Selective Electro-Thermolysis in Aesthetic Medicine: A Review

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The use of radiofrequency (RF) for selective electrothermolysis has been found to produce a highly efficient thermal effect on biological tissue. Different from optical energy, RF energy is dependent on the electrical properties of the tissue rather than on concentration of chromophores in the skin for selective thermal destruction of targeted sites. Good results have been obtained with systems that use RF current alone for skin resurfacing, with efficacy comparable to laser resurfacing but with potentially more rapid healing. A related adverse effect is pain accompanying the procedure, due to a high depth of penetration. Another technology integrates RF energy together with optical energy (using lower energies of both forms of energies). These systems have shown efficacy in hair removal for all hair colors and skin types, as well as wrinkle reduction; and may reduce the risk of side effects associated with either RF or optical treatments alone. This article discusses the properties of electrical current in medicine and reviews the studies to date that have evaluated RF energy for dermatological applications. Lasers Surg. Med. 34:91–97, 2004. © 2004 Wiley-Liss, Inc.

Key words: hair removal; laser; skin rejuvenation; wrinkles; photothermolysis; radiofrequency; electrical current

INTRODUCTION

Thermal treatment using optical energy for various types of dermatologic problems has become very popular over the past 20 years. Light-based therapies with lasers and intense pulse light (IPL) technologies have been increasingly used in aesthetic medicine for epilation, removal of vascular and pigmented lesions, reduction of fine wrinkles, and acne treatment [1]. The fundamental principle behind the use of light-based therapies is based on the theory of selective photothermolysis, which encompasses the following three tenets [2,3]:

1) optical energy penetrates deep enough to reach the treated target;
2) optical energy is mostly absorbed by the target, although surrounding skin may be heated significantly;
3) optical energy is strong enough to create thermal damage of the treated target.

In selective photothermolysis, a pulse of light set at the proper wavelength and proper duration is delivered to targeted sites. Although effective for a broad range of dermatological indications, limitations also have been realized with light-based therapies [4]. One of the main limitations is that optical energy must penetrate the epidermis to reach the depth of the targeted site. Optical energy is absorbed by melanin chromophores in the epidermis and hair shafts, and hemoglobin in blood. In photoepilation, light-colored hair is particularly difficult to remove because it has low levels of melanin and, therefore, may not absorb enough energy to achieve thermal destruction of the hair follicle. Conversely, high pigmentation of the epidermis also poses a problem because it may absorb too much energy, potentially causing adverse effects such as burns and hyperpigmentation. Wrinkles respond poorly to treatment with optical energy because collagen fibers do not contain chromophores. These limitations have stimulated investigators to look for new forms of energy that satisfy the principle of selective thermolysis but are devoid of the main disadvantage of optical energy for dermatological applications; that is, a strong interdependence between treatment efficacy/safety and chromophore levels in the epidermis.

The current article evaluates the use of an alternative source of energy—electrical current—for the selective treatment of different biological targets. Different from selective photothermolysis, the treatment using electrical current is termed selective electro-thermolysis.

ELECTRICAL CURRENT IN MEDICINE

Electrical current has been used in medicine for more than a century. Low frequency or direct current (DC) causes spasms of the muscles and is used at low intensity for biostimulation, such as cardioversion of atrial fibrillation [5]. High frequency current in the range of 0.3–10 Megahertz (MHz), or radiofrequency (RF) current, produces a pure thermal effect on biological tissue that is dependent on the electrical properties of the tissue. The high efficiency of RF current for tissue heating has made it useful for electrosurgery and an attractive source of energy

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for various dermatologic applications [6,7]. The mechanism of tissue heating is based on generating Joules of heat by electrical current. Generated heat is described by Joule's law:

$$H = \frac{j^2}{\sigma}.$$

Where j is the density of electrical current and σ is electrical conductivity [8]. The value opposite to conductivity is named resistance or impedance (ρ). Distribution of electrical current can be calculated using the method described in the Appendix.

Electrical conductivity depends on the frequency of electrical current, type of tissue and its temperature. The distribution of electrical current depends on the geometry of the electrodes. Two typical configurations are used in medicine: unipolar and bipolar. The major difference between the two systems is how the RF current is controlled and directed at the target. However, there is no difference in ultimate tissue effect at the same RF fluence.

Unipolar System

A unipolar or monopolar system delivers energy through one electrode with a relatively small contact point applied to the treatment area while another large size ground electrode is applied to the body at a distance far from the active electrode. A cylindrical electrode is applied to the skin surface, and the schematic flow of electrical current is depicted in Figure 1. Electrical energy is concentrated near the tip of the electrode and decreases rapidly with distance. Penetration depth of RF current can be estimated as half the electrode size. Therefore, a 10-mm unipolar electrode has a penetration depth of approximately 5 mm, which is deep enough to reach muscles.

The advantage of a unipolar system is its ability to create a high power density on the surface of the electrode. This attribute makes it popular in electrosurgery where a small size electrode is used. The disadvantage of a unipolar system is its unpredictable behavior as the current passes through the body to the grounding electrode. In aesthetic medicine, examples of a unipolar system include the

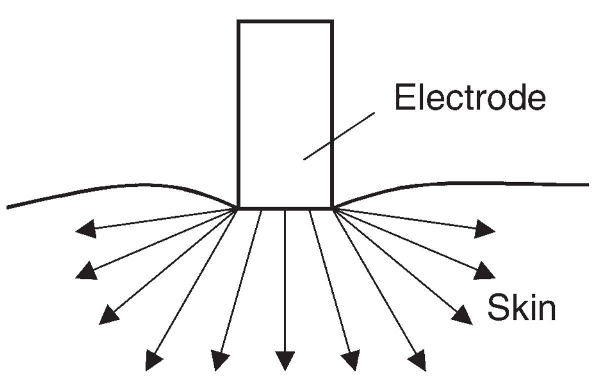

Fig. 1. Schematic representation of the flow of electrical current through the epidermis using a cylindrical unipolar electrode.

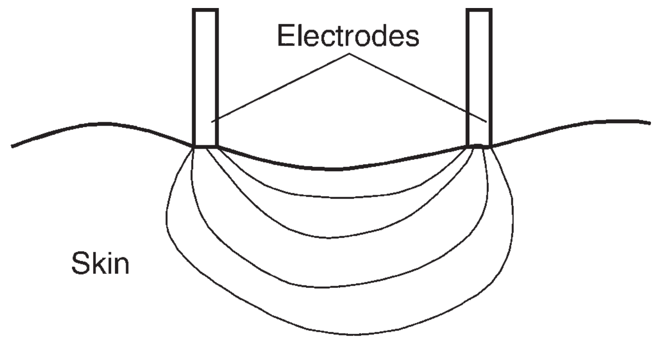

Fig. 2. Schematic representation of the flow of electrical current through the epidermis using a bipolar system.

Visage® ArthroCare Corp., Sunnyvale, CA) and ThermaCool™ (Thermage, Inc., Haywood, CA).

Bipolar System

A bipolar system passes an electrical current between two electrodes at a fixed distance. Both electrodes are applied to the treated area, and electrical current propagation is limited by the area between electrodes. The behavior of electrical current in a bipolar system is depicted in Figure 2. Distribution of electrical current as a function of depth (calculated using the method described in the Appendix) for different distances between electrodes is presented in Figure 3. Using the same definition of penetration depth as used for the electromagnetic radiation and particularly the depth where density of value is decreased by factor $e = 2.72\ldots$, the penetration depth of electrical current can be estimated as half the distance between electrodes.

The main advantage of a bipolar system is the controlled distribution of RF current inside the tissue, which is limited by volume between the two electrodes. Therefore, the bipolar system is less suitable for electrosurgery but appropriate for homeostasis and controlled vessel contraction using an intravascular catheter. In aesthetic medicine,

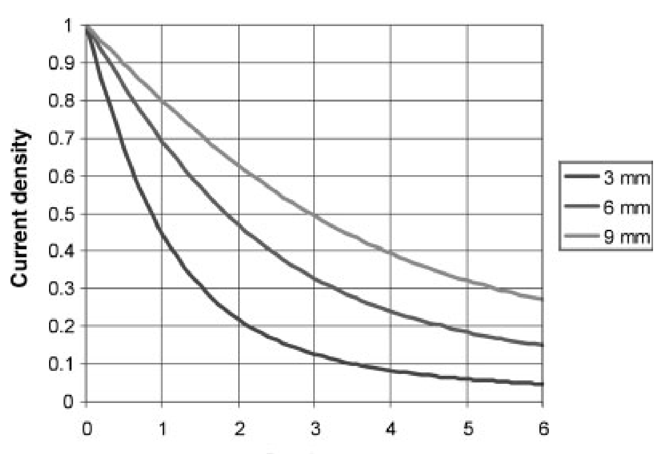

Fig. 3. Normalized distribution of electrical current density as a function of the depth for different distances between electrodes in a bipolar system.

TABLE 1. Electrical Conductivity of Different Types of Tissue at 1 MHz

Tissue	Conductivity (S m m^{-1})
Blood	0.7
Bone	0.02
Fat	0.03
Dry skin	0.03
Wet skin	0.25

examples of bipolar systems include the Aurora™ and Polaris™ systems (Syneron Medical Ltd., Yokneam, Israel).

Electrical Conductivity of Different Tissue Types

Table 1 shows the electrical conductivity of different tissues at normal temperature and a frequency of electrical current at 1 MHz. Blood and parts of the body with high blood content have the highest electrical conductivity. Bone has very low electrical conductivity, and therefore, electrical current does not penetrate the bone but rather flows around it. Dry skin also is resistant to electrical current and must be hydrated to permit passage of electrical current into the tissue. Conductivity of tissue increases proportionally with frequency. In Figure 4, the RF current from the electrodes penetrates the epidermis and concentrates in areas with high electrical conductivity. The pattern of distribution of electrical current demonstrates the possibility for selective treatment of blood vessels using conductive RF.

Temperature Dependence of Electrical Conductivity

Tissue conductivity is significantly correlated with tissue temperature. The thermal coefficient (α) of skin conductivity is approximately 2% C^{-1}; that is, every 1°C increase in temperature lowers skin impedance by 2% [9]. Therefore, the distribution of electrical current can be controlled by pre-cooling or pre-heating different parts of tissue. Figure 5 describes the distribution of electrical current as a function of the depth of tissue with uniform temperature distribution for skin surface that has been pre-cooled by 25°C. Surface cooling drives electrical current inside the tissue, increasing penetration depth. Likewise, pre-heating the target tissue increases conductivity and consequently selective heating by the RF current. Therefore, if the temperature of the target tissue is higher than that of the surrounding tissue, then the RF current will selectively focus to increase heating of the target tissue.

CLINICAL APPLICATIONS

In aesthetic medicine, the use of RF as an energy source for selective electro-thermolysis is a relatively new concept. Systems that incorporate the RF current have been in development for several years but introduced only recently. Studies using these new technologies have demonstrated utility in hair removal, skin rejuvenation, and wrinkle reduction.

Hair Removal

The effective removal of unwanted hair using optical energy has been essentially limited to black and dark and medium tones of brown hair [10]. Treatment of light-

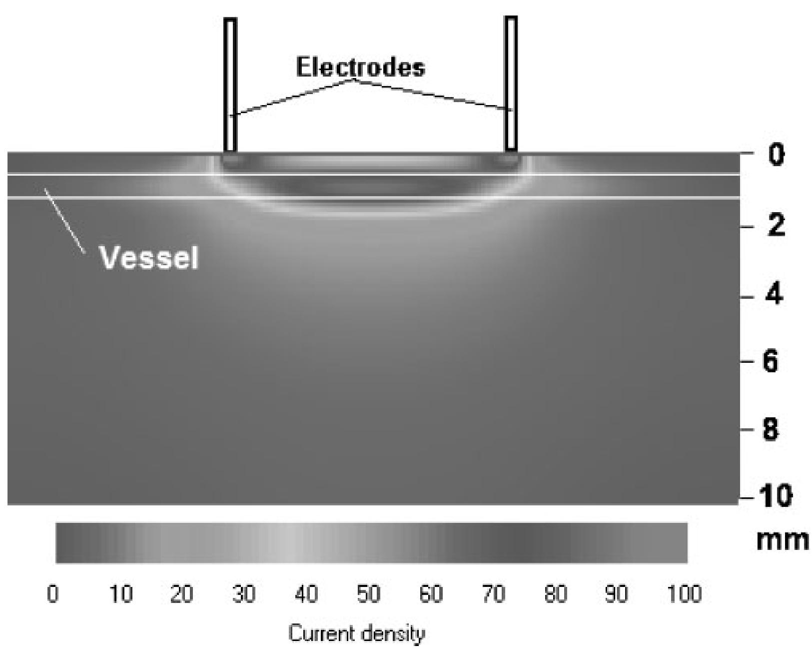

Fig. 4. Normalized distribution of current density in tissue with blood vessel using a bipolar system.

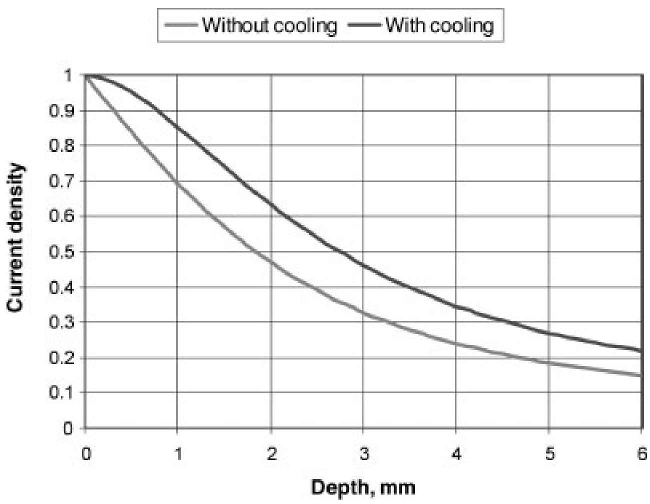

Fig. 5. Normalized current density distribution as a function of the depth for pre-cooled and normal skin.

colored hair has been particularly difficult because of the limited concentration of melanin chromophores in hair follicles. In addition, safety is a concern in dark skin types, who have an increased risk of blistering and dyschromia, even with longer pulse lasers [11]. It would make sense that the combination of low levels of optical energy and electrical conducted RF current, the latter of which is not dependent on melanin for thermal absorption, may be able to effectively and safely remove hair, including light-colored hair, for all skin types.

A recently introduced combined intense pulsed light (IPL)/RF technology integrates optical and electrical energies simultaneously applied to tissue. This technology has been referred to as electron-optical Syneron (ELOS). In the Aurora DS^{TM} system, IPL (680–980 nm) producing optical energies as high as 30 J/cm^2 and a bipolar RF device that generates RF energy as high as 25 J/cm^3, and pulse durations up to 200 milliseconds, are combined and delivered to targeted sites. Pulses of optical and RF energies are initiated at the same time, but the RF pulse is set at a longer duration than the optical pulse, enabling the optical component to preheat the target and increase RF selectivity. The conducted RF energy is applied through electrodes embedded in the system applicator and brought into contact with the skin surface. In this bipolar system, the shape and distance between the electrodes are optimized to provide an RF current penetration depth of 4 mm. During the procedure, the device measures changes in the skin impedance, which is inversely related to temperature and wavelength, and allows active dermal monitoring. Skin temperature is controlled and protected by the epidermal contact cooling maintained at approximately 5°C provided by the system.

The combined use of optical and RF energy for the hair removal system has shown efficacy where light-based therapies have not shown significant efficacy; that is, in the effective removal of light hair and safety in dark skin. In a recent multicenter study, 60 patients with Fitzpatrick's skin types II–V and various hair colors were enrolled for treatment, using the Aurora DS system [12]. In the study, light energy ranged from 15 to 28 J/cm^2, and the RF energy ranged from 10 to 20 J/cm^3. Subjects received three treatments 6–8 weeks apart. Hair counts were performed prior to the first treatment and 3 months after the last treatment. Maximum hair reduction was observed at 2–8 weeks. At 3 months, hair clearance ranged from 64 to 84%, depending on the anatomical site. Treatment was most effective for hair in the axillary. In most cases, higher RF energy (15–20 J/cm^3) was used, and results indicate that efficacy is determined by the level of RF energy, not optical energy.

The primary author has conducted two studies to investigate the efficacy and safety of combined optical and RF energies for hair removal, using the Aurora DS system. The first study consisted of 40 adult subjects with different skin types (Fitzpatrick's II–V) and various hair colors [13]. The second study included 36 adult women with overall lighter skin phenotypes (I–V) and blond or white facial hair [14]. In both studies, subjects received four treatments at 8- to 12-week intervals over a period of 9–12 months. Depending on skin and hair phenotypes, light energy ranged from 15 to 30 J/cm^3. Higher optical energy was used in lighter skin phenotypes and hair color. The RF current ranged from 10 to 20 J/cm^3, depending on anatomical site; higher RF energy was used in facial regions (versus lower body regions). Results were monitored 18 months after the first treatment or 6 months after the last treatment.

In both studies, maximum hair reduction occurred 6–8 weeks following treatment, and hair density was observed to decrease progressively following each subsequent treatment. As observed in the first study, hair removal efficiency was greater in subjects with dark hair (mean clearance 80–85%). This is similar to that reported using other light-based technologies [15]. Both studies showed that light hair phenotypes had hair clearances of between 40 and 60% (Table 2). Results showed no significant dependence of treatment on skin color, as light and dark skin types responded similarly to treatment. Side effects

TABLE 2. Mean Hair Removal Efficiency by Hair Color After Four Treatment Sessions (Month 18), Using Combined IPL and RF Energies With the Aurora DS System [13,14]

Hair color	Study 1 [13]		Study 2 [14]	
	n	Mean clearance (%)	*n*[a]	Mean clearance (%)
Black	16	85	—	—
Brown	13	80	—	—
Blond	5	60	21	52
Red	3	60	—	—
White	3	40	20	44

IPL, intense pulse light; RF, radiofrequency.
[a]Number of subject treatment sites.

were minimal and transient. In the first study, 20% of subjects had mild erythema that resolved within 24 hours post-treatment. In the second study, 8% of subjects had transient hyperpigmentation that did not require therapy, and 14% had mild erythema, which resolved within 24 hours.

Potentially greater effectiveness may be obtained by optimizing treatment parameters and technique for combined optical and RF energies; for instance, manipulating optical and RF frequencies, increasing the number of passes, or increasing the number of treatments over a given time. These methods are currently being investigated.

Skin Rejuvenation

Skin rejuvenation is a complex treatment that includes removal of vascular and pigmented lesions, improving skin texture, and reduction of fine facial wrinkles. Effective treatment of these indications typically entails multiple treatments and more than one light-based device [16–18]. IPL provides good results for vascular, pigmented lesions, and skin texture, but wrinkle improvement is not significant [17]. Long pulse Nd:YAG lasers provide improvement of fine wrinkles but are not effective for pigmented lesions because of low chromophore absorption and show variable results for vascular lesions [18].

The efficacy and safety of combination optical and RF energies for skin rejuvenation have been recently reported [19]. Treatment of the face and upper neck was performed for 100 subjects with Fitzpatrick's skin types II–IV, using the Aurora SR^{TM} system. Most subjects had combined clinical indications that included pigmented and vascular lesions, skin laxity, or enlarged pores. Each treatment consisted of one to three passes over the face using various optical (580–980 nm with pulse durations up to 120 milliseconds) and RF parameters that were determined by individual skin type. Subjects received three to five treatments, depending on lesion type. To determine treatment effect, subjects were followed up after their last treatment and interviewed about their satisfaction level.

Based on results, improvements were observed in erythema and telangiectasias (70%) and lentigines and other hyperpigmentations (78%), as determined by subject satisfaction levels (Table 3). In addition, both physicians and patients observed significant improvements in fine and coarse perioral, periocular, and forehead wrinkles. There was an average improvement of 60% in skin texture and fine wrinkles. The authors noted that wrinkle reduction with combined optical and RF energies was significantly greater than IPL alone (based on clinical experience). Moreover, subjects who had undergone both types of treatments reported a preference for the combined optical and RF procedure because of a greater degree of skin improvement, more rapid onset of effects, and slightly greater treatment comfort. Crusting of pigmented lesion was commonly observed the day following treatment. Small blood vessels vanished typically after two treatments. The typical number of treatment sessions required to get these results is presented in Table 4. Only a small number of subjects (2.8%) were not satisfied with the level of skin texture improvement. The remaining 97.2% of subjects were satisfied with the results and opted to continue with treatment [19].

Wrinkle Treatment

Non-ablative treatment of deep wrinkles remains a difficult challenge in aesthetic medicine. Earlier CO_2 resurfacing techniques often caused long-lasting erythema (=3 months), post-inflammatory hyperpigmentation, and required post-operative pain management. Introduction of the erbium (Er):YAG lasers improved the safety and recovery profile of laser surgery; however, the application is limited primarily to the treatment of fine wrinkles and superficial defects [6].

The first large prospective study to evaluate an RF resurfacing system for the treatment of wrinkles was published in 2000 [20]. Ninety-five subjects (mean age, 52 years) with mild to severe photodamage (Fitzpatrick classes I–III) in the periorbital (75 treatment sites) or perioral (50 sites) regions were enrolled. Prior to treatment, subjects received nerve blocks and local infiltration anesthesia. The RF resurfacing device (Visage) encompassed a multielectrode-tipped stylet to produce a low-heat process termed coblation (cold+ablation). The power setting for the RF resurfacing system was 125–139 V. A maximum of two passes were allowed for class I wrinkles and up to three passes for class II or III wrinkles. The stylet was applied continuously and evenly at a rate of approximately 1.0–1.5 cm per second, with overlap by about 30%. Subjects were examined postoperatively on days 2, 7, 14, and 28, and then at 2, 3, and 6 months. Photographs were taken at baseline

TABLE 3. Patient Satisfaction in Skin Rejuvenation Study Using Aurora SR System [18]

	% Patients ($n = 100$)		
Lesion type	Satisfied (%)	Neutral (%)	Not satisfied (%)
Solar lentigo	78	22	0
Rosacea/telangiectasia	70	30	0
Fine lines	57	40	3
Plumpness	86	11	3
Skin laxity	58	37	5
Pores	63	24	13

TABLE 4. Typical Number of Sessions to get Treatment Results in Skin Rejuvenation Study Using the Aurora SR System [18]

Lesion type	Number of treatments
Lentigios/freckles	1–3
Vascular lesions	2–3
Skin laxity	1–2
Fine line	2–5
Pore closing	3–5
Ace scars	4–7

and 6 months, and five independent panelists scored the improvement in wrinkles. All panel members scored a positive improvement in Fitzpatrick wrinkle score. Similarly, subjects and investigators noted an improvement in wrinkles. The degree of improvement correlated with the severity of wrinkles at baseline. Higher power settings and greater number of passes appeared to result in increased efficacy. All treatment sites were more than 90% re-epithelialized within 7 days. Adverse effects included transient post-inflammatory hyperpigmentation (26%) and hypertrophic scarring (4%). Erythema was uniformly present at week 1 and progressively resolved at each visit up to the 6-month follow-up examination. The authors concluded that RF resurfacing may be comparable in efficacy to laser resurfacing. With regard to safety, they indicated that RF resurfacing may provide more rapid healing and less pain and erythema than that seen following CO_2 laser, but comparable with that after short-pulsed Er:YAG laser.

Another technology delivers RF energy for non-ablative tissue tightening while cooling the skin with a cryogen spray (ThermaCool). Heating of the dermis can lead to shrinkage of collagen fibrils, and thermal injury inflicted on tissue activates fibroblasts for tissue remodeling. A delayed effect of neocollagenesis is probably due to a wound healing response. The resultant effect is collagen contraction and tissue tightening followed by new collagen production over time. The cryogen spray allows parallel cooling during the procedure to preserve the surface of the skin and prevent it from burn. However, a potential adverse effect of this system is pain accompanying the procedure, as a result of a high depth of penetration. Two studies investigating the efficacy of this system for non-ablative skin tightening have recently been published. In a preliminary study, Iyer et al. [21] assessed the ThermaCool to treat the lower face and anterior neck of 40 subjects (age 35–70 years). Subjects received one to four treatment sessions at 6- to 8-week intervals. Energy fluence was approximately 100 J/cm^2. Response to treatment was gradual, with visible effects occurring 4–6 weeks after treatment. Subjects who received more than one treatment noticed further improvement after subsequent treatments. The procedure produced softer nasolabial folds, less visible jowls, sharper and tighter jawline, and less wrinkles on the anterior neck. Treatment was reported to be moderately painful. Three subjects had superficial blisters, but these healed without scarring.

In the other study, Ruiz-Esparza and Gomez evaluated the ThermaCool for wrinkle treatment [22]. Fifteen subjects (age 41–68 years) were enrolled. Five subjects were treated with a 0.25-cm bipolar electrode; eight with a "window frame" electrode; and two with a 1-cm monopolar electrode. A thick layer of ELA*Max* 5% (Ferndale Labs, Inc., Ferndale, MI) was used for topical anesthesia. Pain was used as a clinical indicator of the maximum tolerable energy delivered. The energy used was 52 J/cm^2; the average current was 0.447 A. Photographs were taken at baseline and at each week following treatment for up to 14 months. Four independent physicians outside of the study were asked to review and standardize photographs to evaluate results. In this study, 14 of the 15 patients obtained cosmetic improvement from facial skin tightening, with visible results occurring approximately 12 weeks after the treatment session. Subjects experienced minimal discomfort that required no post-operative care. Treatment was most effective in the preauricular regions and less effective in other areas of the face, such as the nasolabial folds and cheeks. Of note, these authors also studied this system for moderate to severe acne in 22 patients, with excellent response reported in 82% [23].

A combination of diode laser energy and RF current may also have a role in the treatment of wrinkles. The premise is that RF energy will penetrate into the skin and cause heating of the deeper tissue with neo-collagen formation while the laser energy will be synergistic with this effect and also address the more superficial problems of unwanted pigmentation and visible vascularity. In the Polaris WR^{TM} system, the optical energy is produced by a diode laser with wavelength of 900 nm and pulse duration as long as 150 milliseconds that can generate fluence up to 50 J/cm^2; the system can generate RF energy levels as high as 100 J/cm^3 with pulse duration as long as 250 milliseconds. Geometry of electrodes provides a penetration depth of approximately 2 mm. Two case reports have been described using this system and show promising results [24]. Both were women with significant wrinkling, undesirable vascularity, and hyperpigmention of the skin. One was 80 years old; the other was 57 years old. Both subjects had significant reductions in the signs of aging. Following each treatment, both subjects had mild swelling for 1–2 days. Normal activities were not compromised. These preliminary data are encouraging. Studies are currently underway to optimize treatment parameters in order to improve results and treatment comfort, as well as examine the effect on all skin types.

CONCLUSIONS

Current light-based therapies are limited by their dependence on chromophore levels in the epidermis or hair shaft for selective thermal destruction of targeted sites. This dependence on chromophore levels creates a window of efficacy and safety for the treatment of various dermatological indications. In recent years, the use of an alternative source of energy—electrical—has become available through systems that use conducted RF current for selective electro-thermolysis. RF current affects the dermis layer directly while reducing the risk of skin burns and other adverse effects associated with optical energy. Good effects have been obtained with the use of RF current for wrinkle reduction (Visage). Tissue contraction also has been achieved using a high energy RF device (Thermacool), but the major limitation (because of its high depth of penetration) is a lack of improvement in pigmented and vascular lesions. Moderate to severe pain also can accompany the procedure. Studies also have shown significant improvements in the treatment of acne vulgaris [23].

The latest technology ELOS combines RF with optical energies and may expand the efficiency of selective thermal treatment for all skin types. ELOS is based on the premise of a synergistic activity between the two forms of energy that occurs when the various treatment parameters are set optimally, depending on the hair color, skin type, or severity of lesion. By combining RF and optical energies, lower levels of both energies can be used. This may reduce the risk of side effects associated with either RF or optical treatments alone. There are multiple potential uses, including the effective removal of unwanted hair and treatment of all aspects of aging, from pigmented and vascular lesions to texture improvement and wrinkle reduction. Studies using ELOS-based systems have demonstrated its effectiveness in hair removal (Aurora DS), including light hair and all skin types, and skin rejuvenation (Aurora SR) for skin types I–IV. Preliminary case reports evaluating the Polaris WR show promising results of combined treatments for wrinkle reduction. Further studies are underway to optimize treatment parameters and technique.

The use of RF energy alone (Visage or Thermage) or in combination with optical energy (Aurora, Polaris) is likely to become an increasingly popular therapeutic direction in aesthetic medicine. Additional studies are required for quantitative measurement of the effect of RF energy on skin texture. Histological studies are needed to help understand the mechanism of dermal reaction on conducted RF influence.

APPENDIX

Distribution of electrical current is described by continuity equation:

$$\operatorname{div} j = 0. \tag{A1}$$

Where j is density of electrical current. The equation states that electrical current starts in one of the electrodes and have to reach the other electrode closing electrical loop through the electrical circuit.

According to Ohm equation the current density is higher when conductivity and electrical field are higher

$$j = \sigma E. \tag{A2}$$

Where σ is electrical conductivity of tissue and E is electric field strength, which is described by following equation:

$$E = -\operatorname{grad} \varphi. \tag{A3}$$

Where φ is a potential of electric field.

Combining Equations A1–A3 the following equation for potential of electric field can be obtained:

$$\operatorname{div}(\sigma \operatorname{grad} \varphi) = 0. \tag{A4}$$

Electrical conductivity depends on frequency of electrical current, type of tissue and its temperature.

For analyzing electrical current distribution Equation A4 are solved using numerical computerization with boundary conditions depending on geometry of electrodes.

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