Optimum Spectrum and Pulse Shape for Vascular Lesion Treatment: The Science Behind MaxG

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Introduction

The new arc lamp-based Palomar MaxG™ handpiece (Palomar Medical Technologies, Inc., Burlington MA) is designed for the treatment of vascular lesions and pigmented lesions in Fitzpatrick skin types I-IV (Fig. 1). The device employs optical spectral filtering and lamp voltage control to optimize treatment of blood vessels over a wide range of diameters and depths, while reducing the heating of the overlying melanized dermal/epidermal (D/E) junction.

Device Description

Fig. 1: MaxG Handpiece

The treatment spot is defined by a 10x15 mm sapphire optical window with uniform output fluence. The user may select a range of pulsewidths and fluences as shown in Table 1.

Pulsewidth (ms)	Fluence Range (J/cm2)
5	5-25
10	20-50
15	20-60
20	20-68
25	20-74
30	20-80
40	20-80
60	34-80
80	40-80
100	40-80

Table 1: MaxG pulsewidths and fluences on the StarLux 500 system.

The main features of the handpiece described in detail below include:

- Dual-band spectral output
  - o 1st Band: Q-bands of Hb or melanin of pigmented lesions (500-670 nm)
  - o 2nd Band: Near infrared bands of Hb and MetHb (850-1200 nm)
- Controlled power output
- Pulsewidths from 5 ms to 100 ms
- Blood vessel diameters (60 µm-300 µm)
- Dynamic spectrum shift
- More energy at longer wavelengths with increasing pulsewidths
- Optimum heating of larger, deeper vessels
- Contact cooling to 5ºC

Dual-Band Spectral Output

The target chromophores of the MaxG handpiece are melanin and hemoglobin and its fractions, specifically oxyhemoglobin, deoxyhemoglobin, and methemoglobin. Melanin of type II skin (blue curve), venous blood (oxy- and deoxyhemoglobin, red curve) and methemoglobin (green curve) absorption spectra are shown in Fig. 2. While all chromophores absorb over a larger range of wavelengths, the hemoglobin absorption is greatest in the Soret bands (400-450 nm) and the Q-bands (500-600 nm) with less absorption in the near infrared (NIR) bands (800-1200 nm). Note, however, the marked increase in absorption of methemoglobin compared with venous blood in the NIR band. The melanin absorption spectrum is highest for shorter wavelengths and monotonically decreases with increasing wavelength.

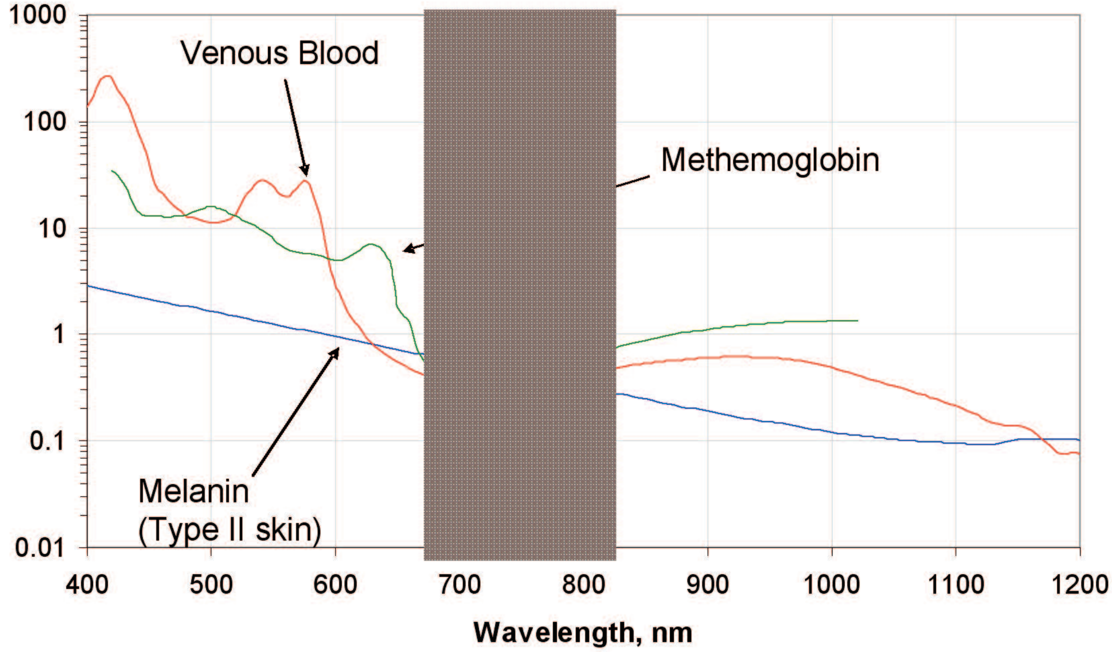

Fig. 2: Hemoglobin, methemoglobin and melanin absorption spectra

The broad-band emission of an arc lamp should be optimized for treatments of vascular and pigmented lesions with optical filtration, allowing specific wavelength bands to preferentially heat blood in the presence of melanin or to treat pigmented lesions. The MaxG spectral output (olive green curve) is depicted in Fig. 3. The full spectrum can be divided into five bands. The first band from 300 nm to 500 nm is blocked because penetration to lower vessels is impeded by high tissue back-scatter and unacceptably high absorption by melanin within the dermal/epidermal junction. The second band from 500 nm to 670 nm targets both the melanin of pigmented lesions and hemoglobin. The wavelengths in the third band (blue-shaded region in Fig. 2) do not provide favorable heating of hemoglobin versus melanin. If this band is excluded the heating of melanin is minimized with respect to hemoglobin. The loss of this range does not compromise treatment of pigmented lesions because of their high melanin content. In contrast to the shorter wavelengths, the fourth band emitting from 850 nm to 1200 nm is scattered less and penetrates deeper into the skin. This band is optimally absorbed by blood to provide more uniform heating across the entire diameter of larger vessels. The role of this wavelength band also increases as hemoglobin is heated and converted to methemoglobin during the pulse. Finally, absorption by water in the skin is eliminated with an absorbing water filter in the handpiece. The water-absorption wavelengths greater than 1200 nm in the fifth band do not heat blood preferentially and would only contribute to increased pain from the non-selective bulk heating of skin.

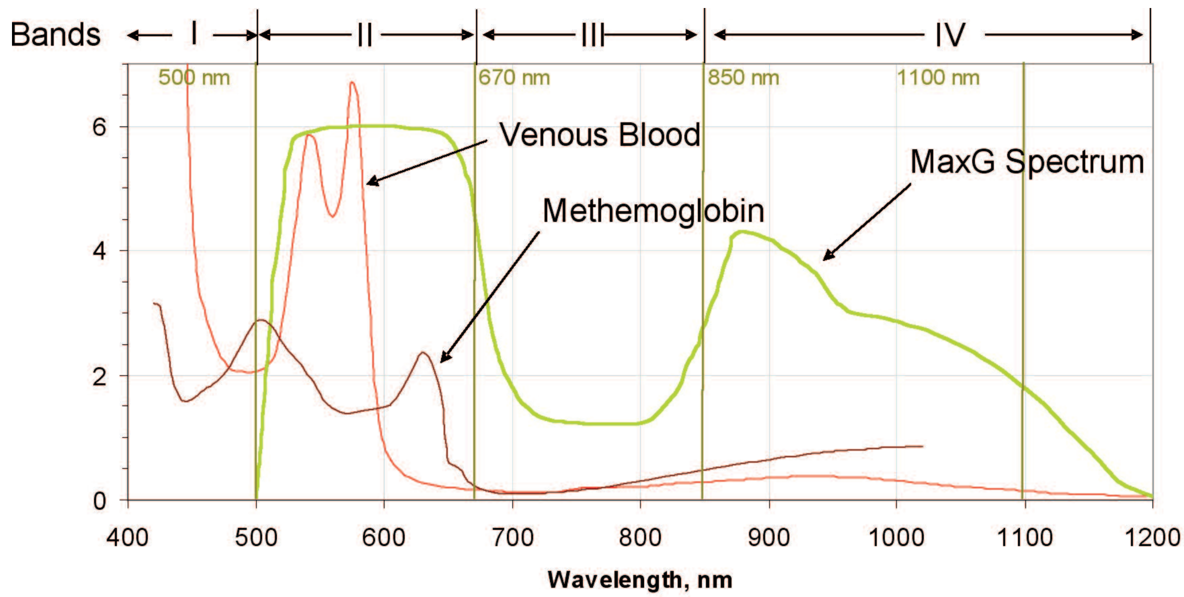

Fig. 3: MaxG output power spectrum is overlaid onto the heat production curves of venous and methemoglobin blood in a vessel 500 microns below the skin surface.

The heat production curves of venous hemoglobin (red) and methemoglobin (brown) are also shown for a blood vessel at 500 micron depth in Fig. 3. By definition, heat production of a chromophore is given by the product of the chromophore's absorption strength and the power density of light at the location of the chromophore in the skin. The heat production curves account for the effect of tissue scatter that is also a function of wavelength. While venous hemoglobin exhibits a difference in absorption from 577 nm to 950 nm by a factor of 50, its corresponding heat production curve for this deep vessel varies only by a factor of 15, mainly because of the effect of scatter: longer wavelengths penetrate deeper. Note the increase in heat production at the longer wavelengths of methemoglobin relative to venous blood. This helps to offset the overall drop in absorption across the second band from 500 nm to 670 nm if venous blood is converted into methemoglobin during the pulse heating. The dual-band MaxG output spectrum shown by the olive curve mirrors the blood absorption curves to maximize total energy absorption.

The importance of absorption strength and scatter is demonstrated in Fig. 4. For example, blood vessels with 300 microns diameter are located 300, 600 and 900 microns below the surface of type II skin. The color bar describes the fraction of coagulation induced by a single pulse of a pulsed dye laser (595 nm, 6 ms, 7.5 J/cm2) and of the MaxG handpiece (10 ms, 36 J/cm2). The deeper vessels are more uniformly coagulated with the broad spectrum of the MaxG than with the pulse dye laser (PDL) 595 nm laser light.

The following interpretation is given: the longer wavelengths of light with lower absorption and scatter contribute to the heating of the deep vessels. They provide more uniform vessel heating than the shorter wavelength laser light with higher absorption (λ< 600 nm and absorption > 5 mm-1). High absorption wavelengths of light are effective on smaller, more superficial vessels but can cause non-uniform heating of the larger blood vessels' walls and incomplete closure.

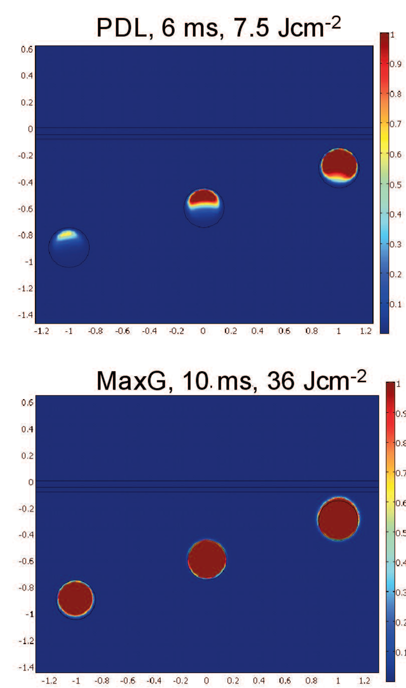

Fig. 4: Full coagulation depicted by the brown region in 300 micron diameter vessels at depths 300, 600 and 900 microns in skin type II. Operating wavelength of the PDL system is 595 nm.

Controlled Output Power

The pulse shapes for optimized treatment of pigmented lesions and vascular lesions follow from the theory of selective photothermolysis and the extended theory of selective photothermolysis, respectively. Selectivity is accomplished by appropriate choice of wavelengths and pulsewidth to satisfy the adiabatic condition, and the average power during this pulse determines the degree of heating (temperature) of the target. Since injury to a vessel wall occurs by thermal transfer from the heated blood consideration must be given to the optical, thermal, and fluidic properties of heated blood during pulses. Note that the absorption strength (i.e., wavelength) affects the adiabatic conditions. For example, highly absorbed wavelengths of light do not penetrate and heat entirely a large blood vessel. In this case, the adiabatic pulsewidths are determined only by the volume of heated blood, not the entire vessel. Less highly absorbed wavelengths that penetrate the entire vessel, in contrast, would require longer pulsewidths determined by the vessel diameter to satisfy the adiabatic requirement and also higher average power to adequately heat the vessel.

Peak powers should be limited to the minimum necessary to avoid temperatures in excess of coagulation temperatures. Otherwise, nonlinear phenomena such as vaporization or ablation occur, which are not ideal mechanisms of injury to vascular components. The combined usage of high absorption wavelengths of light and high peak powers is expected to cause a decrease in the purpuric threshold fluence. For these reasons, the MaxG output power is highly controlled and uniform, free from high peak power spikes (Fig. 5a).

The PDL parameters are 7.5 J/cm² during a 6 ms pulse, and the MaxG parameters are 36 J/cm² during a 10 ms pulse. Note the PDL pulse actually consists of four 100 microsecond pulses during the 6 ms, each with peak intensity of 18.75 kW/cm². In contrast, the MaxG peak intensity is 3.6 kW/cm². PDL information obtained from Sol Kimel et. al., "Vascular Response to Laser Photothermolysis as a Function Of Pulse Duration, Vessel Type, and Diameter: Implications for Port Wine Stain Laser Therapy", Lasers in Surgery and Medicine, 30:160-169 (2002). (Fig. 5b)

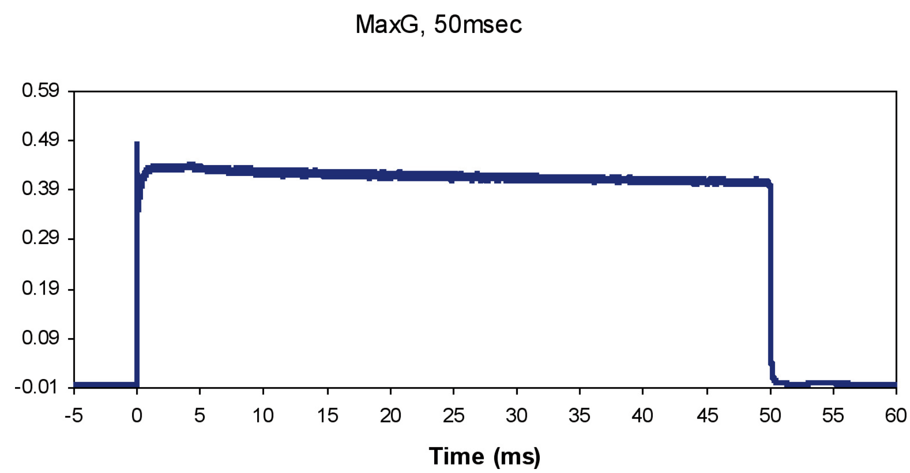

Fig. 5a: Typical pulse structure of the MaxG handpiece.

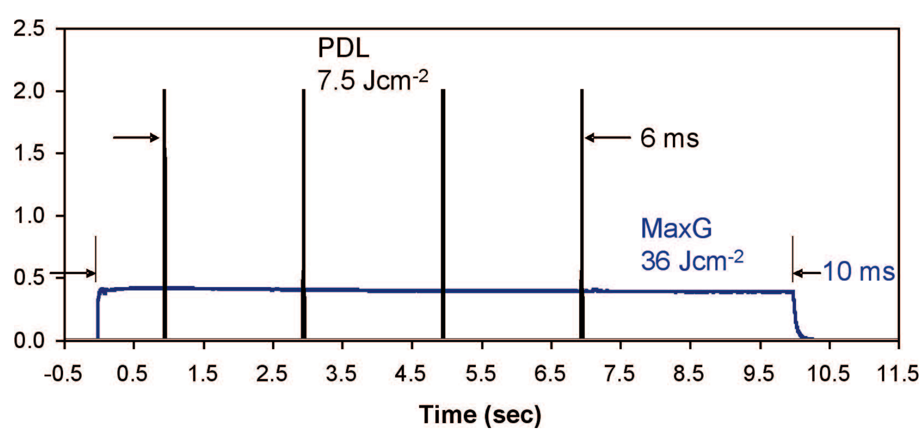

Fig. 5b: Pulsewidth structure of a PDL compared to the MaxG.

Spectrum Shift

A phenomenon quantitatively described by Wien's displacement law (Eq. 1) occurs for all blackbody thermal radiators in equilibrium. As the temperature of the radiator decreases, the peak of the radiator's power spectrum shifts to the longer wavelengths.

Eq. 1: Wien's Displacement Law

$$\lambda T = Const$$

This states that the product of temperature (T) and wavelength (λ) is constant. Although an arc lamp is much more complex than a blackbody in equilibrium, a spectral shift to longer wavelengths is observed with decrease in power. For example, a 30% increase in the percentage of energy in the NIR band of the spectrum occurs when the settings are changed from a fluence of 50 J/cm^2 at 10 ms to 80 J/cm^2 at 100 ms (spectrum changes from the green curve to the red curve, Fig. 6). At the same fluence, as the pulsewidth is increased to optimize treatment of larger diameter vessels with longer thermal relaxation times, the amount of energy emitted in the longer wavelengths of the NIR band increases at the expense of the visible band. This puts more energy into the bands responsible for more uniform heating of deeper lying vessels. (Fig. 6)

In conclusion, the wide band power spectrum and smooth output pulse of the MaxG enable treatment of pigmented and vascular lesions with a large range of vessel diameters and depths. The spectral shift to long wavelengths with longer pulsewidths enhances the device's effectiveness on deeper and larger vessels.

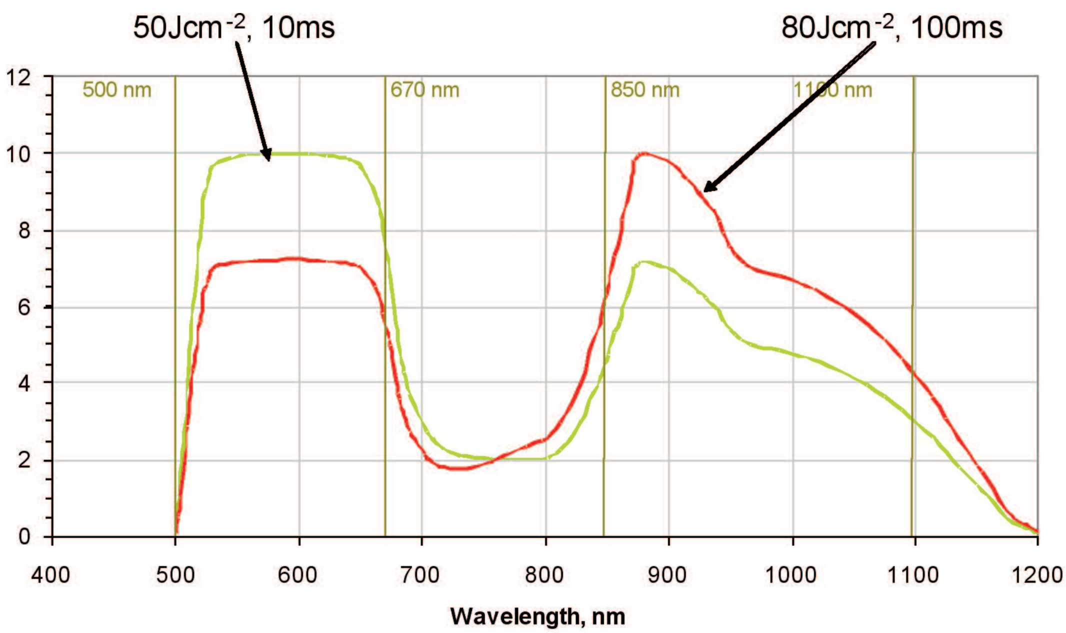

Fig. 6: Spectral shift from green (50 J/cm^2 , 10ms) to orange curve (80 J/cm^2 , 100 ms)