Parameters for the New FRAC3® Nd:YAG Laser Skin Treatment Modality

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ABSTRACT

A novel self-induced, non-ablative, three-dimensional fractional *FRAC3*® method for skin treatments is described. The method utilizes the short pulse duration and high peak power density of *Accelera* mode, Nd:YAG laser pulses. The *Accelera* Nd:YAG pulses produce a three-dimensional fractional pattern in the epidermis and dermis, with damage islands that are predominantly located at the sites of skin imperfections. In-vivo thermal measurements of the skin surface and in-vitro measurements of skin cross-sections, following illumination with *Accelera* Nd:YAG pulses are presented. The measurements demonstrate the emergence of isolated »fractional« hot islands within the skin. Clinical results following *Accelera* Nd:YAG laser treatments are also presented. The *FRAC3*® method offers practitioners another dimension of safety and self-regulating efficacy in non-ablative treatments such as skin rejuvenation and hair removal.

Key words: laser skin rejuvenation, fractional, FRAC3, VSP technology, Nd:YAG lasers, scanner

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I. INTRODUCTION

a) General

Fractional laser treatments affect discrete microspots within the target area, allowing the unaffected sub-areas in the target to act as healing centers. Fractional techniques are gaining popularity because they are associated with shortened recovery periods [2]. Current approaches to fractional treatment make use of fractional illumination in the form of a two dimensional matrix; the illuminated columns below the laser spots are damaged uniformly. These techniques are non-selective to skin imperfections or hair follicles and require special fractional delivery devices. Here we describe a novel self-induced *FRAC3*® laser method, [1, 15] based on Fotona, 1064 nm Nd:YAG, short pulse, Accelera mode characteristics [9]. The method produces a three-dimensional fractional pattern within the epidermis and dermis, with damage islands predominantly located at the sites of minute skin imperfections or inhomogeneities.

If the clinical objective is to cause selective modifications of a specific tissue structure, the laser wavelength should match the highest absorption of the targeted structure relative to the surrounding tissue. However, wavelengths that are highly absorbed in skin imperfections are typically also highly absorbed by non-target structures, e.g. melanosomes [4] or hemoglobin-containing RBCs [3]. These wavelengths consequently do not reach deeper-lying skin imperfections or hair follicles, which can result in excessive damage to healthy skin structures. For this reason, it is often better to select a laser wavelength that penetrates deeper into the tissue, and then achieve selective tissue modification by adjusting the laser pulse duration to the thermal relaxation time of the targeted imperfection. During a lengthy laser exposure in a long laser pulse most of the deposited heat will diffuse away from the target structure, resulting in non-specific thermal damage to adjacent structures. Conversely, an adequately short laser pulse minimizes the time available for heat diffusion and confines the heating effect to the target structure, resulting in maximal temperature differences between the target and adjacent structures [5]. Using the homogeneously penetrating, 1064 nm Nd:YAG laser wavelength [6-8], and targeting skin imperfections by adjusting the laser pulse duration to the cooling times of these imperfections is the paradigm behind the latest

FRAC3®, minimally invasive skin rejuvenation, technique. The method utilizes the fractional nature of the selective photo-thermolysis, at short laser pulse durations [5].

b) FRAC3®: Three Dimensional Fractional Skin Treatment

Upon irradiation with an adequately short laser pulse, energy is deposited into the absorbing structure before a significant amount of heat can be conducted to the surrounding tissue. The temperature rise in an optically and thermally homogenous structure is directly proportional to the absorbed heat, which is itself proportional to the laser fluence (in J/cm^2) delivered to the target. If a significant fraction of the deposited heat diffuses away from the absorbing structure during laser exposure, the peak temperature is reduced, impairing the spatial selectivity of the treatment even if the wavelength provides selective absorption of laser energy. The selection of an appropriate laser pulse duration is therefore paramount. Laser pulses of duration t_p that are significantly shorter than the target thermal relaxation time (τ) will cause a maximal temperature rise in a target structure for constant pulse energy. The relaxation time, τ, 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.

Simplified, the thermal relaxation time (TRT) depends on the diameter of the target structure (d), and the thermal diffusivity of skin (α = 0.11 mm^2/s) as

$$\tau = d^2/(20\,\alpha) \quad . \qquad (1)$$

An exact formula would depend on the shape of the skin structure [7].

Based on the above considerations it is assumed, for the remainder of this paper, that selective heating of a skin structure occurs when the pulse duration is shorter than the relaxation time τ 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 Figure 1, confinement of laser energy within smaller structures requires progressively shorter pulse durations. For structures smaller than 100 μm, pulse durations less than 1 ms must be used.

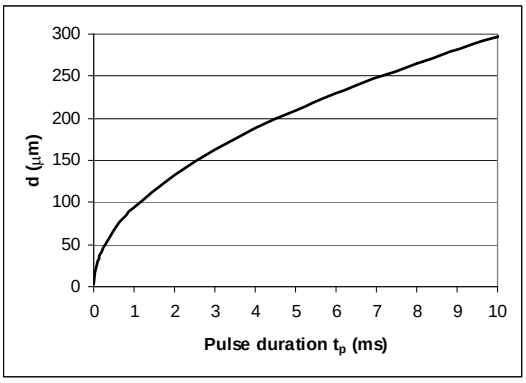

Fig. 1: Minimal size (d) of a skin structure that can be selectively heated by a laser pulse of duration t_p.

Inasmuch as pulses significantly shorter than τ provide the highest temperatures, it would seem that the best approach would be to use extremely short pulses (t_p << 50 μs) to ensure heat confinement in skin structures of all sizes, but this is not the case. Explosive vaporization of selectively absorbing hemoglobin can occur when pulses shorter than 10 μs are used at high laser fluences [3]. Similarly, epidermal melanosomes can be non-uniformly overheated during high fluence laser pulses below 25 μs [4]. The safest and most effective pulse durations for minimally invasive skin rejuvenation are therefore in the 100-1000 μs range.

When Nd:YAG laser pulses in the 0.1-1.0 ms range are used, small skin imperfections, inhomogeneities and hair follicles are selectively heated throughout the illuminated skin tissue (see Fig. 2). Fractional islands of thermally affected skin structures that are formed in the three dimensional skin tissues are the basis for the *FRAC3*® approach to minimally invasive skin rejuvenation.

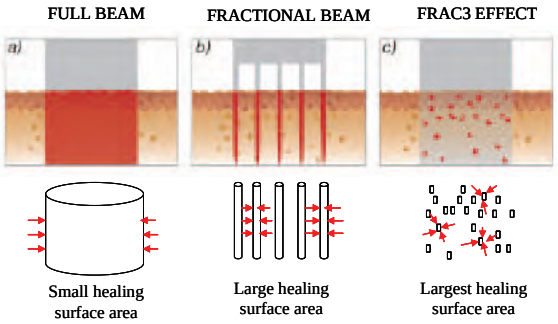

Fig. 2: Laser induced damage islands as healing centers: a) standard uniform laser treatment; b) standard two-dimensional fractional treatment; and c) novel self-induced three-dimensional FRAC3® laser treatment. With the FRAC3® method the tissue is treated only where required, i.e. at skin imperfections. In addition, the healing area is the largest and the healing time is the fastest.

II. MATERIALS AND METHODS

Thermal skin measurements were performed to confirm the *FRAC3*® self-induced, three-dimensional distribution of heat within the skin [1]. A standard, long pulse will cause an approximately uniform rise in skin temperature. The thermal profile of *FRAC3*® laser pulses should exhibit non-uniform temperature peaks (See Fig. 3).

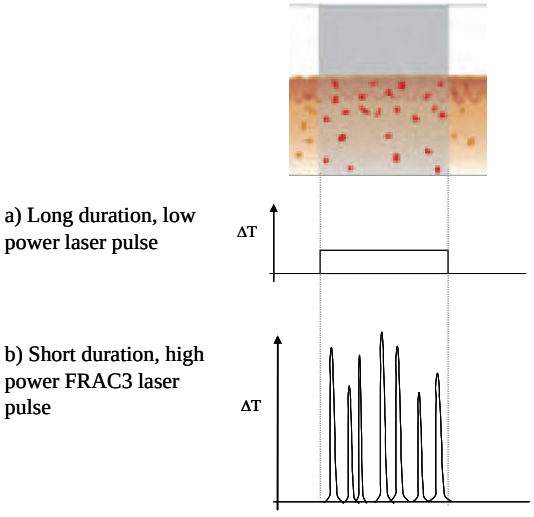

Fig. 3: a) Standard treatment. Small absorbers are not heated; heat diffusion into the surrounding tissue is too rapid; b) FRAC3® treatment. Small absorbers are heated very quickly and there is not enough time for diffusion to proceed.

The experimental set-up is shown in Figure 4. A Fotona XP Dynamis Nd:YAG laser system operating in the *FRAC3*® Accelera (t_p = 0.1 - 1 ms) and standard Versa modes (t_p = 2 - 200 ms) and a thermal imager (Sagem Matis) operating in the 3-5 μm spectral range were used. The image exposure time was approximately 2 ms. The imager sensor detects thermal light emitted from the surface and also some from the subsurface as the light of wavelengths 3-5 μm has a penetration depth of about 50 μm in the tissue. The measured temperatures therefore represented a weighted average of the skin temperature within the penetration depth of the detected thermal radiation.

Skin surface measurements of the temperature distribution following an Nd:YAG laser pulse with a 4 mm spot size were performed in-vivo on patients' dorsal hand skin.

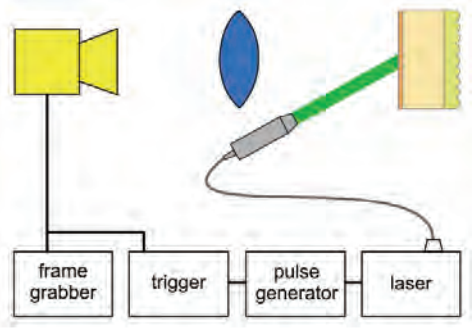

Fig.4: Experimental set-up for thermal imaging measurements.

III. RESULTS

a) Thermal Skin Measurements of FRAC3® Self-Induced, Three Dimensional, Fractional Islands

Figure 5a shows a typical skin temperature profile following a standard 20 ms long, Versa Nd:YAG pulse. Figure 5b shows the temperature profile following a short, 0.3 ms Accelera Nd:YAG pulse.

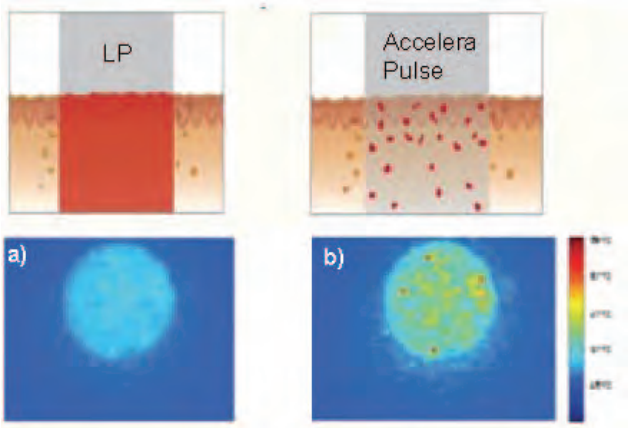

Fig. 5: Skin surface temperature thermal image following a 20 ms (a), and a 0.3 ms (b) Nd:YAG laser pulse.

Self-induced temperature fractionality can be observed following illumination with short Accelera Nd:YAG pulses. For standard-lenght pulse durations, heat conduction from the skin inhomogeneities to the surrounding tissue prevents temperature build-up and no hot skin islands are observed. This is shown in Figure 6 in which ΔT temperature profiles are shown within a patient's skin on the hand's dorsum, illuminated with a Nd:YAG laser of 4 mm spot size and 50 J/cm² at different pulse durations. Only the 0.2 ms laser pulse creates significant self-induced temperature fractionality.

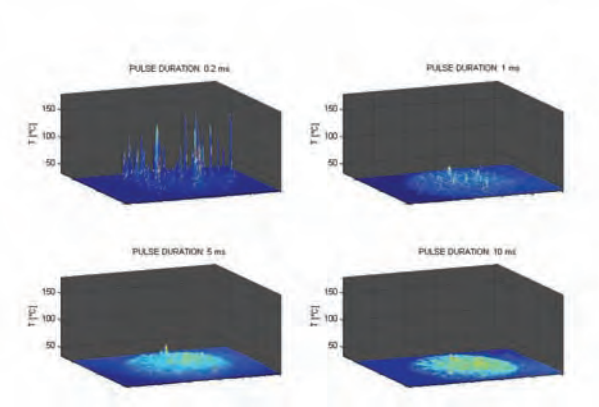

Fig. 6: Skin surface temperature profiles (ΔT) following a 50J/cm² Nd:YAG laser pulse of different pulse duration.

The dependence of the *FRAC3*® effect on the pulse duration for Fitzpatrick skin types I-II is shown in Figure 7; the measured temperature increase, ΔT, versus pulse duration is plotted. The fractional temperature increase is the average value of the highest ten temperature peaks at each laser pulse duration.

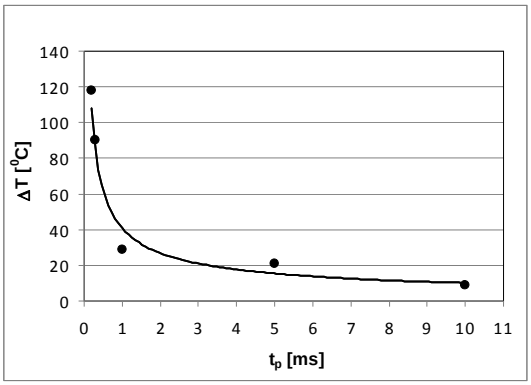

Fig. 7: Measured fractional temperature increase, ΔT, at the skin surface (Fitzpatrick type I-II) as a function of the Nd:YAG laser pulse duration (32 J/cm², 3 mm spot size).

Since the observed skin imperfections close to the skin surface are in the order of 50 μm in size, the fractional temperature increase becomes appreciable in pulse durations shorter than 0.5 ms. This is in agreement with the previous discussion and Figure 1. Note that *FRAC3*® enhances the temperature increase by a factor of ten when the laser pulse duration is reduced from 10 ms to 0.2 ms.

Assuming that the size and absorption characteristics of targets deeper in the skin are similar to those observed at the skin's surface, we can calculate the fractional temperature increase for deep-lying targets (e.g. the micro-vasculature) from the experimental data shown in Figure 7. We should take a reduction of the laser fluence with skin depth into account, which is due to the laser light absorption and scattering. Figure 8 shows the predicted fractional temperature increase (ΔT) for different skin depths as a function of the laser pulse duration for a laser fluence of 40 J/cm², and laser spot size of 3 mm. Similarly, Figure 9 shows the predicted ΔT for a laser fluence of 20 J/cm² .

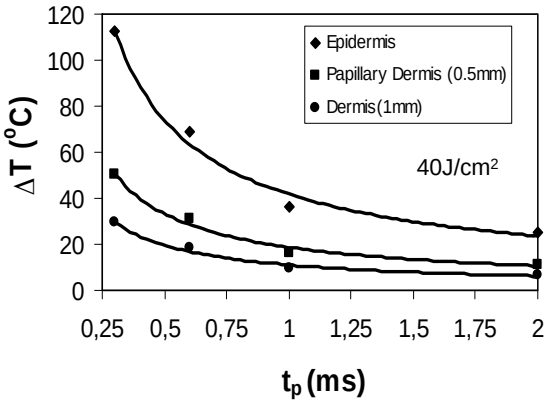

Fig. 8: Calculated fractional temperature increase (ΔT) for different depths within the skin (Fitzpatrick type I-II), as a function of the Nd:YAG pulse duration (40 J/cm², 3 mm spot size).

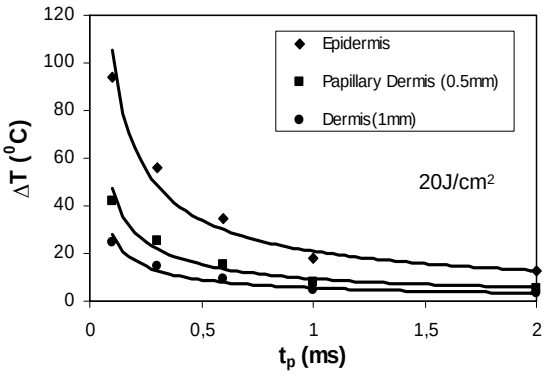

Fig. 9: Calculated fractional temperature increase (ΔT) for different depths within the skin (Fitzpatrick type I-II), as a function of the Nd:YAG pulse duration (20J/cm², 3 mm spot size).

Self-induced temperature fractionality was also observed deeper in the skin, demonstrating the three-dimensionality of the effect. Figure 10 shows thermal images following Nd:YAG pulses as seen in-vitro on a cross-section of human skin, excised from a female's abdomen. Figure 10a shows a typical thermal image of the skin following a standard 20 ms long, Nd:YAG pulse. Figure 10b shows the thermal image following a short duration 0.3 ms Accelera Nd:YAG pulse. Self-induced temperature fractionality can be only observed following illumination with the Accelera Nd:YAG pulses.

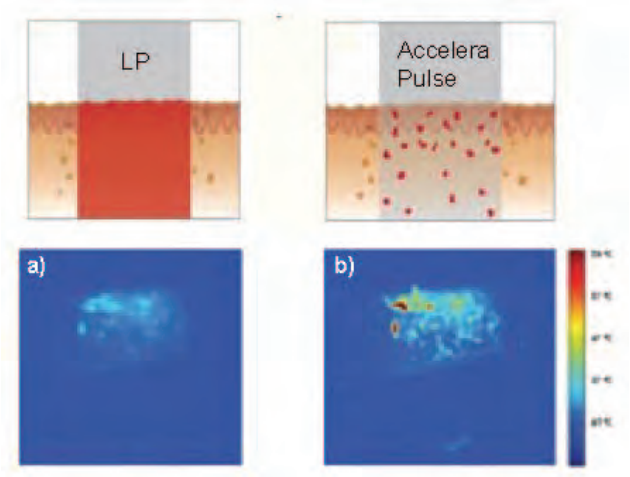

Fig. 10: Skin cross-section thermal images following Nd:YAG laser pulses with a duration of 20ms (a) and 0.3ms (b).

Melanin concentration can vary by a factor of 20 between different human skin phototypes [28]. Safe epidermal fluence levels and subsequent heating therefore depend on how dark and heavily pigmented the patient's epidermis is. For this reason we have performed measurements of the fractional temperature increase for different skin phototypes.

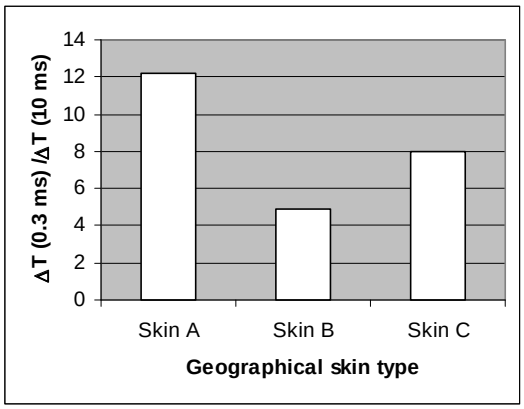

Fig. 11: Relative fractional skin temperature increase at 0.3 ms Nd:YAG pulse duration versus the skin temperature increase at 10 ms pulse duration for three geographical regional groups: Skin A (Europe), Skin B (China, Egypt), and Skin C (India, Japan).

Our study on patients from different geographical regions has shown that in terms of epidermal heating, patients can be grouped in roughly four skin groups: Group A represented by patients with typical skin phototypes for Europe, group B represented typical phototypes for China and Egypt, and group C India and Japan. A fourth group D, not included in our study, would represent for example African skin phototypes. Figure 11 shows the ratios of the fractional temperature increase at 0.3 ms pulse duration with the temperature increase at 10 ms pulse duration. The measured relative fractional temperature increase is not strongly dependent on skin phototype. The largest relative fractional increase was actually observed for the Fitzgerald I-II phototype skin, indicating that FRAC3® can be safely used on darker skin types, providing that overall higher absorption of darker skin types is taken into account. A separate study [19] determined that in comparison to group A patients and their photo-skintypes, and independently of the laser treatment regime, the laser treatment fluence should be reduced by a factor of 1.7 for patients from group B, and by a factor of 2.5 for group C. The radiant exposure that can be safely applied to groups B and C is thus limited the risk of epidermal injury. This limitation can be alleviated by external cooling of the skin surface prior to laser irradiation. Forced cold air cooling is the preferred method of epidermal cooling in Nd:YAG procedures.

IV. DISCUSSION

a) FRAC3® Treatment Method

The *FRAC3®* approach is very effective for treating small-diameter skin imperfections with fast thermal relaxation times (See Fig. 12): i) Rejuvenation of aged skin; ii) Treatment of microvasculature; iii) Removal of unwanted hair; iv) Bacterial reduction in active acne.

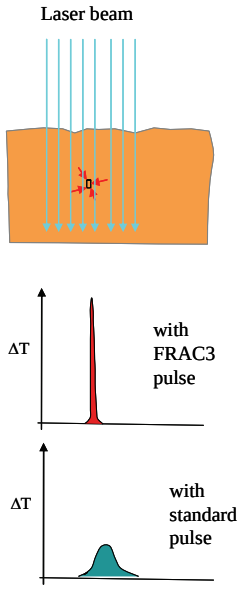

Fig. 12: FRAC3® action is very effective for treating small-diameter skin imperfections with fast thermal relaxation times. With FRAC3® parameters, a small skin imperfection or a thin hair follicle experiences a high localized temperature increase ΔT while with the standard laser parameters the local temperature increase is much smaller.

For the Fotona Dynamis Nd:YAG laser system that was used in our study the recommended *FRAC3®* parameters are as follows:

Table 1: FRAC3® skin rejuvenation parameters.

Treatment Modality:		*FRAC3®*		
Laser System		Fotona Dynamis		
Laser wavelength		Nd:YAG (1064 nm)		
User Interface Mode:		Pulse		
Utilized handpieces:		R31, R33, S11		
	Spot size (mm)	Pulsewidth (ms)	Fluence (J/cm²)	Frequency (Hz)
Skin type I - III	3	0.3 - 0.6 msec	35	1.0 – 3.0
Skin type IV - VI	3	0.6 - 1.0 msec	15-20	1.0 – 3.0

One feature of the *FRAC3®* treatment method is its requirement for relatively high energy and fluences at short pulse durations, which is difficult to achieve with larger spot sizes. *FRAC3®* treatments are therefore typically performed with a 3 mm beam spot size. Yet manually aiming a small to medium spot size laser beam hundreds of times to cover a larger skin area can lead to uneven coverage and can result in missed areas and excess heating due to pulse stacking. The laser must be placed with millimeter precision over the entire area, an impossible task as it is difficult to determine the treated area accurately.

For the above reasons, *FRAC3®* treatment method has until recently not been a viable option. It is only after the introduction of the Acccelera Nd:YAG and Scanner Optimized Efficacy (SOE) technologies that relatively large laser fluences in the range of 35-55 J/cm², with pulse durations of 0.1-1.0 ms have become available for 2-4 mm sizes (See, for example, technical specifications of the latest Fotona XP Dynamis Laser Systems).

SOE (Scanner Optimized Efficacy) technology eliminates these problems by utilizing computer-controlled laser scanner mirrors to automatically place a 3 mm spot size laser beam in a perfect non-sequential pattern [14,15].

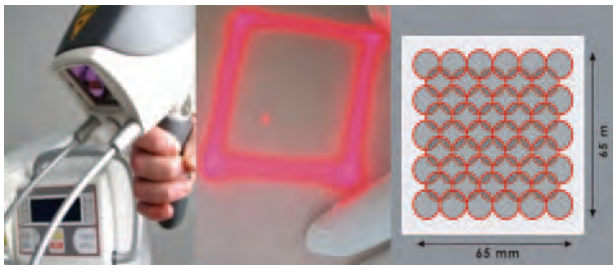

Fig. 13: An example of a VSP (Variable Square Pulse) Nd:YAG laser scanner (S-11 Fotona XP Dynamis)

A scanner allows the use of small spot sizes to cover large skin areas without the need to sacrifice treatment speed and efficiency. Advanced SOE technology-based scanners [10], such as the S-11 from Fotona (Fig. 13) also use 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, as in a manually performed treatment. Fotona's S-11 scanner, for example, 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, standard 'sequential' pass. Such scanning sequence allows the user to perform large area treatments that require high fluence settings at high repetition rates.

b) FRAC3® Epidermal Safety Considerations

A laser treatment is safest when laser pulses can be chosen with pulse duration longer than the TRT_{epi} of the epidermis but shorter than the TRT of the treated skin imperfection. This allows selective heat treatment of the pigment without overheating the epidermis. This is why standard skin treatment guidelines often recommend using longer laser pulses which, at least in theory, are less likely to cause injury to the epidermis.

However, for most treatments and patients this approach is contra-productive because epidermal TRT is typically longer than 25 ms, while the TRTs of small imperfections are typically very short. For such cases, shortening the pulse duration below 25 ms does not significantly alter the temperature increase of the epidermis, while it significantly increases the temperature of the imperfection, and consequently of the treatment efficacy (see Fig. 14). Optimal pulse durations for treating small imperfections are thus in the *FRAC3®* treatment range of pulse durations $t_p < 1$ ms.

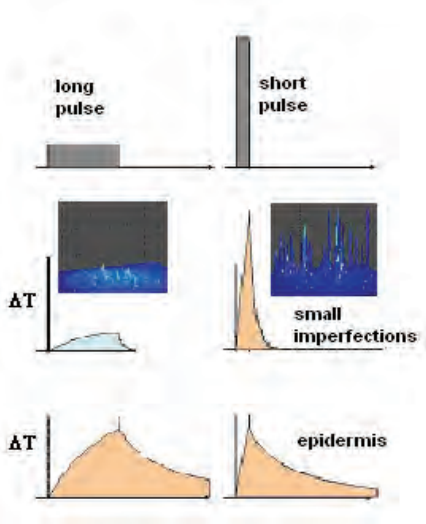

Fig. 14: In FRAC3® treatments where $TRT_{epi} < TRT_{imp}$ situation applies, shortening the laser pulse duration improves treatment efficacy of small skin imperfections without endangering the bulk epidermis. .

c) FRAC3® Skin Depth Considerations

Since *FRAC3*® procedures are most commonly performed with a 3 mm spot size it may be argued that the treatment efficacy will be affected by the reduced skin penetration depth of smaller spot sizes. As 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 [19]. This effect is more pronounced in smaller spot sizes where the spreading of the beam is relatively large compared to the incoming beam spot size (See Fig. 15).

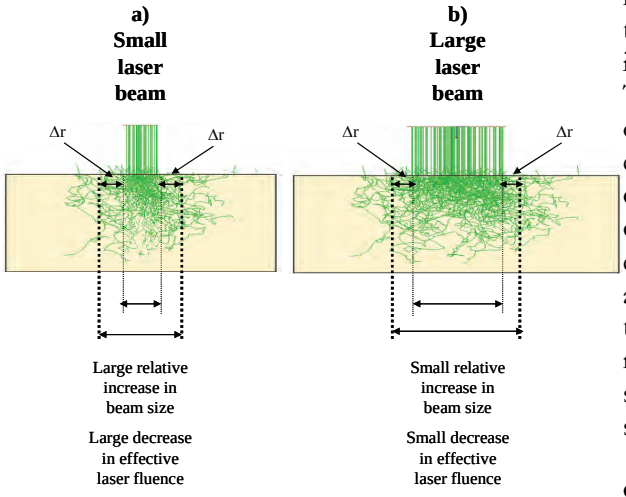

Fig. 15: Influence of scattering on the effective laser beam spot size. The thermal profiles indicate that the beam spreads radially outward on each side by approximately Δr = 0.7 mm. The effect is relatively less significant at larger spot sizes.

This is why, for example, the effective fluence within the skin of a 3 mm incoming laser beam is - by a factor of 1.6 - smaller compared to the effective fluence of a 9 mm laser beam. This results in an approximately 1.6 times smaller temperature increase within the skin when using a 3 mm spot size beam compared to a 9 mm spot size beam. This reduction of the effective fluence within the skin is often interpreted as a reduction 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 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 [19]. The practitioner can therefore also treat deeper-lying skin pigments or hair follicles with smaller beam spot sizes providing that the laser fluence is adjusted accordingly. Table 2 shows the approximate relations among the effective fluences at different spot sizes.

Table 2: Approximate relations among the effective fluences at different incoming beam spot sizes. The values are presented relative to the effective fluence at a 9 mm spot size.

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%

A standard recommended Nd:YAG laser fluence for *FRAC3*® skin rejuvenation is 35 J/cm² at 3 mm spot size. This corresponds to 20 J/cm² (35/1.6) at 9 mm. However, one must also take into account the 5 times more effective fractional heating of the small imperfections at shorter, *FRAC3*® pulse durations. This translates into a relatively high effective fluence of 100 J/cm² for the targeted pigments, while the effective fluence for the bulk skin remains at the comfortable and safe 20 J/cm² level. The practitioner can therefore treat deeper-lying pigments very effectively with the *FRAC3*® treatment modality. In addition, the *FRAC3*® is much more comfortable for the patient as the sensation of pain at 35 J/cm² at 3 mm spot size is 3 times lower compared to the standard treatment settings of 55 J/cm² at 9 mm spot size.

d) FRAC3® Treatments of Microvasculature

The thermal relaxation time of the vessels can be obtained by approximation from the equation for the relaxation time of an infinite cylinder:

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

The equation gives thermal relaxation time for different blood vessel diameters, as shown in Table 1. The *FRAC3*® treatment modality, with pulse durations between 0.1 and 0.4 ms, targets vessels with diameters under 50 μm in size.

Table 3: Thermal relaxation time (TRT) for the range of blood vessel diameters.

Vessel diameter (μm)	Thermal relaxation time (ms)
10	0.057
20	0.23
50	1.42

e) FRAC3® Hair Removal

The *FRAC3*® treatment concept is also applicable to hair removal since it is clinically desirable to selectively treat the hair follicle without injuring surrounding tissue [19]. It has been demonstrated that successful permanent unwanted hair removal can only be achieved by injuring the bulb, the bulge and the outer root sheath of the hair follicle [16, 8]. In order to destroy the target hair tissue and to avoid damage of surrounding tissue, the laser pulse duration should be lower or approximately equal to the hair tissue's TRT. This applies even more so when treating patients with thinner and lighter hair where the TRT and the absorption in hair follicles are the lowest. For this reason, a new Nd:YAG laser hair removal protocol has been recently introduced, that extends the hair removal treatment settings beyond the customary paradigm [19]. The new protocol promises to be a more effective and more patient-friendly approach to laser hair removal.

f) FRAC3® Skin Rejuvenation: Clinical Experience

Clinical results show the self-induced three-dimensional non-ablative Nd:YAG laser fractional treatment to be a safe and effective alternative to more aggressive laser techniques [10, 15]. Typical treatment parameters are 15-40J/cm² at pulse durations of 0.1-0.4 ms. Photographic evaluations show improvement in erythema along with an associated improvement in skin quality [10]. The improvement in pore size, texture and color is attributed to the short pulse targeting of the microvasculature [11]. No side effects apart from transient erythema have been reported.

Ultra-structural analysis of skin treated with 0.3 ms Nd:YAG laser pulses has shown a decrease in overall collagen fiber diameter in the papillary dermis. This is consistent with the formation of new collagen [10,12]. The treatment stimulates new collagen production by producing localized thermal injury to the dermis that initiates a wound-healing response [12]. During wound healing, procollagen and type III collagen fibers are produced initially and have a small diameter. A decrease in collagen fiber diameter has therefore been associated with production of new collagen, which is thought to increase skin firmness and improve skin texture in patients after treatment [13]. The best results were obtained with patients below 50 years of age while older patients did not show a decrease in collagen fiber diameter [10].

V. CONCLUSIONS

A novel, *FRAC3*® non-ablative, fractional laser method is described, that produces a self-induced fractional thermal damage matrix within the skin tissues. The method utilizes the fractional nature of the selective photo-thermolysis at short laser pulse durations. [5]

The *FRAC3*® fractional thermal damage structure forms around existing skin imperfections and inhomogeneities as well as around hair follicles, and is not arbitrarily imposed on the skin by external optics. This makes the method very effective and minimally invasive. An additional advantage of the *FRAC3*® approach when compared to the standard fractional techniques is that the resulting fractional damage islands are not limited to the two-dimensional column matrix but are distributed in a three-dimensional manner throughout the skin volume. In addition, no special optical device is needed, thus leading to better cost-effectiveness of the skin rejuvenation procedure.

The new *FRAC3*® laser method is the next step in improved laser skin treatment procedures, with its efficacy, selectiveness, short healing time and cost-effectiveness.

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