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Energy-Based Skin Rejuvenation: A Review of Mechanisms and Thermal Effects

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Correspondence: Yongqiang Feng (sdfrank@126.com)**Received:** 27 July 2024 | **Revised:** 12 October 2024 | **Accepted:** 17 October 2024**Funding:** The authors received no specific funding for this work.**Keywords:** collagen | electromagnetic | energy-based devices | photoelectric and ultrasonic | skin aging | skin resurfacing and rejuvenation | thermal effect | thermal injury

ABSTRACT

Background: Energy-based photoelectric and ultrasonic devices are essential for skin rejuvenation and resurfacing in the field of plastic surgery and dermatology. Both functionality and appearance are impacted by factors that cause skin to age, and various energy types have variable skin penetration depths and modes of transmission.

Aim: The objective is to advise safe and efficient antiaging treatment while precisely and sensitively controlling and assessing the extent of thermal damage to tissues caused by different kinds of energy-based devices.

Methods: A literature search was conducted on PubMed to review the mechanisms of action and thermal effects of photoelectric and ultrasonic devices in skin remodeling applications.

Results: This paper reviews the thermal effects of energy-based devices in skin resurfacing applications, including the tissue level and molecular biochemical level. It seeks to summarize the distribution form, depth of action, and influencing factors of thermal effects in combination with the mechanisms of action of various types of devices.

Conclusion: Accurate control of thermal damage is crucial for safe and effective skin remodeling treatments. Thorough investigation of molecular biochemical indicators and signaling pathways is needed for real-time monitoring and prevention of severe thermal injury. Ongoing research and technological advancements will improve the accuracy and control of thermal damage during treatments.

1 | Introduction

Skin aging is a complex process involving a combination of stages and factors. This process can affect the structure and function of the skin in the form of wrinkles, sagging, enlarged pores, and abnormal pigmentation. It can be divided into two main types: intrinsic and extrinsic aging. During this process, alterations are observed in both the epidermis and the dermis, with more pronounced differences between the two types of aging in the dermis. Intrinsic aging slowly causes tissue degeneration with age and is also influenced by genes, hormonal changes, and cellular metabolism, resulting in a gradual loss of skin structure

and function [1]. This is characterized by a decrease in eosinophilic and Hales staining substances and smaller fibroblasts in the dermis. Extrinsic aging stems mainly from skin damage caused by ultraviolet radiation, known as photoaging. This process leads to the production of reactive oxygen species and genetic alterations. Reactive oxygen species cause an increase in the oxidative stress and lead to a reduction and breakdown of elastic fibers and collagen, which in turn triggers undesirable changes in skin color and texture [2, 3]. Histologically, we can observe large, eosinophilic-filled areas under the photodamaged dermis [4]. It is crucial to note that chronological aging and photoaging are interconnected processes, jointly contributing to

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the manifestations of skin aging. Aging makes the skin more vulnerable to photodamage, while UV radiation accelerates the intrinsic aging process.

With the improvement of aesthetic standards, there is a growing demand for skin rejuvenation, particularly in the realm of light, ultrasound, and electricity—energy-based systems that have given rise to a variety of new technologies and devices. Photoelectric and ultrasonic technology plays a crucial role in plastic surgery and dermatology. In recent years, it has achieved remarkable results in improving skin aging, scarring, acne, pigmented diseases, skin vascular diseases, and body contouring [5–8]. It is widely favored for its fast, effective, simple, and minimally invasive nature. The main principle of photoelectric and ultrasonic technology is based on the thermal effect produced in tissues through the conversion of various energies into heat. Controlling tissue thermal damage effectively to achieve a favorable thermal effect is a crucial consideration in the treatment process. Therefore, conducting an objective and standardized assessment of the thermal effects of photoelectric and ultrasonic devices in skin remodeling, and avoiding the risk of complications associated with inappropriate thermal damage, is essential to ensure safe and effective treatment.

2 | Thermal Effects and Thermal Damage

Skin rejuvenation is a crucial application area for energy-based devices that thermally stimulate tissues or cells by converting various energies into heat. Ideal thermal stimulation should accurately control the thermal effect on the dermis and subcutaneous fibrous septum or fascia to trigger a series of positive physiological responses beneficial to rejuvenation. These include the activation of fibroblasts, remodeling of collagenous tissue, and revascularization. The magnitude of the tissue temperature increase and the duration of the effect are the two main elements determining the thermal effect on the tissue. When a tissue is exposed to excessive temperature or prolonged heat, the extent of tissue damage exceeds its tolerance range, leading to temporary or permanent abnormal changes in tissue and cell structure, function, and metabolism. These abnormal changes are termed reversible and irreversible thermal injuries, depending on the severity and duration of the thermal stimulus. In clinical practice, the use of photoelectric and ultrasonic devices necessitates precise control of the degree of thermal damage and the induction of controllable thermal damage to elicit beneficial tissue and cellular responses [9–12]. Understanding the mechanism of thermal stimulation, the distribution of thermal effects, and the factors affecting thermal effects is key to guiding safe and effective treatment. In the following, we discuss the control and mechanism of the thermal effect from various aspects.

2.1 | Thermal Effects on Tissues and Cells

The optimal ambient temperature for the growth of most mammalian cells is 37°C. Local tissue temperatures ranging from 37°C to 42°C induce tissue congestion. However, this process is safe and does not result in significant skin changes or adverse tissue effects. Studies have consistently demonstrated that even under prolonged exposure, the threshold for cellular

thermal damage remains at 43°C. Thermal damage to tissues can occur at temperatures above 43°C. However, the extent of damage is not solely determined by temperature but is contingent on the interplay of temperature and exposure time. With increasing temperature and/or duration of action, one or more of the thermal effects of hyperthermia, coagulation, vaporization, carbonization, and ablation can be induced and produce varying degrees of thermal damage to tissues. It may appear to the naked eye as erythema, pallor, darkening, and ablation of the skin. Microscopically, tissue edema, coagulation necrosis, mechanical rupture, and pyrolysis can be observed [11, 13–18].

The kinetics of several morphological and physiological indicators of thermal injury are exponentially dependent on temperature and linearly dependent on exposure time. The exposure time required to cause irreversible damage at any given temperature is estimable. For every 1°C above the threshold temperature (43°C), the time to cause thermal injury to the same number of cells reduces by 50%. Tissue lethality takes 120 min at 43°C, but only about 1 s at 56°C [19–21]. Although utilizing the known thermal effects of tissues at corresponding temperatures can help achieve therapeutic requirements, some potential side effects are difficult to predict. These side effects may include blister formation due to irreversible thermal damage, post-inflammatory hyperpigmentation, hypopigmentation, and scar formation [22–27].

The dermal matrix of adult skin consists of collagen I (80%–85%) and III (10%–15%), along with glycosaminoglycans and elastin fibers, which are synthesized and secreted by fibroblasts. Collagen I mainly affects the thickness of the skin, whereas collagen III is more involved in the formation of the skin's meshwork [28]. The aging process is characterized by a decrease in collagen fibers.

Fibroblasts respond differently to various temperatures, which is crucial as they are involved in skin remodeling. Heat exposure at 43°C for 10 min leads to reversible, slight cellular thermal damage, but the damage recovers later and cellular function is enhanced [29]. Thermal stimulation at 45°C and 60°C for 2 s [30, 31] resulted in the upregulation of type I and type III procollagen, and cells under the action of 60°C showed a more persistent trend of upregulation with increasing time while the proliferation rate decreased.

Collagen also respond directly when received thermal stimulation. Rejuvenation can also be induced by controlled denaturation or ablation of tissue in the microthermal zone. Controlled collagen contraction and denaturation have been found to be effective in inducing tissue remodeling [11, 32–37]. In the early stage of thermal stimulation, with increasing temperature, the collagen fiber helix undergoes partial or complete denaturation and collagen shrinkage, known as thermally induced collagen contraction. This tissue-tightening effect is most pronounced at 63°C [38–40]. Within milliseconds, the fractional form of treatment produces a zone of micro-thermal coagulation or vaporization, causing the surrounding cells to synthesize and exude extracellular matrix such as collagen. The thermocoagulated or vaporized zone, as well as the surrounding sub-thermal zone, produce new collagen, allowing for tissue repair and remodeling [18, 33, 41–43]. Photoelectric and ultrasonic technology has been

found to reverse skin aging by activating cell proliferation and cellular activity, increasing the expression of both collagen I and III [3, 44, 45].

2.2 | Thermal Effects at the Molecular Biochemical Level

Heat stimulation does not usually produce major tissue changes. Sensitive biological markers are required to better understand the cellular response, sublethal heat injury, and dynamic histological heat response. Heat injury affects cells and tissues through a variety of biological processes and communication pathways. Heat shock proteins (HSPs) are among the most common indicators of thermal injury, and they play an important role in the response. HSPs function by aiding normal protein folding, inhibiting protein aggregation and degradation, and participating in cellular stress response and repair processes. Heat injury causes a considerable increase in HSP expression, particularly for subtypes such as HSP70, HSP47, and HSP27. These HSPs were activated and regulated upon thermal injury to assist cells in dealing with heat stress-induced protein denaturation and intracellular disarray. For instance, at 42°C, HSP 70 temporarily activates expression; at 43°C and higher, expression increases quickly and significantly. It is the primary heat-stress-responsive protein and a significant indication of the degree of protein denaturation in cells. HSP 47 expression increases at temperatures above 42°C, and its level is linked to the rate of collagen synthesis. It also has a greater impact on the process of long-term wound healing. In response to heat stress (42°C or above), HSP27's mRNA expression increased rapidly, but protein expression did not alter much. Other HSP isoforms, such as HSP 72 and HSP 60, have variable expression patterns as temperatures change. Tissue-specific HSP72 expression was upregulated at 42°C, and the degree of heat stress influenced the level of expression. However, HSP 60 was less sensitive to temperature variations, with no significant change in expression levels following a 43°C heat shock [22, 31, 46–52]. Furthermore, HSPs regulate heat stress-induced inflammatory responses, prevent apoptosis, and modulate intracellular signaling pathways [53].

The thermal effect may impact several important signaling pathways within skin cells. In terms of the inflammatory response, heat injury can trigger the release of inflammatory factors, leading to a significant upregulation of expression levels of inflammatory cytokines such as tumor necrosis factor- α (TNF- α), interleukin-6 (IL-6), and interleukin-1 β (IL-1 β). These inflammatory factors, through the activation of inflammatory signaling pathways such as NF- κ B and MAPK, participate in regulating the inflammatory response induced by heat stress. These changes play a crucial role in inflammation-mediated cellular damage and repair [54–57]. In terms of oxidative stress, heat injury can lead to increased oxidative stress, affecting the intracellular redox balance. The changes in superoxide dismutase, catalase, malondialdehyde, etc. reflect the alteration of the intracellular oxidative stress state. The Nrf2 antioxidant signaling pathway, PI3K-Akt, and other signaling pathways affect the cell's ability to cope with oxidative stress [58–62]. In terms of apoptosis, heat injury may lead to increased cell apoptosis. This can be evaluated by detecting the activity of apoptosis-related genes such as Bcl-2, Bax, and the Caspase family. These

genes are involved in the apoptotic signaling pathways of cells, including the mitochondrial pathway, death receptor pathway, etc., affecting the cell survival and death decisions [63–69]. Additionally, MAPK, Wnt/ β -catenin, and TGF- β signaling pathways have an impact on important biological processes such as the development, regeneration, cell proliferation, and differentiation of skin tissue [70–75].

In conclusion, the changes in these genes and biological indicators reflect the biological effects of heat injury, involving multiple biological processes and signaling pathways such as the inflammatory response, oxidative stress, cell apoptosis, as well as inflammation and immune responses. In-depth research and analysis of these indicators contribute to a more comprehensive understanding of the biological mechanisms of heat injury, providing important evidence for the assessment, real-time monitoring, and prevention of excessive heat damage.

3 | Distribution and Depth of Thermal Effect

Changes in the different facial tissue are strongly linked to the various signs of aging. The primary causes of skin aging symptoms include decreased epidermal cell metabolic activity, aging and loss of collagen and elastic fibers in the dermis, abnormal microvascular function, and deeper changes like subcutaneous fat volume loss and weakening of the superficial musculoaponeurotic system (SMAS). Generally, the thickness of facial skin is 2–3 mm, with the epidermis averaging 0.03–0.04 mm in thickness. The total thickness of the facial subcutaneous tissue is 3–7 mm, including the superficial fat layer (approximately 1.5–3.5 mm thick), the SMAS (approximately 0.35–0.45 mm thick), the deep fat layer, and the deep fascia [76]. Therefore, the selection of appropriate photoelectric and ultrasonic devices and treatment parameters to target the changes in these tissue layers is crucial for achieving the goal of skin rejuvenation.

We summarize the mechanisms, levels, depths, and distribution patterns of thermal effects in skin remodeling using various energy devices (Table 1). Short or ultrashort pulse widths are typically employed for treating pigmented skin disorders, while long pulse widths (in the millisecond range) are used for vascular issues, and even longer pulse widths (millisecond to second range) are applied for tissue tightening and lifting. It is important to note that the treatment parameters of these energy devices—such as the power, frequency, pulse duration, and spot size—vary across studies. During treatment, physicians adjust these parameters based on their clinical experience and the skin's immediate response to achieve the most effective outcomes.

3.1 | Laser and Light Devices

From the epidermis to the dermis, lasers can act at various wavelengths and strengths to cause a variety of biological effects at different levels (Figure 1). The earliest medical lasers were continuous-wave lasers that removed skin from the entire operated area. However, their thermal dispersion could result in excessive damage to surrounding tissues due to the lack of precise control over the degree and extent of the thermal effect. Subsequently, quasi-continuous wave lasers emerged, reducing

TABLE 1 | Summary of thermal effects of energy device-based skin resurfacing applications.

Device type	Energy modality	Wavelength/ frequency	Target tissue	Mechanism	Thermal distribution	Clinical results
Light energy devices	CO ₂ laser	10 600 nm	Epidermis, middle dermis	Light energy converted to heat, water evaporation causes tissue ablation	Local evaporation and coagulation create micro-damage zones. Ablation of approximately 100 µm of skin with incidental 50–300 µm of adjacent thermal damage.	Improved skin texture, reduced wrinkles, enhanced epidermal smoothness
	Er laser	2940 nm	Epidermis, superficial dermis	High water affinity, superficial tissue ablation	Superficial thermal damage, localized heat effect, ablates 4 µm per 1 J/mm ³ . Each pass causes tissue ablation of 20–40 µm and accompanying thermal damage of 5–30 µm	Reduction of fine lines, improved skin tightness
	Nd: YAG laser	1064 nm (long pulses; Q-switched etc.) 1320 nm	Middle to deep dermis	Deep tissue heating, collagen remodeling, photomechanical effect	Deep thermal effect, induced collagen synthesis and tissue tightening, penetrates 1–2 mm, more than 4 mm	Reduced wrinkles, increased skin thickness
	Alexandrite laser	755 nm	Middle to deep dermis	Selective absorption by melanin and hemoglobin	Energy absorbed by chromophores generates thermal effect, penetrates up to 2–3 mm	Improved vascular lesions, pigmentation issues, and hair removal
	Pulsed dye laser	577/585/595 nm	Superficial dermis, blood vessels	Targets oxyhemoglobin, causes vascular coagulation	Selective thermal damage to superficial blood vessels, penetrates < 1.5 mm	Improved vascular lesions and pigmentation
	Nonablative fractional laser (NAFL)	1320–1927 nm	Deep dermis	Fractional heating creates microthermal zones (MTZs)	Thermal effect without epidermal damage, MTZs (< 100 µm) formation, penetrates into dermis (2–3 mm)	Reduced fine lines, improved scars, pigment reduction
	Intense pulsed light	500–1200 nm	Epidermis, superficial dermis	Selective photothermolysis of pigment and hemoglobin	Even thermal distribution, promotes superficial skin repair, penetrates 2 mm	Reduced pigmentation spots, improved redness, even skin tone

(Continues)

TABLE 1 | (Continued)

Device type	Energy modality	Wavelength/ frequency	Target tissue	Mechanism	Thermal distribution	Clinical results
RF devices	Monopolar RF	3–40.5 MHz frequency, electrodes	Deep dermis, subcutaneous fat	Energy conducted through grounded electrode and skin electrode.	Deep and even thermal effect, penetrates 3–6 mm (half the size of the active electrode)	Skin tightening, wrinkle reduction, improved laxity
	Bipolar RF	3–40.5 MHz frequency, current between two electrodes	Epidermis, superficial dermis	Current between electrodes, with a fixed distance, while both electrodes are in contact to the skin.	More controlled and localized energy distribution pattern. Superficial thermal effect, penetrates 1–2 mm (half the distance between the electrodes)	Improved skin laxity and superficial wrinkles
Focused ultrasound devices	HIFU (high- intensity focused ultrasound)	Frequency 2 MHz, energy 47–59 J/mm ²	Sub-dermis, SMAS layer	Mechanical vibration generates heat and cavitation effect	Strong heat focus, precisely distributed in tissue, penetrates 1.5–4.5 mm	Skin tightening, facial lifting, improved contour
	MFU (micro- focused ultrasound)	Frequency 4–10 MHz, energy 0.4–1.2 J/mm ²	Mid to deep dermis, SMAS layer	Mechanical energy creates thermal damage, stimulates dermis and SMAS	Micro-damage to deep tissue promotes collagen production, depths of up to 5 mm	Significant lifting effect, wrinkle reduction, enhanced skin tightness
High-intensity focused electromagnetic devices (HIFEM)	HIFES (high- intensity facial electromagnetic stimulation)	< 10 kHz electromagnetic field	Muscle tissue, Subcutaneous fat layer	Electromagnetic energy stimulates muscle contraction, enhances muscle tone and firmness	Superficial and focused electromagnetic waves create muscle contractions, minimal heat penetration	Enhanced muscle tone, improved facial contour

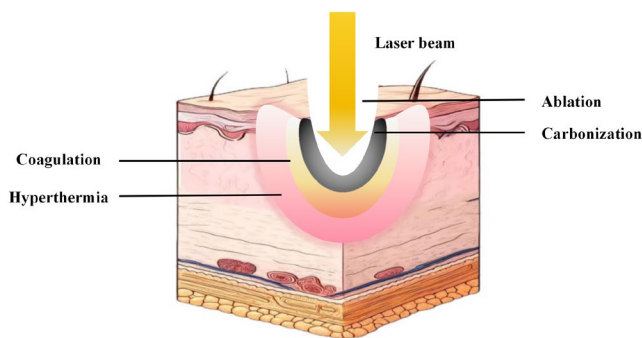


FIGURE 1 | The laser produces a photothermal effect on the tissue, and different temperatures and their duration of action can cause different thermal effects on the tissue.

the risk of thermal damage to some extent, but they remained nonspecific [77–80]. Human tissues contain chromophores that can absorb visible or infrared light. Through selective absorption, lasers target specific tissue chromophores such as melanin, water, hemoglobin, and hydroxyapatite [81–83]. Choosing the appropriate wavelength enables effective targeting and determines the depth of light penetration. This maximizes the effect on the target tissue while minimizing the impact on surrounding structures [6, 28]. The theory of selective photothermolysis proposed by Anderson and Parrish (1983) [13] laid the foundation for a highly selective and safe laser.

The ablative laser can remove the epidermis, while the thermal effect can reach the middle part of the dermis, stimulating the remodeling of collagen. This process improves the skin texture and quality through the coagulative necrosis of epidermal cells and the tissue repair response in the dermis. Common types of ablative lasers include carbon dioxide (CO_2) lasers and erbium-yttrium-aluminum-garnet (Er:YAG) lasers. The 10600 nm CO_2 laser disrupts tissue by rapidly evaporating water, ablating approximately 100 μm of skin, along with adjacent thermal damage ranging from 50 to 300 μm . The Er:YAG laser has a high affinity for water, and the ablation depth of the short-pulse Er:YAG laser is proportional to the total energy irradiated on the skin. For every 1 J/ mm^2 , 4 μm of tissue can be ablated. Therefore, at general energy levels, only shallow thermal damage areas (5–20 μm) are left. Studies have shown that each pass causes tissue ablation of 20–40 μm and accompanying thermal damage of 5–30 μm [39, 84]. Nonablative lasers maintain the integrity of the epidermis, common ones such as the 585/595 nm pulsed dye laser (PDL), which targets oxygenated hemoglobin and acts mainly on the superficial layers of the skin; the 1320 nm neodymium-doped yttrium aluminum garnet (Nd:YAG) laser penetrates well into the papillary dermis and the 1320-nm neodymium-doped yttrium aluminum garnet (Nd:YAG) laser penetrates well into the papillary dermis and the middle dermis, and is absorbed nonspecifically by the water in the dermis; the long-pulsed 1064-nm Nd:YAG laser's thermal effect area is 1–2 mm below the epidermis; the Q-switched 1064-nm Nd:YAG laser acts on the deeper dermis through an opto-mechanical effect; the 755-nm Alexandrite laser selectively affects the melanin and can penetrate up to 2 mm deep into the dermis; the thermal effect of the 1500–1600-nm NAFL reaches the reticular layer of the dermis to a depth of up to 2–3 mm [11, 28, 85–89]. Laser technology has advanced significantly in the last decade, particularly

with the introduction of the fractional laser treatment modality in 2004. This modality offers new treatment options for patients by inducing varying degrees of thermal effects on microdamage foci through either ablative or nonablative laser techniques. It enables the promotion of tissue remodeling within the microscopic treatment area [90–96].

Intense pulsed light (IPL) is a noncoherent light with broad wavelength coverage that passes through the epidermis while retaining its integrity [97]. It directly induces reversible thermal damage to the dermis and functions as a nonexfoliative light energy device. Despite not being a laser, the impact of this light source on tissue can be explained by the principle of selective photothermolysis. By selecting appropriate filters and adjusting the pulse width and the interval between pulses, a specific beam is directed to the target and targets specific chromophores [98–106].

As previously mentioned, the choice of wavelength primarily determines the depth of energy penetration. Furthermore, accurate management of the thermal effect necessitates a combination of appropriate pulse widths, energy fluxes, number of passes, handle movement rates, and spot sizes [18, 107, 108]. At a specific depth, the extent of temperature increase and thermal damage to the skin following laser treatment is directly linked to the laser dose, increasing with energy fluence and pulse width [18, 107, 108]. Second, in laser therapy, the thermal relaxation time is directly related to the target size. Spatial control of thermal damage, ranging from organ to organelle, can be achieved by using different exposure times, also called pulse widths. When the exposure time interval is less than the thermal relaxation time of the target chromophore, selective destruction of specific tissues can be achieved, reducing unnecessary thermal damage to surrounding tissues [13, 109, 110]. The pulse width also determines the mechanism of laser–tissue interaction. The long-pulsed 1064 nm Nd:YAG laser primarily utilizes photothermal effects, while the Q-switched 1064 nm laser primarily employs photomechanical effects [28]. In general, treatment devices can be selected based on the specific skin issues encountered. For instance, PDL systems offer varying wavelengths of laser bands (577, 585, and 595 nm) tailored to address vascular skin conditions and skin pigmentation. However, in practical application, the choice of wavelengths, pulse widths, and other parameters typically hinges on factors such as the nature of the skin problem, the patient's skin color, and the treatment area [111–114]. The Fitzpatrick skin typing system is widely employed to classify skin into six grades (I–VI) based on its reaction to UV light, correlating with increasing melanin content. For example, types IV and VI have a higher melanin content and darker skin color. The epidermis has a wider absorption spectrum, absorbing more light energy and therefore producing relatively more heat. This has the potential to interfere with the depth of laser penetration and affect its efficacy. In practice, while higher energy levels may be indicated, doctors exercise caution to tailor laser parameters to avoid skin damage from excessive melanin absorption. This involves employing specific laser types, adjusting pulse widths, implementing enhanced cooling techniques, and employing other strategies to ensure the treatment's safety and efficacy [115–125]. For patients with darker skin tones, it is preferable to choose laser types that target water to avoid skin damage caused by excessive melanin absorption. In the case of

hair removal on patients with fair skin and dark, dense hair, the long-pulsed 755 nm laser that targets melanin is more suitable.

The addressing of various types of skin problems through light energy has become immensely popular, and light therapy based on these devices is increasingly prevalent in clinical practice. From continuous-wave and quasi-continuous-wave lasers to pulsed and fractional lasers, all are progressing towards the concept of selective photothermolysis. This concept precisely controls the thermal effect on tissues, reducing excessive damage, shortening recovery time, and decreasing the incidence of associated complications. This advancement has improved the efficiency and safety of treatment while enhancing patient satisfaction.

3.2 | Radiofrequency Energy Devices

Radiofrequency (RF) refers to the frequency of oscillations per second of the electric and magnetic fields within the radio wave spectrum of the electromagnetic spectrum [126]. RF therapies use electrical waves in the frequency range of 3 MHz to 40.5 MHz. The intensity of RF penetration into the skin is inversely related to the frequency of the waves, which implies that the lower the frequency, the deeper the penetration of RF [35]. When RF energy is applied to the skin, it utilizes the electrical resistance within the skin layer or subcutaneous tissue to convert electrical energy into thermal energy. This process induces selective thermal skin damage, stimulating collagen neogenesis and rearrangement, resulting in tissue contraction and remodeling [127–131]. Unlike most lasers that target specific chromophores, RF relies on the electrical conductivity of the target tissue for selective electrothermolysis, eliminating the necessity for chromophores. RF energy primarily converts to heat through water within the tissue, rendering it unaffected by epidermal melanin and suitable for all skin types. The quantity of energy released as heat in the tissues is mostly determined by the RF generator's current intensity, tissue impedance, and duration of action. Water, nerves, muscle, collagen, other proteins, and fat are the order in which tissue resistance increases. Adipose tissue, for example, generates more heat due to its high

impedance [33]. Monopolar and bipolar RF systems are the most commonly used in clinics. Monopolar RF concentrates electrical energy close to the electrode tip and penetrates to a depth that is about half the electrode's diameter. A deeper therapeutic depth (3–6 mm) is possible with monopolar devices due to their high current penetration, but at the expense of discomfort. Monopolar RF generates a diffuse current that operates on collagen in the dermis as well as a deeper network of fibrous compartments in the subcutaneous fat layer [132, 133]. In contrast, bipolar RF uses two electrodes that are placed over the treatment area and have current passing between them, which results in a depth of penetration approximately half the distance between them. While bipolar devices offer less penetration, they provide more controlled energy distribution and reduced discomfort (Figure 2). Additionally, bipolar RF devices are frequently combined with light-based technology known as photodynamic synergy [126, 134–141].

The desired depth of RF treatments varies according to specific treatment requirements. Optimal results hinge on selecting the appropriate treatment modality for different skin or tissue concerns. Typically, RF treatments excel at addressing skin laxity, fine lines, scar and acne. Conversely, deeper RF treatments target subcutaneous fat tissues, aiming for localized fat reduction and body contouring through the heating of fat cells and stimulation of collagen regeneration [137, 142–144]. The latest RF devices use fractional technology to deliver RF energy through an array of electrodes, or microneedles. This selectively heats the contact area while keeping the surrounding area intact [145–150]. Additionally, Wilczyński et al. [35] utilized dynamic thermography to investigate skin temperature variations in different anatomical locations subjected to RF action. They showed that applying the same treatment parameters to different anatomical locations may result in distinct thermal responses. Specifically, after RF treatment, the peak skin temperature is higher in areas with a thicker adipose tissue layer. Conversely, in regions with less adipose tissue, patients have a lower tolerance to RF treatment at the same parameters. Therefore, in order to achieve safe and effective RF treatment, we need to consider the type of RF equipment, frequency, energy, duration of action, and individual patient variability.

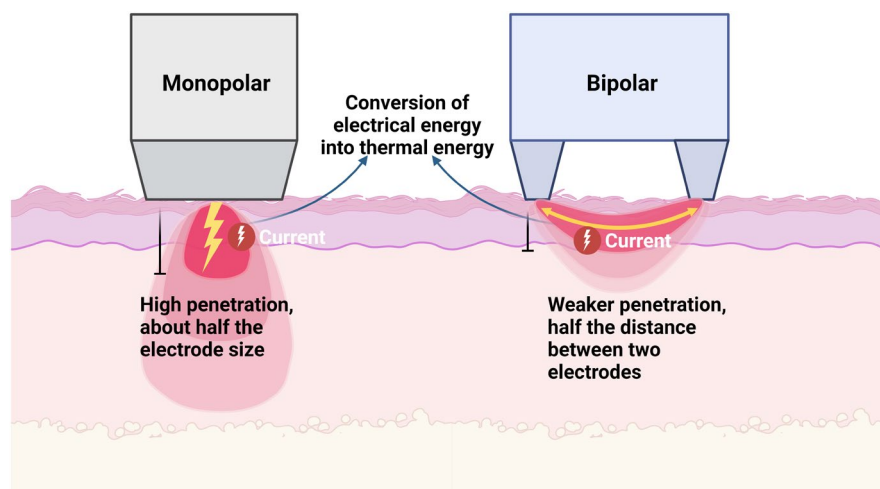


FIGURE 2 | RF devices act on the tissues to convert electrical energy into thermal energy, inducing selective thermal damage to the skin. The main RF systems commonly used are monopolar and bipolar RF.

3.3 | Focused Ultrasound Energy Devices

Focused ultrasonic energy equipment uses high-frequency sound waves above the hearing threshold to cause molecular vibration, which can induce heat and cavitation effects, resulting in cell damage and death. Focused ultrasound allows precise targeting of tissue, producing a small, well-defined, controlled zone of thermal damage with minimal damage to surrounding structures [41, 151]. Different frequencies, depths of focus, and energy levels can be used to create highly selective action areas of depth and size [152]. The two main types of focused ultrasound used in medicine are microfocused ultrasound and high-intensity focused ultrasound. High-intensity focused ultrasound (HIFU) employs high-frequency sound waves, primarily applied in medical aesthetics for ablating fatty tissues and noninvasively contouring the body. Conversely, microfocused ultrasound (MFU) utilizes lower levels of ultrasound energy to target the superficial layers of the skin, effectively achieving skin tightening [153–155]. HIFU energy beams, characterized by their high frequency, can be precisely directed to pass harmlessly through the skin and act on targeted tissues such as fat tissue and the superficial musculoskeletal nervous system [156, 157]. The tissue absorbs the ultrasound energy, causing molecular vibration, converting mechanical energy into thermal energy, and producing immediate micro-thermal damage. This triggers thermal coagulation of the tissue in a specific area [34, 158]. Simultaneously, the propagation of ultrasonic waves through tissues involves repetitive compression and rarefaction, which results in strong shear forces. This shearing motion generates frictional heat while simultaneously causing small bubbles in biological tissue fluids to swell and oscillate until they collapse. The collapse of these bubbles produces high temperatures within, which leads to cell death via mechanical processes caused by the forces produced during collapse [41] (Figure 3). MFU is mostly utilized for skin tightening and wrinkle reduction. The most generally utilized treatment parameters are 0.4–1.2 J/

mm² energy, 4–10 MHz frequency, and 1.5–4.5 mm depth of focus, which can be focused on and in the deep reticular layer of the dermis and subcutaneous tissues while leaving the papillary and epidermal layers undisturbed. The papillary dermis and epidermis remain unaffected. Current transducers emit at 10.0, 7.0, and 4.0 MHz, with focal depths of 1.5 mm (dermis), 3.0 mm (deep dermis), and 4.5 mm (subcutaneous tissues, including the SMAS layer). Clinically, HIFU uses 47–59 J/cm² of energy, a frequency of approximately 2 MHz, and a depth of focus of 1.1–1.8 cm to ablate subcutaneous fat [34, 41, 76, 122].

3.4 | High-Intensity Focused Electromagnetic Devices

High-intensity focused electromagnetic technology (HIFEM) uses low-frequency electromagnetic fields of <10 kHz to activate neurons in skeletal muscles, resulting in intense involuntary muscular contractions [159, 160]. This stimulation causes increased metabolism, raised extracellular fatty acid levels, adipocyte malfunction and apoptosis due to endoplasmic reticulum stress, and new muscle fiber formation by muscle satellite cells, all of which result in myofibrillar hyperplasia and fat loss [157, 161–164]. The combination of HIFEM and RF has been found to be safe and effective in fat loss and muscle strengthening, reducing treatment time and enhancing outcomes [165, 166]. The recently created high-intensity facial electromagnetic stimulation (HIFES) system, which is synchronized with RF technology, was designed exclusively to combat facial aging [167].

HIFES uses electromagnetic pulses to activate small superficial facial muscles, such as the frontalis and zygomaticus, restoring muscle tone, increasing muscle volume, tightening fascia, and remodeling the skin for a volumizing effect. It can also reduce dynamic wrinkles caused by excessive expression muscle movement by strengthening antagonist muscles or weakening dynamic muscle fibers [168, 169]. Kinney et al. [167] used RF in

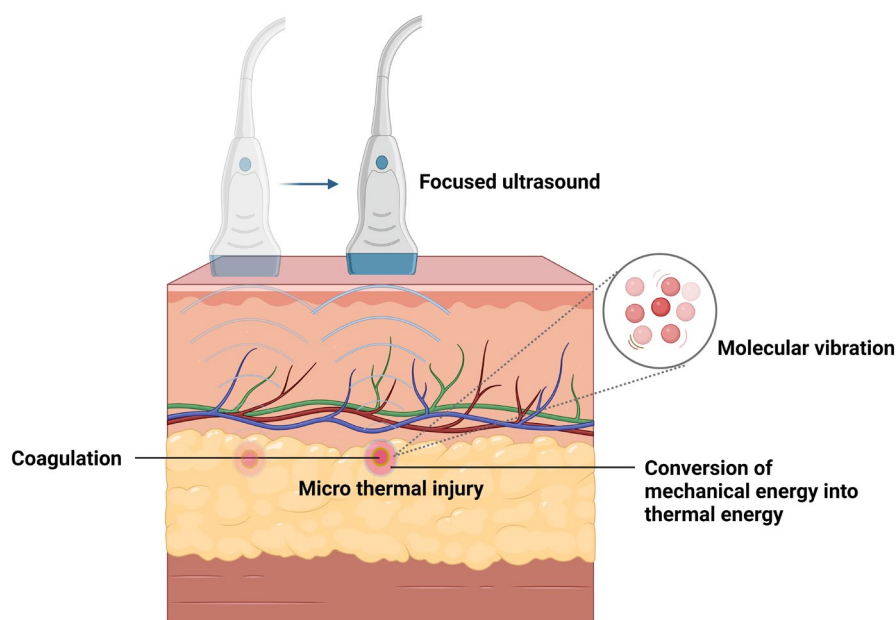


FIGURE 3 | Focused ultrasound energy beams act precisely on the tissue at the level of the focal point. The tissue absorbs the ultrasound energy causing molecular vibrations, converting mechanical energy into thermal energy and producing immediate micro-thermal damage.

combination with HIFES to treat the porcine frontalis muscle, and the follow-up results revealed a significant increase in facial muscle area, density, and mass, as well as histologic evidence of progressive muscle tissue replacement of adipose and connective tissue. Through simultaneous RF and HIFES technology, the tissue is heated within the effective temperature range to promote collagen regeneration and electrical stimulation of specific facial muscles, resulting in noninvasive face lifting, wrinkle reduction, facial contour reshaping, and skin texture improvement [170, 171].

4 | Discussion

Energy-based devices convert thermal energy and transfer it to the target area using various forms of energy like light, focused ultrasound, radiofrequency, etc. This induces a thermal effect on the tissues, treating and repairing the skin for regeneration and remodeling. Utilizing photoelectric and ultrasonic technology for skin rejuvenation involves a rational application of tissue fibrosis. Fibrosis is the process involving collagen synthesis, deposition, and extracellular matrix reconstruction in damaged tissues during tissue repair or pathology. It is a crucial biological process that significantly contributes to enhancing the elasticity, density, and texture of the skin. It serves as the foundation for skin tissue repair and regeneration, yet it is a double-edged sword.

The primary objective of using energy devices in skin rejuvenation is to achieve a controlled and beneficial thermal effect within the dermis and subcutaneous fascia layers while minimizing damage to the epidermis. It is important to consider the threshold of irreversible thermal damage that affects different components of the skin tissue. Within a certain range, a higher intensity of thermal stimulation results in a more favorable thermal effect. Reversible thermal damage and, to a lesser extent or at shallower depths in the skin, irreversible thermal damage can increase the metabolic activity of cells in the treated area or in adjacent tissues. This stimulation promotes the synthesis and deposition of collagen during the repair process, filling in damaged tissues and improving the strength and stability of the skin. However, if irreversible thermal injury is too severe, it can lead to challenging tissue damage, apoptosis (programmed cell death), and excessive necrosis. The subsequent excessive fibrosis can negatively affect the tissues, causing tightness, loss of natural softness and elasticity, and potentially resulting in irregular texture and scar formation on the skin surface. It is important to carefully manage the interval between treatments to allow the skin to recover and generate new collagen after each session. The optimal treatment interval should be determined based on individual skin response, treatment goals, and the specific treatment area to avoid excessive fibrosis.

5 | Conclusion

The thermal effect is critical when using photoelectric and ultrasonic technologies in skin remodeling. Thermal damage and rejuvenating benefits can be assessed by examining tissue changes at various temperatures. Analyzing molecular markers is critical

for tracking injuries and avoiding serious harm. Understanding device processes, treatment settings, and patient variances is essential for controlling thermal effects. Optimizing these characteristics results in more effective outcomes while lowering hazards. Continuous monitoring and research will help us better manage heat damage in skin treatments.

Author Contributions

Ximeng Jia collected the data and wrote the paper. Yongqiang Feng developed the idea and assisted the first author to revise and polish the paper. All authors contributed to the article and approved the submitted version.

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Ethics Statement

All procedures performed in studies involving human participants were in accordance with the institutional and/or national research committee's ethical standards, as well as the 1964 Helsinki Declaration and its subsequent amendments or comparable ethical standards.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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