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Effect of laser radiation absorption in water and blood on the optimal wavelength for endovenous obliteration* of varicose veins

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Abstract. **This work examines laser radiation absorption in water and blood at the wavelengths that are used in endovenous laser treatment (EVLT): 0.81 – 1.06, 1.32, 1.47, 1.5 and 1.56 μm. It is shown that the best EVLT conditions are ensured by 1.56-μm radiation. Analysis of published data suggests that even higher EVLT efficacy may be achieved at wavelengths of 1.68 and 1.7 μm.**

Keywords: *endovenous laser coagulation, venous disease*.

1. Introduction

Lower-extremity venous insufficiency is among the most common peripheral vascular diseases and is characterised by pain in the leg and disease progression, with serious social and economic implications. In recent years, endovenous laser treatment (EVLT) [1], a procedure in which laser energy is applied to the inside of a vein [2], has been used increasingly to treat this disease. A laser fibre is inserted into the vein under ultrasound guidance, and then an anaesthetic solution is injected around the vein to produce a perivenous 'jacket,' which ensures local anaesthesia, vein compression (reduction in vein diameter) and thermal isolation of perivenous tissues when the vein is heated. Next, laser radiation is directed to the fibre, which is gradually pulled back (withdrawn) from the vein. In this process, the laser energy heats the blood and vein wall, leading to coagulation of the vein contents, contraction of the collagen fibres present in the wall (which reduces the vein diameter) and thermal damage to the wall starting at its endothelium, which triggers conversion of the vein being treated to connective tissues. Figure 1 shows photographs of a varicose vein before and seven months after EVLT.

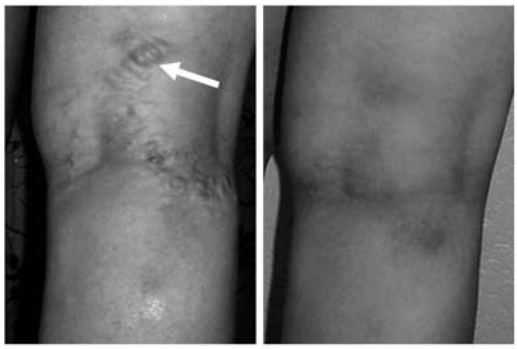

Figure 1. Varicose vein (marked by an arrow) before and seven months after treatment.

This procedure causes less patient discomfort in comparison with standard surgical treatment through the removal (phlebectomy) of incompetent veins, which is quite often accompanied by damage to superficial nerves and lymphatic collectors and may require long-term, painful postoperative treatment.

An important issue pertaining to the EVLT procedure is to optimise the laser wavelength. This issue has not yet been properly addressed in the literature.

2. Distinctions between the mechanisms underlying the responses of biological tissues to laser radiations that are predominantly absorbed in water and haemoglobin

Initially, only laser wavelengths in the range 0.81 – 1.06 μ, where the main chromophore is haemoglobin, were used in EVLT. In this wavelength range, absorption in water can be neglected because the absorption coefficient of water is here approximately 20 – 30 times smaller than that of haemoglobin. The heat deposited in a vein when haemoglobin absorbs laser energy is transferred to the water present in the blood. Heating of the water to 100 °C leads to local boiling and the generation of vapour bubbles. The vapour in turn gives up its heat to the vein wall, causing thermal damage to the wall starting at its endothelium [3]. Thus, the haemoglobin acts to transfer the absorbed laser energy to the water.

To ensure the desired effect, the laser energy must be higher at larger vein diameters. Increasing it by raising the input power or exposure time does not always ensure the proper damage to the vein wall and, hence, does not

*Obliteration (from Latin obliteratio, smoothing): occlusion or closure of a cavernous or tubular organ through the growth of its wall tissue (typically, connective tissue).

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guarantee the desired result, even though the damage is nearly proportional to these parameters.

Moreover, since the fibre cannot be centrally positioned over the entire length of the vein, high local energies produce tiny perforations or a linear cut of the vein wall where it touches the fibre tip, which causes haemorrhage from the vessel and may lead to haematoma formation.

This effect can be understood in terms of the mechanism behind the action of laser radiation that is predominantly absorbed in haemoglobin. At sufficiently high input powers, the thermal energy released in the haemoglobin has no time to be transferred to the water. This leads to rapid heating of the red cells that contain the haemoglobin and their carbonisation at the end face of the fibre, increasing the absorption of the laser radiation, reducing the zone where the heat is deposited and, hence, raising the heating rate. The result is local heating of the fibre tip (up to 1200 °C according to the data presented by R.A. Weiss and H. Valley in their comment on a previous study [4]) and perforation of the vein wall where it touches the fibre. The processes involved are thus similar to those in the widely used contact dissection of biological tissues with the laser scalpel fibre tip. This is not the only drawback to the use of radiation absorbable by haemoglobin in EVLT. Such radiation is weakly absorbed in the vein wall, which is undersaturated with blood, in the perivenous jacket formed by the anaesthetic solution before treatment and in the tissues adjacent to the vein, and may have a strong direct or indirect effect on nerve endings, causing pain.

In connection with this, there is increasing interest in the use of 1.32-μm or longer wavelength laser radiation [4–8], which is better absorbed by the water present in blood, vein walls and the anaesthetic jacket. Such radiation is commonly referred to as water-absorbable [4], which is not quite correct in the case of blood, as will be seen from the following.

The process then takes place in a different way because another channel for the action of radiation on the vein wall comes into play: some of the radiation is absorbed by the water in the blood to generate vapour bubbles, and some is absorbed by the water in the vein wall, leading to heating and thermal damage of the wall. The radiation experiences little or no absorption in the vapour bubbles and freely reaches the vein wall or blood, where absorption begins. The more efficient utilisation of laser energy allows the desired effect to be achieved at lower beam powers. The radiation that leaves the vein wall is then absorbed by the anaesthetic solution jacket surrounding the vein, so that less radiation penetrates the perivenous tissue, which lowers the probability of tissue burns and reduces the associated pain.

Note also that water evaporation involves energy consumption for the latent heat of vaporisation, which is rather high: 2.25×10^6 J kg^{-1}. Since the specific heat of water is 4200 J K^{-1} kg^{-1}, the energy needed to heat water from normal body temperature to 100 °C is 2.65×10^5 J kg^{-1}, which is approximately 8.5 times less than the energy needed to evaporate it. For this reason, the local temperature persists for a rather long time at a level of 100 °C. This is considerably less than the temperature of carbonisation (near 250 °C), which leads to an increase in absorption and, hence, to active tissue burning.

Based on the above, the optimal wavelength for endovenous laser obliteration of varicose veins must meet the following conditions:

(i) It is desirable to minimise the absorption of the laser radiation in the nonaqueous components of blood (primarily in haemoglobin), while ensuring considerable absorption in water.

(ii) The radiation penetration depth in water and water-containing tissues should be from several tenths of a millimetre to about 1–2 mm. At a larger penetration depth, the radiation may reach the perivenous tissue, causing damage to it and pain. At a smaller penetration depth, the radiation will be absorbed in a small volume, and the carbonisation threshold will be reached more rapidly, leading to adverse effects.

3. Optical properties of blood

To obtain reasonable estimates of laser radiation absorption, one must know the optical properties (absorption and scattering coefficients) of water and blood, which are the main chromophores in the system under consideration. Melanin and haematoporphyrin derivatives also have considerable absorption, but their contents in the blood tissues and vein walls are substantially lower.

There are reliable spectral data for water in the literature (see, e.g., Kou et al. [9]), whereas in the case of blood the situation is more complicated. The point is that blood is fairly difficult to study by optical measurements. In addition to the low transmission and strong scattering of light by blood, which hinder the study of its optical properties, these are influenced by red cell aggregation [10, 11]. This process, in turn, depends on the biophysical characteristics and flow of the blood: in stagnant zones, the red cells form aggregates, which break up when the blood flows. For this reason, only rough estimates are possible.

Yaroslavsky et al. [12] measured the absorption and scattering coefficients of whole blood at the boundary between the visible and IR spectral regions. As mentioned above, direct measurements of the mid- and far-IR transmission of whole blood are rather difficult to perform, but its transmission can be estimated from measurements on diluted blood. Figure 2 shows the spectral dependences of the absorption coefficient μ_a for water, oxygenated whole blood (haematocrit, 45%) [12] and oxygenated diluted blood (haematocrit, 5%) [13]. Hereafter, we consider oxygenated blood because it prevails even in venous blood. Also presented in Fig. 2 is the absorption coefficient of blood with a haematocrit of 45% estimated from the data reported by Roggan et al. [13] for a haematocrit of 5%. The estimate is obtained under the assumption that red blood cells contain 30% haemoglobin, which corresponds to a haemoglobin concentration in whole blood of 150 g L^{-1} [9]. The effect of the other components of blood is considered negligible.

Comparison of the absorption coefficients of water and blood allows one to assess the relative amounts of energy absorbed by the water and nonaqueous components of blood. It is clear from Fig. 2 that the nonaqueous components (primarily, haemoglobin) make an appreciable contribution to the absorption.

When radiation propagates through biological tissues, a significant role is played by scattering, which further reduces the penetration depth of the radiation. For example, the 'effective' penetration depth of 0.94-μm radiation in blood is 0.3 mm [3], whereas the absorption coefficient at this wavelength is ~ 1 mm^{-1}, which corresponds to a penetra-

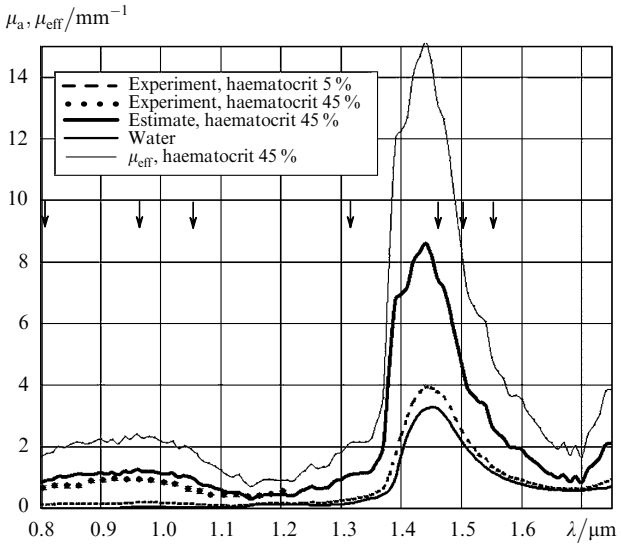

Figure 2. Absorption coefficients μ_a of water [9], oxygenated diluted blood (haematocrit, 5 %) [13] and oxygenated whole blood (haematocrit, 45 %; measured [12] and estimated) and effective attenuation coefficient μ_{eff} of blood. The arrows mark the wavelengths that are used in EVLT.

tion depth of 1 mm. The threefold decrease in penetration depth is the consequence of light scattering in blood. In connection with this, in addition to the absorption coefficients Fig. 2 shows the effective attenuation coefficient μ_{eff} of blood, which takes into account scattering [10]:

$$\mu_{eff} = \{3\mu_a[\mu_a + \mu_s(1-g)]\}^{1/2},$$

where μ_s is the scattering coefficient and g is the anisotropy factor. In our estimates, we used the μ_s and g data from Roggan et al. [13], reduced to a haematocrit of 45 %.

It follows from our data that the effective penetration depth of 0.94- to 0.98-μm radiation in blood is ~ 0.42 mm.

4. Wavelength optimisation

It is clear from Fig. 2 that 1.32-μm radiation can be considered water-absorbable only tentatively because its absorption by the water present in blood, though markedly greater than that in the range 0.8 – 1.1 μm, amounts to only a small fraction of the total absorption. This is however sufficient to improve the EVLT treatment efficacy.

In the range 1.47 – 1.56 μ, the fraction of radiation absorbed by the nonaqueous components of blood is also fairly large, even though smaller than that at 1.32 μm. Radiation at 1.47 μm, utilised in recent studies [5, 6], corresponds to a local maximum in absorption by water. At the same time, the absorption in the nonaqueous components of blood is rather strong at this wavelength. This reduces the radiation power level at which carbonisation and the associated adverse effects may begin. Moreover, absorption at this wavelength is so strong that the estimated penetration depth is within 0.1 mm, and the zone where the absorbed energy is deposited turns out to be too small, which also lowers the carbonisation threshold. It follows from the strong absorption of 1.47-μm radiation in haemoglobin that the addition of 0.98-μm haemoglobin-absorbable radiation, proposed by Neuberger [14] in order to produce a stronger effect on haemoglobin in EVLT, is not only useless but will most likely have an adverse effect.

Somewhat better conditions for thermal effects are ensured by 1.5-μm radiation [7]. The best results so far have been obtained with 1.56-μm radiation [8], which is readily provided by erbium-doped fibre lasers.

Comparison of clinical results for 1.56-μm laser radiation [15] with EVLT results obtained in the range 0.94 – 0.98 μm over several years [1] confirms that 1.56-μm radiation has significant advantages. Owing to the more efficient use of radiation, the energy needed for vein obliteration is about half that in 0.97-μm EVLT. Successful obliteration of varicose veins up to 18 – 20 mm in diameter has been reported, with fewer complications and less pain.

It follows from Fig. 2 that, at wavelengths of 1.68 and 1.7 μm, the effect of absorption in the nonaqueous components of blood is much weaker than that of absorption in water. At these wavelengths, the penetration depth in blood is ~ 0.5 mm, which possibly ensures the best EVLT conditions. This, however, must be confirmed by clinical trials.

5. Conclusions

The optimal conditions for endovenous laser treatment of varicose veins must ensure adequate heating of the vein walls, precluding wall perforation through contact with the hot fibre end and considerable penetration of the radiation into the perivascular tissue, which otherwise might cause adverse effects and pain.

To this end, most of the laser radiation must be absorbed in the water, and the absorption in the nonaqueous components of blood should be minimised. The penetration depth in blood and other biological tissues must be approximately 0.3 – 1 mm. These requirements are met by laser radiation in the range 1.55 – 1.75 μm, as supported by clinical trials at a wavelength of 1.56 μm, which was shown to ensure effective obliteration of varicose veins up to 18 – 20 mm in diameter. The power needed for vein obliteration was reduced by about a factor of 2 in comparison with radiation in the range 0.94 – 0.98 μm, with fewer complications and less pain.

The above analysis suggests that the best EVLT conditions are ensured by 1.68- and 1.7-μm radiation, but this must be confirmed by clinical trials.

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References

1. Sokolov A.L. et al. *Endovenoznaya lazernaya koagulyatsiya v lechenii varikoznoi bolezni* (Treatment of Varicose Veins by Endovenous Laser Coagulation) (Moscow: Medpraktika-M, 2007).
2. Bone Salat C. *Rev. Patol. Vasc.*, **5**, 35 (1999).
3. Proebstle T.M. et al. *Dermatol. Surg.*, **28**, 596 (2002).
4. Proebstle T.M. et al. *Dermatol. Surg.*, **31**, 1678 (2005).
5. Göckeritz O. *Endovenous Laser: 1470 nm versus Closure Fast. Controversies and Update in Venous Disease* (Paris, Jan. 2007, p. 389).

6. Maurins U. *Mid Term Results (12 Month) with 1470 nm. Controversies and Update in Venos Disease* (Paris, Jan. 2007) p. 390.
7. Vandekerckhole P.J., Vuylsteke M. *9th Intern. Cong. of Phlebology. The Use of a New Endovenous Laser Device: Result of the 1500 nm Laser* (Bologna, Italy, 2008) p. 61.
8. Sokolov A.L. et al. *Flebolimfologiya, spetsial'nyi vypusk. VII nauchno-praktich. konf. Assotsiatsii flebologov Rossii* (Phlebolymphology, a Special Issue: VII Research and Practice Conf. of the Russian Association of Phlebologists) (Moscow, 2008) p. 45.
9. Kou L. et al. *Appl. Opt.*, **32**, 3531 (1993).
10. Tuchin V.V. (Ed.) *Opticheskaya biomeditsinskaya diagnostika* (Optical Biomedical Diagnostics) (Moscow: Fizmatlit, 2007) Vol. 1.
11. Lopatin V.N. et al. *Metody svetorasseyaniya v analize dispersnykh biologicheskikh sred* (Light Scattering Techniques in Analysis of Disperse Biological Media) (Moscow: Fizmatlit, 2004).
12. Yaroslavsky A.N. et al. *Proc. SPIE – Int. Soc. Opt.Eng.*, **2678**, 314 (1996).
13. Roggan A. et al. *J. Biomed. Opt.*, **4** (1), 36 (1999).
14. Neuberger W. US Patent Application 20080065058.
15. Sokolov A.L. et al. *Angiologiya* (Angiology and Vascular Surgery), 15 (1), 69 (2009).