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Knee joint diathermy using microwave technology

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ABSTRACT

Abstract: Microwave diathermy (MD) improves knee osteoarthritis pain and function. However, non-adherence to this therapy remains a major concern. The equipment is expensive and requires substantial deployment; thus, it's only available in professional physiotherapy facilities. Consequently, the practicality and widespread applicability of this heating therapy are limited. Therefore, the purpose of this study was to present a new modality treatment of MD specialized for knee joints by developing an applicator that operates at 433.78 MHz with high quality factor (~6000), for localized heating using a re-entrant microwave cavity (RMC). RMC was designed and simulated using COMSOL Multiphysics®4.4. Simulation results have shown the capability of this heating system to develop localized heating at the knee joint and peri-articular structures with a very high-power absorption rate. ~95% of the delivered power to the applicator has been absorbed by the knee joint owing to its high-quality factor. The relatively small volume over which the electric energy is focused makes it an attractive and viable candidate for manufacturing as a small and portable device to be available for patients to use it at home.

1. Introduction

Osteoarthritis (OA) is a chronic joint disease associated with general joint degeneration; leading to joint pain, stiffness, and functional disability [1], where the knee is the most frequently affected joint [2]. Rehabilitation is needed to help OA patients regain mobility and reduce pain [3]. Heat therapy, which has been utilized for a long time in the treatment of knee OA, may be administered using several heating modalities, such as ultrasounds, shortwave [4], microwave diathermy (MD) [5], the use of hot packs [6], and the use of warm water and wax baths [7, 8]. It is hypothesized that hyperthermia induces its effects by causing an elevation in regional blood circulation as a consequence of tissue warming. This increase in blood flow enhances metabolic activities and the elimination of toxins, hence aiding in tissue healing and alleviating pain [8]. Furthermore, the local administration of MD has been shown to stimulate the production of heat shock proteins [9]. These proteins play a crucial role in facilitating correct protein folding and the elimination of cellular waste substances.

MD is a physical therapy modality that produces deep heating by converting electromagnetic energy into thermal energy, utilizes electromagnetic radio waves with frequencies of 27.12 MHz [10], 150 MHz [11], 433.92 MHz [12], 915 MHz [13], 925 MHz [14], and 2.450 GHz [15, 16]. The proposed explanation for the diversity of frequency used in MD among researchers may be attributed to the varying tissue depths at which heat can be generated within biological tissues. Microwaves exhibit preferential absorption into tissues characterized by elevated water content, such as muscular tissue. In light of this, MD is well-suited for treating pathologic conditions affecting the knee joint and its surrounding tissues. Concerning the alleviation of symptoms, MD has shown notable advancements in reducing pain and enhancing physical function among individuals with symptomatic knee OA. These advantages have been seen to extend over a follow-up period of 4 to 12 weeks [17, 18].

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Nomenclature:

E-field	Electric field
FDTD	Finite difference time domain
MD	Microwave diathermy
OA	Osteoarthritis
RMC	Re-entrant microwave cavity
SAR	Specific absorption rate

Symbols

L_1 , L_2	Mmutual inductances
Z_0	characteristics impedance of the coupling feedlines
ω	Wave angular frequency
μ_r	Relative permeability
k_0	Wave number in free space
ε_r	Relative permittivity
σ	Material's electric conductivity
ε_0	Permittivity of the free space
ε_2	Mmaterials' loss factor
Q_n	Aapplicator's quality factor

A microwave-based thermotherapy device for knee joint problems was studied by [16], using a 2.45GHz circular array of dipole antennas. The finite difference time domain (FDTD) approach is used to determine the knee's specific absorption rate (SAR) distribution using electromagnetic simulations. Temperature increases due to microwave radiation are substantially limited by the thermoregulatory system. Inhibiting thermoregulation raises blood temperature. Even if power absorption is restricted to one body location, body temperature will rise. Although the electric field (E-field) takes just 109 seconds to achieve a steady state within biological tissue, it takes roughly 20 minutes for the tissue to attain stable temperature under the given boundary conditions. Considering temperature development throughout time is intriguing. Average knee power linearly affects local and averaged muscle SAR values. Results indicate a linear relationship between tissue temperature (up to 39 °C) and knee power incident. The process of heating by using microwaves is a multifaceted phenomenon contingent upon several factors, including the dielectric characteristics of the material, the configuration and volume of the material, and the design of the microwave structure. The aforementioned characteristics play a critical role in influencing the absorption of microwave power by a material [19, 20]. Microwave energy is capable of penetrating through the dielectric material and undergoing a conversion process, resulting in the generation of thermal energy. Microwaves induce dielectric material heating through their E-field component. Consequently, a rise in the temperature of the material occurs, resulting in a thermal gradient where the internal components experience higher temperatures compared to the surface, mostly owing to the surface's greater heat dissipation to the surrounding environment. As a result, this particular characteristic enables the homogeneous distribution of heat throughout extensive portions of the material. The primary processes on which electricity depends are dipolar polarization and ionic conduction. In the context of dipolar polarization, the response of a dipole inside a material to an external E-field involves an endeavour to align itself with the direction of the field through rotational motion. At microwave frequencies, the dipoles within the dielectric material are unable to respond fully to the rapidly oscillating electric field. Consequently, heat is generated as the dipoles interact with each other. In the ionic conduction mechanism, the movement of charge carriers, including electrons and ions, occurs in a reciprocal manner inside the material in reaction to the E-field generated by microwaves. These movements give rise to electric currents, which lead to Ohmic heating in the dielectric material. The phenomenon of heating arises as a result of the electrical resistance generated by the interactions between charged particles and neighboring molecules or atoms present in the material [21-23]. Despite the potential efficacy of MD in alleviating pain, its use has been restricted by the high equipment cost and limited availability only in specialized physiotherapy centers. Consequently, the widespread adoption of this treatment modality may need to be improved. The intensity of these fields varies based on several criteria, such as the frequency of the unit and the properties of the applicator. Based on these premises, the purpose of the present study is to apply a new approach of MD at the knee joint by developing a compact applicator, operates at 433 MHz, for localized heating by using a re-entrant microwave cavity (RMC). Also, to study the temperature – time relationship and temperature distribution across different areas of the knee joint with the aid of COMSOL, and to address possible parameters that affect them which shed lights on future directions in the use of this approach on the basis of limitations and considerations that should be taken. The localized dielectric heating in the RMC can be attributed to the elevated concentration of the E-field within the gap area between the inner posts of the re-entrant cavity. In contrast, the magnetic field that is linked to this phenomenon is comparatively reduced and spread out over a greater area, leading to less loss of energy on the metal surfaces that are exposed. As a result, the RMC demonstrates a high level of quality. The attractiveness of RMCs originated from their simple mechanical composition and extensive tuning frequency breadth. The presence of a gap in RMCs leads to a decrease in frequency within the low GHz range and concentrates the electric field, all without requiring significant physical dimensions [24].

Figure 1 illustrates a cross-sectional view of the RMC. The active gap area functions as a parallel-plate capacitor, with its capacitance exhibiting an inverse relationship with the width of the gap. The generation of the magnetic field occurs circumferentially by the flow of surface currents in the indicated directions, as seen in Fig. 1.

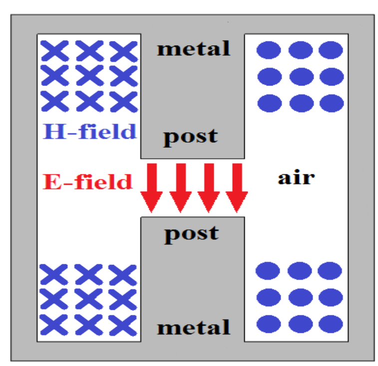


Figure 1. Cross section of an RMC shows the distribution of electric and magnetic fields schematically.

2. Materials and methods

COMSOL Multiphysics®4.4 was used to design and optimize the re-entrant cavity based on the physical dimensions (the gap region between inner posts, applicator height, outer diameter, and the inner posts diameter). In order to perform the interaction between the applicator E-field and the knee joint, a 3D model for the knee is needed, which is supplied by [25] and then processed by using Meshmixer 3.5 to export the final 3D model in stl format. The dielectric parameters of the imported 3D knee joint model have been defined in COMSOL, these parameters were taken from [26].

As described in COMSOL Multiphysics® software, the computation of the wave equation in the frequency domain was performed within the framework of the electromagnetic wave model, as defined by eq. (1):

$$\nabla \times \mu_r^{-1}(\nabla \times \bar{E}) - k_0^2 \left(\varepsilon_r - \frac{j\sigma}{\omega \varepsilon_0}\right) \bar{E} = 0 \quad (1)$$

where (μ_r) is the relative permeability, (k_0) is the wave number in free space, (ε_r) is the relative permittivity and (σ) is the material's electric conductivity, (ω) is the wave angular frequency, and (ε_0) is the permittivity of the free space.

2.1 Applicator design

The resonant frequency of RMC applicator depends on the capacitance and inductance of the structure. Generally, there are two capacitances: the first one is the capacitance of the gap region between the two inner posts, while the second one is linked to the occurrence of charge leakage onto the external surface of the central inner posts [27].

In Fig.2, the dimensions of the RMC used in this study are specified as follows: d = 160 cm, r1 = 165 cm, ro= 68 cm, rn= 85 cm and h = 350 cm. To study the microwave fields and confirm the resonant frequency at 433.78 MHz, 3D simulations were performed using COMSOL Multiphysics® 4.4. Fig. 3 shows the constructional diagram of the designed aluminum RMC. It is designed from two parts (a), they are held together by four fast-release clips to construct the whole compact cavity (b).

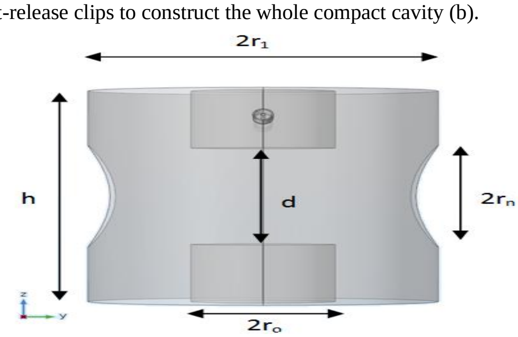
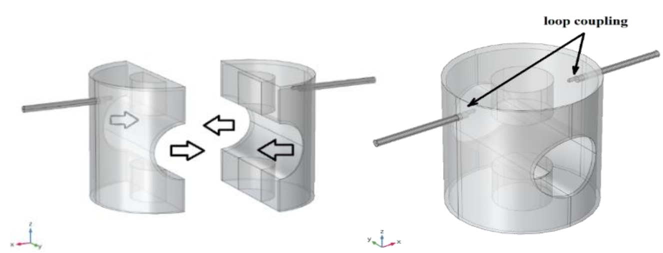


Figure 2. The RMC applicator dimensions.

Feedlines are grounded on the shield conductor of the coaxial cable after their core conductor has been extended into the cavity resonator a certain distance to excite the cavity using a magnetic field. The input impedance is almost the same as a short circuit since the coupling loop's radius is significantly lower than the wavelength. As a result, there is almost no voltage across the loop, yet a significant current runs through it, producing a perpendicular magnetic field to the wall of the hollow like a magnetic dipole. As shown in Figure 1, the magnetic field resonates at an angle that is tangential to the wall and perpendicular to the plane of the loop, and the radiation couples to this field. The loop's orientation becomes crucial in the applicator design to achieve maximum power transfer. Proper alignment ensures effective coupling of the magnetic fields and enhances the efficiency of power transfer into the cavity resonance mode. In the design of the RMC applicator, a crucial parameter taken into account is the surface current. Vertically separating the cavity into two halves has a negligible effect on the resonant frequency and the quality factor Q when the halves are joined together, primarily because the separation line aligns with the direction of the surface current. This design approach is depicted in Fig. 4. Creating the applicator in two parts allows for easy placing of the knee joint (or any other sample or object to be treated) inside the cavity. Once the knee joint is in place, the two parts of the applicator are joined together again using fast-release clips.

This design facilitates convenient sample handling and placement within the cavity while maintaining the cavity's resonant characteristics and performance. The quality factor is calculated from f_r/BW_{3dB}, f_r is the cavity resonant frequency, and BW_{3dB} is the is the 3dB bandwidth which are both extracted from COMSOL results as shown in Figure 5 for the transmission coefficient S21. So, the high-quality factor (~6000) is the feature of our RMC applicator which plays an important role in the power delivery to the knee joint as will be demonstrated in the results and discussion section.



(a) (b)

Figure 3. Schematic of the RMC (a) in two separate parts, (b) the whole applicator where the two parts are joined together

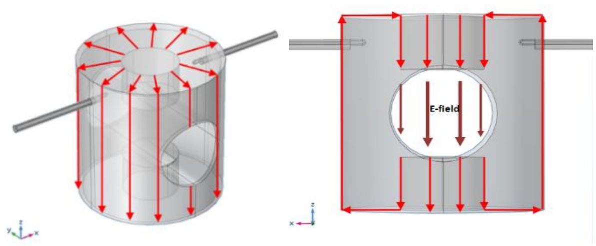
Fig. 6 shows the equivalent circuit for the cavity resonator, with inductive coupling where (L1) and (L2) represents the mutual inductances, and (Z0) is the characteristic impedance of the coupling feedlines (usually 50 Ω). The formula for the transmission coefficient S21 can be derived by circuit analysis [28] , as described by eq. (2):

$$S_{21}(f) = \frac{2\sqrt{g_1 g_2}}{1+g_1+g_2+j2Q\frac{f-f_r}{f_r}} \quad (2)$$

The dimensionless coupling coefficients, (g1) and (g2) can be written as:

$$g_1 = f_r k_1 Q, \quad g_2 = f_r k_2 Q \quad (3)$$

The constants (k1) and (k2) are dependent on the geometrical features of the loop coupling structures. The E-field is illustrated in Fig. 7_(a); which is concentrated in the gap region between the cavity posts, where this region functions as a parallel plates capacitor; its capacitance is inversely proportional to the gap width. While the magnetic field (H-field), Fig. 7_(b), is particularly focused in the space around the posts, it is generated by surface currents flowing in the circumferential direction. The region of highest magnetic field intensity is seen in close proximity to the short-circuited termination, located at the opposing end of the gap. In a re-entrant cavity applicator, as can be observed, there is perfect separation between the regions of maximal electric and magnetic fields.



(a) (b)

Figure 4. Metal-to-metal join has no considerable effect on the frequency nor the performance when joined together, the red arrows are the surface currents (a) 3d view, (b) cross-sectional view.

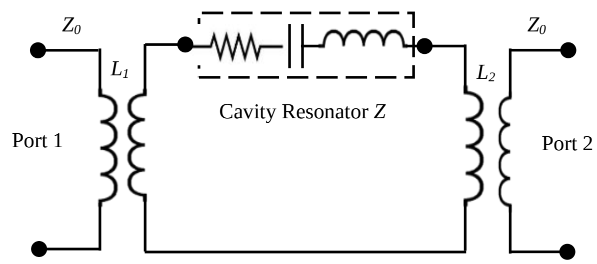


Figure 5. Transmission coefficient $|S_{21}|$.

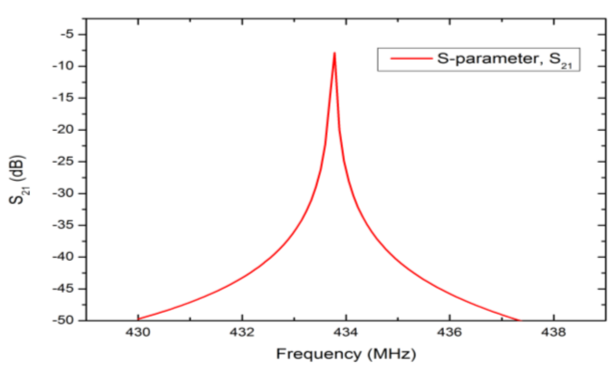
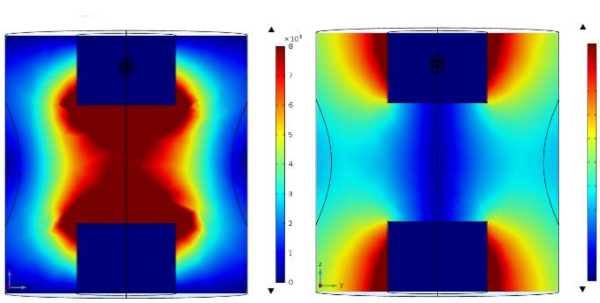


Figure 6. Equivalents circuit of cavity resonator with mutual inductive coupling L_1 and L_2.



(a) (b)

Figure 7. COMSOL simulation results for the (a) E-filed (V/m), and (b) H-field (A/m) distribution.

3. Results and discussion

The electromagnetic wave propagation from the applicator into the treated tissue is sensitive to the dielectric characteristics of the tissue, such as permittivity (ε) and conductivity (σ) [29].Three-dimensional simulations of RMC fields and tissue contact were conducted in COMSOL Multiphysics® 4.4. Fig. 8 illustrates the positioning of the knee joint inside the RMC applicator, specifically within the active gap area located between the two opposing posts. This location is characterised by a high concentration of the electric field. Microwaves exhibit preferential absorption in tissues characterised by high water content, such as intra-articular knee structures.

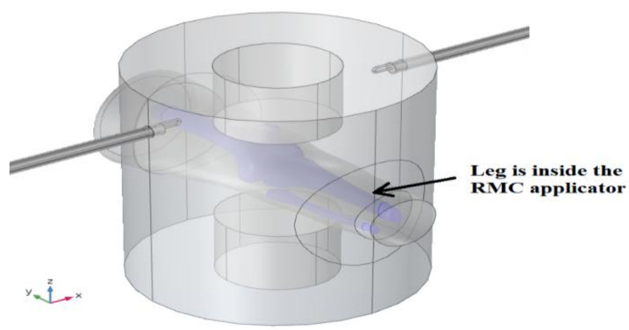


Figure 8. A leg is inside the RMC applicator, where the knee joint is placed in the active gap region for localized heating.

The soft tissues of the knee joint will interact with the electric field, according to their own dielectric properties, and will absorb the power as shown in simulation results of Fig.9. The power absorbed, denoted as P, per unit volume (expressed in W/m3), in the case of a dielectric material, namely a knee joint in the context of our study, can be mathematically represented by eq. (4) [30, 31]:

$$P = 2\pi f E^2 \varepsilon_0 \varepsilon_2 \qquad (4)$$

In the given context, the symbol "f " represents the frequency of the applied electric field, "E" denotes the electric field intensity inside the dielectric material, "ε_2" signifies the materials' loss factor, and "ε_0" represents the free space permittivity. Ensuring that the majority of power sent to the RMC applicator is absorbed by the knee joint, rather than the applicator itself, has significant importance. Let Q_n represents the applicator's quality factor where the knee joint is located between the two opposing posts and Q_o indicates the applicator's quality factor when its empty, the quantity $1 - Q_n/Q_o$ is the fraction of power delivered to the sample. By configuring the RMC applicator in a manner that $Q_n \ll Q_o$, it is ensured that a substantial portion of the power transmitted is effectively absorbed by the knee joint.
The achievement of a high quality factor is heavily influenced by the design of the applicator, which prioritises the prevention of any physical separation within the RMC structure that might intersect the surface current. So, the cut line between the two applicator parts is parallel with the surface current as described earlier, and hence maintain the same high quality factor when joined together like there is not a cut line. Fig 9 shows a trend of power absorption by the knee, from the COMSOL results, $Q_n \approx 250$ and $Q_o \approx 6000$, so approximately 95% of the power delivered into the applicator is absorbed by the intra-articular knee structure.

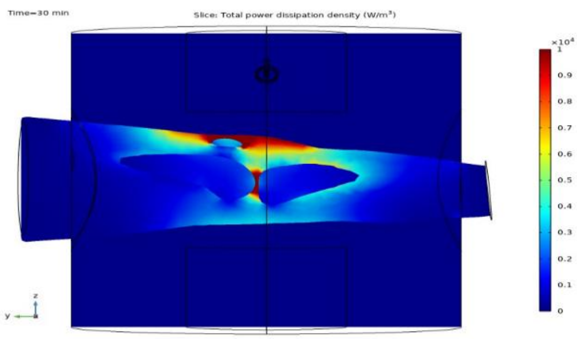


Figure 9. Simulation results for the power absorbed density (W/m3) by the knee joint, when 20-watt power input to the applicator.

Considering temperature development throughout time is intriguing. The findings of this study indicate a gradual increase in knee temperature from 37°C to 41.8 °C over a 30-minute timeframe, with a linear rise in temperature during an initial transitional phase followed by non-linear behaviours, as shown in Figure 10. These findings are consistent with a research conducted by [32], who demonstrated that the absorption of a therapeutic amount of energy leads to a linear rise in temperature during an initial transitional phase lasting around three minutes. This stage is followed by a transition period characterised by non-linear behaviours. During this period, the energy reaches a magnitude that allows for the dissipation of applied energy by blood flow and thermal conduction, hence facilitating temperature stabilisation. These findings may potentially provide an explanation for the observed temperature increase in the knee depth when MD was only administered to the sagittal plane.

A study has shown that MD administered at 434 MHz for 30 minutes, five times a week, is considered as an effective therapy for knee OA subjects [33].

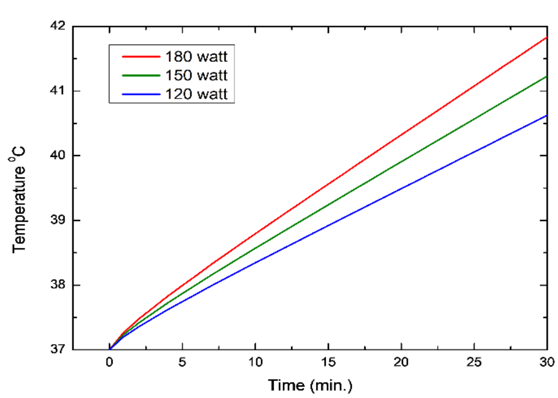


Figure 10. Simulation results for the knee temperature, it increases from 37 0C to 42.8 °C in 30 minutes.

The mechanism of action for MD is hypothesized to enhance local blood circulation, facilitating the delivery of nutrients and oxygen to promote tissue healing [17, 18]. The enhanced capillary permeability caused by deep MD facilitates the infiltration of macrophages and granulocytes into the afflicted region, hence facilitating the elimination of poisons and necrotic material. Hyperthermia has the potential to disrupt the activity of enzymes that play a role in the inflammatory process. Additionally, the application of local MD has been shown to stimulate the production of heat shock proteins, which are crucial for facilitating correct protein folding and eliminating cellular waste material [17, 18].

In order to prevent the collapse of the system, it is essential to maintain strict control over the duration of the treatment as well as the temperature at which it is administered. In the field of musculoskeletal therapy, the recommended maximum temperature for a period of 30 minutes is 45 °C [34]. Accordingly, the temperature developed in the knee by the proposed system is 41.8 °C, which is safe and within the acceptable ranges for effective treatment outcomes. Fig. 11 illustrates the temperature distribution in the knee joint after 30 minutes of time exposure to microwave at an input power of 180 watts using an RMC applicator, with the normal body temperature set at 37 °C as a reference initial temperature. The temperature distribution in a cross section of the knee joint is shown using a colour scale graphic. The temperature distribution inside the knee joint, bone, and tissue is subject to variation due to the differing dielectric characteristics of these components. After a duration of 30 minutes, it can be seen that the maximum temperature remains under the acceptable threshold (below 42 °C). Consequently, this indicates that there is no risk of tissue damage or the formation of burning or hot spots [16]. The position of the knee joint during MD application is an additional issue that has to be addressed. It has been hypothesised that the skin's temperature may be affected by the knee's posture because of differences in tissue resistance to the transition of the electromagnetic field [16]; the enhanced arterial blood flow and heat dissipation by the tissue are both responsible for the uniformity of skin temperature.

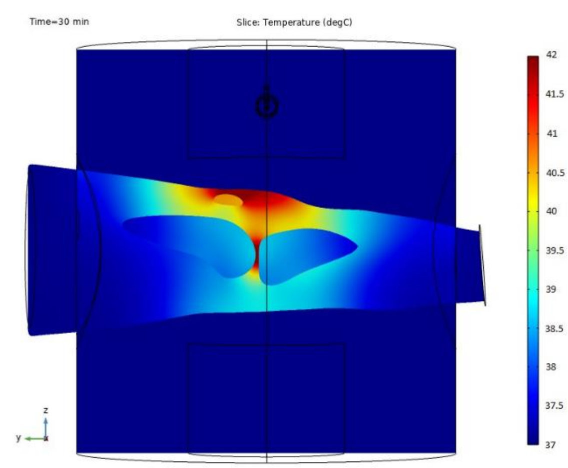


Figure 11. The temperature distribution on the surface and inside the knee joint after 30 minutes.

Concerning the safety issues associated with raising the temperature of the knee joint, a study measured muscle and skin temperature changes in the human thigh during radio frequency-induced hyperthermia at 434 MHz for 30 minutes and assessed muscle damage after a severe session (70 W to raise the temperature close to 45°C) [35]. Histological tests showed no muscle injury or inflammation from the intense heat. It has been found a large difference between the heat threshold at which individuals experience pain and the injury threshold [36, 37]. Sometimes 0.1 minutes at 46 °C is enough to make people uncomfortable. In comparison, causing more serious damage than erythema takes 200, 100, and 50 minutes at 44, 45, and 46 °C [37].

MD is accompanied by some restrictions that need the clinician's awareness. It is essential to use protective eyewear during the utilisation of microwave diathermy due to the potential risk of cataract development caused by microwaves. Furthermore, MD has a specific preference for heating water molecules, making it unsuitable for patients suffering from conditions such as edoema, blisters, or hyperhidrosis. This is due to the potential risk of elevated temperatures causing burns to the skin due to the heating of sweat beads. In this study we acknowledge some limitation factors that may slightly impact the system results such as tissue inhomogeneity, or potential variations in patient anatomies that may affect the temperature distribution due to the variation in their dielectric constant. Also, the blood flow is an important factor in knee joint warming as the blood flow takes the temperature out which may slightly decrease the warming efficiency

4. Conclusion

Diathermy using microwaves to improve pain and function in patients with knee OA has been presented, and accordingly an RMC has been developed and used as an MD applicator to be utilised in heating therapy as it was necessary to develop a method that can concentrate the E-field in a specific region. The feature of our applicator is its high quality factor Q, which ensures that the greatest portion of the delivered power is absorbed by the knee joint. Moreover, the relatively small volume over which the electric energy is focused makes it an attractive and viable candidate for manufacturing as a small and portable device to be available for patients to use it at home. In addition, the high concentration of electric energy per unit volume bodes well for its practicality as a home medical device and facilitates its fabrication as a small, portable unit. The maximum temperature developed in the knee by the system for 30 minutes time exposure is 41.8°C, which is safe and within acceptable ranges. The study measured temperature changes in the peri-articular knee joint during radio frequency diathermy at 434 MHz for 30 minutes and evaluated the temperature distribution at different power ranges from 120 to 180 watt. The temperature distribution inside the knee joint, bone, and tissue is subject to variation due to the differing dielectric characteristics of the knee joint components and on the shape and position of the knee joint inside the RMC applicator. Here, we may propose an RMC that spins, first clockwise 180 degrees, then anticlockwise 180 degrees, and so on. The knee's warmth would be more evenly distributed using this method. Using a low-speed motor to do this might open up a new line of inquiry into finding the optimal rotational speed for uniform temperature distribution. In addition, thermal sensors attached to the knee's outside may be used to monitor the area's true temperature, with the data then being used to set a power regulator or turn off the device if it exceeds a certain threshold.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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This study didn't receive any specific funds.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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