Absorption Characteristics of Tissues as a Basis for the Optimal Wavelength Choice in Photodermatology

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Introduction

The absorption of light by an object is directly correlated to the incident radiation and the absorption coefficient (***AC***) of the object. Objects or materials with a high coefficient of absorption will absorb a large amount of light if the wavelength of the incident light corresponds to the absorption band of the material. Conversely, light can propagate a long distance without much attenuation in a material with a low ***AC***.

The absorption coefficient of bulk materials is measured in units of inverse length (e.g., mm^{-1}). Absorption of a chromophore is often specified as the molar extinction coefficient $\mathcal{E}$, expressed in units of inverse length per molar concentration (e.g., cm^{-1}/(mole/liter) or $M^{-1}cm^{-1}$). When concentration $\mathcal{C}$ [g/liter] of a chromophore in a given material is known, the corresponding partial absorption coefficient can be calculated from the molar extinction coefficient:

$$AC = 2.303 \cdot \frac{\mathcal{E} \cdot \mathcal{C}}{M}, \qquad (1)$$

where M is the molecular weight [g/mole] of the chromophore.

Both the absorption coefficient and the molar extinction coefficient are often plotted on a logarithmic scale. This sometimes makes it difficult to appreciate visually the true difference in the absorption between, for example, two spectral points or between spectral curves of two different materials plotted on the same graph. The reason for such a misperception is, of course, the fact that a two-fold change in the distance along the vertical axis corresponds to a 10-fold change in the plotted quantity. With this in mind, we will look at the various chromophores and the various lasers and light sources in use to determine which product might produce the best results.

The three main chromophores of skin are melanin, hemoglobin, and water. Other compounds (e.g., cytochrom aa_3) can be of interest for some non-thermal applications, but their contributions into the macroscopic absorption characteristics of tissues are small. In this paper, we shall only concern ourselves with the three major chromophores. A wealth of literature on optical properties of tissues and tissue chromophores is available. In this work, we used data from Refs. 1-4. Typical spectra of major tissue chromophores are shown in Fig. 1.

Hemoglobin

Absorption spectra of oxygenated (HbO2) and de-oxygenated (Hb) forms of hemoglobin are somewhat different – hence the difference in color between arterial and venous blood. The absorption curves for both forms have several strong bands in the visible part of the spectrum. The molar extinction coefficient in the "blue" region of the spectrum is very high at the 405 to 420 nm band (reaching values higher than 500 $mM^{-1}cm^{-1}$). Therefore, incident radiation in this range will be very highly absorbed by blood, and the penetration of light through the papillary dermis will be very difficult because of the presence of a plexus of blood vessels. Thus, all effects of blue light in the 400 – 450 nm spectral region will be superficial due to the lack of penetration because of blood, but also because of the presence of melanin (see below).

Moving from the 400 nm range to the 500 nm range shows a drop in the absorption by HbO2 and then a subsequent increase producing two absorption peaks at 538 and 578 nm. These peaks have the $\mathcal{E}$ values of approximately 53 and 55 $mM^{-1}cm^{-1}$, respectively. The Hb has a single peak centered at ~550 nm, with maximum of ~54 $mM^{-1}cm^{-1}$. This is an order of magnitude less than the deep blue region around 400 nm, but in comparison to longer wavelength regions, this still represents tremendous absorption.

Logically, if an equipment designer wants to target blood vessels throughout the papillary dermis, a blue light source in the 400 nm region would limit the penetration too much. A device designed to take advantage of the secondary absorption peaks at 538 and 578 nm would make a lot of sense. However, as has been evident over the years, both Candela and Cynosure have chosen to move their dye laser

outputs off of the 578 nm peak to 585 or 590 nm in order to gain more depth of penetration and produce a larger coagulative effect.

From a peak of 578 (with an $\mathcal{E}$ of ~55 $mM^{-1}cm^{-1}$), the molar extinction coeffecient of the oxy-hemoglobin drops to ~3.2 $mM^{-1}cm^{-1}$ at 600 nm. The 22 nm difference between the wavelengths produces a 17-fold drop in absorption. The $\mathcal{E}$ value drops even further, down to about 0.3 $mM^{-1}cm^{-1}$, between 700 to 800 nm. We often speak of an additional absorption peak for hemoglobin in the 900 to 1000 nm range, but by looking at the curves, the $\mathcal{E}$ only rises to approximately 1.2 $mM^{-1}cm^{-1}$. Although this is a 4-fold increase from a low of 0.3 $mM^{-1}cm^{-1}$, it is almost insignificant when compared to the absorption of hemoglobin in the 525 to 580 nm region.

Continuing to longer wavelengths, the $\mathcal{E}$ drops below ~0.3 $mM^{-1}cm^{-1}$ at 1,064 nm. One can conclude that there is no selectivity at all for blood absorption at the longer wavelengths. Therefore, the only explanation for the coagulative ability of 1,064 nm in treating blood vessels is the non-specific thermal effects of heating the tissue in a localized area. This will be discussed in more detail later.

Melanin

Melanin is comprised of both eumelanin and pheomelanin. The eumelanin is responsible for the brown/black pigment in the skin and in the eyes. The pheomelanin produces the red color in hair. Combinations of both pigments produce various tones of hair, skin and eye color. The pheomelanin's absorption is higher in the short wavelength region and drops off very quickly at wavelengths higher than 700 nm.

Unlike the roller coaster curve of blood, the melanin absorption curve decreases gradually from the "blue" region of the spectrum to the "red" region of the spectrum. For eumelanin, the $\mathcal{E}$ curve drops from 5 $mM^{-1}cm^{-1}$ to approximately 0.1 $mM^{-1}cm^{-1}$ within the range of 400 nm to 1,200 nm, which covers the entire range from blue light to infrared light.

Melanin concentration in a target is very important in determining the success of selectively hitting that target. The melanin concentration is obviously higher in darker skinned individuals so the ability to penetrate dark or tanned skin with "blue" light is nearly impossible. Melanin is produced by the melanocytes in the basal layer of the skin as a response to UV stimulation. The epidermal melanin produced during "tanning" is particularly hard to deal with as a competitive chromophore.

Water

The third chromophore is water. The skin is composed of approximately 70% water and the volume of water presents a large absorption target even for wavelengths of light that have a fairly low water absorption coefficient.

The water ***AC*** is almost non-existent below 800 nm, and even above that range, it is very low in comparison to the other two chromophores. For example, at a wavelength of 900 nm, the ***AC*** is less than 0.1 cm^{-1} and it only increases to 0.15 cm^{-1} at 1,064 nm. Increasing to longer wavelengths, the ***AC*** at 1.32 microns is ~2 cm^{-1}, which is almost fourteen times the ***AC*** for water at 1,064 nm. This translates to 1400% better absorption of water at 1.32 microns than at 1,064 nm.

Therefore, the choice of a 1.32-micron laser (such as the Cooltouch™) for non-ablative skin rejuvenation makes some sense. Increasing the wavelength to 1.45 microns means an ***AC*** of 32 mm^{-1}, obviously 16 times higher than at 1.32 or 1600% more absorption. We can keep extending the wavelength all the way out to 2.94 nm (Erbium:YAG) laser output, and at this point, the water ***AC*** reaches a maximum and water containing tissue is very easily ablated. Because we are only dealing with non-ablative events in this summary, we will not go to wavelengths longer than 1.45 microns.

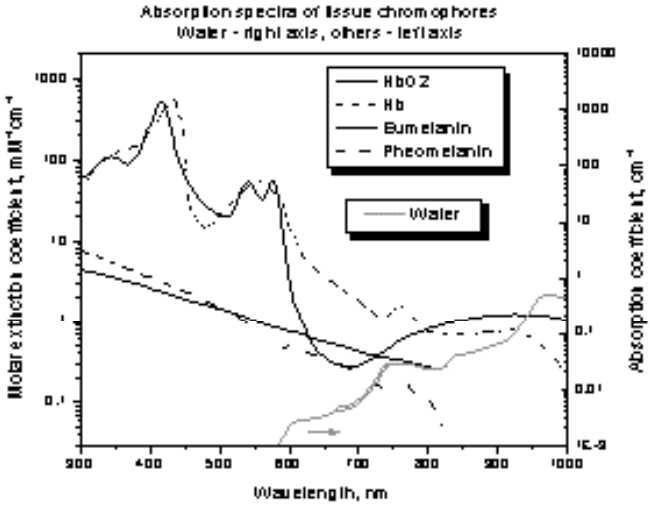

Fig. 1. Absorption spectra of tissue chromophores.

Wavelength Choice

Distribution of chromophores in a tissue will determine the absorptive characteristics of the tissue. It should be kept in mind that most relevant tissues also scatter light, and scattering characteristics can be very important in forming the resulting energy distribution in the tissue. However, in this work we shall not concern ourselves with the scattering properties.

Eq. 1, strictly speaking, is only valid for homogeneous distribution of a chromophore in the material. If chromophore is concentrated in "lumps" (as, for example, hemoglobin in erythrocytes or melanin in melanosomes), other effects, such as "sieve effect" will influence the resulting absorption characteristics. Nevertheless, Eq.1 provides a reasonably good approximation for a number of practically relevant situations. It has been used to calculate the absorption spectrum of blood (assuming 80% oxygenation and hemoglobin concentration of 150 g/l), presented in Fig. 2. This hemoglobin concentration corresponds to normal whole blood, with hematocrit of 41%. The epidermal spectra, also shown in Fig. 2, have been obtained by empirically fitting experimental data [4].

Blood-containing targets

Blood is the primary target in treating all vascular lesions. Without distinguishing between oxyhemoglobin and deoxyhemoglobin, the ***AC*** spectrum for blood in Fig. 2 certainly leads us to believe that in designing a device for selectively treating blood vessels, we would like an output wavelength between 500 and 600 nm.

This logic has spurred the development of numerous 532 nm quasi-CW frequency-doubled-YAG lasers, using KTP and other media, and pulsed dye lasers. These types of lasers have delivered excellent results for years, but do have some shortcomings with regards to power and/or price.

The other choice is a pulsed light source, such as the Palomar EsteLux™ or MediLux™ Systems, or other competitive IPL devices. The Palomar LuxB™ and LuxG™ handpieces provide up to 50 Joules/cm^2 in a range of 470 nm to 1,200 nm. Most of the energy is concentrated in the 470 to 650 region to produce selective coagulative effects on the blood vessels.

Why then would anyone choose to use longer wavelength, non-selective devices to treat vascular lesions? As evident above, the ***AC*** scales indicate that the longer wavelengths around 1,064 nm have almost no selectivity in blood absorption. The only possible mechanism is the non-selective bulk heating of tissue and the resultant coagulation of the blood.

Clearly, this application of 1,064 nm laser light does work. Companies have successfully produced devices that provide adequate cooling of the epidermis and can coagulate and destroy vessels. However, when we look at the treatment parameters, we notice that the average fluence used with the Palomar Systems (with the LuxG handpiece) is 25-30 Joules/cm^2 while the 1,064 nm long pulse YAG treats at 225 to 250 J/cm^2.

In a direct comparison, the 10-times-higher fluence needed by the long pulse YAG is not as much as the huge difference in the ***AC***, but very significant nonetheless. With this large input of non-specific heat comes the increased risk of thermally induced scarring, depressions and hypo- or hyperpigmentation. Even more so, the increased heat load throughout the dermis produces an increase in pain. Most patients complain of the pain from the 1,064 YAG laser treatments more than anything else.

The pain factor is also very evident at 1.32 and 1.45 microns as well. Again, this is true because of the very large target that we are dealing with in the form of water. The bulk heating of the water, in and around a specific target, causes heating of the surrounding nerves and an increase in resultant pain.

Melanin-containing targets

Because the melanin absorption curve has a very gradual slope, there is no single choice for an optimal wavelength. Devices that produce a significant portion of their output energy in the "blue or green/yellow" portion of the spectrum certainly should produce better treatment results than long wavelength systems.

Again, as above, the ***AC*** differences between the short and long wavelength regions clearly favor a short wavelength device to more selectively remove epidermal pigmented lesions. The use of a long wavelength device, as with vascular treatments, has a higher risk factor because the low ***AC*** means that more energy is needed to get any result at all.

Water-containing targets

Because water is such a large target as a percentage of any other chromophore, the lower the ***AC***, the

more energy is generally needed to produce a result. In other words, the bulk heating of tissue is the general rule when water is the chromophore, because water is not selectively located as a single target.

As mentioned above, the ***AC*** for water is virtually non-existent below 800 nm and remains low compared to the above-discussed chromophores. Therefore, long wavelength devices are necessary to produce any absorption at all. But because the ***AC*** is so low, a large amount of energy is needed to produce an effect such as heating the dermis to generate a response by fibroblasts. This larger deposition of energy also heats nerve endings and therefore, in many cases, creates excessive pain.

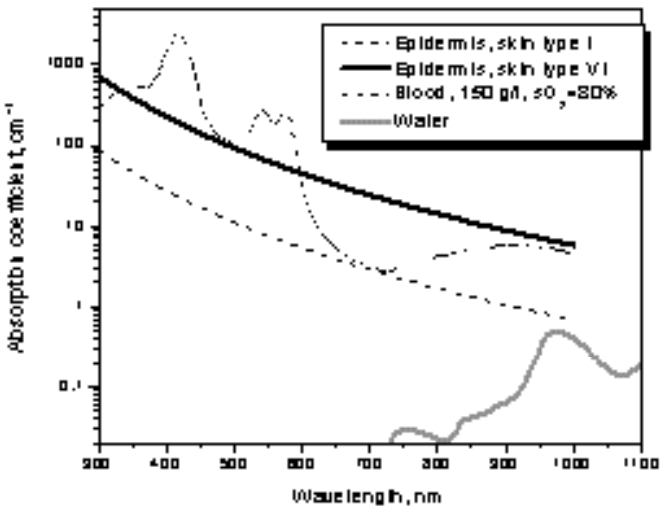

Fig. 2. Absorption spectra of relevant tissues and water.

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