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# Favorable Clinical Outcomes of Endovenous Laser Ablation (EVLA) Transform Surgery into Ambulatory Vascular Intervention: From Numerical Simulation to Optimized Clinical Practice

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SOUHRN

**Cíl:** Cílem této studie je vyhodnotit účinnost a bezpečnost 1940nm diodového laseru pro endovenózní laserovou ablaci (EVLA) v porovnání s vlnovými délkami 1064 nm a 1470 nm. Studie validuje teoretické výhody vysoké absorpce ve vodě u 1940 nm, konkrétně omezení šíření tepla mimo žilní stěnu, korelací dlouhodobých klinických výsledků s kvantitativními daty z 3D numerického teplotního modelování.
**Metody:** Byl analyzován prospektivní 15letý klinický registr (2010–2025) zahrnující 5 086 pacientů, rozdělených do sekvenčních kohort léčených lasery 1 064 nm (15 W), 1 470 nm (10 W) a 1 940 nm (8 W). Souběžně byl vyvinut časově závislý 3D model konečných diferencí řešící Pennesovu rovnici biologického přenosu tepla. Model kvantifikoval kumulativní tepelnou zátěž perivenózní tkáně a radiální teplotní profily pro každou vlnovou délku.
**Výsledky:** Numerické simulace prokázaly, že vlnová délka 1 940 nm snižuje tepelnou zátěž perivenózní tkáně více než 30násobně oproti 1 064 nm a striktně omezuje teplo na cílovou žílu. Klinicky dosáhl protokol 1 940 nm (8 W) míry uzávěru žíly > 98 %, shodné s lasery o vyšším výkonu, avšak při poloviční energetickém nastavení. To vedlo k minimální pooperační bolesti a nízké míře komplikací; sekundární kontroly byly nutné pouze u 4,4 % případů.
**Závěr:** Vlnová délka 1 940 nm optimalizuje selektivní fototermolýzu maximalizací absorpce tepla v žilní stěně. To umožňuje efektivní ablaci při výrazně nižším výkonu, což zajišťuje procedurální úspěšnost při minimalizaci kolaterálního tepelného poškození a zvýšení komfortu pacienta.



*Keywords:*
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ABSTRACT

**Objective:** This study evaluates the efficacy and safety of the 1940 nm diode laser for endovenous laser ablation (EVLA) compared to 1064 nm and 1470 nm wavelengths. The objective was to validate the theoretical benefits of high water absorption at 1940 nm, specifically the confinement of heat distribution within the vein wall, by correlating long-term clinical outcomes with quantitative data from 3D numerical thermal modeling.
**Methods:** A prospective 15-year clinical registry (2010–2025) comprising 5,086 patients was analyzed, divided into sequential cohorts treated with 1064 nm (15 W), 1470 nm (10 W), and 1940 nm (8 W) lasers. Concurrently, a time-dependent 3D finite difference model based on the Pennes bioheat equation was developed to simulate heat distribution. The model quantified the cumulative thermal load on perivenous tissue and radial temperature profiles for each wavelength.
**Results:** Numerical simulations demonstrated that the 1940 nm wavelength reduced the perivenous thermal load by over 30-fold compared to 1064 nm, strictly confining heat to the target vein. Clinically, the 1940 nm protocol (8 W) achieved a venous closure rate >98%; equivalent to higher-power wavelengths despite a 50% reduction in power settings. This resulted in minimal postoperative pain and a low complication rate, with secondary follow-up visits required in only 4.4% of cases.
**Conclusion:** The 1940 nm wavelength optimizes selective photothermolysis by maximizing heat absorption within the vein wall. This allows for effective ablation at significantly lower power, ensuring procedural success while minimizing collateral thermal injury and improving patient comfort.

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## Introduction

Endovenous laser ablation (EVLA) of the dysfunctional saphenous vein is currently the most widely used endovenous thermal ablation technique for the treatment of advanced varicose veins. With a high success rate (90–98%) and a low incidence of complications and recurrence, EVLA is considered an effective alternative to standard surgical treatment.[1–4] However, EVLA introduces a risk of collateral thermal injury to the surrounding perivenous tissue, which can lead to postoperative pain, ecchymoses and dermatitis. To mitigate these adverse effects, the evolution of EVLA has focused on transitioning through various laser wavelengths (from 810 nm up to 1940 nm).

Despite its widespread clinical adoption, the exact mechanisms of laser-tissue interaction at different wavelengths remain incompletely understood, and procedural parameters (e.g. wavelength, pullback speed, and laser power) lack rigorous standardization.[5,6] Consequently, surgeons often rely on empirical settings guided predominantly by fundamental principles of biomedical optics.

The key therapeutic principle of EVLA is selective photothermolysis, where optical laser energy is absorbed by specific tissue chromophores (primarily hemoglobin and water within the venous wall) and converted into heat. The distribution of this thermal energy within the vessel wall follows thermodynamic laws and is described by the bioheat transfer equation, accounting for direct absorption, subsequent conductive heat transfer, and tissue cooling via blood perfusion.[7] While shorter wavelengths (e.g. 1064 nm) heat the vein wall indirectly via heat transfer from a carbonized blood coagulum, water-targeting wavelengths (1470 nm and 1940 nm) enable direct optical energy absorption within the hydrated venous wall.[8,9] This mechanism theoretically leads to more effective ablation at lower total power settings.[10]

The aim of this study was to correlate robust, long-term clinical outcomes with the theoretical advantages of the 1940 nm diode laser. Characterized by a very high level of absorption coefficient in water, the 1940 nm wavelength theoretically confines heat generation to a thin layer of the venous wall. We hypothesize that this mechanism maximizes ablation efficiency, allowing for a 50% reduction in applied laser power (to 8 W) while significantly minimizing perivenous tissue temperature, collateral damage, and postoperative pain. We validate these clinical observations using a comprehensive 3D numerical heat-transfer model.

## Material and methods

### *Clinical study design*

From January 2010 to December 2025, EVLA was performed on an ambulatory basis in a total of 5,086 consecutive patients with incompetent truncal veins. Three types of laser were used successively with the wavelengths of 1064 nm, 1470 nm and 1940 nm, respectively. EVLA was combined with surgical puncture avulsion of visible varicose veins in all patients. Patients were enrolled in a clinical registry prospectively. An early postoperative follow-up visit was scheduled, including a sonographic assessment of venous closure. Additional visits were conducted only in cases of complications.

In the final cohort of 2,358 patients, the Tethys 1940 nm diode laser (GiGAA, China) was employed with an output power reduced to 8 W. The protocol focused on smooth postprocedural course, particularly in patients with multisegment involvement and truncal vein diameters exceeding 10 mm. In all patients, a bare-tip fiber (Corning, NY, USA) with a 600 µm core and plastic coating (1.06 mm total diameter) was used. The Seldinger technique was preferred for catheterization due to its superior flexibility (**Table 1**).

In 2025, the operative technique was standardized among all five participating surgeons, specifically omitting saphenofemoral junction (SFJ) ligation for vein diameters exceeding 10 mm. The procedure was optimized to treat multiple segments bilaterally (e.g., GSV, SSV, AASV, and perforators) using a single fiber. This resulted in an average of 2.1 venous segments treated per patient. Furthermore, to mitigate disease progression, preventive EVLA of the anterior accessory saphenous vein (AASV) was performed in 18% of cases. This comprehensive multi-segment approach was facilitated by advanced ultrasound imaging utilizing an augmented needle mode (Venue Fit, GE Healthcare).

### *Numerical modeling framework*

A time-dependent 3D finite difference model was developed using MATLAB (MathWorks, Natick, MA, USA) to simulate the endovenous laser ablation (EVLA) process. The simulation domain represented a simplified venous geometry comprising five distinct concentric zones: the optical fiber core ($d$ = 0.95 mm), residual blood lumen, vessel wall (subdivided into intima, media, and adventitia), and the surrounding perivenous tissue (with tumescence). The simulation utilized a uniform Cartesian grid with a spatial resolution of d$x$ = 0.15 mm.

### *Optical model and bioheat transfer*

Light propagation in the tissue was simulated using the diffusion approximation of the radiative transport equa-

**Table 1 – Laser generators used in the study**

| Period | Wavelength (nm) | Laser type | Water absorption coefficient ($cm^{-1}$) | Power (W) | LEED (J/cm) | Patients ($n$) |
|---|---|---|---|---|---|---|
| 2010–2016 | 1064 | Nd:YAG (Fotona) | 0.12 | 15 W | 150 | 1117 |
| 2017–2019 | 1470 | DLInGaA (Velas2, Gigaa) | 24.8 | 10 W | 100 | 1611 |
| 2020–2025 | 1940 | DLAlGaIn (Tethys, Gigaa) | 119.8 | 8 W | 50–80 | 2358 |

tion for all investigated wavelengths (1064 nm, 1470 nm, and 1940 nm). The fiber tip was modeled as a volumetric isotropic source located within the fiber core. The photon density distribution was solved iteratively in each time step using a stabilized successive over-relaxation (SOR) solver. The resulting volumetric heat source, $Q_{laser}$, served as input for the thermal model. The spatiotemporal temperature distribution $T(x,y,z,t)$ was governed by the **Pennes bioheat equation**:

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + Q_{laser} + Q_p$$

where ρ, $c_p$, and $k$ denote the tissue density, specific heat capacity, and thermal conductivity, respectively. The term $Q_p$ represents heat loss due to blood perfusion, which was modeled dynamically; perfusion was set to zero in the fiber, lumen, and in tissue regions where temperature exceeded the coagulation threshold.

### *Simulation protocol and analysis*

The simulation replicated a continuous pullback procedure. The laser source moved retrogradely along the $Z$-axis at a constant velocity ($v_{pull}$), determined by the ratio of power ($P$) to linear endovenous energy density (LEED). Three sets of parameters were evaluated:

1. **1064 nm:** $p$ = 15 W, LEED = 150 J/cm
2. **1470 nm:** $p$ = 10 W, LEED = 100 J/cm
3. **1940 nm:** $p$ = 8 W, LEED = 65 J/cm

To assess tissue damage, the cumulative thermal load was quantified by integrating excess heat into voxels exceeding the necrosis threshold (>43 °C). Radial temperature profiles were extracted at the moment of laser cessation at two key locations: directly at the fiber tip and in the distal thermal wake ($Z$ = +2.25 mm).

**Table 2 – Cumulative thermal load in perivenous tissue**

| Wavelength (nm) | Thermal load (>43 °C) (°C · s · mm³) | Normalized ratio (–) |
|---|---|---|
| 1064 | 341.0 | 32.4× |
| 1470 | 65.7 | 6.2× |
| 1940 | 10.5 | 1.0× |

The values represent the time-integrated excess heat in tissue voxels exceeding the necrosis threshold (>43 °C).

## Results

### *Clinical outcomes*

The venous closure rate exceeded 98% across all three laser cohorts, demonstrating comparable efficacy regardless of the wavelength used.[11,13,14] However, in the cohort treated with the 1940 nm diode laser, this procedural success was achieved using exactly half the applied energy compared to previous groups. Specifically, a power output of 8 W and a linear endovenous energy density (LEED) of 50–80 J/cm were sufficient for effective ablation.[12,15] At these parameters, carbonization of the laser fiber tip was entirely eliminated.

Clinically, the incidence of adverse effects was significantly reduced; postoperative swelling and pain over the treated vein were exceptionally rare and inherently mild.[15,16] Consequently, an early follow-up visit was sufficient for 95.6% of patients.[15] Secondary consultations were scheduled exclusively for a minority of patients reporting prolonged moderate pain, which completely resolved within the first postoperative week in all instances.

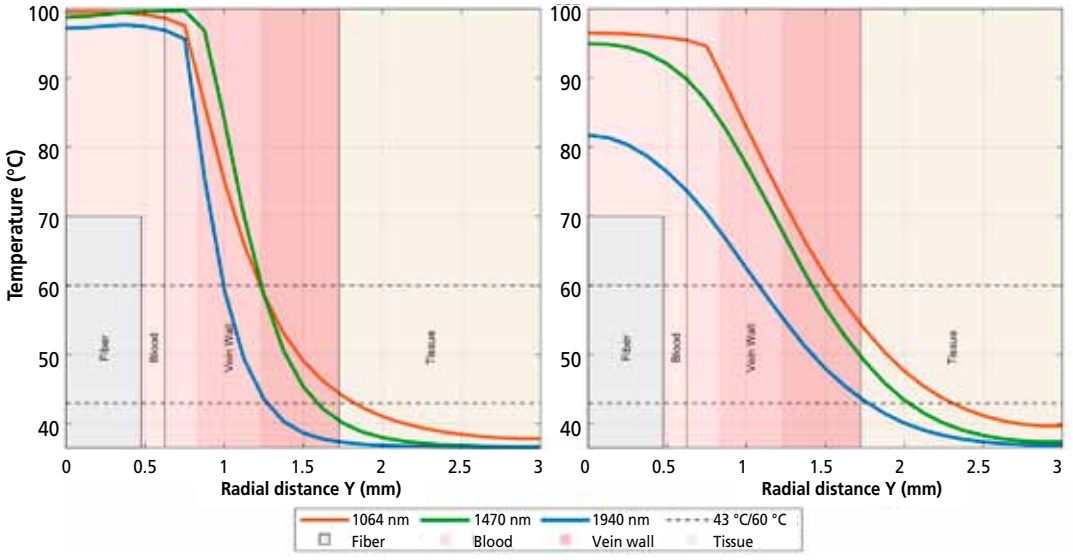


**Fig. 1 – Radial temperature profiles extracted from the simulation at two axial locations: directly at the fiber tip (left) and in the distal thermal wake, 2.25 mm behind the tip (right). The comparison reflects the clinical protocols used: 1064 nm (150 J/cm), 1470 nm (100 J/cm), and 1940 nm (65 J/cm). Note that despite the significantly lower energy density (LEED), the 1940 nm wavelength exhibits the steepest thermal gradient, confirming superior heat confinement to the vessel wall.**

### *Numerical simulation findings*

The numerical model provided insight into the thermal mechanisms underlying the clinical observations. While the temperature increase within the target structures (tunica intima and media) was sufficient for ablation across all wavelengths, the heat distribution into the surrounding perivenous tissue varied significantly.

Radial temperature profiles at the fiber tip and in the thermal wake ($Z$ = +2.25 mm). These profiles, illustrated in **Figure 1**, show that the 1940 nm wavelength generates the steepest thermal gradient at the fiber tip, effectively concentrating energy within the vessel wall, while the distal profiles reflect the subsequent heat redistribution during the cooling phase.

The cumulative thermal load on the surrounding tissue (defined as volume integral of temperature >43 °C over time) was markedly dependent on the wavelength. As shown in **Table 2**, the 1064 nm laser generated a thermal load 32.4 times higher than the 1940 nm laser. The 1470 nm laser reduced this load significantly compared to 1064 nm, but the 1940 nm wavelength resulted in the most confined thermal footprint, minimizing collateral thermal damage.

## Discussion

Our study combines a robust long-term clinical registry with dynamic 3D numerical modeling to validate the superiority of the 1940 nm wavelength for EVLA. The simulation results clearly demonstrate that the 1940 nm wavelength confines thermal energy strictly to the vessel wall, demonstrating a more than 30-fold reduction in perivenous thermal load compared to the 1064 nm wavelength. This correlates strongly with our clinical observations of significantly reduced postoperative pain and a diminished need for secondary follow-ups (4.4%) in the 1940 nm group.

A critical aspect of laser-tissue interaction in EVLA is the underlying mechanism of heat generation. Historically, the use of shorter wavelengths (810–1064 nm), which rely heavily on hemoglobin absorption, leads to a formation of a carbonized blood coagulum at the fiber tip. This carbonized layer absorbs approximately 45% of the emitted laser energy, converting the fiber tip into a superheated thermal probe (>1000 °C) acting as a black body radiator.[6] Consequently, vein closure with 1064 nm was achieved primarily through conductive heating from this "hot tip" rather than direct optical absorption by the vein wall. This mechanism explains the higher rate of fiber tip carbonization observed in our early patient series, as well as the associated risk of vein perforation and pain due to extreme localized temperatures.

In contrast, water-targeting wavelengths (1470 nm and 1940 nm) interact directly with the water-rich tunica intima and media. Although the 1470 nm wavelength represents a significant clinical improvement over 1064 nm, our simulations show that the 1940 nm wavelength provides even stricter thermal confinement. This is driven by the absorption coefficient of water, which is approximately 5 times higher at 1940 nm (119.8 $cm^{-1}$) compared to 1470 nm (24.8 $cm^{-1}$). Our numerical model verifies that this high absorption ensures rapid, localized energy deposition within the target tissue volume.[8,9] This specific volume heating achieves effective collagen denaturation at significantly lower power settings (8 W vs 15 W), preventing the formation of a carbonized layer. Clinically, this was evidenced by the complete absence of carbonization on the fiber tips in the 1940 nm group. By entirely avoiding the "hot tip" effect, the 1940 nm laser minimizes the risk of perivenous thermal injury, directly accounting for lower pain scores reported in recent literature.[16]

## Limitations

It is important to acknowledge that our numerical model utilizes diffusion approximation to simulate light transport. While this is a standard approach for biological tissues[5], it does not account for the dynamic formation of the carbonized layer at the fiber tip. Therefore, the model likely underestimates the maximal tip temperature for the 1064 nm wavelength, where carbonization is prevalent. However, for the 1940 nm wavelength, where carbonization is clinically absent, the model provides an accurate representation of the optical-thermal interaction. Additionally, the clinical registry is non-randomized due to its sequential nature; nevertheless, the large sample size ($n$ > 5,000) provides robust real-world evidence of the benefits of the 1940 nm protocol.

## Conclusion

This study provides both theoretical and robust clinical evidence supporting the efficacy of the 1940 nm wavelength for endovenous laser ablation. Our 3D numerical simulations confirm that the 1940 nm laser provides the highest optical confinement within the venous wall, eliminating the "hot tip" effect, significantly reducing the thermal load by more than 30-fold compared to 1064 nm and further optimizing the thermal profile relative to 1470 nm. This localized energy absorption justifies the feasibility of the low-power protocol (8 W). Clinical outcomes from over 2,300 procedures validate these findings, demonstrating that 1940 nm ablation maintains high closure rates (>98%) while significantly minimizing collateral thermal injury, as evidenced by a decrease in secondary follow-ups for pain to 4.4%. Consequently, EVLA utilizing the 1940 nm laser at reduced power settings can be recommended as a standard of care to maximize patient comfort without compromising efficacy.

**Originality of the work**

As the corresponding author, I declare that the submitted manuscript is original, has not been previously published, and is not currently under review for publication in another journal. All authors contributed to the preparation of the study and agree with the final version of the manuscript.

**Conflict of interest**

All authors declare that they have no conflict of interest regarding the subject matter and results of this study.

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**Ethical statement**
The study was conducted in accordance with the Declaration of Helsinki. Data collection took place within the framework of a long-term clinical registry approved for routine clinical practice. This analysis of anonymized data was conducted in accordance with the institution's ethical standards and did not require additional EC approval for a specific research project, as no patient identifiers were used.

**Informed consent**
Informed consent was obtained from all individual participants included in the study.

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