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Biological and clinical aspects in laser hair removal

J Lepselter[1] and M Elman[2]

[1]Msq P.O. Box 3021, Caesarea 38900, Israel;
[2]Dermatology and Lasers Clinic, 21 Leonardo Devinci Street Tel-Aviv, 64733 Israel

INTRODUCTION: In the past century, unwanted hair has been traditionally treated with multitudes of techniques that were found to be slow, tedious, painful, impractical, and resulted in poor long-term efficacy. Consequently, there has been a public demand for a novel, rapid, reliable, safe, and affordable hair removal technique. In the last decade, laser and light-based technology for hair removal became one of the fastest growing procedures in modern cosmetic dermatology.
OBJECTIVE: To discuss the latest scientific and clinical issues in the field of photoepilation as evolved in the past decade: hair biology, laser physics and skin optics, technology and clinical experience.
RESULTS: From substantial clinical experience, it becomes apparent that in the ideal subject with fair skin and dark hair, a single treatment can reduce hair by 10–40%; three treatments by 30–70%; and repeated treatments by as much as 90%. These results persist for as long as 12 months. Diffuse and perifollicular cutaneous erythema and pigmentary changes are the most common adverse side effects. Most complications are generally temporary.
CONCLUSIONS: Photoepilation, when properly used, offers clear advantages when compared with older, traditional techniques. Although an ever-increasing number of published studies have confirmed the safety and short and long-term efficacy of photoepilation, the technology still has limits and risks. (*J Dermatol Treat* (2004) **15:** 72–83)

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Introduction

Excess hair and/or unwanted hair are of significant medical, social and cultural importance and are therefore the subject of much attention, manipulation and regard in both genders and all races. The multitude of treatments available is testimony to these facts. Traditionally, conditions such as hirsutism, hypertrichosis, and cosmetic elegance have been treated with electrolysis/thermolysis, tweezing, shaving, waxing and sugaring, plucking, threading, depilatories and X-ray therapy.[1] These methods, however, were found to be slow, tedious, painful, impractical for treating large areas, and, in most cases, temporary. Consequently, the need for a long-term, non-invasive, rapid, reliable and safe method became a necessity in our society.

When first described some 7 years ago, laser hair removal created controversy.[2] As the technology matured, laser hair removal generated growing demand not only for a safe, non-invasive, pain-free procedure, but also for effective, rapid pace, easy to operate, and affordable technology. Today, photoepilation by laser and other light-based technology is the fastest growing procedure in modern cosmetic dermatology. As more clinical research and experience is gained in the field of laser hair removal, manufacturers and practitioners have been obligated to seek safer and more effective results.

Although the technology is relatively new, it has already generated much interest among clinicians and patients alike because of its ability to delay hair regrowth, and non-invasively remove large areas of

Correspondence:
Joseph Lepselter, PhD, Msq PO Box 3021, Caesarea 38900, Israel. Tel +972 4 627 5357; Fax +972 4 627 5368; E-mail: lepselt@bezeqint.net

hair with minimal discomfort, and a low incidence of complications.[3] However, efficacy and safety of hair removal by laser and light-based technology varies considerably among manufacturers due to differences in patients' skin–hair biology traits, optimization of electro-optical parameters and clinical protocols.

The purpose of this review is to discuss the major scientific and clinical issues in the field of photoepilation that have evolved in the last decade. Pertaining to our discussion will be the following topics: hair biology; biomedical optics and laser physics; clinical experience with selected technologies; and essential issues in photoepilation.

Hair biology

A hair follicle consists of three regions: the infundibulum, isthmus, and hair bulb. The general anatomy of hair follicle is shown in Figure 1. The inferior segment of the hair follicle lies below the arrector pili muscle insertion and includes the hair bulb and dermal papilla. As will be discussed later, this area is of great importance in photoepilation. On average, the bulb is approximately 4 mm in depth from the surface of the skin, a considerable depth of penetration required by the laser light-based systems.[4] The hair bulb is made up of germinative matrix cells along with interspersed melanocytes. The dermal papilla, located in the base of the bulb, is fed by the bloodstream, which carries nourishment to produce new hair. The bulge is located approximately one-third of the distance down from the skin surface to the follicle bulb. Dermal sheath cells and epidermal outer root cells are found in the follicle bulb. These cell types extend into the isthmus and infundibulum of the hair follicle and play an important role in hair growth.[5,6]

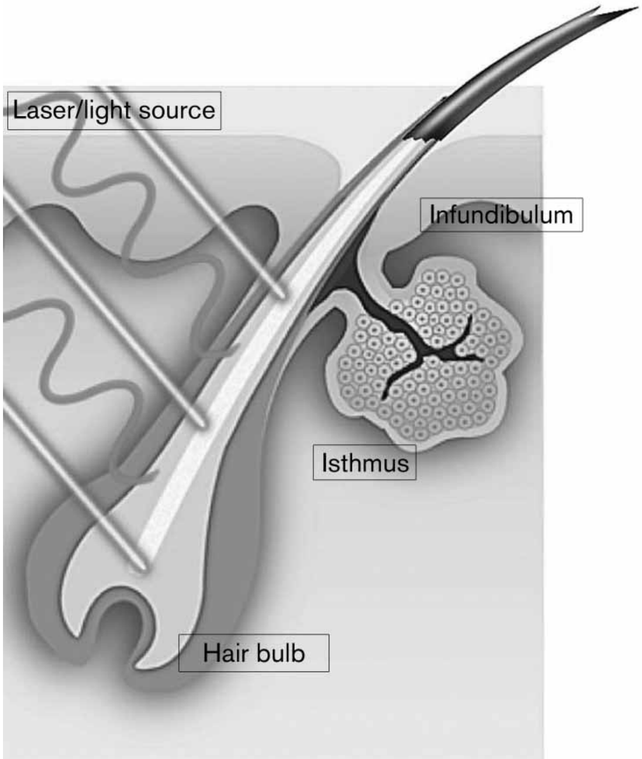

Figure 1
Hair follicle anatomy in photoepilation.

Human hair grows in a cyclic pattern. The cycle consists of a growth or anagen phase followed by intermediate degradation of a portion of the follicle, known as the catagen phase and then by a resting period when no growth occurs – the telogen phase.[7] Figure 2 describes the three phases of the hair growth cycle. It appears that different areas of the body, in addition to having shorter anagen cycles, have varying percentages of hairs actually in the anagen phase.

The anagen duration varies greatly depending on age, season, gender (anagen in thigh hair in men is 54 days versus 22 days in women), body site, hormones and underling genetic susceptibilities.[8] The catagen phase is generally 3 weeks in duration whereas the telogen phase usually lasts approximately 3 months. At any given time, the majority of the hair follicles (80–85%) are in the anagen phase and the remaining follicles are either in the catagen phase (2%) or the telogen phase (10–15%).[9,10] Table I shows the duration and percentage of the hair cycle in relation to body areas.

For effective hair removal a laser/light source should damage one or more growth centers of hair, and the pluripotential cells of the bulge, dermal papilla, and hair matrix must be treated in the anagen cycle. It is during the anagen phase that melanin production occurs and becomes part of the growing follicle. It is also in the anagen phase that damage can affect the structure theoretically responsible for hair generation. During the telogen phase, the dermal papilla moves upward toward the bulge region and stimulates the onset of the anagen phase. In this active growth phase, the papilla moves down away from the bulge mass and the hair matrix cells regress during the catagen phase. Thus, depending on the stage of the hair cycle, the distance between the bulge region and the dermal papilla varies along with the depth of the dermal papilla within the dermis. These structures represent targets for hair follicle damage, and relative movement with respect to the skin structure attenuate their photothermal susceptibility to a fixed wavelength laser beam. Thus, to achieve long-term hair removal, it is essential to destroy the structures that are responsible for hair growth: the bulge and bulb.[11]

Laser physics and skin optics in hair removal

Laser hair removal is a multifactorial process that involves complex photothermal reaction via the epidermis–dermis

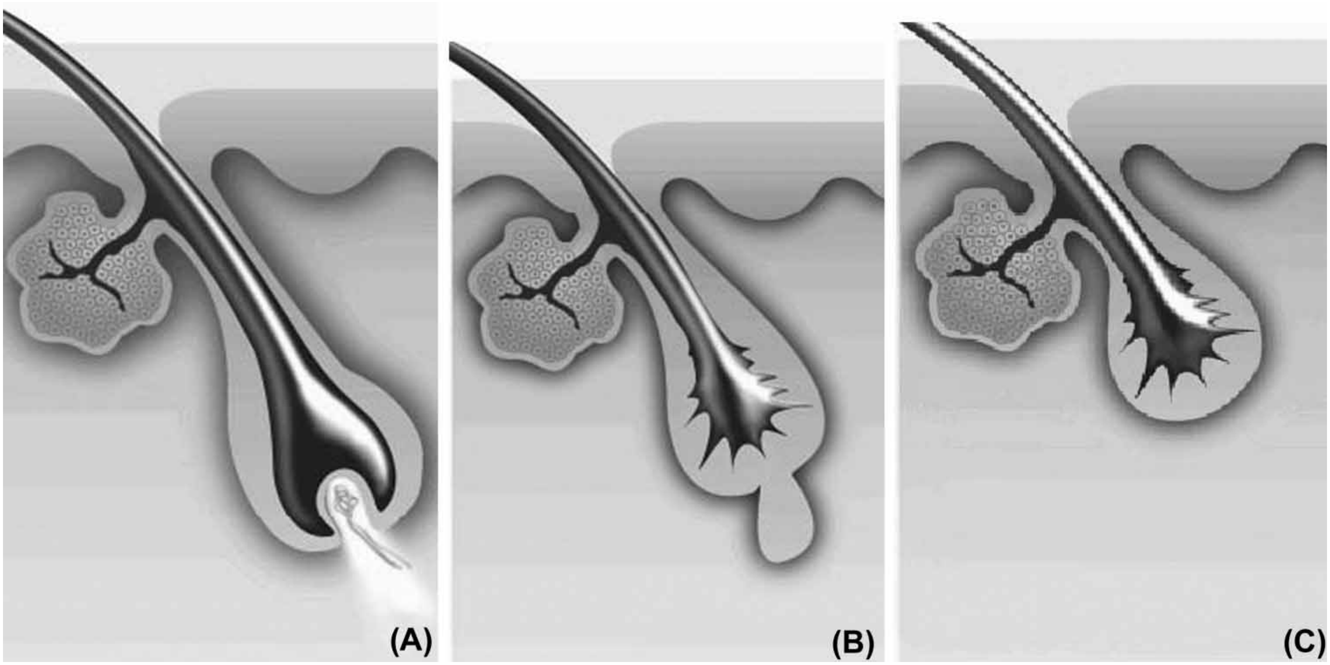

Figure 2

Hair follicle cycle. (A) ***Anagen phase****: hair matrix cells migrate outward from the shaft and the melanin load is at its highest. (B)* ***Catagen phase****: the follicle detaches from the papillae and contracts – eventually falling out. (C)* ***Telogen phase****: mitosis ceases, the hair matrix regresses and the papilla retracts to a place near the bulge (apoptosis).*

Body area	Anagen hair (%)	Telogen duration	Density (cm^2)	Follicle depth
Scalp	85	4 months	350	3–5 mm
Beard	70	10 weeks	500	2–4 mm
Moustache	65	6 weeks	500	1–2 mm
Armpits	30	3 months	65	3–4 mm
Bikini line	30	3 months	70	3–4 mm
Legs	20	4 months	60	2–3 mm

Table I

Duration and percentage of hair in the anagen and telogen phase (ref. 9)

matrix, aimed to cause hair follicle damage while sparing the epidermis. Thus, hair follicle eradication by a laser light source is a function of various laser (e.g. power, spot size, irradiation time and repetition rate) and tissue (absorption and scattering coefficients, density, heat capacity and thermal conductivity) parameters.[12]

The laser source may be continuous mode or pulsed. A continuous mode laser emits a continuous stream of light as long as the medium is excited, resulting in heating and vaporization of the target tissue. Alternatively, a pulsed laser will emit light only in short amounts, which may vary from nanoseconds to as long as seconds. Various sources of laser/light-based technology exist, including continuous light, flashlamp, radio frequency, high-voltage discharge, diodes and others. When the lasing medium is excited, the molecules are stimulated to a higher energy level. These excited molecules tend to decay spontaneously to their original lower energy level realizing a photon. All emitted photons bear a constant phase relationship with each other in both time and phase – coherency. In turn, all laser light photons travel in the same direction with low divergence – collimated. Finally, laser light has high irradiance, since all the light is concentrated into a narrow spatial band resulting in a high radiant power per unit area.

Energy refers to the number of photons delivered and is measured in joules (J). Power is measured in watts (W) and refers to the delivery rate of energy (1 W=1 J/s). Fluence is the total energy delivered per unit area and is measured in J/cm^2. Pulse duration is the amount of time laser energy is applied (ns, ms). The pulse frequency is measured in hertz (1 Hz=1 pulse/s). Wavelength is measured in nanometers (nm) and refers to the distance between the peaks of the light waves and is used to characterize the type of light (green, red, yellow).

The technology employed for hair removal by lasers/ light-based systems is based on the principle of selective photothermolysis. According to this principle, selective thermal destruction of a target will occur if sufficient energy is delivered at a wavelength well absorbed by the target within a time period less than or equal to the thermal relaxation time (TRT) of the target.[12] The TRT is the time it takes for the target to cool (half of its baseline temperature) and transfer the heat to surrounding structures. Under these conditions, it is possible to selectively target structures (e.g. hair follicle) while sparing the surrounding structures or tissues. The target site for the selective destruction of hair follicles can either be endogenous melanin or exogenous chromophore.

A corollary of selective photothermolysis is thermokinetic selectivity. This theory proposes that for the same chromophore, a longer pulse duration allows intrapulse cooling of smaller targets more rapidly than larger targets. Longer pulse durations are predicted to limit thermal damage to the epidermis. If the pulse duration exceeds the thermal relaxation time of the basal cell layer (about 0.1 ms) or entire epidermis (about 10 ms), these structures will cool as they are heated during the laser pulse. In other words, larger targets (hair follicles) can be selectively injured more than smaller targets of the same chromophore (epidermis).[13]

Recently, a novel concept of laser hair removal uses the thermal damage time (TDT) rather than the traditional hair follicle TRT concept that has been described. Studies indicate that the ideal pulse duration for medium to coarse hair reduction may be longer than the TRT of the hair follicle. Since the melanin occupies a much smaller volume compared with the follicle, heat is conducted from the shaft and melanized portion of the bulb to surrounding structures according to the laws of thermal diffusion. It has been suggested that widening the pulse duration allows an increase in the threshold of epidermal damage. As we have learned more about the mechanism of hair removal, it has become evident that the true targets for permanent hair removal are located at a distance from the hair shaft, at the outer root sheath of the follicle (stem cells), and the base of the follicle. This important observation has required reconsideration as to the appropriate laser parameters, particularly pulse width and energy density.[14–16]

When considering photothermal destruction of hair follicles, there are three parameters that need to be considered: wavelength, pulse duration, and fluence. The longer the wavelength, the deeper the laser light penetrates the skin. To damage hair follicles, laser light must be absorbed by a chromophore within the follicle. Most lasers target the endogenous chromophore melanin within the pigmented hair shaft by delivering red or near-infrared wavelengths. Melanin is the primary light absorber in the optical window between 600 nm and 1100 nm. Wavelengths in this range are poorly absorbed by competing chromophores such as hemoglobin and water and penetrate deeply into the dermis.[17] It should be remembered though that the absorption of light by melanin decreases with longer wavelengths and that oxyhemoglobin and melanin have similar absorption at wavelengths at 750–850 nm.

The ability of these wavelengths to damage hair correlates directly with the amount and type of melanin within the follicle: pheomelanin and eumelanin. Dark hair that contains large amounts of eumelanin readily absorbs these wavelengths and is most susceptible to laser-induced damage.[18] In theory, the use of longer wavelengths increases the ratio of energy deposited in the dermis to the epidermis, which results in relative bulb heating and epidermis sparing. However, although there is more melanin absorption at a wavelength of 755 nm than 800 nm, larger energy density (fluence) must be employed during 800 nm than with a 755 nm wavelength laser. In the case of brown and black hairs, where the target chromophore is eumelanin, long-pulsed diode lasers at a wavelength of 800 nm were found to be safe and clinically effective.[19]

The necessary energy density (i.e. fluence) for the coagulation of hair follicle is proportional to the hair shaft diameter, as long as the bulb and follicle thickness are proportionate to hair shaft diameter; the thinner the hair, the smaller the energy density level.[20] In general, the fluence of the laser should be greater than or equal to the threshold fluence for tissue destruction. To confine thermal damage to the hair follicle, the laser pulse duration should lie between the TRT for epidermis, which is approximately 3–10 ms, and the TRT for the hair follicles which is approximately 40–100 ms. Using this concept to deliver light of the right combination of wavelength, energy fluence, and pulse duration, it is possible to precisely target the hair follicle and improve long-term hair removal.

The laser pulse width plays an important role in determining selective photothermolysis. High energy, short pulses of laser light cause extremely rapid heating of the target, with a rapid expansion of the thermal plasma. If the pulse width is too long, however, there will be insufficient time for the heat to dissipate, and undesirable temperature increase will occur with thermal injury to non-follicular structures, which could result in scarring or irregularities in pigmentation.[21]

Ideally, the spot size should be as large as possible to reduce scattering of the light. When light is applied to the skin using a small spot size, the scattering of photons diffuses the beam rapidly. The fluence decays very quickly as a function of depth, so that most of the energy is dissipated in radial directions (outwards) and cannot reach the hair bulbs. With a large spot size, light penetration is more efficient since the ‘source’ of photons has an almost planar geometry. In human skin, about 15–20% of incident light at 700 nm penetrates to a depth of 3 mm. Thus, by using a larger spot size scattering of light in the dermis is lessened, leading to a greater depth of penetration and a lower threshold fluence.[22]

Clinical experience

Since the first laser-assisted hair removal device was cleared in 1995, more than 15 laser systems have been approved by the Food and Drug Administration (FDA) to specifically target hair follicles.[23] These systems include ruby (694 nm), alexandrite (755 nm), diode (800–1000 nm), Q-switched and long-pulsed neodymium: yttrium-aluminum-garnet (Nd:YAG; 1064 nm) and intense pulsed light (IPL) sources (550–1200 nm). Devices that target exogenous chromophores are carbon particles plus Q-switched Nd:YAG laser (1064 nm) and 5-aminolevulonic acid. A summary of different commercially available hair removal devices is presented in Table II.

Normal-mode ruby laser (694 nm)

The pulsed ruby laser was the original system used to perform melanin-based selective photothermolysis of hair. The ruby laser delivers red light at a wavelength of 694 nm. Three ruby lasers have been approved by the FDA for hair removal: EpiLaser/E2000 (Palomar); EpiPulse (Sharplan/ESC); and RubyStar (Aesculap Mediteo). Because of the high melanin absorption at 694 nm, ruby lasers are most useful for light-skinned (Fitzpatrick skin types I–III) individuals with dark hair.

In a recent study, Allison et al studied the long-term hair regrowth in three patient groups: top lip ($n=25$), axillae ($n=25$) and legs ($n=9$). Two treatments were given on the right and left sides at monthly intervals. A third treatment was given randomly to one side. Hair counts of the experimental sites were made at monthly intervals for 1 year. Long-term hair reduction was achieved in all patients. A single treatment reduced hair counts by up to 75%. Three treatments had an impact for 2 additional months, but not long term. Unexpected spontaneous hair reduction was found 5 months following treatment and lasted 2 months. This ruby laser produced a persistent two-thirds reduction in hair count over 8 months of follow-up and no significant regrowth follow-up to 12 months.[24] Studies with short-term follow-up have observed 37–72% reduction at 3 months after one to three treatments, to a 38–49% hair reduction 1 year after three treatment sessions.[25,26]

In a long follow-up study, Grossman et al studied 13 patients with fair skin and dark hair. Patients were treated once on the thighs or back at fluences of 20–60 J/cm^2 and pulses of 270 μsec. In all subjects, hair regrowth was delayed for 1–3 months at all fluences. A complete regrowth was present in five out of 13 patients. At 1–2 years follow-up, four of the seven patients had persistent hair loss, which was greatest in the sites treated with the highest fluence.[27]

Chana and Grobbelaar[28] prospectively assessed the long-term results of ruby laser depilation in 346 consecutive patients who underwent hair removal at 402 anatomical sites. The patients were treated using a ruby laser, with the mean power ranging from 8.6 J to 15.7 J according to skin type. Results were assessed using two outcome measures: the percentage reduction in hair density and the hair-free interval. The median reduction in hair density was 55% (range 0–100%) at a median time of 1 year after the last treatment session. The median hair-free interval was 8 weeks. Patients underwent a median number of four treatment sessions. Forty-three of the 346 patients were treated at more than one anatomical site. Of the sites treated, a 75% reduction in hair density was achieved in 22%, 90% reduction was achieved in 2.2%, and complete depilation was achieved in only 0.7%. Darker colored hair was more effectively treated. Treatment efficacy was not affected by anatomical site, with the exception of the faces of male patients, which were found to be particularly resistant to treatment. There was a significant correlation between the number of treatments given and the outcome. The overall complication rate was 9.0% (36 of 402 sites) with respect to pigmentary changes and blistering, but varied according to Fitzpatrick skin type. The complication rate was highest in skin types V

Laser	Wavelength (nm)	Pulse duration (ms)	Fluence (J/cm^2)	Spot size (mm)	Repetition rate (Hz)	Cooling mean
Mythos-500 (Msq)	810	0–400	5–120	10 × 12	up to 4	Sapphire contact
Q-switched Nd:YAG (Thermolase)	1064	10^{-5}	2–3	7	10	Not needed
Long-pulsed ruby (Palomar)	694	3	10–40	10	1	Sapphire contact
Long-pulsed alexandrite (Cynosure)	755	5, 10, 20, 40	5–50	10–15	up to 2	Cold air flow
LightSheer (Star/Coherent)	810	5–100	10–60	12 × 12	up to 2	Sapphire contact
Long-pulsed Nd:YAG (Laserscope)	1064	1–50	up to 150	1–4	up to 4	Contact cooling
Super-long-pulse 1000 (Palomar)	810	200–1000	up to 100	10	up to 3	Contact cooling
Laser/light source	550–1200	15–100	up to 45	10 × 45 8 × 33	0.5	Circulating cooling

Table II

Parameters of selected hair removal lasers and light sources and VI (24.7%), with no complications in skin type I. Although a greater than 50% reduction in hair density was achieved in half of the 346 patients treated, complete depilation was achieved in only an extremely limited number of patients. In other controlled studies, the ruby laser (one to four sessions) proved to be more efficacious for hair reduction than shaving or waxing only.[29,30]

Alexandrite laser (755 nm)

The alexandrite laser allows greater depth of penetration, making it relatively safe in darker-skinned (Fitzpatrick skin types I–IV) individuals. However, melanin absorption is somewhat less at the wavelength of alexandrite (755 nm) when compared with the ruby (694 nm). Alexandrite lasers for hair removal were cleared by the FDA to market in the USA in 1997. EpiTouch Alex (ESC Sharplan Medical Systems), GentleLASE (Candela Laser Corp.), and Photogenica LPIR (Cynosure, Inc.) are currently available.

The reported success rate of hair removal using the alexandrite has ranged from 40% to 80% at 6 months after several treatments. In a controlled randomized study, McDaniel et al showed a 40% to 56% reduction of hair growth at 6 months after one treatment with a variable-pulsed alexandrite laser on the lip, leg, and back.[31] This study found that one treatment with a variable-pulsed alexandrite laser produced maximum hair regrowth reduction at 6 months of 40–56% for the lip, leg and back. Sites treated with a 10 ms pulse duration were found to have a significantly better hair reduction rate that those treated with 5 ms or 20 ms pulse widths.

Laughlin and Dudley found an average of 43% reduction at 6 months plus 'one growth cycle' after a single treatment at the bikini line, with 60% of sites having greater than 30%.[32] An uncontrolled study, using a uniform protocol, demonstrated a mean of 74% hair reduction 1 year after five treatment sessions at the bikini line. The average patient had a 78% clearance of hair noted at 1 year with no evidence of scarring or pigmentary changes.[33]

In 150 dark-skinned patients (skin types IV–VI) treated with the alexandrite laser (18 J/cm^2, 40 ms), side effects occurred in about 2% of cases.[34] Some studies have shown that the 20 ms pulse duration reduces the risk of epidermal damage and pigmentary alteration, but treatment is more painful when longer pulse durations are used.[35]

Diode laser (800–1000 nm)

Diode lasers for hair removal were cleared by the FDA to market in the USA in 1997. Because of the longer wavelength, the active cooling, and the longer pulse widths, individuals with darker skin can be treated more safely with this system. In general, the diode laser system has been found to be better tolerated by patients with darker skin types (V–VI) than the ruby laser.

Overall, clinical studies with the diode laser system have reported variable success rates ranging from 65% to 75% hair reduction at 3 months after one to two treatments with fluences of 10–40 J/cm^2, to >75% hair reduction in 91% of individuals 8 months after three to four treatments at 40 J/cm^2.[36]

In a recent study, Fiskerstrand and colleagues[15] compared two systems (side-by-side study) with different pulse structures. The radiant exposure was selected to a value of 35 J/cm^2, which is frequently used in the clinic in accordance with the manufacturer's recommendations. Twenty-nine patients with hair color ranging from light brown to black on the upper lip were studied. Three treatments were performed at 6–8 week intervals. The percentage hair reduction and acute and long-term side effects were evaluated after treatment. The average hair reductions 6 months after the first treatment were similar in both diode systems (49% and 48% clearance). 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. No statistically significant differences in hair removal efficacy were observed.

Rogachefsky et al[14] have evaluated the clinical efficacy and side effect profile of a modified 810 nm diode laser device operating in a super-long-pulse mode (200–1000 ms). Ten female subjects with Fitzpatrick skin types I–VI received either one or two laser treatments at eight test sites. Super-long-pulse durations of 200–1000 ms were evaluated with delivered fluences ranging from 23 to 115 J/cm^2. Subjects were followed for 6 months after the first treatment. The clinical results show that safe hair removal in all skin types can be accomplished with an 810 nm diode laser delivering super-long-pulse durations. Pain and complications were greatest at the highest pulse duration (1000 ms) and the highest fluence (115 J/cm^2). Optimal hair reduction at 6 months (31%) was achieved at a thermal diffusion time of 400 ms (46 J/cm^2).

Dierickx et al evaluated the effectiveness and safety in ninety-five subjects with dark hair (Fitzpatrick skin types I–IV). Subjects were treated at baseline and 1, 3, 6, 9, and 12 months after treatment. One versus two treatments were compared. Treatment results demonstrated both hair growth delay (in all patients) for 1–3 months and permanent hair reduction of 46% (40 J/cm^2; 20 ms pulse width).[37]

Several other studies have demonstrated the efficacy of the diode laser hair removal. In one study of 50 patients, quantitative hair counts performed for 9 months after treatment showed long-lasting and possibly permanent hair loss.[38] Lou et al who looked at light-skinned patients with a single session, detected a significant regrowth rate ranging from 65% to 75% 20 months after treatment. Two-session treatments were associated with a longer growth delay, ranging from 47% to 66%.[39] Sadick et al studied 24 female subjects (skin types II–IV) were treated three times at monthly intervals with a new 810 nm diode laser (spot size 12 mm, pulse width 50 ms, fluence 25–35 J/cm^2). A mean hair removal efficiency of 74% and 79% was noted at 3 and 6 months, respectively.[40]

Nd:YAG laser (1064 nm)

The Q-switched 1064 nm Nd:YAG laser with or without topical carbon suspension was one of the first laser systems used to remove hair. The poor absorption by melanin at this wavelength coupled with an epidermal cooling device makes the long-pulsed Nd:YAG laser a safe treatment option for patients with the darkest skin phototypes (III–VI) and, therefore, for darker Fitzpatrick skin types the long-pulsed Nd:YAG is preferred to the ruby laser. However, because of reduced absorption by follicular melanin, very high fluences (50–100 J/cm^2) are required to damage pigmented hair follicles. Theoretical considerations to improve the performance of the Nd:YAG laser have been proposed, including an improvement in the exogenous chromophores used. In addition, the Nd:YAG laser may be useful in the treatment of light hairs, when used with the topically applied carbon suspension. Most of the Nd:YAG systems are Q-switched, with pulses ranging from 10 ns to 30 ms, although Nd:YAG equipment delivering non-Q-switched long pulses is also available. Several long-pulsed Nd:YAG lasers have been approved by the FDA for hair removal or laser treatment of darker skin types.

Overall, clinical studies have demonstrated less hair reduction with the Nd:YAG laser compared with those results published with the ruby or alexandrite lasers. In a recent study, Rogachefsky et al[41] evaluated the efficacy of a long-pulsed Nd:YAG laser system. Twenty-two subjects were treated with a cryogen spray-cooled long-pulsed Nd:YAG laser. Four adjacent sites were assigned to each subject, and were treated with parameters of 50 J/cm^2 with a 25 ms pulse duration; 60 J/cm^2 with a 50 ms pulse duration; 80 J/cm^2 with a 50 ms pulse duration; and control. Hair counts were obtained immediately, and 1 week, 1 month, and 3 months after treatment, and multivariate regression analysis was used to determine the significance of hair reduction. At 3 months, the higher settings of 60 J/cm^2 and 50 ms and 80 J/cm^2 and 50 ms were statistically significant for reduced mean hair counts (p=0.014, p=0.042, respectively), while the lowest setting at 50 J/cm^2 and 25 ms was not significant (p=0.079).

In a prospective clinical study with 29 volunteers, Lorenz et al[42] investigated the efficacy, side effects, and the long-term results of a long-pulsed Nd:YAG for hair removal in different hair colors and skin types. Treatment was performed on the lower leg with a long-pulsed Nd:YAG. Five test areas were treated one to five times at monthly intervals; one served as a control. Follow-up investigations were performed at each session, and 3, 6, and 12 months after the last therapy. The investigators reported after 1 month a hair loss of greater than 50% in 44.9% of the areas treated once. With up to five treatments, this percentage increased to 71.5%. One year after therapy, a greater than 50% hair reduction was still present in 40% of the five-treatment areas and in 0% of the areas treated only once.

Early published medical papers using Nd:YAG with carbon lotion reported a 27% to 66% reduction at 3 months after one treatment.[43] In a different study with long-pulsed Nd:YAG, Goldberg and Samady found that in 15 subjects (Fitzpatrick skin types I–III) hair reduction varied between 50% and 60% at 3 months. Laser energy was delivered through a 1 mm spot size, 30 ms pulse duration and fluences of 125–130 J/cm^2 for facial hair and 150 J/cm^2 for non-facial hair. No complications or adverse effects were reported at any of the follow-up examinations.[44]

Intense pulsed light (550–1200 nm)

This system delivers broad spectrum, non-coherent radiation with wavelengths of 550–1200 nm. One of four filters (590 nm, 615 nm, 645 nm or 695 nm) is used to eliminate shorter wavelengths. In general, filters with higher cut-off values are used with darker skin types. Cooling means are recommended (i.e. gel) when higher energy (30–65 J/cm^2) light pulses are used. These properties allow for great variability in selecting individual treatment parameters and adapting to different skin types and indications. However, because of the wide spectrum of potential combinations of wavelengths, pulse durations, pulse frequency, and fluences, a great deal of experience is required when using IPL technology. Proper patient selection and critical diagnostics serve to keep the adverse effects of the treatment to a minimum.[45]

Treatment with IPL may be useful for light colored hair, although more treatment sessions are generally required. Several studies have demonstrated the long-term efficacy of the device. In a study of 67 subjects of Fitzpatrick skin types I–IV, mean hair loss was 48% at 6 months or more after a single treatment. There were no statistically significant differences in hair count after single versus multiple treatments.[46] In one study, 60% hair reduction was reported 12 weeks after a single treatment with various cut-off filters (34–44 J/cm^2, two to five pulses, 1.5–3.5 ms, 20–50 ms delays). Adverse effects included post-treatment erythema in 7%, hyperpigmentation in 3%, and blistering in 11%.[47] In a non-controlled study of 14 subjects treated with IPL, and followed for more than 12 months after the last treatment, a mean of 83% hair reduction was obtained after two to six treatments.[48] The authors attributed the high success rate obtained to the ability of the technology to provide energy of long wavelengths, selected high-energy fluences on a specific range and long pulse durations. However, the results from this study should be interpreted with caution due to the absence of controls and lack of uniform treatment and follow-up control. Side effects and complications of IPL treatment are similar to those seen after laser-assisted hair removal, and include rare instances of blistering, crusting, and transient dyspigmentation.

In summary, the ruby laser (694 nm), alexandrite laser (755 nm), diode laser (800 nm), intense pulsed light source (550–1200 nm) and the Nd:YAG laser (1064 nm), with or without the application of carbon suspension, work on the principle of selective photothermolysis with the melanin in the hair follicles as the chromophobe. Regardless of the type of laser used multiple treatments are necessary to achieve satisfactory results. After repeated treatments hair clearance of 30–50% is generally reported 6 months after the last treatment. Patients with dark skin (Fitzpatrick skin types IV and V) can be treated effectively with comparable morbidity to those with lighter skin. Although there is no obvious advantage of one laser system over another in terms of treatment outcome (except the Nd:YAG laser, which is found to be less efficacious, but more suited to patients with darker skin), laser parameters may be important when choosing the ideal laser for a patient.[49]

Essential issues in laser hair removal

Terminology

Hair removal is an ambiguous term that may carry different meaning for the patient, the physician and the industry. ‘Permanent hair removal’ should be distinguished from ‘permanent hair reduction’. The former is defined as the long-term, stable reduction in the number of hairs regrowing after a treatment regime, which may include several sessions. The number of hairs regrowing must be stable over time greater than the duration of the complete growth cycle of hair follicles, which varies from 4 to 12 months according to body location. Permanent hair reduction, on the other hand, does not necessarily imply the elimination of all hairs in the treatment area. This means that although laser treatments with these devices will permanently reduce the total number of hairs, they will not result in a permanent removal of all hair. Complete hair loss refers to a lack of regrowing hairs (i.e. the number of regrowing hairs is reduced to zero). Complete hair loss may be either temporary or permanent. Laser treatment usually produces complete but temporary hair loss for 1–3 months, followed by partial but permanent hair loss. Temporary growth delay seems to be caused by laser damage induction of the telogen phase. Permanent hair loss seems to be associated with miniaturization of hair follicles.[50]

Optimal follicle damage

Which hair cycle phase is the most appropriate, and which follicular elements cause hair-shaft regeneration is a subject of debate. In mice, Lin and colleagues noted that during the anagen phase there was heterogeneous, but widespread injury to the epithelium, increasing with increasing fluence (1.47–3.26 J/cm^2). However, no follicular damage was observed during the catagen or telogen phases at any of the fluences used. Full hair regrowth occurred 28–56 days after laser exposure administered during the catagen or telogen phases for all fluence levels. In contrast, regrowth after laser exposure in the anagen phase was fluence-dependent: hair regrowth was moderate (1.47 J/cm^2) and none (3.16 J/cm^2).[51]

In humans it appears that the most essential variable is the presence of the pigmented hair shaft within the skin that functions as a chromophore. It is therefore likely that both anagen and telogen follicles are sensitive to laser treatment. Because the telogen bulb is high in the dermis one might argue that this would be the optimal time for treatment; however, the superficial location is undermined by the bulb being poorly melanized. In early anagen the bulb is well melanized and still fairly superficial; this may present the best time for treatment. If the damage is not permanent during this cycle, follicles move into the telogen stage as they fall out. Because the duration of the hair cycle differs for different body sites (Table I), repeat treatments are usually done when there is a wave of rapid hair regrowth or between 4 and 8 weeks.[52]

Another issue is whether the hair follicle is able to regenerate from the bulge area if the papilla is destroyed by a photothermal source. Some researchers claim that hair follicles can regenerate in the absence of the hair bulb,[53,54] while others maintain that the destruction of the hair papilla is essential for permanent epilation.[55] The recent bulge-activation hypothesis maintains that the bulge area of the outer root sheath near the arrector pili muscle insertion contains pluripotential cells, which contribute to the new hair matrix when induced by the dermal papillae during the late telogen phase.[14] Thus, injury to the stem cells in the bulge area would lead to follicular destruction.

Safety and skin color

Although numerous lasers are available for laser-assisted hair removal, their use in individuals with a dark skin type presents many challenges due to competition from epidermal melanin. The ideal candidate for hair removal is a light-skinned individual with dark terminal hair. Dark skinned patients with high epidermal melanin content are prone to adverse side effects ranging from immediate pain and pigmentary disturbances to scarring. Despite the selection of appropriate wavelengths and pulse widths of the targeted chromophore, there is light absorption by the overlying epidermal melanin (Fitzpatrick skin types IV–VI).

Short wavelength (694, 755 nm) hair removal lasers can be quite successful in lighter skin types. However, laser hair removal in Asians can be difficult, and multiple treatments are usually required for effective treatment. Recently, Hussain et al[56] evaluated the safety and efficacy of alexandrite laser hair removal in 144 Asian subjects with Fitzpatrick skin types III–V. The authors reported that no individuals had scarring or long-term pigmentary changes and concluded that there does not appear to be an exact correlation in Asian skin between complications occurring after test patch treatment and those seen with subsequent treatments.

In a multicenter prospective study, laser hair removal was associated with a low incidence of side effects that were self-limiting in the majority of cases. The highest incidence of side effects was seen in patients with darker skin treated with the long-pulsed ruby laser.[57] However, the parameters for laser hair removal emphasize use for Caucasians (Fitzpatrick skin types I, II, or III). The characteristics of oriental skin and hair are black, coarse hairs in darker skin (Fitzpatrick skin types IV or V) and therefore the hair is more difficult to remove by laser. Recently, Lu et al[58] report 146 oriental patients (156 body sites) who underwent treatment with the long-pulsed alexandrite laser (755 nm wavelength) depilation system. Minimal and transient complications were noted.

In a retrospect study of 900 patients who underwent laser-assisted hair removal, Nanni and Alster[59] found direct association of skin type on the risk of side effects. Table III describes selected adverse side effects that may occur during or following laser/light-based hair removal treatment. Adrian and Shay[60] studied laser hair removal in African-American patients with skin types V and VI. Histologic studies examined efficacy and side effects in an effort to optimize laser hair removal procedures in this patient population. It was found that both laser modes could be used safely in skin type V and VI African-American patients; however, longer pulse durations enabled the delivery of higher fluences with minor and acceptable postoperative complication profiles.

Event	Occurrence
Dyspigmentation (hyper or hypo)	Common
Itching, stinging (during treatment)	Common
Pain	Atypical
Follicular erythema	Common
Epidermal erythema	Common
Purpura	Uncommon
Crusting/scab formation	Uncommon
Swelling	Uncommon
Erosions	Uncommon
Herpes simplex	Uncommon
Scarring	Rare

Table III

Adverse side effects during/following photoepilation

In order to avoid thermal damage of the epidermal matrix, current laser and non-laser devices use various parameters of cooling means by different techniques. Currently popular cooling techniques include contact (circulating cold water at 2–6°C or sapphire), cryogen cooling or forced flow of chilled air. In general, the rational of cooling the skin is to allow the delivery of higher fluences and short pulse widths into the hair follicle.[61] During long pulse modes (>100 ms), however, the epidermis tolerates a narrower temperature gradient in respect of the cooling method applied. Thus, to achieve effective epidermal protection, the hair color (i.e. black, blond), skin type (Fitzpatrick skin types I–VI) and cooling types should be carefully considered. Since adverse side effects are directly correlated with skin type, with darker-skinned and tanned patients experiencing a much higher rate of complications, skin types IV–VI and tanned skin are best treated with a diode laser (800 nm) or a Nd:YAG (1064 nm) laser. A physician who has a good understanding of hair biology, laser optics, and patient skin phenotypes is able to improve patient outcome and reduce untoward adverse side effects. Nevertheless, no system can provide fully predictable results.

Treatment frequency

Factors that affect the outcome of treatment include the hair growth cycle, skin color, hair color and density, and the quality of the individual hairs. Table IV shows factors that may influence photoepilation outcome. Because the duration of the hair cycle differs for different body sites, repeat treatments are usually done. As a general rule, 6 to 10 laser sessions are required during the first year to achieve long-term epilation. With most laser systems, a single treatment can reduce hair by 10–40%; three treatments by 30–70%; and repeated treatments as much as 90%. These results are maintained at post-treatment follow-up for as long as 12 months. Wendy and Geronemus reported a lower level of hair regrowth after three laser treatments on the face compared with the back, shoulders and arms.[62] Based on the duration of cycle length, hairs on the head have a relatively short telogen phase (6–12 weeks). Thus, a 1-month interval between treatments is a sufficient time elapse for progression to the anagen phase. On the trunk, a 2-month interval is more appropriate. Figures 3

Laser parameters
Wavelength
Fluence
Spot size
Pulse width
Skin cooling system
Skin phenotype
Fitzpatrick skin type I–III
Fitzpatrick skin type IV–VI
Hair characteristics
Hair thickness
Hair color
Follicle depth
Anagen/telogen follicles ratio
Hair anatomical location
Hormonal
Cushing syndrome
Polycystic ovarian disease
Hormonal medications
Testosterone and estradiol
Growth factors (IGF-1)
Others
Gender
Photosensitive medications
Plucking, waxing
Sun tanning

IGF=insulin-like growth factor

Table IV

Factors influencing hair removal efficiency

and 4 depict the before (A) and after (B) clinical results of laser hair removal.

Controversies and limitations

With the proliferation of devices targeting hair and unsubstantiated claims by manufacturers, significant confusion exists in this field. Although an ever-increasing number of published studies have confirmed the long-term efficacy of laser and light-based treatments, the technology still has limits and risks. Most studies on laser hair removal are uncontrolled and have included fewer than 50 patients; none have been blinded, and all have used a variety of treatment protocols, equipment, skin types and hair colors. In addition, none of the presently utilized lasers have been proven to destroy hair permanently and long-term results are still lacking. Because lasers and light-based systems were rushed onto the market without a full understanding of their capabilities and limitations, it is vital that researchers, practitioners and consumers continue to make their experience known to the public. Current data on laser and light-based hair removal are limited by the short duration for which this technology has been practiced. More long-term studies with state-of-the-art laser hair removal technology are still needed to elucidate the optimal parameters clinically appropriate for safe and effective results in all skin and hair types/colors.

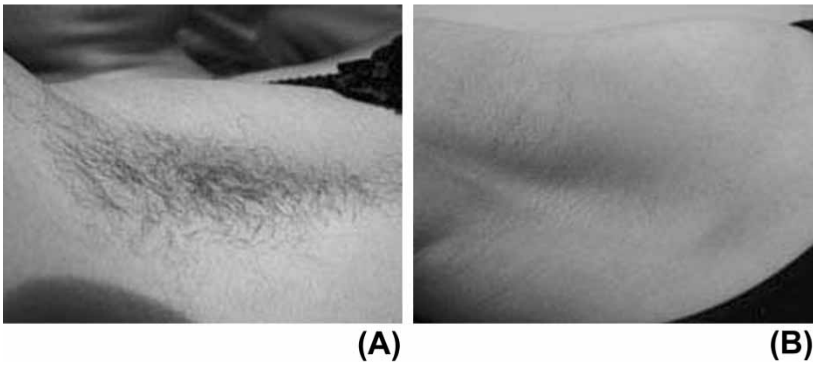

Figure 3

Clinical results. Skin type III: female. (A) Before and (B) 3 months after three treatments. (Courtesy of Pio Donnarumma, MD, Napoly, Italy.)

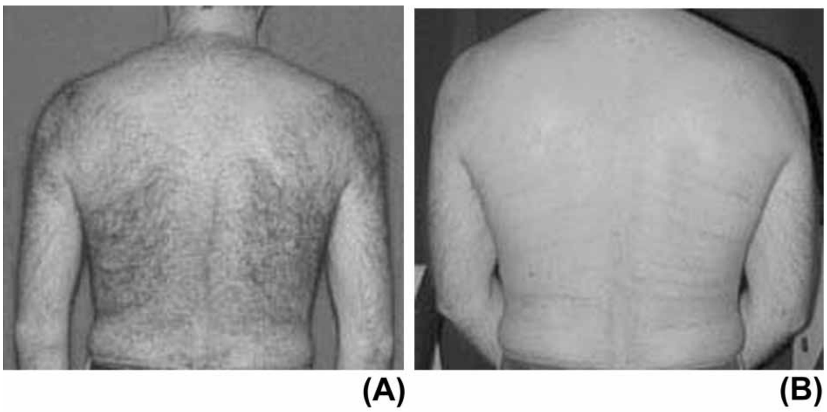

Figure 4

Clinical results. Skin type III: male. (A) Before and (B) 3 months after three treatments plus control. (Courtesy of Pio Donnarumma, MD, Napoly, Italy.)

Summary

The use of lasers/light-based technology in the treatment of unwanted hair has become commonplace in our society. Today, less than a decade after the first laser hair removal debut, there are at least 20 manufacturers producing more than 40 laser/light-based systems.[63,64] The acceptance of photoepilation by both physicians and patients is a direct reflection of the high degree of efficacy, low side effects and few complications. The benefits of this technology, however, have largely been limited to individuals with dark hair and relatively fair skin.

The major challenge in the field of photoepilation continues to be the development of technology that not only permanently and significantly reduces the number of hairs but also provides permanent and complete hair removal for all skin and hair types and colors. With current technology, the average clearance rate is 20–75% after 1–6 months of follow-up. Long-term studies with a follow-up of more than 1 year are needed to find out whether permanent hair removal can be accomplished.

Recently, the increasing public demand for a low-cost hair removal service has urged new manufacturers to develop low-priced, compact sized systems, which still need clinical validation and long-term follow-up.

Photoepilation, although better studied than most methods and more strictly regulated, has yet to be proved permanent in all patients and in all hair colors. With the rapid pace of technological advancements and continued studies of hair biology, laser physics, skin optics and cooling means, it is anticipated that permanent hair removal will be achieved in the near future.

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