The biophysics of photothermal treatments with lasers and intense pulsed light systems

Lasers and intense pulsed lights are commonly used for many skin applications today. An understanding of the basic biophysics is essential to achieve good clinical outcomes. Yet, the author's training experiences demonstrate that many users do not have a good grasp of some of these concepts. In this article, Mike Murphy will address these issues, and the most important parameters that need to be considered when treating the skin with high-energy devices will be identified

How light interacts with skin is actually very complicated (Jacques, 2013; Lister and Wright, 2017), and it depends on the wavelength (colour) of the light, energy, delivery time, spot diameter, repetition rate, skin thickness, contents and absorption characteristics. Reactions in absorbing targets range from a very subtle chemical reaction inside cells, to thermal reactions where proteins denature and physical disruptive processes that tear apart tissues or other targets (Baranoski and Krishnaswamy, 2004).

Possessing a good understanding of these processes is critical in achieving good clinical results. Many laser operators achieve 'adequate' results, simply because they do not fully understand what they are trying to do in the skin with the technology that is available.

Even with a good understanding, many laser operators are unsure how to set up the correct parameters, such as fluence, pulse width and spot size, when tackling skin conditions.

Light energy and the skin

There are many processes—optical and thermal—that may occur as light penetrates deep into the skin.

However, before continuing, it should be considered why light is fired at the skin in the first place. Well, light is a form of energy. When something in the skin is targeted, it is usually to change or alter it in some way. Patients may wish for some unwanted tissue (or another target, such as tattoo ink) to be destroyed, or they may want to enhance something.

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Usually, this means that it should be heated up in a controlled manner. When light energy is absorbed by something in the skin, the energy is mostly converted into heat energy (Mckenzie, 1990). So, in essence, light is being used to transfer energy into the targets in the skin in a safe and controlled fashion.

The journey of light in the skin

So, what happens to the light as it makes its journey into the skin?

Firstly, some of the light that hits the skin surface is reflected back. These are called Fresnel reflections, and may account for up to 5–7% of all light hitting the skin surface.

Secondly, as soon the light enters the stratum corneum (topmost skin layer), it begins to scatter. This can be thought of as photons of light bouncing off atoms and molecules. Consequently, the photons can move in many directions, including back out of the skin, which is known as back-scattering. At the same time, the wavelength of the light changes by shortening. This is due to the change in the refractive index between the air and the skin.

Next, the light enters the epidermis. This layer is around 0.06–0.1 mm thick and comprises of several layers of different cell types. It takes around 0.3 picoseconds for the light to travel through these layers (0.3 trillionths of a second). The light will encounter some melanin granules in this part of the skin. Depending on the colour of the light (wavelength), some will be absorbed by this melanin, which will raise its temperature.

The remaining light enters the basal layer, which is where most of the melanocytes and melanin granules are found (in non-black skin). As above, some of the light energy will be absorbed by the melanin in this layer, raising its temperature. This layer is only around 10 microns thick (0.01 mm), which can cause problems. If there is a lot of absorption of the light energy, this layer can become very hot. Since it is so

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Many laser and intense pulsed light treatment problems are caused by excessive heating of the basal layer

thin, it will lose its heat very rapidly into the epidermal layer above and the upper dermis below. This is where blisters are usually formed, due to excess heating.

Most skin temperature and pain receptors are near the basal layer (both above and below), which explains why such treatments can be painful. Once the local temperature exceeds 45°C, pain is felt instead of heat.

The dermis

Many laser and intense pulsed light (IPL) treatment problems are caused by excessive heating of this basal layer, simply due to absorption in the melanin. Surface skin cooling is essential to reduce the damaging effects of this heating. Proper cooling will greatly reduce any likelihood of skin damage by drawing out any excess heat energy from this layer. It will also make the treatments more comfortable.

Any light that is not absorbed in the basal layer may then propagate into the dermis below. By this stage, there may be anything between 70–90% of the original light energy left, depending on the amount of melanin in the basal and epidermal layers, and epidermal back-scattering (Murphy, 2020). This layer can be between 3–5 mm thick, depending on the body area and ethnicity of the patient.

Now, the interesting thing about the dermis is that it is a highly scattering medium—much more than the epidermis. So, any light entering the dermis will bounce around excessively. This has two very important effects:

- Firstly, as the light progresses into the dermis, it spreads out, due to scattering. In other words, the beam diameter increases, thereby reducing the fluence (the fluence is the energy divided by the spot size area, measured in Joules/cm^2). This can significantly affect the outcome of any treatment
- Secondly, a proportion of this scattered light may be turned through 180°, which may cause it to leave the skin completely, thereby reducing the total amount of energy left for any treatment.

Scattering in the dermis is hugely significant in many laser and IPL treatments (Jacques, 2013; Lister and Wright, 2017). It can easily reduce the effectiveness of treatment, simply through loss of light energy and reduced fluences.

The dermis also contains many potential absorbing sites: haemoglobin, tissue water, melanin, keratin and bilirubin, etc. Consequently, much of the light energy will be absorbed in this layer. All of these absorptions will raise the temperature of those sites.

It is a simple fact of physics that many sites within the dermis will heat up, regardless of the chosen wavelength.

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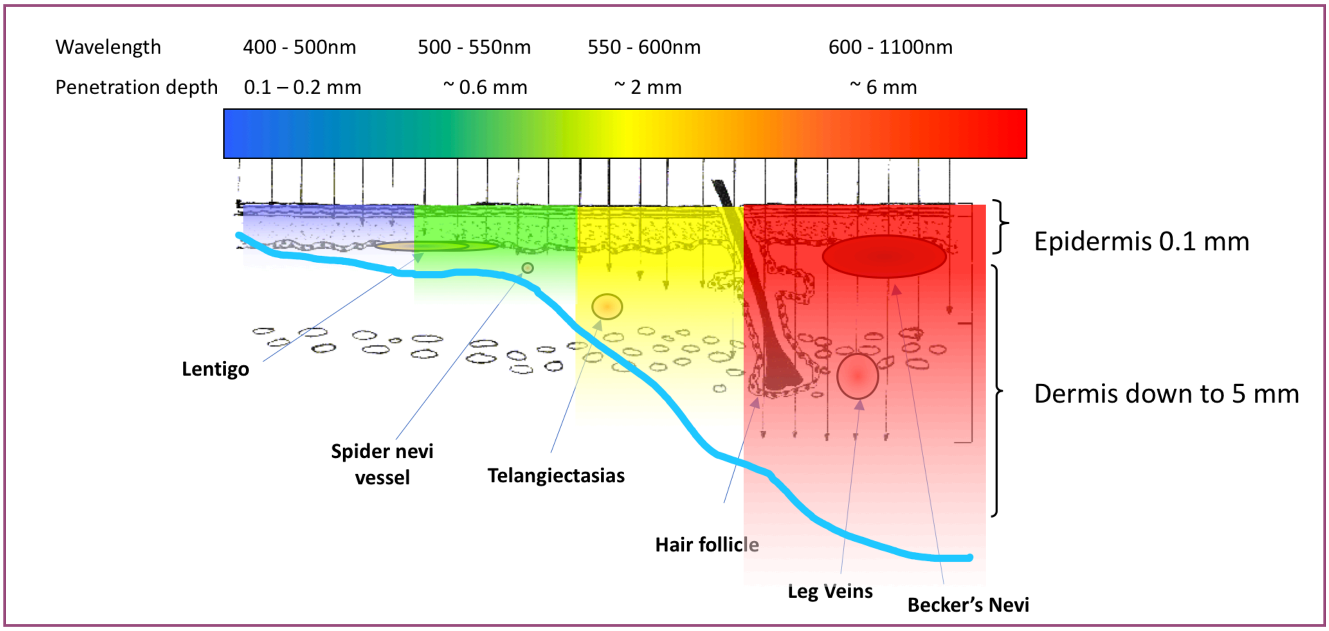

Light penetration in the skin

The heating of some absorption sites can be maximised by carefully choosing the wavelength of the device, but there will always be unintended absorption in adjacent areas.

If the wavelength is chosen properly, then the temperature of the intended targets can be raised specifically, compared with the surroundings. This is the basic principle of selective photothermolysis—a theory which has proved to be very useful in light-skin therapies for nearly 40 years (Anderson and Parrish, 1981; Altshuler et al, 2001; Murphy and Torstensson, 2013).

If some of the light gets through the dermis without being absorbed, then it may continue its journey to deeper layers, such as the fatty tissues. By this point, the energy will be very low compared with the surface value. This is known as transmission through the dermis.

An interesting fact about laser light penetrating the skin is that it cannot be regarded as 'laser' light as soon as it enters the skin. Scattering causes it to lose its directionality almost immediately, and it also loses its coherence. These are two of the main defining features of laser light, and the third is its monochromaticity (single wavelength/colour).

If the scattering events in the skin are 'elastic'—meaning that the photons do not lose any energy in each event—then the scattered light will retain the original wavelength. So, while the light entering the skin may be 'laser', it rapidly loses two of its main features, meaning that it cannot be considered 'laser light' once it is in the skin.

As mentioned above, light undergoes a series of processes when it is in the skin. Much of it may be lost through back-scattering, unwanted absorption or transmission. In fact, calculations show that less than 0.5–2% of the light energy used for hair removal is absorbed by hair follicles in the dermis. This means that the remaining 98–99.5% may be lost to back-scattering or unintended absorptions, leading to a general heating of the dermis and epidermis. This explains why skin cooling is so critical in all photo-thermal treatments.

Choosing the correct laser and intense pulsed light parameters

Choosing the correct parameters for IPL removal of hair (or blood vessels or pigmentation) can be difficult and cannot be fully covered in this article. However, factors that are important to consider will be identified.

First, what are the critical parameters? Many laser and IPL systems allow a number of parameters to be selected, including the wavelength, fluence, pulse width, spot size and skin cooling (*Table 1*) (Babilas et al, 2020; Barikbin et al, 2010; Adamic et al, 2007). However, in the author's experience, most laser and IPL users do not fully understand how to select these properly, particularly when faced with certain skin conditions.

Considerations

If all the parameters that are detailed in *Table 1* are properly selected, then the desired result should always be achieved, without damaging the surrounding tissues. Knowing how to choose the best parameters for any given situation is down to training and experience. Unfortunately, the author's experience is that most practitioners are not adequately trained.

Other important issues that must be considered when treating the skin with lasers and IPLs include leaving appropriate time between repeat sessions (which depends strongly on the skin repair processes), properly diagnosing skin conditions and laser and IPL calibration (many systems do not output what they claim on the screens).

Table 1: Laser treatment fundamentals	
Wavelength	The wavelength must be chosen according to two important criteria: first, the wavelength must be preferentially absorbed by the target (significantly more than by the surroundings); and second, the wavelength must be able to penetrate the skin sufficiently and with enough energy to do the task in hand
Fluence	Fluence is the energy per unit area (in J/cm^2). This can be thought of as the concentration of light energy into a spot. It determines the temperature rise in the target tissues, and also in the surrounding tissues. Too high a fluence will cause unwanted damage, while too a low a value will not achieve the end result
Pulse width	The pulse width (also known as the pulse duration or pulse length) is how long the energy is applied for. It is a critical parameter, because it determines whether the desired clinical end point will be achieved
Spot size	This may seem obvious, but it is not. Contrary to popular misconception, larger spot diameters result in a deeper penetration of light energy, compared to smaller sizes. So, to target particularly deep tissues, as large a spot size as possible must always be used, while maintaining the required fluence
Cooling	When sending light energy into the skin, a thermal response (in photothermal treatments) is deliberately being created. This means that excess heat is being generated in the tissues. This is where problems begin, and it must be mitigated against by good surface cooling. Too much heat will result in too much tissue damage and scarring. A balance should always be considered—the more energy that is applied, the more cooling must also be applied. This not only reduces the pain that is felt by the patient, but it also reduces the risk of scarring

Conclusion

A good understanding of the considerations detailed in this article will greatly assist in achieving good clinical results. Many treatments go wrong, simply because of a poor understanding of the condition or the technology. Laser and IPL treatments can be quite complex, and obtaining good, consistent results can be difficult. However, it is much more difficult if the basics are not properly understood.

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