# Illumination Geometry: The Importance of Laser Beam Spatial Characteristics

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BACKGROUND. Laser hair removal is becoming an increasingly popular alternative to traditional methods such as shaving, waxing, depilatory creams, or electrolysis. Numerous laser systems are currently available offering different methods of illuminating the treatment area. The fluence distribution within the tissue and, thus, the treatment efficacy depends upon the illumination geometry, namely the index matching at the skin surface, the incident spot size, and the energy distribution within the incident beam.

OBJECTIVE. To analyze and discuss the various aspects of illumination geometry in the context of laser hair removal.

METHODS. Detailed calculations of the influence of each aspect on the energy distribution during the treatment pulse were performed.

CONCLUSION. Calculations using typical skin parameters for wavelengths of 650–1100 nm show that matching of the index of refraction at the skin surface by illumination of the treatment area through sapphire in contact with the skin, for example, alone (i.e. aside from the beneficial heat-sinking effects) can reduce the epidermal heating up to 30% by minimizing the amount of internally reflected photons at the skin surface. Thus, by providing favorable index matching at the skin surface, sapphire contact enables the safe use of higher, more effective fluence levels.

The calculations also show that a 10-mm diameter spot size (or 9-mm square) produces a fluence level at target depths of 1–3 mm equal to 73–88% (depending on depth) of the fluence level at the same depths produced by an infinitely wide beam of equal incident fluence. This means that little additional penetration is achieved with larger spot sizes. In addition, most commercial laser hair removal systems that provide larger spot sizes (>14 mm in diameter) are unable to produce adequate fluence at the larger beam sizes to achieve the same level of efficacy of systems with 8–14 mm diameter beams. In contrast, a 5-mm diameter spot size produces a fluence level at target depths of 1–3 mm of only 37–52% (depending on depth) that of an infinitely wide beam of equal incident fluence. Because of the epidermal heating resulting from the relatively high fluence level at the skin surface, the penetration of smaller diameter beams can not be made to match that of broader beams by simply increasing the incident fluence. Thus, laser hair removal systems that provide smaller spot sizes (<8 mm in diameter) may be unable to safely produce the desired therapeutic effect.

Calculations using typical skin parameters for wavelengths of 650–1100 nm show that, for equivalent epidermal heating, up to 54% higher fluence can be applied using a beam with a flat energy distribution profile versus a gaussian profile, resulting in significantly deeper and broader penetration of the beam. For this reason, a laser hair removal systems with a predominantly flat beam profile will be more effective and induce fewer complications than a laser with a largely gaussian profile (i.e. with a central "hot spot").

LASER HAIR REMOVAL is becoming an increasingly popular alternative to traditional methods such as shaving, waxing, depilatory creams, or electrolysis. With a global device market estimated at approximately $200 million per year, laser hair removal is currently by far the largest opportunity in aesthetic lasers. Consequently, numerous manufacturers are now producing laser and non-laser based systems aimed specifically at serving this market.

In order to compare the relative merits of each of these systems, it is important to consider the underlying principles governing the treatment. This technical note, the second of a series discussing the important aspects of laser hair removal, focusses on illumination geometry and its effect on the fluence distribution within the tissue.

## *Photothermal Epilation*

Hair removal using lasers is achieved by selectively depositing energy into the hair shaft and pigmented follicular epithelium, such that the rapid rise in temperature and subsequent heat transfer to adjacent tissue causes local thermal necrosis of the follicles' regenerative structures. For time periods characteristic of photothermal epilation, the threshold temperature for thermal necrosis is on the order of 70°C [1]. The selective deposition of energy is accomplished by illuminating the treatment area with sufficient fluence (energy per unit area) at a wavelength that is preferentially absorbed by the endogenous melanin of the target hair shaft and pigmented follicular epithelium, but not by the surrounding tissue. In order to localize the thermal effects, the fluence is typically delivered within a time less than or comparable to the thermal relaxation time of the target structure. The process of selective absorption leading to local thermal necrosis is known as selective photothermolysis [2].

As one might expect, the effectiveness of the treatment (i.e. the percentage of follicles permanently damaged) scales with the amount of fluence used. In a study of 92 patients (45 males and 47 females of varying hair color and skin type) treated with a Lumenis LightSheer™ Diode Laser System at the Massachusetts General Hospital in Boston and the Laser and Skin Surgery Center of New York in New York City, 32.5% hair reduction was observed at 12 months following a single treatment using a fluence of 40 J/cm$^2$ and a pulsewidth of 20 ms, while 25.9% was observed for settings of 20 J/cm$^2$ and 10 ms [3]. Interestingly, multiple pulses (3×) using the same fluence levels did not produce measurably better results.

The above results indicate that the higher the peak temperature reached by the target structures, the more effective the treatment. The peak target temperature is directly proportional to the fluence level at the 1–3 mm target depth. What is not obvious is that, for a given wavelength, the fluence distribution within the tissue depends upon the illumination geometry, namely the *index matching* at the skin surface, the incident *spot size*, and the *energy distribution* within the incident beam. Each of these contributing factors are examined individually in what follows.

## Illumination Geometry

In order to understand the importance of each aspect of illumination geometry, it is helpful to schematize

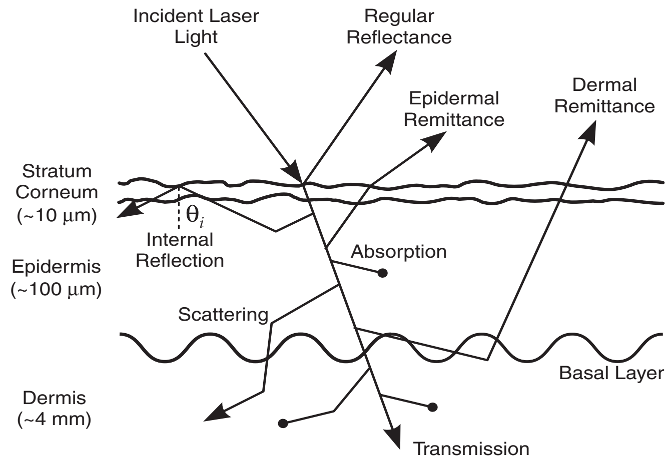


**Figure 1.** A schematic representation of laser-tissue interaction [4].

the optical pathways in skin, as shown in Fig. 1. As the skin is illuminated, a small fraction of the incident radiation is reflected from the skin surface as a result of the change in refractive index. For normally incident radiation, this *regular reflectance* is on the order of 4–7% [4]. The remaining 93–96% of the radiation entering the skin is either *scattered* or *absorbed*. The type of scattering referred to here is an elastic interaction between a photon and matter in which only the direction of propagation of the photon is altered. Elastic scattering results from inhomogeneities in the skin's index of refraction corresponding to the physical boundaries of anatomical features, such as collagen fibers, and is characterized by the wavelength-dependent scattering coefficient, $\mu_s(\lambda)$ (cm$^{-1}$).

Once absorbed, the radiation is predominantly converted nonradiatively (i.e. without luminescence) into heat by the absorbing chromophore molecules. When there are pigmented tissue structures present that are more strongly absorbing at the laser wavelength than the surrounding tissue, e.g. hair shafts, the photons propagating randomly within the tissue will tend to be absorbed selectively by the pigmented structures. Thus, given enough deposited energy, *selective photothermolysis* of the pigmented structures will occur. Absorption by the pigmented structures or the surrounding tissue is characterized by their respective wavelength-dependent absorption coefficients, $\mu_a(\lambda)$ ($cm^{-1}$).

The penetration of light into a scattering and absorbing medium is dependent on both $\mu_s$ and $\mu_a$. However, the predominant chromophore in the dermal tissue is hemoglobin, which is only weakly absorbing in the wavelength range of interest (650–1100 nm). For example, for a uniformly distributed 1.0% volume fraction of blood in the dermis, $\mu_a$ is equal to approximately 0.3 $cm^{-1}$, whereas $\mu_s$ is equal to approximately 40 $cm^{-1}$. Thus, the penetration of 650–1100 nm light in typical skin is almost entirely determined by the disproportionately high scattering.

## *Index Matching*

Because skin is a predominantly scattering medium, incident photons penetrating the skin will most likely experience multiple scattering events before being absorbed or backscattered out of the skin. This causes the spatial distribution of the radiation within the skin to spread and become rapidly isotropic (i.e. uniformly diffuse). Both the loss of backscattered photons and the spreading of the beam reduce the intensity of the radiation as it penetrates into the tissue. However, in a highly scattering medium such as skin, a given photon experiencing multiple scattering events can contribute to the fluence rate at many locations or multiple times at one location before being absorbed or backscattered out of the skin. Thus, the fluence rate within the skin may build up to be several times that of the incident beam [5]. This effect is enhanced somewhat by the internal reflection of photons at the skin surface when the index of refraction of the external medium, $n_e$, is less than that of the skin, $n_s$ (~1.33). Photons incident on such a boundary from within the tissue with an incident angle $\theta_i$ equal to or greater than the critical angle $\theta_c = \sin^{-1}(n_s/n_e)$ will be internally reflected, thereby increasing the local fluence rate, especially near the skin surface.

The results from a Monte Carlo simulation [6,7] of the penetration of radiation along the centerline of a 10-mm beam applied through external mediums of air ($n_e = 1.0$) and sapphire ($n_e = 1.76$) for typical skin parameters are shown in Fig. 2. The skin surface has

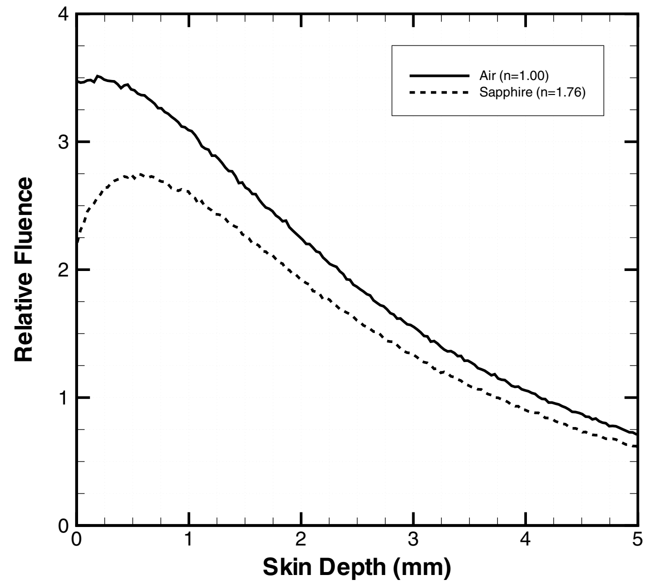


**Figure 2.** Influence of a mismatch in index of refraction at the skin surface. The solid and dashed curves represent the relative fluence distribution for 10-mm diameter beams of equal incident fluence applied through external mediums of air ($n_e$=1.00) and sapphire ($n_e$=1.76), respectively. The results were obtained by a Monte Carlo simulation [7].

been assumed to be smooth, and back reflections from the opposing sapphire-air interface have been neglected. In practice, however, some of the photons scattered out of the skin and into the sapphire will be reflected back into the skin (i.e. recycled) by the opposing sapphire-air interface. In addition, the actual coupling of photons into and out of the skin depends somewhat on the roughness of the skin surface. As a consequence, the curves representing the external mediums of air and sapphire would actually lie somewhere between the two shown.

As illustrated schematically in Fig. 1, internal reflection favors high-angle (relative to normal incidence) photons which propagate predominantly within a narrow region along the reflecting surface, thereby contributing in a biased fashion to the fluence rate within this region. As shown in Fig. 2, for typical skin parameters, the scattered photons reflected internally by the air-skin interface enhance the fluence level up to 55% at the surface and 45% at a depth of 60 μm compared to the same beam applied through a sapphire-skin interface. Beyond approximately 1 mm in depth, the enhancement becomes uniform and is equal to approximately 16%.

The buildup of fluence at the skin surface has important implications when attempting to protect the pigmented epidermis at a depth of 0–100 µm during treatment. Based on the above results, for equivalent target heating at depths of 1–3mm, matching of the index of refraction at the skin surface by illumination of the treatment area through sapphire in contact with the skin, for example, alone (i.e. aside from the beneficial heat-sinking effects) can reduce the epidermal heating up to 30% by minimizing the amount of internally reflected photons at the skin surface. Thus, by providing favorable index matching at the skin surface, sapphire contact enables the safe use of higher, more effective fluence levels.

## *Spot Size*

In a highly scattering medium such as skin, light diffusion at the edges of the beam causes spreading of the beam as it penetrates into the tissue. As a consequence, a larger incident beam results in a higher cumulative energy density at a given depth. This effect is illustrated schematically in Fig. 3, where the shaded region demarcates the extent of the higher fluence area as indicated by the higher density of light rays. Fig. 4 shows actual calculated fluence profiles for flat 3-mm and 10-mm diameter beams of equal fluence obtained by Monte Carlo simulation [8] using typical skin parameters for wavelengths of 650-1100nm. The red region represents the extent of the illumination zone, which is arbitrarily defined as the area in which the fluence level is equal to or higher than the incident fluence. There is considerable lateral spreading of the smaller, 3-mm diameter beam as the photons are scattered away from the beam path, weakening the beam and limiting its penetration. With the larger 10-mm diameter beam, the probability of the photons being scattered out of the beam path is somewhat lower. Thus, the concentration of light along the beam path of a relatively large incident

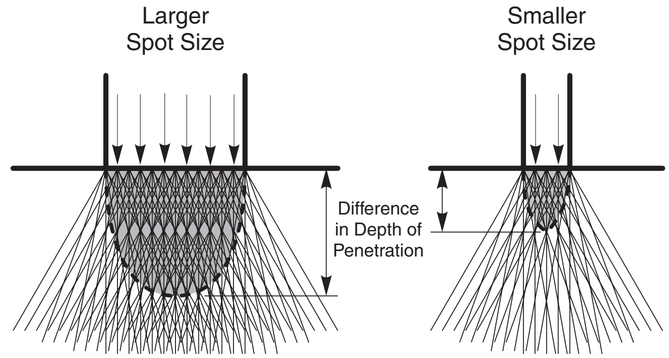


**Figure 3.** A schematic representation of spot-size-dependent depth of penetration.

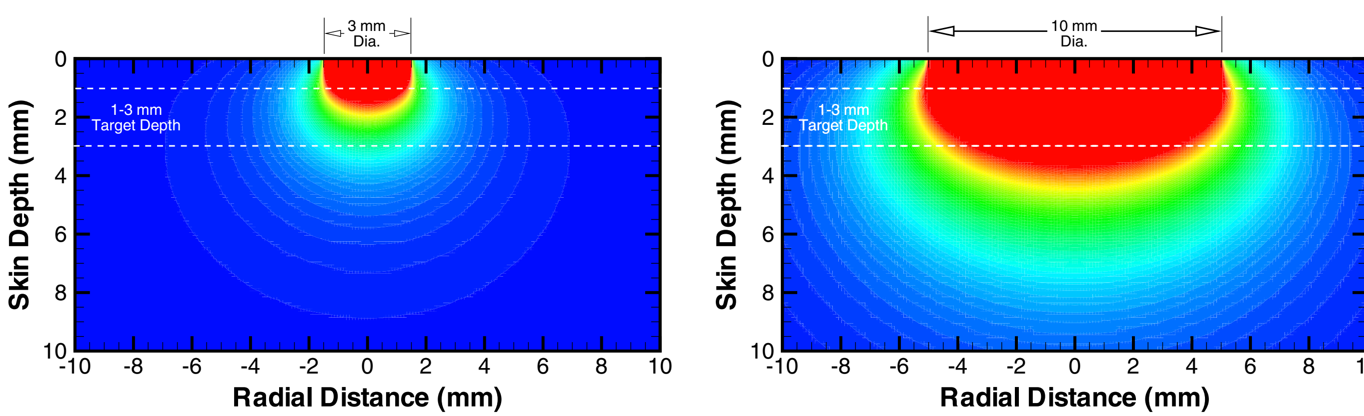


**Figure 4.** Calculated fluence profiles for flat 3-mm and 10-mm diameter beams of equal incident fluence obtained by Monte Carlo simulation using typical skin parameters for wavelengths of 650–1100nm [8]. The red region represents the extent of the illumination zone, which is arbitrarily defined as the area in which the fluence level is equal to or higher than the incident fluence.

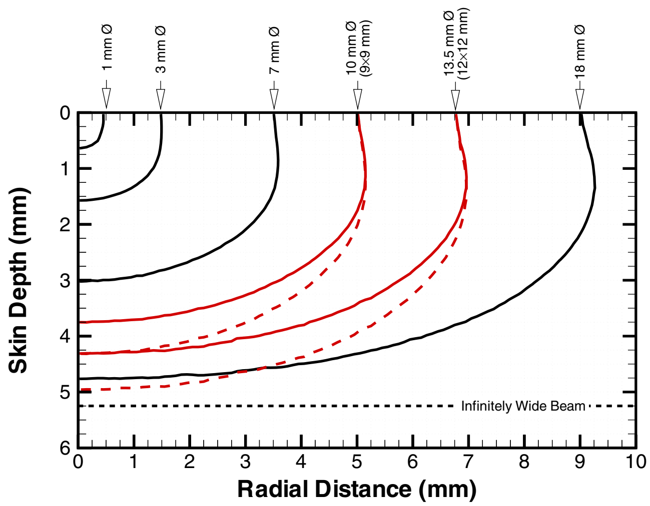


**Figure 5.** Effect of laser beam diameter on penetration. Calculated isofluence contours obtained by Monte Carlo simulation using typical skin parameters [9] for beams of increasing diameter, but equal incident fluence. The contours represent the extent of the illumination zone, which is arbitrarily defined as the area in which the fluence level is equal to or higher than the incident fluence. The dashed lines for the 9×9-mm and 12×12-mm beams indicate the estimated increase in the effective depth of penetration as a result of skin compression.

beam will remain relatively high resulting in deeper penetration into the tissue. Note that for round or square beams, the penetration of the light into the tissue is primarily a function of the beam area. Thus, the fluence distribution of a 9-mm square beam, for example, would be comparable to that of a 10-mm round beam. In practice, square beams are more desirable because they are easier to position and require minimal to no beam overlap in order to completely cover the treatment area.

The effect of scattering on the depth of penetration is illustrated further in Fig. 5, which shows the calculated isofluence contours obtained by Monte Carlo simulation using typical skin parameters [9] for flat beams of increasing diameter, but equal incident fluence. The curves represent the extent of the illumination zone, which is arbitrarily defined as the area in which the fluence level is equal to or higher than the incident fluence. As can be seen, once the beam approaches sufficient size, the photons scattered from the edges are absorbed before they reach the central axis, and the fluence profile takes on the shape characteristic of an infinitely wide beam. As this limit is reached, the penetration of the beam reaches a maximum, and the illumination zone simply becomes wider with additional increases in beam size.

Clearly, the larger the spot size, the larger the area that can be treated with each pulse. However, it should be noted that some hair removal systems offer relatively large spot sizes (>14 mm in diameter) in the interest of claiming high coverage rates. But, because the energy output of the laser is limited, the maximum fluence available and, thus, efficacy falls precipitously with increasing beam area.

The dashed lines for the 9×9-mm and 12×12-mm beams in Fig. 5 indicate the estimated increase in the effective depth of penetration as a result of skin compression when using sapphire contact, for example. Compressing the skin squeezes the blood, a competing chromophore, out of the treatment area and forces the hair follicles to lie down bringing the roots closer to the surface. As a result, the effective penetration of the beam is improved up to 15%.

To further illustrate the influence of beam diameter on the fluence distribution and, thus, the hair removal efficacy, Fig. 6 shows the calculated fluence levels (within a 1–3 mm deep target zone) of beams

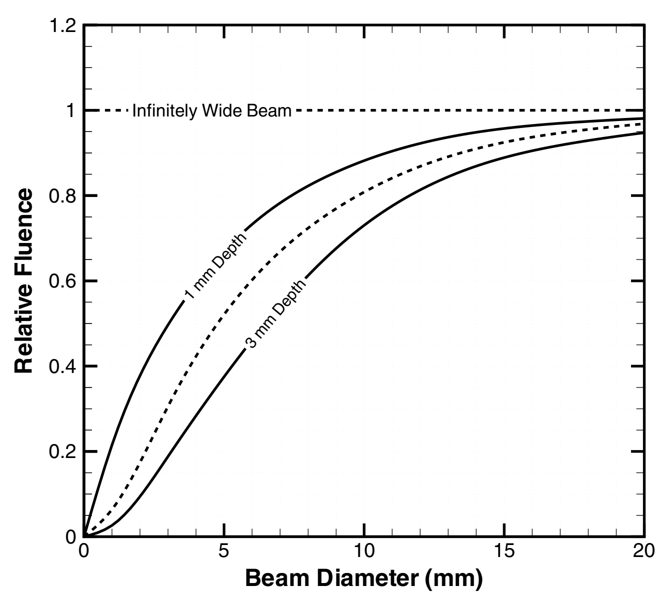


**Figure 6.** Calculated fluence levels (within a 1–3 mm deep target zone) of beams up to 20 mm in diameter relative to that of an infinitely wide beam of equal fluence.

up to 20 mm in diameter relative to that of an infinitely wide beam of equal fluence. The results indicate that a 10-mm diameter beam (or 9-mm square), for example, would produce a fluence level equal to 73–88% (depending on depth) that of an infinitely wide beam of equal incident fluence. This means that little additional penetration is achieved with larger spot sizes. In contrast, a 5-mm diameter spot size produces a fluence level at target depths of 1–3mm of only 37–52% (depending on depth) that of an infinitely wide beam of equal incident fluence. However, because of the epidermal heating resulting from the relatively high fluence level at the skin surface, the penetration of smaller diameter beams can not be made to match that of broader beams by simply increasing the incident fluence. Thus, laser hair removal systems that provide smaller spot sizes (<8 mm in diameter) may be unable to safely produce the desired therapeutic effect.

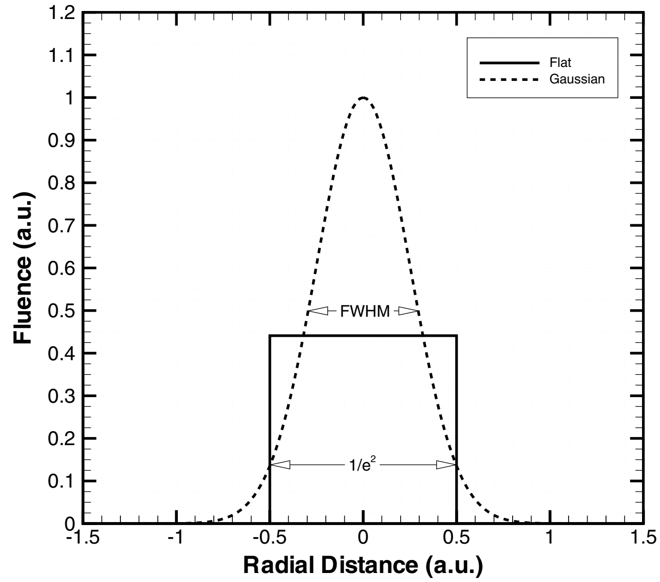


**Figure 7.** Cross-sections of the relative energy distribution profiles for flat and gaussian beams of equal diameter and fluence.

## *Energy Distribution*

As one might expect, the energy distribution within the incident beam also affects the energy distribution in the skin. Hair removal laser beams typically have intensity distribution profiles ranging in shape from flat to gaussian. Fig. 7 shows cross-sections of the relative energy distribution profiles for flat and gaussian beams of equal diameter and fluence. As illustrated in Fig. 7, the energy of a flat beam is evenly distributed over its entire area. On the other hand, the intensity of a gaussian beam peaks at its center and decreases exponentially with radial distance. The width of a gaussian beam is typically specified as either the full width at half maximum (FWHM) or the $1/e^2$ (13.5% of peak intensity) points.

The results from a calculation of the epidermal temperature [8] at a basal layer depth of 60μm resulting from the illumination of the skin by 10-mm diameter flat and gaussian beams of equal incident fluence are shown in Fig. 8. The epidermis was assumed to have been precooled to 15 °C prior to the laser pulse. As can be seen, the flat beam with its uniform intensity distribution produces a 35% lower temperature rise at a depth of 60 μm than the gaussian beam. Although not included in the above calculation, heat-sinking of the epidermis through contact with a chilled sapphire window during illumination with the flat laser pulse would, in fact, make the difference in epidermal heating even more dramatic.

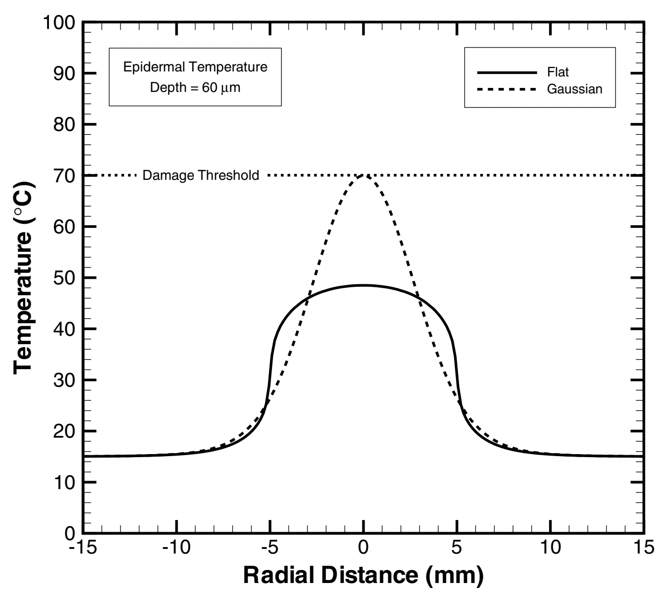


**Figure 8.** Calculated epidermal temperature profiles at a basal layer depth of 60μm resulting from the illumination of the skin by 10-mm diameter flat and gaussian beams of equal incident fluence [8].

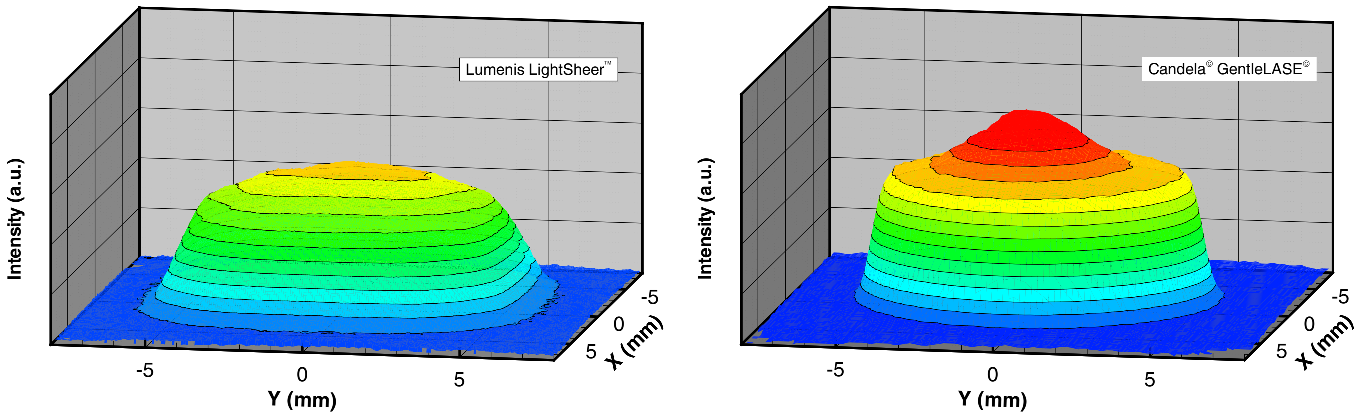


**Figure 9.** Measured energy distributions at the skin surface plane produced by 9×9-mm Lumenis LightSheer Diode Laser and 10-mm diameter Candela GentleLASE alexandrite laser hair removal systems. The homogenization and condensation of the direct-diode radiation in the Lumenis LightSheer's ChillTip™ handpiece results in a predominantly flat intensity profile ensuring relatively deep, uniform, and broad penetration. In contrast, the fiber-coupled design of the Candela GentleLASE produces a substantial "hot spot" in the center of the beam, which increases the risk of epidermal damage and/or limits the amount of fluence that can be used.

Interestingly, the two beams are virtually indistinguishable and equally effective at a target depth of 3 mm because of the rapid diffusion of the beam via scattering. However, as previously discussed, the maximum amount of fluence (for a given pulse duration) that can be safely delivered is limited by the heating of the epidermis. Thus, for equivalent epidermal heating, 54% higher fluence can be applied using a beam with a flat energy distribution profile versus a gaussian profile, resulting in significantly deeper and broader penetration of the beam.

Fig. 9 shows actual measured energy distributions (obtained using a SensorPhysics™ LaserTest LS-2000 Beam Profiler) at the skin surface plane produced by a 9×9-mm Lumenis LightSheer Diode Laser and a 10-mm diameter Candela® GentleLASE® alexandrite laser. The homogenization and condensation of the direct-diode radiation in the Lumenis LightSheer's ChillTip™ handpiece results in a predominantly flat intensity profile ensuring relatively deep, uniform, and broad penetration. In contrast, the fiber-coupled design of the Candela GentleLASE produces a substantial "hot spot" in the center of the beam. The intensity of this particular "hot spot" is approximately 50% greater than the general plateau of the beam. Such a "hot spot" increases considerably the risk of epidermal damage and limits the amount of fluence that can be safely used. For this reason, a laser hair removal system with a predominantly flat beam profile will be more effective and induce fewer complications than a laser with a largely gaussian profile (i.e. with a substantial "hot spot").

## Conclusions

The fluence distribution within the tissue and, thus, the treatment efficacy depends upon the illumination geometry, namely the index matching at the skin surface, the incident spot size, and the energy distribution within the incident beam. Calculations using typical skin parameters for wavelengths of 650–1100 nm show that matching of the index of refraction at the skin surface by illumination of the treatment area through sapphire in contact with the skin, for example, can alone (i.e. aside from the beneficial heat-sinking effects) reduce the epidermal heating up to 30% (depending on depth) by minimizing the amount of internally reflected photons at the skin surface. This means that, for equivalent epidermal heating, sapphire contact enables the safe use of higher, more effective fluence levels.

The calculations also show that a 10-mm diameter spot size (or 9-mm square) produces a fluence level at target depths of 1–3 mm equal to 73–88% (depending on depth) of the fluence level at the same depths produced by an infinitely wide beam of equal incident fluence. This means that little additional penetration is achieved with larger spot sizes. In fact, most laser hair removal systems that provide larger spot sizes (>14 mm in diameter) are unable to produce adequate fluence at the larger beam sizes to achieve the same level of efficacy of systems with 8–14 mm diameter beams. In contrast, a 5-mm diameter spot size produces a fluence level at target depths of 1–3 mm of only 37–52% (depending on depth) that of an infinitely wide beam of equal incident fluence. However, because of the epidermal heating resulting from the relatively high fluence level at the skin surface, the penetration of smaller diameter beams can not be made to match that of broader beams by simply increasing the incident fluence. Thus, laser hair removal systems that provide smaller spot sizes (<8 mm in diameter) may be unable to safely produce the desired therapeutic effect.

The energy distribution within the incident beam has important implications as to the level of fluence that can be safely used. Calculations using typical skin parameters for wavelengths of 650–1100 nm show that, for equivalent epidermal heating, up to 54% higher fluence can be applied using a beam with a flat energy distribution profile versus a gaussian profile, resulting in significantly deeper and broader penetration of the beam. For this reason, a laser hair removal system with a predominantly flat beam profile will be more effective and induce fewer complications than a laser with a largely gaussian profile (i.e. with a central "hot spot").

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7. Calculation assumed a smooth skin surface, negligible back reflections from the opposing sapphire-air interface and $\mu_a = 0.3\,cm^{-1}$, $\mu_s = 40\,cm^{-1}$, $g = 0.8$.
8. Calculation assumed a smooth skin surface, an air interface and $\mu_a = 0.3\,cm^{-1}$, $\mu_s = 40\,cm^{-1}$, $g = 0.8$. Effects attributable to skin compression were not considered.
9. Calculation assumed a smooth skin surface, an air interface and $\mu_a = 0.3\,cm^{-1}$, $\mu_s = 40\,cm^{-1}$, $g = 0.8$. Estimated 15% increase in depth of penetration as a result of skin compression.


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