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Enhanced Hair Removal based on the "Avalanche Effect" of the AvalancheLase® Hair Removal Laser System

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ABSTRACT

The "avalanche effect," in which the absorption of laser light in hair is increasingly enhanced following each successively delivered laser pulse, was measured for two laser hair removal wavelengths, alexandrite (755 nm) and Nd:YAG (1064 nm).

Based on the results of the study, an "avalanche" laser hair removal protocol was developed for the alexandrite and Nd:YAG laser wavelengths of the AvalancheLase® hair removal system, which is equipped with novel DMC™ (Dry Molecular spray Cooling) skin-cooling technology.

In conclusion, the measured avalanche effect enables the performance of very effective "avalanche" hair removal by delivering a series of relatively low fluence pulses to hair follicles.

Key words: hair removal, avalanche effect, alexandrite laser, Nd:YAG laser.

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I. INTRODUCTION

Excess or unwanted hair is a common problem affecting both genders. First introduced in the mid-1990's, laser hair removal has become an accepted treatment modality for patients seeking to reduce unwanted hair, and it has also been found to improve quality of life for many patients [1, 2]. The types of lasers currently in use for hair removal include alexandrite, neodymium: yttrium-aluminum-garnet (Nd:YAG) and diode [3-12].

While all skin types can be treated (given the appropriate laser), in general, the greater the difference in pigmentation between the skin and hair, the better the result. The darker an individual's skin becomes, the more melanin they have, so the skin begins to heat more with the application of the laser, potentially leading to pain and epidermal damage. Therefore, darker skinned individuals must be treated at lower fluence levels and often require more treatments to attain good hair reduction [14-17].

Another challenge involves patients whose hair contains low melanin content, resulting in low absorption of laser light in treated hair. For this reason, early hair removal techniques were based on infiltrating black carbon into hair ducts in order to increase the absorption of hair at the treatment laser's wavelength [18].

However, more recently, it has been proposed that the absorption of laser light in hair could be enhanced by the treatment laser light itself [19, 20]. An "avalanche" effect was observed where the absorption of the treated hair became increasingly enhanced following each subsequently delivered laser pulse.

This phenomenon has led to an improved, "avalanche" hair removal protocol that consists of delivering a series of laser pulses to the same skin area, with the laser pulse parameters being optimized for the maximal avalanche effect. This technique is different from a standard "stamping" technique where the laser handpiece is positioned over the treated skin from spot to spot without any overlapping, and single high fluence pulses are delivered to each of the spots [7, 12].

In this paper, we study the avalanche effect by measuring hair temperature changes during the avalanche hair removal pulse series modality of an AvalancheLase® laser system that is capable of delivering extremely powerful and controlled outputs at alexandrite (755 nm) and Nd:YAG (1064 nm) wavelengths, and utilizes a novel DMC™ (Dry Molecular spray Cooling) skin-cooling technology.

II. MATERIALS AND METHODS

a) Laser system

The laser system used in the study was an

AvalancheLase® (manufactured by Fotona d.o.o., Slovenia; see Fig. 1) consisting of two ultra-performance solid crystal laser sources delivering two highly effective and well-known hair removal laser wavelengths, the Alexandrite (755 nm) and Nd:YAG (1064 nm) wavelengths. The system can be fitted either with an R35 manual handpiece (with 2-30 mm spot sizes) or an LX-Runner scanning handpiece (with individual spot size diameters of 9 and 11 mm, and an adjustable scan area of up to approximately 8 x 8 cm^2).

Fig. 1: AvalancheLase® alexandrite and Nd:YAG laser system.

In addition, AvalancheLase® is equipped with a novel proprietary DMC™ (Dry Molecular spray Cooling) technology integrated into the handpieces to allow for very fast, effective and non-contact cooling of the irradiated skin using a controlled very fine ("dry") water spray mist. This technology improves comfort and safety since it uses room temperature air and water, avoiding the risk of cryo-injury by over-cooling the skin [25].

b) Hair temperature measurements

The experimental set-up is shown in Fig. 2.

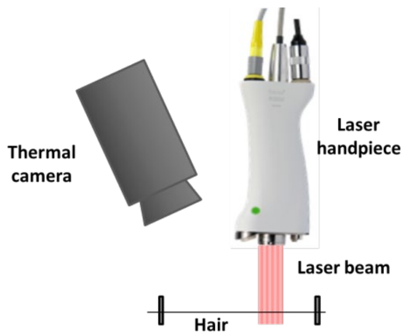

Fig. 2: Experimental set-up. A human hair was pulled out of a human scalp, and fixed in the air in a straight horizontal position. The Nd:YAG or alexandrite laser beam was directed onto the hair, and the resulting hair temperature increase was measured with a thermal video camera.

The Nd:YAG or alexandrite individual laser pulses (t_p = 2 ms) were directed onto the hair, and the resulting hair temperature increase following each laser pulse was measured with a thermal video camera (Flir ThermaCAM P45), set to record the maximal pump temperature increase (ΔT) of the hair sample. A room temperature air blower was used to shorten the hair cooling time following pulsed irradiation. The pulses were delivered at sufficiently long separation times ($t_s \geq$ 2 s) to allow the hair to cool down to the ambient temperature in-between pulses.

A typical thermal image of the irradiated hair following a laser pulse is shown in Fig. 3.

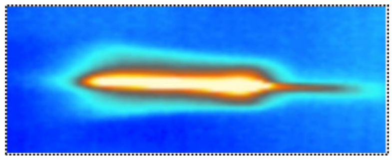

Fig. 3: A typical thermal image of the irradiated hair following a laser pulse.

c) Skin temperature measurements

In order to study how the skin temperature increase may limit the maximal laser pulse repetition rates during avalanche hair removal, the temporal evolution of the superficial skin temperature following a single Nd:YAG or an alexandrite laser pulse was also measured. Measurements were made for conditions without external skin cooling, and as well with DMC™ and cold air cooling.

III. RESULTS

a) Hair temperature results

Fig 4 shows the evolution of temperatures as observed by applying a series of individual Nd:YAG laser pulses to the same hair section with consecutively increased fluence (F_p) from F_p = 5 J/cm^2 up to F_p = 25 J/cm^2.

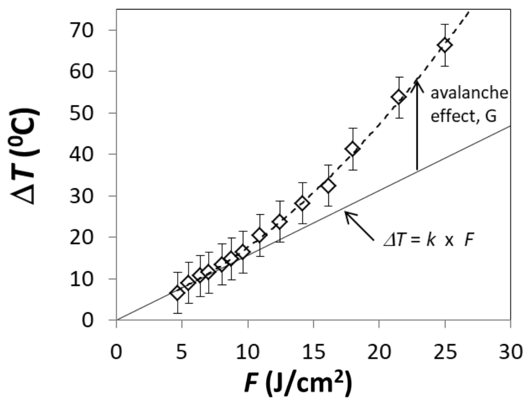

Fig. 4: Temperature increase ΔT of the same hair section following a series of individual Nd:YAG laser pulses with consecutively increased fluence. The pulses were delivered at sufficiently long separation times to allow the hair to cool down in-between pulses.

The line in Fig. 4 represents the linear dependence of the temperature increase on the delivered fluence according to:

$$\Delta T_{lin} = K \text{ x } F \,, \qquad (1)$$

as would be expected if there was no influence of laser irradiation on the hair's thermal characteristics. The temperature coefficient K (with K_{Nd} = 1.56 ^{0}C.cm^2/J) defines the linear growth of ΔT with F as observed at low laser fluences.

We attribute the observed deviation of ΔT from the linear dependence of Eq. 1 to the "avalanche" effect, i.e. to the increased thermal response of the human hair after being irradiated by a laser pulse with $F > F_a$, where F_a is the threshold fluence for the avalanche effect. For the used Nd:YAG laser parameters and the measured hair, the avalanche threshold was found to be at about $F_a \approx 10$ J/cm^2. Similarly, for the alexandrite laser we determined the avalanche threshold to be at about $F_a \approx 3$ J/cm^2.

Taking the avalanche effect into account, the dependence of the temperature increase on the delivered fluence can be expressed as:

$$\Delta T = G_a \text{ x } \Delta T_{lin} = G_a \text{ x } K \text{ x } F \,, \qquad (2)$$

where G_a is the "avalanche gain", characterizing the influence of the avalanche effect on the measured hair's thermal response. The total temperature increase is therefore represented by the sum $\Delta T = \Delta T_{lin} + \Delta T_a$, where $\Delta T_a = (G_a - 1) \text{ x } \Delta T_{lin}$ is the additional temperature increase caused by the avalanche effect.

Figure 5 shows the evolution of temperatures during the delivery of a series of N = 50 Nd:YAG or alexandrite laser pulses with the fluences (F) of 14.4 J/cm^2 (for Nd:YAG) and 5 J/cm^2 (for alexandrite) set to be just above the corresponding avalanche threshold values.

As can be seen from Fig. 6, the initial avalanche gain as observed for the first pulse in the sequence becomes significantly further enhanced during the first 20-30 pulses in the series.

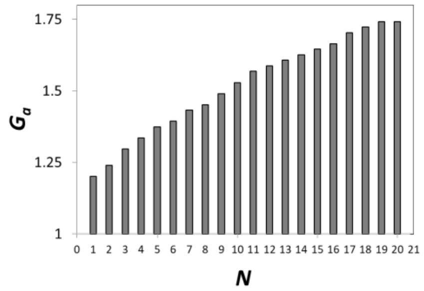

Fig. 6: Gradual increase of the avalanche gain G_a during the delivery of Nd:YAG pulses from Fig. 5a.

b) b) Skin temperature results

Figure 7 shows the measured skin temperature evolution following a single Nd:YAG or an alexandrite laser pulse when no external cooling was used. The observed initial fast decay is caused by the large temperature gradient between the melanin-rich epidermis and the deeper-lying dermis. As expected, the decay is faster for Nd:YAG due to the larger initial temperature difference between the epidermis and dermis. Therefore, the avalanche repetition rates can be faster when using an Nd:YAG laser.

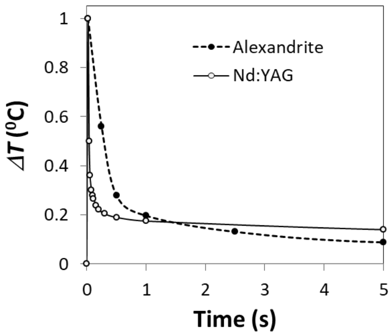

Fig. 7: Temperature evolution following a single Nd:YAG or alexandrite laser pulse when no external skin cooling is used.

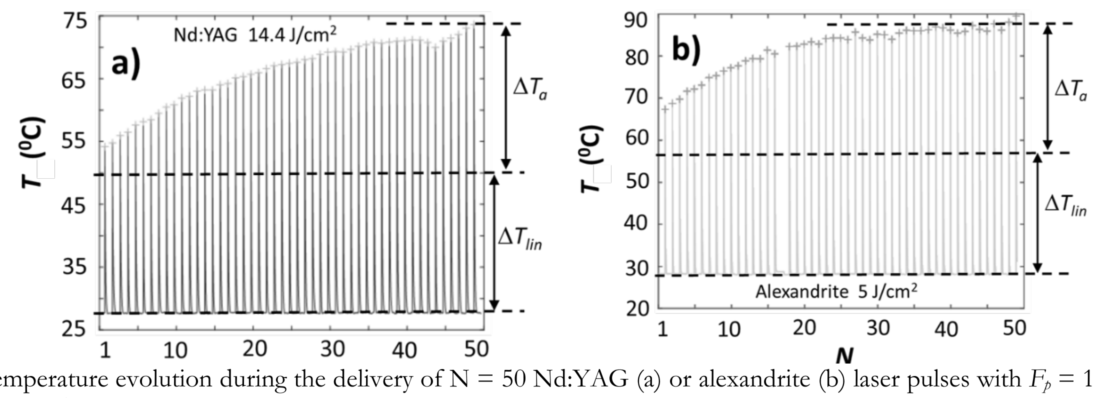

Fig. 5: Temperature evolution during the delivery of N = 50 Nd:YAG (a) or alexandrite (b) laser pulses with F_p = 14.4 J/cm^2 and F_p = 5.0 J/cm^2, correspondingly. The pulse repetition rate was 0.5 Hz. Room temperature forced air was used to cool down the hair in-between measurements.

Figure 8 shows the measured skin cooling rate of non-irradiated skin during cold-air and DMC™ cooling.

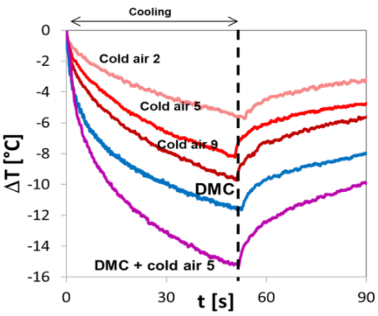

Fig. 8: Comparison of the DMC™ cooling characteristic with that of the standard cold-air cooling.

As can be seen from Fig. 8, the DMC™ cooling technology delivers fast cooling rates, enabling fast and comfortable non-contact avalanche hair removal on all body areas.

IV. DISCUSSION

Our measurements demonstrate an avalanche effect which occurs when hair is subjected to an individual laser pulse of a sufficiently high fluence, or to a series of lower fluence laser pulses. This effect leads to an enhancement of the temperature response of the irradiated hair.

Based on the results of our study, laser hair removal treatment can be performed at laser fluences much lower than what is required when performing hair removal using the stamping technique [7, 12, 14]. By repeating the treatment irradiation within the same treatment session, the effect of each treatment irradiation is enhanced, until the hair removal temperatures within the hair follicle are reached.

A major limitation of the study is that temperature measurements were carried out on hair suspended in air, while in a clinical situation the hair is embedded within the skin matrix. Nevertheless, simulations of the hair temperature under Nd:YAG and alexandrite irradiation indicate that the observed avalanche phenomenon may apply also to hair located within the skin matrix. In a study by Žaneček and Milanič [24], a numerical model of laser epilation was developed, which also used experimentally obtained hair and skin parameters to calculate the temperature increase along the hair shaft down to the hair follicle. The temperatures of the hair located within the skin matrix were found to be similar or higher than those obtained for the hair suspended in air. This is due to the scattering of the laser light within the skin matrix, effectively enhancing the number of photons that become trapped within the highly absorbing hair, in spite of the beam being progressively absorbed by the skin chromophores.

Therefore, the hair temperatures under a clinical setting are expected to be above the avalanche threshold when using relatively low fluence values for the Nd:YAG and alexandrite laser epilation.

When performing hair removal based on the observed avalanche effect using a manual handpiece, the treatment is performed using a brushing technique. This technique involves higher pulse rates (3-5 Hz), with the R35 handpiece in a constant movement backwards and forwards at a speed of 2-3 cm/s until a sufficiently high cumulative energy is delivered to the whole treated area. So rather than lasing each hair follicle individually with a high powered beam, the avalanche technique accumulates the delivered energy into the entire treated area over a larger number (N) of lower-fluence pulses, to a point in which the hair follicles get damaged.

An example of the clinical efficacy of the avalanche hair removal technique is presented in Fig. 9, which shows the persistent avalanche hair removal effect four (4) months following only a single treatment with the alexandrite wavelength of the AvalancheLase® hair removal laser system.

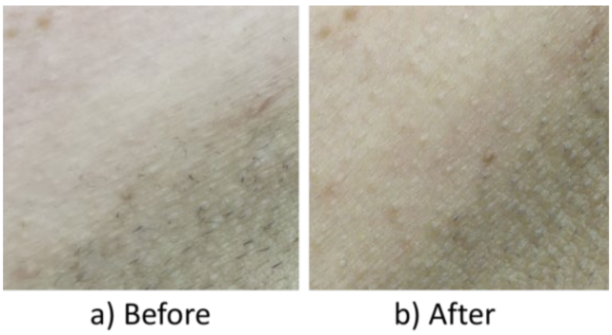

Fig. 9: Underarm hair removal a) before; and b) 4 months after a single avalanche treatment with alexandrite laser using the following parameters R35X handpiece, 10 Jcm², 3 Hz, 2 ms, 12 mm.

V. CONCLUSIONS

In conclusion, the measured avalanche effect enables the performance of very effective "avalanche" hair removal by delivering a series of relatively low fluence pulses to hair follicles. This characteristic, combined with the proprietary skin cooling DMC™ technology, enables fast, painless and very effective hair removal using the AvalancheLase® laser system.

Based on the carried out temperature measurements and clinical experience, the following treatment parameters are recommended for performing avalanche hair removal with the Alexandrite (Figure 10) and Nd:YAG laser (Figure 11), in conjunction with the AvalancheLase's DMC™ skin cooling technology. The parameters are given for different body areas, skin types (I-VI) and hair thicknesses (thin, medium and thick). The estimated number (N) of delivered avalanche pulses to the same follicle, and the estimated time (in minutes) required to treat the whole selected body area, are also provided.

Alexandrite (755 nm)						
Avalanche Hair Removal Parameters						
Body area	Fluence F_P (J/cm²)	Spot size (mm)	Pulse duration (ms)	Freq (Hz)	N	Estimated total treatment time (min)
	I-II-III-IV-V-VI	I-VI	Thin-Medium-Thick	I-VI	I-VI	I-VI
Thigh	11-9-7-5-4-3	20	2 - 3 - 4	3	4-10	7-26
Lower leg	11-9-7-5-4-3	20	2 - 3 - 4	3	4-10	6-24
Chest & Abdomen	11-9-7-5-4-3	20	2 - 3 - 4	3	4-10	10-38
Underarm	11-9-7-5-4-3	12	2 - 3 - 4	5	4-10	1-2
Bikini	11-9-7-5-4-3	12	2 - 3 - 4	5	4-10	1-4
Face	11-9-7-5-4-3	12	2 - 3 - 4	5	4-10	0.5-1.5
Back	11-9-7-5-4-3	20	2 - 3 - 4	3	4-10	9-32

Fig. 10: Recommended avalanche hair removal parameters for the alexandrite (755 nm) laser wavelength of the AvalancheLase® system, equipped with an R35X laser handpiece and DMC™ skin cooling technology (water 1-2, air 5).

Nd:YAG (1064 nm)						
Avalanche Hair Removal Parameters						
Body area	Fluence F_P (J/cm²)	Spot size (mm)	Pulse duration (ms)	Freq (Hz)	N	Estimated total treatment time (min)
	I-II-III-IV-V-VI	I-III, IV-VI	Thin-Medium-Thick	I-VI	I-VI	I-VI
Thigh	22-18-14-10-8-6	12,20	2 - 3 - 4	3	4-15	13-29
Lower leg	22-18-14-10-8-6	12,20	2 - 3 - 4	3	4-15	12-26
Chest & Abdomen	22-18-14-10-8-6	12,20	2 - 3 - 4	3	4-15	19-42
Underarm	22-18-14-10-8-6	12	2 - 3 - 4	5	4-15	1-2.5
Bikini	22-18-14-10-8-6	12	2 - 3 - 4	5	4-15	1.5-4.5
Face	22-18-14-10-8-6	12	2 - 3 - 4	5	4-15	0.5-1.5
Back	22-18-14-10-8-6	12,20	2 - 3 - 4	3	4-15	16-36

Fig. 11: Recommended avalanche hair removal parameters for the Nd:YAG (1064 nm) laser wavelength of the AvalancheLase® system equipped with an R35X laser handpiece and DMC™ skin cooling technology (water 1-2, air 5)

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REFERENCES

1. Goldberg D.J., Laser hair removal, Martin Dunitz, 2000.
2. Olsen EA. Methods of hair removal. J. Am Acad Dematol.; 1999,40:143-55.
3. Landthaler M et al, Effects of argon, dye and Nd:YAG lasers on epidermis, dermis and venous vessels, Lasers Surg Med 1986, 6:87-93.
4. Wanner M., Laser hair removal, Dermat.Therapy, 2005,Vol.18, 209-216.
5. M. Lukac, L. Grad, Scanner Optimized Aesthetic Treatments with the VSP Nd:YAG Lasers, J. Cosmetic Laser Therapy, Vol. 10, No.2, June 2008.
6. M. Lukac, L. Grad, K. Nemes Scanner Optimized Efficacy (SOE) Hair Removal with the VSP Nd:YAG Lasers, LA&HA J. Laser and Health Academy, Vol. 2007/1, No.3; www.laserandhealth.com.
7. L. Grad, T. Sult, R. Sult, Scientific Evaluation of the VSP Nd:YAG Laser for Hair Removal, LA&HA J. Laser and Health Academy, Vol. 2007/1, No.2, www.laserandhealth.com.
8. Lukac M, Gorjan M, Zabkar J, Grad L, Vizintin Z, Beyond customary paradigm: FRAC3 Nd:YAG laser hair removal, LA&HA J. Laser and Health Academy, Vol. 2010/1, No.1, 35-46; www.laserandhealth.com
9. Bencini P.L et al, Long term epilation with long pulsed neodimium:YAG laser, Dermatol.Surg, 1999, 25:3, 175:178.
10. Ferraro G.A et al, Neodymium Yttrium Aluminum garnet long impulse laser for the elimination of superfluous hair: Experiences and considerations from 3 years of activity, Aesth.Plast.Surg., 2004, 28:431-434.
11. Raff K., Landthaler M., Hohenleutner U., Optimizing treatment for hair removal using long-pulsed Nd:YAG lasers, Lasers in Med.Sci., 2004,18:219-222
12. Goldberg D.J., Silapunt S., Hair removal using a long pulsed Nd:YAG laser: Comparison at fluences of 50, 80 and 100 J/cm2, Dermatol Surg 2001, 27: 434-436.
13. Anderson R, Parrish J., The optics of human skin, J Invest Dermatol.; 1981,88:13-19.
14. Galadari I., Comparative evaluation of different hair removal lasers in skin types IV, V, and VI, Int.J. Derm., 2003, 42, 68-70.
15. Battle E, Hobbs L.M., Laser assisted hair removal for darker skin types, Derm.Therapy, 17, 2004, 177-183.
16. Tanzi E.L., Alster T.S., Long Pulsed 1064 nm Nd:YAG laser assisted hair removal in all skin types, Dermatol. Surg, 2004,30:13-17
17. Lukac M, Gorjan M, Zabkar J, Grad L, Vizintin Z, Beyond customary paradigm: FRAC3 Nd:YAG laser hair removal, LA&HA J. Laser and Health Academy, Vol. 2010/1, No.1, 35-46; www.laserandhealth.com
18. Tankovich N, Hair removal device and method, patent US 6267771 (1996)
19. Eltarky A, Kazic M, Lukac M, Avalanche FRAC3 Nd:YAG Laser Hair Removal. J LA&HA; J. Laser and Health Academy, Vol. 2013/1, No.1, 23-31; www.laserandhealth.com.
20. Dierickx C, Ross V, Childs J, Perchuk I, Smirnov M, Yaroslavsky I, Smotrich M, Altshuler G, Increasing hair absorption of light in situ by light, Lasers in Surg Med 45, Issue Supplement 25 (March 2013); pp 36.
21. Kohl FR, Grieco C, Kohler B. Ultrafast spectral hole burning reveals the distinct chromophores in eumelanin and their common photoresponse. Chem Sci (2019). DOI: 10.1039/c9sc04527a.
22. Torres JH, Motamedi M, Pearce, JA, Welch AJ. Experimental evaluation of mathematicalmodels for predicting the thermal response of tissue to laser irradiation. Appl Opt (1993) 32(4): 597-606. DOI: 10.1364/AO.32.000597
23. Sobol EN, Kitai MS, Jones N, Sviridov AP, Milner T, Wong BJF. Heating and Structural Alterations in Cartilage Under Laser Radiation. IEEE J Quant Electr 1999, 35(4): 532-538. DOI: 10.1109/3.753657
24. Klaneček Ž, Development of a numerical model of laser epilation, MSc thesis, University of Ljubljana, Faculty of Mathematics and Physics_ 2019.
25. Lee SJ, Park SG, Kang JM, Kim YK, Kim DH. Cryogen-induced arcuate shaped hyperpigmentation by dynamic cooling device. J Eur Acad Dermatol Venereol. 2008;22:883–4.

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Avalanche FRAC3® Nd:YAG Laser Hair Removal

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ABSTRACT

An "avalanche effect" was observed where the absorption of laser light in hair gets increasingly enhanced following each successively delivered laser pulse. The avalanche process continues until the absorption becomes high enough for the hair to get carbonized. The avalanche effect was found to be most pronounced with the *FRAC3®* Nd:YAG laser parameters.

Based on the results of the study, a new, "avalanche" *FRAC3®* Nd:YAG laser hair removal protocol is introduced that improves the efficacy of current hair-removal procedures, reduces patient discomfort and in most cases eliminates the need for skin cooling. For patients from the Middle East, in particular, the new "avalanche" *FRAC3®* Nd:YAG laser hair-removal protocol provides effective yet completely pain-free hair removal with no external cooling required.

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

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I. INTRODUCTION

a) Long Pulse Nd:YAG Hair Removal

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 [1-2]. Commercial laser 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 [3].

The choice of wavelength is dictated by the need for good absorption of the laser energy in the hair follicle lying deep in the skin. Typically, however, the wavelengths that are highly absorbed in skin imperfections are also highly absorbed by non-target structures, for example, melanosomes or hemoglobin containing RBC [5]. Consequently, these wavelengths do not reach deeper-lying hair follicles, and can result in excessive damage to the epidermis and other skin structures. For this reason, it is better to select a laser wavelength that penetrates more deeply into the tissue, and then achieve selective tissue modification by adjusting the laser pulse duration to the thermal relaxation time of the targeted hair. A wavelength that fits this requirement is produced by the Nd:YAG laser. Its long wavelength of 1064 nm lies in an optical absorption window that allows light at this wavelength to penetrate deeply into the skin, while its absorption in the hair follicle is strong enough to destroy the follicle [6-8]. The Nd:YAG laser has been cleared for hair removal (i.e., stable long-term or permanent hair reduction) for all skin types, Fitzpatrick I-VI, including tanned skin [9-10]. Standard Nd:YAG hair removal procedures are performed with "long pulse" (LP) parameters, typically in the range of 15-50 ms [6-15]. Clinical experience using LP Nd:YAG parameters has demonstrated that hair removal with LP Nd:YAG lasers is one of the safest and most effective methods for light-based hair removal [9-15].

b) FRAC3® Hair Removal

Longer pulse (LP) durations of the Nd:YAG laser have been used with a goal to minimize damage to the epidermis [6-8]. Longer pulse durations have been at least partially mandated also by technological limitations. Namely, large spots require high pulse energies, which laser systems have not been able to deliver reliably at short pulse durations.

However, recent technological advances and better understanding of the thermal dynamics during laser hair removal have led to a further improvement of the already very effective LP Nd:YAG hair removal technique.

It has been demonstrated that successful permanent unwanted hair reduction can only be achieved by injuring the bulb, the bulge and the outer root sheath of the hair follicle [1, 2, 4]. In order to destroy the targeted hair tissue and to avoid damage to surrounding tissue, the laser pulse duration (width) should be lower or approximately equal to the hair tissue's thermal relaxation time (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.

One of the advantages of the latest technology Nd:YAG laser devices lies in their advanced variable square pulse technology (VSP) [16], which enables the temporal delivery of sufficiently high laser energy in shorter time periods than the thermal relaxation time (TRT) of skin imperfections or hair. Exploiting the Nd:YAG VSP's unique capabilities, an advanced, *FRAC3*® [17], non-ablative fractional laser method was developed [18-20] 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, and has been found to be extremely suitable for performing hair removal treatments [20].

The *FRAC3*® hair removal method differs from the standard, LP Nd:YAG hair removal method. While standard LP treatments are performed with laser pulse durations within the 15-50 ms range, the *FRAC3*® method is optimized to deliver the laser energy in extremely short times, less than 2 ms, and preferably between 0.3 and 1.6 ms. The method is based on a finding that the thermal relaxation time of the epidermis is relatively long [20]. The epidermal TRT is typically longer than 25-50 ms, while the target hair's TRT is typically shorter than 2 ms [22]. The duration of the *FRAC3*® high intensity laser pulses is thus sufficiently short for most hair types while still avoiding unnecessary damage to the epidermis (See Fig. 1).

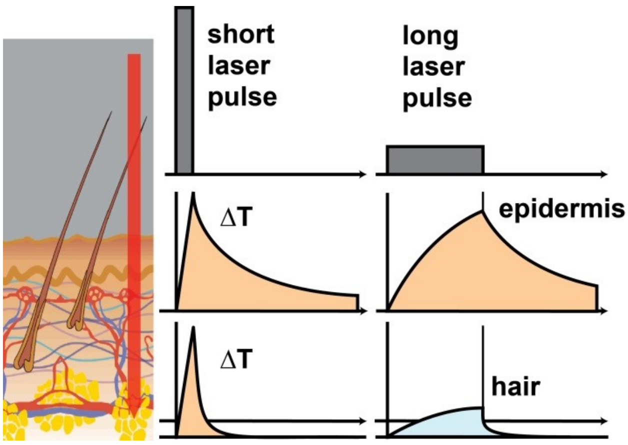

Fig. 1: A situation commonly found in patients. Epidermal peak temperature is independent of whether a short, *FRAC3*® pulse (< 2ms), or a long, standard (15-50 ms) laser pulse is used, however, the hair follicle gets heated only at shorter, FRAC3® laser pulse durations. The figure is reprinted with permission from reference #20.

The thermal dynamics shown in Fig. 1 is confirmed also by the measured dependence of the feeling of pain on laser pulse duration when a patient's skin is irradiated by the Nd:YAG laser. As can be seen from Fig. 2, the pain threshold (defined as the Nd:YAG laser fluence when the patient reports pain) is approximately independent of the pulse duration in the broad range of 0.3 – 25 ms [20].

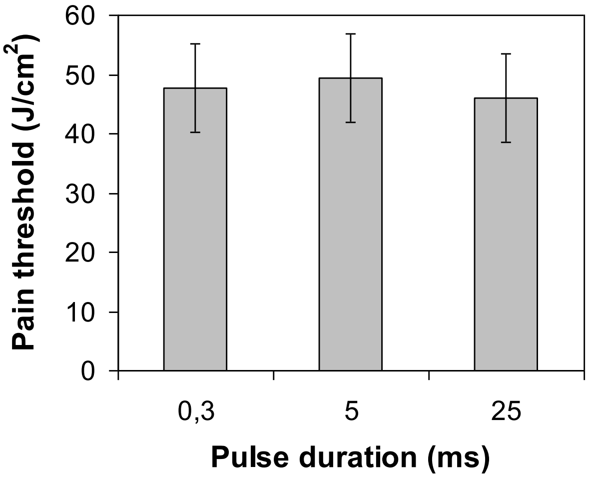

Fig. 2: Measured dependence of the feeling of pain, i.e. of the pain threshold fluence, on the Nd:YAG laser pulse duration. The figure is based on data from reference #20.

This can be explained as follows. Since the TRT of the epidermis is longer than 25 ms, no significant cooling of the epidermis can occur during laser pulses shorter than 25 ms. All pulses below 25 ms thus result in the same peak temperature of the epidermis and consequently the same discomfort for the patient.

On the other hand, the hair damage threshold depends significantly on laser pulse duration, and is much lower for shorter pulse durations (See Fig. 3).

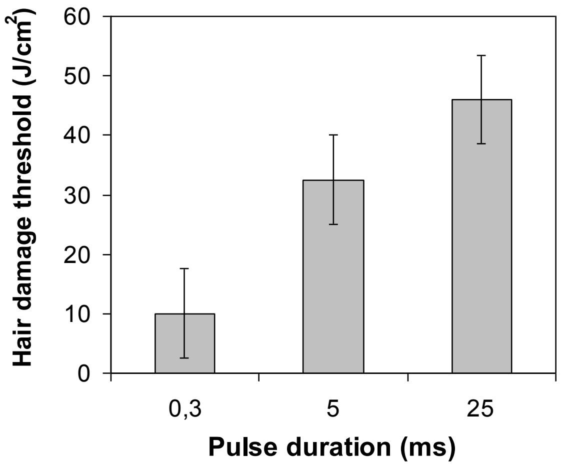

Fig. 3: Measured dependence of the hair damage threshold (defined by the lowest fluence at which visible hair damage occurs) on the Nd:YAG laser pulse duration. The figure is based on data from reference #20.

As demonstrated by Figs. 2 and 3, hair removal is much more effective at *FRAC3*® laser pulse conditions, while still not causing unnecessary damage to the epidermis.

The new, improved hair removal parameters based on the *FRAC3®* self-induced 3-dimensional fractional concept are summarized in Table 1 below. Note that these parameters represent a rough guideline only. Clinical treatment parameters depend also on the selected *FRAC3®* pulse duration and on the patient's hair type, as will be shown later in the paper.

Table 1: Recommended *FRAC3®* Nd:YAG laser hair removal parameters (based on data from reference #20).

Spotsize	Mode	Fluence
3 mm	FRAC3	Skin type I, II : ≤ 55 J/cm^2 Skin type III, IV: ≤ 40 J/cm^2 Skin type V, IV: ≤30 J/cm^2
6 mm	FRAC3	Skin type I, II : ≤ 45 J/cm^2 Skin type III, IV: ≤ 30 J/cm^2 Skin type V, VI: ≤ 25 J/cm^2
9 mm	FRAC3	Skin type I, II: ≤ 40 J/cm^2 Skin type III, IV: ≤ 25 J/cm^2 Skin type V, VI: ≤ 25 J/cm^2
12-15 mm	FRAC3	Skin type I, II: ≤ 35 J/cm^2 Skin type III, IV: ≤ 20 J/cm^2 Skin type V, VI: ≤ 20 J/cm^2

Our clinical studies have demonstrated the improved hair-removal efficacy of the *FRAC3®* procedure in comparison with the standard, LP Nd:YAG laser protocol. As an example, Figs. 4 and 5 show a patient's back that was treated on the left side with LP and on the right side with *FRAC3®* parameters.

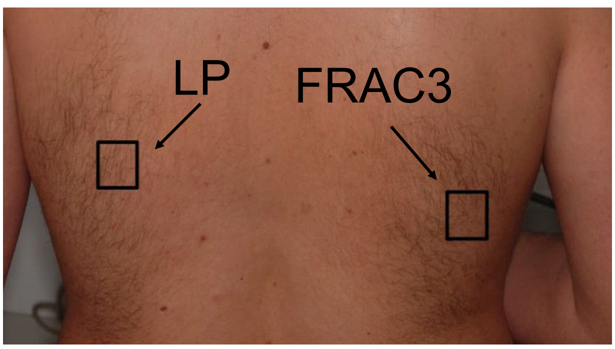

Fig. 4: A male patient's back (age 26; skin: Fitzpatrick II; hair: dark, medium) was treated on the left side with LP parameters (25 ms, 50 J/cm^2), and on the right side with *FRAC3®* parameters (1.6 ms, 50 J/cm^2). The Nd:YAG laser used was an SP Dynamis (manufactured by Fotona), with a 9 mm spot-size S11 scanner.

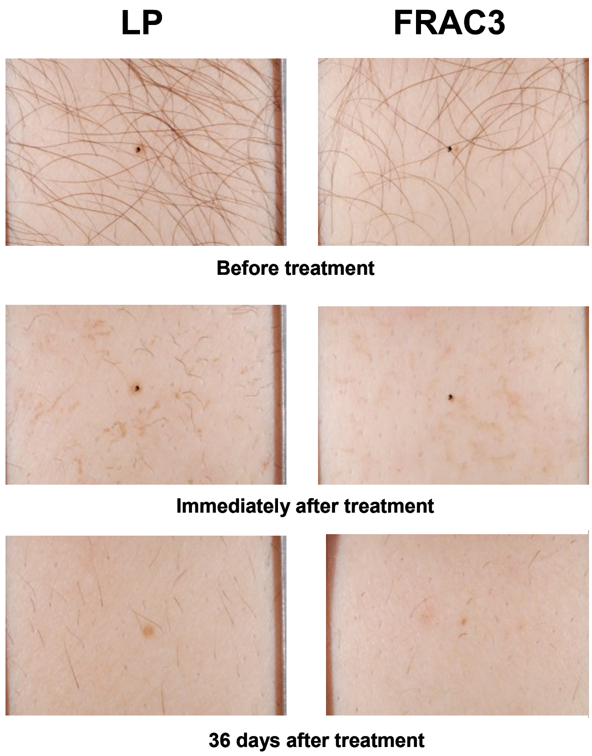

Fig. 5: Treated areas of the patient's back: before, immediately after, and 36 days after the first treatment. Left side: standard LP Nd:YAG parameters. Right side: *FRAC3®* Nd:YAG parameters. The right, *FRAC3®* side shows improved hair removal efficacy.

Similarly, Fig. 6 shows a female's under-arms treated with either LP or *FRAC3®* hair removal parameters. Again, the *FRAC3®* approach resulted in a higher efficacy.

Fig. 6: Patient's underarms before and 32 days after the first hair removal treatment at 55 J/cm^2 with either LP Nd:YAG parameters (above) or *FRAC3®* Nd:YAG parameters (below). The Nd:YAG laser used was an XP Dynamis (manufactured by Fotona), with a 3 mm spot-size S11 scanner.

A clinical example of the excellent long-term results of the *FRAC3®* hair removal method is shown in Fig. 7.

Fig. 7: A patient's arm (female 29, skin: Fitzpatrick II; hair: light brown, thin) following a single treatment with Nd:YAG *FRAC3®* parameters (1.6 ms, 50 J/cm^2). The Nd:YAG laser used was an SP Dynamis (manufactured by Fotona), with a 9 mm spot-size S11 scanner.

b) Avalanche FRAC3 Hair Removal

One of the challenges when performing laser hair removal is the relatively low absorption of laser light in the treated hair, especially when the hair is blond or grey. For this reason, early hair removal techniques were based on infiltrating black carbon into hair ducts in order to increase the absorption of hair at the treatment laser wavelength [23].

However, carbonization of the hair also occurs naturally when it is irradiated by a laser power density above its damage threshold (See Fig. 8).

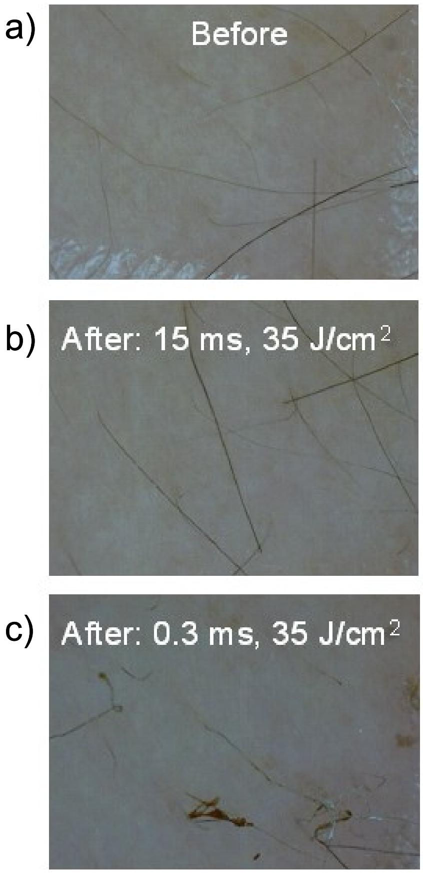

Fig. 8: a) Hair before laser irradiation; b) Hair irradiated with long-pulse Nd:YAG; no visible change is observed; c) Hair irradiated with *FRAC3®* Nd:YAG pulse; the hair is carbonized and blackened. Figure is reprinted with permission from reference #20.

This suggests that perhaps the absorption of laser light in hair could be enhanced by the treatment laser light itself. Namely, by delivering the treatment energy to the same skin area several times during the same session, the hair absorption might increase following each delivery. This would lead to an avalanche in the hair temperature changes, resulting in effective hair removal even at lower laser parameters than those required when a single-delivery hair removal is performed. The *FRAC3®* laser parameters that exhibit the lowest hair damage thresholds (See Figs. 3 and 8) are especially suited for this purpose.

In this paper, we report on a study of the avalanche effect from the multiple delivery of laser energy during a single hair-removal session. An improved, “avalanche” *FRAC3®* hair removal method is introduced which offers a more effective and comfortable approach to laser hair removal.

II. MATERIALS AND METHODS

The experimental set-up is shown in Fig. 9.

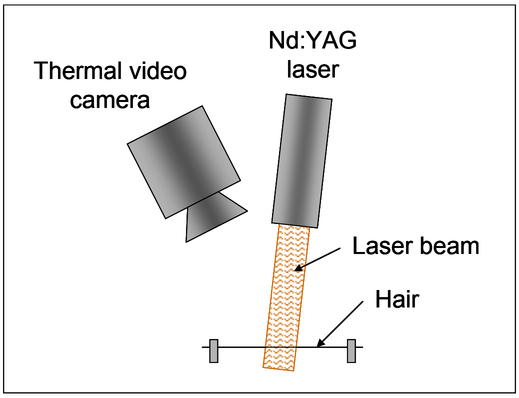

Fig. 9: Experimental set-up. A human hair was pulled out of a human scalp and fixed in the air in a straight horizontal position. The Nd:YAG laser beam was directed onto the hair, and the resulting hair temperature increase was measured with a thermal video camera.

The Nd:YAG laser used in the study was an SP Dynamis (manufactured by Fotona) fitted with an R33 handpiece set to a 6 mm laser spot size. A human hair was pulled out of a human scalp and fixed in the air in front of the laser handpiece. The Nd:YAG laser beam was directed onto the hair, and the resulting hair temperature increase was measured with a thermal video camera (Flir ThermaCAM P45), set to record at every time instant the maximum temperature of the hair sample. The camera detector’s signal integration time was approximately 10 ms. Therefore, for pulses shorter than 10 ms, and especially for higher temperatures, the peak hair temperatures were measured to be somewhat lower than actual. For this reason, most of the data is analyzed in terms of the relative ratio of temperature data points.

A typical thermal image of the irradiated hair following a laser pulse is shown in Fig. 10.

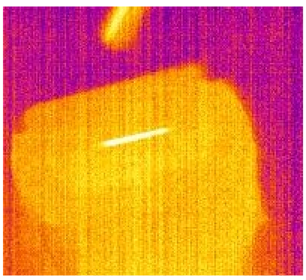

Fig. 10: A typical thermal image of the irradiated hair following an Nd:YAG laser pulse.

When several consecutive laser pulses were delivered to the same spot, the pulses were delivered at a slow rate of 0.5 Hz, which was sufficiently slow to allow the hair to cool down to its initial temperature during the time between pulses.

In order to minimize the influence of the hair diameter on the results, sets of measurements were performed on limited sections of long hair samples pulled out of a human scalp. Each measurement was also made on a different section of the tested hair in order to avoid any influence from previous irradiations.

III. RESULTS

Figure 11 shows a typical hair temperature increase following three subsequent laser pulses with the same fluence per pulse.

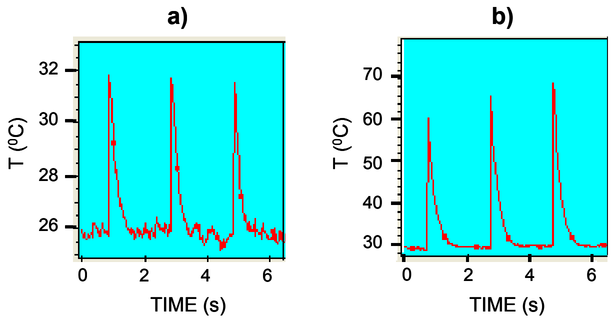

Fig. 11: Typical measured hair temperature during three consecutively delivered *FRAC3®* Nd:YAG laser pulses of the same a) low; or b) high single-pulse fluence. Note that for high-fluence pulses, the temperature increase starts to grow with each subsequent laser pulse.

As can be seen from Fig. 11, at low laser fluences, all pulses result in the same hair temperature increase, ΔT. However, at sufficiently high laser pulse fluences, the absorption of laser light, and consequently ΔT, begin to increase with each subsequently delivered laser pulse. We call this phenomenon a heating avalanche effect, and the fluence above which this effect occurs, the avalanche threshold fluence.

The heating avalanche effect can be observed by applying a sequence of consecutive laser pulses of the same above-threshold fluence to a hair sample. Figure 12 shows the measured temporal evolution of the avalanche factor for two types of tested hairs (Hair #1 and Hair #2) during a sequence of consecutively delivered laser pulses with the same fluence per pulse. The avalanche factor, α is defined as the ratio of the temperature changes following the N^{th} and 1^{st} delivered laser pulse, $\alpha_N = \Delta T_N / \Delta T_1$.

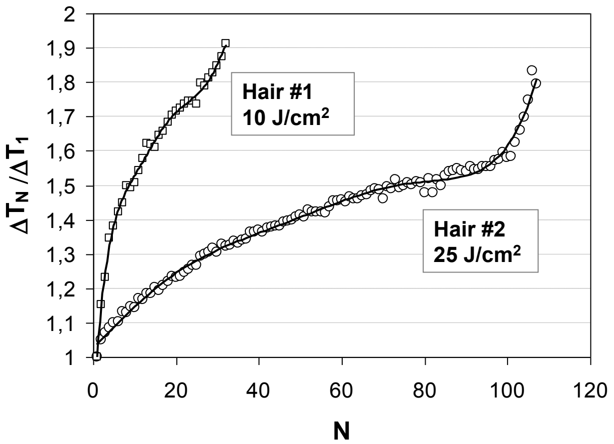

Fig. 12: Measured evolution of the avalanche factor $\alpha_N = \Delta T_N / \Delta T_1$ for two tested hairs (Hair #1 and Hair #2) following Nd:YAG laser pulses in a consecutive sequence. The duration of laser pulses of 1.6 ms was within the *FRAC3*® range. The fluence used on Hair #1 was 10 J/cm² per pulse while the fluence used on Hair #2 was 25 J/cm² per pulse. For each hair sample, the measurement was stopped immediately after a carbonization and breaking of the tested hair occurred.

Figure 12 clearly demonstrates the heating avalanche effect. Since for each hair sample the fluence used was just slightly above the avalanche threshold for that particular hair sample, the avalanche factor starts at $\alpha \approx 1$, and then grows from pulse to pulse until the end of the pulse sequence when an accelerated temperature "run-off" is observed. The pulse sequence was stopped when a carbonization and resulting breaking of the tested hair occurred. It is important to note that the temperature "run-off" of Hair #1 occurred much earlier (during the 33rd pulse) than for Hair #2 (during the 108th pulse), even though a much lower single-pulse fluence of 10 J/cm² was used on Hair #1, as compared to the fluence of 25 J/cm² applied to Hair #2. Since Hair #1 was darker than Hair #2, we attribute this difference at least partially, to the difference in color, and therefore to the initial difference in absorption of the Nd:YAG laser light in the tested hair.

Because of the hair breaking during the last pulse, the thermal camera did not capture the temperature when the carbonization occurred. However, our measurements in a temperature controlled oven show that the carbonization of hair occurs abruptly at temperatures above 240-250 ^{0}C, independently of the hair type. We conclude that during the last pulse in the sequence, i.e. when the hair was observed to carbonize, the temperature of the hair was elevated to at least 240 ^{0}C, representing a temperature increase above the initial hair temperature of $\Delta T \geq 210$ ^{0}C. Since the temperature increase during the first pulse was only $\Delta T_1 = 24$ ^{0}C for Hair #1, and $\Delta T_1 = 36$ ^{0}C for Hair #2, this represents an approximate increase in the absorption of the laser light in the tested hair by the avalanche factor, α of greater than six (for Hair #2), and eight for Hair #1.

Since the delivery of a large number of pulses may not be practical for performing hair removal, we measured also the avalanche factor $\alpha_2 = \Delta T_2 / \Delta T_1$, for two consecutively delivered pulses (See Fig. 13). Figure 14 shows the dependence of the two-pulse avalanche factor on laser pulse fluence, for three different hair samples.

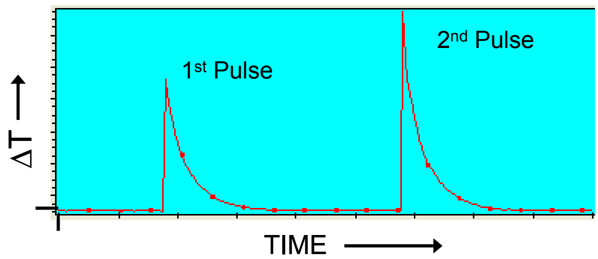

Fig. 13: Typical measured hair temperature increase during an irradiation sequence of two *FRAC3*® Nd:YAG laser pulses. Due to the avalanche effect, the temperature increase during the second pulse is much higher, even though the fluence of both pulses is the same.

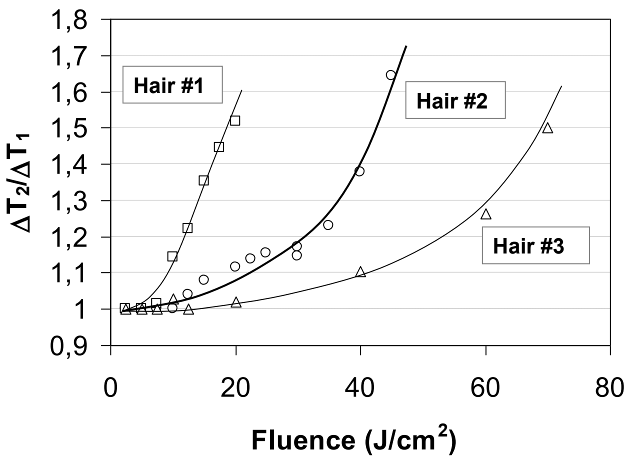

Fig. 14: Measured dependence for three hair samples of the two-pulse avalanche factor, $\alpha_2 = \Delta T_2 / \Delta T_1$ on the Nd:YAG laser fluence per pulse. A *FRAC3*® pulse duration of 1.6 ms was used.

As can be seen from Fig. 14, the avalanche factor depends strongly on the hair type. The avalanche threshold fluences for the three tested hair samples were at approximately 9 J/cm² (Hair #1), 18 J/cm² (Hair #2) and 40 J/cm² (Hair #3).

We believe that the three hair samples used were good representatives of the black (Hair #1), brown (Hair #2) and light brown (Hair #3) hair types. Based on Fig. 14, the two-pulse "run-off" threshold fluences for the three hair types are from black to light brown at approximately 20, 50 and 70 J/cm², respectively.

A comparison was also made between the LP and *FRAC3®* hair removal parameters in terms of the achieved hair temperature increase and avalanche factor. Figure 15 shows the measured temperature changes during a sequence of three pulses with the same fluence of 15 J/cm² per pulse, with either LP or *FRAC3®* pulse duration characteristics.

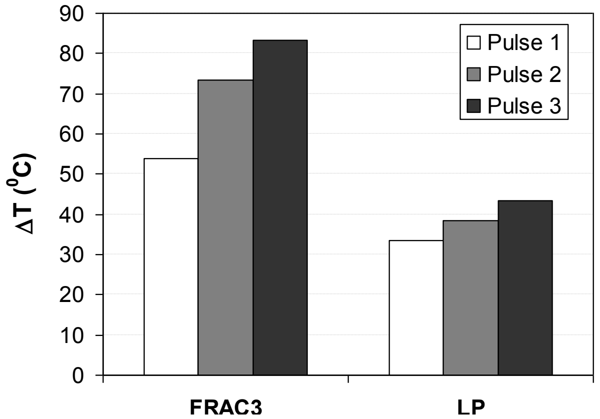

Fig. 15: Measured hair temperature increase during a sequence of three Nd:YAG laser pulses with *FRAC3®* or LP pulse duration characteristics.

The *FRAC3®* laser parameters are clearly at an advantage in comparison to the LP parameters. The *FRAC3®* laser parameters result in considerably larger temperature changes and avalanche factors. Note that the advantage of the *FRAC3®* parameters becomes even more pronounced under the actual hair removal conditions. Since the treated hairs are located within the skin matrix which has a much larger thermal conductivity than air, the hairs cool down considerably faster during an LP pulse than during a *FRAC3®* pulse, reducing further the efficacy of the LP protocol.

IV. DISCUSSION

Our thermal camera measurements demonstrate an avalanche "hair darkening" effect which occurs when hair is subjected to a series of laser pulses. This effect leads to an enhancement of laser absorption and therefore to a progressively larger temperature increase. Note that this enhancement is not a consequence of a temperature build-up during the consecutive pulse delivery. The enhancement can be observed also when pulses are delivered at very long inter-pulse intervals.

Based on the results of our study, laser hair removal treatments can be performed at laser fluences much lower than what has been considered as required to affect hair growth. By repeating the treatment irradiation within the same treatment session, the effect of each irradiation gets enhanced, until the hair removal temperatures within the hair bulb, the bulge and the outer root sheath of the hair follicle are reached.

The enhancement of the laser absorption from pulse to pulse ("the avalanche factor") depends on the hair type, and on the laser parameters such as laser pulse duration and fluence. The *FRAC3®* parameters were found to be more effective than standard, LP (Long Pulse) parameters for obtaining the avalanche effect.

Even though our temperature measurements were carried out on hairs suspended in air, the obtained avalanche and carbonization fluence thresholds apply approximately also to the hair located within the skin matrix. Figure 16 depicts graphically an approximate relationship between the treatment laser fluence as exiting the laser handpiece, and the resulting fluence after the laser light enters the skin.

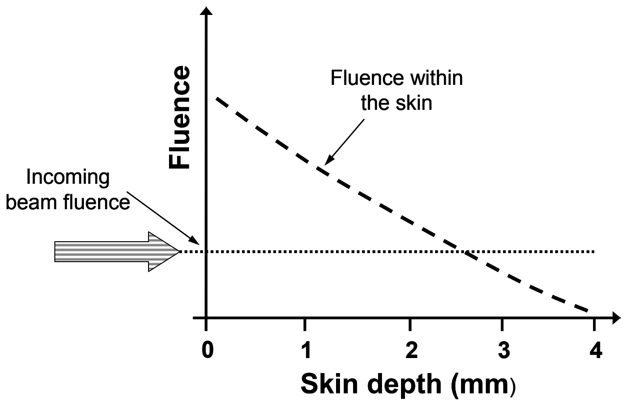

Fig. 16: Graphical representation of the relationship between the treatment laser fluence before entering the skin and the resulting fluence within the skin.

As a result of back scattering of the laser light within the skin matrix, the fluence inside of the skin is actually higher than the fluence of the incoming beam within the first 2-3 mm from the skin's surface, in spite of the beam being progressively absorbed by the skin chromophores. Therefore, on average, the fluence that is affecting the hair bulb, the bulge and the outer root sheath of the hair follicle can be considered to be approximately the same, or even higher, than that of the incoming beam.

When performing laser hair removal, what is desired is high treatment efficacy for all skin and hair types, with as little as possible discomfort for patients. With this in mind, we introduce an improved "Avalanche" *FRAC3®* hair removal protocol (See Fig. 17).

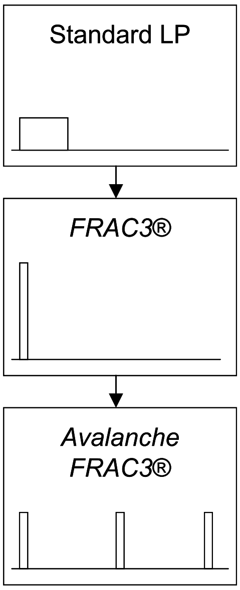

Fig. 17: Evolution of the Nd:YAG laser hair removal protocols. The gold standard LP (Long Pulse) hair removal has been superseded by the *FRAC3*® protocol, which is now improved upon by taking into account the temperature avalanche enhancement effect of subsequently delivered *FRAC3*® laser pulses.

The LP (Long Pulse) Nd:YAG protocol represents a gold standard for hair removal which has been used for all skin types due to its extreme efficacy and safety [6-15]. Recently, an improved, *FRAC3*® Nd:YAG hair removal protocol has been introduced [20], which is based on the self-inducing fractional nature of very short Nd:YAG pulses [18-19]. This protocol is now being improved upon by taking into account the avalanche absorption enhancement effect of multiple irradiations during the same hair-removal treatment session.

The following starting test procedure has been recommended when performing *FRAC3*® hair removal treatments [20]. Before performing the treatment, the hair from the treatment area is to be irradiated with increasingly higher laser fluences until visible hair damage is observed. To avoid discomfort to the patient, this procedure can be performed, for example, on hair which has been cut or shaven off from the area to be treated. Using this procedure, the practitioner determines the laser fluence where the carbonization of the patient's hair occurs (i.e., the carbonization threshold fluence). It is important that during this procedure the same hair segment is not irradiated with more than one laser pulse, as the avalanche effect will cause the measured fluence threshold to be too low.

When performing the single pass *FRAC3*® hair removal protocol the practitioner would set the laser fluence at or above the measured value for the carbonization threshold, in order for the treatment to be effective. For example, when treating hair types with avalanche characteristics as shown in Fig. 14, the patients with hair types #1 , #2 and #3 would have to be treated with fluences of at least 20 J/cm^2, 50 J/cm^2, and 70 J/cm^2, correspondingly. Note that especially for the patient with the #3 type hair, the treatment fluence would be considerably above the pain threshold (See Fig. 2) and may also be excessive from the viewpoint of treatment safety. Treatments of patients with #2 and #3 type hairs would also require skin cooling.

With the new "Avalanche" *FRAC3*® protocol, the practitioner would take a different approach.

Firstly, when a better efficacy is desired, and the carbonization threshold is not excessively high, the practitioner would treat the hair with more than one pass. The time over which the passes are to be repeated during a single session is not important, and can be over several hours. However, they should be separated by at least 250 ms in order to allow the epidermis to cool down in between the passes. And, in order to benefit from the hair temperature increase following a previous pass, the next pass should be preferably delivered within 0.5 - 5 seconds from each other in order not to let the bulk skin to cool down considerably.

On the other hand, when treatment safety (for example when the measured carbonization threshold fluence is very high) and/or the patient's comfort are of concern, then the avalanche *FRAC3*® approach would be as follows. The practitioner would reduce the treatment fluence to a value below the carbonization threshold, and optionally also below the patient's pain threshold. The patient would then have to get treated with an appropriate number of passes over the treatment area. Of course, the fluence should not be reduced to a value where no significant avalanche effect occurs. For example, when performing only 2-3 passes, a #2 hair type patient would have to be treated with a fluence of 30-35 J/cm^2, while a #3 hair type patient would require a higher fluence of approximately 50 J/cm^2. Lower treatment fluences would require a larger number of passes. In fact, any fluence above the avalanche threshold would affect hair growth providing that a correspondingly sufficient number of pulses are delivered to the treatment area. A gradual pass-to-pass decrease of fluence, and/or an increase in pulse duration may also be employed in order to avoid the cumulative bulk skin temperature build-up at higher repetition rates, or the loss of thermal contact of the hair with surrounding cells.

Based on the above, effective pain free Nd:YAG laser hair removal, without any skin cooling, is now available using the new avalanche *FRAC3®* protocol. This applies especially to patients with the #1 type hair, what is typical, for example, for patients from the Middle East. As demonstrated in clinical use, for this segment of patients, hair removal can be performed painlessly and without cooling by treating their hair with 2-3 passes within a single treatment session, using the avalanche *FRAC3®* fluence parameters of 15 J/cm² per pulse, and spot sizes of 9-15 mm.

V. CONCLUSIONS

An avalanche effect was observed where the absorption of laser light in hair is increasingly enhanced following each successively delivered laser pulse [25]. The avalanche process continues until the absorption becomes high enough for the hair to get damaged. The avalanche effect was found to be most pronounced with the *FRAC3®* Nd:YAG laser parameters.

Based on the results of the study, a new "Avalanche" *FRAC3®* Nd:YAG laser hair removal protocol has been introduced that improves the efficacy of current hair-removal procedures, reduces patient discomfort, and in most cases eliminates the need for skin cooling. For patients from the Middle East, in particular, the new "avalanche" *FRAC3®* Nd:YAG laser hair-removal protocol provides effective yet completely pain-free hair removal with no external cooling required.

Acknowledgment

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REFERENCES

1. Goldberg D.J., Laser hair removal, Martin Dunitz, 2000.
2. Olsen EA. Methods of hair removal. J. Am Acad Dematol.; 1999,40:143-55.
3. Landthaler M et al., Effects of argon, dye and Nd:YAG lasers on epidermis, dermis and venous vessels, Lasers Surg Med 1986, 6:87-93.
4. Wanner M., Laser hair removal, Dermat. Therapy, 2005,Vol.18, 209-216.
5. Anderson R, Parrish J., The optics of human skin, J Invest Dermatol.; 1981,88:13-19,
6. Lukac M, Grad L, Scanner Optimized Aesthetic Treatments with the VSP Nd:YAG Lasers, J. Cosmetic Laser Therapy, Vol. 10, No.2, June 2008.
7. Lukac M, Grad L, Nemes K. Scanner Optimized Efficacy (SOE) Hair Removal with the VSP Nd:YAG Lasers, LA&HA J. Laser and Health Academy, Vol. 2007/1, No.3; www.laserandhealth.com.
8. Grad L, Sult T, Sult R, Scientific Evaluation of the VSP Nd:YAG Laser for Hair Removal, LA&HA J. Laser and Health Academy, Vol. 2007/1, No.2, www.laserandhealth.com.
9. Galadari I., Comparative evaluation of different hair removal lasers in skin types IV, V, and VI, Int.J. Derm., 2003, 42, 68-70.
10. Battle E, Hobbs LM. Laser assisted hair removal for darker skin types, Derm.Therapy, 17, 2004, 177-183.
11. Bencini P.L et al, Long term epilation with long pulsed neodimium:YAG laser, Dermatol.Surg, 25:3, 175:178.
12. Ferraro GA et al, Neodymium Yttrium Aluminum garnet long impulse laser for the elimination of superfluous hair: Experiences and considerations from 3 years of activity, Aesth.Plast.Surg., 2004, 28:431-434.
13. Raff K, Landthaler M, Hohenleutner U, Optimizing treatment for hair removal using long-pulsed Nd:YAG lasers, Lasers in Med.Sci., 2004,18:219-222.
14. Goldberg DJ, Silapunt S, Hair removal using a long pulsed Nd:YAG laser: Comparison at fluences of 50, 80 and 100 J/cm2, Dermatol Surg 2001, 27: 434-436.
15. Tanzi EL, Alster TS, Long Pulsed 1064 nm Nd:YAG laser assisted hair removal in all skin types, Dermatol. Surg, 2004,30:13-17.
16. Variable Square Pulse (VSP) is a Fotona d.d. (www.fotona.com) proprietary technology for the generation and control of laser pulses.
17. *FRAC3®* is a Fotona trademark for the self–induced three-dimensional fractional approach to skin treatment.
18. Lukac M, Zabkar J, Gorjan M, Sult T, FRAC3: Three Dimensional Non-Ablative Fractional Laser Skin Rejuvenation, LA&HA J. Laser and Health Academy, Vol. 2008/1, No.5, www.laserandhealth.com.
19. Lukac M, Sult T, Zabkar J, Gorjan M, Vizintin Z, Parameters for the New FRAC3 Nd:YAG Laser Skin Treatment Modality, LA&HA J. Laser and Health Academy, Vol. 2010/1, No.1, www.laserandhealth.com.
20. Lukac M, Gorjan M, Zabkar J, Grad L, Vizintin Z, Beyond customary paradigm: FRAC3 Nd:YAG laser hair removal, LA&HA J. Laser and Health Academy, Vol. 2010/1, No.1, 35-46; www.laserandhealth.com.
21. Bevec T, Lukac M, Fractional FRAC3 and TwinLight laser skin treatments, LA&HA J. Laser and Health Academy, Vol. 2011, No.1, 43-48; www.laserandhealth.com .
22. Majaron B, Nelson JS, *Laser treatment of port wine stains*. Ljubljana: 2009 http://complex.ijs.si/publications_PDF/Biosystem/Laser_PWS_Majaron_Nelson_2009.pdf.
23. Tankovich N, Hair removal device and method, patent US 6267771 (1996).
24. B.C. Wilson and G. Adam. A Monte Carlo model of absorption and flux distributions of light in tissue. Med. Phys. 1983,10, 824-830.
25. After the submission of this paper, research results on the same topic were reported also by Dierickx C, Ross V, Childs J, Perchuk I, Smirnov M, Yaroslavsky I, Smotrich M, Altshuler G, Increasing hair absorption of light in situ by light, Lasers in Surg Med 45, Issue Supplement 25 (March 2013); pp 36.