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Comparative Clinical Study and Thermal Modelling of Photoepilation of Thin Hair by Primelase Excellence 810nm and Blend and Soprano XL 810nm

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Abstract: *Laser hair removal (photoepilation) is one of the most sought-after techniques in the field of aesthetic medicine. Although photoepilation techniques are constantly advancing, there is still a lot of scope for improvement in order to guarantee efficacy and the safety of the subject, especially for people with thinned hair and those with dark skin. We compared two pieces of diode laser photoepilation equipment (Soprano XL and Primelase Excellence), and the results obtained were compared with simulations made by a mathematical 3D simulation of hair and skin heating and thermal damage developed by Cocoon Medical, using COMSOL Multiphysics® software. Our results show that high-power Primelase equipment (up to 4800 W) increases the effectiveness of photoepilation treatments. After three treatments, the average hair reduction was 53% with Soprano XL and 69% with Primelase Excellence, which represents a 55% greater efficacy with primelase. Thermal simulations revealed that untreated or original hair showed very similar results for Soprano XL and Primelase Excellence, but simulations of thinned hair as it appears in treated areas showed significant differences between the two lasers, with an average improvement of 65% for Primelase Excellence for the cases analysed in this study. This improvement is due to the shorter laser pulses of Primelase which are in turn due to its greater power and to the possibility of using a multi-wavelength blend diode laser with higher fluences under safe conditions for dark skin types, which provides greater energy delivery to the hair follicles for all skin types. Nevertheless, neither system achieved permanent hair removal in three treatments. Additional photoepilation treatments and long-term results evaluation would need to be performed. In conclusion, this clinical study corroborates the results of the simulations which predict that the Primelase system is more effective for thin hair using comparable or lower energies and shorter pulses than the Soprano system, and using a blend diode laser for the darker skin types.*

Keywords: *PHotoepilation, hair removal, soprano, primelase, selective phototermolysis, diode laser, permanent hair removal, 810 nm, blend, mathematical simulation, COMSOL.*

I. Introduction

Laser photoepilation is one of the most sought-after permanent hair removal therapies in modern society. Photoepilation basically consists of laser light being absorbed by a specific chromophore (melanin in hair) that transforms the energy into heat. The resulting thermal damage can lead to denaturization or irreversible coagulation of proteins of the hair follicle. Permanent hair removal is associated with additional thermal damage in the stem cells within the bulge region (1, 2).

Laser photoepilation technology has advanced considerably in the past two decades and continues to be in constant evolution. Development of versatile equipment for faster and safer hair removal adapted to each type of skin is constant. In the late 1990s, Alexandrite's high-power solid-state laser caused a revolution in the sector. However, this laser has serious versatility problems, since it emits laser light on only one wavelength (755 nm) and it is not suitable for subjects with darker skin. Moreover, the treatment with the Alexandrite laser is quite expensive, due to the high cost of maintenance and consumables (3).

Then the first versatile diode lasers for hair removal emerged (e.g. LightSheer ST from Lumenis) (4). However, these lasers were not yet able to treat all skin types (5). With the commercialization of Nd:YAG equipment, the treatment of dark skin types became feasible, but the efficacy was lower and there was still the problem of depilating tanned skins (6).

Early in the 2010s, a new concept of progressive selective photothermolysis appeared (7). It involves the application of low-energy laser pulses, generated by a diode laser module, at low energies at a high repetition frequency, in order to accumulate energy dynamically in the treated area. In this way, dark skin types and/or tanned skins were depilated more effectively than with the Nd:YAG equipment (8). The drawbacks of this method were the difficult and time-consuming manipulation and low efficacy due to low energy application.

In order to improve the results, the industry has introduced higher power diode lasers to be able to produce shorter pulse duration improving the effectiveness of treatments, similar to Alexandrite lasers, but without the versatility limitation (9). Higher laser power means shorter pulses can be applied thus increasing the heating and damage of the hair structure and stem cells responsible for hair re-growth, which produce a more lasting and permanent hair removal.

For further improvement of photoepilation, the use of multiple wavelengths offers improved efficacy with dark skin types. The use of the so-called blend laser reduces skin heating, improves safety and offers deep penetration of the hair follicle with high laser power (10).

The aim of this study was to compare the efficacy and safety of Primelase Excellence (4,800 W) with those of Soprano XL. Both devices had spot size of approximately 2 cm^2 so that the results could be standardised (10). Two

Primelase diode lasers with wavelengths of 810 nm and blend (1060 + 940 + 810nm) were compared with a 810nm Soprano diode laser (11). We used a mathematical 3D COMSOL simulator to set up the parameters for the equipment and to predict the expected thermal damage (12). Simulations take into account parameters such as skin type, hair thickness, density and colour, and accurately predict the fluence necessary to cause thermal damage in the hair structure without increasing the temperature of the epidermis, for safety reasons (14, 15). Based on the hypothetical results in the simulator and those obtained through this clinical study, we sought to demonstrate that: a) the short pulse duration is more effective than the long one; b) the blend wavelength 1060 + 940 + 810 nm offers safer and more effective results in the treatment of dark skin types than the 810 nm wavelength, and allows the application of greater fluences.

II. Materials and Methods

2.1. Study population

10 subjects were recruited for this study, of both sexes (8 women and 2 men), with skin types II to IV and with axillary hair not previously treated. The exclusion criteria used according the medical history were: pregnancy, lactation, children under 18, heat urticaria, photosensitising medication and presence of skin diseases (16). Table I depicts the patient characteristics for this study.

Table 1: Characteristics of subjects selected for the study

Subject	Skin type	Gender	Hair color	Hair type
1	II	F	Brown	Fine
2	III	F	Black	Thick
3	II	F	Black	Thick
4	III	F	Black	Thick
5	II	F	Black	Thick
6	II	F	Black	Thick
7	III	F	Brown	Fine
8	II	F	Brown	Fine
9	IV	M	Black	Thick
10	IV	M	Brown	Fine

2.2. Study design and assessment

This is a side-by-side comparison study designed to compare two types of photoepilation systems (Primelase Excellence, Soprano XL) for permanent hair removal. The treatments were always applied to the axillary area, since it is an area of hair with little hormonal influence and with no influence of external elements such as sun tanning. Three treatments spaced over a month and a half were applied. Subjects received the Primelase Laser Diode on the left armpit and the Soprano Laser Diode on the right armpit.

Efficacy and safety were assessed for each treatment. For the efficacy assessment, iconographies were taken before each treatment and a month and a half after the third treatment, and hair counts and semi-quantitative scales (1 = no result, 2 = poor result, 3 = good result, 4 = very good result, 5 = excellent result) were used. Hair was manually counted at baseline and at the last visit, which took place a month and a half after the third treatment. Efficacy was assessed by two investigators and then averaged.

For the safety assessment, the side effects, such as perception of pain, presence of erythema, oedema and burn, were evaluated during and immediately after each treatment. To assess the pain during the treatment, the subjects were asked to rate, on a scale of 1 to 5, the discomfort that occurs during treatment of the right armpit and then again during treatment of the left armpit. Accordingly, 1 = no pain, 2 = mild, 3 = moderate, 4 = severe, 5 = unbearable. Adverse events were assessed at all visits.

Each patient's satisfaction was assessed at the last visit, a month and a half after the third treatment.

2.3. Laser devices

In order to guarantee the safety of the patient during laser hair removal, the temperature of the epidermis should not exceed 43°C during the procedure. We used our simulation 3D model to calculate the epidermis temperature. The values of fluences used in this study are the maximum values for an epidermis temperature of below 43ºC, except for skin type II and for the blend applicator, where the suggested fluence was 35J/cm2 to avoid the use of longer pulses.

The Primelase Excellence device from Cocoon Medical was always applied to the left armpit. In subjects with light skin type (II), the 810 nm head was used at energies of 35J / cm2 and pulse duration of 19 ms. For subjects with intermediate skin type (III), the 810 nm 20x9 head was used at energies of 15 J / cm2 and pulse duration of 6 ms. In cases of dark skin type (IV), the blend 20x9 head of 1064 + 940 + 810 nm was used with energy of 35J / cm2 and pulse duration of 27 ms (Table I).

In the right armpit, the Soprano XL equipment from Alma Lasers, with 810 nm 20x10 head, was used, with energies of 35 J / cm2 and pulse duration of 40 ms in skin types II and III, and energies of 25 J / cm2 and pulse duration of 40 ms in skin type IV (Table 2).

Table 2: Summary of parameters of used lasers set up

Skin type II	
Soprano XL 20x10 810nm	35J/cm ^{2} – 40ms
Primelase Excellence 20x9 810nm	35 J/cm^2 – 19ms
Skin type III	
Soprano XL 20x10 810nm	35J/cm^2 – 40ms
Primelase Excellence 20x9 810nm	15 J/cm^2-6ms
Skin type IV	
Soprano XL 20x10 810nm	25J/cm^2 – 40ms
Primelase Excellence 20x9 Blend	35 J/cm^2 – 27ms

Before treatment, the area was shaved to achieve an approximate hair length of 1mm, and a cold Carbopol gel film with a thickness of approximately 1 mm was applied (Fig. 1a). The contact of the diode laser head with the skin is made by exerting slight pressure on it (Fig. 1b). Both devices emit the laser energy through a cold sapphire crystal window, which is used to cool the skin by continuous contact cooling.

The shots were made at 1Hz of frequency and 1 pass was performed on each patient.

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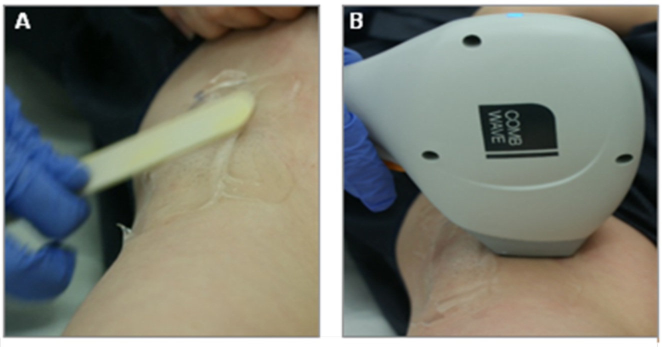

Figure 1: Illustration of photoepilation processing. A cold Carbopol gel film with a thickness of approximately 1 mm had been applied to the treated area (A). Contact with the skin was made by exerting slight pressure on it (B).

2.4. Simulation study

The used settings of Primelase Excellence and Soprano XL devices were simulated by a 3D in silico mathematical model of hair and skin heating using COMSOL Multiphysics® (12). This 3D model, which includes sapphire contact cooling, epidermis, dermis and hair follicle structure, was developed by Cocoon Medical. The hair model was divided into three zones: upper shaft, lower shaft and bulb. Furthermore, two different sheaths enveloping the hair were considered to calculate the effect on the cells in close proximity to the hair: one at 10 µm from the surface of the bulb to account for cells located on the bulb that are responsible for hair growth, and the other at 100 µm from the surface of the shaft to account for the stem cells located in the bulge that are responsible for its re-growth (12). The geometric model used in the numerical simulation was separated into a fine mesh in which the numerical equations for light diffusion, heat transfer and thermal damage were solved simultaneously to simulate the heating of the skin and hair follicle and to determine the temperature and thermal damage, in particular for the skin and hair types of the subjects included in this study. The parameter of thermal damage was used to evaluate the efficacy of both devices and to compare it with the clinical results.

Regarding the hair model, different dimensions were considered in the simulations (Table 3): untreated or original hair with fine and thick dimensions, and the so-called "residual" hair, which is the treated thin or thick hair (2, 13, 14).

Table 3. Hair parameters used in the simulation. The term "residual" is used for thinned hair after hair-removal treatments.

Type of hair	Depth (mm)	Bulb radius (mm)	Shaft radius (mm)
Untreated fine	2,5	0,094	0,03
Untreated thick	3,5	0,141	0,04
Residual fine	2,5	0,047	0,02
Residual thick	3,5	0,047	0,02

2.5. Statistical analysis

Complete data sets were analysed using one-way ANOVA with Bonferroni post-test. Individual differences within each treatment were analysed by a paired student t-test. Mean value and standard error (SE) were used to evaluate all data. A P-value < 0.05 was considered to indicate statistical significance. On the graphs, error bars represent the standard error. All the data were analysed with Prism 5.0 (Graphpad, La Jolla, CA) and Microsoft Excel.

III. Results

3.1. Clinical study comparing Soprano and Primelase diode laser equipments.

The purpose of this study was to evaluate and compare the effectiveness of two different diode laser photoepilation systems. Three treatments were carried out in both armpits of ten volunteers in parallel, using the Soprano diode laser equipment from Alma Lasers in the right armpit and the Primelase diode laser equipment from Cocoon Medical in the left armpit. In all cases there was hair reduction in both armpits.

3.1.1. Efficacy of the treatment's evaluation

Regarding the hair counting, the average reduction of hair in the right armpit was 53% ± 8% and the average reduction in the left armpit was 69% ± 4% (p = 0.016) (Fig. 2). In average, the Primelase device demonstrated 55% ± 22% greater hair reduction at 2 months after 3 treatments than the Soprano XL.

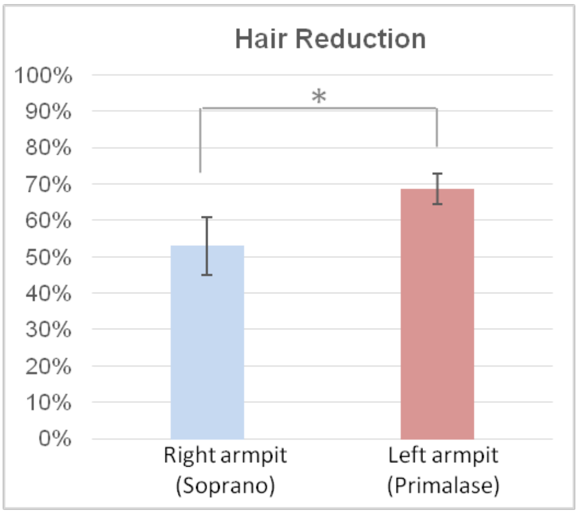

Figure 2. Hair reduction comparison of devices. Hair was manually counted. Efficacy assessment was performed by two investigators and then averaged (right armpit treated by Soprano and left armpit treated by Primelase). Statistically significant result with P-value > 0,05 is marked with *.

This quantitative assessment agrees with the subjective assessment scale, also performed by two investigators. They observed significantly better depilation in the left armpit than in the right armpit (p= 0.01). Accordingly, an average of 2.5 ± 0.12 (2 poor result and 3 good result) was observed for right armpit and 3.0 ± 0.18 (3 good result) for left armpit treated with Primelase (Fig. 3A).

Regarding patient satisfaction, there were also significantly more satisfied subjects with depilation in the left armpit (p = 0.008). An average of 2.5 ± 0.17 (2 poor result and 3 good result) was observed in the right armpit and an average of 3.2 ± 0.63 (3 good result and 4 very good result) for the left armpit (Fig 3B.).

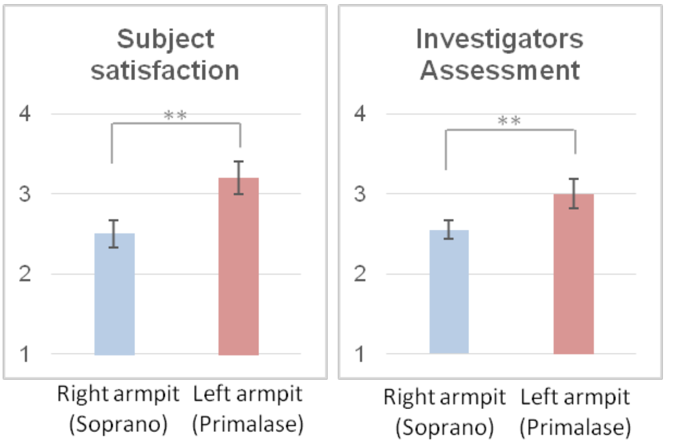

Figure 3: Treatment evaluation according subjects (A) and investigators (B). Statistically significant results with P-value > 0,01 are marked with **.

Examples of hair removal are illustrated in figure 4 (Fig. 4).

Figure 4: Examples of photoepilation results: Subject 5 with Skin type II and thick black hair (top); and subject 7 with Skin type III and thin brown hair (bottom).

3.1.2. Side effects evaluation of the treatments

According to the subject's subjective pain evaluation, there was significantly less perception of pain in the left armpit than in the right armpit in the first ($p = 0.013$) as well as in the second ($p = 0.021$) photoepilation treatment. In the first treatment, an average of 3.6 ± 0.22 (3 moderate pain and 4 severe pain) in the right armpit and an average of 2.6 ± 0.34 (2 mild pain and 3 severe pain) in left armpit were experienced (Fig 5). In the second treatment, an average of 4.1 ± 0.35 (4 severe pain and 5 unbearable pain) in the right armpit and 3.0 ± 0.37 (3 moderate pain) in the left armpit were experienced. However, the results were the opposite in the third treatment, where subjects reported an average of 2.6 ± 0.22 (2 mild pain and 3 moderate pain) in the right armpit and 3.2 ± 0.36 (3 moderate pain and 4 severe pain) in the left armpit (p=0,088) (Fig. 5).

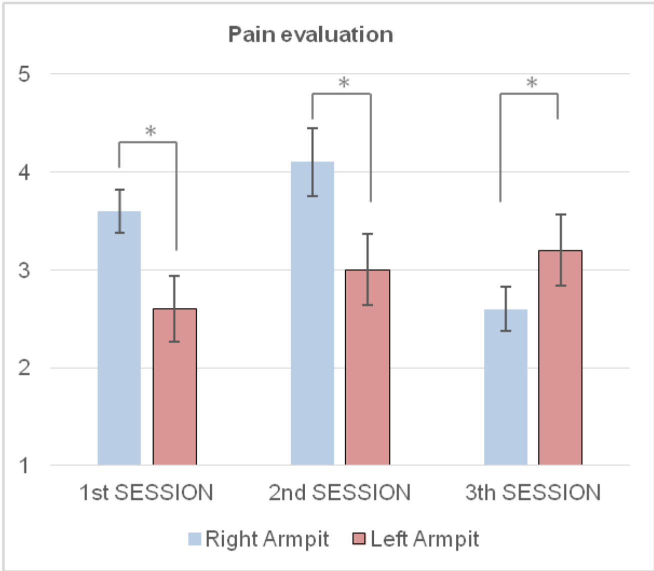

Figure 5. Subjective evaluation of pain perception during photoepilation. Three treatments were carried out in both armpits of ten volunteers in parallel, using the Soprano diode laser equipment from Alma Lasers in the right armpit and in the left armpit the Primelase diode laser equipment from Cocoon Medical. Statistically significant results with P-value > 0,05 are marked with *.

Regarding the end point, in the first treatment, perifollicular erythema was observed in all cases in both armpits and perifollicular oedema was observed in 6 cases in the left armpit and in 2 cases in the right armpit. In the second and third treatments, perifollicular oedema was not observed in either of the armpits, but perifollicular erythema was always observed.

In addition, it should be noted that the results obtained with the Blend applicator in Skin type IV were very satisfactory: high fluences of up to 35J / cm^2 were used without side effects and with a percentage of hair reduction similar to those obtained with lower skin types. However, due to the small number of subjects treated with blend applicator (2 subjects), more studies are necessary in order to confirm these results.

3.2. In silico simulations comparing Soprano and Primelase diode laser equipments

We have compared the experimental results with the data obtained by simulating skin and hair heating, using a 3D "*in* *silico*" model (12). The temperature and thermal damage in hair of different characteristics were determined. In addition, the temperature reached by stem cells localized in the bulge and around the bulb, and their thermal damage, were also determined (12).

All the results of the simulations are summarised in Table 4.

Treated	Skin type	Hair color	Hair Type	F (J/cm2)	t on (ms)	Epid. T (ºC)	Shaft Hair T (ºC)	Shaft Hair q	Shaft Stem cells T (ºC)	Shaft Stem cells q	Bulbe Hair T (ºC)	Bulbe Hair q	Bulbe Growing cells T (ºC)	Bulbe Growing cells q	Average hair damage
Left armpit	II	Brown	Fine	35	19	33	127	1,00	71	0,49	89	1,00	62	0,15	0,66
			Residual fine	35	19	33	107	1,00	64	0,38	79	1,00	59	0,00	0,59
			Thick	35	19	33	132	1,00	68	0,45	67	0,60	45	0,00	0,51
			Residual Thick	35	19	33	100	1,00	58	0,28	62	0,35	44	0,00	0,41
		Black	Fine	35	19	33	147	1,00	82	0,60	97	1,00	69	0,55	0,79
			Residual fine	35	19	33	123	1,00	72	0,50	85	1,00	65	0,25	0,69
			Thick	35	19	33	153	1,00	77	0,55	72	0,78	48	0,00	0,58
			Residual Thick	35	19	33	115	1,00	64	0,38	65	0,55	47	0,00	0,48
Right armpit	II	Brown	Fine	35	40	30	91	0,88	61	0,31	75	0,75	56	0,00	0,48
			Residual fine	35	40	30	77	0,75	54	0,18	65	0,50	51	0,00	0,36
			Thick	35	40	30	97	0,83	60	0,30	60	0,30	43	0,00	0,36
			Residual Thick	35	40	30	73	0,65	50	0,08	54	0,00	41	0,00	0,18
		Black	Fine	35	40	30	103	0,95	69	0,46	80	0,85	61	0,23	0,62
			Residual fine	35	40	30	86	0,90	60	0,28	69	0,70	55	0,00	0,47
			Thick	35	40	30	111	0,90	67	0,44	64	0,40	45	0,00	0,43
			Residual Thick	35	40	30	81	0,80	55	0,18	56	0,00	43	0,00	0,24
Left armpit	III	Brown	Fine	15	6	38	111	1,00	57	0,26	69	0,70	49	0,00	0,49
			Residual fine	15	6	38	99	1,00	55	0,23	67	0,60	49	0,00	0,46
			Thick	15	6	38	108	1,00	53	0,19	54	0,00	41	0,00	0,30
			Residual Thick	15	6	38	93	1,00	51	0,15	55	0,00	41	0,00	0,29
		Black	Fine	15	6	38	128	1,00	63	0,36	73	0,90	53	0,00	0,57
			Residual fine	15	6	38	113	1,00	60	0,33	71	0,80	53	0,00	0,53
			Thick	15	6	38	124	1,00	58	0,29	57	0,05	42	0,00	0,33
			Residual Thick	15	6	38	105	1,00	55	0,25	57	0,05	42	0,00	0,33
Right armpit	III	Brown	Fine	35	40	44	89	0,85	61	0,30	74	0,73	55	0,00	0,47
			Residual fine	35	40	44	76	0,70	54	0,15	64	0,45	51	0,00	0,33
			Thick	35	40	44	96	0,83	60	0,29	60	0,30	43	0,00	0,35
			Residual Thick	35	40	44	72	0,65	50	0,08	53	0,00	41	0,00	0,18
		Black	Fine	35	40	44	101	0,93	68	0,44	79	0,83	60	0,20	0,60
			Residual fine	35	40	44	85	0,85	59	0,25	68	0,65	54	0,00	0,44
			Thick	35	40	44	109	0,90	66	0,43	63	0,38	45	0,00	0,43
			Residual Thick	35	40	44	80	0,80	54	0,18	56	0,00	43	0,00	0,24
Left armpit	IV	Black	Fine	35	27	42	106	0,83	67	0,43	79	0,85	61	0,18	0,57
			Residual fine	35	27	42	90	0,65	59	0,28	69	0,70	57	0,00	0,41
			Thick	35	27	42	114	0,78	65	0,41	63	0,38	46	0,00	0,39
			Residual Thick	35	27	42	85	0,55	55	0,20	57	0,05	44	0,00	0,20
Right armpit	IV	Black	Fine	25	40	42	82	0,80	59	0,26	66	0,55	53	0,00	0,40
			Residual fine	25	40	42	71	0,60	52	0,13	59	0,15	49	0,00	0,22
			Thick	25	40	42	88	0,78	57	0,23	55	0,13	42	0,00	0,28
			Residual Thick	25	40	42	67	0,55	49	0,03	50	0,00	41	0,00	0,14

Table 4: Summarised results of the skin and hair heating simulations, using 3D in silico model (right armpit treated by Soprano and left armpit treated by Primelase). Fine and thick correspond to untreated hair, while residual thin and residual thick correspond to thinned treated hair.

3.2.1. Simulations of heating of standard hair

First, we simulated the hair with the standard dimensions for fine hair and thick hair. Figure 6 shows the results of the simulation for the laser parameters and for the skin and hair types used in this study. For skin type II and fine brown hair, the shaft and bulb were heated in the right armpit to 104ºC and 85ºC respectively with 35J/cm^2 and pulse duration of 40ms, and in the left armpit to 146ºC and 100ºC with same fluence and 19ms. For skin type III and fine brown hair, the same parameters were considered for the right armpit but

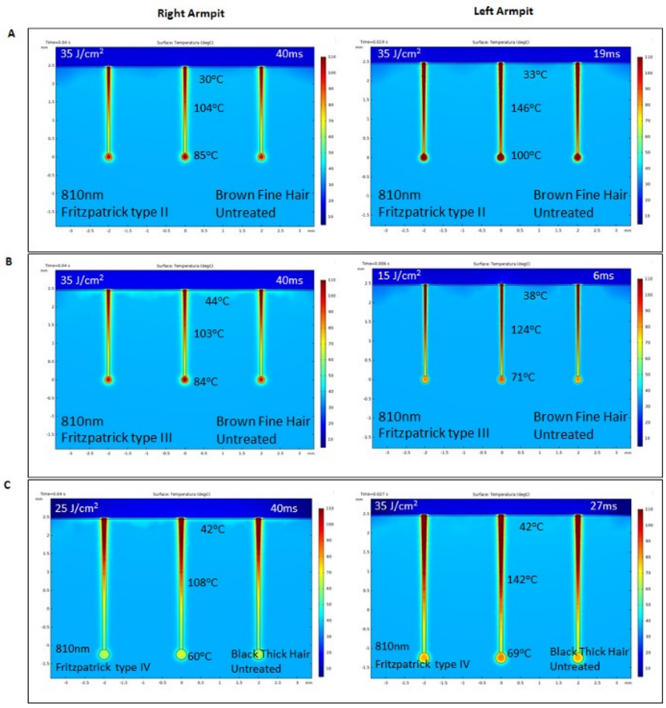

Figure 6: Simulation of heating of untreated hair recreating the first treatment in the right armpit and in the left armpit, for skin type II and fine brown hair (A), for skin type III and fine brown hair (B) and for skin type IV and thick black hair (C) (right armpit treated with Soprano and left armpit treated with Primelase).

lower fluence was used for the left armpit for safety: the shaft and bulb were heated in the right armpit to 103 ºC and 84 ºC respectively, with 35 J / cm^2 and 40 ms, and in the left armpit to 124 ºC and 71 ºC with 15 J / cm^2 and 6 ms. Finally, for skin type IV and thick black hair, lower fluence was considered for the right armpit for safety and a blend diode laser was used for the left armpit: shaft and bulb were heated in the right armpit to 108 ºC and 60 ºC with 25 J / cm^2 and 40 ms and in the left armpit to 142 ºC and 69 ºC with 35 J / cm^2 and 27 ms (Fig 6). The thermal damage simulated for the left armpit (Primelase) was 7% greater than for the right armpit (Soprano), but it was found to be not statistically significant.

3.2.2. Simulations of heating of residual hair

The same simulations were performed with thinned hair that was expected to be present in the subsequent treatment sessions (the so-called residual hair). Figure 7 shows the simulations of hair heating for the different skin types. The differences in hair shaft and bulb temperature between right and left armpits were as follows: a) skin type II and fine brown hair, 77 ºC and 65 ºC with 35 J / cm^2 and 40 ms (right armpit) and 107 ºC and 79 ºC with 35 J / cm^2 and 19 ms (left armpit); b) skin type III and fine brown hair, 76 ºC and 64 ºC with 35 J / cm^2 and 40 ms (right armpit) and 99 ºC and 67 ºC with 15 J / cm^2 and 6 ms (left armpit); c) skin type IV and thick black hair, 67 ºC and 50 ºC with 25 J / cm^2 and 40 ms (right armpit) and 85 ºC and 57 ºC with 35 J / cm^2 and 27 ms (left armpit) (Fig. 7). Worthy of note is that all the simulated temperatures of the residual hair in the left armpit (Primelase) were found to be higher than those obtained in the right armpit (Soprano) (Table 4).

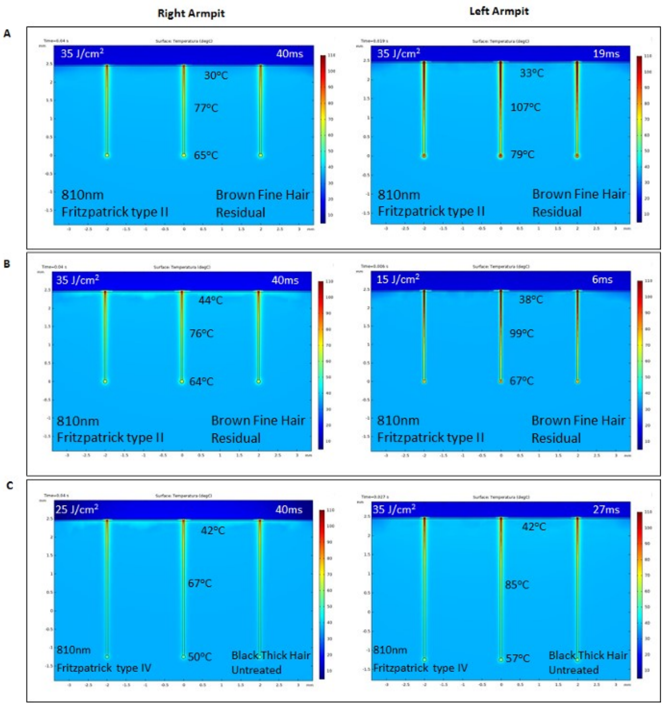

Figure 7: Simulation of heating of residual or treated hair recreating the second and third treatments in the right armpit and in the left armpit, for skin type II and fine brown hair (A), for skin type III and fine brown hair (B) and for skin type IV and thick black hair (C). (right armpit treated with Soprano and left armpit treated with Primelase).

In consequence, the simulated thermal damage was 65% significantly higher (p`= 0.00028) in residual hair using Primelase equipment, when compared to Soprano laser (Fig. 8).

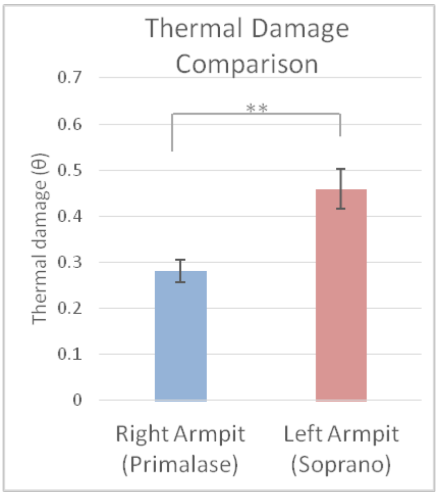

Figure 8: Average thermal damage comparison between Soprano and Primelase for untreated hair and residual hair (right armpit corresponding to Soprano and left armpit to Primelase). P-value > 0,01 is marked with **.

3.3. Comparison of in silico simulations with the clinical results

In Table 4 and Figures 6-8, we have shown separately the simulation values for both untreated and treated (residual) hair. In order to compare the *in silico* simulations with the real clinical results, which are evaluated after the three treatments (untreated and also residual hair is depilated), we have calculated the weighted average of the two simulations and produced the statistics from the simulation results for the 10 subjects. Figure 9 shows the statistical results for the pulse duration and simulated temperatures for right armpit (Soprano) and left armpit (Primelase). It shows that the temperature of the hair structures (hair shaft ($p = 3{,}81x10^{-5}$), hair bulb (p=0,01), hair stem cells (p = 0.03)) for the right armpit is significantly lower than the temperature for the left armpit, and that the pulse duration used for the right armpit is longer than the used for the left armpit ($p=3{,}69x10^{-6}$). Accordingly, the resultant thermal damage was found to be 25% higher for the left armpit than for the right armpit (p = 0,012).

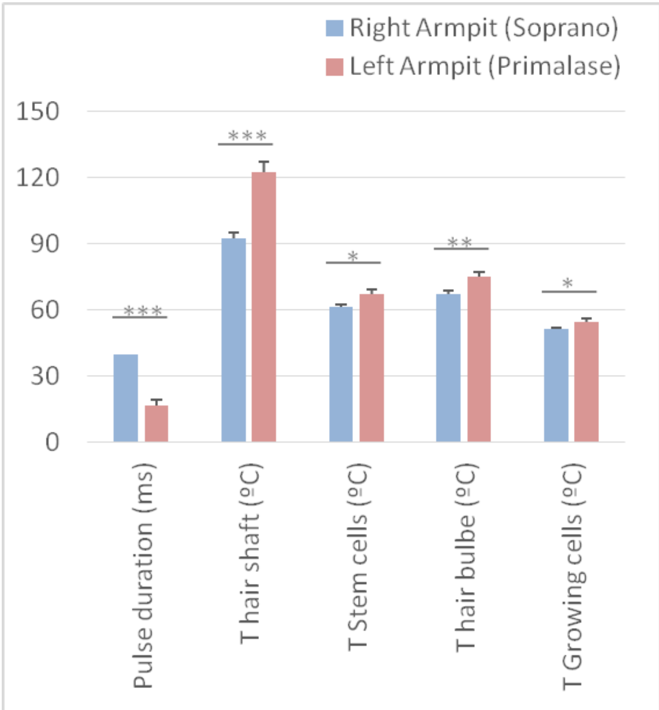

Figure 9. Weighted average differences in pulse duration ($p=3{,}69x10^{-6}$), temperatures of hair shaft hair ($p=3{,}81x10^{-5}$), stem cells (p=0.03), hair bulbe (p=0,01) and growing cells (p=0,05) according to the *in silico* simulation with untreated and treated hair, comparing right armpit (Soprano) and left armpit (Primelase).

IV. DISCUSSION

Laser hair removal is one of the most frequently requested cosmetic procedures. In the past decade the use of the diode laser in the cosmetic industry has become widespread due to its high energy efficiency, low production costs and far fewer maintenance requirements compared with solid state lasers. However, the main problem of diode lasers is their low power compared with solid state lasers. Here we investigate the

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results of a high-power diode laser of 4,800W (Primelase) compared with equipment of lower power (Soprano).

In theory, more power allows one to use shorter pulse times, keeping the used fluence constant. Hence, the efficacy of the treatment is expected to be improved, since the hair has less time to cool down during the short pulse duration. This is particularly important in order to treat thinned hair, which has a thermal relaxation time (TRT) of a few milliseconds (12). Increased temperature may also cause more thermal damage in the surrounding hair stem cells by thermal heat diffusion, which is necessary to produce a permanent hair removal. The difference in the TRT of the different types of hair is a key factor in laser hair removal. High power allows shorter pulse durations, which increases the heating of the hair due to the TRT. Laser pulses shorter than the TRT result in efficient heating of the hair follicle and surrounding structures. Pulses longer than the TRT will result in insufficient heating of the target.

Subjective pain perception reported by patients indicates that during the first two treatment sessions the most uncomfortable equipment is the one with less power (Soprano). However, in the third session, the pain produced by Primelase is slightly more than the sensation of pain produced by Soprano. In the first two sessions, due to the long duration of its pulses, Soprano generates more pain than Primelase. However, in the third session when the hair is thinned, the long pulses of this equipment do not allow heating of residual hair as much as Primelase, since such a long pulse (40ms) is much longer than the TRT of residual hair (less than 10ms). In contrast, Primelase's high power does allow it to heat residual hair more than Soprano equipment, which produces a greater perception of pain.

Consequently, the treatment assessment was more favourable after Primelase laser depilation, according to the subjects.

Similarly, the assessment of the investigators after treatments, and with the evaluation of the iconographies (hair counting) before and after the treatments, was more favourable after Primelase hair removal. It should be noted that the evaluation by investigators after treatments is considered as subjective evidence of the higher efficiency of the Primelase laser, and that the hair iconographies performed by two independent researchers are considered as objective evidence that the Primelase equipment is more effective than the Soprano laser.

Importantly, high fluencies of blend applicator have been used without side effects in skin type 4 patients and with hair reduction percentage similar to those obtained with lower skin types. The novel diode laser of Primelase with blend wavelength 810/940/1060nm has enabled the use of high fluences with safety on darker skin while maintaining high efficacy of treatment.

The side-by-side comparison of laser hair removal from the axilla is an effective means of evaluating differences between devices. The 69% hair reduction observed with Primelase compared to the 53% obtained with Soprano is statistically significant. The higher efficacy observed with Primelase is a consequence of the combination of a higher peak power and the use of blend wavelength for dark skin types, providing more energy to the hair follicles without reducing skin safety.

Worthy of note, in the present study, is the fact that only 3 treatment sessions were carried out on the study subjects. However, to achieve permanent hair removal, 6 to 8 sessions are necessary. For this reason, there was no permanent hair removal in any subject, but the thickness of the hair was reduced until it became residual fine hair in all subjects. Moreover, the greater efficacy of the Primelase equipment with residual hair suggests that the number of sessions needed to achieve permanent hair removal will be smaller.

All this evidence, both subjective and objective, matches the results given by the simulations performed with our "in silico" model (12). Simulations indicate that for untreated hair there is a difference in favour of Primelase equipment in generated thermal damage; however, it is not statistically significant. Importantly, there is a significant difference in favour of Primelase when comparing the thermal damage produced in residual hair. As mentioned above, this is probably due to the high power of the Primelase equipment, which is capable of heating very fine hair thanks to its short pulse duration, which is shorter than its TRT. Consequently, for untreated hair the results are very similar for both lasers, but for thinned residual hair, the high power of Primelase achieves better results than those of Soprano equipment.

Simulations have become a very useful tool for calculating the effect of new treatments on the skin and hair. The fact that the clinical results match the results of the simulations further validates our simulation model and provides a very powerful tool for assessing the effectiveness of future treatments.

V. CONCLUSIONS

So, this study shows that, using comparable or lower energies, the high power of the Primelase system makes it more efficient than the Soprano system. In three sessions of side-by-side comparison of laser hair removal, the 69% ± 4% hair reduction observed with Primelase Excellence was 55% ± 22% in average more effective than the 53% ± 8% hair reduction observed with the Soprano XL ($p = 0.016$). As it uses much shorter pulses, it improves the result and favours the patient's comfort (less pain perception).

In addition, the clinical data presented here demonstrate that the blend diode laser of Primelase, combining 810, 940 and1064 nm, has proved to be safe and effective for hair removal from dark skin. This novel diode laser maximizes hair removal results while minimizing treatment risks. More studies are planned to further substantiate the potential clinical contribution of the newly developed blend wavelength concept.

These results are consistent with our mathematical 3D simulations of the hair-removal process, and reveal that the main differences between the two lasers are obtained with the thinned or residual hair as it appears after several sessions (thermal damage being 65% greater with the Primelase parameters), thanks to the higher peak power and shorter pulse duration of the Primelase equipment, which supplies more effective energy to the thinned hair follicles.

Accordingly, fewer sessions are needed to achieve total hair removal with a high-power Primelase laser (4,800 W). We believe that the trend will be towards the use of high-power equipment, increasing the effectiveness and comfort of photoepilation treatments.

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