

Micro-Fractional Ablative Skin Resurfacing with Two Novel Erbium Laser Systems

Christine C. Dierickx, MD,^{1*} Khalil A. Khatri, MD,² Zeina S. Tannous, MD,³ James J. Childs, PhD,⁴ Richard H. Cohen, PhD,⁴ Andrei Erofeev, PhD,⁴ David Tabatadze, PhD,⁴ Ilya V. Yaroslavsky, PhD,⁴ and Gregory B. Altshuler, Dr Sc⁴

¹*Skin and Laser Center, Boom B-2850, Belgium*

²*Skin and Laser Surgery Center of New England, Nashua, New Hampshire 03060*

³*Harvard Medical School, Boston, Massachusetts 02114*

⁴*Palomar Medical Technologies, Inc., Burlington, Massachusetts 01803*

Background and Objectives: Fractional ablation offers the potential benefits of full-surface ablative skin resurfacing while minimizing adverse effects. The purpose of this study was to evaluate the safety, damage profile, and efficacy of erbium fractional lasers.

Materials and Methods: Histology from animal and human skin as well as clinical evaluations were conducted with erbium YAG (2,940 nm) and erbium YSGG (2,790 nm) fractional lasers varying pulse width, microbeam (μb) energy, number of passes, and stacking of pulses.

Results: Single-pulse treatment parameters from 1 to 12 mJ per 50–70 μm diameter microbeam and 0.25–5 milliseconds pulse widths produced microcolumns of ablation with border coagulation of up to 100 μm width and 450 μm depth. Stacking of pulses generated deeper microcolumns. Clinical observations and in vivo histology demonstrate rapid re-epithelization and limited adverse side effects. Facial treatments were performed in the periorbital and perioral areas using 1–8 passes of single and stacked pulses. Treatments were well-tolerated and subjects could resume their normal routine in 4 days. A statistically significant reduction in wrinkle scores at 3 months was observed for both periorbital and perioral wrinkles using blinded grading. For periorbital treatments of four passes or more, over 90% had ≥ 1 score wrinkle reduction (0–9 scale) and 42% had ≥ 2 . For perioral wrinkles, over 50% had substantial improvements (≥ 2).

Conclusion: The clinical observations and histology findings demonstrate that micro-fractional ablative treatment with 2,790 and 2,940 nm erbium lasers resulted in safe and effective wrinkle reduction with minimal patient downtime. The depth and width of the ablated microcolumns and varying extent of surrounding coagulation can be controlled and used to design new treatment procedures targeted for specific indications and areas such as moderate to severe rhytides and photodamaged skin. *Lasers Surg. Med.* 40:113–123, 2008.

© 2008 Wiley-Liss, Inc.

Key words: erbium lasers; fractional laser; fractional ablation; micro-fractional ablation

INTRODUCTION

Treatment of photoaged skin with ablative lasers has been shown to produce clinically efficacious results in a number of studies [1–4]. However, these procedures are painful, have significant downtime and adverse side effects such as infection, pigment alterations, long-lasting erythema, and scarring [5–9]. The downtime from the recovery process encompasses both the time for physiological processes associated with re-epithelization to occur and the time needed for the patient to return to normal activity without any psychological discomfort resulting from the appearance of the treated areas. Full-surface ablative procedures with a CO₂ laser, for example, have been shown to produce 1–2 weeks of downtime and erythema lasting for an average of 2–4.5 months [5]. Extended downtime and long-lasting erythema are obvious drawbacks for patients undergoing this procedure.

Recent application of fractional technology to non-ablative skin rejuvenation techniques has potential to provide efficacy while maintaining advantages of minimal to no downtime. Fractional non-ablative treatments have been useful in treating conditions such as mild to moderate rhytides [10], photodamaged skin [11], acne scarring [12,13], leucodermic scars [14], melasma [15,16], and non-facial skin rejuvenation [17]. Investigators have reported re-epithelization in 24 hours with this procedure [18,19], thereby reducing downtime for the patient. Furthermore, there has been a noted absence of the side effects typically associated with full-surface ablation [9]. However, despite these safety advantages the clinical efficacy profile does not match that of the full ablative process, especially with respect to moderate to severe rhytides [10].

Contract grant sponsor: Palomar Medical.

*Correspondence to: Christine C. Dierickx, MD, Skin and Laser Center, Beukenlaan 52, 2850 Boom, Belgium.

E-mail: mail@cdierickx.be

Accepted 4 December 2007

Published online in Wiley InterScience
(www.interscience.wiley.com).

DOI 10.1002/lsm.20601

Fractional ablative procedures have the potential to provide greater efficacy for treatment of rhytides, while minimizing downtime and side effects. Fractional ablative CO₂ lasers have been shown to reduce downtime and result in more rapid wound healing [20–24]. The reliability and compactness of the Er:YAG, and Er:YSGG laser sources are also worth consideration, particularly if they can be adapted to provide ablation with a sufficient residual layer of tissue coagulation. Interaction between laser light and tissue in the ablative regime is dominated by water absorption; therefore, the water absorption coefficient is a major factor in wavelength selection. The water absorption coefficients for the three above-mentioned wavelengths differ by an order of magnitude ($\sim 10^3 \text{ cm}^{-1}$ for CO₂ laser at 10,600 nm, $\sim 10^4 \text{ cm}^{-1}$ for Er:YAG laser at 2,940 nm, and $\sim 10^2 \text{ cm}^{-1}$ for Er:YSGG laser at 2,790 nm). Even though there is considerable knowledge on skin ablation with wide beams, the interaction of microbeams with tissue can be substantially different, due to vast increases in local intra-beam power density and fluence. Another important factor that governs the formation of ablative and coagulative zones is the pulse width. In this work, we compared the effects of Er:YAG and Er:YSGG lasers using both short- and long-pulse modes in order to optimize ablative fractional device parameters for new treatment regimens.

MATERIALS AND METHODS

Device Description

Two unique erbium fractional lasers were developed as accessories to the StarLux™ Pulsed Light & Laser System platform (Palomar Medical Technologies, Inc., Burlington MA). Each laser consists of an active rod pumped by a Xenon flash lamp: an erbium-doped Yttrium Aluminum Garnet crystal (Y₃Al₅O₁₂, Er:YAG) emitting at 2,940 nm and an erbium-doped Yttrium Scandium Gallium Garnet (Y_{2.93}Sc_{1.43}Ga_{3.64}O₁₂, Er:YSGG) emitting at 2,790 nm. One of the fractional handpieces is shown in Figure 1.



Fig. 1. Erbium Lux2940 _fractional laser.

The fractional beam emission pattern of the laser is user selectable by an interchangeable optical tip. The “fractional” pattern consists of an array of focused microbeams ($\sim 75 \mu\text{m}$ diameter) that have up to 12 mJ/ μb of energy with a beam density from 170 to 1,000 $\mu\text{b}/\text{cm}^2$ (illustrated in Fig. 2). The number of microbeams delivered to the skin depends upon the spot size, the distance between the microbeams (i.e., microbeam pitch) as well as the number of passes.

Histology

Six millimeter punch biopsies from ex vivo Yucatan pig and human abdomen skin were used to characterize the damage profile after treatment with the erbium fractional lasers. Series of 2 mm punch biopsies were also collected from the periauricular area of the face at various time points after in vivo treatment with the erbium fractional lasers to demonstrate healing responses.

For the ex vivo skin testing, abdominal skin of the Yucatan pig was harvested and treated within 24 hours of excision. Human abdominal skin was obtained following abdominoplasty and stored frozen for 2 days prior to treatment. Porcine and human skin samples maintained

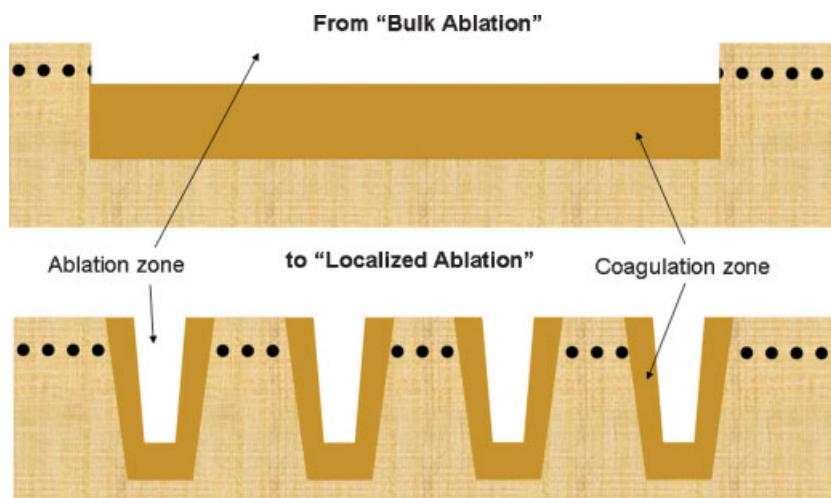


Fig. 2. Fractional versus flat beam erbium ablation.

TABLE 1a. Ex Vivo Single-Pass Treatment Parameters

Wavelength (nm)	Energy (mJ/ μ b)	Pulse width (milliseconds)	Stacked pulses
2,790	4–12	2–5	Up to 3
2,940	1–9	0.25, 2, 5	Up to 3

at 30°C with a warming plate were treated at parameters summarized in Table 1a. Samples were fixed in formalin for serial sectioning and staining with hematoxylin and eosin (H&E) in preparation for histologic examination.

For in vivo human histology, the healing response was characterized using 26 biopsies collected from 4 subjects at various time points after facial treatment. Table 1b summarizes the treatment parameters and time of biopsies. All subjects consenting to these biopsies were scheduled for a facelift procedure.

Clinical Procedures

Subjects. The clinical study involved 108 treated areas across a total of 13 subjects with mild to moderate photo-damaged and aged facial skin. Fitzpatrick skin types ranged from I to III and the participants ages ranged from 33 to 62. Testing was performed with FDA approval. Informed consent was obtained from all subjects, and the study was approved by the Essex Institutional Review Board of Lebanon, NJ.

Treatment procedure. Subjects were treated with the 2,940 nm erbium fractional laser using parameters ranging from 1 to 9 mJ/ μ b and a pulse width varying from 250 microseconds to 5 milliseconds. Subjects were also treated with the 2,790 nm handpiece using parameters ranging from 4 to 12 mJ/ μ b and a pulse width varying from 2 to 5 milliseconds. Areas were treated with multiple passes varying from 1 to 8 total passes and included passes with stacked pulses.

If needed, treatments were applied with topical anesthetic or adjunctive cooling. In several instances, the treated areas were subdivided into smaller areas in order to evaluate a range of parameters, while in the other treated areas the region was treated uniformly with a single parameter. Subjects were instructed to clean and

apply ointment to treated areas three times daily for 4 days after treatment.

Clinical evaluations. A total of 108 treatment areas were evaluated for wound healing and side effects immediately post-treatment and at 3 follow-up visits: 3–4 days, 1 week, and 1–3 months post-treatment. Included in the evaluations were 21 periorbital and 19 perioral areas for assessment of wrinkle reduction. At all observational time points, side effects of erythema, edema, bruising, debris, crusting, bleeding, hyper- and hypopigmentation, scarring, atrophy, blistering were evaluated on a 9 point scale (0 = none, 1–3 mild, 4–6 moderate, and 7–9 severe). During treatment, subjects rated pain on a 0–10 scale to help evaluate procedure safety and patient tolerance. Wrinkle appearance 3 months after the single treatment was evaluated on a 0–9 scale in a randomized, blinded side-by-side fashion by three dermatologists. A standardized *t*-test and Wilcoxon signed-rank statistic were conducted on the difference score (post-pre) using JMP 7 (SAS Institute, Cary, NC).

Photo documentation system. All photographic documentation was performed with a facial photo fixture using a NikonD100 and a Canon PowerShot S2 stand-off camera (Canfield Scientific, Fairfield, NJ). The fixture ensured a fixed distance and fixed angles between the camera and the patient. Flash lamps placed in fixed positions to the camera ensured even illumination of all parts of the face and the ability to examine subjects under controlled lighting.

RESULTS

Histologic Findings

Porcine ex vivo histology. Figures 3–5 depict three porcine skin histology slides that demonstrate micro-beam ablation and coagulation after single-pulse treatments

TABLE 1b. In Vivo Single-Pulse Treatment Parameters and Biopsy Time Points for Histology

Subject	Biopsy #	Wave-length	Energy (mJ/ μ b)	Pulse width (milliseconds)	Biopsy time (days)									
					0	1/4	1/2	1	2	4	7	14	21	28
S#1	1–10	2,940	9	0.25	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)
S#4	11–18	2,790	12	5	(✓)			(✓)	(✓)	(✓)	(✓)	(✓)	(✓)	(✓)
S#5	19	2,790	8	5	(✓)					(✓)				
	20	2,790	8	2	(✓)					(✓)				
	21	2,940	5	5	(✓)					(✓)				
	22	2,940	5	2	(✓)					(✓)				
S#6	23	2,790	8	5	(✓)					(✓)				
	24	2,790	8	2	(✓)					(✓)				
	25	2,940	5	5	(✓)					(✓)				
	26	2,940	5	2	(✓)					(✓)				

All biopsies were taken from the periauricular area of the face. The “zero” column for biopsy time refers to immediate post-treatment.

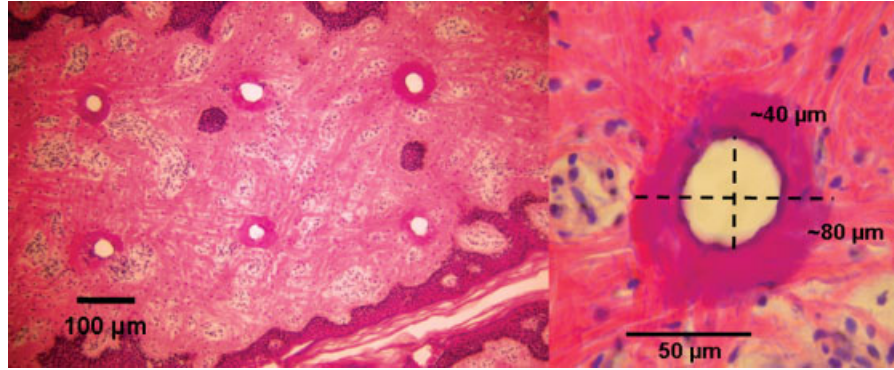


Fig. 3. **a**: Longitudinal section at 60–100 μm depth of Yucatan pig skin treated with the 2,790 nm laser device at 8 $\text{mJ}/\mu\text{b}$ and 2 milliseconds pulse width. **b**: Magnified image of one micro-channel with 40 μm diameter ablation zone surrounded by a 20 μm thick coagulation zone.

with the 2,790 nm wavelength and 2,940 nm wavelength laser devices. Figure 3 shows a horizontal section at 60–100 μm depth of skin treated with the 2,790 nm device. The treatment parameters were 8 $\text{mJ}/\mu\text{b}$ and 2 milliseconds pulse width. Figures 4 and 5 exhibit similar damage profiles after treatment with the 2,940 nm wavelength device (5 $\text{mJ}/\mu\text{b}$ with 2 milliseconds and 0.25 milliseconds pulse widths, respectively).

Human ex vivo histology. Figure 6 depicts typical histology obtained after treatment of excised human abdominal skin with the 2,940 nm device. The approximate intra-beam fluence for the 0.25 milliseconds pulse treatment is 60 J/cm^2 , which is significantly greater than the ablation threshold fluence. By increasing pulse width to 5 milliseconds at the same energy, the erbium laser generated ablated columns with wider surrounding zones of coagulation as shown in Figure 6.

Incremental increase in depth of damage was achieved with either increasing energy, decreasing pulse width for fixed microbeam energy, or multiple stacking of pulses. For example, for the long-pulse mode (2–5 milliseconds), the depths of microcolumn damage, ablation plus coagulation, increased in a linear fashion from 50 to 140 μm at settings

from 1 to 5 $\text{mJ}/\mu\text{b}$. Over the same range microcolumns from the short-pulse mode (0.25 milliseconds) were 20 to 25% deeper. Average depths of over 250 μm were observed with stacking of 2–3 pulses at a 2 Hz repetition rate with 2 milliseconds pulse widths and 5 $\text{mJ}/\mu\text{b}$.

Human in vivo tissue healing. The tissue healing response was evaluated from the time series of biopsies taken from the periauricular region after a single-pass treatment. The histology findings for the 2,940 nm wavelength treatment are shown in Figure 7 and indicate that within 12 hours there is a very rapid re-epithelization (Fig. 7c). For 2,790 nm treatment, re-epithelization was observed at the shortest post-treatment biopsy time of 24 hours. Re-epithelization was noted as a continuous dermal/epidermal junction with an overlying continuous layer of basal cells in all serial sections through the microcolumn zones. At 12 and 24 hours, the damage zones could be identified with dermal collagen coagulation or by columnar-shaped regions of neutrophilic infiltration associated with inflammation (Fig. 7c, 24 hours not shown). At a few days following treatment, necrotic debris was observed entrapped in the upper epidermis above the micro-columns.

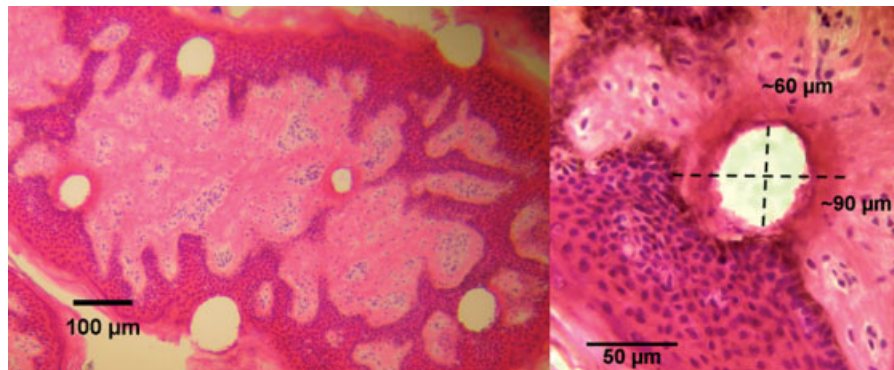


Fig. 4. **a**: Longitudinal section at 50–80 μm depth of Yucatan pig skin treated with 2,940 nm laser (5 $\text{mJ}/\mu\text{b}$ and 2 milliseconds pulse width). **b**: Magnified micro-channel with a 60 μm diameter ablation hole surrounded by 15 μm thick coagulated layer.

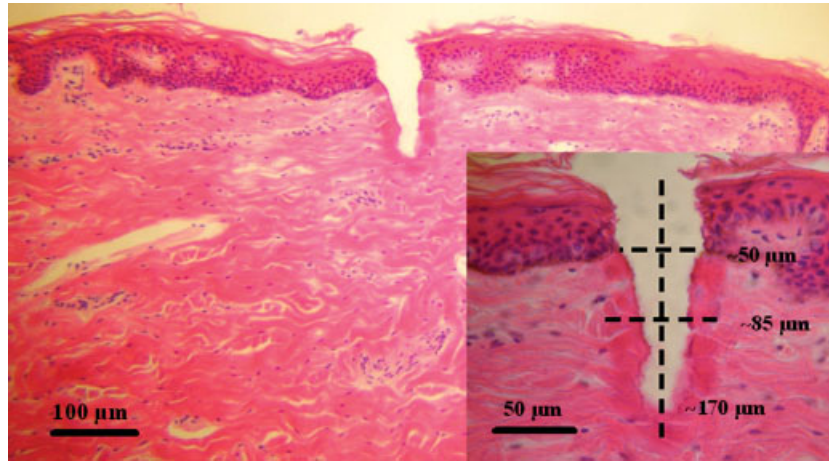


Fig. 5. Cross-section of Yucatan pig skin treated with the 2,940 nm laser at 5 mJ/µb and 0.25 milliseconds pulse width. The damage profile extends down to 170 µm with approximately a 15 µm thick coagulation zone surrounding the ablation column.

Clinical Findings

Safety. A total of 85 treatment areas were observed for side effects and healing during the first week after treatment. Skin reactions and discomfort from fractional erbium YSGG (2,790 nm) and erbium YAG (2,940 nm) treatments were mild, transient, and short-lasting when compared to traditional full-surface ablative resurfacing. As early as 4 days after treatment, subjects could apply make-up and resume their normal hygiene routines.

Pain ratings show that for small test areas the procedure was well-tolerated without anesthetics. With greater number of passes and treatment of larger areas, topical anesthesia and adjunctive cold air were typically used. A maximum pain rating of 4 or less was observed in periorbital treatments. For most subjects, pain ratings

increased by 1 U with additional passes. Perioral treatments were less painful, with an overall rating of 3 or less, and ratings did not increase with additional passes.

Table 2 summarizes the skin reactions observed after the erbium fractional treatment with the 2,940 and 2,790 nm wavelength devices using short- and long-pulse modes, 0.25 milliseconds and 2 or 5 milliseconds, respectively. Minor bleeding with edema was observed only with the 2,940 nm device treatments. Consistent with the histology findings of wider coagulation zones, only sparse and pin-point bleeding was observed with the longer pulse widths, in comparison to the mild diffuse bleeding from areas treated with the 0.25 milliseconds pulse width. Immediately after treatment nearly all subjects developed mild or moderate erythema, with predominance of mild erythema. The incidence of erythema was markedly reduced by week 1,

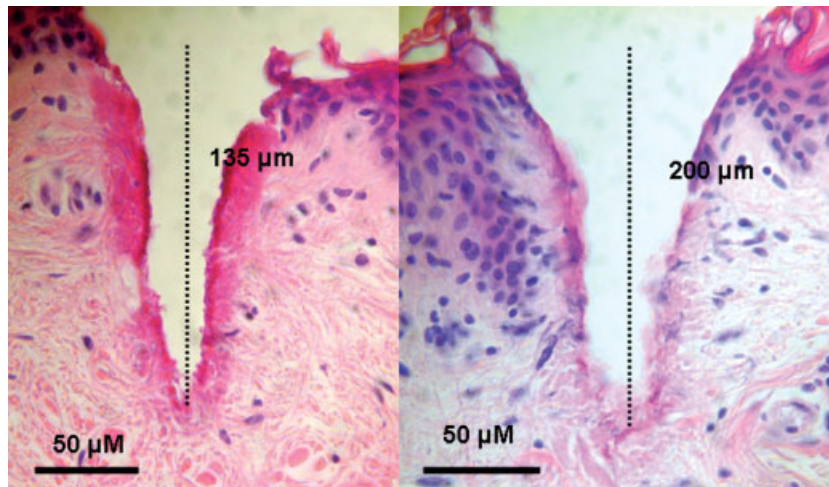


Fig. 6. Cross-sections of ex vivo human abdominal skin treated with the 2,940 nm laser at 5 mJ/µb and (a) 5 milliseconds and (b) 0.25 milliseconds pulse widths. Note the increase in coagulation layer thickness for the 5 milliseconds parameter.

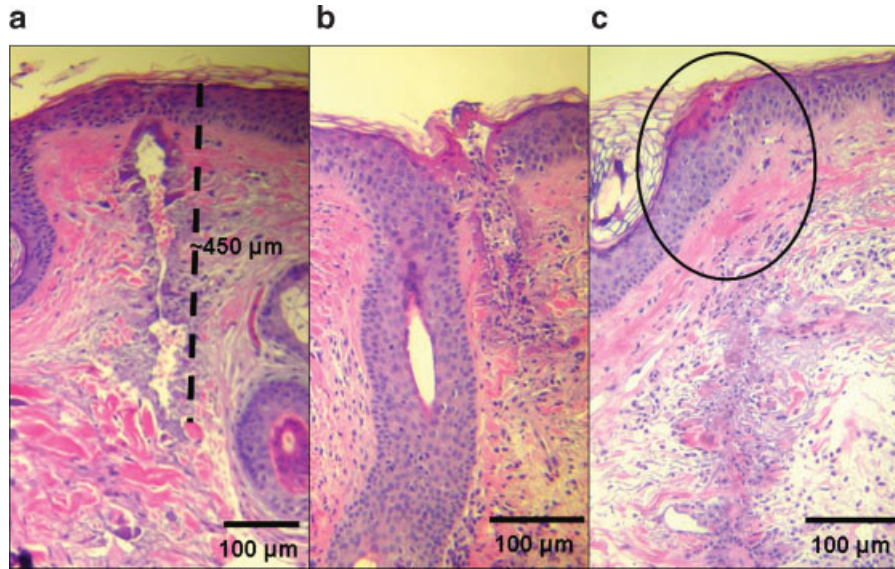


Fig. 7. H&E histology at three time points post-treatment with 2,940 nm device at 9 mJ/µb, and 0.25 milliseconds illustrate rapid healing response to microbeam damage zones. **a:** Immediately post-treatment a 450 µm deep ablation channel is observed with a surrounding thin coagulation zone. Note the angle of the section missed the ablated epidermis. **b:** Six hours post-treatment biopsy reveals partial re-epithelization of the epidermis with significant inflammatory response within and surrounding the microchannel. **c:** At 12 hours post-treatment, the epidermis has completely re-epithelized and necrotic debris is observed at the skin surface.

with mostly trace and mild ratings for either of the two wavelengths. For the 2,940 nm treatments with 4 or greater passes, mild post-inflammatory erythema was present at 3 months post-treatment in 2 of 12 periorbital areas and in 2 of 7 periorbital areas (Tables 3a and 3b). For the 2,790 nm periorbital treatments, two of four tests with one to two passes had post-inflammatory erythema present at 1- and 3-month observations.

Although the immediate skin reactions increased in some cases from mild to moderate with increasing passes, the overall time course and speed of healing were similar. All treatment areas showed the presence of necrotic debris that sloughed off by day 4 revealing pinkish healthy skin. Other skin reactions included an instance of bruising under the eye and burning discomfort lasting for just over 12 hours. For the 39 treatment areas observed for at least 1 month, there were no incidents of hyper- or hypopigmentation. The remaining treatment areas were not available for observations after 1 week due to planned facelift procedures.

Clinical observations. For all areas treated with the fractional erbium laser, well-defined microbeam columns of ablation were evident immediately at the skin surface

that over the course of the next few days were replaced by necrotic debris. At the end of 1 week natural skin texture was restored. An example of the surface appearance of skin from the microbeam 2,940 nm fractional ablation using 5 mJ/µb at 2 milliseconds pulse width and the time course of healing are shown in Figure 8.

The time course of skin reactions and the healing from multi-pass treatment with the 2,940 nm handpiece are illustrated in Figure 9. The subject received periorbital treatment of four passes of 920 µb/cm² per pass, each at 5 mJ/µb at 5 milliseconds pulse width. The sequence of pictures was taken before, immediately after, and at 4, 7, and 14 days post-treatment. The oozing that is evident immediately after treatment resolved and necrotic tissue was replaced with a faint pink skin by day 4 (top right Fig. 9). Natural healthy skin tone and texture was fully restored by 1 week (bottom left Fig. 9). This subject's reactions are representative of the tested parameters and show a rapid healing and restoration of the skin consistent with the rapid re-epithelization observed in the biopsy time series.

Efficacy of treatments from 21 periorbital areas and 19 periorbital areas was examined at 3 months. Because

TABLE 2. Side Effects Observed Immediately After Treatment

Erbium fractional laser wavelength	Pulse width (milliseconds)	Bleeding or oozing	Edema	Lingering sensitivity
2,940 nm (<i>n</i> = 36)	0.25	100% mild	100% mild	8% mild
	2–5	52% mild	43% mild	28% mild
2,790 nm (<i>n</i> = 49)	2–5	None	None	20% mild, 4% moderate

TABLE 3a. Periorbital Wrinkle Reduction After Micro-Fractional Erbium Treatment

Handpiece	# Periorbital sites	Parameters, energy (mj/ μ b)	Passes		Erythema		Wrinkle reduction (two out of three graders using 0–9 scale)	
			Stacked	Total	% of test sites at 1 month	% of test sites at 3 months	% of test sites with score improvement ≥ 1	% of test sites with score improvement ≥ 2
2,790	4	8–9	0	1–2	50	50	50	0
2,940	5	3–6	0	1	0	0	60	20
2,940	8	3–6	0	4–6	38	12	88	38
2,940	4	5	2	6–8	75	25	100	50

TABLE 3b. Perioral Wrinkle Reduction After Micro-Fractional Erbium Treatment

Handpiece	# Perioral sites	Parameters, energy (mj/ μ b)	Passes		Erythema		Wrinkle reduction (two out of three graders using 0–9 scale)	
			Stacked	Total	% of test sites at 1 month	% of test sites at 3 months	% of test sites with score improvement ≥ 1	% of test sites with score improvement ≥ 2
2,790	6	6–9	0	1	0	0	16	0
2,940	6	5	0–2	2–3	16	0	33	0
2,940	7	5	1–2	4–6	29	29	57	57

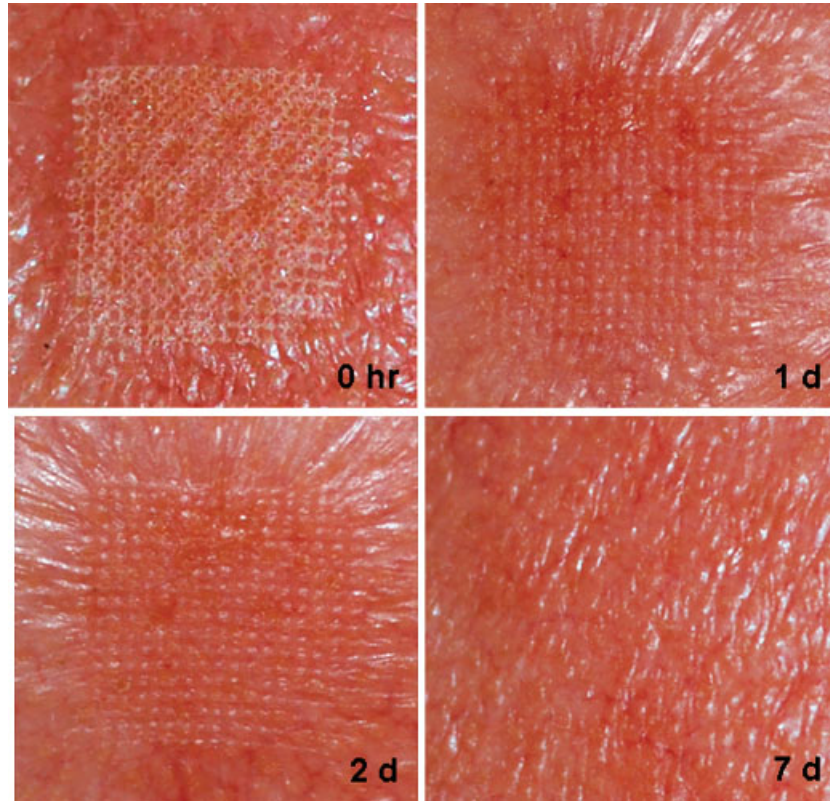


Fig. 8. Appearance of skin surface following fractional skin ablation from a single 5 mJ/ μ b, 2 milliseconds pulse of the 2,940 nm device at a density of 920 μ b/cm² shows rapid healing. By day 7 the skin surface is restored.

parameters were varied for each patient from side to side, left and right sides were evaluated as independent test sites. Results for the 2,790 and 2,940 nm handpieces summarized in Tables 3a and 3b include the percentage of tested areas having erythema at 1 and 3 months and the percentage of areas with wrinkle score reductions. The number of treated sites with at least two of the three graders giving a score reduction of one or more (2nd to last column) or two or more (last column) was divided by the total number of treatment sites to determine percentage.

A total of 12 periorbital sites were treated with four passes or more and over 90% had ≥ 1 score wrinkle reduction (0–9 scale) and 42% had ≥ 2 . The overall average reduction in the periorbital wrinkle score (post-pre) was statistically significant (*t*-test or Wilcoxon signed-rank statistic: -1.26 ± 1.11 , $n = 21$, $P < 0.0001$). The use of four or more passes resulted in an average reduction of 1.5, but with the addition of double-stacked pulses the average reduction increased to 2.4. Figure 10 shows before (top) and after (bottom) photos following a single 2,940 nm periorbital treatment of six passes at 5 mJ/ μ b, 5 milliseconds pulse width and density of 920 mb/cm² per pass. The left side received double-stacked pulses at two pulses per second for the first two passes and shows greater reduction in wrinkles, but mild post-inflammatory erythema at

3 months. Instances of erythema, a mild pink to slight red below the eye, were present at the 3-month observation in 2 of 17 cases with 2,940 nm treatments. Because erythema for the 2,790 nm treatments (see Table 3a) appeared to last longer, testing was subsequently focused on defining parameters for the 2,940 nm handpiece.

Substantial improvements in perioral wrinkles were observed with aggressive treatments. For the seven treatment sites receiving four or more passes over 50% had ≥ 2 score improvement. The overall average reduction in wrinkle score (post-pre) was statistically significant (*t*-test or Wilcoxon signed-rank statistic: -0.74 ± 1.43 , $n = 19$, $P < 0.05$). Those receiving four or more passes had an average reduction of 1.5 and for the four cases with improvements the average reduction was 2.7. Figure 11 shows before (top) and after (bottom) photos following a 2,940 nm perioral treatment at 5 mJ/ μ b, 5 milliseconds pulse width and density of 920 μ b/cm² per pass. The first pass on both sides was double-stacked at two pulses per second. The right side had an additional double-stacked pass and six passes total, while the left side had four total passes. The right side shows greater reduction in wrinkles, but mild post-inflammatory erythema at 3 months.

These clinical and histologic findings demonstrate the efficacy of micro-fractional ablative treatments in wrinkle

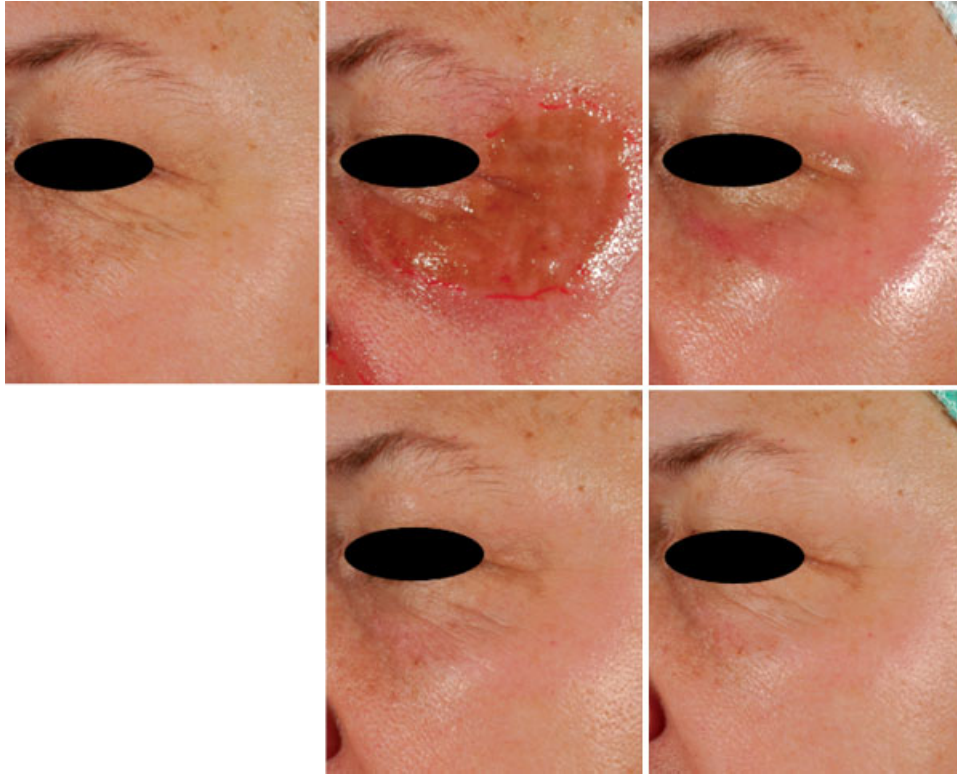


Fig. 9. The rapid healing from multi-pass treatment with the 2,940 nm handpiece is shown in the sequence of pictures. The **top row** from left to right shows the periorbital test area taken before, immediately after, and 4 days post-treatment. The **bottom row** shows the test area 7 and 14 days post-treatment. The subject received periorbital treatment of four passes of $920 \mu\text{b}/\text{cm}^2$ per pass, each at $5 \text{ mJ}/\mu\text{b}$ at 5 milliseconds pulse width. The oozing that is evident immediately after treatment resolved by day 2 and necrotic tissue was replaced with a faint pink skin by day 4. Natural healthy skin tone and texture was fully restored by 1 week.

reduction. In addition, this new approach is associated with mild side effects and reduced downtime compared to traditional ablative resurfacing methods.

DISCUSSION

The novel micro-fractional ablative device investigated in this study provides a wide range of new capabilities for skin rejuvenation. The depth and width of the ablated microcolumns and extent of surrounding coagulation can be varied and used to design procedures targeted for specific indications and areas. With a user selectable optic of $920 \mu\text{b}/\text{cm}^2$, both erbium lasers caused similar ablative damage profiles with diameters for single-pulse mode ranging from 60 to $100 \mu\text{m}$ and ablation depths from 20 to $250 \mu\text{m}$ at energy settings up to $5 \text{ mJ}/\mu\text{b}$. Stacked pulses provided even deeper columns as compared to respective single pulses. Coagulation zones around the ablated microcolumns varied in thickness from 5 to $25 \mu\text{m}$ and depended upon pulse width and wavelength (Figs. 3–6). At equivalent settings, the 2,790 nm wavelength handpiece generated somewhat greater thermal damage than the 2,940 nm handpiece. Traditional erbium ablation has

very minimal zones of thermal injury due to the combination of high water absorption and short-pulse mode. One novel feature of the 2,940 nm system is its ability to provide smooth, long (millisecond range) pulses. This feature, combined with the micro-fractional delivery configuration, produced relatively large consistent zones of coagulation surrounding the ablative microcolumns. Because the 2,940 nm handpiece could provide both ablative (short-pulse) and ablative plus coagulative (long-pulse) modes of micro-fractional treatments, efforts were subsequently focused on evaluating the 2,940 nm handpiece to define safety limits and optimum treatment parameters for further clinical investigations.

The treatment tests with single-pass parameters clearly demonstrate the safety and rapid healing of the micro-fractional ablative approach. Histologic findings confirm that the epidermis undergoes a rapid re-epithelization (<24 hours) following micro-ablative ablation at settings of $9\text{--}12 \text{ mJ}/\mu\text{b}$ (Fig. 7, histology from 2,790 not shown). Based upon the observed ablative column diameters of $75\text{--}100 \mu\text{m}$, approximately 4–5% of the skin surface is ablated in each pass when using an optical tip with a $920 \mu\text{b}/\text{cm}^2$ density. With multiple passes, however, there is an



Fig. 10. Before (**top**) and 3-month post-treatment photos (**bottom**) following a single 2,940 nm periorbital treatment of six passes at 5 mJ/ μ b, 5 milliseconds pulse width and density of 920 μ b/cm² per pass. The left side received double stacked pulses at two pulses per second for the first two passes and shows greater reduction in wrinkles, but mild post-inflammatory erythema.



Fig. 11. Before (**top**) and 3-month post-treatment photos (**bottom**) following a single 2,940 nm perioral treatment at 5 mJ/ μ b, 5 milliseconds pulse width and density of 920 μ b/cm² per pass. The first pass on both sides was double stacked at two pulses per second. The right side had an additional double stacked pass and six passes total, while the left side had a total of four passes. The right side shows greater reduction in wrinkles, but mild post-inflammatory erythema.

accumulating effect on the skin and an increasing probability that micro-columns will merge or overlap enlarging the zones of thermal injury ultimately extending the healing time. If the density is great enough, the injury is, in essence, a full-ablative procedure. A series of clinical tests were performed, therefore, varying density from 1 to 8 passes at periorbital and perioral areas to determine the skin tolerance and efficacy following a single ablative treatment that involves 5–40% of the skin.

The advantages of the fractional approach were confirmed by the mild to moderate skin reactions and rapid healing after treatments. Subjects could apply make-up and moisturizers after 4 days with only mild lingering erythema that generally resolved in 1 month. While not quantified in this study, UV-induced pigment irregularities were also noticeably reduced after treatment. At 3 months there is no evidence of scarring or long-term dyspigmentation. For the periorbital and perioral tested areas wrinkle reduction tended to improve with increasing number of passes and stacking of pulses. For periorbital treatments of four passes or more over 90% had ≥ 1 score wrinkle reduction (0–9 scale) and 42% had ≥ 2 . For perioral wrinkles over 50% had substantial improvements (≥ 2). For some subjects the reduction in wrinkles was substantial and similar to the improvement observed in full-ablative procedures. Because of the large subject-to-subject variability, however, a side-by-side comparative study would be required before drawing conclusions regarding efficacy relative to traditional full-surface ablative skin resurfacing.

In conclusion, micro-fractional ablative treatment with 2,790 and 2,940 nm erbium lasers resulted in the safe and effective reduction in mild to moderate rhytides. In comparison to full-surface ablative skin resurfacing there is very rapid re-epithelization, limited adverse side effects and reduced subject downtime to 4 days or less.

The size, density, and damage profile of the fractional zones that maximize efficacy with minimal downtime and high margin of safety are not known. The size and density of the individual fractional zones as recently reported [20–24] show a significant influence on the healing time, potential for adverse effects and overall response. With the erbium micro-fractional handpiece many combinations of depths, density, and patterns of damage are possible thus making it a useful tool in the arsenal of laser methods available to achieve the ultimate goal of consistent and substantial efficacy for severe rhytides with reduced down-time and high safety margins.

ACKNOWLEDGMENTS

Equipment and research grant from Palomar Medical (CCD, KAK).

REFERENCES

- Ross EV, Miller C, Meehan K, McKinlay J, Sajben P, Trafeli JP, Barnette DJ. One-pass CO₂ versus multiple-pass Er:YAG laser resurfacing in the treatment of rhytides: A comparison side-by-side study of pulsed CO₂ and Er:YAG lasers. *Dermatol Surg* 2001;27(8):709–715.
- Manuskiatti W, Fitzpatrick RE, Goldman MP. Long-term effectiveness and side effects of carbon dioxide laser resurfacing for photoaged facial skin. *J Am Acad Dermatol* 1999; 40(3):401–411.
- Fitzpatrick RE, Goldman MP, Satur NM, Tope WD. Pulsed carbon dioxide laser resurfacing of photo-aged facial skin. *Arch Dermatol* 1996;132(4):395–402.
- Zachary CB. Modulating the Er:YAG laser. *Lasers Surg Med* 2000;26(2):223–226.
- Ratner D, Tse Y, Marchell N, Goldman MP, Fitzpatrick RE, Fader DJ. Cutaneous laser resurfacing. *J Am Acad Dermatol* 1999;41(3):365–389.
- Horton S, Alster TS. Preoperative and postoperative considerations for carbon dioxide laser resurfacing. *Cutis* 1999; 64(6):399–406.
- Sripachya-Anunt S, Fitzpatrick RE, Goldman MP, Smith SR. Infections complicating pulsed carbon dioxide laser resurfacing for photoaged facial skin. *Dermatol Surg* 1997; 23(7):527–536.
- Schwartz RJ, Burns AJ, Rohrich RJ, Barton FE, Byrd HS. Long-term assessment of CO₂ facial laser resurfacing: Aesthetic results and complications. *Plast Reconstr Surg* 1999;103(2):592–601.
- Nanni CA, Alster TS. Complications of carbon dioxide laser resurfacing. An evaluation of 500 subjects. *Dermatol Surg* 1998;24(3):315–320.
- Narurkar VA. Skin rejuvenation with microthermal fractional photothermolysis. *Dermatol Ther* 2007;20(Suppl 1): S10–S13.
- Rostan EF. Laser treatment of photodamaged skin. *Facial Plast Surg* 2005;21(2):99–109.
- Hasegawa T, Matsukura T, Mizuno Y, Suga Y, Ogawa H, Ikeda S. Clinical trial of a laser device called fractional photothermolysis system for acne scars. *J Dermatol* 2006;33(9):623–627.
- Weiss RA, Gold M, Bene N, Biron JA, Munavalli G, Weiss M, Beasley K. Prospective clinical evaluation of 1440-nm laser delivered by microarray for treatment of photoaging and scars. *J Drugs Dermatol* 2006;5(8):740–744.
- Glaich AS, Rahman Z, Goldberg LH, Friedman PM. Fractional resurfacing for the treatment of hypopigmented scars: A pilot study. *Dermatol Surg* 2007;33(3): 289–294.
- Rokhsar CK, Fitzpatrick RE. The treatment of melasma with fractional photothermolysis: A pilot study. *Dermatol Surg* 2005;31(12):1645–1650.
- Tannous ZS, Astner S. Utilizing fractional resurfacing in the treatment of therapy-resistant melasma. *J Cosm Laser Ther* 2005;7(1):39–43.
- Geromenus RG. Fractional photothermolysis: Current and future applications. *Lasers Surg Med* 2006;38(3):169–176.
- Fisher GH, Geronemus RG. Short-term side effects of fractional photothermolysis. *Dermatol Surg* 2005;31(9 Pt 2): 1245–1249.
- Manstein D, Herron GS, Sink RK, Tanner H, Anderson RR. Fractional photothermolysis: A new concept for cutaneous remodeling using microscopic patterns of thermal injury. *Lasers Surg Med* 2004;34(5):426–438.
- Hantash BM, Bedi VP, Chan KF, Zachary CB. Ex vivo histological characterization of a novel ablative fractional resurfacing device. *Lasers Surg Med* 2007;39(2):87–95.
- Hantash BM, Bedi VP, Kapadia B, Rahman Z, Jiang K, Tanner H, Chan KF, Zachary CB. In vivo histological evaluation of a novel ablative fractional resurfacing device. *Lasers Surg Med* 2007;39(2):96–107.
- Weiss RA, Weiss MA, Beasley KI. Prospective clinical trial of a fixed spacing array computer scanned fractional CO₂ laser for rhytids. *Laser Surg Med* 2007;S19:49.
- Rahman Z, Tanner H, Tournas J, Jiang K, Kelly K, Berkowitz L, Zachary C. Ablative fractional resurfacing for the treatment of photodamage and skin laxity. *Laser Surg Med* 2007;S19:45.
- Levy JL, Fournier N, Mordon S. CO₂ fractional resurfacing combined with aircooling: Histologic investigation and optimal parameters determination. *Laser Surg Med* 2007; S19:51.