European Journal of Vascular and Endovascular Surgery 44 (2012) 77–81

Contents lists available at SciVerse ScienceDirect

European Journal of Vascular and Endovascular Surgery

journal homepage: www.ejves.com

Endovenous Simulated Laser Experiments at 940 nm and 1470 nm Suggest Wavelength-Independent Temperature Profiles

R.R. van den Bos[a,*], P.W.M. van Ruijven[b], C.W.M. van der Geld[b], M.J.C. van Gemert[c], H.A.M. Neumann[a], T. Nijsten[a]

[a] *Department of Dermatology, Erasmus Medical Center, Rotterdam, The Netherlands*
[b] *Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands*
[c] *Department of Biomedical Engineering and Physics, Academic Medical Center, University of Amsterdam, Amsterdam, The Netherlands*

ARTICLE INFO

Article history:
Received 10 December 2010
Accepted 20 April 2012
Available online 22 May 2012

Keywords:
Laser therapy/instrumentation
Laser therapy/methods
Temperature
Varicose veins/blood
Varicose veins/surgery
Angioplasty
Laser/instrumentation
Endothelium
Vascular/injuries
Models
Cardiovascular
Thermal conductivity

ABSTRACT

Background: EVLA has proven to be very successful, but the optimum methods for energy delivery have still not been clarified. A better understanding of the mechanism of action may contribute to achieving a consensus on the best laser method and the most effective use of laser parameters, resulting in optimal clinical outcomes, maintaining high success rates with minimal adverse events. The aim of this study is to assess the impact of wavelength, pullback speed and power level on the endovenous temperature profile in an experimental setting.
Methods: In an experimental setting, temperature measurements were performed using thermocouples. The experimental set-up consisted of a transparent box in which a glass tube was fixed. Different laser parameters (wavelength and power) and 2 different pullback speeds (2 and 5 mm/s) were used. Thermocouples were placed at different distances from the fiber tip. Validity of the experimental setting was assessed by performing the same temperature measurements using a stripped varicose vein. The maximal temperature rise and the time span that the temperature was above collagen denaturation temperature were measured.
Results: The experiments showed that decreasing the pullback speed (2 mm/s) and increasing the power (up to 14 W) both cause higher maximal temperature and a longer time above the temperature for collagen denaturation. The use of different laser wavelengths (940 or 1470 nm) did not influence the temperature profile.
Conclusion: The results of our experiments show that wavelength on its own has not been demonstrated to be an important parameter to influence the temperature profile.

Endovenous laser ablation (EVLA) is most frequently used as thermal therapy for saphenous varicose veins. EVLA is a challenging traditional surgery as the gold standard for varicose vein treatment because of its very high success rate (>90%),[1] low rates of complications[2] and recurrences. Although EVLA has proven to be very successful, the exact working mechanism is still not fully identified, and the procedure is, therefore, not yet standardised (i.e., wavelength, pullback speed and power). Several studies, some of them retrospective cohort analyses, suggest that a minimal energy delivery of 60 J cm^{-1} should be administered to achieve occlusion of a vein.[3–5] The lack of knowledge on working mechanism may have contributed to the commercially driven proliferation of different laser wavelengths and modifications such as fibre tips with radial emission of laser light.

Thermal injury to the venous wall is generally accepted to be responsible for vein occlusion in endovenous thermal treatments. However, the exact mechanism of EVLA-induced temperature rise is not well documented. Four main theories on the heat induction of EVLA have been proposed: (1) direct absorption of the scattered laser light by the vein wall,[6,7] (2) heat transport by steam bubbles emerging from the hot fibre tip and heat release associated with their condensation,[8,9] (3) direct contact of the laser fibre with the vein wall[7,10] and (4) heat diffusion from the hot fibre tip.[11]

Knowledge about heat generation and heat transport is important. Two studies measured intravenous temperatures during EVLA (810 and 980 nm) of 61–140 °C and perivenous temperatures of 35–48 °C.[12–14] The effect of the various laser parameters that may affect the rise in temperature, such as wavelength, power level and pullback speed (which are not standardised in EVLA) is poorly

---

* Corresponding author.
E-mail addresses: r.vandenbos@erasmusmc.nl (R.R. van den Bos), t.nijsten@erasmusmc.nl (T. Nijsten).

1078-5884/$ – see front matter © 2012 European Society for Vascular Surgery. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.ejvs.2012.04.017

documented. The aim of this study is to assess the impact of wavelength, pullback speed and power level on the endovenous temperature profile in an experimental setting.

Methods

The experimental set-up consisted of a transparent box in which a glass tube was fixed. The glass tube was open at both ends so that the laser fibre and some thermocouples were introduced from opposite ends. The box was filled with water (room temperature) and the tube was filled with heparinised pig blood. Three thermocouples were positioned within the tube (tc 1, 2, 3) and four thermocouples were positioned at the outside of the tube and at different distances from the tube wall (tc 4, 7: 0 mm, tc 5: 1 mm, tc 6: 2 mm) (Figs. 1 and 2). The internal thermocouples inside the tube were placed at three different positions because it was expected that the temperature profiles would differ for various axial positions due to development of the heat caused by the laser fibre moving from left to right. To assess the validity of the experimental setting, a stripped human great saphenous vein (GSV) was used for similar temperature measurements. In these experiments, thermocouples were placed inside the vein and at the outer surface of the vein. This was done since positioning thermocouples at a certain distance from the outer surface was not possible due to flexibility of the vein.

Two laser wavelengths were used: 940 nm (Diode, Dornier Diomed LTD) and 1470 nm (neodymium:yttrium–aluminium–garnet, ELVeS Biolitec AG, Germany). To assure a centred position of the laser fibres in the tube (i.e., fixed distance to the thermocouples), the end-emitting laser fibres (core diameter of 0.6 mm) were centred in the tube using a 'tulip' piece attached to the fibre tip.[15] We used a new fibre after two experiments, after one experiment the tip was cleft. The temperature experiments were repeated for two pullback speeds, *v*, (2 and 5 mm s^{-1}), two laser wavelengths, λ, (940 and 1470 nm) and several values for laser power, *P* (continuous mode). The measured output was different from the power setting. At 940 nm the measured power was 4.58 W at a power setting of 5 W, 12.8 W (setting 14 W) and 18.3 W (setting 20 W). At 1470 nm, the measured output was 4.6 W (setting 5 W) and 12.7 W (setting 14 W). For each of the 10 possible combinations of parameters, temperature measurements were repeated 5 times. To assess the endovenous temperature profile, $\Delta T_{\max}$ and Δt_{den} were calculated from this graphical representation. $\Delta T_{\max}$ was defined as the maximal temperature increase above the initial temperature (about 20 °C) measured by any of the thermocouples inside the tube and by the outer thermocouples, and Δt_{den} was defined as the time span that the temperature was above 50 °C (i.e., temperature at which collagen denatures). This time span reflects the damage to the collagen of the vein wall, which is assumed to be required for successful thermal ablation.[16–18] Mean outcomes and standard deviation (SD) were calculated for $\Delta T_{\max}$ and Δt_{den} for the measurements of the experiments that were repeated 5 times. The SD in Figs. 3 and 4 are presented with vertical error bars; the horizontal error bars indicate uncertainty in measurement location.

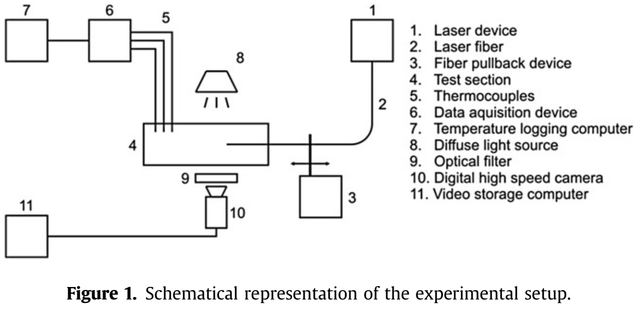

Figure 1. Schematical representation of the experimental setup.

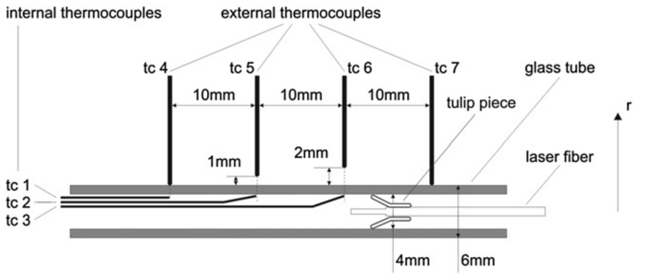

Figure 2. Position of the thermocouples and fiber with definition of the radial distance, *r*.

Statistical Analyses

Continuous variables are presented as means with a SD and were compared between groups using a Student *t*-test. We used Statistical Package for the Social Sciences (SPSS) 15.0 software (SPSS Inc., Chicago, IL, USA), and two-sided *p*-values were considered significant if <0.05.

Results

The results for $\Delta T_{\max,}$ are graphically depicted per wavelength and by measured power (Fig. 3) and per pullback speed (Fig. 4) at radial distance *r* (mm) from the fibre tip. The time span that the temperature was above the threshold value for collagen denaturation (Δt_{den}) is listed in Table 1.

Increasing the speed from 2 to 5 mm s^{-1} resulted in a decrease in $\Delta T_{\max}$ for both wavelengths (Fig. 3). In addition, higher pullback speed resulted in lower Δt_{den} (Table 1). Increasing the power level from 4.6 W to 12.8 W resulted in higher $\Delta T_{\max}$, but only a minor effect on $\Delta T_{\max}$ was observed for a further increment to 18.3 W in the 940 nm laser wavelength (Figs. 3 and 4). However, Δt_{den} increased nearly linearly with increasing power (Table 1).

Since the measured power value at the fibre output proved to be lower than the set values during the experiments (power measurements: sensor Ophir 30 A (power accuracy ± 3%), meter Ophir Nova), with differences slightly depending on the laser used, an additional comparison was made using a measured power output of 12.8 W for both lasers. Variations in $\Delta T_{\max}$ due to wavelength can only occur within a distance of about 2 mm from the laser tip (Fig. 5). More and more accurate measurements are required to give conclusive results regarding the wavelength dependency of the time-dependent temperature field around the fibre. The applied laser wavelengths (940 nm or 1470 nm) had only little effect on $\Delta T_{\max}$.

Fig. 6 shows the temperature results using a varicose vein (GSV). Although the obtained maximum temperatures were higher than the temperatures in the glass tubes, the differences were not statistically significant for the combinations of different laser settings and distances to the laser tip, except for the 12.8 W, 5 mm s^{-1} at a distance of 3 mm ($p = 0.02$).

Discussion

Our simulated experiments of EVLA confirmed that pullback speed and power level both influence the temperature profile. We showed that only combinations of laser power and pullback speed that supply a relatively high administered energy per cm resulted in substantial Δt_{den} values. At 940 nm, $\Delta T_{\max}$ and Δt_{den} increased when the power was increased from 4.6 W to 12.8 W and at 1470 nm, $\Delta T_{\max}$ and Δt_{den} increased when the power was increased

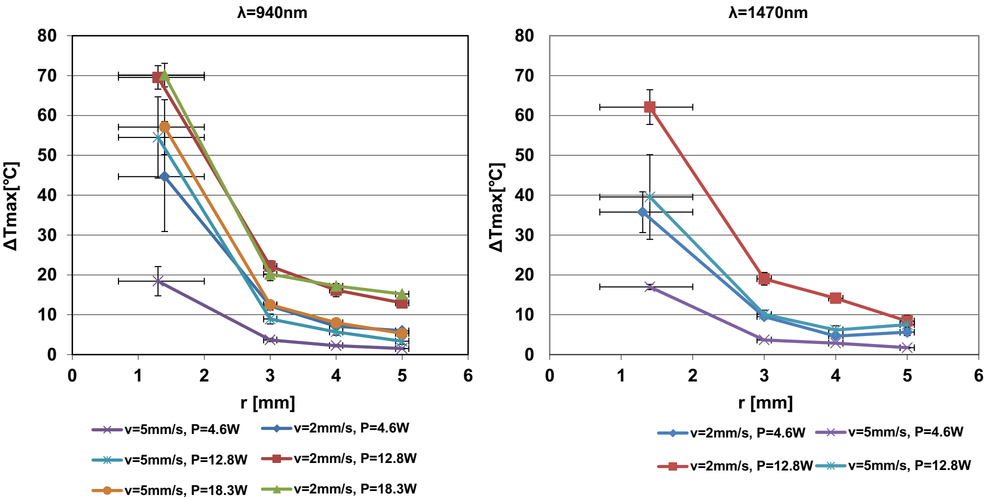

Figure 3. ΔT_{max} as a function of distance from the fiber tip for combinations of power (output) and pullback speed, left for 940 nm and right for 1470 nm. *P*, Power; W, watt; *v*, speed; *r*, radial distance.

from 4.6 W to 12.8 W. However, at 940 nm, when further increasing the power to 18.3 W, only the Δt_{den} further increased and ΔT_{max} did not. This means that further increasing the power to 18.3 W at 940 nm may cause more damage to the vein wall. At 1470 nm, this experiment could not be performed because the power setting was limited to 14 W. The stagnation in maximum temperature is explained by noting that the maximum temperature approaches the boiling point, which limits further increase of temperature. Only combinations of power level and pullback speed that supply a relatively high administered energy per cm (approximately $>$60 J cm^{-1}) result in substantial Δt_{den}, which is in line with previous studies suggesting a threshold of 60 J cm^{-1} for durable vein occlusion.[3–5] It was not our aim to propose the appropriate energy dosing based on our experiments. Ideally, this should be based on a comparative randomised trial using different laser parameters studying effectiveness and side effects. However, based on our experimental data, we could hypothesise that, for effectiveness, at least 12.8 W in combination with a pullback speed of 2 mm s^{-1} should be administered independent of laser wavelength. To prevent side effects, it seems logical to prevent vein wall perforations by preventing direct contact of the laser tip with the vein wall, for example, by using a tulip piece around the tip.[15]

The most important conclusion drawn from the experimental results is that the temperature profiles of 940 and 1470 nm laser wavelengths are virtually identical at equal pullback speed and power. The wavelengths used in this study cover the clinically applied range of wavelengths to a large extent. Light at 940 nm is primarily absorbed by haemoglobin with about 0.16 mm^{-1} blood absorption coefficient, very comparable to the 0.12–0.17 mm^{-1} blood absorption coefficients between 810 and 1064 nm,[19] and light at 1470 nm primarily by water with about 2.5 mm^{-1} blood absorption coefficient. The resulting temperature profiles are virtually identical for different laser wavelengths. Consequently, possible differences in outcome between different EVLA studies may not be explained by different laser wavelengths but rather by differences in other laser parameters such as pullback speed, power and fibre tip design.[20]

In addition to virtually identical ΔT_{max} and Δt_{den} for equal power and pullback speed for both 940 nm and 1470 nm laser wavelengths, the extreme temperature near the laser fibre tip is likely to be comparable as well. In a recent study, the tips of fibres used for 940 nm and 1470 nm were both damaged suggesting temperatures of more than 800 °C.[21]

It has been suggested that only intraluminal thrombosis caused by EVLA may be sufficient for vein occlusion. If that is the case, our

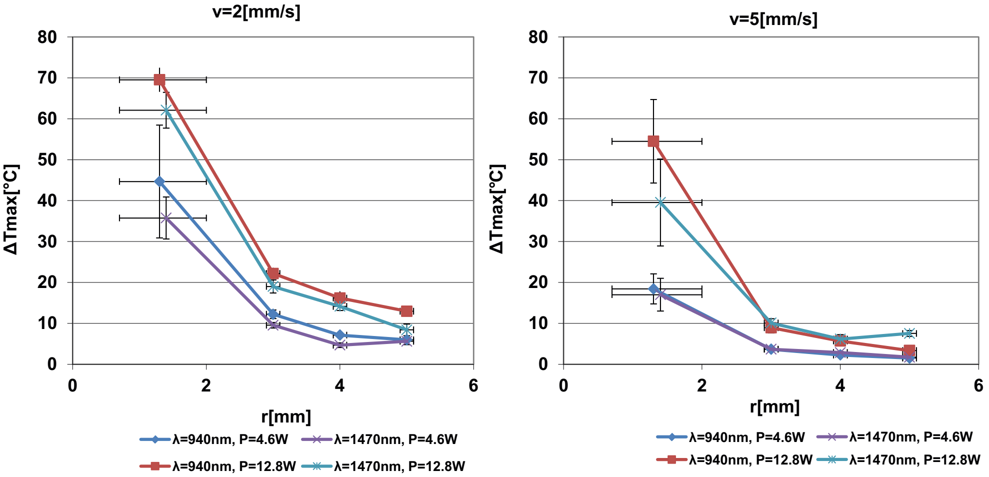

Figure 4. Comparison between wavelengths of ΔT_{max} at various power (output) levels and pullback speeds ($v = 2$ mm/s and $v = 5$ mm/s). *P*, Power; W, watt; *v*, speed; *r*, radial distance.

Table 1
Values for Δt_{den} (seconds), mean ± SD for three different power outputs[a] and two pullback speeds.

	$v = 2$ [mm/s]				
	4.6 W[b]	4.6 W[b]	12.8 W[c]	12.8 W[c]	18.3 W[d]
r[mm]	940	1470	940	1470	940
2	2.6 ± 2.9	2.3 ± 1.5	8.3 ± 1.4	9.7 ± 0.8	9.6 ± 1.8
	$v = 5$ [mm/s]				
	4.6 W[b]	4.6 W[b]	12.8 W[c]	12.8 W[c]	18.3 W[d]
r[mm]	940	1470	940	1470	940
2	0.1 ± 0.1	0.0 ± 0.1	2.4 ± 1.5	1.5 ± 1.4	3.7 ± 1.5

[a] Power output differed from power setting.
[b] Power setting 5 W.
[c] Power setting 14 W.
[d] Power setting 20 W.

minimal threshold of 50 °C needed for collagen denaturation of the vein wall may not be needed. We based this threshold on the histological studies post-EVLA and the observation of RFA-induced venous remodelling assuming that collagen alteration is important for durable occlusion. However, changing the threshold of 50 °C to, for example, 40 °C would not change the conclusion of this study that a wavelength change from 940 nm to 1470 nm did not demonstrate a change in temperature rise.

In the experiments with a varicose vein, peak temperatures were higher, but not statistically significant, to those measured in the glass tube. We hypothesise that the thermocouples were located closer to the fibre tip in the varicose vein because the vein might have been compressed and contracted during the experiments. A thermocouple location of only 0.5 mm closer to the fibre tip would already explain the increase in maximum temperatures in Fig. 6. Subcutaneous tissue and water have similar heat diffusivity. More importantly, also the glass tube material has a similar heat diffusivity of about 0.16 10^{-6} m^2 s^{-1}. Two significant transport mechanisms of heat, diffusion and radiation, are therefore virtually the same in actual veins and in the mock-up we employed. Altogether, the findings in the varicose vein and glass tube were very comparable confirming the validity of the experimental setting of a glass tube. The latter is also more suitable for the performed measurements because of its constant shape and position, yielding better reproducible measurement conditions.

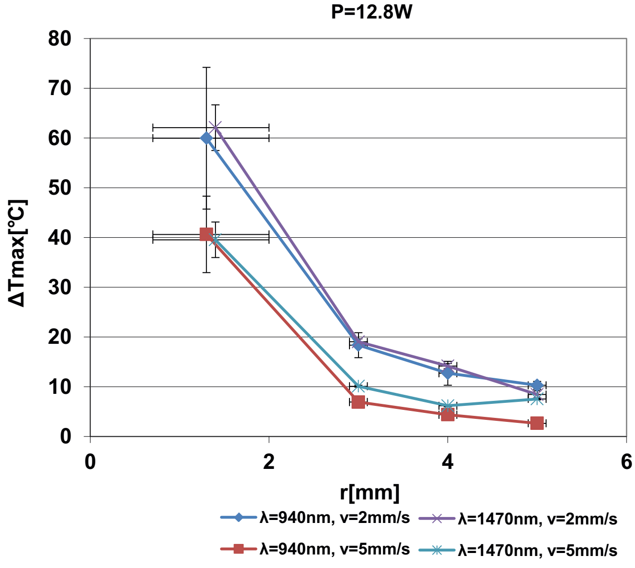

Figure 5. Peak temperature values at 12.8 W. Variations in $\Delta T_{\max}$ due to wavelength variation can only occur within a distance of about 2 mm from the line over which the laser tip is moving. *P*, Power; W, watt; *v*, speed; *r*, radial distance.

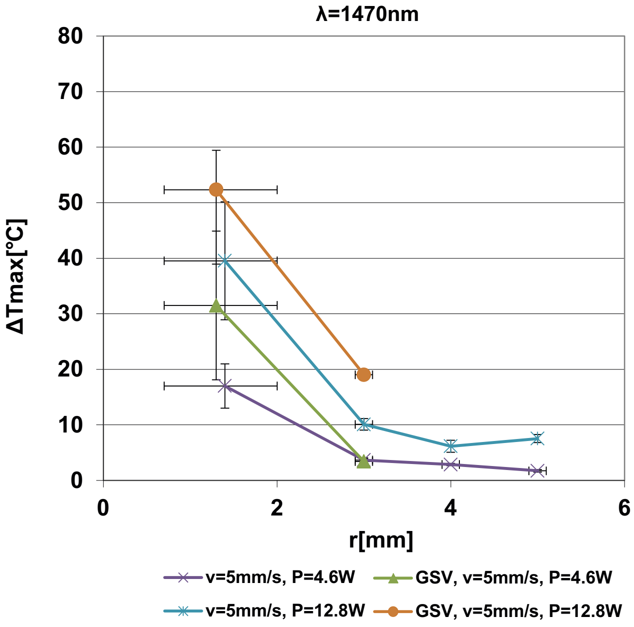

Figure 6. Comparison of $\Delta T_{\max}$ for experiments with a great saphenous vein (GSV) and a glass tube. *P*, Power; W, watt; *v*, speed; *r*, radial distance.

Our results are in line with a previous study in which we showed that fibre tips after EVLA had a carbonised layer of blood on the tip and destruction of the fibre glass was visible, suggesting that the temperature rise close to the fibre tip is high. These results were also independent of laser wavelength. The carbonised layer on the fibre tip absorbed between 30% and 70% of the laser light emission suggesting that heat diffusion is a major mechanism for EVLA, independent of wavelength.[21] This observation also supports two other temperature-related mechanisms, namely, steam bubble formation and direct contact of the fibre tip with the vein wall, since both mechanisms are based on exceedingly high fibre tip temperature.

Conclusions

The findings of this study are that increasing power (up to 18.3 W) and decreasing pullback speed (from 5 mm s^{-1} to 2 mm s^{-1}) result in higher peak temperatures. Only a relatively high administered energy per unit length results in high enough temperatures to cause collagen denaturation. In addition, wavelength has not been demonstrated to be an important parameter to influence the temperature profile in EVLA. These observations suggest that the working mechanism of EVLA is independent of laser wavelength. In future studies, standardised clinical parameters based on this study could be applied and tested in a randomised clinical trial. A better understanding of the mechanism of action may contribute to achieving a consensus on the laser settings resulting in an optimal risk–benefit ratio (high effectiveness, with minimal adverse events).

Conflict of Interest/Funding Statement

There are no conflicts of interest.

References

1 van den Bos R, Arends L, Kockaert M, Neumann M, Nijsten T. Endovenous therapies of lower extremity varicosities: a meta-analysis. *J Vasc Surg* 2009;**49**:230–9.

2 Van Den Bos RR, Neumann M, De Roos KP, Nijsten T. Endovenous laser ablation-induced complications: review of the literature and new cases. *Dermatol Surg* 2009;**35**:1206–14.

3 Proebstle TM, Moehler T, Herdemann S. Reduced recanalization rates of the great saphenous vein after endovenous laser treatment with increased energy dosing: definition of a threshold for the endovenous fluence equivalent. *J Vasc Surg* 2006;**44**:834–9.

4 Timperman PE, Sichlau M, Ryu RK. Greater energy delivery improves treatment success of endovenous laser treatment of incompetent saphenous veins. *J Vasc Interv Radiol* 2004;**15**:1061–3.

5 Theivacumar NS, Dellagrammaticas D, Beale RJ, Mavor AI, Gough MJ. Factors influencing the effectiveness of endovenous laser ablation (EVLA) in the treatment of great saphenous vein reflux. *Eur J Vasc Endovasc Surg* 2008;**35**:119–23.

6 Mordon SR, Wassmer B, Zemmouri J. Mathematical modeling of 980-nm and 1320-nm endovenous laser treatment. *Lasers Surg Med* 2007;**39**:256–65.

7 Disselhoff BC, Rem AI, Verdaasdonk RM, Kinderen DJ, Moll FL. Endovenous laser ablation: an experimental study on the mechanism of action. *Phlebology* 2008;**23**:69–76.

8 Proebstle TM, Lehr HA, Kargl A, Espinola-Klein C, Rother W, Bethage S, et al. Endovenous treatment of the greater saphenous vein with a 940-nm diode laser: thrombotic occlusion after endoluminal thermal damage by laser-generated steam bubbles. *J Vasc Surg* 2002;**35**:729–36.

9 van der Geld CW, van den Bos RR, van Ruijven PW, Nijsten T, Neumann HA, van Gemert MJ. The heat-pipe resembling action of boiling bubbles in endovenous laser ablation. *Lasers Med Sci* 2010;**25**:907–9.

10 Fan CM, Rox-Anderson R. Endovenous laser ablation: mechanism of action. *Phlebology* 2008;**23**:206–13.

11 van den Bos RR, Kockaert MA, Martino Neumann HA, Bremmer RH, Nijsten T, van Gemert MJ. Heat conduction from the exceedingly hot fiber tip contributes to the endovenous laser ablation of varicose veins. *Lasers Med Sci* 2009;**24**:247–51.

12 Viarengo LM, Poterio-Filho J, Poterio GM, Menezes FH, Meirelles GV. Endovenous laser treatment for varicose veins in patients with active ulcers: measurement of intravenous and perivenous temperatures during the procedure. *Dermatol Surg* 2007;**33**:1234–42. discussion 41–42.

13 Weiss RA. Comparison of endovenous radiofrequency versus 810 nm diode laser occlusion of large veins in an animal model. *Dermatol Surg* 2002;**28**:56–61.

14 Zimmet SE, Min RJ. Temperature changes in perivenous tissue during endovenous laser treatment in a swine model. *J Vasc Interv Radiol* 2003;**14**:911–5.

15 Vuylsteke M, Van Dorpe J, Roelens J, De Bo T, Mordon S, Fourneau I. Intraluminal fibre-tip centring can improve endovenous laser ablation: a histological study. *Eur J Vasc Endovasc Surg* 2010;**40**:110–6.

16 Biesman BS, Khan J. Laser incisional surgery. *Clin Plast Surg* 2000;**27**:213–20 [x].

17 Moritz AR, Henriques FC. Studies of thermal injury: II. The relative importance of time and surface temperature in the causation of cutaneous burns. *Am J Pathol* 1947;**23**:695–720.

18 Vangsness Jr CT, Mitchell 3rd W, Nimni M, Erlich M, Saadat V, Schmotzer H. Collagen shortening. An experimental approach with heat. *Clin Orthop Relat Res* 1997:267–71.

19 Roggan A, Friebel M, Dorschel K, Hahn A, Muller G. Optical properties of circulating human blood in the wavelength range 400-2500 NM. *J Biomed Opt* 1999;**4**:36–46.

20 Almeida J, Mackay E, Javier J, Mauriello J, Raines J. Saphenous laser ablation at 1470 nm targets the vein wall, not blood. *Vasc Endovascular Surg* 2009;**43**:467–72.

21 Amzayyb M, van den Bos RR, Kodach VM, de Bruin DM, Nijsten T, Neumann HA, et al. Carbonized blood deposited on fibres during 810, 940 and 1,470 nm endovenous laser ablation: thickness and absorption by optical coherence tomography. *Lasers Med Sci* 2010;**25**:439–47.