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Optimal parameters for the treatment of leg veins using Nd:YAG lasers at 1064 nm

W. Bäumler, H. Ulrich, A. Hartl, M. Landthaler and G. Shafirstein*

Department of Dermatology, University of Regensburg, 93042 Regensburg, Germany
**Vascular Anomalies Centre, Arkansas Children's Hospital, Little Rock, AR 72202, U.S.A.*

Correspondence
Wolfgang Bäumler.
E-mail: baeumler.wolfgang@klinik.uni-regensburg.de

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Conflicts of interest
None declared.

Summary

Background The treatment of large vessels such as leg veins is successfully performed in clinical practice using pulsed Nd:YAG lasers. However, it is still unclear how laser parameters such as wavelength, fluence and pulse duration influence vessel destruction in leg veins.

Objectives To elucidate the governing parameters in selective photothermolysis of large vessels.

Methods A recently developed mathematical model for photothermolysis has been adapted for the treatment of leg veins. The model was used to analyse the effectiveness of the selective photothermolysis process in laser treatment of leg veins by Nd:YAG at 1064 nm. The efficiency of laser-induced vessel heating was defined as a ratio between the absorbed and delivered energy.

Results The efficiency improved with increasing vessel diameter, in agreement with clinical findings in various studies. The pulse duration made a minor contribution for laser fluences of 100–400 J cm^{-2}, whereas the efficiency was better for a small spot. The use of moderate fluences of 100–200 J cm^{-2} reduced excess dermis heating and pain.

Conclusions We provide reference parameters for optimal treatment of leg veins using Nd:YAG lasers at 1064 nm. Our model predicts a maximal efficiency of a range of fluences (100–200 J cm^{-2}) and pulse durations (10–100 ms).

The use of lasers has significantly improved the treatment of vascular cutaneous disorders in the last 20 years. In practice, laser light is applied to the skin and is selectively absorbed by the haemoglobin within the blood vessels. The absorbed energy is converted to heat, leading to a temperature increase inside the vessel. Blood coagulation within the vessel will occur at temperatures higher than 70 °C.[1] The thermal damage can be restricted to the vessel, and the adjacent dermis is spared by using an appropriate pulse duration.[2] It has been more than 20 years since Anderson and Parrish[3] published the well-known therapeutic approach of selective photothermolysis. The theory was successfully applied to the treatment of cutaneous vascular malformations such as port wine stains (PWS),[4] and telangiectasia on the head, neck and limbs.[5,6] For abnormal PWS with blood vessels ranging in size from 10 to 300 μm, it was found that pulsed dye lasers with pulse durations of 1–10 ms should enable the maximum coagulation rate and lead to optimal clinical outcomes.[7–10]

In the case of large vessels up to a few millimetres in diameter, such as those found in abnormal leg veins, the wide range of lasers employed by clinicians indicates that the principle of selective photothermolysis is not paramount. Various lasers have been used to treat large venous vessels including pulsed dye lasers at 595 nm,[11] alexandrite lasers at 755 nm,[12] and Nd:YAG lasers at 1064 nm.[13–23] In the infrared range of the spectrum (700–1100 nm), light penetrates deep into the dermis and blood vessels. Consequently, superficial abnormal leg veins, consisting of blood vessels of 0·5–4 mm in diameter, can be coagulated readily.

For Nd:YAG lasers, the optimal parameters for the treatment of vascular malformations have been suggested via mathematical modelling[3,7,24] and clinical investigations.[25–27] None the less, two major problems remain unsolved. Firstly, based on a previous model of selective photothermolysis,[7] a pulse duration of 1000 ms is considered suitable for a vessel diameter of 1·5 mm (typical size of leg veins). However, in clinical practice pulse durations of < 100 ms are used.[13–23] Furthermore, it has been reported that large leg veins respond better to laser treatment than small ones.[13–15] Secondly, while clinical results are considered satisfactory in most cases, there is no agreement on an optimal pulse duration, fluence or spot size for the particular Nd:YAG laser used to treat the lesions. A review of the literature indicates that a wide range of parameters is applied clinically. In particular, fluences can range from 90 to 400 J cm^{-2}, pulse durations may vary from 10 to 100 ms and spot sizes from 1 to 10 mm in order to coagulate leg veins of 0·1–4 mm. Moreover, many researchers have reported noticeable pain, which extends from mild to severe. In light of the wide variance in clinical laser applications, there continues to be ongoing discussion in the field of laser science as to which laser parameters are optimal to treat leg veins effectively, while maintaining a low side-effect profile.

This study addresses the problem of standardization of clinical laser practices by applying computer-assisted modelling to the Nd:YAG laser. Specifically, we have modified our recently published mathematical model for the selective photothermolysis of small PWS vessels[24] and calculated the temperature within vessels ranging from 0·2 to 2 mm in diameter. Calculations were performed for a wide range of clinical settings including different fluences, pulse durations and spot sizes. Detailed analysis was conducted for each combination of parameters using three different vessel diameters. The results of the modelling were compared with outcomes of published clinical studies. Using this approach we have been able to delineate the critical parameters in Nd:YAG laser treatment of leg veins and recommend a range of parameters for good clinical response with minimal side-effects. We also have generated a reference table and graph that may be useful to clinicians who treat leg veins with the Nd:YAG laser.

Materials and methods

Laser irradiation of leg veins was simulated using a recently developed model.[24] To determine the temperature in the tissue, the heat and optical diffusion equations were solved simultaneously using the finite element method. This was achieved with commercial software (Femlab 3.1; Comsol, Burlington, MA, U.S.A.). Cooling of the epidermis was considered by setting the temperature of the epidermis to 10 °C. The effect of blood flow on cooling was included using maximal blood perfusion. The optical parameters at 1064 nm were taken from the literature.[24–26]

The centre of the vessels was set in the mid-dermis at a depth of 1·5 mm at diameters of 200, 500, 1000, 1500 or 2000 μm. The results of computer-assisted modelling are displayed in a two-dimensional, vertical cut into the skin like a virtual biopsy (Fig. 1a). To analyse the published data, 96 independent calculations were carried out for combinations of four different energy densities (100, 200, 300 or 400 J cm^{-2}), four pulse durations (10, 30, 60 or 100 ms), two spot sizes (2·5 or 6 mm) and three vessel diameters (0·4, 1·0 or 1·5 mm).

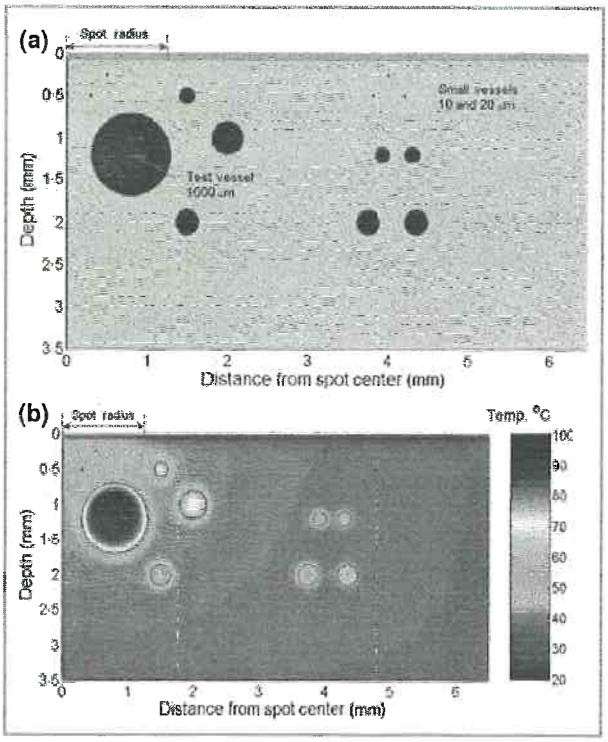

Fig 1. Schematic geometric model of the skin (a) comparable with a histological slice, which is divided in two layers, the epidermis (150 μm, coloured orange) and the dermis. The z-axis shows the depth of the skin (greatest depth 3·5 mm). There are 13 vessels displayed in the dermis, ranging from 10 to 1000 μm, which is the diameter of the leg vein used for calculations at a depth of 1·5 mm (test vessel). The radius of the spot size is shown (point 0 on the x-axis: centre of the spot) for a 2·5-mm spot (radius 1·25 mm); for a 6-mm spot the geometry was changed accordingly. The resulting temperature (b) at the end of the pulse (duration 60 ms, fluence 100 J cm^{-2}) is shown as a virtual two-dimensional cut.

Vessels are coagulated at elevated temperatures (> 70 °C). There is a higher probability that a vessel will be properly coagulated as the temperature increases. Therefore, we estimated the thermal damage in the respective vessel by integrating the temperature course over time as long as the temperature is maintained greater than 37 °C. The resulting value is usually known as thermal dosage, which is equivalent to thermal damage.[27] Thus, we use the term 'thermal damage' in our modelling:

$$\textit{Thermal damage} = \int_0^{\tau} T(t)\,dt$$

The integration starts at time t = 0 (start of laser pulse) and ends with t = 3 s, that includes the time for heating (pulse duration) and the major part of cooling of the vessel. Additionally, the laser efficiency of the respective laser parameters was calculated (Table 2). We define the laser efficiency as the ratio of the thermal damage in the targeted vessel to the applied laser energy (J):

$$\textit{Laser efficiency} = \frac{\textit{Thermal damage of vessel}}{\textit{Laser energy}}$$

This value describes the efficiency of converting laser energy into photothermal coagulation. Low efficiency means that most of the energy applied will lead to nonspecific heating of the extravascular tissue. High efficiency means that most of applied laser energy is converted to vessel coagulation.

Results

Commonly used parameters for clinical application of Nd:YAG laser

There have been various treatment approaches to prominent leg veins and varicosities. Table 1 enumerates the multitude of publications for laser parameters of leg vein therapy cited in the relevant literature. Laser parameters such as fluence, pulse duration and spot size are listed corresponding to each clinical study. In addition, the degree of pain reported by the patient and vessel size treated are also included. The large number of studies and the varied treatment conditions used in the clinical setting underscore the lack of unanimity and difficulty in standardization of Nd:YAG laser treatment of leg veins.

Laser efficiency

In order to test the laser efficiency of the Nd:YAG laser in leg veins, we compared three different vessel diameters with two different spot sizes using four separate fluences (Table 2). Laser efficiency was maximal for the lowest fluence (100 J cm^{-2}). A larger vessel diameter seemed to correlate with greater laser efficiency. In addition, it is clear from the Table that a 2·5-mm spot size is more efficient than a 6-mm spot size. The smaller spot size is also associated with a lower risk for adverse reactions.

Table 2 Reference table for the efficiency of the laser treatment of leg veins at 1064 nm. As the differences between results are small for the applied pulse durations, the values are merged and displayed independent of the pulse duration. The values were normalized to the maximal value (numbers in bold). Due to a higher risk of adverse reactions for large spot sizes, a small spot size (e.g. 2·5 mm) should be preferred

	Laser efficiency (% of maximal value)					
Vessel diameter (μm)	400		1000		1500	
Spot size (mm)	2·5	6	2·5	6	2·5	6
Fluence (J cm^{-2})						
100	86	17	**100**	19	**100**	22
200	53	11	61	11	64	11
300	39	8	42	8	44	8
400	31	6	33	6	33	6

In Figure 1b, the calculated temperature shows a homogeneous heating of the entire vessel of 1 mm in diameter at the end of the laser pulse duration. The temperature distribution inside the vessels of all diameters was also homogeneous (data not shown).

Vessel diameter and temperature

A critical factor in thermal coagulation is related to the vessel diameter. Figure 2 shows the time course of temperature in

Table 1 The laser parameters for treating leg veins used in different clinical studies reported so far

Vessel size (mm)	Spot size (mm)	Fluence (J cm^{-2})	Pulse duration (ms)	Reported pain	Authors
3–4	7	90–100	40–50	No statement	Rogachefsky *et al.*[15]
1–3	10	100	50	Pain	Omura *et al.*[14]
0·6–1	6	100–110	10	No statement	Weiss and Weiss[16]
0·5–2	2·5	100–125	10	Pain	Levy *et al.*[19]
0·1–0·5	5·5	125–150	25	Mild treatment pain	Lupton *et al.*[22]
0·5–1·5	5·5	125–150	50	Mild treatment pain	Lupton *et al.*[22]
1–3	6	100–130	14–16	No statement	Weiss *et al.*[16]
0–2	6	130	2 × 7	Mild discomfort	Trelles *et al.*[18]
0–4	6	130	14	No statement	Sadick *et al.*[17]
2–4	6	140	3 × 14	Mild discomfort	Trelles *et al.*[18]
0·5–2	3	130–190	50–100	Yes, mostly severe	Coles *et al.*[20]
0·25	7	140	10–15	No statement	Rogachefsky *et al.*[15]
0·3–1	6	150	25	Yes, topical anaesthetics	Eremia *et al.*[13]
1–2	6	150	25–50	Yes, topical anaesthetics	Eremia *et al.*[13]
2–3	6	150	75–100	Yes, topical anaesthetics	Eremia *et al.*[13]
0·5–2	5	100–200	50–70	Yes, mostly severe	Coles *et al.*[20]
High fluence					
0·8–1·4	1·5	317	70	Important: the mean value is 6 of a 0–10 visual analogue scale	Passeron *et al.*[21a]
0·4–0·8	1	306	30		Passeron *et al.*[21a]
0–0·4	0·5	306	10		Passeron *et al.*[21a]
0·25–1	1·5	320–350	15–30	Yes, mostly severe	Coles *et al.*[20]
0·5–3	1·5–5	140–400	30–100	Mostly moderate pain	Chen *et al.*[23]

[a] Using a 940-nm diode laser comparable with Nd:YAG at 1064 nm.

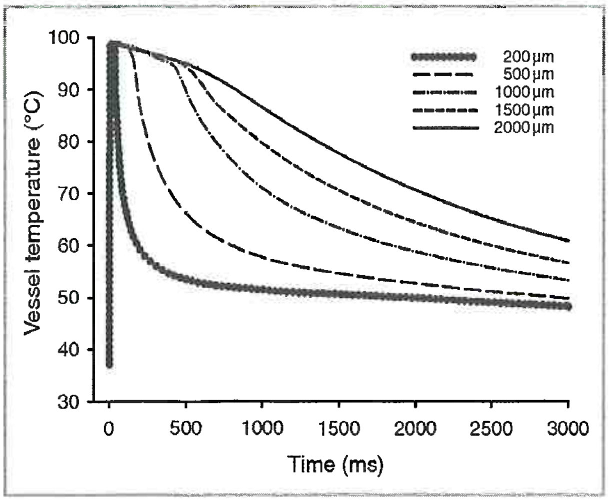

Fig 2. The course of temperature of heating and cooling of the different vessels up to 3 s using a pulse duration of 60 ms and a fluence of 300 J cm^{-2} (spot size 2·5 mm). Depending on the diameter, temperatures of up to 100 °C are achieved. The elevated temperatures last for up to a few seconds.

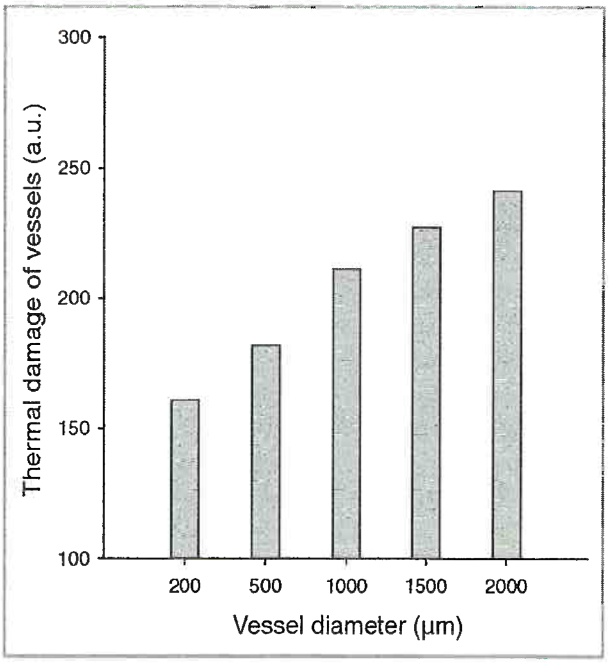

Fig 3. The thermal damage (in arbitrary units, a.u.) is calculated by integrating the temperature course over time (see Fig. 2): pulse duration 60 ms, spot size 2·5 mm, fluence 300 J cm^{-2}. The values increase with vessel diameter.

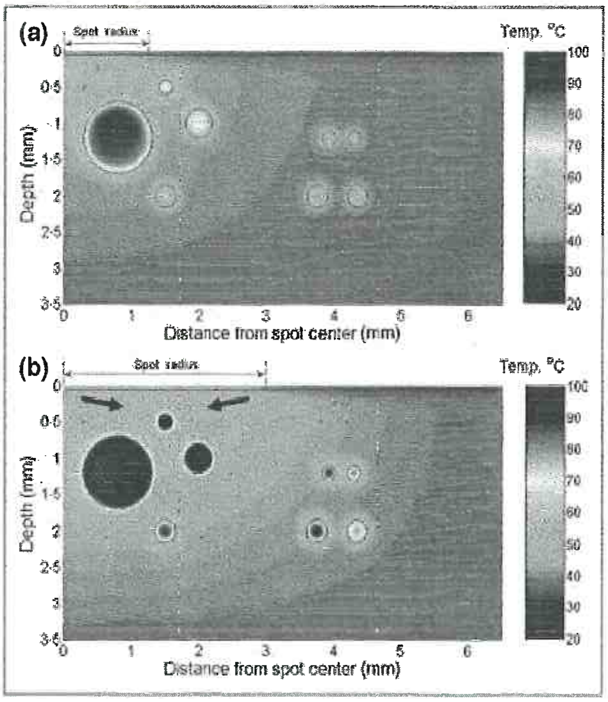

Fig 4. The temperature distribution for the 1-mm vessel at the end of the laser pulse (60 ms, 100 J cm^{-2}). For the 2·5-mm spot size (a) the dermis between the vessel and the epidermis is at a temperature of 40–45 °C. For the 6-mm spot size (b) there is a temperature increase up to 60 °C in a large area in the dermis (black arrows). The heating of the dermis correlates to the photon distribution, i.e. there is direct heating of the dermis by light absorption of water. Therefore, large spot sizes should be avoided.

the centre of vessels of different diameters during the entire heating and cooling process (300 J cm^{-2}, 60 ms). The maximal temperature is achieved within milliseconds. The vessels remain at elevated temperature for up to a few seconds before cooling leads to temperature values below 50 °C. Interestingly, maximal temperature (100 °C) is attainable in a manner that appears to be independent of the vessel diameters. The temperature inside large vessels remained elevated longer as compared with small vessels. By integrating the temperature course over time, pulse duration, spot size and fluence, the integrated values of thermal damage can be shown to increase continuously with increasing vessel diameter (Fig. 3).

The temperature in the adjacent dermis increased up to 60 °C (Fig. 4) due to direct heating of the dermis by light absorption in water. The effect is more pronounced when using a spot size of 6 mm instead of 2·5 mm. In Figure 5, the temperature distribution is shown for different laser parameters at the 500-ms time point. This figure shows an extensive flow of heat energy from the hot vessel to the adjacent dermis.

Thermal damage and fluence

We used laser parameters from previous clinical studies to calculate the thermal damage within blood vessels. For vessel sizes of 400, 1000 and 1500 μm, a fluence of 100, 200, 300 or 400 J cm^{-2} was applied at pulse durations of 10, 30, 60 or 100 ms and a spot size of 2·5 mm or 6 mm. For either spot size, the thermal damage increased with increasing fluence but showed only little correlation with the pulse duration (Fig. 6).

Discussion

In the last two decades, it has generally been agreed that the laser wavelength, pulse duration and fluence determine the

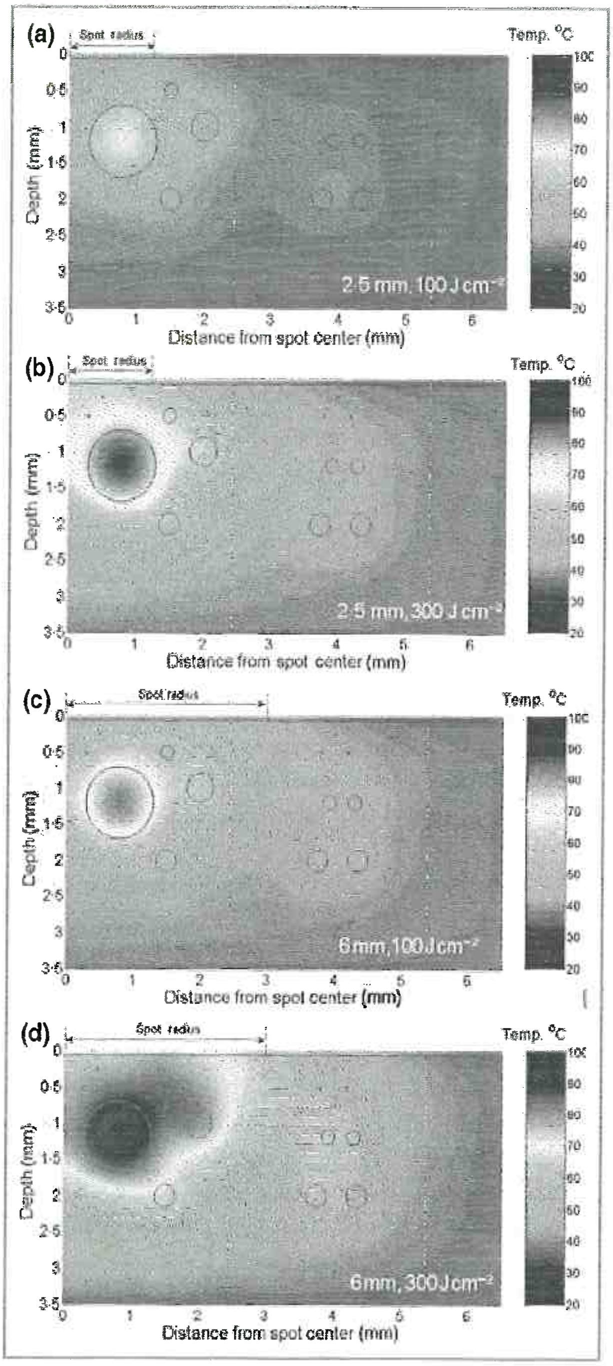

Fig 5. The temperature distribution in the virtual skin section at a time of 440 ms after the end of the laser pulse (total time 500 ms). The laser parameters were 60 ms pulse time at different fluences and spot sizes. Most of the elevated temperature in the dermis is now due to heat flow from the hot vessels. Comparable with the direct heating (see Fig. 4), there are higher temperatures in the dermis for the 6-mm spot size than for the 2·5-mm spot size at 100 or 300 J cm^{-2}, respectively.

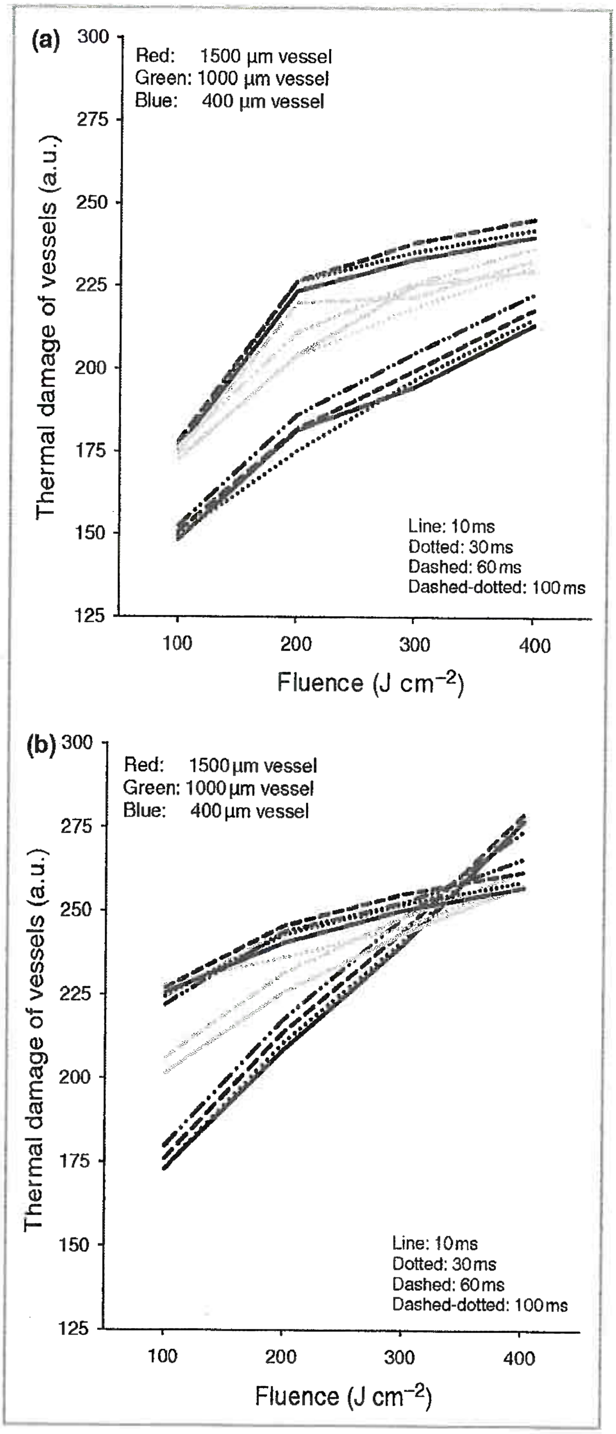

Fig 6. The thermal damage (in arbitrary units, a.u.) was calculated for a small spot size of 2·5 mm (a) using a fluence of 100, 200, 300 or 400 J cm^{-2} at pulse durations of 10, 30, 60 or 100 ms. The different colours show the different vessel sizes of 400 µm (blue), 1000 µm (yellow) and 1500 µm (red). The same calculations were performed for a spot size of 6 mm (b).

destruction of a target and hence the selectivity of the laser treatment. However, in the treatment of leg veins with Nd:YAG laser at 1064 nm the results of clinical studies seem to be independent of the pulse duration, which can range from 5 to 100 ms, or the fluence (100–400 J cm^{-2}). There is also no explanation for the better clinical response to Nd:YAG lasers in the large vessels.[13–15] To find answers to these questions, a recently published computer-assisted model for selective photothermolysis[24] was adapted to study laser treatment of large vessels. Based on our own clinical experience with leg veins and Nd:YAG lasers, the results of the modelling were compared with the outcome of clinical studies published in recent years.

At the wavelength of Nd:YAG (1064 nm), the absorption of light in oxyhaemoglobin substantially decreases up to a factor of 100 as compared with pulsed dye lasers (595 nm), which are also used to treat vascular lesions.[10,28,29] Due to a low absorption coefficient of oxyhaemoglobin at 1064 nm, no gradient of light energy should appear inside large vessels. Thus, the homogeneous distribution of photons inside large vessels should lead to a homogeneous heating. This is confirmed by our present modelling (Fig. 1b), where the calculations show a nearly homogeneous temperature distribution in the entire vessel area. This helps to coagulate the entire blood vessel even for large diameters, as was shown in the clinical findings and theoretical considerations of Ross and Domankevitz.[30] These authors also concluded that longer wavelengths are more likely to heat the vessel uniformly in comparison with highly absorbing wavelengths. Our model, therefore, agrees with other theoretical studies and clinical observations suggesting that Nd:YAG at 1064 nm is the preferred laser for treatment of large vessels such as leg veins.

Although the light absorption in haemoglobin is little at 1064 nm, it is still about 10 higher than the light absorption in water, which is the major chromophore of the dermis in the near infrared spectrum. This allows selective photothermolysis, but the selectivity is significantly decreased as compared with 585 nm. Consequently, one must exercise reasonable care to choose the correct laser parameters in order to achieve high efficiency at a low rate of side-effects.

It is known that part of the haemoglobin molecule is changed to methaemoglobin under Nd:YAG laser irradiation.[31] The absorption coefficient of methaemoglobin is about three times higher as compared with oxyhaemoglobin at 1064 nm,[32] whereas the exact concentration of methaemoglobin in the vessel is unknown. The presence of methaemoglobin would lead to somewhat higher temperatures for all vessel sizes but would not change the main conclusions of our model.

When using Nd:YAG laser at 1064 nm, our results show a temperature increase inside the vessel up to the maximal temperature within milliseconds, a time span that corresponds to the pulse duration. At the end of the laser pulse, the temperature begins to drop. However, the time of blood vessel cooling is significantly longer than the heating cycle, except for the small 200-μm vessel (Fig. 2). The effect of vessel size on the thermal damage was calculated by integrating the temperature course T(t) in the vessels over time, including the heating and cooling time (0–3 s). The value increases with vessel diameter (Fig. 3). These results can be explained as follows.

Once the temperature in the vessel is higher than in the adjacent tissue, heat energy will flow from the hot vessel into the skin (dermis) with a certain cooling rate. The cooling rate depends on two parameters: firstly, the temperature difference between the heated vessel and the adjacent tissue; secondly, the ratio of surface area to volume of the vessel. When using a fluence higher than 100 J cm^{-2}, the maximal temperature is 80–100 °C within the blood vessels (0·2–2 mm) at the end of the pulse duration (10–100 ms). At the same time, the temperature in the adjacent dermis is in the range of 45 °C to about 60 °C independent of the vessel diameter. Our modelling showed that the temperature difference between vessel and dermis is similar for large and small vessels. Additionally, the temperature gradient within these small and large vessels is also similar.

However, the ratio of surface area to vessel volume is up to a factor of 10 times smaller for large vessels (2 mm) in comparison with small ones (0·4 mm). The heat flow from the hot vessel into the dermis needs much more time to cool a large vessel than a small vessel. Thus, in a large vessel the elevated temperature will remain above critical temperature (70 °C) for a longer time than in a small vessel. Consequently, the effectiveness of leg vein coagulation increases with vessel size. This correlates very well with our own clinical experience with the Nd:YAG laser (data not shown) and with the results of clinical studies published by several other groups.[13–15]

The pulse duration is usually adjusted to the size of the respective vessel. This might be correct for small vessels even at 1064 nm,[33] in particular those < 400 μm in diameter. For large leg veins, this correction becomes nonsignificant.

Due to the low absorption coefficient in blood at 1064 nm wavelength, high laser fluence must be applied. Hence, there is always the risk of overheating the vessels and the surrounding dermis. This may lead to adverse reaction such as cutaneous hyperpigmentation or even atrophic scars. In addition, pain during laser treatment is sometimes a unwanted side-effect.

To illustrate the possible effects of excess heat energy and heat flow, the temperature distribution in the entire dermis was calculated at 500 ms, a time clearly longer than all pulse durations. This allows the presentation of temperature distribution in blood vessels and dermis after laser impact. At a fluence of 100 or 300 J cm^{-2}, the temperatures in the adjacent dermis exceed 60 °C for a long time (> 0·5 s). Besides the vessel damage itself, this could be partly responsible for the pain that has been reported in many studies.

On the one hand, the high temperature in the dermis results from heat transfer of excess thermal energy from the targeted large vessel to the dermis. On the other hand, as discussed in the previous paragraph, there might be direct heating of the dermis derived from the targeted vessels, in particular when using a large spot size (e.g. 6 mm) in clinical practice. The temperature increase in the dermis can be barely prevented by surface cooling, which is usually applied to protect the epidermis.[34] A better way to minimize this pain and possibly other adverse reactions is to reduce the laser energy to a value that yields optimal thermal damage of the vessel but no excess heating of the dermis.

When calculating the thermal damage of vessels, the values increase with increasing fluence and are somewhat higher for the spot size of 6 mm as compared with 2·5 mm. This can be explained by the fact that with the 6-mm spot size, more laser photons (in total) are delivered and thus more thermal energy will be generated. Additionally, the number of photons increases not only in the vessel but also outside the vessel, in particular when treating a 1-mm leg vein with a 6-mm spot size. These excess photons, not used for vessel coagulation, may lead to adverse reactions in the dermis. At 1064 nm, these photons can be absorbed in water, which may lead to a direct heating of the aqueous dermis. In Figure 4 we show direct dermis heating. It can be seen that relatively high temperatures are obtained for a 6-mm, in comparison with a 2·5-mm spot size. Thus, the spot size of Nd:YAG laser at 1064 nm should be kept as small as possible. As a guide we recommend that the spot size should be about 25% larger than the maximum vessel size of the leg veins that are being treated.

Despite different fluences, the maximal temperatures inside the vessels are in the range of about 80–100 °C for nearly all laser parameters and vessel diameters (data not shown). Only for the parameters of 6-mm spot size and 400 J cm^{-2} fluence were temperatures of more than 100 °C (up to 142 °C) calculated within a 400-μm diameter vessel. In this case, the unusually high temperature results from excessive energy delivered to a small volume. It has already been shown that such a high fluence may cause steam and bubbles.[1] Thus, these laser parameters should be avoided, and indeed, they are rarely used in clinical practice.

Laser efficiency is calculated as the ratio of the thermal damage to the applied laser energy (J). The laser efficiency is simply a value which gives an estimate of how many applied photons are successfully converted to heat inside the targeted vessel. Ideally, all laser photons applied would be used to heat only the vessels. This can never be achieved, as during photon propagation in the skin many photons are scattered and absorbed by other skin constituents. In our modelling, the laser efficiency was calculated for every set of laser parameters and vessel sizes.

As the pulse duration of the laser has only a minor effect on the efficiency, the results are presented as a short reference table (Table 2). The values are given as percentages of the maximum efficiency calculated for the present set-up and parameters. Our modelling showed, for all pulse durations and vessel diameters, that the laser efficiency decreases with increasing fluence (J cm^{-2}). Thus, with increasing fluence more and more photons do not contribute to the thermal damage of the vessel and may be absorbed in targets elsewhere in the dermis. This increases unnecessarily the risk of side-effects and might be responsible for excess pain during treatment.

However, the small spot size yields higher efficiency than the large spot size because less energy (J) is used at equal fluence. For example, for a fluence of 100 J cm^{-2} an energy of 4·9 J is necessary for a 2·5-mm spot size, but 28·3 J is needed for a 6-mm spot size. Even for the highest fluence at 2·5 mm, the laser efficiency is higher as compared with the lowest fluence at 6 mm. As mentioned above, a spot size as small as possible is recommended, which is adapted to the size of the vessel. This helps to avoid the unnecessary interaction of laser photons outside the vessel in the normal skin. Other studies[14–16] also support our recommendation to keep the spot size as small as possible.

The computer-assisted modelling yielded a range of safe and effective parameters for the treatment of leg veins using an Nd:YAG laser with 1064 nm wavelength. This range is defined as a compromise between laser efficiency and thermal damage to vessels. To achieve optimal thermal damage of vessels and high laser efficiency, the modelling results recommend a range of 100–200 J cm^{-2} at a pulse duration of 30–60 ms. This range fits very well with most clinical studies (see Table 1).

However, the main goal of laser treatment of leg veins is vessel closure that can be seen clinically. If the vessel does not close, it is necessary to depart from the range that is recommended in the reference table, in particular for small vessels with diameters < 0·5 mm. The problem with small vessels is due to the low light absorption of oxyhaemoglobin at 1064 nm together with the low number of light-absorbing erythrocytes in small vessels. There are two options to overcome this problem. Firstly, one can increase the fluence up to 300 J cm^{-2} to achieve coagulation. Such a high fluence leads to an increased risk of side-effects as the laser efficiency is significantly smaller as compared with that at a low fluence. The high fluence application must be accompanied by a very careful cooling of the skin surface. Secondly, the pulsed dye laser can be used if available. This is a good treatment option for leg veins < 0·7 mm in diameter.[29]

Conclusion

So far, it is generally agreed that laser parameters such as wavelength, fluence and pulse duration govern the vessel destruction in selective photothermolysis. In the case of large vessels, we demonstrated that the diameter of the vessel itself determines a successful destruction by photothermal action. The rate of vessel damage is proportional to the integrated heat within blood vessels during and after laser irradiation. This was shown by direct comparison of outcomes of clinical studies published so far with results of mathematical modelling. The present mathematical model is a fair representation of the selective photothermolysis process in Nd:YAG laser treatment of large vessels. Hence, the model is a useful tool to delineate the key parameters that govern photothermolysis in treatment of leg veins by Nd:YAG laser at 1064 nm. The reference table (Table 1) could be used to select laser parameters for various laser systems and vessel sizes (i.e. clinical parameters), whereas the clinically visible closure of the vessel during laser irradiation remains the main goal. Departing from this range of recommended parameters does not automatically lead to side-effects such as scarring, but it increases the possibility. The reference table should be used as a guide: it does not aim to replace clinical experience but to help in treatment planning.

Currently the model cannot describe the complex nature of thrombotic or haemorrhagic processes, which may follow minutes or hours after laser impact and which might influence the clinical endpoint of vessel destruction.[35,36] None the less, a good agreement of our modelling and vascular response to laser therapy using an animal model was recently presented.[37] Additional work must be performed to compare the findings prospectively with clinical outcomes.

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References

1 Black JF, Barton JK. Chemical and structural changes in blood undergoing laser photocoagulation. *Photochem Photobiol* 2004; **80**:89–97.

2 Lahaye CT, van Gemert MJ. Optimal laser parameters for port wine stain therapy: a theoretical approach. *Phys Med Biol* 1985; **30**:573–87.

3 Anderson RR, Parrish JA. Selective photothermolysis: precise microsurgery by selective absorption of pulsed radiation. *Science* 1983; **220**:524–7.

4 Tan OT, Whitaker D, Garden JM, Murphy G. Pulsed dye laser (577 nm) treatment of portwine stains: ultrastructural evidence of neovascularization and mast cell degranulation in healed lesions. *J Invest Dermatol* 1988; **90**:395–8.

5 Hammes S, Raulin C. Evaluation of different temperatures in cold air cooling with pulsed-dye laser treatment of facial telangiectasia. *Lasers Surg Med* 2005; **36**:136–40.

6 Ackermann G, Hartmann M, Scherer K *et al.* Correlations between light penetration into skin and the therapeutic outcome following laser therapy of port-wine stains. *Lasers Med Sci* 2002; **17**:70–8.

7 Kimel S, Svaasand LO, Hammer-Wilson M *et al.* Differential vascular response to laser photothermolysis. *J Invest Dermatol* 1994; **103**:693–700.

8 Lanigan SW, Taibjee SM. Recent advances in laser treatment of port-wine stains. *Br J Dermatol* 2004; **151**:527–33.

9 Suthamjariya K, Farinelli WA, Koh W, Anderson RR. Mechanisms of microvascular response to laser pulses. *J Invest Dermatol* 2004; **122**:518–25.

10 van Gemert MJ, Welch AJ, Pickering JW *et al.* Wavelengths for laser treatment of port wine stains and telangiectasia. *Lasers Surg Med* 1995; **16**:147–55.

11 Loo WJ, Lanigan SW. Recent advances in laser therapy for the treatment of cutaneous vascular disorders. *Lasers Med Sci* 2002; **17**:9–12.

12 Kauvar AN, Lou WW. Pulsed alexandrite laser for the treatment of leg telangiectasia and reticular veins. *Arch Dermatol* 2000; **136**:1371–5.

13 Eremia S, Li C, Umar SH. A side-by-side comparative study of 1064 nm Nd:YAG, 810 nm diode and 755 nm alexandrite lasers for treatment of 0·3–3 mm leg veins. *Dermatol Surg* 2002; **28**:224–30.

14 Omura NE, Dover JS, Arndt KA, Kauvar AN. Treatment of reticular leg veins with a 1064 nm long-pulsed Nd:YAG laser. *J Am Acad Dermatol* 2003; **48**:76–81.

15 Rogachefsky AS, Becker K, Weiss G, Goldberg DJ. Evaluation of a long-pulsed Nd:YAG laser at different parameters: an analysis of both fluence and pulse duration. *Dermatol Surg* 2002; **28**:932–5.

16 Weiss RA, Weiss MA. Early clinical results with a multiple synchronized pulse 1064 nm laser for leg teleangiectasias and reticular veins. *Dermatol Surg* 1999; **25**:399–402.

17 Sadick NS, Prieto VG, Shea CR *et al.* Clinical and patho-physiologic correlates of 1064-nm Nd:Yag laser treatment of reticular veins and venulectasias. *Arch Dermatol* 2001; **137**:613–17.

18 Trelles MA, Allones I, Martin-Vazquez MJ *et al.* Long pulse Nd:YAG laser for treatment of leg veins in 40 patients with assessments at 6 and 12 months. *Lasers Surg Med* 2004; **35**:68–76.

19 Levy JL, Elbahr C, Jouve E, Mordon S. Comparison and sequential study of long pulsed Nd:YAG 1,064 nm laser and sclerotherapy in leg telangiectasias treatment. *Lasers Surg Med* 2004; **34**:273–6.

20 Coles CM, Werner RS, Zelickson BD. Comparative pilot study evaluating the treatment of leg veins with a long pulse Nd:YAG laser and sclerotherapy. *Lasers Surg Med* 2002; **30**:154–9.

21 Passeron T, Olivier V, Duteil L *et al.* The new 940-nanometer diode laser: an effective treatment for leg venulectasia. *J Am Acad Dermatol* 2003; **48**:768–74.

22 Lupton JR, Alster TS, Romero P. Clinical comparison of sclerotherapy versus long-pulsed Nd:YAG treatment for lower extremity telangiectases. *Dermatol Surg* 2002; **28**:694–7.

23 Chen JZ, Alexiades-Armenakas MR, Bernstein LJ *et al.* Two randomized, double-blind, placebo-controlled studies evaluating the S-Caine Peel for induction of local anesthesia before long-pulsed Nd:YAG laser therapy for leg veins. *Dermatol Surg* 2003; **29**:1012–18.

24 Shafirstein G, Bäumler W, Lapidoth M *et al.* A new mathematical approach to the diffusion approximation theory for selective photothermolysis modelling and its implication in laser treatment of port-wine stains. *Lasers Surg Med* 2004; **34**:335–47.

25 Welch AJ, van Gemert MJ (eds).*Optical-Thermal Response of Laser-Irradiated Tissue*. New York: Plenum Press, 1995; Chapter 9.

26 Roggan A, Dörschel K, Minet O *et al.* The optical properties of biological tissue in the near infrared wavelength range – review and measurements. In: *Laser-Induced Interstitial Thermotherapy* (Müller GJ, Roggan A, eds). Bellingham, WA: SPIE, 1995; 10–44.

27 Sapareto SA, Dewey WC. Thermal dose determination in cancer therapy. *Int J Radiat Oncol Biol Phys* 1984; **10**:787–800.

28 Kono T, Yamaki T, Ercocen AR *et al.* Treatment of leg veins with the long pulse dye laser using variable pulse durations and energy fluences. *Lasers Surg Med* 2004; **35**:62–7.

29 Hohenleutner U, Walther T, Wenig M *et al.* Leg telangiectasia treatment with a 1·5 ms pulsed dye laser, ice cube cooling of the skin and 595 vs 600 nm: preliminary results. *Lasers Surg Med* 1998; **23**:72–8.

30 Ross EV, Domankevitz Y. Laser treatment of leg veins: physical mechanisms and theoretical considerations. *Lasers Surg Med* 2005; **36**:105–16.

31 Randeberg LL, Bonesronning JH, Dalaker M *et al.* Methaemoglobin formation during laser induced photothermolysis of vascular skin lesions. *Lasers Surg Med* 2004; **34**:414–19.

32 Kuenstner A, Norris KH. Spectrophotometry of human haemoglobin in the near infrared region from 100 to 2500 nm. *J Near Infrared Spectrosc* 1994; **2**:59–65.

33 Ozturk S, Hoopman J, Brown SA *et al.* A useful algorithm for determining fluence and pulse width for vascular targets using 1,064 nm Nd:YAG laser in an animal model. *Lasers Surg Med* 2004; **34**:420–5.

34 Majaron B, Svaasand LO, Aguilar G, Nelson JS. Intermittent cryogen spray cooling for optimal heat extraction during dermatologic laser treatment. *Phys Med Biol* 2002; **47**:3275–88.

35 Falati S, Gross P, Merrill-Skoloff G *et al.* Real-time *in vivo* imaging of platelets, tissue factor and fibrin during arterial thrombus formation in the mouse. *Nat Med* 2002; **8**:1175–81.

36 Rosen ED, Raymond S, Zollman A *et al.* Laser-induced noninvasive vascular injury models in mice generate platelet- and coagulation-dependent thrombi. *Am J Pathol* 2001; **158**:1613–22.

37 Babilas P, Shafirstein G, Bäumler W *et al.* Selective photothermolysis of blood vessels following FPDL-irradiation: *in vivo* results and mathematical modelling are in agreement. *J Invest Dermatol* 2005; **125**:335–42.