Hair Removal With Long Pulsed Diode Lasers: A Comparison Between Two Systems With Different Pulse Structures

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Background and Objectives: The aim was to study hair removal efficacy, and possible side effects of two commercially available long pulsed diode lasers. The radiant exposure was selected to a value of 35 J/cm^2, which is frequently used in the clinic in accordance with manufacturer's recommendations.
Study Design/Materials and Methods: A prospective clinical study was performed on twenty-nine patients with hair color ranging from light brown to black on the upper lip. One half of the upper lip was randomly selected for treatment with the MedioStar® laser; the contralateral half of the lip was treated with the LightSheer® laser. Three treatments were performed at 6–8 week intervals. Percent hair reduction and acute- and long-term side effects were evaluated after treatment.
Results: The average hair reductions 6 months after the first treatment were 49% with the MedioStar® laser and 48% with the LightSheer® laser. No scarring or pigmentary change of the skin was observed after any of the treatments with either laser. However, differences in acute side effects such as degree of erythema and burned hairs were observed.
Conclusions: No statistically significant differences in hair removal efficacy were observed. These results agree with mathematical modeling, which also offers a method to estimate hair removal efficacy and adverse effects for a range of hair characteristics and laser parameters. Lasers Surg. Med. 32:399–404, 2003. © 2003 Wiley-Liss, Inc.

Key words: hair follicle destruction; optical absorption; heat diffusion

INTRODUCTION

There is an increasing demand for safe, effective, and low-cost methods of permanent hair removal. A variety of laser systems have been evaluated, but many studies are of limited value due to short clinical follow-up times. Permanency must be documented by clinical follow-up throughout the entire hair growth cycle (anagen to anagen phase) including, at the minimum, a 6-month period to compensate for the prolonged delay of hair regrowth induced by thermal injury to the follicle [1–7]. Based on anatomic location there is wide variability in the durations of anagen and telogen phases, as well as follicle depth [1]. Hence, care must be used when extrapolating results for a specific body region to other anatomical locations. Moreover, the durations of the anagen and telogen phases depend on patient age and hormonal cycle, which makes it very difficult to compare multiple laser systems on different groups of subjects.

Permanent hair removal requires that wavelength, pulse duration, spot size, and radiant exposure must be properly selected to induce adequate thermal damage to the entire follicle [6,8]. Simultaneously, the epidermis must be preserved to avoid scarring and dyspigmentation. Optimal laser treatment parameters have been proposed based on the analysis of light propagation in human skin, as well as the optical and thermal properties of the follicle and its adjacent structures [4,6]. In the case of brown and black hairs, where the target chromophore is eumelanin, long pulsed diode lasers at a wavelength of 800 nm have shown promising results [2]. The optimal pulse duration depends on physical dimensions of the hair follicle. Maximal selective thermal damage is obtained when the pulse duration permits heat to diffuse from the primary heat source, i.e., the melanin-containing follicle, through the outer root sheath and into the stem cells located in the bulge area [6]. In the case of terminal hair follicle bulbs with diameters of 200–300 μm, theoretical modeling has suggested that the pulse duration should be in the range of 40–100 milliseconds [7]. Moreover, longer pulses increase the threshold of epidermal damage when skin cooling is used in conjunction with laser irradiation. Laser beam diameter (spotsize) should be greater than 10 mm because optical scattering reduces light penetration of narrower beams into human skin [4,7]. The present study was primarily aimed to compare the hair removal efficacy of two long pulsed diode laser systems with different pulse structures. The clinical response was evaluated with respect to hair color,

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thickness, and density. Secondarily, the study investigated side effects such as burned hair, erythema, edema, and pain.

MATERIALS AND METHODS

Patients

After signing an informed consent, forty-one North-European females, aged 23–69 years, with Fitzpatrick skin types II–IV and hair color ranging from light brown to black on the upper lip were enrolled in the study. The average patient age was 48 ± 11 years. Three treatments using both long pulsed diode laser systems were performed at 6–8 week intervals. All treatments were completed by February 2002. Thirty-six patients completed three treatments. However only twenty-nine patients were available for final evaluation 6 months after their last treatment.

Laser Systems

The MedioStar HC Professional® diode laser (Asclepion-Meditec AG, Jena, Germany) uses a semiconductor diode at 810 nm wavelength with two separate variable duration pulses (up to 100 milliseconds), dependent on spot size and radiant exposure (incident fluence).

The laser was used in the PRO 1-mode with a 12 mm spot size and radiant exposure 35 J/cm^2. For this study, the total pulse consisted of two identical 45 milliseconds pulses separated by an interval of 40 milliseconds. The epidermis was cooled immediately before laser irradiation by placing a cold aluminum applicator plate onto the skin surface.

The LightSheer® diode laser (Coherent, Inc., Santa Clara, CA) system utilizes a semiconductor diode at a wavelength of 800 nm with a variable pulse duration of 5–30 milliseconds, adjustable radiant exposures of 5–60 J/cm^2, and spot size of 9×9 mm. For this study, the pulse duration and radiant exposure were 30 milliseconds and 35 J/cm^2, respectively. The epidermis was cooled before, during, and after laser irradiation by placing a sapphire window based cooling system (ChillTip®) set at 5°C onto the skin surface.

Treatment Protocol

After enrollment, the upper lip was photographed and shaved. Prior to treatment a transparent optical index-matching gel was applied to the skin surface. One half of the upper lip was randomly selected for treatment with the MedioStar® laser; the contralateral half was treated with the LightSheer® laser. For both lasers, pulses were overlapping by 10–20%. The laser hand pieces were placed onto the skin surface with moderate pressure in order to flatten the skin, empty cutaneous blood vessels and, most importantly, bring the targeted hair follicles closer to the skin surface.

Immediately after the first laser treatment, patients were evaluated for the presence of burned hair, erythema, edema, and pain according to the criteria described in Table 1. Hair counts were performed on 2 cm^2 areas on both sides of the upper lip before the first treatment, and 6 months after the third and final treatment. At the last follow-up visit 6 months after the final laser treatment, evaluation included photography and documentation of clinical response evaluation for long-term adverse effects.

TABLE 1. Criteria for Clinical Evaluation of Selected Side Effects

	Score			
	0	1	2	3
Percentage of burned hair	0	1–25	26–50	51–100
Erythema	Absent	Mild	Moderate	Severe
Edema	Absent	Mild	Moderate	Severe
Pain	Absent	Mild	Moderate	Severe

RESULTS

Hair Reduction

The clinical responses for all the 29 patients who completed the study protocol are listed in Table 2, which gives the number of patients in four percentage response groups. The average hair reductions were 49 ± 21 and $48 \pm 20\%$ (mean value $\pm$ standard deviation) for the MedioStar® and LightSheer® lasers, respectively. These results, which correspond to a P-value of $P = 0.68$, reveal no statistically significant difference in hair removal efficacy between the two lasers under study. The three best responders (10% of patients) obtained average hair reductions of 86 ± 4.9 and $85 \pm 5.4\%$, respectively, for the MedioStar® and LightSheer® lasers. These data also show no significant correlation between obtained result and hair density or hair thickness, i.e., $P > 0.05$. However, there is a marginally statistically significant better response for patients with dark brown hair as compared to patients with lighter brown hair, i.e., $P \sim 0.05$. The results are summarized in Table 3.

Side Effects

No scarring or pigmentary change of the skin was observed after treatment with either laser system. However, differences in the incidence of acute side effects such as presence of burned hairs and erythema were observed and summarized in the three last columns of Table 4. Burned hairs were present on 26 of the sites treated with the LightSheer® laser, as compared to only 4 treated with the MedioStar® ($P < 0.001$). The degree of lip erythema was greater with the LightSheer® laser, as compared to that

TABLE 2. Percent Hair Reduction by Treatment Site

	Number of treatment sites	
Hair reduction in %	MedioStar®	LightSheer®
0–25	2	4
26–49	13	12
50–74	10	10
≥75	4	3
Total number treatment sites	29	29

TABLE 3. Percentage Responses of Hair Removal by Hair Density, Color, and Thickness

Laser	Hair density <60/cm^2	Hair density ≥60/cm^2	Light brown to brown hair Fitzpatrick II–III	Dark brown to black hair Fitzpatrick III–IV	Fine to medium hair diameter	Larger than medium hair diameter
MedioStar®	55 ± 21	41 ± 16	45 ± 14	52 ± 25	49 ± 20	50 ± 21
LightSheer®	50 ± 24	47 ± 14	41 ± 19	53 ± 20	45 ± 26	50 ± 16

(Mean value ± standard deviation).

seen with the MedioStar® treatment ($P < 0.001$). However, it should be noted that this difference in erythema might not necessarily be due to the pulse structures, but rather the utilization of different cooling systems.

No statistically significant differences were observed in the level of pain during treatment, and the degree of edema after treatment was approximately the same with either laser, i.e., $P > 0.05$.

DISCUSSION

Modeling

The thermal distributions in and around a hair follicle during and after laser irradiation are shown in Figure 1. This figure is based on the exact solution of the heat diffusion equation for a uniformly heated sphere embedded in a medium with identical thermal properties (Eqn. A1). The thermal diffusivity and conductivity used are assumed to be the same for the follicle and perifollicular structures, i.e., $\chi = 1.2 \times 10^{-7}$ m^2/second and $\kappa = 0.4$ W/mK, respectively. Light depletion due to follicular absorption has been accounted for by introduction of an effective optical absorption coefficient corresponding to the average light absorbed over the entire follicle bulb (Eqn. A2).

The value for the optical absorption coefficient was estimated by determining the threshold for hair burning in free air; the threshold fluence for dark brown hair was determined at 19 J/cm^2. Assuming no heat loss from hair during laser irradiation, together with a carbonization temperature of 200°C, gives an estimate of $\mu_a \approx 3500$ m^{-1}. The corresponding value for light brown hair was found to be $\mu_a \approx 2200$ m^{-1}. An absorption coefficient $\mu_a = 3500$ m^{-1} is a comparatively low value when considering that values up to $\mu_a = 10000$ m^{-1} have been reported in the literature [6]. However, depletion of light within the follicle results in an effective absorption that is not linearly dependent on μ_a, e.g., the amount of light absorbed in a 200 μm diameter follicle bulb only increases by 90% for a threefold increase of $\mu_a$effective 3500–10000 m^{-1}. The corresponding increase for a 300 μm bulb is only 70%.

Figure 1a shows the temperature rise for a 30 milliseconds laser pulse of fluence 35 J/cm^2 at 800 nm wavelength; the maximum temperatures at the follicle center (distance = 0) and at the follicle cortex (distance = 150 μm) are 250 and 108°C, respectively. The temperature in the outer sheaths also increases after the laser pulse, as heat stored in the melanin containing inner region diffuses out. The damage threshold has been taken at 65°C [6], which is represented by the horizontal layer in the figure. The

TABLE 4. Scores (0–3) for Acute Side Effects as Burned Hair, Erythema, and Edema by Treatment Site

Laser	Score 0–3			
	Burned hair	Erythema	Edema	Pain
MedioStar®	0.1 ± 0.3	1.1 ± 0.7	0.4 ± 0.7	2.0 ± 0.7
LightSheer®	1.2 ± 1.0	1.9 ± 0.7	0.6 ± 0.7	1.9 ± 0.7
P-value	<0.001	<0.001	>0.05	>0.05

(Mean value ± standard deviation).

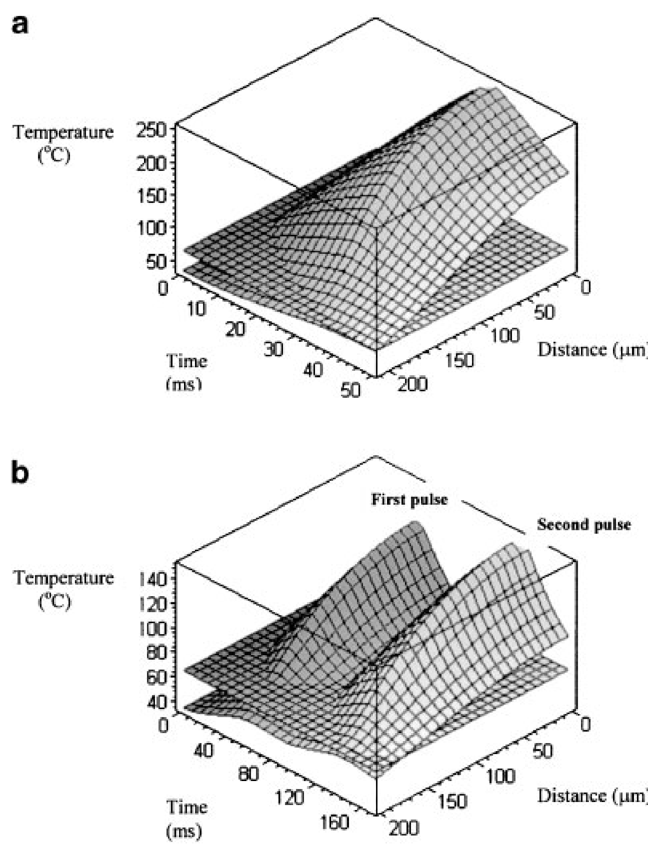

Fig. 1. Temperature rise (°C) vs. time (milliseconds) and distance (μm) from the center of a 300 μm diameter follicle. Fluence 35 J/cm^2; $\mu_a = 3500$ m^{-1}; ambient skin temperature 35°C. **a** (**upper**): Pulse duration 30 milliseconds. **b** (**lower**): Pulse duration 2 × 45 milliseconds separated by an interval of 40 milliseconds.

maximum zone of damage around the follicle is approximately 60 μm from the cortex, and this zone is reached 10–20 milliseconds after the end of the laser pulse.

The corresponding values for two identical pulses, each of 45 milliseconds duration separated by an interval of 40 milliseconds and fluence of 35 J/cm^2 at 810 nm wavelength, are shown in Figure 1b. There is no damage outside the follicle cortex after the first laser pulse. However, heat accumulates in the follicle as well as in the perifollicular tissues and the second pulse generates damage to a zone of approximately 40 μm from the cortex. This value is reached at 140 milliseconds, i.e., 10 milliseconds after the end of second laser pulse. The maximum temperatures at the center of the follicle and at the surface are 140 and 95°C, respectively.

In summary, the zone of damage from the follicle cortex is not very different, i.e., 60 μm vs. 40 μm, for the two laser systems studied. However, the temperature rise in the center of the follicle is much higher for the 30 milliseconds pulse, i.e., about twice as high as compared to the two 45 milliseconds pulses separated by a 40 milliseconds interval.

Thus, the therapeutic result in terms of obtaining hair reduction is expected to be the same for both lasers, whereas the presence of burned hair is significantly higher for the 30 milliseconds pulse laser. The tendency to burn hair is, however, expected to be maximal in the infundibulum region of the hair shaft proximal to the skin surface where the optical fluence is highest and thermal contact between the hair shaft and tissue is reduced.

The temperature rise for hair follicles less than 300 μm in diameter will be lower compared to the values given in Figure 1. The maximum temperatures at the center and at the cortex of 200 μm diameter follicles exposed to a 30 milliseconds pulse at 35 J/cm^2 are 250 and 108°C, respectively, and the depth zone is 45 μm around the follicle cortex. The corresponding values for two 45 milliseconds pulses separated by an interval of 40 milliseconds are 110°C at the center, 80°C at the cortex, and zone of damage is 25 μm. The zone of damage for the 200 μm diameter follicle, i.e., 25–40 μm, is approximately half of the value for the 300 μm bulb, but might still be adequate to achieve permanent hair removal.

In the case of very small follicle bulb, e.g., 100 μm diameter, the damage is essentially negligible for both pulse structures and adequate heating will require shorter laser pulses.

The values given in Figure 1, which are valid for a fluence of $\psi = 35$ J/cm^2 and an absorption coefficient of $\mu_a = 3500$ m^{-1}, can be scaled to other combinations of ψ and μ_a by noting that the temperature rise is proportional to the product of ψ and μ_a (Eqn. A1). This is shown in Figure 2, where the effect of light depletion within the follicle also is taken into account (Eqn. A2). Figure 2 shows that the same temperature distribution for a 300 μm diameter follicle (as shown in Fig. 1), which is obtained for a fluence of $\psi = 35$ J/cm^2 and $\mu_a = 3500$ m^{-1} will be obtained for other combinations of ψ and μ_a such as, e.g., $\psi = 24$ J/cm^2 for $\mu_a = 7000$ m^{-1} or $\psi = 21$ J/cm^2 for $\mu_a = 10000$ m^{-1}.

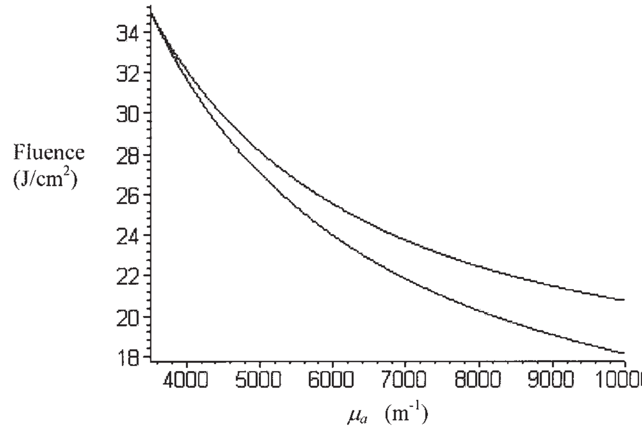

Fig. 2. Curves for combinations of fluence and absorption coefficient giving the same follicular temperature rise as a fluence of $\psi = 35$ J/cm^2 with $\mu_a = 3500$ m^{-1} (isodose curves). Upper curve: Follicle diameter 300 μm; lower curve: Follicle diameter 200 μm.

It should also be noted that an increase in the laser pulse duration at equal radiant exposures will decrease the temperature rise within the follicle while minimally affecting the zone of damage, e.g., increasing the pulse duration from 30 milliseconds to 200 milliseconds, for example shown in Figure 1a results in a maximum follicle temperature of 105°C together with a 30 μm zone of damage from the cortex.

Clinical Results in View of Modeling

The two laser systems studied demonstrated almost identical hair reduction, i.e., about 50%. Modeling indicates that an in situ fluence of 35 J/cm^2 should be adequate for obtaining a 40–60 μm zone of damage from the cortex of a 300 μm diameter follicle bulb of moderately pigmented hair for both laser systems. In the case of absorption coefficients of $\mu_a = 7000$ m^{-1} and 10000 m^{-1}, the corresponding fluence requirements will be about 30% and 40% less, respectively (Fig. 2). Due to backscattering of light, the in situ fluence at wavelengths of 800–810 nm is higher than the radiant exposure in regions proximal to the skin surface. In the present case with a radiant exposure of 35 J/cm^2 the fluence at the skin surface is about 100 J/cm^2 and remains higher than the radiant exposure to a depth of about 1.7 mm. Fluence then drops off exponentially with distance at greater skin depths. The calculated light distribution in skin at 800 nm wavelength is shown in Figure 3 [8,9]. The total absorption coefficient of skin takes into account a hair density of 100 cm^{-2} with an average shaft diameter of 100 μm and $\mu_a = 3500$ m^{-1}. This light distribution is in good agreement with values in the literature, which report a fluence of 24% of the radiant exposure at a depth of 3 mm [4]. The depths of the follicle bulbs on the human upper lip are in the range of 1–2.5 mm, thus it follows from Figure 3 that the more superficial bulbs are exposed to a fluence of 35 J/cm^2, whereas the deeper follicles receive only 17 J/cm^2. This supports the explanation that the observed hair reduction efficacy of 48–49% is due to the limited penetration of 800–810 nm light into human skin. Superficially located bulbs might be sufficiently destroyed, whereas deeper bulbs are only partially damaged. However, the in situ fluence is sufficient to cause burning of the upper segment of the hair shaft, and this phenomenon is expected to be significantly more pronounced for a single 30 milliseconds laser pulse than for the 2×45 milliseconds pulse structure.

It should also be noted that the optical penetration depth is dependent on hair density and pigmentation. The penetration depth will increase after subsequent treatments as the density of terminal hair in the upper skin layers becomes reduced, as less light will be absorbed superficially. For example, if all terminal hairs in the case shown in Figure 3 are converted to colorless vellus hairs then the depth for an in situ fluence of 35 J/cm^2 will increase from 1.7 mm to 2.2 mm. The rationale for repeated treatment is therefore not only to destroy follicles that were in the catagen or telogen phases during previous treatments, but also to deliver a sufficiently high fluence to more deeply located anagen bulbs.

The absorption of light in dermis will also give rise to bulk heating of human skin. The time required for heat diffusion across a distance of d = 1–3 mm is on the order of $t \sim \frac{d^2}{\chi}$ (10–100 seconds). Thus, very limited heat diffusion will occur over a timescale of 30–100 milliseconds pulses. A typical reflection coefficient for fair Caucasian skin is 0.4–0.5 at 800 nm, and approximately 5–10% will be absorbed by epidermal melanin [8,9]. Therefore, in a case where 24% of the energy remains at a depth of 3 mm, 15–30% will be absorbed in the upper dermal layers. An radiant exposure of 35 J/cm^2 will produce an average dermal temperature rise of 5–10°C, which contributes to damage to superficially located follicles but also limits the clinically safe radiant exposure. An increase in radiant exposure to a level required for complete destruction of deeply located follicles might easily result in non-selective thermal injury to the dermis. Thus, targeting the most deeply located follicles will require protection of the dermis by cutaneous cooling [10,11]. The required cooling time will, as discussed above, be in the range of tens of seconds. Skin cooling for dermal protection can therefore not be done during irradiation, such as for epidermal protection with a thermal diffusion time of 30–80 milliseconds, but must occur prior to laser exposure. A disadvantage of deep cooling is that the steepness of the temperature profile becomes significantly reduced as compared to epidermal cooling. Cooling of the skin surface to 5°C for 10 seconds will give in situ temperatures of 20 and 33°C at depths of 1 and 3 mm, respectively. The corresponding temperatures for a 100 seconds cooling time are 10 and 20°C at the same depths, respectively [12]. However, the temperature gradients are still large enough to enable a cooling induced temperature difference of 10–15°C between tissues at these depths.

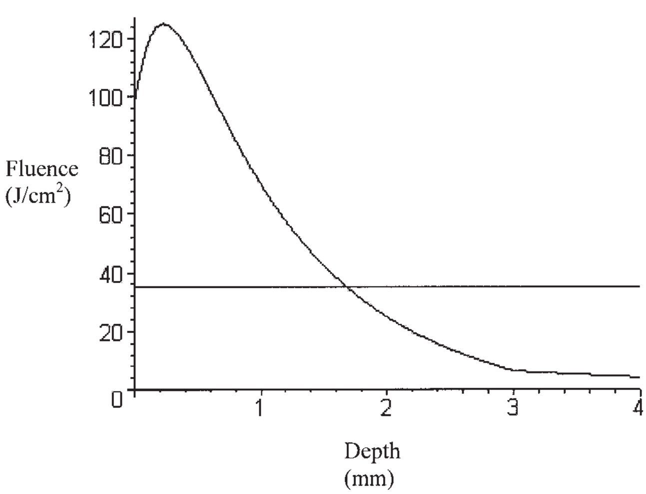

Fig. 3. Fluence (J/cm^2) vs. depth (mm) from skin surface at 800 nm wavelength. The radiant exposure (incident fluence) is 35 J/cm^2 as indicated by the horizontal line. Epidermal and dermal thicknesses 0.1 and 3 mm, respectively. Index of refraction 1.4. Absorption coefficient, reduced scattering coefficient, (penetration depth): epidermis 610 m^{-1}, 5300 m^{-1}, (0.3 mm); dermis 65 m^{-1}, 5200 m^{-1}, (1.0 mm); and subcutaneous fat 50 m^{-1}, 1000 m^{-1}, (2.5 mm).

CONCLUSIONS

This randomized treatment study revealed average hair reductions on the female upper lip of $49 \pm 21\%$ for the MedioStar® laser and $48 \pm 20\%$ for the LightSheer® laser. No statistically significant differences were found in hair removal efficacy with the laser parameters used in this study. However, differences were observed in the incidence of acute erythema and presence of burned hairs. The degree of erythema with the LightSheer® laser was clinically higher as compared to the MedioStar® laser. The LightSheer® laser also resulted in a higher incidence of burned hair. Edema and pain induced by the two lasers were not statistically different. These results agree with mathematical modeling, which also offers a method to estimate hair removal efficacy and adverse effects for a range of hair characteristics and laser parameters. The present study, which is based on a relatively moderate radiant exposure, should in future studies be supplemented with exposures in the range of 60–80 J/cm^2. At these high radiant exposures epidermal protection will be very important, and differences in the efficacy of the various cooling systems might be a very important issue. Further on, studies should also compare the efficacy at various wavelengths; although light penetrates deeper in skin with increasing wavelength, the corresponding melanin absorption decrease very strongly. A relevant clinical study would therefore be to compare the efficacy of alexandrite ($Cr:BeAl_2O_4$) lasers at 755 nm, gallium–aluminum–arsenide (GaAlAs) diode laser in the 800 nm region and neodymium-yag ($Nd:Y_3Al_5O_{12}$) lasers at 1064 nm wavelength.

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REFERENCES

1. Olsen EA. Methods of hair removal. J Am Acad Dermatol 1999;40:143–155.
2. Lou WW, Quintana AT, Geronemus RG, Grossman MC. Prospective study of hair reduction by diode laser (800 nm) with long-term follow up. Dermatol Surg 2000;26(5):428–432.
3. Lloyd JR, Mirkow M. Long-term evaluation of the long-pulsed alexandrite laser for the removal of bikini-hair at shortened intervals. Dermatol Surg 2000;26(7):633–637.
4. Ross EV, Ladin Z, Kreindel M, Dierickx C. Theoretical considerations in laser hair removal. Dermatol Clin 1999;17(2): 333–355.
5. Altshuler GB, Anderson RR, Manstein D, Zenzie HH, Smirnov MZ. Extended theory of selective photothermolysis. Lasers Surg Med 2001;29:416–432.
6. Ort RJ, Anderson RR. Optical hair removal. Semin Cutan Med Surg 1999;18(2):149–158.
7. Anderson RR, Parish JA. Selective photothermolysis. Precise microsurgery by selective absorption of pulsed radiation. Science 1983;226:524–527.
8. Svaasand LO, Norvang LT, Fiskerstrand EJ, Stopps EKS, Berns MW, Nelson JS. Tissue parameters determining the visual appearance of normal skin and port-wine stains. Lasers Med Sci 1995;10:55–65.
9. Svaasand LO, Fiskerstrand EJ, Kopstad G, Norvang LT, Svaasand EK, Nelson JS, Berns MW. Therapeutic response during pulsed laser treatment of port-wine stains; dependence on vessel diameter and depth in dermis. Lasers Med Sci 1995;10:235–243.
10. Nelson JS, Milner T, Anvari B, Tanenbaum BS, Kimel S, Svaasand LO, Jacques S. Dynamic epidermal cooling during pulsed laser treatment of port-wine stains-a methodology with preliminary clinical evaluation. Arch Dermatol 1995; 131:695–700.
11. Nelson JS, Majaron B, Kelly KM. Active skin cooling in conjunction with laser dermatologic surgery. Sem Cut Med Surg 2000;19:253–266.
12. Carslaw HS, Jaeger JC. Conduction of heat in solids. Oxford: Clarendon Press, 1959.

APPENDIX

The spatial and temporal temperature distributions T(r, t) of a uniformly heated sphere embedded in an infinite large medium with the same thermal properties can be expressed [10].

$$\begin{aligned}T(r,t) = \frac{\mu_a\psi\chi}{\Delta t\kappa}\sum_{n=1}^{2}(-1)^{n-1}\Bigg[\langle(t-\Delta t(n-1))\Bigg\{1-\frac{1}{r}\Bigg[2a\Bigg(i^2\mathrm{erfc}\Bigg(\frac{a-r}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\\ +i^2\mathrm{erfc}\Bigg(\frac{a+r}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\Bigg)-4\sqrt{\chi(t-\Delta t(n-1))}\Bigg(i^3\mathrm{erfc}\Bigg(\frac{a-r}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\\ -i^3\mathrm{erfc}\Bigg(\frac{a+r}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\Bigg)\Bigg]\Bigg\}h(t-\Delta t(n-1))\rangle h(a-r)\\ +\Bigg\langle\frac{2(t-\Delta t(n-1))a}{r}\Bigg\{(i^2\mathrm{erfc}\Bigg(\frac{r-a}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)+i^2\mathrm{erfc}\Bigg(\frac{r+a}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\\ -\frac{2\sqrt{\chi(t-\Delta t(n-1))}}{a}\Bigg[i^3\mathrm{erfc}\Bigg(\frac{r-a}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\\ -i^3\mathrm{erfc}\Bigg(\frac{r+a}{2\sqrt{\chi(t-\Delta t(n-1))}}\Bigg)\Bigg]\Bigg\}h(t-\Delta t(n-1))\Bigg\rangle h(r-a)\Bigg]\end{aligned}\qquad (A1)$$

where ψ, r, and t are the fluence, distance from the center, and time from onset of the laser pulse. The radius of the follicle is given by a, pulse duration is Δt, and the coefficients χ, κ, and μ_a are thermal diffusivity, thermal conductivity, and optical absorption coefficient, respectively. The function h(x) is the Heaviside step function defined by $h(x)=0$ when $x<0$ and $h(x)=1$ when $x>0$, and the function $i^n\mathrm{erfc}(x)$ is the n'th integral of the complimentary error function, defined as, $i^n\mathrm{erfc}(x) = \int_x^\infty i^{n-1}\mathrm{erfc}(\xi)d\xi$, where $i^0\mathrm{erfc}(x)=\mathrm{erfc}(x)$ is the complimentary error function. When depletion of light in the follicle occurs, i.e., when the optical penetration depth $\delta=\frac{1}{\mu_a}$ is comparable or smaller than the radius, the absorption coefficient in Equation A1 can be substituted with an effective value average $\mu_{a,eff}$ expressing an absorption coefficient averaged over the entire sphere, i.e., the average absorbed energy density is $\mu_{a,eff}\psi$,

$$\begin{aligned}\mu_{a,eff} &= \frac{3}{4\pi a^3}\int_{\phi=0}^{\pi/2} 2\pi a^2\sin\phi\cos\phi(1-e^{-\mu_a 2a\cos\phi})d\phi\\ &= \frac{3}{8}\frac{(1+2\mu_a a)e^{-2\mu_a a}+2\mu_a^2a^2-1}{\mu_a^2a^3}\end{aligned}\qquad (A2)$$

This expression reduces to $\mu_{a,eff}\Rightarrow\mu_a$ when depletion of light is negligible, and when depletion is predominant its value becomes $\mu_{a,eff}\Rightarrow\frac{3}{4a}$ corresponding to total absorption of all incident light. This equation, which is exact for a collimated beam, is expected to be an acceptable approximation even in heavily scattering media such as skin where the light distribution is more isotropic.