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Review Article

Physics of fractional microneedle radiofrequency – A review

Somodyuti Chandra[1], Venkataram Mysore[2], Swapnil Shah[3], Deepthi Malayanur[4], Shivani S R[4]

[1]Department of Dermatology, Medica Superspeciality Hospital, Kolkata, West Bengal, [2]Department of Dermatology, The Venkat Centre for Skin and Plastic Surgery, Bengaluru, Karnataka, [3]Department of Dermatology, Ashwini Rural Medical College, Hospital and Research Centre, Solapur, Maharashtra, [4]Department of Dermatology, The Venkat Center for Skin, Ear, Nose, and Throat and Plastic Surgery, Bengaluru, Karnataka, India.

***Corresponding author:**
Deepthi Malayanur,
Department of Dermatology,
The Venkat Center for Skin,
Ear, Nose, and Throat and
Plastic Surgery, Bengaluru,
Karnataka, India.

deepthi.malayanuru@gmail.com

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ABSTRACT

Fractional microneedle radiofrequency (RF) is a novel device that is gaining popularity in the treatment of many esthetic and dermatological conditions. The encouraging effectiveness and side-effect profile, along with little or no recovery time makes it an attractive therapeutic option. The device allows non-thermal penetration of microneedles into the dermis followed by RF-induced coagulation. The aim of this article is to provide a thorough understanding of the working principle and physics of this technology so that the clinicians can modulate its various parameters for effective treatment of a variety of dermatological conditions in all skin types. Methods used for locating, selecting, extracting, and synthesizing data include usage of key words such as microneedling, fractional, and RF using multiple search engines such as PubMed and Google search. Multiple articles were surveyed and finally, 30 articles including a few chapters from the textbook were refined into our search. This article is an attempt to simplify the physics of fractional microneedling RF.

Keywords: Microneedling, Fractional radiofrequency, Impedance, Insulated needles

INTRODUCTION

As the interest and demand for cosmetic treatments increase, there is a gradual shift of preference from surgical correction to less invasive treatment modalities with minimal downtime. Over the past few decades, energy-based devices have enjoyed increasing popularity for the treatment of a wide array of skin conditions. The radiofrequency (RF) devices are one such example. These devices have come a long way from the monopolar systems to the fractional RF devices and have revolutionized skin esthetics. In dermatology, the US FDA approved the first RF device in 2002 for non-ablative treatment of periorbital rhytids; and in 2004, it was approved for full face rejuvenation.[1] Later, in 2006, the use of this monopolar RF device was expanded to non-facial indications.[2] Hantash *et al*., in 2009, devised a fractional RF system fitted with pairs of microneedles as electrodes to deliver RF energy at accurate depth in the dermis, called microneedle RF (MNRF).[3] An advantage of this fractional RF is that, it causes less epidermal disruption, only 5%, compared to 10–70% by fractional ablative laser systems. The healing process is faster with minimal downtime.[4]

Although the use of fractional MNRF (FMNRF) devices has become popular among clinicians in the past few years, with indications expanding by the day, there is a dearth of exact treatment parameters and therapeutic guidelines in literature. The goal of this review is to understand the working principle and physics of the FMNRF system, its parameter settings and their effects, suitable technique, and newer modifications in the device.

THE PHYSICS OF RADIOFREQUENCY (RF) TECHNOLOGY

Fractional skin treatment was introduced in esthetic medicine using lasers. Unlike lasers where the thermal coagulation is resistance restricted to the periphery of the ablation crater, FMNRF produces an area of coagulation at selected depth in the dermis surrounded by a zone of non-coagulative volumetric heating, thus adding volumetric heating to fractional treatment. In contrast to lasers that have photothermal effects, the RF technology works by electrothermal tissue reaction. There is no predilection for any chromophore as in lasers, and hence, RF is color blind. It is free from the influence of diffraction, scatter, absorption, and other tissue interactions, making it suitable for controlled deep tissue penetration in all skin types.[5]

RF is a high-frequency alternating current that is generated using electromagnetic radiation in the frequency range of 3 kHz to 300 MHz.[2] When this current passes through the tissue, it meets with resistance inherent to that tissue. This is called the impedance, which evokes high frequency oscillation in the water molecules in the dermis and subsequently leads to heat generation. As per the Joule's law of heating, the amount of heat generated can be calculated by the following formula:

$$\text{Energy (Joule)} = I^2 \times R \times T$$

Wherein, I = current, R = tissue impedance/Resistance, T = time of application.[6]

This equation demonstrates that the amount of energy delivered to the tissue is directly proportional to impedance or resistance offered by the tissue, amount of current delivered, and the time of application of the current. Thus, the high impedance tissues, like the subcutaneous tissue, generate greater heat and account for the deep dermal effects of the RF devices.[6]

Skin is a heterogeneous structure with its surface penetrated by sweat glands that are variably filled with sweat. The impedance offered by dry and wet skin differs considerably. Dry stratum corneum is almost impermeable to electric current and, hence, offers higher resistance than wet stratum corneum. Furthermore, the granular layer and the basement membrane offer high resistance, due to the tightly packed nature of the cells in these layers. The stratum germinativum, on the other hand, is more permeable, due to the presence of large intercellular canaliculi. The papillary dermis consists of loosely arranged tissue and offers less resistance than reticular dermis. The subcutaneous tissue, muscle, and bone offer the highest resistance to RF.[7]

The impedance offered by the skin, not only varies in-between individuals but also between different body sites and its relative humidity level in the same individual. The reasons for this observation are unclear but may be supported by studies that observed regional variations in stratum corneum lipid content in intact human skin (face > abdomen> leg > plantar stratum corneum) and were directly related to their barrier permeability.[8] It can also be altered by external manipulations, such as application of moisturizers or by infiltration of local anesthetics, both of which increase tissue conductivity by increasing water and salt content.[9,10]

The impedance of a tissue can be calculated by the following formula:

$$R = \rho \times L/S$$

Wherein, R = resistance, ρ = resistivity of tissue, S = cross sectional area of tissue experiencing RF, and L = distance between two electrodes.[11]

Resistivity is defined as the resistance offered by the material per unit length for a unit cross-section. The International system of units (SI) of resistivity is ohm-meter. Resistivity increases linearly with temperature.

Electrical conductivity (or specific conductance) is the reciprocal of electrical resistivity

The relative conductivity of different biological tissues was studied by Gabriel *et al*., and it is summarized in Table 1.[12]

The impedance of biological tissue also depends on the frequency of RF device, as well as the temperature of the tissue. It is directly proportional to the device frequency in the range of 100 kHz to 1 MHz, with minor change at higher frequency. Increasing temperature of tissue reduces its impedance, till the point of coagulation. Thereafter, with further increase of temperature (at 90–100°C), tissue impedance increases substantially, due to evaporation of water.[12] Temperature also changes the conductivity of the skin or its impedance.

The RF current prefers the heated warm tissue. Therefore, by changing the temperature of the tissue, we can direct the RF current. For example, using a cooling contact tip on the surface of the skin, the RF current flows deeper into the dermis.[13]

The frequency range of the RF devices used in dermatology varies from 0.5 MHz to 40 MHz. The frequency of RF is inversely proportional to the penetration depth. The lower frequencies have higher depth of penetration. Most of the microneedling RF devices use 1 MHz or 2 MHz frequencies.[14]

RF can be divided based on the electrode configuration: monopolar RF has a single electrode with a grounding

Table 1: Conductivity of biologic tissues at 1 MHz.

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

pad; unipolar RF is through antenna transmission; and bipolar and tripolar RF employ multiple electrodes in the handpiece tip whereby the current traverses the skin through a closed circuit. The penetration depth of multipolar RF when delivered on the skin surface averages about one-half the distance between the electrodes. MNRF delivery bypasses these barriers and delivers energy directly into the dermis and subcutis. The singular breakthrough of the first MNRF device (Profound; Candela Medical, Wayland, MA) is based on thermistors within electrode needle tips, allowing real-time feedback of both impedance and temperature.[15-18]

Various subtypes include:

1. Monopolar RF
    a. Probe-delivered monopolar radiofrequency
    b. Microneedle-delivered monopolar radiofrequency
2. Unipolar radiofrequency
3. Bipolar radiofrequency
    a. Skin surface bipolar radiofrequency
    b. Needle-delivered bipolar radiofrequency

TISSUE INTERACTIONS FOLLOWING MICRONEEDLE RADIOFREQUENCY (MNRF) TREATMENT

The RF energy when fractionally delivered into the skin through a series of microneedles generates heat due to electrical impedance. This creates controlled microscopic zones of denatured collagen called RF thermal zones (RFTZ), interspersed with normal tissue as mentioned in Figure 1. Prominent neutrophilic infiltration around these cocoon-shaped RFTZs are seen, as early as 24 h after the procedure, that shifts to a lymphocyte and histiocyte predominant infiltrate after 3 days, which persists up to a month.[4] The surrounding unaffected tissue serve as reservoir of cells to promote and accelerate wound healing.[19]

MNRF treatments induce active dermal remodeling through immediate collagen contraction and shrinkage, followed by activation of fibroblasts and increased expression of several cytokines, growth factors, heat shock proteins (HSP), and extracellular matrix proteins. These include HSP 47, HSP 70, HSP 72, matrix metalloproteinases (MMP-1, 3, 9 and 13),

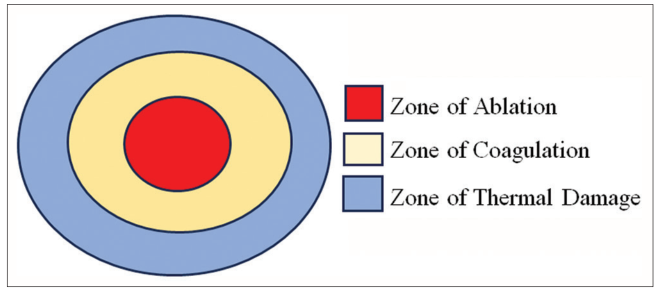

Figure 1: Formation of Radiofrequency Thermal Zones.

transforming growth factor-β, tumor necrosis factor-α, and interleukin-1β. As a result, there is neocollagenesis and neoelastogenesis that can be detected as early as 1-month post-treatment.[20,21] In addition, it also increases epidermal proliferation, differentiation, and hyaluronic acid content, together bringing about clinical dermal rejuvenation.[22]

While studying the histometric effects of MNRF on mini-pig models, Hantash *et al*. found significant differences in impedance and permittivity between papillary dermis, reticular dermis, and subcutaneous fat. The superficial papillary dermis having the least impedance produces a smaller zone of thermal injury compared to the reticular dermis. Hence, the epidermis is relatively spared from the thermal effects.[3] Sparing of the adnexal structure and adipose tissue was another noteworthy finding. The follicular epithelium and the perifollicular structures undergo coagulation, with or without disruption of the follicular structural integrity, depending on the treatment parameter. Follicular disruption is typically seen at higher energy level (50 V) rather than with higher pulse duration.[20] While coagulating the periadnexal and interstitial collagen, the RF energy leaves the sweat glands, sebaceous glands, blood vessels, and adipose tissue unscathed.[3]

MNRF PARAMETERS AND THEIR CLINICAL RELEVANCE

The main disadvantage one faces in this technology is that parameters are product dependent and, hence, have individual variations depending on the proprietary machine. There is indeed a deficit of standard guidelines and uniformity in their various settings in published literature. However, few basic parameters are mostly common in all MNRF systems and are discussed below.

- Pulse-A pulsed wave is an oscillating wave having an "on" and "off" time at regular intervals. Machines have either single or repeat mode pulses. In single mode pulse, only one energy wave is passed into the skin when the foot switch is pressed; while in repeat mode, multiple waves are passed during the "on" time.

- Pulse duration-Pulse duration or the exposure time determines the volume of thermal coagulation. Longer the pulse duration, larger will be the area of dermal coagulation. Pulse width, along with needle depth, are the most important parameters as, according to histometric studies, needle depth and pulse duration, but not the energy level, have been found to significantly affect the extent of RF-induced thermal coagulation.[20,23]
- Energy or Power level-The level of power setting determines the intensity of the electrothermal damage. That is, higher the energy, greater is the degree of tissue destruction and desiccation, at the same needle penetration depth and RF conduction time.[23]
- Needles-The machines available use several types of disposable microneedles of varying type, length, and density (pins/cm^2). These needles are made of stainless-steel and are available in 30G (e-Prime®), 32G (Evolastine®), or 34G (Infini®) sizes. They serve as electrodes that are arranged in a bipolar array, delivering short pulses of RF energy at appropriate depths in the dermis.
- Type of needles-The MNRF devices are provided with either insulated or non-insulated microneedles, while few machines have the provision of both. The insulated needles have a gold coating to enhance conductivity, along with a double layer of silicone covering, except for the terminal 300 µm at the tip. The insulation of these needles allows the RF energy to be delivered only at a specific depth in the dermis, thereby protecting the insertion site from thermal damage. In the non-insulated needles, on the other hand, the entire length of the needle serves as the active electrode.

In an *in vivo* micropig study, it was found that the insulated needle produces an oval water drop-shaped zone of coagulation at the tip of the needle and not in between the needles, immediately after the treatment.[20] While studying electromagnetic initiation and propagation of RF in tissue using non insulated needles, Jongju *et al*. found that the coagulation column develops separately around each microneedle; however, RF-induced reaction between the needle and epidermis does not occur. They also concluded that there is no difference between the zones of coagulation between insulated and non-insulated needles, neither there is any epidermal thermal damage.[23]

The Infini® and Ultracell® machines have only insulated needles, while the Intensif®, Secret®, Explore®, and Scarlet® platforms have only non-insulated needles. The Bodyshape RF® and Vivace® machines have the provision of both – insulated and non-insulated needles.

- Number of needles-The machines are provided with sterile, single-use disposable tips, fitted to a handpiece and having 12, 24, 25, 36, 40, or 49 sets of microneedles. With a higher number of needles, larger areas can be treated simultaneously.
- Depth of needle insertion-The microneedles are available in 0.5-, 0.8-, 1.5-, 2-, or 2.5 mm sizes. Some machines have the facility of user-variable depths of penetration ranging from 0.5 mm to 3.5 mm. With such machines, several different depths of the dermis can be simultaneously and predictably treated, creating multi-layered zones of thermal injury, with a better overall therapeutic outcome.

Needle length is an important consideration for tissue damage. Harth and Frank objectively evaluated the effect of needle length and energy density on the area of thermal coagulation. They found that other parameters being unchanged, reducing the needle length decreases the needle surface area, and thereby increases the energy density. This, in turn, leads to an increase in the width of the coagulated zone.[24] Similarly, Jongju *et al*. reported that deeper penetration with microneedles generates larger columns of coagulation at same RF energy and time.[23]

The treatment depths are usually altered according to the skin thickness of the treated area [Table 2]. However, these depths are altered according to the specific condition that is being treated. For example, while treating deep acne scars or traumatic atrophic scars depths up to 3.5 mm may be reached. Nevertheless, in all cases, the least depth attained is 0.5 mm, which is below the dermoepidermal junction.[19]

- Thickness of needles-Usually, the needle thickness is 0.3 mm but needles as thin as 0.2 mm (Infini® device) or thicker ones (Ultracell® device) are also available. The needles taper at the end to a very sharp tip. The diameter of the needle affects the pain level during treatment. The thinner the needle, smoother is its entry into the skin and less is the patient discomfort.
- Method of needle insertion-The needles may be inserted manually or may be automatically controlled. Although manual insertion is simple, there can be a difference in the depth of penetration depending on the force applied by the user. Whereas, in the automated needle insertion, the handpiece pushes the needle to the same depth every time, giving precision to the treatment.

Table 2: Recommended depth of needle insertion according to treatment sites.

Sites	Depth of needle insertion (mm)
Periorbital area	0.5–1
Forehead	0.8
Chin	1
Temple	1
Cheek	2
Submental (adipose tissue)	4
Abdomen	4.5

- Angle of needle insertion-The microneedles penetrate the skin perpendicularly in most machines. However, in the e-Prime® system, the needles penetrate the skin at a 25° angle, whereas in the Evolastine® system, they penetrate tangentially. Tangential or acute angle insertion makes the exact depth of penetration into the skin unpredictable. Other limitations of these machines include increased incidence of pain, incorporation of fewer needles in the head, risk of bending of the needles, and the necessity of epidermal cooling. On the other hand, perpendicular insertion ensures more accurate knowledge of the depth of thermal ablation in the dermis and additionally enables the usage of more needles in the tip for coverage of larger area at a time.
- Passes-Single or multiple (2–4) passes can be used depending on the area being treated and the machine used. While using machines where the needle depth can be altered, multi-pass layering is recommended; starting with the maximal desired depth and decreasing successively with subsequent passes. In such cases, the energy level and pulse duration should also be reduced simultaneously as the epidermis is approached to reduce unwanted epidermal thermal damage. This is particularly correct if we are using insulated needles. Since the zones of coagulation occur only at the tip of the needle, it is better to give three passes at three different depths starting from the longest needle depth and decreasing successively. This will enable the total coagulation of dermis around the needle. There is no advantage of giving multiple passes while using non insulated needles for obvious reasons. Stacking at the same depth should be avoided since the tissue impedance decreases with rise in the temperature and hence, the energy delivered at the second pass will be erratic.

EFFECT OF MICRONEEDLE RADIOFREQUENCY (MNRF) ON EPIDERMIS

The MNRF primarily acts on the dermis, but nevertheless, there is a non-thermal penetration of microneedles through the epidermis. This effect resembles a simple physical needling to damage the epidermis and thus results in rearrangement of stratum corneum and increase in epidermopoiesis. It also causes superficial micro-bleeding and release of various growth factors, thus improving the overall appearance and texture of skin.

Microchannels created by simple needling damage to the stratum corneum and basement membrane coupled with thermal coagulation at the dermis, increases the permeability of the skin by many folds. This may provide a novel way of delivering many drugs, particularly the hydrophilic ones, into the skin transdermally.[25]

Sasaki investigated the change in transepidermal water loss (TEWL) as a measure of lipid-barrier permeability and its renewal after microneedling and MNRF procedure.[26] The study demonstrated that TEWL values were greatest immediately after injury by MNRF and sloped steadily downward toward baseline values within 2–3 h after disruption. Interestingly, scalp and mid-face recorded the highest post-procedure increase in TEWL within the first hour of the procedure compared to other body sites like neck, chest, arm and thighs.

Physician knowledge of the onset and recovery period of a penetrated epidermal lipid barrier system would be advantageous for optimizing the passage of safe products such as growth factors and platelet-rich plasma through the microchannels after needling. On the other hand, an intentional delayed application of cosmeceuticals, sunscreen blockers, and drugs on a restored barrier system may reduce the incidence of other complications such as product sensitivities and allergies.[26]

NOVEL TECHNOLOGIES

Given the quest for improvement, companies are continuously upgrading themselves to minimize patient discomfort and enhance their satisfaction. The newer modifications to the FMNRF devices are as follows:

- Cooling system-Machines with cooling systems integrated into the tips have come. These have digitally pulsed delivery of RF energy, wherein the RF is interrupted after every set pulse duration by a burst of cool air. This ensures further alleviation of pain and discomfort.[27]
- Vibratory hand piece-These help in dampening pain based on Gate Control Theory of Pain Mitigation. The activation of α-nerve fibers by the vibratory stimulus excites the inhibitory neurons, which, in turn, blocks conduction of pain impulses through the small C-fibres.[27,28]
- Impedance sensing tips-Newer generation devices come with impedance sensing tips and warn about the correct selected energy delivery. It is a considerable safety feature by which one can avoid over or under treatment.
- Temperature and pressure sensing tips-These machines continuously monitor temperature and pressure of the tissue. They automatically shuts-off when the handpiece is not in full contact with the skin. This feature prevents the phenomenon of RF "arcing" which is felt like static shock by the patient.[27]
- Vacuum stable FMNRF device-These devices have incorporated a vacuum system in the handpiece. The vacuum sucks and holds the skin in position, so as to stabilize the treatment area. In addition, it causes numbness and blanching of the center where the microneedles are inserted. This decreases pain and bleeding and makes the procedure comfortable, particularly around eyes and over bony prominences.

NOVEL TECHNIQUES FOR APPLICATION OF MICRONEEDLE RADIOFREQUENCY (MNRF)

Pall and Pall[29] have outlined an innovative approach of treating acne scars with bipolar rotational stamping (Wosyet vital technique) and monopolar criss-cross technique with insulated microneedling RF in Asians.

Wosyet vital technique (Bipolar rotational stamping)

Initial treatment was carried out using rotational stamping at multiple depths for individual scars. In the described rotational method, the initial needle length of 1.5 mm was chosen and the procedure was carried out with bipolar RF technology. The handpiece was, further, rotated at 30° angles with each shot using a round direction around a single axis until the scar and scar rim consisting of a few areas of normal tissue were evenly covered. Cumulatively, three shots were being given at every site. Furthermore, rotational stamping treatment was carried out on the same scar by decreasing the needle length to 0.8 mm and 0.5 mm. Interestingly, adjustment of needle length was done to make sure every individual scar is treated using high RF energy without injuring the epidermis.

MONOPOLAR CRISS CROSS TECHNIQUE

Subsequently, the whole of each side of the face was covered using the criss-cross principle using the monopolar RF mode. The depth of the needle was calibrated to 2 mm and the probe is then made to move in a linear path and subsequently rotate the angle by 45°, further bringing the probe back in the same linear path in a reverse motion. Hence, monopolar RF was given at 2 passes throughout the entire procedure area. Similar pattern of procedure was then carried out on the other side of the face.

DIFFERENCE BETWEEN MONOPOLAR AND UNIPOLAR DEVICES

Unipolar RF is applied with a single electrode. Unipolar RF has to be differentiated from monopolar RF that uses single active electrode and one return electrode.[30]

CONCLUSION

FMNRF devices are a novel technology providing a minimally invasive therapeutic option. Its impressive efficacy and safety record in all skin types make it an invincible asset to the dermatologists. Some commercial companies also provide separate heads (Superficial fractional RF) to noninvasively (using fractional RF energy externally) treat superficial dermis and epidermis. It achieves results similar to fractional lasers while avoiding the side effects of post-inflammatory hyperpigmentation and, hence, is useful in treating Indian skin types. There are no major side effects and minimal or no down time. However, multiple sessions are required to achieve good results and equipment is costly. The importance of accurate knowledge of the machine settings, parameters, and their proper modulation to treat a wide range of clinical conditions cannot be overstated.

Authors' contributions

Somodyuti Chandra was instrumental in acquisition of data, drafting and compiling. Venkataram Mysore had substantial contributions to the design of framework, analysis, interpretation of the data and critical revision of data. Swapnil Shah had a substantial contribution to the design of the framework, analysis and interpretation of the data. Deepthi Malayanuru had contributed in drafting the article and critically revising it. Shivani SR had contributed to drafting the article and acquisition of Data.

Ethical approval

The Institutional Review Board approval is not required.

Declaration of patients consent

Patient's consent was not required as there are no patients in this study.

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Conflicts of interest

Dr. Venkataram Mysore and Dr. Swapnil Shah are on the Editorial Board of the journal.

Use of artificial intelligence (AI)-assisted technology for manuscript preparation

The authors confirm that there was no use of artificial intelligence (AI)-assisted technology for assisting in the writing or editing of the manuscript and no images were manipulated using AI.

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