Beyond Customary Paradigm: FRAC3® Nd:YAG Laser Hair Removal

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ABSTRACT

VSP (Variable Square Pulse) Nd:YAG laser devices hold the most prominent position among all available laser sources for hair removal. This is due to the long wavelength (1064 nm) which Nd:YAG devices produce. Light with a wavelength of 1064 nm lies in a biological absorption region that allows light to penetrate deep into the skin, but at the same time its absorption in hair follicles is strong enough to destroy them. In addition, when coupled with air cooling and scanner technology, next-generation VSP Nd:YAG devices provide the best possibilities to adjust treatment parameters to fit individual cases. They thus provide optimized treatment efficacy while protecting epidermis from unwanted damage. In this paper we report on FRAC3® the latest, self-induced fractional, treatment modality that even further improves safety, efficacy and patient comfort of the VSP Nd:YAG in laser hair removal.

Key words: laser hair removal; VSP technology, Nd:YAG lasers, Accelera, FRAC3®, scanner

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I. INTRODUCTION

General

Laser hair removal has in recent years received wide clinical acceptance in both medical and aesthetics settings because of its long-term results, non-invasive nature, minimal treatment discomfort and the speed and ease with which procedures can be performed [1]. Commercial laser and flashlamp light (IPL) systems differ in wavelength, pulse duration, fluence, laser beam delivery system and skin cooling method, all of which have an effect on the outcome of the treatment. When deciding on the most appropriate light source for laser hair removal treatments, tissue interactions should be thoroughly analyzed and taken into consideration. The currently available light sources for hair removal include IPL (broad spectrum), ruby lasers (694 nm), alexandrite lasers (755 nm), diode lasers (810 nm), and Nd:YAG lasers (1064 nm) [2, 3].

Achieving satisfactory results, when using a laser to treat unwanted hair, depends on many factors. It has been demonstrated that successful permanent hair removal can only be achieved by injuring the bulb, the bulge and the outer root sheath of the hair follicle [1]. The region in which these structures lie is therefore the target for any method used to create the required injury to permanently remove hair. During the process of laser or IPL hair removal, light is absorbed by chromophores (usually melanin in the hair shaft and follicle) and transformed into heat energy, resulting in a rise of the hair temperature. When the temperature is high enough, irreversible damage may occur to the hair structures, thus preventing or altering the growth of the hair. Success is determined by tissue physics, hair physiology and the device used in the treatment. In order to select an effective laser hair removal device, one must understand how each laser light produces its specific biologic effect in human tissue. The following characteristics and parameters need to be considered: wavelength, pulse duration, pulse shape, spot size, fluence, treatment speed and epidermal cooling.

A scientific evaluation of the safety and efficacy of the Variable Square Pulse (VSP) [4] Nd:YAG laser in comparison with other commercially available light sources has determined the latest VSP Nd:YAG lasers, combined with the computer-controlled Scanner Optimized Efficiency (SOE) technology [5,6,7] to probably be the optimal choice to perform safe and effective hair removal [8]. The following advantages of the VSP Nd: YAG lasers were identified:

a) An appropriate wavelength with low absorption in epidermis and deep penetration down to the hair follicles.

b) The possibility to treat all skin types by sparing the epidermis from damage.
c) The capability of delivering top-hat beam profiles.
d) Using VSP laser technology, the ability to deliver high energies, high pulse powers and average laser powers in the same device.
e) Using the large range of available spot sizes, the ability to adjust treatment depth to the specific skin type and position on the body.
f) The safe and fast skin coverage with computer-controlled SOE scanners.
g) The capability of generating adequately high fluences at sufficiently short pulse durations in order to be able to treat thinner and/or lighter hair.

The last listed advantage has become a focus of recent new developments in VSP Nd:YAG hair removal treatment modalities. When short Nd:YAG laser pulses in the 0.1-5.0 ms range are used, selective heating of small skin imperfections, inhomogeneities and hair follicles occurs in the illuminated skin tissue (see Fig. 1). Self-induced fractional islands of thermally affected skin structures, formed in the three dimensional matrix within the skin tissues, are the basis for the latest *FRAC3*® [9] approach to minimally invasive skin rejuvenation [10, 11].

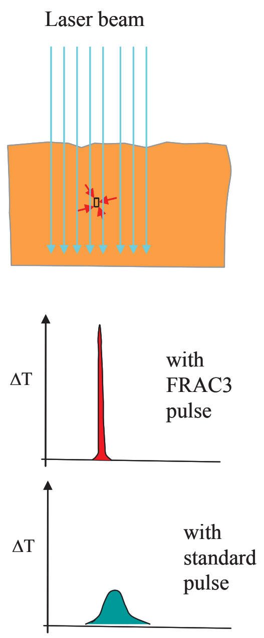

Fig. 1: FRAC3® action is very effective for treating small-diameter skin imperfections with fast thermal relaxation times. With FRAC3® parameters, a small skin imperfection or a thin hair follicle experiences a high localized temperature increase ΔT while with the standard laser parameters the local temperature increase is much smaller.

A generally accepted paradigm in laser hair removal embraces large laser spots and medium to long laser pulse durations. Typical Nd:YAG hair removal parameters are as follows: 6 - 20 mm spotsize, 15 - 50 ms pulse duration, 35 - 55 J/cm² [12-14]. In this paper we present arguments and experimental evidence for a novel Nd:YAG hair removal treatment regime that is based on the self-induced, three-dimensional, fractional *FRAC3*® skin treatment concept. The new treatment regime is performed with 2 - 4 mm spot size and pulse durations below 5 ms. It promises to offer higher hair removal efficacy and higher patient comfort without unduly sacrificing the safety of the epidermis.

II. MATERIALS AND METHODS

a) Measurement of Skin Temperatures

The Nd:YAG laser used in the study was a Fotona XP Dynamis laser system with R33 and R34 non-contact handpieces with spotsizes, d, from 2 - 20 mm (See Fig. 2). The laser was operating in the *FRAC3*® Accelera (t_p=0.1 – 1 ms) and standard Versa modes (t_p=2 – 200 ms).

Fig. 2: Fotona XP Dynamis Nd:YAG laser system. [25]

A thermal imager (Matis, Sagem) operating in the 3 to 5 μm spectral range was fixed in position above the skin surface and focused on the treatment site (Fig. 3). Thermal camera images were taken at 20 ms intervals starting at approximately 2.5 ms following a laser pulse. The image exposure time was approximately 2 ms. The imager sensor detects thermal light emitted from the surface and also some from subsurface as the light of 3-5 μm wavelengths can penetrate to up to 50 μm into the skin. The measured temperatures therefore represented a weighted average of the skin temperature within the penetration depth of the detected thermal radiation.

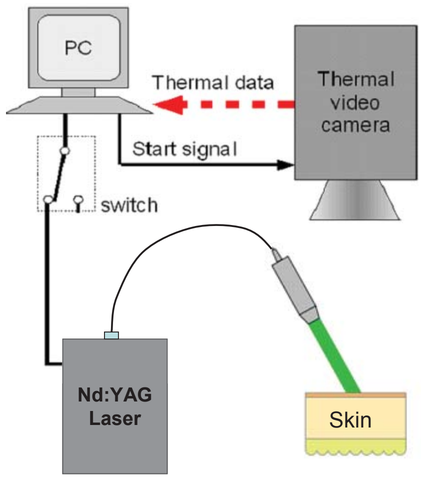

Fig. 3: Experimental set-up.

Skin surface measurements of the temperature distribution following a Nd:YAG laser pulse were performed in-vivo on hand dorsum of subjects. No external skin cooling was applied. Subjects from different geographical regions participated in the study.

b) Measurement of Hair Thermal RelaxationTime

A rough measurement of the hair's thermal relaxation time was made by irradiating external un-plucked hair with (1064 nm) Nd:YAG laser pulses (XP Dynamis, Fotona) of different pulse durations and fluences, and then determining at what laser fluence and pulse duration the hair suffered visible thermal damage. The hair damage threshold was defined with the lowest fluence at which visible hair damage occurred. Measurements were made in-vivo on the arm hair of subjects with Fitzpatrick I-II skin type. No external cooling was applied.

c) Measurement of Sensation of Pain

Measurements of pain perception at different laser spot sizes and pulse durations were also made. A Fotona XP Dynamis laser system with S11 Nd:YAG scanner was used in the experiment. For each measurement subjects were exposed to a linear scan of 7 consecutive laser spots at a 2 Hz repetition rate (see Fig. 4). A linear scan of 7 spots was chosen in order to give patients sufficient time and number of pulses for a reliable and repeatable pain perception. Three, six and nine millimeter spot sizes were used. Influence of pulse duration on subjects' discomfort was made by observing at what single spot laser fluence and pulse duration subjects reported subjective pain. Measurements were made on hairless healthy skin on the back arms of five subjects with Fitzpatrick I-II skin type. No external cooling was applied. Sufficient time was taken between the measurements in order to avoid any accumulation of heat and/or pain fatigue. Patients were blindfolded and, the fluence and pulse width were varied in a quasi random manner.

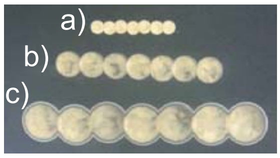

Fig. 4: Patients were exposed to linear scans of 7 consecutive laser spots of 3 mm (a), 6 mm (b) and 9 mm (c) spot size. Pain threshold fluence was determined by measuring at which single spot fluence the patient reported subjective feeling of pain.

III. RESULTS

a) Laser Spotsize Considerations

The fluence (F) is one of the main settings for hair removal. It is defined as energy density:

$$F = E/A \qquad (1)$$

Where E is the energy of the laser pulse and A is the spot size area, $A = \pi\, d^2/4$, of the laser beam at the skin surface. Usually it is calculated in J/cm^2. Typical Nd:YAG fluences for hair removal are between 30 and 100 J/cm^2 [12-14].

Figure 5 shows the measured skin surface temperature increase, ΔT, at the center of the irradiated spot for the incoming beam fluence of 30 J/cm^2 and 10 ms pulse duration. Note the large variation in the temperature increase among patients of the same Fitzpatrick phototype.

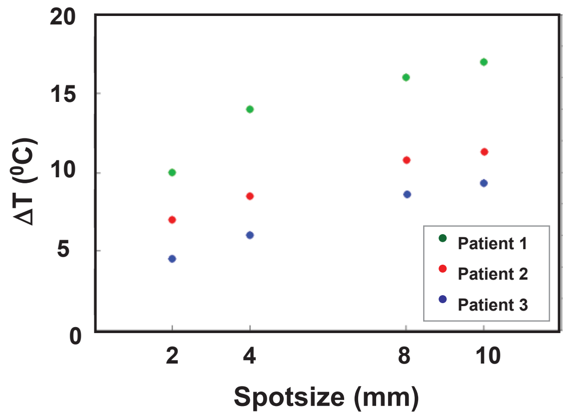

Fig. 5: Measured dorsal hand skin surface temperature increase following a 10 ms, 30J/cm² Nd:YAG laser pulse. The three subjects were of Fitzpatrick I-II phototype (geographically from Europe).

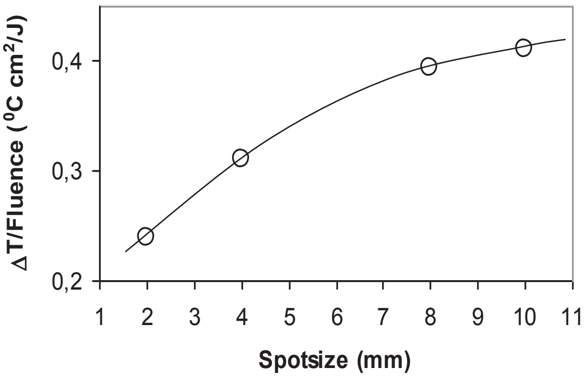

Fig. 6: Measured average skin surface temperature increase per laser fluence as a function of the laser spot size for Fitzpatrick I-II phototype patients. The connecting line has been added to help the eye.

Figure 6 shows the average central surface temperature increase in terms of the laser fluence, ΔT/Fluence. As can be seen from Figs. 5 and 6, for the same incoming laser beam fluence the surface skin temperature increases with the laser spotsize. For example, the ratio of temperatures at 9 mm and 3 mm spotsizes is 1.6.

The above measurements are in excellent agreement with theoretical predictions. Figure 7 shows the dependence of the surface temperature increase ΔT/Fluence on laser spot size based on our computer simulations. We used a Monte Carlo numerical method [8,15] to obtain these results.

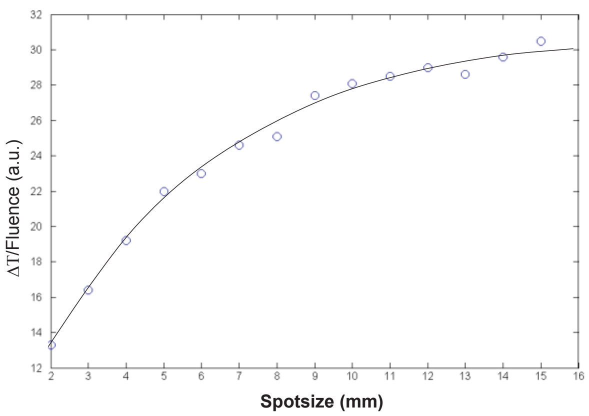

Fig. 7: Computer-simulated dependence of the temperature increase on the laser spot size. The connecting line has been added to help the eye.
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The theoretically predicted ratio of temperatures at 9 mm and 3 mm spot sizes is 1.6 (Fig. 7), in good agreement with the measurement (Fig. 6).

The inexperienced laser system user may not always recognize the importance of the spot size of the emitted beam as a treatment parameter. [16]. One would naively expect that if the spotsize is decreased and the laser energy is simultaneously decreased to maintain the same fluence, the clinical effect should be similar. However, due to random laser light scattering, spotsize does make a difference to the treatment outcome [17]. A a beam propagates into the skin, light scattering spreads the beam radially outward on each side, which decreases the beam's effective fluence as it penetrates into the skin. This effect is more pronounced in smaller spotsizes where the spreading of the beam is relatively large compared to the incoming beam spot size (See Fig. 8).

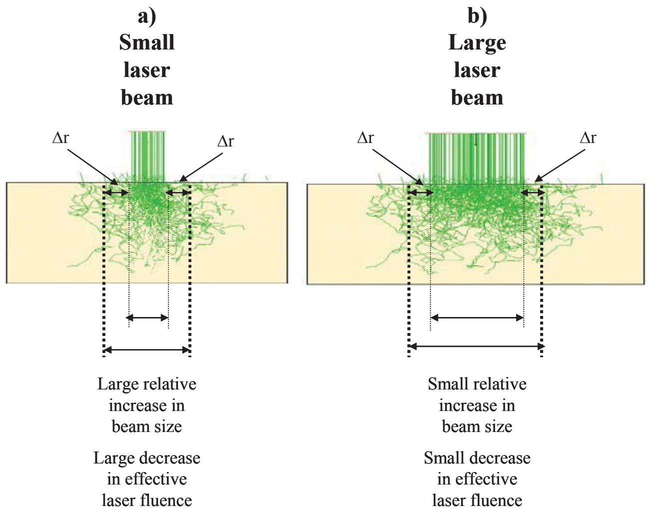

Fig. 8: Influence of scattering on the effective laser beam spotsize. The thermal profiles indicate that the beam spreads radially outward on each side by approximately Δr = 0.7 mm. The effect is relatively less significant at larger spot sizes.

This is why, for example, the effective fluence within the skin of a 3 mm incoming laser beam is 1.6 times smaller than the effective fluence of a 9 mm laser beam. This results in approximately 1.6 times lower temperature increase within the skin when using a 3 mm spot size beam compared to a 9 mm spot size beam. When the incoming laser fluence is the same for both spot sizes, the resulting skin temperature is higher not only on the surface but also deeper in the skin. The computer-simulated temperature distributions within the skin for the 3 and 9 mm spot size beams are shown in Fig. 9.

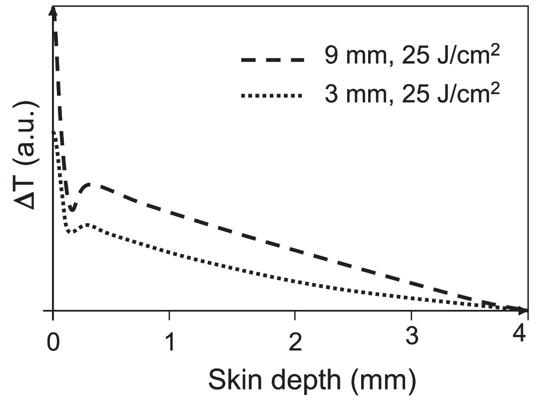

Fig. 9: Computer-simulated temperature distribution immediately after a Nd:YAG laser pulse for a 9 mm and a 3 mm incoming spotsize beam. When the incoming laser fluence is the same for both spotsizes, the 9 mm beam appears to "penetrate" deeper into the skin.

The reduction of the effective fluence within the skin is often interpreted as a decrease in the penetration depth of smaller size laser beams [1,8,12,16]. However, this is not entirely correct. For example, if the incoming fluence of the 3 mm laser beam in Fig. 9 is increased by a factor of 1.6, the penetration and the temperature distributions resulting from 3 mm and 9 mm laser beams become similar (see Fig. 10).

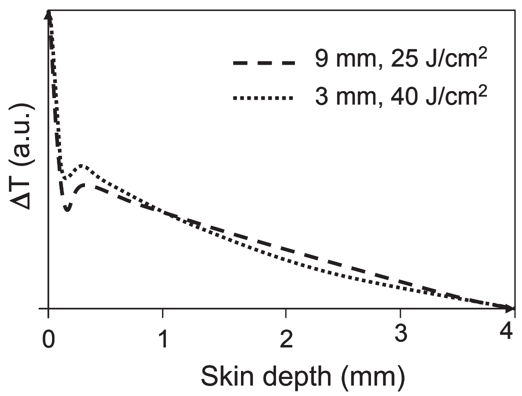

Fig. 10: Computer-simulated temperature distribution immediately after a Nd:YAG laser pulse for a 9 mm and a 3 mm incoming spot size beam. When the incoming fluence of the 3 mm beam is 1.6 times larger than the incoming fluence of the 9 mm beam, the two temperature distributions become very similar.

The practitioner can therefore treat deeper-lying skin pigments or hair follicles with smaller beam spot sizes if the laser fluence is adjusted accordingly. Table 1 shows the approximate relations between the effective fluences at different spot sizes.

Table 1: Approximate relations between the effective fluences at different incoming beam spotsizes. The values are presented relative to the effective fluence at a 9 mm spotsize.

Spot size	3 mm	6 mm	**9 mm**	12 mm	15 mm	20 mm
Effective fluence relative to the effective fluence at 9 mm	62%	88%	**100%**	107%	112%	117%

For example, a typical recommended hair removal Nd:YAG fluence for a 9 mm beam is 55 J/cm^2. to attain the same levels of clinical safety and efficacy, and keeping all other laser parameters the same, the incoming 3 mm beam laser fluence should be increased by a factor of 1.6 (1/0.62), and the 20 mm beam laser fluence should be decreased by a factor of 0.85 (1/1.17).

b) Skin Phototype Considerations

Because light has to pass through the epidermis, the fluence at the substrate target locations, such as deep-lying hair follicles, will also be affected by the absorption by epidermal melanin. Moreover, melanin absorption causes localized heating of the epidermis, which may cause pain and transient or permanent complications such as skin depigmentation and scarring. In the visible and near-infrared spectrum, melanin absorption decreases rapidly with wavelength (see Fig. 11), thereby favoring longer wavelength lasers such as the (1064 nm) Nd:YAG [8].

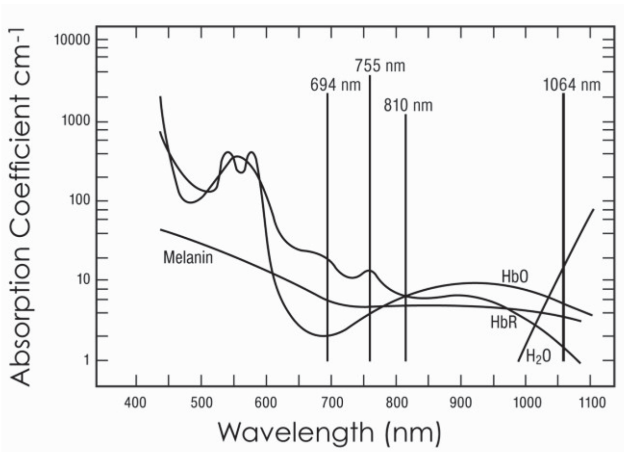

Fig. 11: Absorption characteristics of the various skin structures. The 1064 nm wavelength lies at the skin's "optical window" [1].

In addition and as discussed above, penetration of light into human skin is limited by optical scattering. The scattering coefficients of epidermis and dermis decrease with wavelength in the visible and near-infrared parts of the spectrum (see Fig. 12), again favoring use of the Nd:YAG laser wavelength [1,8].

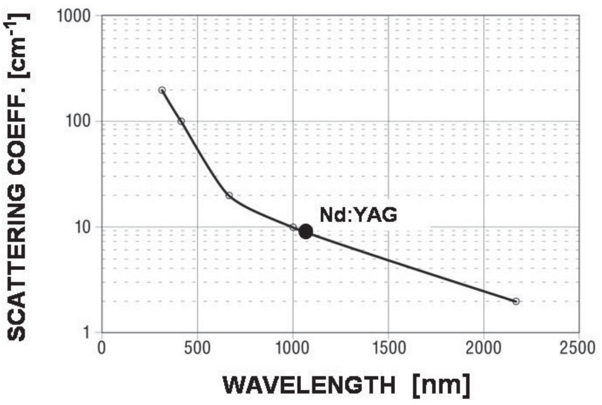

Fig. 12. A log plot of the scattering coefficient for skin as a function of wavelength. Note that the scattering effect decreases with increasing wavelength. The Nd:YAG laser has a low scattering coefficient and thus penetrates further than other laser wavelengths that are also used in laser hair removal treatments.

The melanin concentration can vary by a factor of 20 between different human skin phototypes [19]. Consequently, safe epidermal fluence and heating levels depend on how dark and heavily pigmented the patient's epidermis is. Figure 13 shows the results of our thermal measurements of skin surface heating on different skin phototypes.

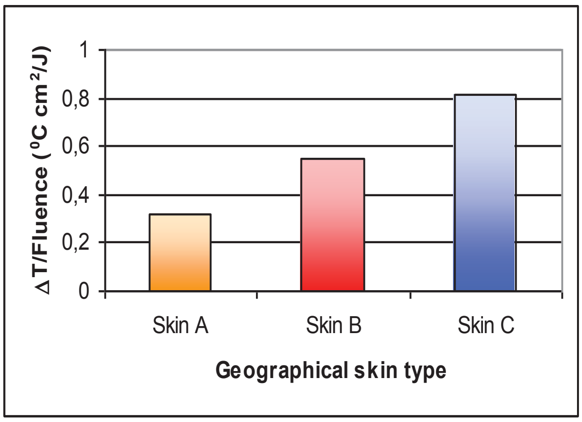

Fig. 13: Skin surface temperature increase following Nd :YAG laser radiation for three geographical region groups: Skin A (Europe), Skin B (China, Egypt), and Skin C (India, Japan).

Our pilot study on subjects from different geographical regions has shown that in terms of epidermal heating. Subjects can be grouped into four groups based on their skin phototype. Group A included subjects with skin phototypes typical to Europe, Group B subjects with phototypes typical to China and Egypt and Group C phototypes typical to India and Japan. The fourth group D, not included in our study, but would be represented by African skin phototypes [20 - 21]. In comparison to standard hair removal treatment parameters for Fitzpatrick types I - II skin (group A), the laser treatment fluence should be reduced by a factor of 1.7 for the patients from group B skin and by a factor of 2.5 for the patients from group C. The radiant exposure that can be safely applied in groups B and C is thus limited by the acceptable risk of epidermal injury and directly affects the therapeutic outcome. This limitation can be alleviated by external skin surface cooling prior to laser irradiation.

c) Laser Pulse Duration Considerations

Upon irradiation with a suitably short laser pulse, energy is deposited in the hair follicle before heat can diffuse into the surrounding tissue. If the pulse is not short enough, then a significant fraction of deposited heat may diffuse away from the hair follicle during laser exposure. This reduces the peak temperature of the hair follicle and impairs the spatial selectivity of heating, even though the Nd:YAG wavelength laser light is selectively absorbed. Proper selection of laser pulse duration, which governs spatial confinement of deposited heat in hair follicles, is therefore just as important as laser fluence [18].

Laser pulses t_p that are significantly shorter than the target thermal relaxation time (TRT) maximize the temperature rise of the targeted structure. TRT represents the time interval in which the amplitude of a hypothetical temperature rise decreases by approximately a factor of 2 due to the diffusion of heat into surrounding tissue.

TRT of a hair follicle with diameter d can be obtained by observing the thermal relaxation time of an infinite cylinder [17].

$$TRT = d^2/(16\,\alpha) \quad . \qquad (1)$$

Here, α is the thermal diffusivity of skin (α = 0.11 mm²/s) [17].

To simplify the analysis and based on the above considerations, we will assume that the selective heating of a skin structure occurs when the laser pulse duration is smaller than the relaxation time τ of the skin structure by a factor of two. Figure 1 shows the dependence of the minimal size d of the imperfection or hair that can be selectively heated by a laser pulse of duration t_p. In accordance with Fig. 14, confinement of laser energy within smaller structures requires progressively shorter pulse durations. For structures smaller than 100 μm, pulse durations below 1 ms must be used.

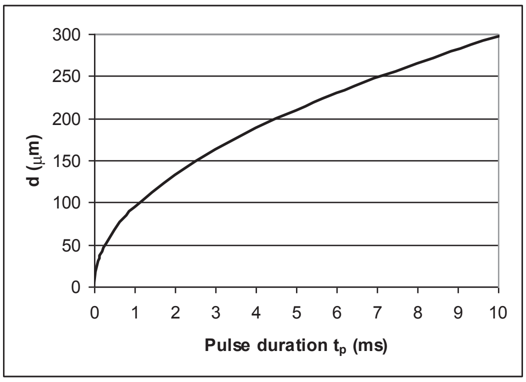

Fig. 14.: Minimal size d of a skin structure that can be selectively heated by a laser pulse of duration t_p.

Figure 15 shows the measured dependence of the hair damage threshold fluence on the Nd:YAG laser pulse duration.

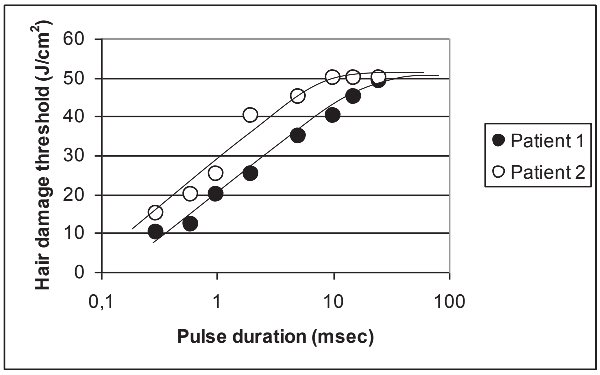

Fig. 15: Measured dependence of the hair damage threshold (defined by the lowest fluence where hair damage occurs) on the laser pulse duration. Hair removal is much more effective at shorter, FRAC3® laser pulse durations and powers. Repeatability of measurements was within 10J/cm².

The laser fluence that is required to damage a hair is significantly reduced (by a factor of five) towards shorter pulse durations. The exact threshold curve depends on the individual hair color and diameter. Thinner and lighter hair requires shorter pulse durations, i.e. stronger FRAC3® treatments.

By comparing the results shown in Fig. 14 with Fig. 15, it can be concluded that the measured hair's diameter was in the range of 50 -150 microns, and that the hair's thermal relaxation time (TRT_{hair}) was below 3 ms. The actual TRT_{hair} of a hair follicle is even shorter, below 1 ms, since within the skin it is in good thermal contact with the surrounding skin tissue and the heat can be more rapidly transferred to the surrounding tissue by conduction.

Because pulses significantly shorter than TRT_{hair} provide the highest temperatures the critical question becomes – "Is the best approach to use pulses with t_p < TRT_{hair} to ensure heat confinement in hair follicles?" The answer depends on the tissue relaxation time of the epidermis, TRT_{epi}. To avoid unwanted injury to the epidermis, it would be of benefit if laser pulse duration was much longer than the TRT of the epidermis.

Let us therefore consider thermal relaxation time TRT_{epi} of the melanin-rich epidermal layer as a whole. The theoretical equation for this case has been derived in [19]:

$$TRT_{epi} = 3\, d^2_{epi}/(16\, \alpha) \quad . \tag{2}$$

In a non-tanned, light skin phototypes, melanosomes are concentrated primarily in a d_{epi} =10 μm thick basal layer (typically located 50-100 μm below the skin surface) while in tanned, darker skin phototypes more melanin is distributed throughout the epidermis. As a result, the epidermal TRT can vary from less than 1 ms to over 100 ms [19]. In most cases, and especially in tanned, darker skin types, where epidermis is heated the most, the TRT of the epidermis is relatively long. This has been confirmed also by our measurements. Figure 16 shows the measured normalized temperature decay times following a 1 ms Nd:YAG laser pulse for the three geographical skin groups (Fig. 13).

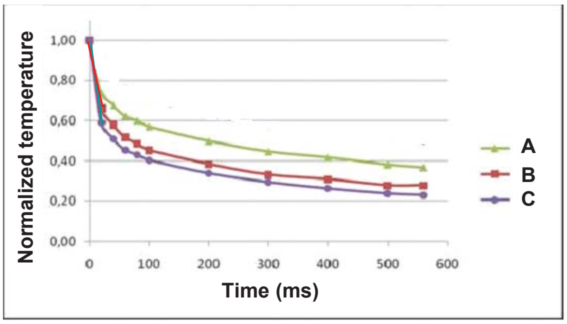

Fig. 16: Skin surface normalized temperature decay curves following a 1ms pulse duration, 4 mm spotsize, 30J/cm² Nd:YAG laser pulse for geographical skin types A (Europe), B (China, Egypt) and C (India, Japan).

The initial fast decay times, TRT_{epi}, can be approximated from data in Fig. 16 to be 35 ms (type A), 33 ms (type B) and 26 ms (type C). As expected, the fastest decay occurs for the skin from group C. In skin types where light is strongly absorbed within the epidermis, the absorbed heat is concentrated closer to the surface and the deeper-lying dermal skin layers are less heated. Since conduction is faster for larger temperature gradients, the group C epidermis can cool more readily into the slightly cooler dermis below.

While applying pulses longer than TRT_{epi} would help reduce the peak epidermal temperatures, this is not a viable approach to enhancing selective hair removal skin treatments, because TRT_{hair} is most often much shorter than TRT_{epi}. The temperature of hair follicles would never rise above the ambient skin temperature if laser pulse durations longer than TRT_{epi} were used. A similar limitation has been discovered also in vascular laser treatments [19]. It is therefore most optimal to use laser pulses with $t_p < TRT_{hair}$ to ensure *FRAC3®* heat confinement in hair follicles. The epidermis must be protected by other means, such as by external cooling of the skin surface prior to laser irradiation.

d) Patient Comfort Considerations

Figure 17 shows the measured dependence of the feeling of pain, i.e. of the pain threshold fluence, on the laser spot size and pulse duration.

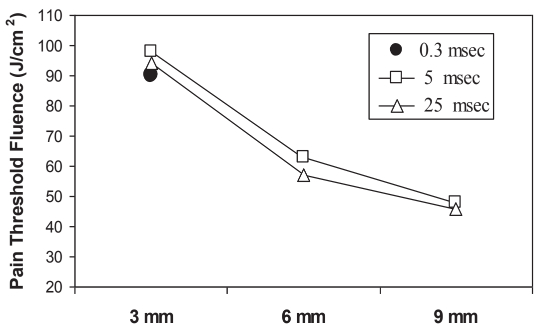

Fig. 17: Measured dependence of the feeling of pain, i.e. of the pain threshold fluence, on the laser spot size and pulse duration. Repeatability of single patient measurements was within 10 J/cm². Variation among patients was within 15 J/cm².

A very important finding is that the feeling of pain on healthy hairless skin is within the measurement variation of ± 15 J/cm², independent of pulse duration in the broad range of 0.3 - 25 ms. This finding is in agreement with the temperature decay curves in Fig. 16. Namely, since TRT_{epi} is longer than 25 ms, no significant cooling of epidermis can occur during laser pulses shorter than 25 ms. All pulse durations below 25 ms thus result in the same peak temperature of the epidermis and consequently in the same discomfort for the patient.

The sensation of pain was found to depend on the laser spot size. The larger the spot size, the more discomfort was felt by the subjects. The measured pain threshold fluence with the 3 mm spot size laser beam was determined to be 2 times higher than the pain threshold with the 9 mm spot size beam. This can be at least partially attributed to the 1.6 time reduction of the effective laser fluence of the 3 mm laser beam within the skin as compared to the effective laser fluence of the 9 mm laser beam. We tentatively attribute the remaining reduction in discomfort to lower pain sensitivity of smaller skin areas.

IV. DISCUSSION

a) Beyond the Customary Paradigm

A generally accepted paradigm in laser hair removal is to use large laser spots and medium to long laser pulse durations [1, 2, 22-24]. Typical Nd:YAG hair removal parameters are as follows: 6 - 20 mm spot size, 20 - 50 ms pulse duration, 35 - 55 J/cm². Large laser spots are preferred in order to penetrate deeper into the skin and to cover the skin surface quicker. Longer pulse durations are used with a goal to minimize damage to the epidermis. Longer pulse durations are also, at least partially, mandated by technological limitations. Namely, large spots require high pulse energies that laser systems cannot deliver reliably at short pulse durations.

However, as our study has demonstrated another, more optimal *FRAC3®* set of Nd: YAG laser hair removal parameters exist: 2 - 4 mm spotsize, 0.1 - 5 ms pulse duration and 35 - 55 J/cm² fluence. Smaller spotsizes are more comfortable and shorter pulses are more effective without sacrificing the safety of the epidermis.

Hair removal is safest when a laser pulse duration longer than the TRT_{epi}, but shorter than the TRT_{hair} can be chosen. This allows selective heat treatment of the hair follicle without overheating the epidermis (see Fig. 18). This is why standard hair removal treatment guidelines recommend using longer laser pulses which at least in theory are less likely to cause injury to the epidermis.

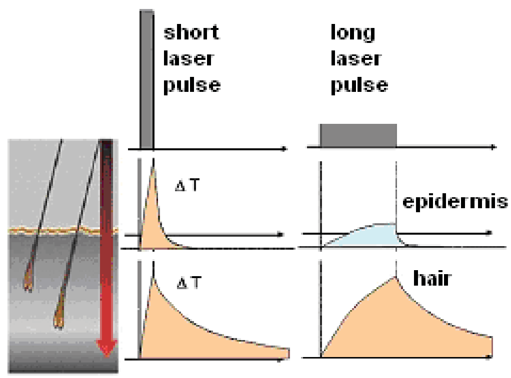

Fig. 18: Ideal situation for standard hair removal settings ($TRT_{epi} < TRT_{hair}$). With a suitably long laser pulse it is possible to heat up the hair follicle while sparing the epidermis.

For most patients, however, this approach is counter productive. Namely, TRT_{epi} is typically longer than 25 ms (see Fig. 16) while TRT_{hair} is typically shorter than 10 ms (See Fig. 15). For such patients, long pulses (10 - 25 ms) do not significantly protect epidermis and are ineffective for hair removal (See Fig. 19). To achieve satisfactory results with a standard hair removal regime in such patients, high fluences must be used. This leads to unnecessary overheating of the epidermis. Optimal pulse durations for hair removal are thus in the *FRAC3®* treatment range of pulse durations, t_p < 5 ms. This applies even more when treating patients with thinner and lighter hair in which the TRT and absorption in hair follicles are the lowest.

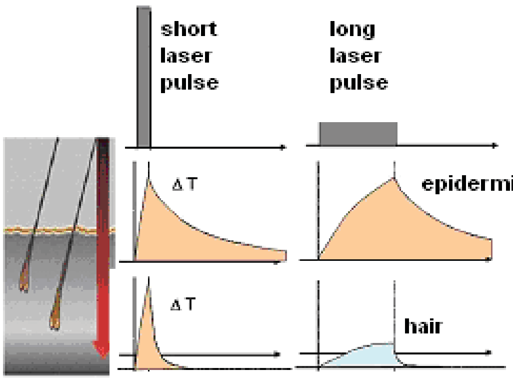

Fig. 19: A situation, most commonly found in patients (TRT_{epi} > TRT_{hair}). Epidermal peak temperature is independent of the pulse duration while the hair follicle gets heated only at shorter at pulse durations. For such patients, short, FRAC3®laser pulses are mandatory.

The *FRAC3®* treatment regime has until recently not been a viable option. It is only after the introduction of the Accelera Nd:YAG and SOE technologies that relatively large laser fluences in the range of 35 - 55 J/cm² with pulse durations of 0.1 - 2.0 ms became available for 2 - 4 mm sizes (See, for example, technical specifications of the latest Fotona XP Dynamis laser system).

Accelera Nd:YAG short pulses that hold high enough energy content to be effective are generated by VSP technology [4]. Fig. 20 shows a square pulse generated using VSP technology compared to a standard Pulse Forming Network (PFN) laser pulse. A significant difference between the two types of pulses is that the average power and the peak power of a square pulse is nearly the same, which cannot be said for PFN-generated pulses. This means that the effect of VSP pulses on the skin are more predictable than the effects of PFN pulses, which ultimately leads to superior treatment outcomes, with less discomfort and fewer side effects.

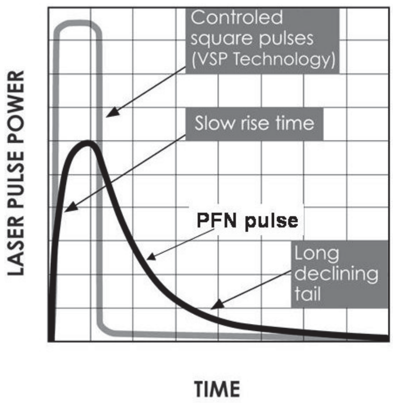

Fig. 20. Comparisons between PFN and VSP shaped pulses.

An additional advantage of VSP technology is that it allows the user to easily adjust the pulse duration and laser power. It is even possible to form a controlled train of micropulses within a larger overall pulse, thereby optimizing the efficacy and safety of treatments by making each pulse with a particular pulse duration completely predictable from a clinical outcome point of view.

SOE technology [5] eliminates the need for manually aiming a small to medium spot size laser beam hundreds of times to cover a larger skin area. SOE utilizes computer-controlled laser scanner mirrors to automatically place a 3, 6 or 9 mm spot size laser beam in a non-sequential, rectangular pattern [14,15].

Fig. 21: An example of a VSP Nd:YAG laser scanner (S11, XP Dynamis, Fotona) [25].

A scanner allows the use of small spot sizes to cover large skin areas without sacrificing treatment speed and efficiency. Advanced scanners, such as the S-11 from Fotona (Fig. 21) based on the SOE technology [10] also utilize top-hat distribution technology to minimize hot spots in the scanning pattern. In addition, long-term clinical experience has shown that the use of a scanner significantly reduces discomfort during the treatment. Since the coverage is computer-controlled, the laser spots do not have to be applied onto the skin sequentially next to one another, as would be the case in a manually performed treatment. For example, the Fotona S-11 scanner is able to scan the entire scan area during the given time period without ever depositing one spot directly next to another. The scanning sequence 'skips' spots and lines, with the 'gaps' being filled in progressively with each pass. In this way it requires four passes to cover the entire scan area completely, doing this as fast as a single 'Sequential' pass. Such scanning sequence allows the user to perform hair removal treatments that require high fluence settings at high repetition rates.

b) Clinical Guidelines

In laser hair removal, laser settings must always be balanced so that hair follicles are damaged while epidermal damage is avoided. When deciding on the treatment settings, first consider the structure of the hair and the skin type.

A thicker hair will draw in more energy and hold the energy longer. Its TRT is long and longer pulse durations can be used. When the absorbed energy has to be kept under the damage threshold of the epidermis, lower fluences are usually used. Thinner hair has a short TRT and the best clinical results are obtained with higher fluence and shorter pulse TRT settings.

To work safely, test spots are highly recommended. Adequate time should be allowed between the test and the treatment to allow for any adverse effects to appear. In general, darker hair in darker skin types requires lower fluence values for effective and efficient hair removal. For the group A skin types recommended hair removal fluence is below 70 J/cm². Group B skin types require more caution and fluences above 50 J/cm² are not recommended. For group C, recommended fluences are below 30 J/cm² (see Fig. 13).

Table 2 presents typical recommended FRAC3® hair removal settings. As with standard hair removal procedures, skin cooling before and after the treatment is recommended to additionally protect the epidermis.

Table 2: FRAC3® hair removal settings.

Treatment Modality:		***FRAC3® Hair Removal***		
Laser System		Fotona Dynamis		
Laser wavelength		Nd:YAG (1064 nm)		
User Interface Mode:		Pulse (Accelera)		
Utilized handpieces:		S11 scanner		
	Spot size (mm)	Pulsewidth (ms)	Fluence (J/cm²)	Frequency (Hz)
Skin group A	3	0.3- 5.0 msec	<55	15
Skin group B	3	0.3 - 5.0 msec	<35	20
Skin group C	3	0.3 - 5.0 msec	<25	25

Since the *FRAC3®* treatments are performed with a 3 mm spot size some users may argue the effective laser fluence may be too low due to scattering. However, this is not the case. A standard recommended Nd:YAG laser fluence for effective hair removal at a 9 mm spot size and 15 - 30 ms pulse duration is 55 J/cm². Taking into account the 1.6 time reduction in effective fluence within the skin when using the 3 mm spotsize, the *FRAC3®* fluence of 55 J/cm² corresponds to 40 J/cm² at 9 mm. However, one must also take into account at least 3 times more effective fractional heating of the hair follicles at shorter *FRAC3®* pulse durations. This translates into an effective fluence of 120 J/cm², well above the required fluence for standard hair removal procedures. The practitioner can therefore treat deep hair follicles very effectively with the *FRAC3®* treatment modality. In addition, hair removal is more comfortable for the patient because the sensation of pain at 55 J/cm² at 3 mm spotsize is 2 times lower compared to standard hair removal parameters - at 55 J/cm² and 9 mm spotsize (See Fig. 12)).

Table 3 summarizes the difference between the standard hair removal regiment and the recommended *FRAC3®* hair removal regiment.

Table 3: Comparison of the standard and FRAC3® hair removal treatment regimes.

Hair removal treatment regime	Fluence	Pulse duration	Spotsize	Hair removal efficacy	Pain
Standard	55 J/cm²	15-25 ms	9 mm	1	2
FRAC3®	55 J/cm²	1 ms	3 mm	2.2	1

When in doubt regarding the protocol, we recommend the following pre-treatment procedure. Shorten the hair with scissors and irradiate the hair starting with standard conservative hair removal parameters, 35 J/cm² fluence and 35 ms pulse duration, before shaving the treatment area. For patients represented in groups B and C, reduce the starting fluence accordingly. Observe whether any visible damage occurs on the irradiated hair (See Fig. 22). In case no damage is seen, continue reducing the pulse duration until the hair damage threshold is reached. In case no hair damage can be achieved even at pulse durations below 1 ms, increase the starting fluence by 10 J/cm² and repeat the procedure. When the damage threshold pulse duration is determined, use this pulse duration and the starting fluence, increased by 15-20 J/cm², for treating the patient. Note that for patients with Fitzgerald type skin V-VI, post-treatment hypo-pigmentation has been reported when pulses below 3 ms were used.

Fig. 22: Example of the observed hair damage at different pulse durations; a) Patient 1; hair damage is observed already at pulse durations below 25 ms; b) Patient 2; hair damage is observed only at pulse durations below 1 ms.

Cold air cooling is the latest method of active skin cooling (see Fig. 23). It increases treatment comfort by inducing a better analgesic effect for patients and providing unlimited post-treatment cooling. Pre- and post-treatment cooling is important as it has been shown to reduce side effects and healing time. The treatment is more practical, safer and more pleasant when using cold air cooling. Faster treatments are possible since there is no need for time intervals to apply a cryogenic spray or contact cooling. The treatment area remains visible at all times during the treatment. The procedure is not dependent on surface topography facilitating access to specify more complex areas, e.g. bikini, intergluteal fold, ears and nostrils. Furthermore, there is no medium disturbing the path of the laser beam and no interface inducing energy losses caused by dispersion, transmission and reflections. No disposables are required during FRAC*3*® treatment.

Fig. 23: A Fotona S-11 scanner with an air cooling flow nozzle. [25]

V. CONCLUSIONS

Skin surface temperatures following pulsed Nd:YAG laser irradiation were measured for different laser spot sizes and skin phototypes. For the same incoming laser beam fluence, the skin surface temperature was observed to increase with the laser spot size. This dependence was found to be in good agreement with Monte Carlo numerical simulations and is attributable to the optical scattering of the laser beam. The epidermal temperature was observed to differ by a factor of 2 to 4 between different skin phototypes. The hair and epidermal TRTs were also measured. Epidermal TRTs were found to be longer than 25 ms and longer than the hair's TRT. Measurements of patient's pain perception during Nd:YAG laser hair removal were also made. The sensation of pain was found to be independent of laser pulse duration in a broad range of 0.3 - 25 ms, in agreement with the measured long epidermal TRT. In addition, patient discomfort was observed to decrease with the laser spot size.

Based on the results of our study, a new Nd:YAG laser hair removal protocol is introduced that extends the hair removal treatment settings beyond the customary paradigm. The new protocol is based on the *FRAC3*® treatment modality [9-11] and promises to be a more effective and more patient-friendly approach to laser hair removal.

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