

Ablative Fractional Resurfacing for the Treatment of Traumatic Scars and Contractures

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After a decade of military conflict, thousands of wounded warriors have suffered debilitating and cosmetically disfiguring scars and scar contractures. Clearly, there is a need for effective scar treatment regimens to assist in the functional and cosmetic rehabilitation of these patients. Traditional treatments, including aggressive physical and occupational therapy and dedicated wound care, are essential. Adjunctive treatments with established laser technologies, such as vascular lasers and full-field ablative lasers, have had a somewhat limited role in scar contractures due to modest efficacy and/or an unacceptable side effect profile in compromised skin. Refractory scar contractures often require surgical revision, which can be effective, but is associated with additional surgical morbidity and a significant risk of recurrence. Furthermore, current scar treatment paradigms often dictate scar maturation for approximately a year to allow for spontaneous improvement before surgical intervention. Since 2009, the Dermatology Clinic at the Naval Medical Center San Diego has been treating scars and scar contractures in wounded warriors and others using ablative fractionated laser technology. Although traditionally associated with the rejuvenation of aged and photo-damaged skin, our clinical experience and a handful of early reports indicate that laser ablative fractional resurfacing demonstrates promising efficacy and an excellent side effect profile when applied to the functional and cosmetic enhancement of traumatic scars and contractures. This article discusses our clinical experience with ablative fractional resurfacing and its potential prominent role in rehabilitation from traumatic injuries, including a possible shift in scar treatment paradigms toward earlier procedural intervention. Potential benefits include the optimization of scar trajectory and higher levels of full or adapted function in a more favorable time course.

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It is estimated that each year in the United States, at least 10,000 children are burned, and 650,000 people sustain burns that require medical intervention. It is further estimated that as many as 22 million people currently live in the United States with permanent disabilities from cutaneous

burns that are either close to or have reached maximal benefit from traditional burn scar rehabilitation and surgical revision.¹ After a decade of military conflict, thousands of wounded warriors have suffered debilitating and cosmetically disfiguring scars and scar contractures. Clearly, there is a need for effective scar treatment regimens to assist in the functional and cosmetic rehabilitation of these patients. Traditional treatments, including aggressive physical and occupational therapy and dedicated wound care, are essential. Adjunctive treatments with established laser technologies, such as vascular lasers and full-field ablative lasers, have had a somewhat limited role in the treatment of scar contractures due to modest efficacy and/or an unacceptable side effect profile in compromised skin. Refractory contractures often require surgical revision, which can be effective but is associated with additional surgical morbidity and a significant risk of recurrence. Furthermore, current scar treatment par-

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adigms often dictate scar maturation for approximately a year to allow for spontaneous improvement before surgical intervention.²⁻⁴

Since 2009, the Dermatology Clinic at the Naval Medical Center San Diego has been treating scars and scar contractures in wounded warriors and others using ablative fractionated laser technology. Although traditionally associated with the rejuvenation of aged and photo-damaged skin, our clinical experience and a handful of early reports indicate that laser ablative fractional resurfacing (AFR) demonstrates promising efficacy and an excellent side effect profile when applied to the functional and cosmetic enhancement of traumatic scars and contractures.⁵⁻⁹ Herein, we discuss our clinical experience with AFR and its potential prominent role in rehabilitation from traumatic injuries, including a possible shift in scar treatment paradigms toward earlier procedural intervention. Potential benefits include the optimization of scar trajectory and higher levels of full or adapted function in a more favorable time course. A detailed discussion of scar pathophysiology is beyond the scope of this manuscript. However, paramount to the safe application of this potentially high-risk procedure is an understanding of fractionated laser-tissue interactions (LTIs).

Ablative Fractional LTIs

Ablative fractional LTIs differ from traditional confluent wounds. In those injuries, ablation and heating events can be modeled in a planar 1 dimensional geometry. Conservation of energy, as in all LTIs, applies to the ablation and heat components in so-called “macrofractional” wounds, that is, those wounds where the beam diameter exceeds 500 μm , and the depths are <200 μm . In these wounds, so long as the instantaneous power densities permit ablation speeds that exceed the rate of heat diffusion, minimal residual thermal damage (RTD) will be observed. In “microspot” fractional wounds, the most common type applied in burn scar management, the spot diameters (<500 μm) are small enough that high fluences are created. The subsequent ablation dynamics are more complicated and possibly involve nonlinear processes, plume interactions, and variable RTD along the perimeters of the normally cylindrical wounds. Despite the complexities of LTI under these conditions, one does not have to understand the details from first principles to have an intuitive feel for how fractional lasers affect the skin. In contrast, a fundamental understanding on a nonmathematical level will better equip the operator to optimize settings with this expensive equipment. From the *Journal of the Society of Mechanical Engineers* 1994, Vossen Menoogole, shows an equation that describes the concept of temperature changes in ablation. When one applies ablative lasers under normal conditions, wavelengths ranging from 2.7-3 μm to 10.6 μm will ablate (vaporize) tissue.^{10,11} Nonablative lasers will not remove tissue. Basically, when one irradiates the surface, the interaction with tissue establishes 2 “fronts,” one comprised ablation and the other heating. Imagine 2 race horses that are next to each other. One is the ablation front and represents how fast you are removing tissue ($\Delta X/\Delta t$). This rate is

large with efficient ablative systems with high-power densities (so called char-free ablation). At the end of that front you have a heating front (the speed of the thermal wave), which is based on the local temperature gradient and the thermal properties of the tissue. As long as the ablation front “outpaces” the heating front, you will have little RTD (the lower limit being the optical penetration depth in tissue of the respective laser wavelength). When one applies low powers, almost counterintuitively, the heating front starts to outpace the ablation front, and there is more RTD. With high-power densities, one achieves efficient ablation with little thermal damage. For example, a continuous wave CO₂ laser with a 2-mm spot applied to the skin at 3 W will generate surface heating and little ablation. In contrast, at 20-30 W, a crater will evolve with much less thermal damage.¹²

The mathematical models that characterize these LTIs can become complicated. However, by making some approximations, one can eschew differential equations and apply some “back of the envelope” algebraic calculations whose results are consistent with common sense experiments and real-life observations related to heating (ie, cooking an egg or ironing a shirt, or inadvertently touching a hot stove). An understanding of LTIs relies partly on an intimate knowledge of the absorption spectra of the 3 most important skin chromophores (hemoglobin, water, and melanin). Just as a cardiologist appraises an electrocardiography (ECG) or a neurologist examines an electroencephalogram (EEG), one should memorize the skin spectra, where wavelength is on the X axis, and the relative absorption of the respective chromophore is on the Y axis. The key chromophore in ablative LTIs is water. Water absorption is negligible at <950 nm. Between 1 and 10.6 μm , there are multiple peaks and valleys.

Collagen, as a direct chromophore, has been reported but no one has applied the respective wavelengths on a practical level.¹³ The 2 major ablative wavelengths in use are at 10.6 and 3 μm . The nonablative laser wavelengths range from 1.3 to 2 μm . They are nonablative because the absorption coefficient for water is lower and therefore heating exceeds ablation. One drawback with conventional CO₂ resurfacing lasers was the risk of side effects. Striping, melasma, hypertrophic scars, and lines of demarcation were seen when inappropriate thermal damage and haphazard application of the beams occurred. We now use fractional technology to improve these side effects. Lines of demarcation are created when patients lose their pigmentation and their skin color becomes the same as that of their sun-protected areas. In contrast to conventional full-field resurfacing, fractional technologies typically do not cause hypopigmentation in the absence of overtreatment and scarring. The fractional concept originated many years ago and was formalized about 6 years ago. But, in the early 1980s, a plastic surgeon, Dr David Apfelberg, was pinholing scars with a conventional CO₂ laser and a 0.2-mm spot without a scanner. However, his approach was not practical over larger scars and was too operator dependent. “Needling” of scars and tattoos has been reported for many years.¹⁴ Technological improvements in scanners and electronic modulation of lasers allow for practical reproducible fractional applications. Within the fractional arena, there are

different fractional geometries. There are macro-spot fractional devices where the beam is bigger than a millimeter. With these spot sizes, the penetration depth is small. These create a “lily pad on a pond” type of injury that is relatively broad but not very deep. With microspot injuries, there are deep and narrow injuries with a depth:width ratio greater than 1. This is the key type of injury that we apply in scar tissue treatments.

Hantash et al^{15,16} examined the histology of the fractional CO₂ laser both ex vivo and in vivo. With their system, a 120- μm spot beam creates shrinkage of the tissue that is noticed while treating the patient. The pattern of the RTD was consistent over multiple specimens and showed greater RTD at the base of the cylindrical crater than the sides (about 50 μm at the sides and up to 200 μm at the base). The group’s ex vivo work showed ablation depths of about 20-30 $\mu\text{m}/\text{mJ}$ and an additional 200 μm of RTD at the wound base. The immediate collagen denaturation is associated with collagen shrinkage and instantaneous wound contraction. There is controversy about what role that initial collagen shrinkage plays in the wound-healing cascade. Most physicians agree that heating does produce more collagen than a purely ablative wound. In other words, heating probably produces more collagen per unit volumetric injury than an incisional injuries created by a needle or a knife. A surgeon, Dr M. Anthony Pogrel,¹⁷ did a study in 1981 where he created incisional wounds with a scalpel and with a tightly focused (a 0.2-mm spot) CO₂ laser. He showed more hyaluronidase production in the CO₂ versus the scalpel wounds 12 days after injury. Thus, at least for incisional wounds, a wound with collateral thermal injury increases hyaluronidase, which might act as an agent for enhanced neovascularization.

The types of wounds created with a pulsed, microspot, fractional laser can be very deep with larger pulse energies. There is a somewhat linear relationship between the pulse energy and the depth of penetration. There is also a zone of thermal damage. However, there are different ways to “skin a cat.” Numerous technologies deliver the same type of microspot fractional wounds, so long as the density does not exceed a critical threshold, is that they heal quickly. Nonfractional wounds take up to 2 weeks to heal, depending on the depth of wound and the degree of RTD. In contrast with a pulsed fractional CO₂-induced healing cascade where at 48 hours, the wound has already filled in.¹⁵ Then, there is a progression from inflammation to fibrosis. Histologically, you see a “tornado” of fibrosis 3 months after treatment. Again, this is different from the small zone of fibrosis that you get with a conventional wound where one observes a linear band of fibrosis similar to that after shave biopsy. The question remains, how does the skin heal aesthetically and functionally with focal zones of fibrosis, covering only a fraction of the skin’s surface area versus a parallel zone of fibrosis over the entire surface of the skin with lesser depths? Research does support that fractional injury produces less hypopigmentation and a lower risk of infection than its nonfractional counterparts.

There are numerous commercially available fractional devices, whose sheer number does not allow any one provider

to use every device. Each machine has advantages and drawbacks. Different laser companies use variable terminologies, beam diameters, pulse durations, and handpiece types. Some lasers display density or percent coverage. Others use the “pitch” between adjacent spots. Given the same microspot size, shorter pulses will create deeper craters and less RTD. The Lumenis Deep FX CO₂ will create narrow deep wounds with a thin zone of thermal damage. Fraxel re:pair wounds tend to have slightly more thermal damage because the pulse durations are longer. Thermal damage is a 2-edged sword. The advantage of thermal damage is better hemostasis. The disadvantage of thermal damage is that it impedes wound healing. One company has modeled the way tissue responds to fractional CO₂ wounds as a function of pulse width. If you create holes with a laser and put the same amount of energy in and you deliver it for a longer period, the ratio of ablation to coagulation increases. Because there are many different combinations of pulse width, wound depth, microspot size, density, there is no consensus on what parameters are optimal in scar management. Whether for scars or for wrinkles, physicians are using settings that work based on their cumulative patient experiences.

The physics of the initial laser injury creation is much simpler than the complex cascade of wound-healing events. That sequence is variable depending on the patient, particular anatomical region, as well as the lesion pathology. Given the large number of variables and the sheer workload and cost of well-controlled studies, it is likely that small stepwise changes in protocols and observations of the impact of those changes in actual patients will continue to play a role in parameter optimization. Wound “shrinkage” with the fractional CO₂ laser occurs during the pulse, or as Christopher Zachary, MD, FRCP, refers to as “dermal plumping.” Intuitively, one might expect that drilling deep CO₂ holes in scars should create more heat and more scars. One site reported worsening of some scars with fractional CO₂.¹⁸ Although 95% of the time, when used properly, these devices probably will make things better, but caution is again urged when doing this work. When a pulsed CO₂ laser creates a crater, there is an initial fast rise in temperature followed by a slower cooling period. The immediate cooling period is fast. The temperature degradation from the peak temperature to about 30% of that peak temperature is fast—on a time scale of quarters of a second or even less. But the time for complete cooling around that crater can be many seconds. This is important when using multiple passes where bulk heating can be a serious problem because the injuries are no longer independent of one another. Therefore, when performing multiple fractional passes a 5-to-10-second interval will allow for cooling between passes.

The erbium and CO₂ lasers have respective advantages and drawbacks. The biggest advantage of Er:YAG laser is decreased analgesia requirement versus CO₂ lasers for same depths and densities of injuries. One disadvantage is a greater risk of hemorrhage related to a lack of thermal damage. One can try to increase lateral thermal damage in the Er:YAG case, but because of the high-power densities and small ablation threshold (0.1 J/cm² vs 3-5 J/cm² in the CO₂ case)^{19,20} applied

in AFR, longer pulse durations do not extend the RTD as much as in the CO₂ case.²¹ Ideally, a CO₂ laser with a short pulse duration or an Er:YAG with a longer pulse duration are best configured for deeper microwounds with sufficient but not excessive RTD. However, total hemostasis is unlikely with the deep fractional wounds used in burn scar treatment. Using the ER:YAG in a porcine model, we attempted to determine whether alterations in pulse duration with fractional and nonfractional wounds could create better hemostasis and a little more thermal damage, thus combining the best attributes of Er:YAG laser (fast wound healing, less pain) with the advantages of CO₂ (better hemostasis and sufficient thermal damage to enhance the wound-healing response). However, when we applied the fractional Er:YAG with a range of pulse energies and pulse durations (0.5-32 ms), we observed neither differences in the gross wounds nor any significant changes in lateral thermal damage over the pulse duration range.

In contrast, the Sciton Er:YAG graphic user interface depth settings correlated well with the histologically measured penetration depths. However, when the coagulation settings were changed by extending the pulse duration, there was no histologic difference in coagulation or ablation observed. The absence of variability in thermal damage with the fractional Er:YAG is not surprising because when working with these high-power densities with the high absorption coefficient for water at 2940 nm, the ablation is so efficient that little RTD occurs. Another option is to use other patterns rather than microspots, such as the “groove” optic on an Er:YAG (Palomar, StarLux). This device creates a grid-like pattern over the skin, but as long as the energies do not penetrate too deep, the handpiece achieves a high degree of surface coverage per pass, little RTD, and rapid healing. Like all fractional devices, there is a risk of imprinting if the ablation is carried out too deep and wide. The groove is a unique type of wound geometry. For scars, this wound type might be optimal, as one would expect the scar would have a greater range of motion (ROM), much like cutting groves in an eraser with a knife will allow the eraser to bend better. The “groove” erbium wounds create little thermal damage and will therefore bleed when you reach the dermis with pulse stacking.

Nonablative lasers may be better for some patients because of the absence of bleeding. A nonablative wound has no true “hole” but rather a cylindrical zone of coagulation. The advantage of nonablative technology is the reduction of downtime. One technique to enhance nonablative fractional resurfacing (NAFR) is the point compression approach. In this configuration, the handpiece pushes multiple points of sapphire on the skin, compressing the dermis, and allowing the beam to propagate deeper than without compression. By compressing the tip, water is displaced and, based on index of refraction arguments, the beam is able to reach 1.5-2 mm into the skin.²²

The concept of combining ablative and nonablative devices has been explored. The goal is to mimic the enhanced results of ablative wound results but preserving the low recovery time for the nonablative system. In a sense, each CO₂ crater represents a “combination” wound consisting of the

ablation crater and a peripheral zone of RTD. We can generate a similar effect by sequentially delivering purely coagulative 1540 nm wounds followed by almost purely ablative Er:YAG craters in the same session.

There are pitfalls with every fractional device. A major drawback is the lack of a clinical end point. Some complications with fractional devices occur because of the “treat by recipe” nature of the treatment. In some cases, providers either overestimate the skin’s tolerance or underestimate the depth or density of injury, especially in thinned skin areas like the neck or a nascent scar. We have observed blisters due to excessive depth and densities with both AFR and NAFR. Furthermore, with stamping technologies, bulk heating can occur from inadequate intervals between overlapping “stamps.” With scanning/rolling types of handpieces, scans can be applied quickly in a back-and-forth motion. The drawback with all fractional devices is that no matter how many passes are applied one will not achieve 100% coverage. In the case of pigment dyschromias, the result is often incomplete pigment clearance. If the pigment appears markedly improved, the “honeymoon” period endures for 2 to 4 months after which there is a rapid relapse.

The concept of power as it relates to fractional devices is sometimes confusing. Many CO₂ lasers display power and pulse duration on the graphic user interface; the power usually represents the average power and not necessarily the instantaneous power or peak power. Some devices display the pulse energy per microbeam, and the pulse duration is not displayed. For example, the DEKA Smart DOT laser, the display might read 25 W and 800 μ s. In this configuration, the peak power is 5-8 \times the average power, but the bulk of the energy is delivered in the initial portion of the pulse, leaving a tail in the pulse profile. Less average power means you will have a longer treatment session time. A longer pulse width with a CO₂ laser normally creates more RTD. However, no study has shown where, for example, a 20- μ s pulse is preferable to a 1-ms pulse with other like pulse characteristics. This author studied short pulses of CO₂ at 0.25 and 10 ms. There was more charring with a pulse that is 40 \times longer. Most of the CO₂ lasers available presently have shorter pulse durations and result in little clinically evident char.

Another unknown in fractional resurfacing is the optimal shape. Is a cylinder the best shape? Regardless of shape, fractional “craters” rely on a large surface-to-volume ratio for rapid healing. Despite movies from the 1950s, an amoeba the size of a room cannot survive because the surface-to-volume ratio is too low for it to be able to get sufficient nutrition and oxygen. This logic explains the need for alveoli in our lungs. Likewise, with a large laser-induced hole, the surface-to-volume ratio is less, the wound healing is delayed, and scarring and imprinting is more likely. If one examines various shapes, a narrow cylinder provides the best ratio. But for any geometry—whether a cube or a cylinder or other shape—as length increases the surface-to-volume ratio decreases.

In terms of LTIs and the treatment of scars with fractional lasers, there are still a number of unanswered questions. Is

there a role for pure NAFR or is ablation a necessary condition for meaningful scar reduction? Multiple reports support a role for NAFR in scar improvement. Given the decrease in short-term morbidity, a side-by-side trial on scars with similar morphologies comparing NAFR and AFR would be useful. If one compares 2 wounds that have the same total volume of damaged cells but one is ablative and the other is nonablative, they heal differently. The ablative wound heals more slowly, possibly with a better cosmetic outcome, but with more downtime. Jeff Orringer in Michigan has done extensive research with biochemical markers to define collagen deposition for different wound sizes and different wound types. He feels that there is probably a 3:1 ratio of new collagen deposition when comparing the ablative wound with the nonablative wound with the same geometry. Thus, there is probably more "bang for the buck" per unit energy for ablative fractional compared with nonablative fractional lasers.

Ablative Fractional Treatment Protocol and Rationale

Background

The apparent safety and efficacy of AFR in the functional and cosmetic enhancement of traumatic scars and contractures observed by the authors over hundreds of treatments have yet to be confirmed in the course of controlled trials. Furthermore, optimal parameters such as time after injury; treatment interval; wavelength; ratio of ablation to coagulation; adjunctive treatments, such as steroids; and laser settings have yet to be defined. What follows is an overview of the general technique and rationale used by the authors in a population frequently characterized by devastating explosive injuries, resulting in significant functional limitations. However, the fundamental technique is applicable in a wide range of clinical situations, both military and civilian.

A signed consent and thorough discussion of the procedure is the priority. This must include medical and ocular risks, potential benefits and expected side effects, limitations of the procedure, and other options. This procedure does carry inherent risks, and reports of worsening scarring and new scarring in the setting of cosmetic applications for AFR exist in the literature.^{18,23-25} The goals of the procedure must be clearly defined, as scars cannot be removed but only improved. A team approach is vital, as AFR should not generally be considered a monotherapy for traumatic scars. Physical and occupational therapy should be ongoing throughout the course of treatment to optimize scar remodeling and functional enhancement. Surgical revision may still be required, although AFR appears to have a significant role in optimizing results after surgical intervention, to limit the extent of future surgery, or to increase the quality of skin in the field before surgery. To the extent that cutaneous scarring is responsible for the patient's functional limitations, a course of AFR may be beneficial. However, a therapeutic ceiling may exist depending on concurrent injuries, such as nerve damage, un-

derlying muscle and tendon deficits, heterotopic ossification, and damage to adjacent joints.

At the initial preoperative visit, a thorough history and physical examination should be performed. Pertinent information includes the time and mechanism of injury, complications, current symptoms and limitations in daily activities, anticipated upcoming procedures, and response to ongoing therapy. Scar characteristics, such as erythema, degree of healing, pliability, texture, dyspigmentation, thickness, and degree of contracture, should be noted, as they are the primary determinants of fractional laser treatment parameters. They also dictate the need for any adjunctive scar treatments such as corticosteroids and vascular lasers. Evidence of prior reconstructive procedures, such as skin grafts (partial thickness, full thickness) and composite flaps, should be noted. Other important features include the proximity of the scar to joints and free edges (eyelids, lips), the relationship to topographic features, such as convexities and concavities, and any future association with prosthetic devices. Baseline and periodic photos and ROM measurements should be obtained to document progress. This includes both active and passive ROM, and possibly the use of objective measuring tools, such as a goniometer. Pinch testing of the scar for a rough determination of pliability and scar thickness is central in determining settings and goals. Although beyond the scope of this manuscript, adjunctive procedures such as laser hair reduction and Q-switched laser treatment of traumatic tattoos are frequently integrated into the treatment plan depending on the related circumstances.

Also critical, but not necessarily as obvious to the provider, include any ongoing issues related to the traumatic event, such as post-traumatic stress, traumatic brain injury, or pain syndromes. These factors will weigh heavily on downstream treatment decisions, such as method of pain control. Although the majority of AFR treatments occur in the clinic after topical or injected local anesthesia alone, conscious sedation or even general anesthesia may be pursued in the setting of significant procedure fatigue or post-traumatic stress. Even without a high level of patient sensitivity, the provider should still attempt to mitigate the varied sensory inputs associated with the procedure that may mimic events surrounding the traumatic injury. These include the loud noises, burning smell, and the sensation of heat.

AFR treatments are custom designed for each patient at every treatment opportunity. Although actual settings will vary based on the device used, the primary determinant of treatment depth is the thickness and degree of contracture of the scar. Given the practical limits in penetration depth of current ablative fractional devices, up to approximately 2 mm of total thermal injury according to manufacturer charts, an estimation of scar thickness through palpation is probably sufficient in most cases without resorting to ultrasound or other more precise methods outside of research settings. Multiple ablative fractional laser platforms exist at present, and optimal treatment parameters have yet to be defined. In the opinion of the authors, a degree of coagulation is likely important to induce optimal remodeling. However, safe ap-

plication of the technique requires avoidance of excessive thermal injury to help prevent worsening scarring.

Laser Settings and Technique

Pain control during AFR is frequently not as difficult as it may initially appear. Grafted and traumatized sites are often insensate or have reduced sensation. In these cases, pain is mostly limited to the border of normal skin surrounding the traumatic scar. In the majority of cases, preoperative anesthesia is achieved with commercially available topical anesthetic preparations applied under occlusion for 1 hour or more before treatment. Focal hyperesthetic areas can be anesthetized with injectable local anesthetics. These measures are often supplemented during treatment by parallel cooling with a forced chilled-air device (Zimmer Cryo, Zimmer MedizinSystems, Irvine, CA). Some may require systemic preoperative analgesics or anxiolytics, but in the experience of the authors, this is a minority of patients. For cases involving large surface areas or if the patient exhibits poor tolerance of the procedure while awake, conscious sedation or general anesthesia can be used.

With the previous discussion on LTIs in mind, treatment technique and laser parameters should be selected to limit the degree of bulk heating. Important general fractional laser characteristics likely include a relatively short pulse width approximating the thermal relaxation time of tissue (1 ms or less) and a relatively narrow beam diameter (<500 μm) to limit excessive collateral thermal damage and healing issues in compromised skin. The platform most commonly used currently for AFR by the authors for the treatment of traumatic scars and contractures is a fractionated CO₂ laser (Ultrapulse Encore, DeepFX, Lumenis Ltd, Yokneam, Israel). The selected pulse energy generally varies from 15 to 50 mJ and is proportional to the scar thickness and desired treatment depth. Scar treatments are most often performed with a single pulse, in a single pass, without overlap. The higher pulse energies that accompany the treatment of thickened scar contractures require a concomitant reduction in treatment density. In the opinion of the authors, low-density fractional treatment is vital to reducing the risk of complications when treating scars, and an early report by Lin et al.²⁶ hints that it may also prove to be more effective. In most cases, contractures are treated at the lowest density setting of 5%. Isolated textural and pigment changes or atrophic scars are often treated with somewhat lower pulse energies and higher densities, although even in these situations, the selected density rarely exceeds 15% per pass. The treatment area includes the entire scar sheet and a 1 mm to 2 mm rim of normal skin. Treatments are initiated as early as approximately 2 months after injury or final reconstructive surgery, but AFR appears to have benefits for scars of virtually any age after this point. The treatment interval is generally 1 to 2 months, and treatments may be continued until therapeutic goals are achieved or a plateau in improvement occurs.

Postprocedure care includes several times daily application of petrolatum- or petrolatum-based ointment with

nonstick dressings applied for convenience depending on the location. Patients may resume showering the following day and begin gentle daily cleansing of the area. Diluted vinegar compresses are often initiated several times daily in off-face locations. This regimen is continued until the site is fully epithelialized, usually within 3 to 4 days of treatment. Patients may resume physical therapy and essentially normal activity immediately, although full immersion, such as in a pool or the ocean, is not recommended until the treatment area is fully healed. Basic contact and hygiene precautions are followed, as with any cutaneous surgical procedure. Pre- and postoperative topical or oral antibiotics are not used under routine circumstances, although they may certainly be entertained in higher-risk situations. Likewise, when treating the face, viral prophylaxis should be considered.

Adjunctive Treatments

The emergence of AFR does not obviate the need for other established scar treatments, such as vascular lasers (long pulsed 532 nm [potassium-titanyl-phosphate (KTP)] or 595 nm [pulsed dye laser (PDL)]) or steroids, such as triamcinolone acetonide suspension (TAC), particularly for the erythematous, hypertrophic scars seen frequently in the first year after injury and beyond. Two recent reviews highlight the successful use of PDL for hypertrophic scars.^{27,28} Vascular laser settings are detailed elsewhere, but in the practice of the authors, a vascular laser is often combined with intralesional TAC in alternating sessions with AFR. A PDL or KTP treatment can also be applied concurrently with AFR safely, but the use of high concentrations of intralesional TAC and AFR in the same treatment session is not recommended due to an increased risk of scar breakdown. The authors' rule of thumb is to use intralesional TAC at least 2 weeks before or after an AFR treatment session. Another way to combine AFR and TAC is to apply the suspension topically immediately after the fractional treatment, as described by Waibel et al.²⁹ Ostensibly, the penetration of the TAC is enhanced by the fractional pretreatment. In the experience of the authors, using concurrent TAC and AFR in this manner has a lower risk of scar breakdown. This is likely due to a lower effective dose of TAC in the tissue when applied topically than when injected intralesionally.

Effective wound care is essential in minimizing scar formation after trauma and in optimizing the AFR treatment regimen in patients with active wounds. A myriad of dressings and techniques are available, and professional wound care should certainly be considered in conjunction with procedural interventions, as indicated. Silver nitrate sticks are another low-tech treatment that can be helpful in areas with excessive granulation tissue.

Clinical Outcomes and Discussion

As previously stated, randomized controlled trials regarding the efficacy of AFR for functional and cosmetic benefits in traumatic scars and contractures are lacking in the literature. As a result, evidence of therapeutic efficacy is currently lim-

ited to clinical experience and number of anecdotal reports in the literature. However, in the experience of the authors treating hundreds of patients with diverse injuries for >2 years, AFR appears to be well tolerated and results in improvements in virtually 100% of patients after each treatment using our stated protocol. It is important to recognize, however, that some results are more meaningful than others. Outcomes can vary from modest enhancements in texture and color to relatively rapid, cumulative, and sustained improvements in ROM and wound healing, obviating planned revision surgeries, and facilitating earlier return to full or adapted function or the use of prosthetic devices.

Initial improvements are usually observed within the first 2 weeks of AFR treatment. There seems to be an immediate photomechanical effect, perhaps analogous to the expansion of a split-thickness skin graft after mechanical fenestration, associated with a small but noticeable increase in ROM in a few patients at the time of treatment. This is followed in the ensuing days, weeks, and months by collagen remodeling. Associated with this remodeling is an aesthetic effect that is appreciated as early as 4 weeks postoperatively. We have used relatively repetitive protocols across a large range of pathologic scar types. The most dramatic functional results occur in plaque-like scars with multiple vectors of restricted movement. The mechanism of injury seems to be less important than the scar morphology and location. For instance, a similar result would be expected when treating a sheet of scar resulting from a split-thickness skin graft placed after a burn as compared with a comparable-sized graft placed after a surgical fasciotomy. However, in terms of overall functional outcome, the mechanism of injury is important, as there may be significant injuries to deeper structures that will not be affected by transcutaneous irradiation of the laser.

Commonly, we observe functional and subjective improvements out of proportion to the cosmetic appearance. Conversely, the cosmetic appearance of these scars predictably improves even when our treatment goals are focused on improving ROM. In the absence of controlled studies, how do we attribute patient improvements to AFR and not to spontaneous improvement alone? Supporting the role of AFR in patient improvements is the rapidity of the response to an AFR treatment. Frequently, patients are referred to the Dermatology Clinic having reached a plateau in improvement for several months, despite aggressive physical therapy. Initial incremental functional improvements are routinely seen within days of the procedure, and they are a positive predictor of overall outcome. Furthermore, there appears to be minimal tendency for these enhancements to recede, and they accumulate with each procedure. AFR alone may be sufficient procedural intervention for mild or even moderate contractures. However, the technique should be viewed as a way to optimize outcomes rather than as a replacement for surgical revision. Even in cases necessitating future surgery, enhancements in skin pliability and mobility through AFR may limit the extent of surgery or may facilitate surgery by improving the quality of the tissue in the operative site.

The flow characteristics of military patients out of the war zone and the inherent timing of the rehabilitative and disposition process have resulted in many patients presenting to the Dermatology Clinic for scar treatment well before the 1-year time frame dictated by conventional scar treatment paradigms. As a result, the authors have initiated AFR as early as 2 months after injury or final reconstructive surgery, and well before 1 year in most cases. Not only does AFR appear to be safe and effective before 1 year after injury, it seems to alter the trajectory of contracture formation and may even facilitate the healing of chronic wounds. If used in this way, AFR can be a highly effective adjunct to standard rehabilitative treatments, such as physical therapy, wound care, and prosthetic implementation. In the experience of the authors, patients can achieve higher levels of full or adaptive function at earlier time points in their rehabilitative course through the mitigation and prevention of worsening scar contractures and earlier, and more extensive, use of prosthetic devices, such as artificial limbs.

The basis for these improvements is the generation of a stereotypical wound healing and remodeling response following the unique ablative fractional pattern of injury. Although the process has not been fully described, it likely involves the coordinated expression of heat shock proteins and other factors, such as transforming growth factor- β and matrix metalloproteinases, which ultimately result in tissue repair and scar remodeling.³⁰⁻³³ Although a relatively small percentage of scar is treated in a given session, improvements are seen throughout the treatment area. The resulting remodeling process appears to be flexible enough such that the same platform, with nuances in technique, can result in tightening of aged and photodamaged skin and relaxation of scar contractures.^{34,35}

Complications

Routine side effects of the application of AFR to scars include a transient erythema and hive-like swelling for up to several hours after treatment. Bleeding is sporadic and ephemeral when using a fractionated CO₂ laser due to the increased zone of coagulation. A mild serous discharge is relatively common for 1 to 2 days after treatment, and is the primary reason why nonstick dressings are initially applied in covered locations. In most cases, postprocedure pain is minimal and rarely necessitates even over-the-counter pain medications. Approximately one-quarter of patients describe mild intermittent itch for up to several days after the procedure. Diluted vinegar compresses and cold packs are frequently sufficient to mitigate the itch, and antihistamines are only rarely required. This may indicate a candidosis, and one should consider empiric oral antifungals if the symptoms persist. Uncommon side effects include prolonged erythema, pain lasting for >2 hours, transient hyperpigmentation, and scar exfoliation. However, using our relatively conservative treatment protocol, no cases of worsening scarring or permanent hypopigmentation have been documented by the authors during the course of many hundreds of treatments.



Figure 1 Patient in case 1 at pretreatment baseline 4 years after suffering extensive burns with a refractory flexion contracture at the elbow, shown here at maximum extension.

Bacterial infection is the primary concern of the authors when performing AFR. Many patients have high amputations and/or minimal soft-tissue coverage over bony prominences, and progressive infection or osteomyelitis is a serious potential complication. However, despite the infrequent use of prophylactic antibiotics, the infection rate appears to be significantly $<1\%$ of treatments. No cases of progressive infection have been documented, and 3 cases of minor infections have responded to traditional courses of oral antibiotics without further incident.

The authors would like to emphasize that traumatic scars should not be expected to tolerate laser treatment to the same extent as normal skin treated for cosmetic indications. For these reasons, we have maintained a conservative approach, generally avoiding aggressive settings and multiple concur-

rent procedures. The authors recommend that any area treated with AFR remain untreated by these other modalities for at least 2 weeks. The combination of thermal injury at different tissue levels with concurrent treatments increases the risk of excessive cumulative fluence and collateral thermal damage, and therefore should only be performed by experienced laser experts. In addition, when a traumatic scar or graft involves the entire circumference of a limb, we recommend that a single treatment should not completely encircle the limb. Maintaining a “less is more” philosophy by never trying to do too much in 1 treatment session has allowed us to enjoy reliable efficacy with an excellent safety record.

Case Examples

Case 1

A 52-year-old white male suffered burns over 35% of his body surface area due to an aviation accident 4 years before presentation. His immediate burn care necessitated the placement of multiple split-thickness skin grafts. His primary complaint was a refractory flexion contracture at the right elbow, shown in Fig. 1 at baseline in full extension. To attempt to correct the contracture, surgical release and split-thickness skin grafting were performed by Plastic Surgery. Although improved on presentation in the Dermatology Clinic 2 months after surgery, there was a persistent flexion contracture refractory to intensive physical therapy and a persistent nonhealing ulcer despite dedicated wound care (Figs. 2A and 3A). Informed consent was obtained. Pretreatment of the area was performed with

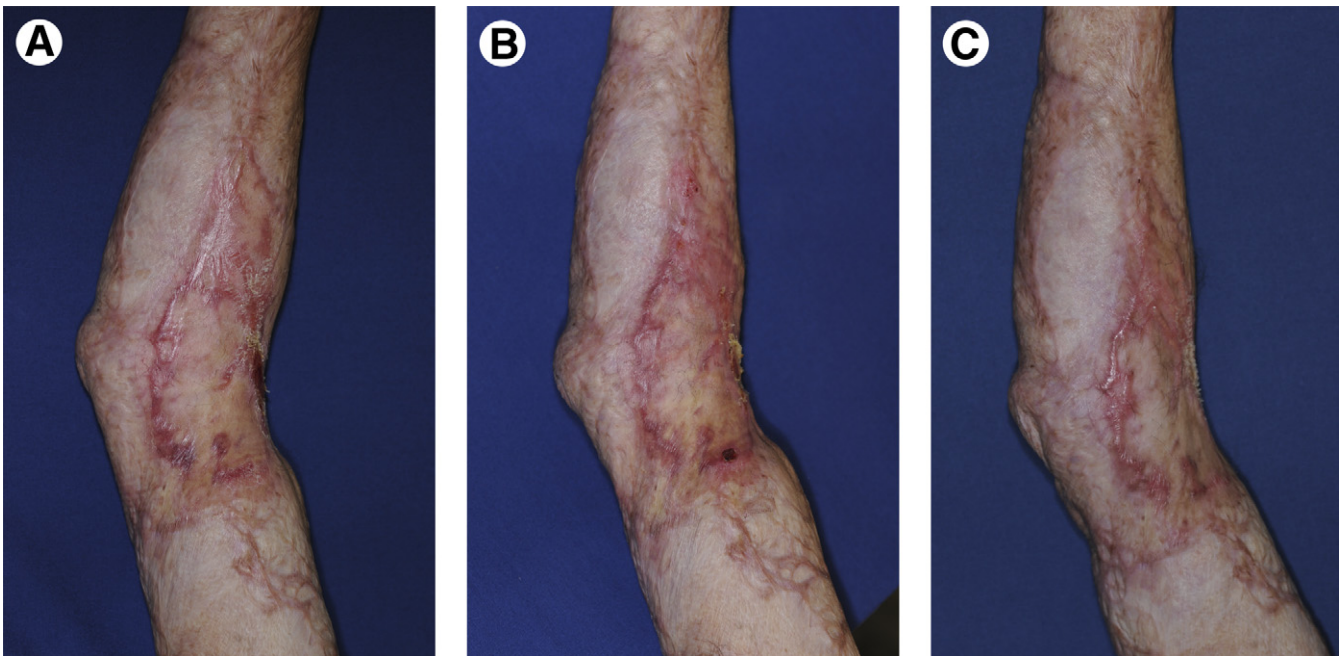


Figure 2 (A) Patient at presentation in dermatology 2 months after surgical contracture release and split-thickness skin grafting with a refractory contracture. (B) 2 weeks after a single ablative fractional resurfacing (AFR) treatment demonstrating 12 degrees increased extension. (C) Five weeks after a single AFR treatment demonstrating additional improvement in extension.

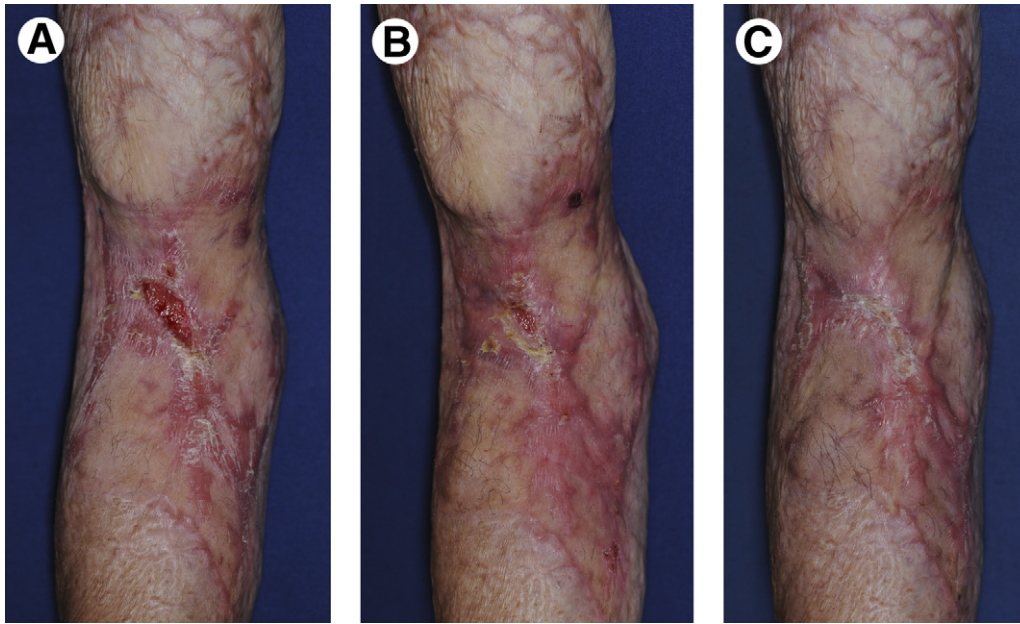


Figure 3 (A) Patient at presentation in dermatology 2 months after surgical contracture release and split-thickness skin grafting with a refractory ulcer. (B) 2 weeks after a single AFR treatment demonstrating significant interval healing in the previous ulcer. (C) Five weeks after a single AFR treatment demonstrating complete reepithelialization of the previous ulcer.

a 595-nm pulsed dye laser (Vbeam, Candela Corporation, Wayland, MA) over the entire grafted area and surrounding erythematous bands with the following settings: 10-mm spot, fluence of 4 J/cm², pulse width of 1.5 ms, and DCD setting of 30/20 ms. A single AFR treatment was then performed over the same area with a fractionated CO₂ laser (Ultrapulse Encore, DeepFX, Lumenis, Ltd, Yokneam, Israel) at a pulse energy of 40 mJ and density of 5%. The ulcerated area itself was treated with a reduced pulse energy of 20 mJ at the same density. At his first follow-up approximately 2 weeks after AFR, the patient had obtained an additional 12 degrees of extension and significant interval healing of the previous ulcer (Figs 2B and 3B). At his

next follow-up approximately 5 weeks after treatment, additional increased extension and full reepithelialization of the previous ulcer was noted (Figs 2C and 3C). Figure 4 demonstrates excellent improvement in ROM 5 weeks after AFR. In this case, a combined approach of surgical contracture release followed by AFR resulted in significant functional improvements compared with baseline. In addition to increased ROM, enhancements in skin texture and pliability were noted.

Case 2

A 29-year-old man suffered numerous injuries related to an improvised explosive device detonation 3 months before pre-



Figure 4 Five weeks after a single AFR treatment, combined surgical contracture release and postprocedure AFR have resulted in significant functional improvements compared with baseline shown in Fig. 1.



Figure 5 Patient in case 2 at presentation in dermatology 3 months after blast injury. Contracted bands limited range of motion and functionality in his remaining digits.

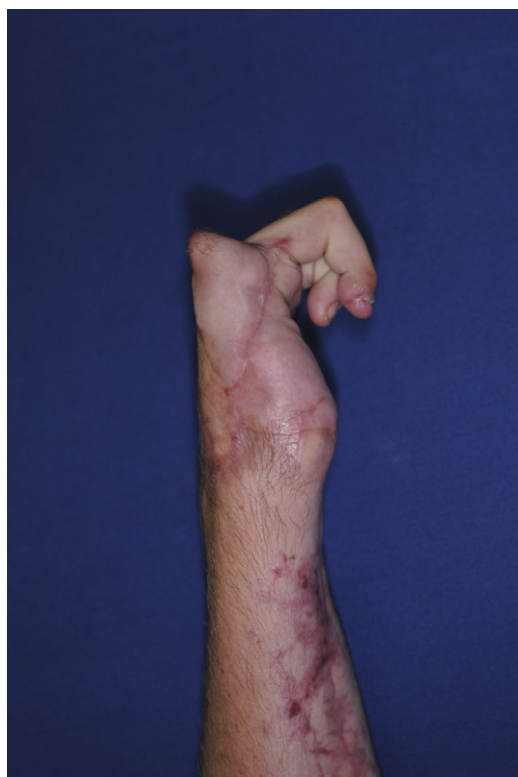


Figure 6 At presentation, 3 months after blast injury with decreased range of motion, including finger flexion.



Figure 7 Patient in case 2 after 2 AFR treatments, 5 months after his initial treatment. Moderate enhancements in range of motion can have large functional impacts for patients with severe traumatic injuries.

sentation, resulting in right above-knee amputation, right distal arm and hand amputation, and amputation of the left thumb, index, and middle fingers. One of his primary complaints was decreased ROM in his remaining digits due to progressive contracted bands on the dorsal and medial aspects of his remaining left hand refractory to aggressive physical therapy (Figs. 5 and 6). After informed consent, a course of AFR was initiated at a pulse energy of 50 mJ and density of 5% to the contracted bands. The patient reported a progressive increase in ROM of his fingers beginning within 2 weeks of his initial treatment. A second treatment was performed 4 months after his initial treatment at the same settings. Five months after his initial treatment, the patient reported incremental improvements in ROM and functionality of the remaining digits.

Conclusions

We have just begun to recognize the potential of the unique ablative fractional laser-induced thermal injury and healing response in the treatment of traumatic scars and contractures. Early clinical observations suggest that it demonstrates consistent efficacy and an excellent safety profile. Although its precise role and optimal treatment protocols have yet to be fully defined, in the opinion of the authors, AFR should assume a prominent role as a minimally invasive yet powerful

tool in the rehabilitation of patients following traumatic injuries (Fig 7).

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