; reserve modifiers; aftercare; healing time; and adverse events.

The six dimensions can then be reconstructed or estimated rather than inferred from a single proprietary density level.

Laser-assisted drug delivery makes this need particularly clear. Channel depth, density, coagulation, drug physicochemical properties, application timing and occlusion can all change delivery and safety.

Evidence-based and international consensus statements support deliberate selection of device and drug variables, but they do not replace a tissue-dose representation.[17-19] The 6D framework supplies the laser side of a broader delivery protocol.

VALIDATION AGENDA

The framework generates testable hypotheses. Content validity should first be examined through a multidisciplinary Delphi process involving laser surgeons, dermatologists, biomedical engineers, dermatopathologists and wound-healing specialists. Each proposed dimension should be rated for relevance, independence, clarity and feasibility, and operational definitions should be revised before clinical scoring is tested.

Second, platform-specific calibration studies should map displayed settings to ablation and coagulation geometry using standardized ex vivo tissue, histology and optical imaging. Third, prospective registries should record the six dimensions with a common data dictionary and collect region-specific efficacy, time to re-epithelialization, persistent erythema, infection, PIH, hypopigmentation and scarring.

Fourth, predictive models should compare the full 6D representation with simpler alternatives such as energy alone, density alone or total field energy. Incremental predictive value, calibration, discrimination and external validity across devices are more important than a visually appealing score.

The model would be supported if the complete profile predicts outcomes better than device settings alone and if its operationalized categories are reproducible between trained clinicians.

It should be revised or rejected if dimensions cannot be measured reliably, add no predictive information or conceal rather than clarify device-specific biology.

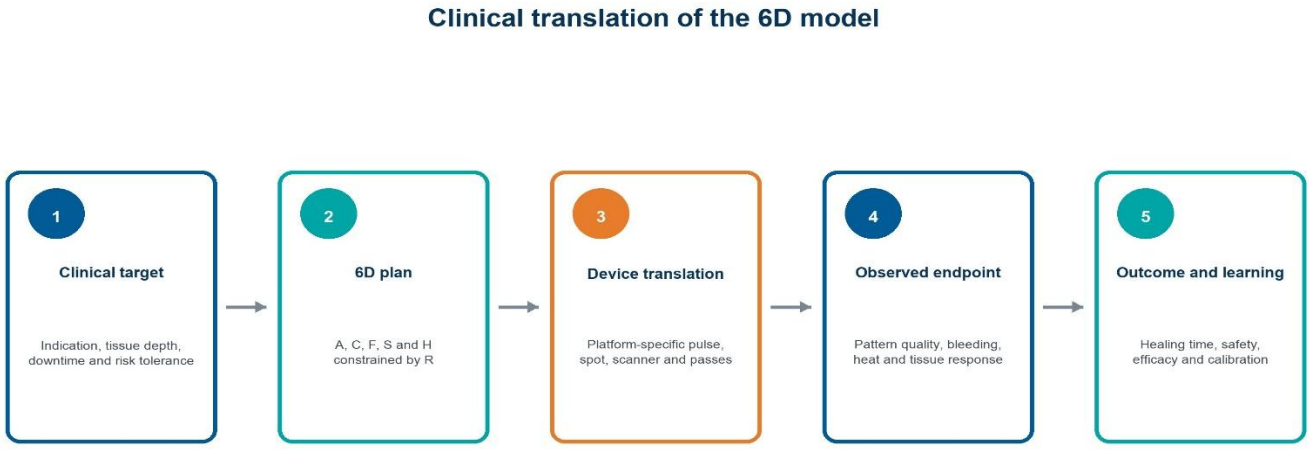


Figure 2: Clinical translation workflow.

*The clinical target defines a six-dimensional tissue plan, which is translated into platform-specific settings. Immediate endpoints and longitudinal outcomes feed a prospective calibration loop. Workflow deliberately separates tissue intent from proprietary device inputs.

Table 1: Operational definition of the six dimensions.

Dimensions	Operational question	Measurement or proxy	Failure mode if omitted
A-Ablation geometry	What tissue is physically removed from each microzone?	Channel depth, width, volume and shape by histology, OCT or validated platform calibration.	Equal displayed energy is mistaken for equal vertical removal.
C-Coagulation geometry	What thermally altered tissue remains around and below the cavity?	Coagulation width, depth, volume and ablation-to-coagulation relationship.	Thermal burden, hemostasis, remodeling and channel behavior are reduced to 'depth'.
F-Treated fraction	How much surface or volume is treated during the session?	Effective coverage derived from lesion area, spot density and passes; report nominal density separately.	Sparse deep and dense shallow exposures appear equivalent.
S-Spatial distribution	Where are microzones placed, and where are the hotspots?	Pattern regularity, clustering, field edges, overlap, stacking, folds and focal-versus-field treatment.	Average coverage conceals local confluence and edge accumulation.
H-Heat accumulation	How is energy distributed in time?	Pulse duration and repetition, dwell, scan speed, pass timing, cooling and thermal-relaxation interval.	Total energy conceals temporal summation and residual heat.
R-Healing reserve	Can this site and patient safely repair the planned insult?	Anatomy, appendage density, vascularity, phototype, inflammation, scar history, disease, medication, aftercare and adherence.	A technically reproducible exposure is assumed to be biologically portable.

*OCT: optical coherence tomography. Dimensions are conceptual constructs; measurement methods require platform-specific validation.

Table 2: Illustrative 6D profiles by clinical context.

Clinical context	Illustrative 6D profile	Dominant constraint	Clinical implication
Fine periocular rhytides	A: superficial-moderate; C: limited; F: low; S: high precision; H: low; R: limited by thin skin and ocular anatomy.	Functional anatomy and hotspot avoidance.	Prioritize spatial control and a low thermal burden; a facial preset should not be copied automatically to eyelid.
Midfacial texture and photodamage	A: superficial-moderate; C: indication dependent; F: low-moderate; S: uniform field; H: controlled; R: generally greater than neck.	Balance efficacy, downtime and PIH susceptibility.	Depth and fraction can be adjusted separately instead of escalating both.
Focal atrophic acne scars	A: focal moderate-deep; C: controlled; F: low field burden with focal targeting; S: morphology led; H: avoid unplanned stacking; R: site and scar dependent	Local targeting without confluent field injury.	Separate focal scar dose from surrounding-field dose in documentation.

Continued.

Clinical context	Illustrative 6D profile	Dominant constraint	Clinical implication
Neck or décolleté rejuvenation	A: superficial-moderate; C: limited; F: low; S: avoid fold and edge overlap; H: low; R: constrained by appendage density and published scarring signal.	Healing reserve.	Use a more conservative profile than robust facial skin and monitor delayed healing closely.
Laser-assisted drug delivery	A: channel depth matched to target; C: minimize if it impedes transport or increases toxicity; F: task specific; S: uniform; H: low; R: includes drug and occlusion risk.	Combined laser-drug exposure.	Document the 6D laser profile together with formulation, concentration, timing and occlusion.

*Profiles are qualitative examples for framework illustration, not parameter recommendations or treatment presets.

Limitations

This is a conceptual framework derived from a targeted narrative synthesis. The novelty search was not a systematic review and cannot establish absolute bibliographic priority. The proposed dimensions are not fully independent: pulse energy can affect ablation, coagulation and effective coverage, while spatial overlap contributes to heat accumulation. Healing reserve is a composite construct and may prove harder to operationalize than physical lesion geometry. The model also does not specify indication-specific therapeutic thresholds, account for every topical or injectable co-intervention, or substitute for device training, ocular protection and clinical governance. A further limitation is that current literature reports settings and outcomes heterogeneously. Direct device comparison is therefore not possible from published inputs alone. This limitation is also the rationale for the model: a shared structure is needed before comparable datasets can be built.

CONCLUSION

To our knowledge, the six-dimensional tissue-dose model is the first device-independent fractional ablative laser framework to integrate ablation geometry, coagulation geometry, treated fraction, spatial distribution, heat accumulation and healing reserve. Its central claim is modest: a safe and reproducible tissue dose cannot be represented by millijoules or nominal density alone. The model offers a common language for planning and reporting while explicitly acknowledging its conceptual status. Prospective validation should determine whether this language improves prediction, cross-platform comparability and patient safety.

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