Chapter 1. Introduction

This chapter provides a comprehensive overview of hyperthermia treatments using microstrip patch antennas, highlighting their significance and current challenges. Additionally, it introduces the classifications of the microstrip antenna for hyperthermia. Finally, the chapter concludes with motivation, research gap, objective, and thesis organization.

1.1.Introduction

Hyperthermia, the intentional elevation of body temperature, has emerged as a promising modality in cancer treatment due to its potential to enhance the effectiveness of various therapeutic strategies. The application of hyperthermia in cancer therapy dates back centuries, with historical anecdotes suggesting its use by ancient civilizations. However, its resurgence in modern medicine stems from advancements in technology and a deeper understanding of its biological effects.

All living things are composed of cells, which are the smallest units in the human body responsible for structure and function. In the human body, there are about 100 trillion cells [1]. Human cells, with complex structures featuring charged surfaces, exhibit specific characteristics vital for proper body function. Subject to force, these cells can change orientation due to charged atoms and molecules. Reproducing through mitosis, cells follow a genetic blueprint stored in the nucleus. Biological tissues include epithelial, connective, muscular, and nervous types. Tumor formation may result from abnormal tissue growth, though not all changes lead to cancer. Cancer arises from genetic and epigenetic changes in normal cells, causing uncontrollable growth. DNA damage transforms normal cells into cancer cells, disrupting communication and accelerating growth compared to healthy cells [2].

Hyperthermia applicators play a crucial role in the field of medical treatment, particularly in the context of cancer therapy where elevated temperatures are employed to selectively target and destroy malignant cells. Among the various types of hyperthermia applicators, patch antennas stand out for their specific design considerations. Patch antennas, when utilized in hyperthermia applications, must adhere to stringent requirements to ensure effective and controlled (specific absorption rate) SAR performance of targeted tissues. These requirements include precise tuning of the antenna to operate at the desired frequency for optimal absorption by the targeted tissue, efficient power delivery to induce controlled hyperthermic effects, and careful consideration of the antenna's size and shape to facilitate its integration into medical devices.

1.1.1. History of Hyperthermia Treatment

Hyperthermia is derived from two Greek words, HYPER (meaning rise) and THERME (meaning heat). It denotes the elevation of body temperature or specific tissues to achieve a targeted therapeutic outcome [3]. The utilization of hyperthermia for cancer treatment has an extensive historical background, reaching as far back as approximately 3000 B.C. The application of elevated temperatures for treating diverse illnesses, including cancer, has been a prevalent practice across different cultures since ancient times. Essentially, the significance of heat was often sacred and linked to the therapeutic influence of the Sun [4]. Hence, it was employed to address specific areas or the entire human body experiencing localized issues. This involved utilizing hot water and sand (mud baths) sourced from natural thermal springs, as well as harnessing hot air and steam found in volcanic caves. Heat treatment was initially performed by an Egyptian diviner named Imhotep around 2655 – 2600 B.C. The Edwin Smith papyrus, dating back to around 1700 B.C. and likely a reproduction of a thousand-year-old document, reveals that ancient Egyptians employed "fire drills" involving hot blades and sticks to treat breast cancer [5]. The procedures included the incineration of cancerous cells and were unrelated to an increase in body temperature. It's important to mention that both local and systemic hyperthermia treatments were widely practiced in ancient China and India [6]. During ancient times in Greece and Rome, numerous medical practitioners believed that mastering the ability to regulate the human body's temperature would enable them to treat various illnesses, including cancer. The understanding of cancer pathology was well-established and documented during 460-370 BCE [7]. An illustration of this conviction can be found in the words of the Greek philosopher Parmenides, who strongly believed in the efficacy of hyperthermia, stating, "Give me the power to produce fever and I will cure all diseases" [8]. The inaugural documentation on hyperthermia, dating back to 1866, was authored by the German surgeon Carl D. W. Busch. In this work, he chronicled the instance of a 43-year-old woman grappling with an advanced sarcoma on her face [9]. Following the surgical removal of the tumor, the patient contracted erysipelas, a malady that induced elevated body temperature, ultimately resulting in tumor regression. This discovery triggered heightened interest in hyperthermia, prompting numerous trials to induce infectious fever in cancer patients, such as through the application of contaminated bandages or the infusion of blood from individuals afflicted with malaria into open wounds [10]. Aside from Busch's research, a young American surgeon named William B. Coley explored the connection between infection and cancer regression. Coley conducted studies involving the injection of various bacterial pyrogens into tumors and observed their responses. In 1891, he created a toxin that induced typical erysipelas, complete with its characteristic fever [11]. This led to Coley being recognized as the pioneer of contemporary hyperthermia and immunotherapy in the fight against cancer. The substance known as Coley's toxin was employed in the treatment of various cancer types for nearly a century. After 1800, attempts to treat cancer with electricity became feasible. The Italian physicist and physiologist Alessandro G. A. A. Volta pioneered this effort, drawing inspiration from his compatriot Luigi Galvani. Volta's invention of the electric cell, later known as the voltaic pile, marked the initial phase of electric battery development, producing direct current. Although a single electric pile generated a modest voltage of 1–2 V, the connection of several piles in series created a potent energy source [12]. Around 1830, the French surgeon and gynecologist Joseph C. A. Recamier employed electric heat for the treatment of uterine cancers [4]. A significant contribution to the application of heat in women's oncology came from the American surgeon John Byrne. Renowned for inventing a unique liquid storage battery, Byrne provided ample electrical current to cauterize pathological changes in the uterus [13]. He substantiated existing knowledge indicating that "cancer cells situated deeper within tissues can be destroyed with less heat than that required to damage normal tissues". The Italian surgeon Enrico Bottini conducted comparable procedures on men, introducing a unique device for prostate cancer cauterization called the "cauterio termogalvanico" in 1874 [3].

Following the formulation of his electromagnetism theory in 1873 by English physicist James C. Maxwell and its confirmation in 1886 by German physicist Heinrich Hertz (1857–1894) through the construction of the Hertz oscillator, there was an imminent rapid development of various types of AC devices. Among those who recognized the potential of utilizing high-frequency currents for therapeutic purposes was physicist Nikola Tesla. In his publications in the “Electrical Engineer,” Tesla not only discussed the physiological effects but also highlighted the tissue-heating capability of alternating current above a specific frequency. Intriguingly, Tesla himself experienced a miraculous cure for pulmonary tuberculosis in 1899 through the application of high-frequency currents [14]. Nevertheless, the individual credited with laying the foundation for the application of high-frequency currents in capacitive and inductive heating of tissues was the French physicist and physiologist Jacques-Arsene d'Arsonval . In 1891, he conducted a significant experiment, passing a 3A current through his own body, during which he noted the absence of any sensation except for heat [4]. Subsequently, in 1898, he repeated a similar experiment with a 500mA current, experiencing heightened heating effects. These experiments led him to coin the term "auto conduction," which essentially referred to induction induced by a high-frequency electromagnetic field [15]. Following these breakthroughs, d'Arsonval began utilizing high-frequency currents in the treatment of various diseases.

In 1899, von Zeyneck elucidated the specific processes of heating through high-frequency current. He posited that the heat arises from the current traversing the tissue, much like the generation of heat when an electric current passes through resistance [14]. In 1907, Karl Franz Nagelschmidt, illustrated the potential for profound tissue heating through the application of high-frequency energy. He proposed utilizing this method for addressing conditions related to blood circulation and joint diseases. Two years later, in 1909, he introduced the term "diathermy" to describe the heating effects within tissues, commonly referred to as "thermo-operation," induced by high-frequency currents [4].

Apart from Nagelschmidt, an Austrian physician named Gottwald Schwarz independently introduced the concept of heat tissue penetration, also known as "thermo-penetration," in 1909. In the following year, in 1910, a German physician named Christoph Müller employed diathermy to implement this technique. This therapeutic approach entailed electrically heating the tissue without causing damage, aiming to enhance blood circulation [7].

The identification of ionizing radiation in 1895 by German scientist Wilhelm C. Rontgen resulted in the application of X-rays for cancer treatment, causing a temporary decline in the interest in hyperthermia during the early twentieth century. Challenges such as inadequate and underdeveloped heating methods, limited temperature measurement techniques, and the absence of favourable clinical outcomes led to the withdrawal of approval for hyperthermia treatment. Consequently, traditional surgical approaches, along with radiotherapy and chemotherapy, became the predominant methods for managing cancer [9].

In 1912, Mueller provided a comprehensive examination of the clinical impacts resulting from the combined application of radiotherapy and hyperthermia. Additionally, Mueller shared the outcomes of treating 100 patients with diverse tumors using an extended treatment approach [7].

In 1927, the findings of experimental research on the application of high-frequency heat to tumors in rats were presented by Nils Westermark, a Swedish gynecologist and the son of F. Westermark, in his dissertation [16]. Westermark suggested that tumors might exhibit greater sensitivity to heat compared to healthy tissues, advocating for a temperature range of 40–45 ^{o}C for targeted tumor heating. The use of shortwave diathermy was pioneered in 1928 by German physician Erwin Schliephake, who employed it to treat a furuncle on his nose [14]. Initially, Schliephake explored the biological effects of shortwave treatment on various tissue types before introducing it to clinical applications.

Following the year 1929, E. Schliephake devised a system of coupled electrodes designed to generate capacitive heat in more severe instances of uterine cancer.

Employing radio frequencies ranging from 20 to 50 MHz and wavelengths spanning 6 to 15 meters, he applied varied heating durations, lasting up to 40 minutes. Notably, he observed enhanced destruction of tumor tissue when heat treatment was combined with X-ray exposure [4].

The resurgence of attention to hyperthermia took place following World War II, with the commencement of research into the biological factors behind hyperthermia. In 1962, George W. Crile Jr., an American surgeon, achieved renown by revealing that maintaining elevated temperatures, ranging from 42 to 50°C, could selectively eliminate certain tumors without harming surrounding healthy tissues [9].

In 1948, L. L. Siems conducted research comparing the impact of shortwave and microwave diathermy on blood flow. A couple of years later, A. E. Gessler and colleagues likely became the pioneering group of physicians to employ RF energy at microwave frequencies in experimental cancer treatment. Between 1977 and 1983, Swedish oncologist Jens Overgaard conducted 204 distinct clinical studies involving 10,265 participants, affirming the efficacy of thermotherapy in treating cancer [16]. Ever since then, hyperthermia has been recognized as a conventional approach to the treatment of cancer.

In 1971, A. Westra and W. C. Dewey, American researchers, conducted the initial significant experiment involving hyperthermia in mammalian cells. This groundbreaking study catalyzed investigating the radio- and chemo-sensitivity of tumor cells post hyperthermia treatments. Shortly afterward, E. Ben-Hur confirmed the efficacy of a more potent heat treatment in conjunction with radiotherapy [17].

In 1977, Dewey demonstrated that subjecting cells to temperatures exceeding 40°C for an extended period (beyond 30 minutes) led to cell death. Additionally, it was observed that temperatures surpassing 42.5°C resulted in a notable rise in cell mortality with even a slight increase in temperature (in the range of tenths of a degree) [17].

A significant advancement in hyperthermia emerged with the innovation of microwave heating techniques and their application in the field of medicine. The evolution of these technologies provided improved alternatives for precisely heating tumors, even those situated deep within the human body, known as local-regional hyperthermia. In the late 1930s, H. E. Hollman explored the therapeutic potential of 25cm waves, envisioning their focused application to generate deep tissue heating without causing excessive warmth to the skin. In 1946, the Federal Communications Commission designated the 2450 MHz frequency for physical medicine, asserting its perceived superior therapeutic value [14].

In 1990, Alan J. Fenn, an electrical engineer at MIT's Lincoln Laboratory, conceived a method for warming deep-seated tumors using adaptive microwaves. These microwaves adapt to the characteristics of the patient's tissue, directing the microwave energy precisely to the tumor location. The adaptive microwaves are produced through several microwave antennas forming an adaptive phased array encircling the human body [18].

1.1.2. Current State of Hyperthermia Treatment

In contemporary oncology, hyperthermia has emerged as a promising and effective treatment method. Despite having a long history, hyperthermia is still in its early stages of development. The positive therapeutic outcomes associated with this approach hinge on factors such as the temperature applied, duration of exposure, and the extent of tissue subjected to electromagnetic fields. Enhancing the efficacy of heat treatment is possible by synergizing hyperthermia with other cancer treatments like radiotherapy, chemotherapy, immunotherapy, and gene therapy. Hyperthermia has been applied in the treatment of various tumors, including those affecting the breast, skin, head and neck, brain, esophagus, prostate, uterus cervix, and urinary bladder. Nevertheless, the precise mechanisms leading to cell death during hyperthermia are not fully understood, and ongoing research explores new heating methods. The advent of nanotechnology and the recent observation of magnetic fluid hyperthermia offers numerous opportunities for further advancements in this field.

1.2. Microstrip Antennas for Hyperthermia Treatment

Hyperthermia treatment employs elevated temperatures to selectively eliminate tumor cells, minimizing harm to the adjacent healthy tissue. The accumulation of heat in the tumor, facilitated by poor blood circulation, is utilized to effectively destroy the tumor. Previous studies have demonstrated the effectiveness of patch antennas, waveguide antennas, and phased arrays in hyperthermia treatment [19-21].

Microstrip antenna for hyperthermia application can be classified as discussed below:

1.2.1. Depending on the Frequency Bands

The choice of frequency bands depends on various factors, including the depth of penetration into the tissue and the specific characteristics of the target tissue. In terms of frequency bands, the Medical Implant Communication Service (MICS) band and the Industrial, Scientific, and Medical (ISM) bands are often considered for medical applications, including hyperthermia. Lower frequencies, such as those in the MICS band, may provide better penetration into biological tissues. However, higher frequencies, such as those in the ISM bands, may offer more focused heating. These bands are allocated by regulatory bodies for specific purposes.

1. **MICS Band:** The MICS bands are typically allocated around 402-405 MHz and 434 MHz for medical implant communication services. This band is commonly used for communication with medical implants, but it may also be considered for hyperthermia applications.

2. **ISM Bands:** The ISM bands are unlicensed frequency bands reserved for industrial, scientific, and medical purposes. They are widely used for various applications, including hyperthermia treatment. Common ISM bands include 915 MHz, 2.4-2.5 GHz, and 5.15-5.35 GHz.

1.2.2. Depending on Applications

Hyperthermia applicators can be generally categorized as either noninvasive or invasive. Noninvasive applicators employ external devices to generate an electric field, whereas invasive applicators penetrate the body through the skin or other natural body openings. The classification is further based on the heating mechanism, including capacitive, inductive, and radiative applicators, each of which will be explored in the subsequent section.

1.2.2.1. Capacitive Applicators

These applicators are typically utilized for deep heating with a relatively low applied frequency. An illustrative example of such an applicator is outlined in [22]. In this design, RF current flow is generated through a pair of capacitively coupled electrodes, resulting in heating focused on the central portion of the phantom without inducing superficial heating. The key advantage of a capacitive applicator lies in its simplicity and the adaptability of the electrodes to conform to the skin's contours. However, a notable drawback of these applicators is the tendency to cause burns on the body's superficial areas when attempting to heat deeper tissues. To mitigate the risk of skin burns, it is recommended to place a water bolus between the electrodes and the tissue region.

1.2.2.2. Inductive Applicators

An inductive applicator utilizes an external coil to generate a magnetic field within the body. While the magnetic field alone does not induce any heating, the presence of a time variation in the magnetic field leads to the generation of an internal electric field, resulting in heating. These applicators are specifically designed to function at low to moderate frequencies, typically ranging from 13 to 27 MHz. Due to their low-frequency operation, they are primarily employed for deep tumor heating. However, a significant drawback of inductive applicators is the suboptimal electric field pattern for deep tissue heating, characterized by a parabolic shape in the heating pattern. Surface heating emerges as another noteworthy challenge associated with inductive applicators. In [23], a method for focusing heat onto a deeper portion of the phantom using a pair of inductive aperture-type applicators is thoroughly explained.

1.2.2.3. Radiative Applicators

These applicators function by combining electric and magnetic fields to deliver electromagnetic energy to tissues, facilitating both surface and deep tissue heating. Higher frequencies are employed for localized surface heating, while lower frequencies are used for deeper penetration. Two common types of applicators are the waveguide applicator and the patch antenna applicator. Low-frequency radiators are preferred for heating large tissue volumes, and deep body heating is accomplished using an array of antennas that focus heat energy on the targeted tumor region. However, low-frequency operation results in reduced penetration depth and increased applicator size. Achieving localized heating at low frequencies is challenging, and there is limited capability for heat localization in deeper tissue regions with these applicators.

1.2.2.4. Invasive Applicators

To achieve targeted heating in deeper tissue areas, practitioners employ invasive applicators. These applicators are introduced into the bloodstream or directly through the skin using flexible catheters. Typically, a single antenna or multiple antennas are employed around the tumor region to generate the desired heating pattern. For instance, in [24], a floating sleeve coaxial dipole antenna is utilized to attain a localized Specific Absorption Rate (SAR) pattern for microwave ablation of the liver. The advantage of employing interstitial applicators lies in their ability to achieve localized heating in a smaller volume at greater depths.

1.2.3. Depending on Specific Characteristics

Designing an antenna for hyperthermia applications involves considering specific characteristics to ensure effective and safe treatment. Here are some considerations:

1. Antenna Type: The choice of antenna type depends on the specific requirements of the application. For example, dipole antennas, slot antennas, and microstrip antennas are commonly used in hyperthermia systems.
2. Directionality: The antenna should be designed to focus energy on the target tissues and minimize energy absorption by surrounding healthy tissues. Directional antennas or phased array antennas may be used for this purpose.
3. Power Density Control: Controlling the power density is crucial to avoid damage to healthy tissues. The antenna design should enable precise control of the energy delivered to the treatment area.
4. Biocompatibility: Consider the materials used in the antenna to ensure biocompatibility and minimize any adverse reactions when the antenna is in contact with biological tissues.
5. Safety Mechanisms: Include safety features such as temperature sensors to monitor the temperature of the tissues during treatment. This can help prevent overheating and ensure the safety of the patient.
6. Size and Shape: The size and shape of the antenna can affect its ability to target specific areas. Consider the anatomical features of the treatment site when designing the antenna.

7. Impedance Matching: Ensure proper impedance matching between the antenna and the transmission system to maximize power transfer and minimize reflection.
8. Regulatory Compliance: Adhere to regulatory standards and guidelines for medical devices to ensure the antenna's safety and effectiveness.

1.2.4. Advantages of Microstrip Antennas for Hyperthermia Treatment

There are many advantages of microstrip patch antennas in hyperthermia treatment some of them are given below:

1. Compact Size: Patch antennas are known for their compact size, especially when compared to waveguides and horns. This compactness makes them suitable for applications where space is limited, such as medical devices used for hyperthermia treatment.
2. Low Profile: Patch antennas are typically planar structures that lie flat on a substrate. This low profile enables them to be easily integrated into various devices, including wearable or implantable medical devices for hyperthermia treatment.
3. Scalability: Patch antennas can be easily scaled to operate at different frequencies, making them versatile for various hyperthermia applications. By adjusting the dimensions of the patch, the resonant frequency can be tuned to match the desired frequency range for optimal energy absorption.
4. Wide Beam-width: Patch antennas can have a wide beam-width, allowing for a broader coverage area during hyperthermia treatment. This wider coverage can be beneficial when targeting a larger region or when the exact location of the target tissue is not precisely known.

5. Efficient Energy Coupling: Patch antennas are known for their high radiation efficiency, meaning they can effectively convert electrical energy into electromagnetic waves. This efficiency contributes to maximizing the power delivery and absorption in the targeted tissue during hyperthermia treatment.
6. Low Cost: Patch antennas can be manufactured using low-cost materials and fabrication techniques, such as printed circuit board (PCB) technology. This affordability makes them more accessible for hyperthermia applications, where cost-effectiveness is an important consideration.

1.2.5. Limitations of Conventional Microstrip Antennas for Hyperthermia Treatment

The majority of antenna structures previously reported for hyperthermia applications have been highly directive, making them suitable for localized heating or generating hotspots within phantom tissue to target cancerous cells. However, when cancerous tissue spreads across the superficial skin rather than being confined to a single point, these previously reported antennas may not be appropriate for treatment. This is because the requirement shifts from localized concentration to uniform energy distribution.

To address such cases, novel antenna structures with modifications are necessary. By introducing slots either on both the patch and ground sides or solely on the patch side, we can achieve uniform energy distribution over the skin's surface, with minimal impact on antenna directivity. This modification ensures the safe prevention of localized heating [25, 26].

Uniform heating effect is enhanced, as compared to the conventional rectangular patch antenna. A conventional rectangular patch antenna induces an elliptical heating pattern due to the electric field distribution which is dominant on the horizontal side of the patch. For improving the therapeutic effect, hyperthermia radiator has to induce uniform heating pattern on a tumor cell [27].

The conventional circular patch fed antenna produces a tangential E-field distribution with two hot spots near the surface. The circular patch fed antenna SAR distribution is characterized by large values at the superficial tissues with two hot spots on deeper tissues [28].

In the conventional square patch, the radiating edge adjacent to the feed point dominates the SAR. profile while the pattern due to opposite edge is reduced. Peak values are less than 0.07W/kg and a large null exists in the patch centre [28].

1.2.6. Types of Microstrip Antennas used for Hyperthermia Treatment

Hyperthermia is a medical treatment that involves raising the temperature of a specific part of the body to damage or kill cancer cells. In this context, microstrip patch antennas are used for delivering electromagnetic energy to the targeted tissue.

Several types of microstrip patch antennas can be adapted for hyperthermia applications, and the choice of design depends on the specific requirements of the treatment. Some common types include:

1. Rectangular Microstrip Patch Antenna: Simple rectangular patches are often used in hyperthermia applications. The dimensions of the patch can be adjusted to achieve the desired operating frequency and radiation characteristics.
2. Circular Microstrip Patch Antenna: Circular patches can provide a more compact design and can be suitable for specific applications where circular polarization or other radiation characteristics are desired.
3. Annular Ring Microstrip Patch Antenna: The annular ring design involves a circular patch with a centre hole. This design can provide additional flexibility in

tuning the antenna's characteristics, making it suitable for specific hyperthermia treatment requirements.

4. Dual-Frequency Microstrip Patch Antenna: These antennas are designed to operate at two different frequencies, which can be useful for specific hyperthermia treatments that require multiple frequencies for optimal performance.
5. Multilayer Microstrip Patch Antenna: Multilayered designs can be employed to achieve better performance or to integrate additional features, such as impedance matching or bandwidth improvement.
6. Aperture-Coupled Microstrip Patch Antenna: In aperture-coupled designs, the radiating patch is coupled to the feed line through an aperture. This configuration can offer improved bandwidth and radiation characteristics.
7. Microstrip Antenna Arrays: Arrays of microstrip patch antennas can be used to enhance gain, directivity, and beam-steering capabilities, which may be beneficial in certain hyperthermia treatments.
8. Dielectric Resonator Antenna (DRA) Fed Microstrip Patch Antenna: Combining microstrip patch antennas with dielectric resonators can result in improved bandwidth and efficiency.
9. Dual-Polarized Microstrip Patch Antenna: For certain hyperthermia applications, dual-polarized antennas may be preferred to achieve specific polarization characteristics.
10. Flexible Microstrip Patch Antenna: Flexible materials can be used to design microstrip patch antennas that conform to irregular body shapes, allowing for more adaptable and patient-specific hyperthermia treatments.

1.2.7. Specification for Hyperthermia Applicator's antennas

1.2.7.1. Specific Absorption Rate (SAR)

The specific absorption rate (SAR) is defined as the measure of how much transmitted EM energy is absorbed by human tissue. SAR depends on factors such as the frequency of the radiation, the intensity of the field, and the dielectric properties of the tissues. The polarization of the antenna affects the orientation of the electromagnetic field it produces, but once that field interacts with the body, its polarization becomes less relevant compared to other factors [29].

SAR is primarily influenced by the polarization of the incident electromagnetic field with respect to the orientation of the body tissues, rather than the polarization of the antenna itself. Cross-polarization of the selected antenna typically does not play a significant role in the Specific Absorption Rate (SAR) amount [29].

However, in certain specific scenarios where the antenna polarization aligns with the orientation of the body tissues, there might be some minor influence on SAR. Nonetheless, this influence is generally negligible compared to other dominant factors affecting SAR. Therefore, while cross-polarization may have some theoretical impact, it's typically not a significant consideration in SAR assessment.

$$\text{SAR} = \frac{\sigma|\vec{E}|^2}{2\rho} \ \text{(W/kg)} \tag{1.1}$$

where ρ denotes the mass density of the object, E is the electric field intensity, and σ is the conductivity.

Here the electric field intensity ($\vec{E} = \overrightarrow{E_{co}} + \overrightarrow{E_{cross}}$) is a vector quantity at a given point in space. Electric field intensity can be decomposed into two components, the co-polarized component i.e. E_{co}, and the cross-polarized component i.e. E_{cross}.

The presence or absence of the $\overrightarrow{E_{cross}}$ component in the electric field intensity does not hold significance in the measurement of SAR. Ultimately, it is the final magnitude, denoted as $|\vec{E}|$, which plays a crucial role in determining SAR levels [29-32].

It is crucial to establish a restriction on the safe level of exposure for individuals, and these limitations vary depending on the frequency. Higher frequencies result in less penetration depth, restricting radiation to superficial layers of tissue. The acceptable limits of absorbed energy are typically specified in terms of 1 or 10 g of tissue. The guidelines for restricting electromagnetic exposure are designed to safeguard against adverse health effects [29].

1.2.7.2. Selection of Substrate

Selecting the appropriate substrate material for a microstrip patch antenna used in hyperthermia applications involves considering various factors related to the specific requirements of the application. Hyperthermia typically involves heating biological tissues, and the substrate choice can affect the antenna's performance, efficiency, and safety.

Here are some key considerations

1. Dielectric Properties: Choose a substrate with a dielectric constant (ε_r) that suits the desired operating frequency. The dielectric constant affects the wavelength in the substrate, and a higher ε_r allows for a smaller physical size of the patch. Consider low-loss dielectric materials to minimize energy absorption by the substrate, as excessive heating may occur.

2. Thermal Properties: Since hyperthermia involves heating, consider the thermal conductivity of the substrate material. A substrate with good thermal conductivity can help dissipate heat efficiently and prevent overheating.
3. Biocompatibility: If the microstrip patch antenna will be in direct contact with biological tissues, choose a biocompatible substrate material to ensure safety and minimize potential health risks.
4. Frequency of Operation: Different hyperthermia applications may require different operating frequencies. Choose a substrate material that provides good performance at the desired frequency range.
5. Mechanical Strength: Consider the mechanical strength and durability of the substrate, especially if the antenna will be implanted or used in a medical device that requires robustness.
6. Thickness: The substrate thickness affects the impedance and bandwidth of the microstrip patch. Choose a thickness that balances the desired electrical performance with practical considerations.
7. Manufacturability: Consider the ease of fabrication and manufacturability of the substrate material. Some materials may be more challenging or expensive to work with.
8. Radiation Safety: Ensure that the chosen substrate material does not pose radiation safety concerns. Some materials may interact with electromagnetic fields in a way that could be harmful.
9. Cost: Consider the cost implications of the substrate material, especially if you are working within a budget constraint.

10. Environmental Considerations: Evaluate the environmental impact of the substrate material, especially if the application involves disposal or if there are specific environmental regulations to adhere to.

Common substrate materials for microstrip patch antennas include FR-4, Rogers materials, and polytetrafluoroethylene (PTFE) based materials like Teflon. However, the specific choice will depend on the unique requirements of your hyperthermia application.

1.3. Some Others Antennas for Hyperthermia Treatments

Antenna types like pyramidal horns, extremely wideband antennas (such as unidirectional spiral antennas), polarization reconfigurable antennas, and tunable directional antennas can find applications in hyperthermia treatments, which involve heating specific tissues in the body for therapeutic purposes. Here's how each type of antenna could be utilized:

1.3.1. Pyramidal Horn Antenna

These antennas offer high directivity and can efficiently deliver focused electromagnetic energy to a specific target area. In hyperthermia applications, pyramidal horn antennas can be used to concentrate microwave energy onto tumor sites within the body, allowing for precise and controlled heating [33, 34].

1.3.2. Extremely Wideband Antennas (e.g., Unidirectional Spiral Antennas)

These antennas have the advantage of operating across a wide frequency range, which can be beneficial for hyperthermia treatments that require flexibility in frequency selection. Unidirectional spiral antennas, for example, can provide broadband coverage, allowing for effective heating of tissues at various depths within the body [35].

1.3.3. Polarization Recongigurable Antennas

By altering the polarization of the electromagnetic waves, polarization reconfigurable antennas can adapt to different propagation environments and optimize energy delivery to the target tissue. In hyperthermia applications, these antennas can help overcome polarization mismatch issues and improve heating efficiency [36, 37].

1.3.4. Tunable Directional Antennas

Tunable antennas offer the flexibility to adjust their radiation pattern and frequency characteristics, enabling precise control over the heating process. In hyperthermia treatments, tunable directional antennas can be optimized to focus energy on specific regions of the body, enhancing treatment efficacy while minimizing damage to surrounding healthy tissue [38, 39].

1.4.Motivation

The motivation for conducting research for a Ph.D. thesis on cancer treatment is multifaceted and encompasses various aspects, each contributing to the advancement of medical science and improving the lives of cancer patients. Some Key motivations for pursuing this research area include:

1. Hyperthermia is a promising medical technique that involves raising the temperature of specific body tissues to treat cancer.
2. It has the potential to enhance the efficacy of traditional cancer treatments such as radiation therapy and chemotherapy.
3. Antenna-based systems have shown great potential for providing localized and focused heating, making them a suitable choice for hyperthermia applications.
4. Hyperthermia treatment may not be widely available in all major cancer centers.

In summary, the motivation for conducting research for a Ph.D. thesis on cancer treatment is grounded in the desire to make a positive impact on cancer patients, contribute to scientific knowledge, and advance the field of oncology through innovative and translational research.

1.4.1. Challenges in Microstrip Antenna Design for Hyperthermia

Microstrip patch antennas for hyperthermia applications face several challenges that designers need to address.

Here are some main challenges in designing microstrip patch antennas for hyperthermia applications:

Biocompatibility and Safety, Specific Absorption Rate (SAR) Control, Frequency and Penetration Depth, Temperature Monitoring and Control, Size and Form Factor, Integration with Medical Devices, Tissue Variability, Power Delivery Efficiency, Regulatory Compliance, and Patient Positioning and Mobility.

1.5. Research Gap

Limited studies have been done on the application of patch antennas in the Medical Implant Communication Service (MICS) and Industrial, Scientific, and Medical (ISM) bands, specifically for hyperthermia treatment. Based on the detailed literature review in **Chapter 2**, the following research gaps have been identified.

1. Only a few papers specifically explore patch antenna implementation in hyperthermia treatment.
2. There is a scarcity of research focusing on designing and optimizing patch antennas to operate effectively within MICS and ISM bands for hyperthermia applications.

3. Limited exploration of antenna configurations and techniques that optimize power delivery and minimize potential side effects.
4. Limited focus on measured SAR performance.

1.6. Objective

The antenna plays a fundamental role in the design of a hyperthermia applicator. Further, in accordance with the objective, four important tasks have been attempted in the present research, which are as follows:

- Design and optimize patch antennas at MICS (434 MHz) and ISM (2.4-2.5 GHz) bands to efficiently deliver electromagnetic energy with standards according to ICNIRP for hyperthermia treatment.
- Analyze and measure the controlled and localized SAR distribution within the tissues.
- Simulated antennas are fabricated and experimentally tested using tissue equivalent liquid phantom models to validate their performance.

1.7. Thesis Organization

This thesis can be divided into four parts. The first part includes chapter 1 and chapter 2. Chapter 1 provides the history, introduction, dielectric properties, measurement setup, motivation, objective, and the structure of the thesis while chapter 2 describes the detailed literature review of microstrip antenna for hyperthermia application. The second part of the thesis presents microstrip antennas for hyperthermia applications in MICS bands, which includes chapter 3. The third part is chapters 4 and 5, describing miniaturized microstrip antenna for hyperthermia application in ISM bands. The last part of the thesis, contained in chapter 6, summarizes the work done in this thesis and makes a recommendation of possible work for future research. The content in each chapter is summarized below. A tree diagram of the thesis is given in Fig 1.4.

Chapter 1 gives a brief introduction to hyperthermia which includes history, current state of treatment, classifications of microstrip antenna for hyperthermia based on different parameters, and advantages and disadvantages of microstrip antenna in hyperthermia application. The motivation, research gap, and objective of the thesis are also described.

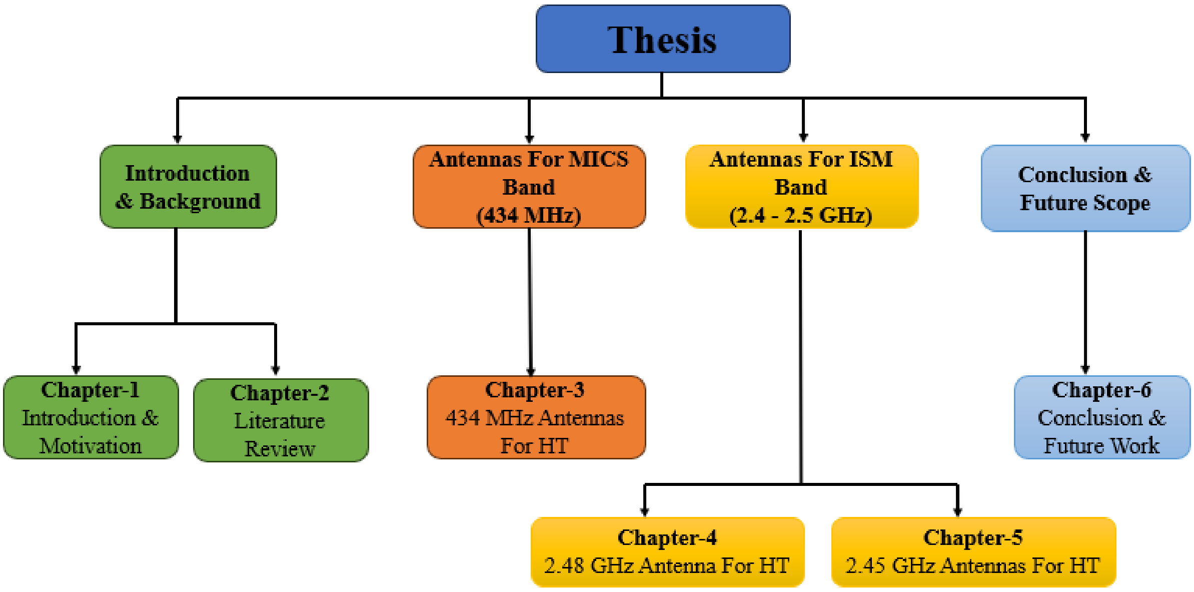

Figure 1.1 A tree diagram of the thesis

Chapter 2 presents the literature review of MICS bands (434 MHz) antenna, ISM band (915 MHz), ISM band (2.4-2.5 GHz), higher ISM band (5.15-5.35 GHz), and dielectric properties of phantom and its measurement setup, specific absorption rate (SAR) theory and measurement setup.

Chapter 3 introduces a hexagon and a pentagon patch antenna with ground loaded slot at 434 MHz. The antenna has a planar geometry, and the ground plane of the structures is covered with orthogonal rectangular slots. The slots in the ground plane act like a load that can be used to bring the input impedance point closer to the characteristic impedance when being added to the antenna. A 50-ohm coaxial feed is applied inside the annular ring with an inner radius of 0.47 mm to power the antenna. Simulated and measured results are discussed and compared.

Chapter 4 demonstrates an elliptical ISM band antenna that operates at 2.48 GHz. The presented structure is made with a dielectric Rogers RT/duroid 5880 copper laminated substrate of a height of 1.58 mm, dielectric constant 2.2, and loss tangent 0.0009. The performance of the proposed antenna is analyzed in terms of reflection coefficient and SAR in free space, and with two different phantoms De-ionized and tissue equivlent liquid (DI water and TEL).

Chapter 5 focuses on the design of compact cross-slot microstrip antenna and corner-slot microstrip antenna for HT applications in the ISM band of 2.45 GHz. The desired ISM band frequency has been achieved by etching the slots along the diagonal axis of the square patch and from the corner of the square patch. Antenna size miniaturization is realized by increasing the slot perimeter.

Chapter 6 summarizes this work and reports conclusions. Future work is also provided to further improve microstrip patch antenna designs.

After introduction of hyperthermia and the advantages of patch antennas in hyperthermia, the motivation and objective of the research, the detailed analysis of patch antennas and MICS and ISM band will covered in upcoming chapter 2.