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Numerical Modeling of The Dysplastic Vessel Heating in PWS by Yellow 578 nm Copper Vapor Laser Radiation for Different Skin Phototypes

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Abstract

Introduction: Many clinical studies and protocols have been written about laser treatment for fair skin phototypes. However, for dark-skinned phototypes, information is limited, and the risk of burns is higher, especially if the same settings are recommended for fair skin. Competitive epidermal melanin absorption decreases the light energy reaching dysplastic vessels in a port-wine stain (PWS), preventing the vessel from achieving the temperature of the desired clinical result. Therefore, the choice of safe laser settings for different skin phototypes can be realized using numerical modeling of PWS vessel heating. This study aimed to demonstrate the algorithm for choosing both effective and safe photodestruction of dilated dermal vessels in PWS with the copper vapor laser (CVL) at 578 nm for different skin phototypes.

Methods: We used the multilayered skin model with different melanin content for detecting the safe laser parameters for PWS treatment. The calculation of the selective heating of the vascular component with CVL radiation at yellow 578-nm wavelengths for different skin phototypes was performed via Matlab mathematical programming system and its application Femlab for solving partial differential equations using the Finite element method.

Results: We determined the location, depth, and size of blood vessels that could be selectively heated to coagulation temperature for different skin prototypes. CVL fluence values need to be reduced almost two times for skin phototype IV than for skin phototype II to provide safe CVL treatment. The maximum depth of the location of the vessels, which can be selectively heated to coagulation temperature, also decreased for dark skin phototypes. Histological and histochemical findings validated the results of our calculations.

Conclusion: To our knowledge, the use of numerical simulation to optimize has not yet been considered. According to our calculations, CVL could selectively heat the dilated vessel, which occurred in purple and proliferative-type PWS for dark skin at the reduced fluence range and depth.

Keywords: Copper vapor laser; Selective vessel heating; Computer simulation; PWS treatment; Dark skin.

Introduction

"Port-wine stains" (PWSs) are capillary malformations consisting of dilated vessels, ranging from 10 microns to 474 microns in diameter.[1] The vessels in PWSs are located in the dermis at a depth of up to 750 microns.[2,3] PWS is divided into four grades of ectasia based on the vessel diameter range according to https://birthmark.org/pws-paper-by-dr-mihm-and-l-rozell-shannon/.

Copper vapor laser (CVL) radiation at a yellow wavelength at 578 nm provides the maximum heating selectivity of dysplastic vessels and clinical effectiveness and safety in the PWS treatment of patients.[4] The choice of laser treatment parameters allows the photodestruction of dysplastic vessels in PWSs with minimal post-radiation changes in dermal collagen.[5]

There has been little clinical data using the CVL in PWS treatment in Asian people with Fitzpatrick skin type III-V.[6,7] PWS treatment is more difficult and unpredictable in patients with darker skin phototypes since skin of color absorbs light energy better than fair skin. Laser treatment of PWSs in patients with skin of color remains challenging.

We use numerical modeling to determine the safe CVL settings for selectively heating the dysplastic vessel to coagulation threshold temperature without overheating the surrounding tissue for patients with different skin phototypes.

Model

The simulation was based on the theory of radiation transfer in the diffusion approximation and thermal

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conductivity theory. For modeling, we used the Matlab mathematical programming system and its application Femlab for solving partial differential equations using the Finite element method.[4,5]

The geometry of the model is shown in Figure 1. A three-layer model, including the dermis, in which the vessel was located, the epidermis with a thickness of 70 microns, and the epidermal basal layer, with a thickness of 15 microns, represented the skin. The vessels of different diameters were located in the dermis at depths more than 150 microns from the skin surface. The optical and thermophysical constant values were taken from.[5,8-11] Table 1 demonstrates absorption coefficients at 578 nm for main skin chromophores, thermal conductivity, and diffusivity constants.

Our simulations were based on the optical and thermal diffusion processes' dynamics using radiation transfer theory (in the diffusion approximation) and the heat conduction theory. In order to calculate the temperature distribution in the skin, the thermal conductivity equation was used[12]:

$$\rho \cdot c\,\frac{\partial T(\vec{r},t)}{\partial t} = \left(\nabla \kappa \nabla T(\vec{r},t)\right) + Q(\vec{r})$$

where ρ $^{\rho}$= density, c = thermal capacity, t = time, ϰ = α·ρ·c - thermal conductivity, and α = thermal diffusivity.

The $Q(\vec{r})$ value is the heat source bulk density in a medium calculated as follows[12]:

$$Q(\vec{r}) = \mu_a.\varphi(\vec{r}).\frac{E_0}{\tau_p}$$

where μ_a = absorption coefficient, $= \varphi(\vec{r})$ total illuminance at the $\vec{r} = (x, y)$ point, including both the collimated and diffusion components, and E_0 = radiation energy density.

The collimated illuminance component was decaying by the exponential law due to absorption and scattering[12]:

$$E(\vec{r},\hat{s}_0) = E_0(\vec{r},\hat{s}_0)\exp(-\mu_t l)$$

Here $E_0(\vec{r},\hat{s}_0)$ is the intensity at the $\vec{r}$ point in the absence of the medium (tissue), $\hat{s}_0$ = the direction of the primary beam propagation, $\mu_t = \mu_a + \mu_s$ - total attenuation coefficient, μ_a = absorption coefficient, μ_a = scattering coefficient, and l = the depth of the unchanged photons' propagation in the tissue between the biological tissue entry point and the $\vec{r}$ point of the volume element under consideration.

In order to solve the thermal conductivity equation, it is required to know the illuminance distribution in the medium, which was calculated using the equation of radiation transfer in the diffusion approximation[13]:

Table 1. Absorption Coefficients of Main Skin Chromophores and Parameters Used for the Calculation

Constant			Ref
Hb absorption coefficient, mm^{-1}		20.7725	11
Melanin absorption coefficient, mm^{-1}		41.585	11
	Density, kg/m^3 [10]	**Thermal Capacity, J/kg·K [10]**	**Thermal Conductivity, W/m·K [10]**
Epidermis	1120	3050	0.29
Dermis	1080	3500	0.41
Blood	1000	4350	0.65

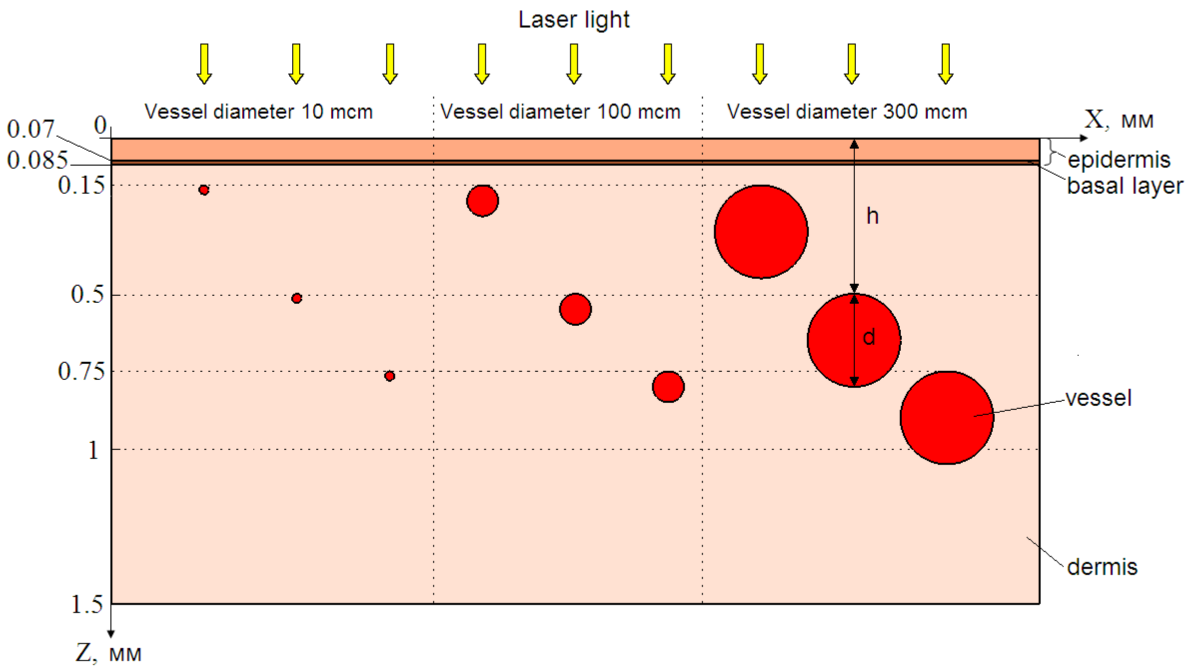

Figure 1. The Geometry of the Model. d - vessel diameter, h - distance from the skin surface to the upper point of the vessel (location depth). We control the temperature of the different points of vessels with diameters of 30, 100, 300 microns, located at various depths in the dermis (b).

$$\nabla^2\varphi_s(\vec{r}) - 3\mu_a\mu_{tr}\varphi_s(\vec{r}) + 3\mu_s\mu_{tr}$$
$$E(\vec{r},\hat{s}_0) - 3\mu_s g\nabla\cdot(E(\vec{r},\hat{s}_0)\hat{s}_0) = 0$$

Where $\varphi_s(\vec{r})$ is the illuminance diffusion component at the $\vec{r}$ point, $\mu_{tr}=\mu_a+(1\text{-}g)\mu_s$ - attenuation transfer coefficient, and g=average cosine of the scattering angle (scattering anisotropy factor).

The calculated distribution of light intensity at a 578 nm CVL wavelength is shown in Figure 2a. The calculated temperature distribution at the end of CVL exposure time of 200 ms is shown in Figure 2b.

The concentration of melanin in the basal layer for skin phototypes II and IV in the calculation was taken 5% and 14% respectively.[14] The temperature distribution in the vessel and different skin layers was calculated at various CVL settings (see Figure 1).

We calculate the effective depth of selective vessel heating by the CVL radiation for skin phototypes II and IV to a temperature of 65-100°C at which their coagulation can occur.[15]

Results and Discussion

Figure 3 represents the result of our calculation for skin phototype II. We can see the maximum temperature of nine blood vessels with a diameter of 30, 100, 300 microns, located at various depths of 370, 670, and 920 microns respectively, under the skin surface after exposure for 200 ms with CVL radiation at a 578-nm wavelength. We can

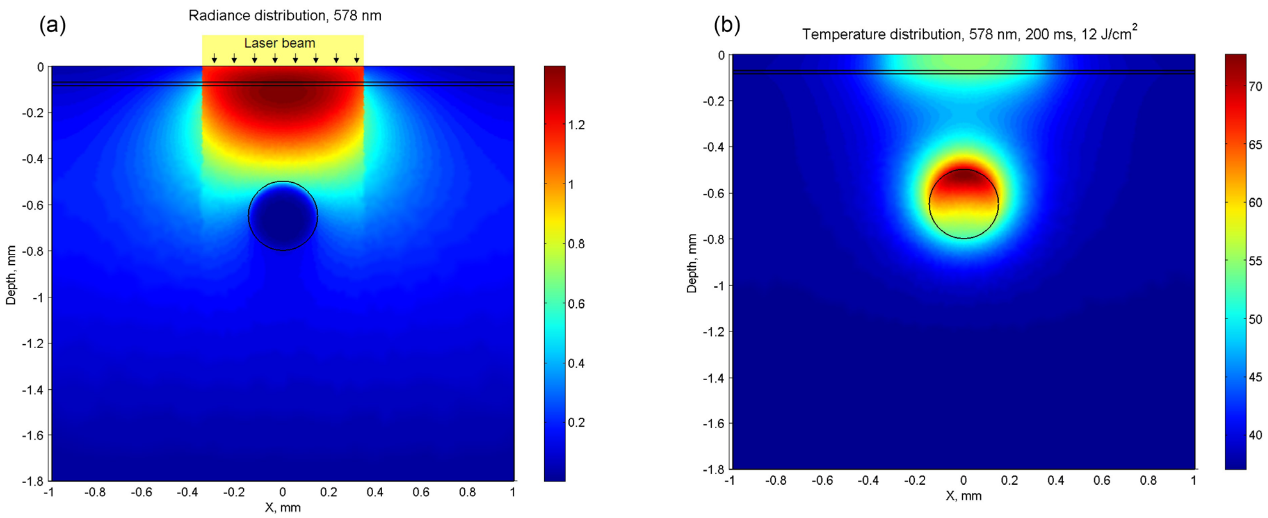

Figure 2. The Calculated Distribution of Light Intensity at a 578-nm CVL Wavelength in the Arbitrary Unit (a) and Calculated Temperature Distribution at the End of CVL Exposure Time of 200 ms (b). Vessel diameter – 300 microns, vessel depth – 500 microns.

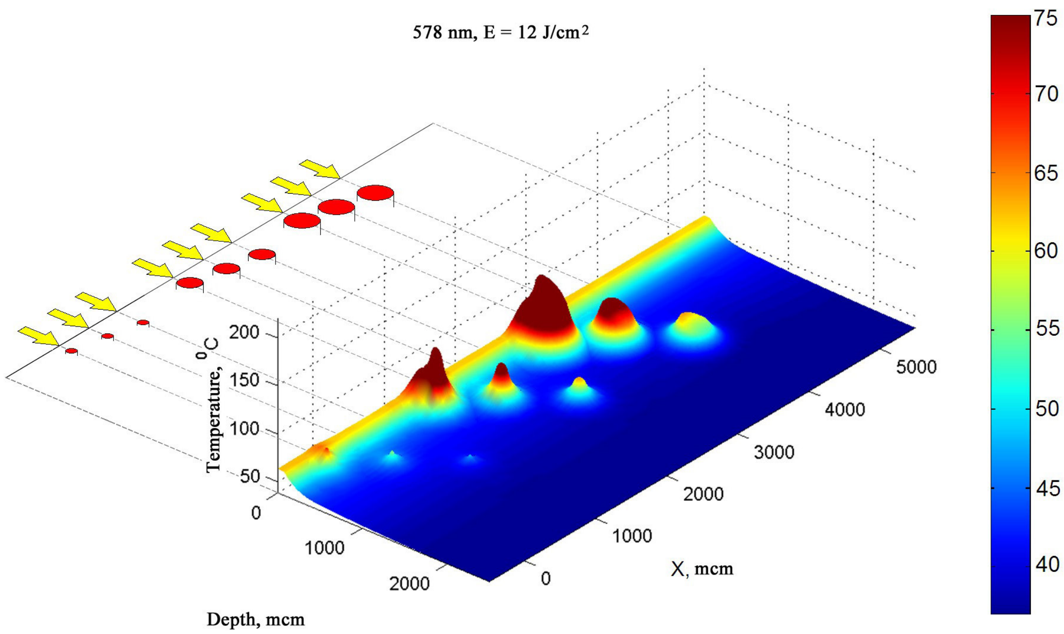

Figure 3. The Distribution of the Maximum Temperature of Three Vessels With a Diameter of 30, 100, and 300 Microns, Located at a Depth of 370, 670, and 920 Microns Respectively, Under the Skin Surface, Heated by CVL Radiation At a 578-nm Wavelength With an Exposure Time of 200 ms for II Skin Phototype. Fluence value of 12 J/cm².

see the tissue temperature below 65 degrees Celsius and vessel temperature higher than 65 degrees Celsius. In that case, we can get the selective vessel heating regime, which is safe for PWS treatment.

The CVL fluence values at which the tissue and vessel temperature reaches more than 65°C correspond to the upper limit of selective vessel heating. Using the fluence values above this limit leads to nonselective vessel heating, that is, “hot iron effect.”

Due to the competing absorption of melanin for skin of color, we can suggest a narrower therapeutic fluence range and a smaller effective depth at which CVL selectively heats the vessels compared to skin phototype II. According to our calculations, CVL fluence values need to be reduced almost twice for patients with skin of color.

Our calculation also demonstrated the diameter range and effective depth at which selective heating of PWS vessels provided for different skin phototypes (See Figure 4). The calculated maximum depth at which vessels of various diameters can be selectively heated to the temperature of 65-100 degrees Celsius for skin phototypes II and IV is listed in Table 2. The maximum effective depth of the location of the vessels decreased up to three times for skin phototype IV compared to skin phototype II. The diameter ranges of PWS vessels, which CVL can treat, remains the same.

We compared the results of our simulations with the histological and histochemical investigations of PWS treatment with CVL radiation for various skin phototypes.

The maximum depth of CVL (at a 578-nm wavelength) selective vessel heating was found to be 0.7 mm in histological studies of Tan et al[16] and Walker et al.[17] Neumann et al showed that for Caucasian skin, selective heating of PWS blood vessels with small perivascular fibrosis was observed at CVL fluence values of 8-15 J/cm^2, and diffuse coagulation necrosis epidermis and dermis at CVL fluencies of 20 J/cm^2.[18]

Simultaneously, histological findings of PWS treatment with CVL for skin phototypes III-V indicate the selective vessel coagulation at fluencies of 6-8 J/cm^2 and diffuse coagulation necrosis at fluencies of more than 10 J/cm^2.[19] They also found that the maximum penetration depth at which vessel selective coagulation can occur for CVL was 0.4 mm; the range of fluences at which the selective vessel damage can occur is much narrower for skin of color than that for Caucasian skin.

OCT measurements demonstrated the depth (226.89 ± 61.14 microns) and diameter (125.63 ± 19.09 microns) of dilated vessels for the purple-type PWS and the depth (195.59 ± 59.45 microns) and diameter (193.93 ± 32.43 microns) for the proliferative-type PWS.[2] Another OCT data indicates that the PWS lesion presents blood vessels of a mean diameter of 114 ± 92 microns at the mean depth of 304 ± 99 microns.[1]

According to our calculations, CVL provided the selective heating of PWS dilated vessels at such depths and diameters.

Thus, the calculated fluence range and penetration depth of PWS treatment with CVL for the results of different skin phototypes are in good agreement with the experimental data.

Table 2. Calculated Maximum Depth in microns (mcm) at which selective vessel heating occurs for more than 65°C for skin phototypes II and IV

Vessel diameter, mcm	10	20	30	50	100	200	300
Maximum depth for Skin phototype II, mcm	145	265	465	715	915	825	515
Maximum depth for Skin phototype IV, mcm	100	120	140	215	365	270	-

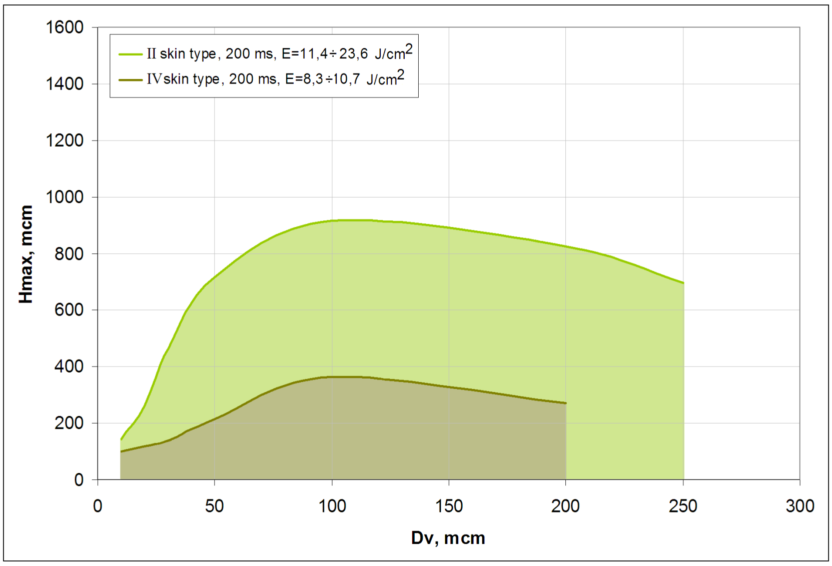

Figure 4. Maximum depth H_{max} at which PWS vessels of different diameters can be selectively heated to the temperature of 65-100 °C with CVL for skin phototypes II and IV.

Conclusion

CVL fluence values need to be reduced almost twice for skin phototype IV than skin phototype II to provide selectivity. It corresponds to a smaller depth for selective PWS vessel heating. CVL can selectively heat dilated vessels of 10-200 microns in diameter, which occur in purple and proliferative-type PWS for different skin phototypes. The results presented in this paper will be useful in optimizing the modes of PWS dysplastic vessel heating. A computer simulation is a valuable tool for adjusting laser settings according to the skin phototypes, specific diameter, and location of the dysplastic vessels in PWS.

The computer simulation method opens up the possibility of personalized adjustment of the parameters of patients' laser treatment according to the individual assessment of the skin's optical pattern. It can serve as the basis for software development for the new generation of laser medical systems.

Conflict of Interests

The authors declare that there is no conflict of interest.

Ethical Considerations

Not applicable.

References

1. Latrive A, Teixeira LR, Gomes AS, Zezell DM. Characterization of skin Port-Wine Stain and Hemangioma vascular lesions using Doppler OCT. *Skin Res Technol*. 2016;22(2):223-229. doi:10.1111/srt.12253
2. Barsky SH, Rosen S, Geer DE, Noe JM. The nature and evolution of port wine stains: a computer-assisted study. *J Invest Dermatol*. 1980;74(3):154-157. doi:10.1111/1523-1747.ep12535052
3. Zhao S, Gu Y, Xue P, Guo J, Shen T, Wang T, et al. Imaging port wine stains by fiber optical coherence tomography. *J Biomed Opt*. 2010;15(3):036020. doi:10.1117/1.3445712
4. Pushkareva AE, Ponomarev IV, Topchiy SB, Klyuchareva SV. Comparative numerical analysis and optimization of blood vessels heated using various lasers. *Laser Physics,* 2018;28(9):1-7. doi:10.1088/1555-6611/aac903
5. Ponomarev IV, Topchiy SB, Kazaryan MA, Pushkareva AE, Klyuchareva SV. Numerical Simulation Optimization of Selective Heating of Blood Vessels in "Port-Wine Stains" under Laser Irradiation in Various Modes. *Bull Lebedev Phys Inst*.2018;45(7):204-208. doi: 10.3103/S1068335618070035
6. Chung JH, Koh WS, Lee DY, Lee YS, Eun HC, Youn JH. Copper vapour laser treatment of port-wine stains in brown skin. *Australas J Dermatol*. 1997;38(1):15-21. doi:10.1111/j.1440-0960.1997.tb01092.x
7. Bhatt N, Alster TS. Laser surgery in dark skin. *Dermatol Surg*. 2008;34(2):184-195. doi:10.1111/j.1524-4725.2007.34036.x
8. Roggan A, Friebel M, Do Rschel K, Hahn A, Mu Ller G. Optical Properties of Circulating Human Blood in the Wavelength Range 400-2500 nm. *J Biomed Opt*. 1999;4(1):36-46. doi:10.1117/1.429919
9. van Gemert MJ, Jacques SL, Sterenborg HJ, Star WM. Skin optics. *IEEE Trans Biomed Eng*. 1989;36(12):1146-1154. doi:10.1109/10.42108
10. Sekins K, Emery A. Thermal science for physical medicine Therapeutic Heat and Cold. 1982. ed JF Lehmann. Ponomarev IV, Topchiy SB, Klyuchareva SV, Pushkareva AE. Rhinophyma Treatment by Copper Vapor Laser With the Computerized Scanner. *J Lasers Med Sci*. 2019;10(2):153-156. doi:10.15171/jlms.2019.24
11. https://omlc.org/spectra/index.html
12. Niems M H. *Laser–Tissue Interactions: Fundamentals and Applications*. Springer, Berlin, Heidelberg; 1996.
13. Welch A, Van Gemert M (ed). *Optical-Thermal Response of Laser-Irradiated Tissue*. Springer, Dordrecht; 2011.
14. Del Bino S, Duval C, Bernerd F. Clinical and Biological Characterization of Skin Pigmentation Diversity and Its Consequences on UV Impact. *Int J Mol Sci*. 2018;19(9):2668. doi: 10.3390/ijms19092668.
15. Klyuchareva SV, Ponomarev IV, Pushkareva AE. Numerical Modeling and Clinical Evaluation of Pulsed Dye Laser and Copper Vapor Laser in Skin Vascular Lesions Treatment. *J Lasers Med Sci*. 2019;10(1):44-49. doi:10.15171/jlms.2019.07
16. Tan OT, Stafford TJ, Murray S, Kurban AK. Histologic comparison of the pulsed dye laser and copper vapor laser effects on pig skin. *Lasers Surg Med*. 1990;10(6):551-558. doi:10.1002/lsm.1900100607
17. Walker EP, Butler PH, Pickering JW, Day WA, Fraser R, Van Halewyn CN. Histology of port wine stains after copper vapour laser treatment. *Br J Dermatol*. 1989;121(2):217-223. doi:10.1111/j.1365-2133.1989.tb01801.x
18. Neumann RA, Knobler RM, Leonhartsberger H, Gebhart W. Comparative histochemistry of port-wine stains after copper vapor laser (578 nm) and argon laser treatment. *J Invest Dermatol*. 1992;99(2):160-167. doi:10.1111/1523-1747.ep12616789
19. Chung JH, Koh WS, Youn JI. Histological responses of port wine stains in brown skin after 578 nm copper vapor laser treatment. *Lasers Surg Med*. 1996;18(4):358-366. doi:10.1002/(SICI)1096-9101(1996)18:4<358::AID-LSM4>3.0.CO;2-R
20. Zhou Y, Yin D, Xue P, Huang N, Qiu H, Wang Y, et al. Imaging of skin microvessels with optical coherence tomography: potential uses in port wine stains. *Exp Ther Med*. 2012;4(6):1017-1021. doi: 10.3892/etm.2012.711.