THEORETICAL CONSIDERATIONS IN LASER HAIR REMOVAL

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Recent clinical trials have underscored the possibility of using light to selectively destroy hair follicles.[5, 10, 15, 17, 19, 22, 24, 50] Although there are many systems in various configurations, at present, the procedure has not resulted in predictable permanent follicular destruction of an entire operative field. Permanent removal that does occur using these systems appears to be a result of multiple treatment sessions. In this article we will examine the biological and physics bases of laser hair removal. The first section gives an overview of the anatomy and biology of the follicle, particularly within the context of designing optimal laser parameters for effective laser hair removal. The second section deals primarily with physical considerations but constantly attempts to relate optical-thermal phenomena of light-based hair epilation to the unique anatomic and physiologic features of the hair follicle.

EMBRYOLOGY AND ANATOMY

The first hair follicles are formed at the end of the second and the beginning of the third month of gestation in the eyebrow region, upper lip, and chin. The bulk of the remaining follicles begin to develop at 4 to 5 months' gestation in a cephalad to caudal direction. No further neogenesis occurs after birth.[25, 26, 54, 55, 78]

Each follicle is formed by an interaction between dermal and epidermal components. In the pregerm stage, there is an accumulation of cells from both components: focal crowding of nuclei of basal cells and an associated cluster of mesenchymal cells form the primitive hair germ. A solid column of epidermal cells progressively penetrates into the dermis passing through the germ, peg, and bulbous peg stages of development to form a rudimentary hair follicle. The peg is a solid column of epidermal cells that grows obliquely downwards. The broad tip becomes concave and encloses the dermal papilla (bulbous peg). Two swellings appear at the posterior edge of the follicle with the upper swelling representing the future sebaceous gland and the lower bulge representing the site of attachment of the arrector muscles. The hair emerges from the surface at an angle such that the arrector pili muscle (and bulge) are located along the deeper aspect of the follicle.

Anatomically, the hair is divided into three units: infundibulum, isthmus, and inferior

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segment. The infundibulum includes the region from the hair follicle orifice to the sebaceous duct entrance. The isthmus encompasses the region between the entrance of the sebaceous duct and the arrector pili muscle. The inferior segment is the region that extends from the insertion of the arrector pili muscle to the base of the follicle and includes the hair bulb.

The hair bulb is the extended lower portion of the hair follicle and is composed of matrix cells, interspersed by melanocytes. It encloses a mass of richly vascular connective tissue known as the dermal papilla, which is continuous with the fibrous sheet that envelops the entire follicle. The germinative matrix cells of the hair bulb differentiate along separate pathways and form, from the outside inward, the outer root sheet, the three layers of the inner root sheet (Henle, Huxley, and cuticle of the inner root sheet), and the three layers of the hair shaft itself (cuticle of the hair shaft, cortex, and medulla).[27, 31]

The hair shaft is a cornified structure that protrudes above the surface of the skin. The innermost layer, the medulla, is discontinuous and sometimes absent. The hair cortex consists of densely packed, fusiform, cornified cells that are aligned with their long axes parallel to the shaft of the hair. The cells of the hair cortex contain a type of keratin that is rich in disulfide bounds, which gives the hair its tensile strength.[14, 20, 21] The flattened cells of the cuticle overlap each other to form an imbricated cylinder around the cortex.

Hair Growth Cycles

The growth of hair is characterized by cyclic periods of growth and rest, called respectively anagen and telogen. The transition period between growth and rest is known as catagen.[46] The duration of anagen and telogen differs from one part of the body to another, as attested by the different lengths of hairs in different parts of the human integument.[47, 61] Scalp hair has a longer anagen cycle than in other body regions and can last up to 4 to 6 years,[40, 41, 47, 61] whereas the telogen phase usually lasts approximately 3 months.[61] Hairs from other body sites—eyebrows, hands, ears, chest, arms, and legs—have much shorter anagen phases, ranging from 4 to 7 months, and comparatively longer telogen phases, lasting up to 9 months.[46, 55, 68] The catagen phase is relatively constant and lasts generally for 3 to 4 weeks. Because each follicle has its own cycle, independent of adjacent follicles, accurate measurements of the duration of phases of the hair cycle are difficult. This is in contrast to other animals, for example rats and mice, where all hairs in a region are synchronized.

At any given time, the majority of hair follicles on the scalp are in anagen (80% to 85%), and the remaining follicles are either in catagen (2%) or telogen (10% to 15%).[40, 41, 46, 55, 68, 78] On other body parts (hands, arms, and legs) 50% or more of the follicles are in telogen.[61] Therefore, the length of hair in any region is primarily a function of the relative durations of anagen and telogen, although even within the anagen phase, there are variable "per day" growth rates specific to body region.

The histologic appearance of a hair follicle also differs dramatically with the stage of growth.[41] The anagen follicle penetrates deepest in the skin, typically to the level of subcutaneous fat. Catagen is characterized by pyknotic changes in the nuclei of the keratinocytes, followed by apoptosis of the transient portion of the follicle. The entire transient portion (which begins at the level of the insertion of arrector muscle and extends to the deepest portion) is absorbed, except for the basement membrane, which folds up like an accordion, causing follicular retraction and therefore higher placement of the papilla within the dermis. At this stage, the epithelial strand is reduced to a "secondary germ." This bud and the underlying dermal papilla form the telogen germ unit from which a new anagen hair is believed to develop.[29] Recently, it has been proposed that new anagen growth is initiated by cells that reside in the "bulge."[16, 42, 65] As a new anagen progresses, the secondary hair germ descends, enlarges, and begins to produce a new hair shaft.

Laser Hair Removal

Laser hair removal is based on the principle of selective photothermolysis.[4] In analogy

with the destruction of blood vessels (where hemoglobin is the chromophore to target the surrounding endothelial cells) the pigmented hair shaft is chosen as the chromophore, to destroy the surrounding follicular epithelium. Many factors need to be taken into consideration when targeting hair follicles. In analogy with laser treatment of vascular lesions (where different vessels have a different hemoglobin content, vessel diameter, and vessel depth) hair follicles produce hair with widely different features at different sites. Follicles and their resultant hair shafts differ in type, diameter, depth, and color.

Types of Hair

Hair can be classified according to its texture and length; therefore, there are lanugo, vellus, and terminal hairs, and a whole range of intermediate types. Lanugo hair is the soft, fine hair that covers much of the fetus and is shed just before birth. The prominence of various hair shaft features (amount of pigment, hair shaft diameter, and extent of medulla formation) increases from vellus hairs to terminal hairs. The hair diameter is determined by the size of the papilla and the hair bulb.[74] The cross-sectional diameter of the bulb from terminal hairs ranges from 200 to 300 μm.[8,9] Typical diameters of the associated terminal hair shafts are somewhat smaller, ranging from 40 to 120 μm.[28] Vellus hairs shafts are not pigmented and are arbitrarily defined as having a cross-sectional diameter of 30 μm or less.[29] Secondary vellus hairs, or miniaturized or hypoplastic terminal hairs, have a similar diameter as vellus hair but are still pigmented.[77] Both vellus and terminal hairs go through all stages of the follicular life cycle, but the length of anagen is much shorter in vellus hairs.

The type of hair produced by any particular follicle can change. The most striking example is the replacement of vellus by terminal hairs at puberty.[59] On the other hand, in male pattern baldness, the terminal hairs are replaced by fine, short hairs that resemble vellus hairs.[26] Prior to the final transition to vellus status, there is a reduction in size of both the papilla and the matrix; therefore, early baldness appears to be largely owing to a progressive diminution in the size of terminal hairs.[74]

Depth

The bulb of terminal, anagen hair follicles is usually located in the subcutaneous fat. Depending on the thickness of the skin, this depth can vary from 2 to 7 mm. The bulb of vellus hairs and miniaturized terminal hairs lies considerably higher in the dermis, such that vellus hair bulbs extend to a depth less than 1 mm. During late telogen-early anagen, the bulb is more superficially located, in close vicinity of the bulge (1.5 mm deep).[74] The bulge, an area of pleuripotential cells near the insertion of the arrector pili muscle, maintains a constant depth throughout the hair cycle.

Hair Color

Hair color is genetically determined and depends upon the pigment content of the hair shaft.[13,51] Mammalian follicular melanocytes produce two types of melanin: the brownish black *eumelanin* and the reddish *pheomelanin*. They are biogenetically related and arise from a common metabolic pathway in which dopaquinone is a key intermediate.[57] The UV and visible spectra of eumelanin and pheomelanin show a gradual decrease in absorption in this range.[5,44] The absorbance at 694 nm is 30 times lower for pheomelanin compared to eumelanin.[45] Pheomelanin absorption is very small (Fig. 1) for wavelengths longer than 700 nm.[45]

Melanocytes characteristically occur in the upper part of the hair bulb and in the outer root sheath of the infundibulum. Amelanotic melanocytes are present in the outer root sheet of the mid and lower parts of the follicle and bulb. These melanocytes can become activated. Under the appropriate stimulus, the cells become dendritic, migrate upwards, and gradually become dopa-positive. They play an important role in repigmentation of epidermis of vitiliginous skin and after dermabrasion.[30,62–64] Concerning the distribution of these active and inactive melanocytes,

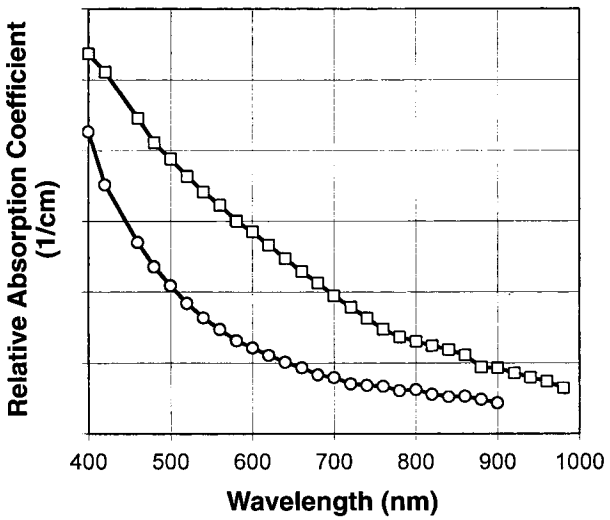

Figure 1. Relative absorption coefficients for black *(squares)* and blond *(circles)* hairs. Note that blond hair absorption is very small by 750 to 800 nm.

Staricco divided the hair follicle into four portions. Portion A and D, melanotic portions, constitute the upper part of the infundibulum and the upper part of the bulb, respectively. Portion B and C, amelanotic, is the mid and lower part of the follicle and the outer root sheet of the bulb, respectively.[62]

The pigmentation of hair follicles follows sequences of events identical to those seen in the epidermis. Analogous to the manner in which epidermal keratinocytes apocopate melanosomes from the dendritic processes of epidermal melanocytes, hair matrix cells that eventually differentiate to become the hair cortex and medulla also apocopate melanosomes from melanocytes within the hair bulb.

Follicular melanocytes differ from epidermal melanocytes in many aspects. They synthesize larger melanosomes and are only active during anagen stages III through VI.[12, 67] Also, hair melanocytes typically contain more melanosomes than their epidermal counterparts. Also, whereas there is only 1 melanocyte per 25 keratinocytes in the epidermis, that ratio increases to 1:5 in the hair matrix. Hair melanosomes stain the whole length of hair because they are only slightly degraded by keratinocytes.

At the onset of catagen, melanogenesis in the melanocytes of the bulb comes to a halt, the dendrites contract, and the cells assume a round shape with further dedifferentiation during telogen. Concomitantly, the transfer of pigment granules into the cortical cells also stops. Therefore the bulbous tip of a telogen hair is unpigmented. Melanogenesis resumes again in early anagen of the next hair cycle.

The relative composition of melanin pigments (eu- versus pheomelanin), as well as their absolute quantities, determines the wide range of colors of mammalian hair. Black or dark brown hair contain large, ellipsoidal, heavily melanized eumelanosomes, whereas red hair contains spherical pheomelanosomes.[32, 38] In blond hair, the melanocytes in the hair bulb produce fewer melanosomes or incompletely melanized melanosomes resulting in less light absorption than in dark hair (see Fig. 1). In gray hair, the melanocytes in the hair bulb are reduced in number and the melanosomes are poorly melanized. In senile white hair, there are no dopa-positive melanocytes.[13]

What Is The Best Target?

Yet to be solved questions for permanent destruction are the location of the key follicular target and the possible influence of the hair growth cycle on laser-induced hair removal. For many years, it has been assumed that hair stem cells are found in the matrix area of the bulb (which is located deep in the

dermis, typically 3 to 7 mm); however, recent evidence suggests that follicular stem cells are located in the outer root sheet, in an area called the bulge, near the attachment of the arrector pili muscle, approximately 1.5 mm below the epidermis.[43, 65] Interestingly, investigators have recently shown the presence of active dendritic melanocytes in the bulge. This melanization in the stem cell area was independent of hair cycle. Although the concentration of melanin was found to be far less than the bulb, the presence of any pigment may allow for direct bulge targeting rather than relying on heat diffusion from the well-melanized shaft.[49] Both bulge and bulb could be important for permanent hair follicle destruction. Because the depth and pigmentation of the bulb are dependent on the stage of the hair cycle, it is possible that the cycle influences the susceptibility to laser injury (vide infra).

Selective photothermolysis requires absorption of light, and the bulb of a telogen hair is unpigmented because of cessation of melanogenesis during catagen.[41] During early anagen, melanogenesis in the bulb resumes and the bulb is more superficially located, in close vicinity of the bulge. The bulge cells are rapidly dividing during this stage, making them also more susceptible to injury. They also lie in close proximity to the secondary hair germ. As anagen progresses, the bulb and papillae descend deeply into the dermis and beyond, such that late anagen hairs may also be relatively resistant to laser pulse injury. The bulge cells also become more quiescent. It follows that follicles should be most easily inactivated by laser pulses during early anagen.

PHYSICAL CONSIDERATIONS IN LIGHT-BASED* HAIR REMOVAL

The physical basis for laser hair removal is rooted in tissue optics and thermal responses to absorption of laser irradiation. Once the thermal response is known at the site of an absorber, tissue damage is characterized by rate processes. There will always be *some* heat diffusion away from the primary absorber, even in cases of apparent thermal confinement. In most instances, this collateral damage is undesirable; however, as the reader will discover in the following discussion, some thermal diffusion is necessary for follicle destruction outside the initial melanin target. The cascade of events can be summarized as follows (Fig. 2).[75]

1. *Analysis of beam propagation in tissue.* First, we must characterize the effective absorption and scattering losses from the epidermis down. This implies some knowledge of the wavelength-dependent optical properties of skin.
2. *Analysis of the optical and thermal properties of the hair shaft and surrounding structures.* This is important in predicting what happens once the beam interacts with the shaft and bulb. Optical properties determine the behavior of light within the hair shaft and bulb, including the relative amount of absorption of incoming photons. Once energy is absorbed, the rise in temperature is largely predicted by the thermal properties of the shaft, thermal properties of the surroundings, and the pulse duration.
3. *Next, heat is conducted from the shaft and melanized portion of the bulb to surrounding structures according to the laws of thermal diffusion.*
   a) *The thermal diffusion wave should achieve adequate time-temperature combinations for cell death and follicular unit destruction.* Equations of rate processes can predict the completeness of denaturation.
   b) *Finally, conduction of heat away from the peripheral follicle must also be considered.* Ideally, there should be minimal damage to collateral dermal structures.

Based on the anatomy and physiology of the hair follicle, one can argue that the hair bulge and bulb, as well as the entire follicle epithelium, are appropriate final targets for laser hair removal. Simultaneously, the epidermis should be preserved. Setting these criteria as conditions for successful laser hair

*During the discussion, the term "laser" will be used; however, the reader should realize that other light sources can be and are applied in hair removal. In general, the coherent properties of laser light are not relevant in tissue for photothermal phenomena.

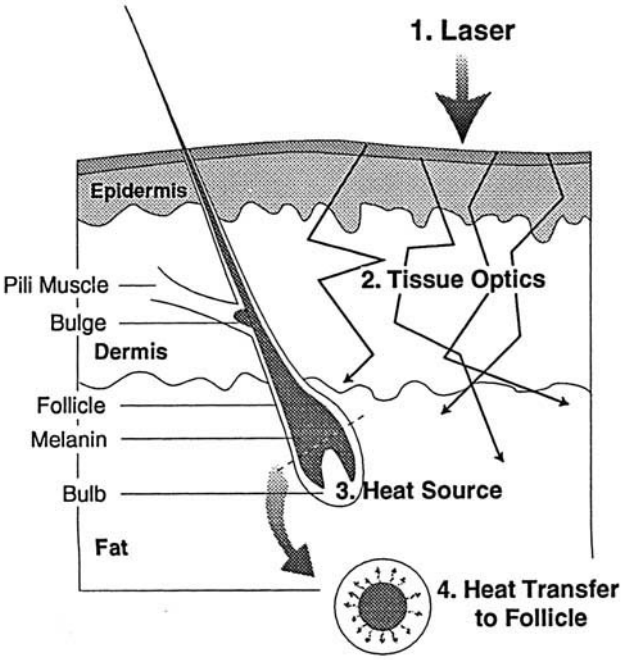

Figure 2. Cascade of events culminating in heating of the shaft and follicle. Note the relative positions of the bulge and bulb.

removal (LHR), we can develop a logical, scientifically rigorous, yet mathematically simplistic approach. Most present strategies use visible and near IR (infrared) light (700 to 1064 nm) with melanin as the chromophore. *Melanin*, although not a perfect target, offers the following advantages in therapy.

1. It is the major chromophore in the optical window between 600 and 1100 nm. This window allows for relatively deep penetration. Shorter wavelengths are associated with increased scattering (therefore limiting beam penetration) and competition with other chromophores (i.e., hemoglobin). Very long wavelengths (i.e., 1064 nm) show such diminished melanin absorption that very large fluences or very short pulse durations must be applied for significant hair shaft heating.[2, 5, 36, 44]
2. Most individuals demonstrate greater melanin density in hair versus the epidermis such that the absorption coefficient of the hair shaft and bulb is roughly 2 to 6 times that of the epidermis. This is consistent with casual observation, as even in a very pigmented person, the hair will appear much darker.
3. Melanin density tends to be highest in the bulb (this structure's destruction may be necessary for temporary or permanent hair removal). The other structure proposed as an important target, the bulge, was believed to be devoid of active melanocytes, but may contain small amounts of melanin (vide supra).

ANALYSIS OF BEAM PROPAGATION IN TISSUE

When discussing the physics of laser hair removal, the first consideration is delivery of photons to the target (melanin in the bulge, hair cortex, and bulb areas). It follows that one should have at least a rudimentary knowledge of tissue optics so that beam propagation can be understood. Because the skin is turbid, photons must negotiate a maze of absorbers and scatterers to reach melanin in the hair follicle. Briefly, when an incident laser beam strikes tissue, a part of the beam is reflected (8% specular reflection) and the remainder enters the tissue. Photons (light)

that enter the tissue are either absorbed or scattered. *Heat will only be produced at sites of photon absorption.*[33, 52, 75] Scattered light can be either backscattered or forward scattered. For the wavelength range we are considering, one can think of the epidermis as an absorbing medium and the dermis primarily (with the exception of the hair follicles) as a scattering medium.

During a .5-joule laser pulse, $>10^{15}$ photons enter the skin. Obviously, we cannot track each one as it propagates through tissue; however, because of the processing power of computers, their migratory behavior can be predicted by statistical models (called "Monte Carlo" models, interestingly, in reference to the "chance" element in photon migration). Typically, the person running the model inputs measured absorption and scattering coefficients for a particular wavelength. The computer then reports "traffic patterns" in tissue.[76] An analogy to photon migration is a modified pinball machine, where the metal balls represent photons. Now let us create some depressions on the playing surface of our special photon pinball machine. One of these depressions can represent our intended target (melanin in the shaft, bulge, and bulb). We will allow other depressions to represent potential unintended absorbers (i.e., melanin in the basal cell layer of the epidermis). In the course of a pinball traversing the table surface, it may be bounced about multiple times (representing *scattering*), in some instances even ricocheted back toward the top of the table. In other instances, the ball may fall into one of our depressions; at this point it is "out of the game" for practical purposes (representing *absorption*). Eventually, if we send enough balls into play, many will bypass all depressions and bumpers and finally be lost (these represent transmitted photons or photons scattered out of the beam).

Generally, light is attenuated as it propagates through tissue. In turbid tissue (i.e., the dermis, where collagen acts as the major scatterer), the fluence attenuation can be described by:

$$I(z) = I_o\, k\, e^{(-z/\delta)} \qquad \text{[Eq. 1]}$$

where $I(z)$ is the local subsurface fluence at some depth z, k is a constant that accounts for backscattered light and δ is the wavelength dependent optical penetration depth of light (Table 1 lists definitions and symbol conventions that are used throughout the text). δ is the depth at which there is attenuation to 37% of the surface value (37% $\sim 1/e$, where $e = 2.7$, the base of the natural logarithm). This depth is determined by absorption and scattering coefficients, as related by the simple equation below[56]:

$$\delta = \frac{1}{\sqrt{\mu_a(\mu_a + \mu_s(1 - g))}} \qquad \text{[Eq. 2]}$$

As μ_a and μ_s increase, δ decreases accordingly. Based solely on depth of penetration, longer wavelengths such as 800 and 1064 nm should be preferable to 694 and 755 nm. In the visible light range, this is why red light can penetrate one's hand when shining a flash light on the surface. Scattering decreases roughly proportional to $\lambda^{3/2}$, so that, for example, an 800-nm photon will on average travel about 1.3 times as far in tissue as a 700-nm photon without being scattered (Fig. 3). It follows that for more scattering wavelengths, there will be greater accumulation of photons near the surface. In addition to scattering, this superficial convergence of photons is based on index of refraction mismatches between air and tissue.[33] Accordingly, light must be deposited more slowly for shorter wavelengths to avoid heating the superficial tissue

Table 1. SYMBOLS USED IN TEXT

Symbol	Meaning
μ_a	Absorption coefficient, defined such that $1/\mu a$ is the distance over which light is attenuated to 37% of the surface fluence
μ_s	Scattering coefficient, where $1/\mu s$ indicates the mean free path between scattering events
k	Backscattering coefficient
Iz	Subsurface fluence at some depth 'z'
Io	Incident fluence
τ_r	Thermal relaxation time
τ_p	Pulse duration
δ	The optical penetration depth for a particular wavelength; this is determined by the scattering and absorption coefficients, as well as 'g', called the anisotropy factor, defined as $<\cos\theta>$, where θ is the photon deflection angle per scattering event (in tissue this is about 26°)

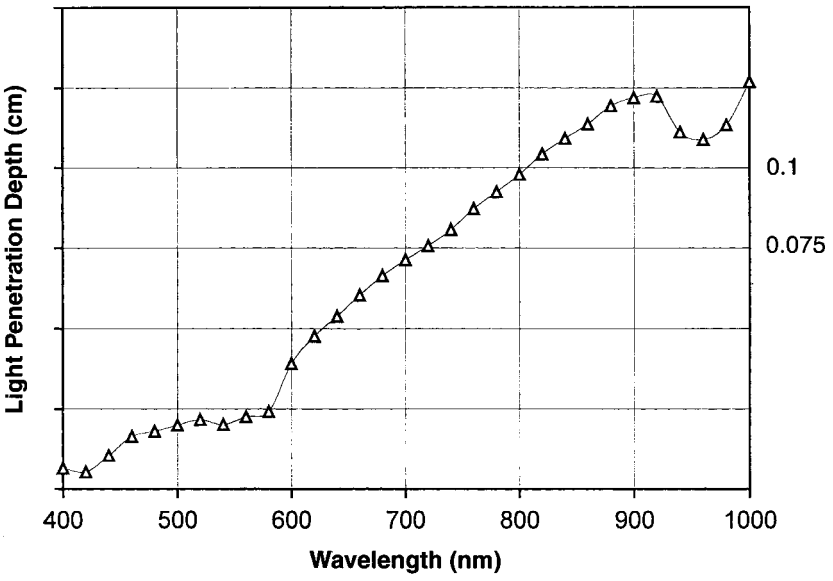

Figure 3. Light penetration depth into the skin as a function of wavelength.

too much. This is very important in LHR, because the epidermis is co-located with the bulk of backscattered photons.[56] Most importantly, as noted in Figure 4, backscattering results in the peak subsurface fluence being *larger* than the incident surface fluence.

A graph of skin reflectance is instructive to review (Fig. 5) as an aid in understanding

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Figure 4. Laser penetration and effect of scattering. Broad-beam laser penetration into clear versus turbid tissue. The penetration of a broad beam is plotted as fluence rate (W/cm^2) versus depth (mm) in a Monte Carlo simulation with an air-tissue surface boundary. With scattering, the light is backscattered toward the surface, where it accumulates. Note that the surface concentration of light exceeds the delivered irradiance, Ψ_o = 1 W/cm^2. The optical properties are absorption, μ_a, = 0.3 cm^{-1}; scattering, μ_s, = 40 cm^{-1}; anisotropy, g, = 0.9, and effective scattering, μ_s, = 4 cm^{-1}, which are typical for a red wavelength in tissue. The dashed line indicates the approximate expression $\phi(z) = \phi_o k \exp(-z/\delta)$, for $z > \delta$, where k is 4.4 and δ is 5.1 mm. (*From* Jacques SL: Laser-tissue interactions: Photochemical, photothermal, and photomechanical. Surg Clin North Am 72:539, 1992; with permission.)

tissue optics and beam propagation. Figure 5 shows the relative percentage of photons returned from the skin. It may seem surprisingly high, and it emphasizes the scattering nature of the dermis (and relates the relative inefficiency of laser applications in this wavelength range—we are wasting 70% of our photons). One observes that diffuse reflectance is the same over the 700- to 1000-nm range. This can be explained as follows: although shorter wavelength photons are more likely to be scattered back to the surface, proportionally more of them are absorbed by epidermal melanin. The net effect is that the same proportion of incident photons is remitted over this wavelength range.

ANALYSIS OF THE OPTICAL AND THERMAL PROPERTIES OF THE HAIR SHAFT AND SURROUNDING STRUCTURES

Heating the Hair Shaft and Bulb

Let us assume that to destroy the follicle we need to sufficiently heat the hair bulb, approximately 2.5- to 4-mm deep in the skin. Before designing an optimal set of laser parameters based on anatomic and physical principles, we can first determine a time-temperature combination that should result in transfollicular denaturation. Then we can backtrack and determine a spot size, wavelength, pulse duration, and fluence combination that achieves this goal. A reasonable time temperature combination for destruction (i.e., 3 msec and 100 degrees) is based on *rate kinetics*. Cell death and collagen denaturation are governed by rate processes where tissue constituents transition from the native to damaged state. In general, for every 5°C increase in temperature, one should reduce the time exposure a factor of 10 for equivalent damage. For very short times (<0.1 seconds), accurate rate constants are unavailable and may not coincide with predictions based on those for longer exposure domains.[1, 39, 53, 58, 71, 75, 76] Still, a 100°C, 3-msec combination should be sufficient for cell death and at least some denaturation of collagen fibrils.

From this target temperature rise in the bulb, we can use simple energy balance and approximations of tissue optics formulas to calculate the necessary incident fluence for bulb destruction at 700 nm. Unlike μsec and nsec exposures, where melanosomes are vaporized at 694 nm through thermal confinement with low fluences (2 to 5 J/cm^2)[35] for permanent hair removal, we should heat the

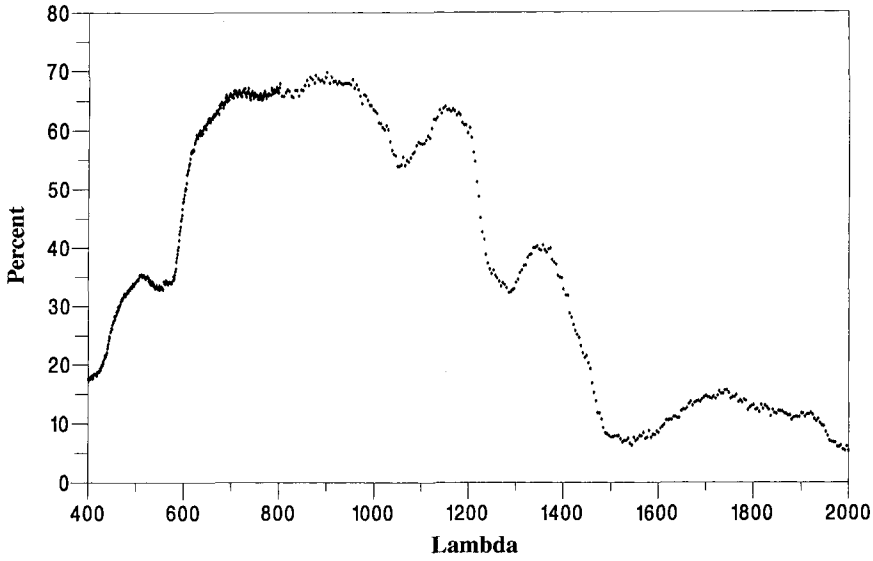

Figure 5. Reflectance of skin in Type II skin.

melanosomes more slowly so that thermal diffusion *is allowed* during the pulse. This allows for gentle heating of the melanosomes, which prevents their vaporization. By gently heating the melanosomes, which is allowing heat to "leak out" during irradiation, we achieve two goals.[2] One, we prevent the melanosomes from reaching very high temperatures. This helps to preserve the epidermis (so long as we don't heat too long). Secondly, we ensure adequate heat diffusion to the surrounding follicle from the melanized bulb and shaft.

We can simplify our energy absorption and subsequent heat generation by assuming that the melanosomes are distributed such that the shaft and bulb are treated as a homogenous absorber with weighted melanin content rather than innumerable discrete absorbers. Although not entirely rigorous, studies support such an approximation, especially when looking at thermal responses great distances away from the absorber.[60] In fact, the multiple small heat sources produced by local melanosome absorption within the basal cell layer, hair shaft, and hair bulb appear as one cylindrical or plane source from tens of microns away. An analogy is viewing a string of streetlights from an airplane at night. They appear as one solid line of lights until the plane is close enough that the eye can resolve them into individual sources.

Now consider our melanized hair cortex and bulb as a cylinder with uniform absorption coefficient. We consider it to have dimensions of approximately 200 μm in diameter. Then ΔT_{max} is determined by the expression:

$$\mu_a F = \rho c \Delta T \qquad \text{[Eq. 3]}$$

which follows from conservation of energy. (Recall the high school physics expression, $E = m c \Delta T$, where E is the energy deposited and m is the mass of the body to be heated, and c is the specific heat, or the energy required to raise the temperature of a gram of material by 1°C.)

In the above expression, F is the local subsurface fluence, ρ is the hair density, and c is the specific heat in J/°C-g. Recall that only absorbed photons generate heat; this accounts for the factor "μ_a" in the expression. (Approximate μ_a values are listed in Table 2 for dark/light hair and skin). It follows from simple algebra that:

Table 2. APPROXIMATE VALUES FOR μ_a FOR 700 nm LIGHT (CM^{-1})*

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*Values for hair from unpublished data of David Lin, PhD, MD, Wellman Laboratories of Photomedicine, Boston, MA.

$$\Delta T = \mu_a F/\rho c \qquad \text{[Eq. 4]}$$

This expression simply states that the temperature rise in the target is proportional to the amount of absorbed energy. It is accurate, however, only if there is perfect thermal confinement; that is, no heat can diffuse during the laser pulse (approximate τ_r values for relevant structures are listed in Table 3). Otherwise the maximal temperature will be reduced as some of the energy will have "leaked out" of the chromophore during irradiation (vide supra).

In determining the thermal properties of the tissue components, we consider the shaft, bulb, and epidermis as composites of protein, water, and melanin. We then allow this composite body to assume physical parameters based on weighing the respective thermal properties of the components, so that:

ρ (hair density) = 1.3 g/cm³
c = specific heat ~ specific heat of water (× 0.2 for the shaft, and 0.7 for the bulb)
= ~1.5 J/°C-g for the shaft
= ~3.5 J/°C-g for the bulb
c for water = 4.2 J/°C-g

This allows us to calculate the temperature rise of the bulb area for a 700-nm (near ruby)

Table 3. THERMAL RELAXATION TIMES FOR VARIOUS STRUCTURES

Structures	τ_r
Whole epidermis (100 μm)	10 msec
Hair shaft—mid dermis	3–5 msec
Basal cell layer of epidermis	0.1 msec
Hair follicle (mid dermis)	20–30 msec
Individual melanosome	0.001 msec
Hair bulb	20–40 msec

3-msec laser exposure. As noted previously, we base our calculation on conservation of energy [there should be minimal diffusion out of the bulb during the laser pulse because 3 msec $<\tau_{r\ bulb}$ (~20 msec)]. It can be shown that as a first order approximation:

$$\Delta T_{max} = \frac{\mu_a (I_o)\, k\, e^{-z/\delta}}{\rho c} \qquad \text{[Eq. 5]}$$

Where k = the backscattering coefficient = ~3 (this coefficient accounts for the photons that accumulate near the skin surface from being bounced back toward the epidermis): δ = 750 μm (a good estimate for 700 nm for type II skin).

If we set the threshold temperature for destruction at 100°C, then ΔT should be ~65°C (assuming a baseline temperature of 37°C) if we assume perfect thermal confinement. Solving for I_o, we calculate an incident fluence of 20 J/cm²; however, even at ~0.1X τ_r (3 msec for a structure with 30 msec τ_r), there will be some heat diffusion during the laser pulse such that the derived value for I_o should be multiplied by ~1.2. It follows that the threshold surface fluence for bulb destruction at 700 nm should be roughly 25 J/cm².

Now we must determine if the epidermis can tolerate the 25 J/cm² necessary for bulb destruction. By using the following equation

$$\Delta T_{max} = (I_z\, k\, \mu_a/pc)\, (\tau_r/\tau_r + \tau_p)] \qquad \text{[Eq. 6]}$$

we derive that ΔTmax for the basal cell layer (with μ_a of 100 cm⁻¹ and τ_r of 0.1 msec) will be roughly 70°C. Assuming a baseline temperature of 37°C, the peak temperature will be about 110°C. The factor $(\tau_r/\tau_r + \tau_p)$ scales the effect of thermal diffusion during the pulse. This will be significant for 3-msec pulses and allows for some basal cell layer cooling through heat diffusion to the surrounding dermis and upper epidermis. This "gentle" heating reduces Δ Tmax from the >1000°C that would result from μsec or nsec domain pulse durations at this wavelength; however, in Type II skin, even a 110°C temperature elevation might result in epidermal necrosis, so that use of a surface cooling device would be prudent (vide infra).

Deep in the follicle, we calculated a ΔT_{max} nearly identical to the basal cell layer. This appears counterintuitive because the hair bulb is buried deep in the dermis, and the local subsurface fluence is considerably less; however, the similarity in ΔT max can be explained by:

1. The larger μ_a for the hair bulb.
2. More rapid cooling of the thinner basal cell layer.

HEAT DIFFUSION TO BULGE AND SURROUNDING TISSUE

Once we have established a temperature rise in the bulb and shaft, we now have a hot black cylinder that cools to 1/2 T_{max} on the order of 3 to 40 msec (3 to 5 msec for the mid-shaft and 20 to 40 msec for the bulb, respectively). We have already established that the 3-msec pulse is sufficient to raise the bulb temperature to a lethal time-temperature combination; however, have we provided enough heat for bulge destruction? This will require that significant thermal diffusion occurs from the mid-shaft. Because of the 3-msec pulse duration, this will occur primarily after the pulse. Using our previous formula for calculation of ΔT_{max}, we find the mid-shaft temperature for a surface fluence of 25 J/cm² will be ~600°C. We can estimate the temperature to be 100 μm outside the shaft at τ_p = 3 msec by using a first-order approximation of the solution for the heat conduction equation. Thermal diffusion is driven by the temperature difference between the hot hair shaft and cooler surrounding tissue. The solution yields a ΔT_{max} of only 11°C at the end of the laser pulse; however, after another 3 msec (or 2× τ_r of the hair shaft), the temperature will rise by about 100°C at the bulge as the thermal diffusion wave travels radially, and the temperature profile broadens. This suggests that it is *possible* to destroy the hair bulge with fluences on the order of 25 J/cm² with the ruby laser. It should be pointed out, however, that our calculation assumes pure conductive heat diffusion, when in fact some melanosomes may vaporize in the shaft. This will lead to lower temperatures in the tissue surrounding the bulb and hair shaft, and may account for reports of only sporadic permanent hair removal with 3-msec ruby-based hair removal systems.

In our calculations we have made approximations. For example, we have assumed uniform heating in any cross-section of the hair at a particular depth, when in reality the hair fiber will demonstrate a temperature gradient radially as well as axially (along the shaft). Because the bulb and fiber are not infinitely thin cylinders, the surface facing the epidermis will be preferentially heated. One would therefore expect greater effects surrounding the epidermal "side" of the bulb and shaft. Indeed this is the case; in some instances one will see greater photomechanical effects and even vacuoles on this side of the shaft; sometimes these vacuoles extend into the dermis as small tracts. These may represent focal zones where steam attempted to "vent" through the tissue. Unfortunately, the bulge resides on the deep aspect of the follicle; this may attenuate the local temperature rise in this zone of pleuripotential cells.

It should be noted that because the specific heat of the hair shaft is approximately half that of the dermis (due to its smaller water content), a given amount of light energy absorption will cause the hair temperature to increase roughly by a factor of two, compared to the temperature rise of the dermis. Therefore, even if the absorption of dermis and hair are equal (i.e., there is no color contrast between the hair and the surrounding tissue) hair can still reach twice the final temperature of the dermis as a result of laser treatment.

Also, because the thermal conductivity of fat is about 70% that of dermis, the bulb will take longer to cool by a factor of about 1.3×. In short, the fat insulates the bulb (increases the thermal resistance) so that the thermal relaxation time increases (from about 30 msec to 50 to 100 msec). Therefore, equivalent local subsurface fluences should raise the follicle temperature at the level of the bulb to a greater degree than at the level of the arrector pili muscle.

Recently, longer pulses (~20 msec) have been used with longer wavelengths (800 nm) and higher fluences (40 to 60 J/cm^2). This combination of parameters has been shown to cause more complete follicular destruction, with thermal denaturation sometimes extending to the surrounding dermal stroma. Microscopically, damage is more consistent with pure subablative heating, with little evidence of steam bubble formation in the shaft of photomechanical disruption of the inner root sheath (IRS) or outer root sheath (ORS) (which can be seen with the 3 msec ruby laser).[17, 18] Although fluence, wavelength, and pulse width were all changed in relation to the previously discussed ruby configuration, physical models would predict that pulse duration is most responsible for the different histologic findings. For comparison, we have calculated ΔT_{max} for the mid-shaft, bulb, and bulge for an 800 nm diode laser with 20 msec pulse duration, and 25 J/cm^2 surface fluence based on the same simple formulas used above. These results are in Table 4 along with our results for the 25 J/cm^2, 3 msec 700 nm system (ruby-like).

SPECIFIC THEORETICAL ISSUES IN LASER HAIR REMOVAL

Spot Diameter

Spot diameter should play a role in optimizing laser hair removal. This is because larger spots, although they do not increase intrinsic scattering, allow for a greater likelihood that photons will be scattered back into the incident collimated beam. This results in less beam broadening. Photons that are scattered out of the beam are essentially wasted. Traveling "alone", they do not carry enough energy to cause macroscopic thermal responses in tissue. The effect of spot size in beam propagation is not necessarily intuitive, as most novices assume that a smaller beam, even with the same surface energy density, somehow results in deeper penetration. The consequences of spot size are explained as follows. Basically, for small beams (narrow) scattered photons are carried out of the beam path only after a few scattering events. In essence these photons are now in such low density that they have no tissue effect in the subsurface broadening beam.[17, 18, 72, 73] A good analogy is a highway with exits. With a narrow highway, any movement obliges the auto to "take" the exit, and the car does not return to the road. On the other hand, on a superhighway with many lanes, cars can move

Table 4. 700 nm VS. 800 nm: THERMAL RESPONSE FOR DARK HAIR AND FAIR CAUCASIAN SKIN

λ	700 nm (3-msec pulse)	800 nm (3-msec pulse)	800 nm (20-msec pulse)
δ	750 μm	1200 μm	1200 μm
T max dermato-epidermal junction	110°C	72°C	45°C
T max mid-shaft as level of bulge (1.5 mm)	600°C	260°C	170°C
T max bulge	120°C	60°C	102°C
T max bulb (3 mm)*	100°C	230°C	125°C

*Because of insulation by fat, these temperatures may be underestmiated.

about and stay within the original boundary of the thoroughfare. Only cars on the extreme left and right are likely to "get" off the road.

In reviewing Figure 6, one sees that greater photon density is present deeper in the tissue for larger spots. Note that even for the larger spot (20 mm), there are edge effects. This means that for deeper targets such as the hair bulge and bulb, one might expect variability in treatment success based on the precise location of the spot. Areas treated near the edge of the beam are more likely to receive lesser subsurface fluences. Generally, spot diameter should be at least 4× δ. In effect, larger spots increase the dermal/epidermal damage ratio as well as the relative penetration depth.

Advantages and Disadvantages of a Broad Band Source

Nonlaser light sources have been shown to achieve effective hair removal.[19] Recall that the melanin absorption curve is fairly smooth across 600 to 1000 nm (see Fig. 1). Therefore, one could design a light source whose output spectrum extends across the 600- to 1000-nm range. Furthermore, a high output source such as a xenon arc lamp can be filtered such that shorter wavelengths are blocked for darker patients, therefore avoiding high temperatures in the epidermis. On the other hand, the shorter wavelengths (starting at 600 nm) could be used in lighter patients with brown and dark hairs, therefore maximally exploiting the contrast between skin and hair color. Also, red-brown hair could still be theoretically targeted. A disadvantage is that present broad-based sources are configured with large rectangular spots so that it is impossible to treat hair-bearing areas where there are extreme convexities or concavities.

Focusing the Laser Beam

A trick to increase the dermal to epidermal damage ratio is use of a convergent lens. The goal is to increase the local photon density at the bulge and bulb while sparing the epidermis. Theoretically, one should be able to use smaller incident fluences, therefore achieving some protection of the epidermis. Because of tissue scattering and subsequent beam broadening, the increased subsurface photon densities that would be predicted in a transparent medium are not realized. Still, there should be a relative increase in deeper photon density versus using a more collimated beam. Overall, using a converging lens becomes less effective when the depth of the target exceeds δ. This is because the photons will have been scattered by this depth and less likely to stay on a converging course.

Compacting the Dermis

This leads to the next trick, decreasing the depth photons must propagate by simply applying pressure over the skin. It can be shown that this maneuver may decrease the relative depth of the bulb and bulge up to 30% relative to the skin surface. Disadvantages might include variability in the amount of pressure, such that adjacent treatment areas are exposed to different subsurface fluences. Also, it is unclear if compacting the dermis might alter its scattering properties. In theory, compression should decrease water content and improve dermal transmission.

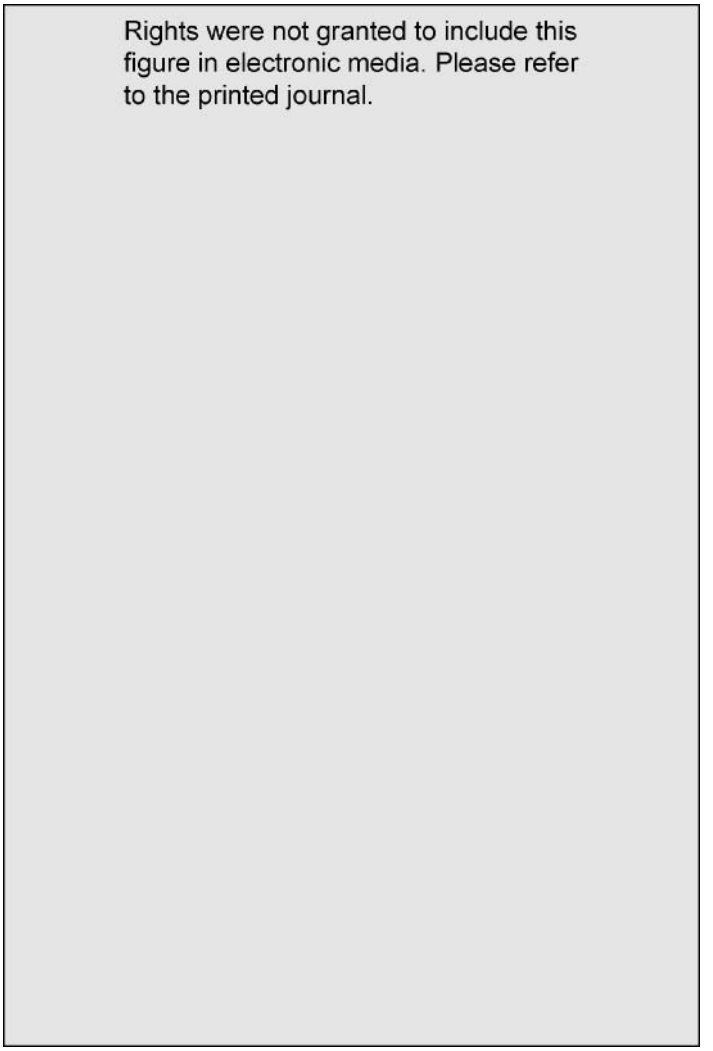

Figure 6. Narrow beam laser penetration into tissue. *A*, Broad beam, with a radius of about 4δ where δ is the optical penetration depth, achieves the maximum penetration with the minimum fluence rate near the surface. *B*, Narrow beam, with same total energy (3124 mW) as *A*, achieves similar penetration but causes a very high fluence rate near the surface, which will ablate the tissue surface. *C*, Narrow beam, same irradiance (1 W/cm^2) as *A*, has low fluence rate near surface but very little total energy so the penetration is shallow. (*From* Jacques SL: Laser-tissue interactions: Photochemical, photothermal, and photomechanical. Surg Clin North Am 72:541, 1992; with permission.)

Pulse Duration and Multiple Pulses

There are at least two arguments for using longer pulse durations than those that allow for thermal confinement of the melanosome. As noted previously, one is to increase the likelihood of full transfollicular destruction (Figs. 7 and 8). In contrast to treatment of epidermal pigmented lesions, where we desire thermal confinement to the melanosome, in laser hair removal some heat diffusion is desirable. Q-switched lasers have been used in animal studies of pigmented skin. Anderson et al showed that the Q-switched ruby laser produced leukotrichia.[3] Basically, the melanin was "super" selectively vaporized, leaving vacuoles in the hair shafts; however, the follicle units survived.

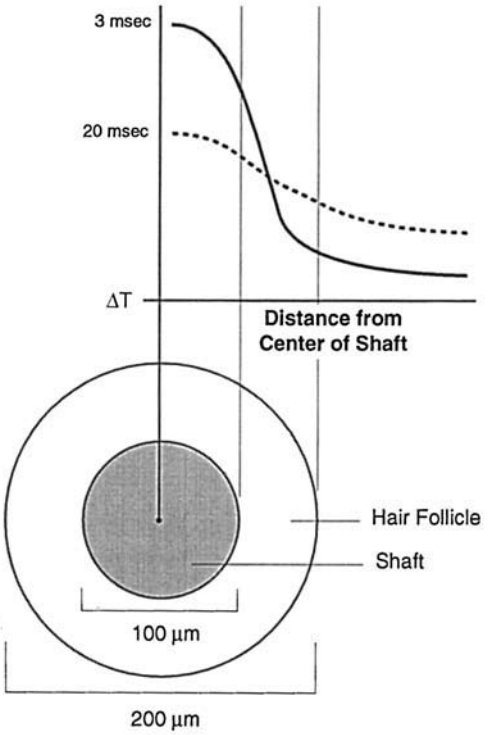

Figure 7. Effect of pulse duration on broadening of radial temperature profile. Note that longer pulse results in less heating of the mid shaft but comparatively greater heating of the peripheral follicle.

The second justification for longer pulses is to spare the epidermis from melanosome vaporization and therefore intense heating. This is the concept of "gentle" heating (in a sense the opposite of selective photothermolysis). With short exposures (near τ_r for the melanosome, about 1 to 5 μsec), heat accumulates within the melanosome with very little diffusion out of the organelle during the pulse. With longer heating times, the basal cell layer is allowed to *cool as it is heated* (an analogy is a bucket where water in the bucket represents heat. If we put holes in the bottom of the bucket and slowly fill it with water, the bucket never fills, and water (heat) leaks out to surrounding area; however, if we fill the bucket quickly, initially the water fills the bucket, and it only begins to empty after we stop flooding it). With gentle heating, the melanosome peak temperature is diminished, albeit at the expense of surrounding cells in the upper epidermis and dermis. This should allow for greater epidermal preservation.

Theoretically, one should design the pulse duration to lie between τ_r of the basal cell layer of the epidermis and the follicle (0.5 to 35 msec). Preferably, for the sake of the basal cell layer, one would like to be several times the lower duration limit (0.5 msec), so that there will be sufficient heat leakage during the pulse to avoid disruption of the pigment containing cells. On the other hand, if exposures >50 to 100 msec are used, there may be significant heat diffusion during the laser pulse. This may result in significant epidermal and superficial dermal damage. In the extreme case, there may be scarring, both from diffusion from the hot epidermis, the so-called "iron heater" effect,[2, 69–72] as well as from the hair follicle.

Should one use single or multiple pulses (i.e., is there any physical basis for stacking pulses in LHR)? Because the τ_r for the epidermis (10 msec) is less than that for the follicle, the epidermis should cool faster than the bulb and mid-follicle (including the bulge). Therefore one should be able to deliver multiple pulses with a short delay and ramp up the bulb and bulge temperature at a greater rate than the epidermal temperature. Generally, however, for sufficient cooling to baseline temperature, many times the τ_r (10 to 100×) is required (for the epidermis, this would require about 0.1 to −1 sec cooling intervals between pulses).[11] Shorter pulse delays might result in small but still damaging temperature increases in the epidermis.

Epidermal Cooling

One way to protect the epidermis is to integrate surface cooling into delivery configurations. Cooling strategies are typically either conductive or evaporative in nature. As noted previously, there is a tendency for accumulation of energy near the skin surface for scattering media. This results in unwanted epidermal heating. In general we can achieve epidermal sparing by directing our efforts at the dermato-epidermal junction where the highest concentration of epidermal melanin resides. We have already calculated the temperature rise at this junction for a 25 to 30 J/cm^2 pulse in Type II skin. By extracting heat

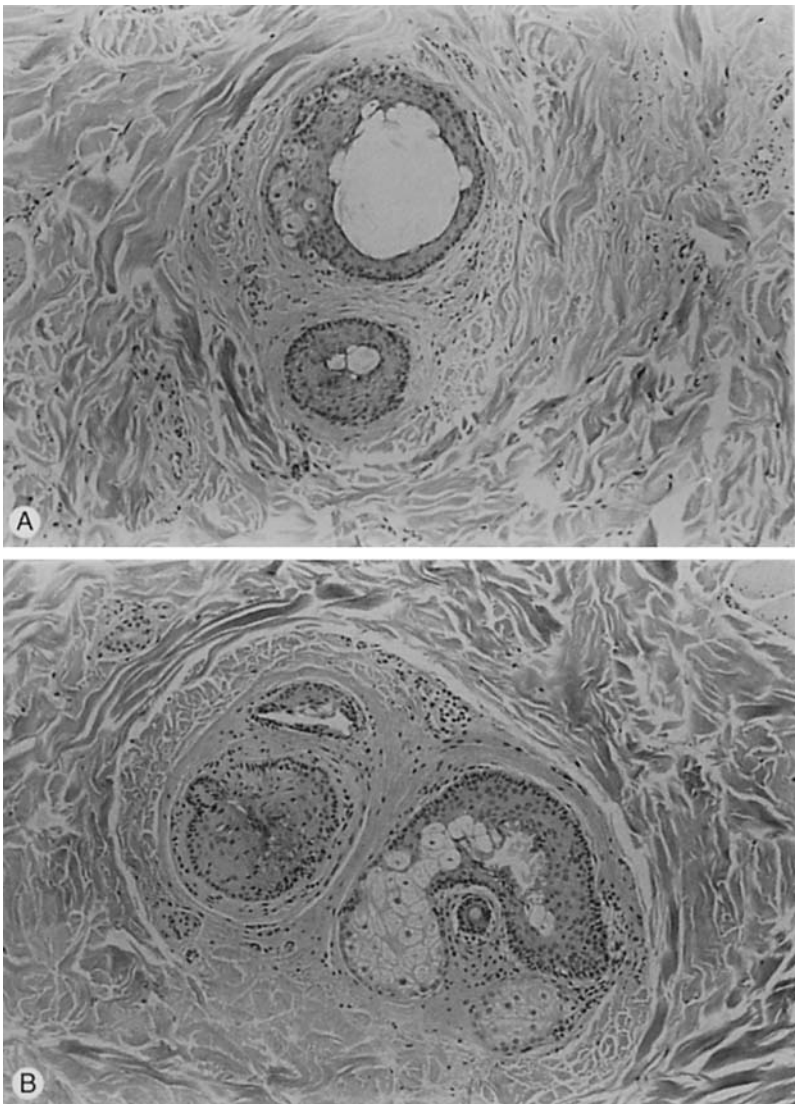

Figure 8. Transverse sections of hair follicle for *(A)* 0.3 and *(B)* 3-msec exposures. Note the greater thermal effect with the longer pulse duration. (Hematoxylin and eosin stain, original magnification × 100).

from the skin both before and during the pulse, some epidermal protection can be conferred. For conductive cooling, the relative rate of heat extraction will be determined by the temperature at the skin surface as well as the thermal conductivity of the cooling medium. Unfortunately, air is a good insulator, with a thermal conductivity only 1/25 that of water, which is only 1/50 that of sapphire. In general, four types of cooling are used in conjunction with laser hair removal. These include the following:

1. Passive cooling with an aqueous gel (like ultrasound gel).
2. Active cooling with water encased in a glass housing.
3. Active conductive cooling with water encased in a sapphire window.
4. Dynamic active cooling with a cryogenic spray.

The cooling time of epidermis is determined by the thermal properties of its components. Heat exchange between skin and cool-

ing device is realized via the stratum corneum, which is a superficial layer of dead cells with low water content. Low heat conductivity of this layer limits heat transfer from the skin. To increase hydration of the stratum corneum, water or water-based gel can be applied to the skin surface. Topically applied gel is inexpensive and improves the thermal conductivity at the skin surface; however, the temperature gradient (which drives the heat extraction) will be smaller than with active devices. Moreover, because the temperature is not maintained by an external chiller, the gel can only extract a small amount of heat, after which the temperature gradient decays and heat transfer ceases (the gel becomes hot at the expense of the skin surface). If a thick enough a layer is used, there will be improved heat extraction; more importantly, because of index matching between the stratum corneum and gel, there will be decreased backscattered light into the epidermis and therefore less subsurface energy accumulation (which will aid in epidermal preservation). Because some applications combine pressure with the gel application, the thickness is usually not great enough to decrease backscatter. Precooling the gel will aid in establishing a lower initial temperature at the basal membrane zone.

One can also use a sapphire window through which water at ~2–6°C circulates. The advantage is the speed of heat extraction from the surface. For example, within 0.5 seconds of application of a sapphire lens cooled to 0°C, one will see a temperature drop of roughly 20°C at the basal cell layer. This allows for rapid movements of the handpiece without fear that the melanized basal cell layer will not be sufficiently cooled. For application times more than 0.5 seconds, the hair bulge will just "start" to feel the impact of surface cooling. Application times of several seconds may result in undesirable levels of cooling of the bulge and shaft. Conversely, for the glass window, the bulge is more likely to be affected by precooling because the contact time will typically need to be longer than sapphire to establish an optimal pre-treatment temperature at the dermato-epidermal junction. Sapphire is very resistant to moisture and impact and transmissive at the wavelengths in the visible and near IR. Additionally, the high index of refraction optimizes coupling of the laser light into the tissue and reduced backscatter. One disadvantage of the cooling "window" is possible water condensation on the surface, particularly in a humid environment. This "frost" can result in beam attenuation.

Precooling the skin with ice can also be performed. This, like water cooling at 0°C with a glass window, will decrease the dermato-epidermal junction temperature depending on time of application (on the order of several seconds); however, because of the limited thermal conductivity of glass, ice, and water, longer application times will be required than that with sapphire for significant epidermal cooling. The longer application times will result in smaller temperature differences between the bulge and epidermis, therefore potentially compromising treatment.

Evaporative cooling systems typically use a cryogen spray delivered just prior to the laser pulse. Because evaporative cooling is intrinsically more efficient, one is able to create larger gradients between the dermis and epidermis.[6,7] This allows for greater protection of the epidermis with less risk of inadvertent dermal cooling (a drawback to conductive cooling). It follows that cryogen sprays are most useful when one needs to combine epidermal protection with targeting of very superficial dermal structures (i.e., vessels 0.2- to 4-mm deep in PWS). Although cryogen sprays are effective in LHR, their use is not imperative, because the bulge and bulb are quite deep. It follows that the dermis can tolerate the inevitable superficial cooling associated with conductive devices.

One device presently used incorporates a cryogen spray that is applied for 10 to 50 msec, followed by delivery of the laser pulse within 5 to 10 msec. This typically cools the epidermis to −10°C for a short period of time (<100 msec) and spatially limits significant cooling to about 200 μm. On the downside, cryogen spray devices rely on atomization of the cryogen spray for uniform dispersal of the droplets; any irregularities in droplet size may lead to variable localized cooling. Moreover, although the heat extraction is up to 20

times more efficient than conductive devices, the lack of optical coupling at the skin surface may increase backscatter. Also, condensation that may occur in a humid environment may impede the subsequent laser pulse.

To summarize the cooling configurations, Table 5 gives an approximate guide for fluence increases for the 3-msec ruby that should allow for epidermal preservation compared with no surface cooling.

Optimal Wavelength

Wavelength is an important consideration in laser hair removal. In examining the melanin absorption spectrum, one notes that the absorption coefficient decreases almost linearly between 700 and 1100 nm (see Fig. 3). Based on the previously discussed tissue optics arguments as well as absorption coefficient arguments, a case can be made for wavelengths longer than 700 nm (or 694 nm ruby). For example, at longer wavelengths (i.e., 800 nm), there is still sufficient melanin absorption for hair removal (albeit with larger fluences than at 700 nm), and more importantly, the ratio of energy deposited in the dermis to the epidermis is greater because of increased penetration (Fig. 9). Color contrast between epidermis and the hair shaft (and bulb) are paramount in determining the optimal wavelength (Fig. 10). For high contrast (dark hair, light skin), the low range of λ (650 to 700 nm) can be used without risking serious damage to the epidermis (and subsequent hypo- or hyperpigmentation). For lighter hair and darker skin, longer wavelengths (800 nm and greater) should be used.

Table 5. PROTECTION AFFORDED BY VARIOUS COOLING DEVICES*

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*From personal communication with G. Autshuler, PhD, of Palomar Laser (Lexington, MA).

For example, using Jacques' expression for beam propagation[33, 37] and Anderson's values for δ and own skin reflectance data,[5] it can be shown that 3 mm deep in the tissue (the bulb) only ~5% of the incident fluence remains for 700 nm, but fully 24% will remain for 800 nm (Fig. 9) (these percentages include backscattered irradiation). On the other hand, the ruby laser may be most appropriate for hair types other then deep brown or brown-black, as the pheomelanin that is seen in red and red-brown hair absorbs 800 to 1100 nm light poorly. Also, the larger overall energy required at 800 nm might increase the level of pain during treatment. At even longer wavelengths (i.e., 1064 nm), melanin absorption decreases to a level where very high fluences (50 to 100 J/cm^2) would be required for destruction of the bulb or bulge.

Other Considerations

It has been suggested that there may be a waveguide effect in laser hair removal such that the laser beam might propagate down the shaft like a fiber optic. Because the index of refraction of the hair is likely larger than connective tissue (1.5 vs 1.4), light might propagate down a fiber to some degree though total internal reflection; however, because of the high absorption coefficient of the shaft, it is unlikely that this is important for darker hairs. On the other hand, it might be relevant for less pigmented hairs, where light could be guided down the shaft toward the bulb.

Pain Considerations

The hair follicle is well endowed with pain fibers arranged in a well-organized neurovascular bundle. Pain during laser hair removal is either epidermal or dermal in origin. With increasing pulse duration, heat diffusion is likely to raise the temperature around the follicle and increase the level of pain.

Number of Sessions

There is evidence that multiple treatment sessions (usually spaced 4 to 6 weeks apart)

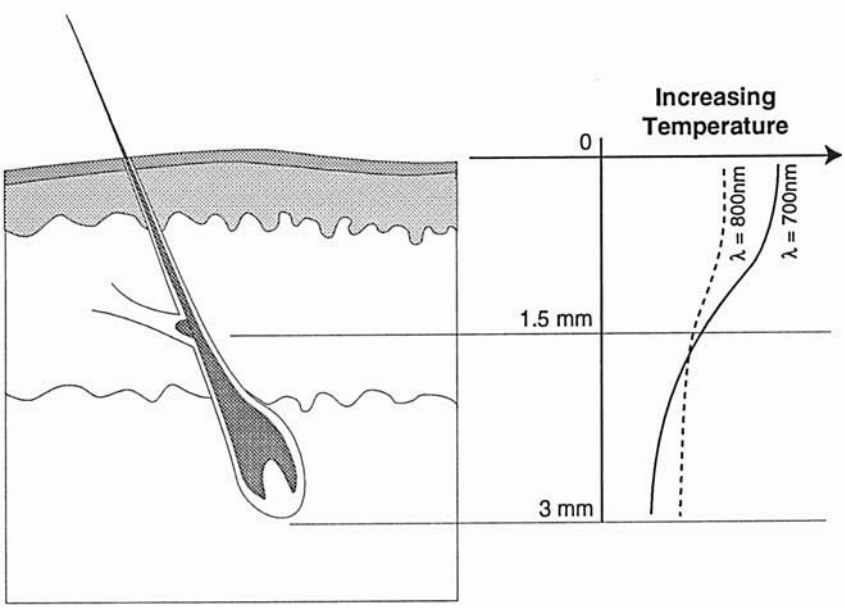

Figure 9. Effect of wavelength on temperature distribution as a function of depth where other parameters are held constant. Note that the longer wavelength results in relative bulb heating and epidermal sparing.

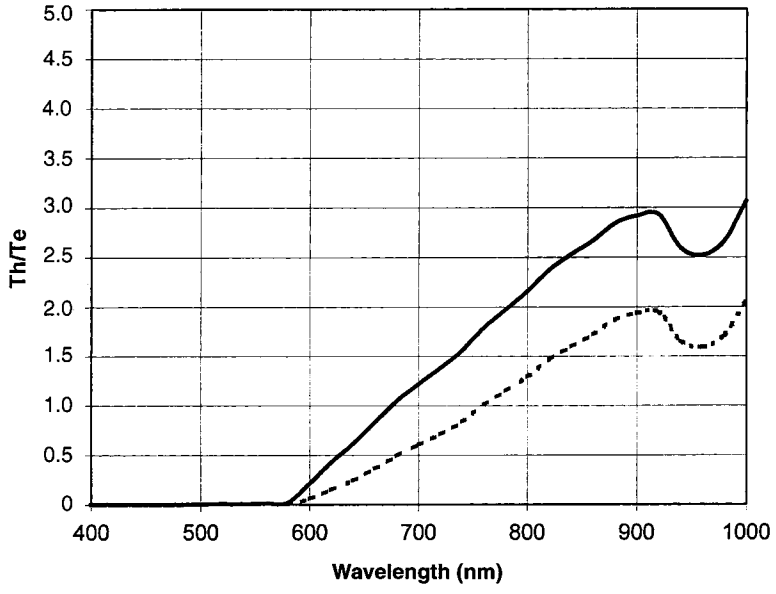

Figure 10. Ratio between hair bulb (Th) and epidermis (Te) temperature as a function of wavelength for hair depth of 3 to 4 mm. Hair-skin color contrast is equal to 5 *(dashed line)* and 10 *(solid line)*. Peak of water absorption at 980 nm decreases the light penetration depth at this wavelength. Note that longer wavelength results in more optimal ratios. (*Data from* Svaasand LU, Boerslid T, Oeverraasen M: Thermal and optical properties of living tissue: Application to laser-induced hyperthermia. Lasers Surg Med 5:589–602, 1985; and Jacques S: The role of skin optics in diagnostics and therapeutic uses of laser. *In* Steiner R, Kaufman R, Landthaler M, et a (eds): Lasers in Dermatology. Berlin, Springer-Verlag, 1991.)

increase the response rate in terms of regrowth rates. There may be several factors that play a role in this observation. One is that the treated areas are exposed to different focal areas within the incident spot. Therefore, edge effects could account for variable efficacy within a treatment region. Also, for treatments in which the bulb and bulge are damaged but not completely denatured, it appears that hair may be induced into catagen/telogen. This may increase the synchrony of the hair cycle such that many hairs are in early anagen by the second treatment. Early anagen is unique in that the bulb is pigmented yet usually only 1- to 1.5-mm deep the dermis. This should allow for greater temperature increases in the bulb with the same surface fluences.

RELEVANCE OF THE BIOLOGY OF THE FOLLICLE IN LASER HAIR REMOVAL

Based on data presented to date and our knowledge of the biology and physics of hair removal, we conclude with a discussion of observations that possibly relate to the future of light-based hair removal. It appears as if there are three responses to laser treatment for hair removal.

1. There is bulb damage that results in induction of catagen and telogen. Subsequent hairs may be similar in number but lighter and thinner.
2. With damage to the bulge one sees more complete miniaturization into a permanent "vellus-like" hair.
3. In extreme cases with high fluences, longer λ, and long pulse durations (20 to 50 msec) there is complete degeneration of the follicle.

Finally, what is the optimal phase of the growth cycle for application of laser hair removal? Because the telogen bulb is high in the dermis (almost at the depth of the bulge), one might argue that this would be the optimal time for treatment, because relatively large amounts of energy could be delivered 1- to 1.5-mm deep to the surface; 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 represent the best time for treatment. Furthermore, as there is evidence that sublethal laser doses induce catagen and telogen, it follows that it might be possible to synchronize the follicles to some degree with low fluences. Then, once the follicles are in early anagen, larger fluences with longer pulse duration can be used to destroy the entire follicle unit.

Another consideration in laser hair removal is that vessels in and around the papilla might be damaged, especially at wavelengths of 755 (alexandrite) and 800 nm (diode). Although there may be a role for vessel destruction in LHR, there is little histologic evidence to support a major contribution.

OTHER APPROACHES TO LIGHT-BASED HAIR REMOVAL

Although this article has focused on laser hair removal via thermal mechanisms, photochemistry has also been used for follicle destruction. The most commonly used drug is aminolevulinic acid (ALA), which when applied topically converts to the photosensitizing compound protoporhyrin IX. Red light is then applied to the surface, which results in singlet oxygen production and destruction of cells. As ALA accumulates preferentially in the sebaceous glands, it follows that it should be somewhat selective for the follicle.[23] Early studies are encouraging. An advantage of PDT is that hair color is irrelevant.

Another method for hair removal involves the combination of an exogenous chromophore (carbon particle) and a Q-switched Nd:YAG laser. In this procedure, a carbon solution is placed on the skin, some of which deposits in the follicle. Using low fluences (1 to 3 J/cm^2) the skin is irradiated and the carbon is selectively vaporized, resulting in vaporization and destruction of the hair shaft (if not already epilated manually), and parts of the follicle. As per our earlier arguments, one drawback with the configuration, although it appears safe for the epidermis and may be applied to all hair colors, is that car-

bon vaporization results in poor thermal diffusion into the peripheral follicle. On the other hand, there may be effective photomechanical disruption of the epithelium. This has been shown in some instances where the entire epithelium was eliminated down to the bulb (Curt Littler, MD, Scripps Clinic, San Diego, CA, personal communication, 1998). Even in these cases, the dermal sheath appears to persist (which may contain cells capable of follicular recovery). Continued optimization of this device, however, may allow for more complete and permanent follicular destruction in the future. Q-switched high-powered Nd:YAG lasers have also been used without exogenous chromophores. These systems may allow for treatment of even the darkest skin types.

CONCLUSIONS

In this article we have introduced basic concepts that should aid in understanding the rationale for development of light-based hair removal systems; however, the reader should be cautioned that although physical and biological models can be quite useful in establishing effective "ball park" laser parameters, their actual validation can be accomplished only through careful experimentation, preferably in human models. These trials are presently being performed at various centers. Probably most important, further cooperation among hair biologists, scientists, and clinicians will be required to exploit the features of the hair follicle that make it vulnerable to the effects of laser irradiation.

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