ABSTRACT

Hyperthermia is a therapeutic procedure used to raise the temperature of the cancerous region in the range 41 – 45 ^{o}C. Various techniques are employed to produce hyperthermia in the cancerous tumor region. These techniques include microwave, RF and ultrasound techniques. Microwave radiation has the potential to heat the cancerous tumor (near spherical- or irregular-shaped tumor) effectively due to the fact that it can easily be focussed within the tumor region. External microwave applicators are designed and optimized to non-invasively couple the electromagnetic energy through human skin to kill cancerous cells. Effectiveness of hyperthermia is dependent on the type of applicator and its size, specific absorption rate (SAR) (which is a function of microwave power, frequency, wave polarization, dielectric properties and density of tumor), duration of treatment and blood flow rate. Various forms of waveguide/horns and planar applicators are available in the literature for microwave hyperthermia. At microwave frequencies penetration depth (PD) is generally shallow. Researchers are continuing to refine the existing waveguide/horn/planar antenna applicators and devise better applicators so that these systems can provide enhanced heating depth in the medium to treat tumors at greater depth. Focussing of electromagnetic energy at the tumor site is easily possible through high resolution exposure at microwave frequencies.

This thesis deals with simulation, experimental and/or theoretical studies of efficient, practical, non-invasive, direct-contact horn antennas/conformal antenna (designed at 2450 and/or 915 MHz) in direct contact/close proximity with bio-medium/bio-media which can provide almost uniform power-absorption at greater depth in bio-medium/bio-media, have the focusing ability and/or remain compatible with the curved portion of the human body. These antennas include water-loaded conventional metal diagonal horn, water-loaded improved metal diagonal horn, water-loaded metal-dielectric wall diagonal horn (MDWDH) terminated in a bio-medium/bio-media along with a novel conformal and modified microstrip slot antenna integrated with a novel and compact artificial magnetic

conductor (AMC) in close proximity with a bio-medium/bio-media. All the proposed diagonal horn applicators provide circularly symmetric SAR distributions in the transverse plane to effectively heat spherical or near spherical tumors. Furthermore, a new conformal hyperthermia applicator integrated with a novel AMC is proposed. The person/operator operating this kind of proposed conformal and compact hyperthermia applicator will not get exposed to hazardous level of microwave radiation due to highly suppressed back field response/high front-to-back ratio of the applicator.

The simulation/experimental/theoretical investigations of the fields, SAR and temperature distributions in a bio-medium/bio-media owing to water-loaded diagonal horns/conformal antenna applicators carried out during the course of the research work are described in six chapters.

Chapter 1 provides discussion pertaining to general introduction for hyperthermia, properties of cancerous cells, microwave hyperthermia, microwave interaction with biological tissues, antenna applicators used for hyperthermia, selection of frequencies for hyperthermia, and literature survey of the work done on different types of direct-contact non-invasive waveguides/horn antennas and planar antenna applicators terminated/close proximity in a bio-medium/bio-media. Since hyperthermia waveguide/horn applicators are bulky and have fixed form of aperture, use of planar antenna applicators may solve the aforesaid problems associated with waveguide/horn applicators because planar applicators are small in size, flexible and light in weight. Literature survey of waveguide/horn and planar antenna applicators include brief description of all major simulation, experimental and theoretical studies reported so far in this field. It also makes an attempt to track the stages of development in the area to bring out the state-of-the-art. The work presented in this thesis directly stems from the latest trends in the area as described in this chapter.

One possible solution to heat localized spherical (near spherical) tumor in superficial region of the body is conventional metal diagonal horn (MDH) due to its attractive radiation properties such as reasonable gain as well as beamwidth, and its radiation pattern in the far field possesses almost perfect circular symmetry so that the 3, 10 and 20 dB beamwidths are very closely equal, not only in the principal E- and H-planes, but also in the 45^o and 135^o planes. In other words, the electric field distribution over the aperture of diagonal horn is identical in E- and H-planes, resulting in circularly symmetric field distribution in the bio-medium/bio-media. Therefore, a conventional MDH terminated in a bio-medium/bio-media has the potential to be used as hyperthermia applicator for the treatment of localized spherical (or near spherical) tumors in superficial abdominal/limb region of the body. In chapter 2, water-loaded conventional MDHs are investigated through simulation, theoretically and experimentally at 2450 MHz and through simulation and theoretically at 915 MHz for hyperthermia application. A conventional MDH is a type of multimode horn in which the internal field consists of superposition of the orthogonal TE_{01} and TE_{10} modes in the square waveguide. Therefore, the electric field distribution over the aperture of conventional MDH is identical in E- and H-planes, resulting in circularly symmetric field distribution. The conventional MDH is filled with high dielectric constant material (water). By loading the applicator with water, matching between the antenna and phantom bio-medium is improved since the effective dielectric permittivity of the bio-medium/bio-media is close to that of water. Also, size of the antenna applicator reduces considerably. Direct-contact water-loaded conventional MDHs were designed at 2450 and 915 MHz using computer simulation technology microwave studio (CST MWS) 2011 software, which is based on finite integration numerical technique. Further, the horn designed at 2450 MHz was fabricated to demonstrate the technical feasibility of the horn. The experimental study of relative SAR distributions in a phantom bio-medium of known physical properties is carried out at 2450 MHz. The simulation results for SAR distributions in the phantom bio-medium (muscle medium) at 2450 and 915 MHz are compared with the corresponding theoretical and/or experimental results. The theoretical investigation of fields in the planar phantom muscle medium due to each water-loaded diagonal horn antenna makes use of plane wave spectral technique for computation of SAR distribution in the medium. The theoretical field components and SAR distributions are numerically evaluated using

MATLAB software. The simulation study of SAR and temperature distributions in realistic tri-layered bio-media without and with embedded tumor due to the water-loaded conventional MDHs designed at 2450 and 915 MHz are also provided in this chapter. The results indicate that SAR distributions in the bio-media at both frequencies are circularly symmetric. It is also observed that the values of PD and effective field size (EFS) in the bio-media are significantly higher at 915 MHz as compared to those at 2450 MHz. Moreover, presence of tumor does not alter PD and EFS significantly. However, the value of SAR increases in the tumor region due to higher conductivity of tumor as compared to the healthy tissue. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the conventional MDH designed at 915 MHz with 13 W input power can be used as effective hyperthermia applicator for oval-/irregular-shaped tumors in superficial abdominal/thoracic region of the body.

Although the horn studied in chapter 2 provides circularly symmetric heating pattern, the PD in the bio-medium/bio-media is not good enough. Therefore, it is thought to modify the aperture field distribution of the water-loaded conventional MDH without changing its aperture size in order to obtain enhanced PD in addition to symmetric EFS in the biological medium/media. Keeping this aspect in view, water-loaded improved MDHs are investigated through simulation, theoretically and experimentally at 2450 MHz and through simulation and theoretically at 915 MHz for hyperthermia application in chapter 3. Improved MDH is a modified version of conventional MDH in which the aperture field is modified by introducing two pairs of conducting pins at appropriate locations near the horn aperture. Due to presence of conducting pins, the resultant field over the aperture of each of the improved MDH antennas designed at 2450 and 915 MHz and terminated in a bio-medium/bio-media corresponds to a combination of TE_{10}, TE_{30}, TE_{01}, and TE_{03} mode fields. Hence, field distribution over the aperture of each improved MDH is a closer approximation to the uniform distribution that may ensure uniform absorbed-power distribution in the bio-medium/bio-media and prevent steep power gradient in bio-media. Each improved MDH is filled with water to provide good impedance match between the horn and bio-medium/bio-media, which ensures good transmission into the bio-medium/bio-media. Direct-contact water-loaded improved MDHs were designed at 2450 and 915 MHz and optimized using CST MWS 2011 software. Further, the improved MDH designed at 2450 MHz is also fabricated to demonstrate the technical feasibility of the horn for hyperthermia. Simulation study was performed to study i) the modification of aperture field distributions of water-loaded improved MDHs designed at 2450 and 915 MHz due to introduction of conducting pins slightly inside the horn apertures, and ii) the resulting SAR distributions in phantom muscle due to these horns. To verify the simulation results for aperture field distributions of the water-loaded improved MDHs designed at 2450 and 915 MHz, theoretical analysis is carried out which includes the effect of higher order TE_{30} and TE_{03} modes also in addition to TE_{10} and TE_{01} modes. The simulation of aperture field distributions of both the horn antennas and SAR distributions in phantom muscle due to these antennas is carried out using CST MWS software. The theoretical investigation of fields in the planar phantom muscle medium due to each water-loaded improved MDH antenna makes use of 'plane wave spectral technique' for computation of SAR distribution in the medium. The theoretical field components, aperture field distributions and SAR distributions are numerically evaluated using MATLAB software. The simulation results for relative SAR distribution in the phantom bio-medium due to the horn designed at 2450 MHz are compared with both theoretical and experimental results. Further, simulation results for SAR distribution in phantom muscle due to the horn designed at 915 MHz are compared with corresponding theoretical results. The results indicate that water-loaded improved MDH presented in chapter 3 provides higher PD and almost same EFS as compared to the horn presented in chapter 2. Hence, it can also be said that the improved horns are superior to corresponding conventional diagonal horns for effective hyperthermia of superficial tumors at greater depth. Further, the work was extended by performing simulation study of SAR and temperature distributions in a planar realistic tri-layered bio-media without and with embedded irregular-/oval-shaped tumors due to the two water-loaded improved MDHs designed at 2450 and 915 MHz. It is observed that presence of tumor does not alter PD and EFS significantly in each case. Additionally, it is observed that values of PD in the tri-layered bio-model due to the water-loaded improved MDHs designed at 2450 and 915 MHz are sufficient to cover whole tumor depth for effective hyperthermia of superficial tumors and provides circularly symmetric distributions. Also, values of SAR observed at the skin surface using each of the improved water-loaded diagonal horn applicators are minimum. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed improved MDHs with 4 and 10 W input power at 2450 and 915 MHz respectively can be used as effective hyperthermia applicators for treating oval-/irregular-shaped tumors in superficial abdominal/limb region of the body.

Another technique for modifying the aperture field distribution of water-loaded conventional MDH is presented in chapter 4. A new form of conventional diagonal horn is proposed in which the central portions of all the four walls of the respective conventional MDHs are replaced by Perspex dielectric ($\varepsilon_r' = 2.59$) while remaining wall portions are made of metal, considering the region of the antenna from throat to aperture. Water-loaded MDWDHs are investigated through simulation and experimental study at 2450 MHz and through simulation study at 915 MHz. Simulation is performed to study i) the modification of aperture field distributions of water-loaded MDWDHs designed at 2450 and 915 MHz due to the presence of partial dielectric material on the walls of the horns, and ii) the resulting SAR distributions in phantom muscle due to these horns. The simulation results for SAR distribution in the phantom bio-medium at 2450 MHz have also been compared with corresponding experimental results and these distributions have been found to be nearly in agreement with each other. The values of PD in the phantom bio-medium due to the proposed MDWDHs are higher than the corresponding values obtained due to their conventional counterparts. Hence, it can be said that the proposed MDWDHs are superior to their conventional metal counterparts for hyperthermia applications. Further, the work was extended by performing simulation study of SAR and temperature distributions in a planar realistic tri-layered bio-media without and with embedded oval-/irregular-shaped tumors due to the two water-loaded MDWDHs. Results show that the values of PD in the tri-layered bio-model due to the water-loaded MDWDHs are sufficient to heat whole tumor depth in muscle region effectively. It is observed that shape of tumor does not alter PD and EFS significantly in each case. In addition, these horns are also providing circularly symmetric SAR and temperature distributions in the bio-media. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed horns with 4 and 9 W input power at 2450 and 915 MHz respectively can be used as effective hyperthermia applicators for treating oval- and irregular-shaped tumors located in the abdominal/thoracic region of the body.

Applicators studied in chapters 2-4 are horn applicators. The disadvantages of waveguide/horn applicators are that these applicators are heavy, large in size and have fixed form of aperture. Use of microstrip antenna applicator can solve most of these problems, because these types of applicators are small in size, flexible and light in weight. Several approaches can be used to improve the efficacy of conventional microstrip patch antenna for hyperthermia. The use of a slot antenna and microstrip feedline improves the bandwidth, EFS and PD. However, slot antenna has bidirectional radiation, which leads to safety concerns. Several techniques have been reported in the literature to solve the aforesaid problem including the use of back shield and conducting ground plane which would make the applicator either of large profile or complex. An AMC could be the better option to suppress back field/redirect the back field constructively toward the patient in hyperthermia treatment for low profile applicators. The characteristics of conventional slot antenna with AMC in free space are described in the literature but its application to hyperthermia was not explored yet. Keeping this aspect in view, a new conformal slot antenna integrated with a novel and compact AMC for hyperthermia application is presented in chapter 5. This hyperthermia applicator was designed at 2450 MHz using CST MWS software. The simulated input characteristics along with near field distribution of the proposed antenna with AMC reflector in close proximity with phantom bio-medium/multi-layered bio-media and SAR distributions in phantom muscle

medium/multi-layered bio-media without and with oval-/irregular-shaped tumors due to the applicator are investigated at 2450 MHz. Further, the proposed antenna with AMC was fabricated and the reflection coefficient-frequency characteristic of the applicator and normalized SAR distribution in phantom muscle medium due to the proposed antenna with AMC reflector were measured at 2450 MHz and the experimental results are compared with the respective simulation results. It is found that experimental results are nearly in agreement with respective simulation results. The AMC structure is utilized to provide in-phase reflection, which significantly enhances the front-to-back ratio and consequently enhances the PD in the muscle medium/multi-layered bio-media. Further, the input characteristics and SAR parameters for the proposed antenna without AMC, conventional rectangular patch antenna without AMC, the proposed antenna-AMC, and the antenna-conventional perfect electric conductor (PEC) combinations have also been compared through simulation at 2450 MHz. It is inferred that the proposed antenna without AMC is compact and provides more uniform SAR distribution as compared to the conventional rectangular patch antenna. Moreover, it is observed that as compared to the antenna-conventional PEC combination, the proposed antenna-AMC combination is of lower profile and provides greater PD as well as wider EFS. Furthermore, the effects of variations in the dielectric properties of bio-medium on the input reflection coefficient-frequency characteristic of the proposed antenna with AMC have also been studied through simulation. Additionally, the effects of change in the radius of curvature of proposed applicator and bio-model on SAR distributions in both homogeneous and tri-layered bio-models are investigated as well. Thermal simulation is also performed for the realistic tri-layered bio-model without and with oval-/irregular-shaped tumor, which is in close proximity with the antenna-AMC combination. The temperature distributions in the realistic bio-models obtained through thermal simulation indicate that the proposed applicator designed at 2.45 GHz with 2.6 W input power can be used as effective hyperthermia applicator for oval- and irregular-shaped small tumors in superficial abdominal region of the body. Further, work was extended by simulating the proposed applicator with AMC in close proximity with cylindrical thigh and arm models for the treatment of tumor present in limb regions of the body and input power levels were optimized. It is found that desired temperature range (41 – 45 °C) in the cylindrical thigh and arm models for effective hyperthermia are achieved for 3.5 and 2.2 W input power levels respectively. The unique characteristic features of this new type of applicator include its compactness, high efficiency, relative insensitivity to variations in the dielectric property of bio-medium, providing enhanced heating depth, the safety for the person/operator operating this kind of hyperthermia applicator who would not get exposed to hazardous level of microwave radiation due to highly suppressed back field response/high front-to-back ratio of the applicator, and its compatibility with the curved surface of human body such as abdomen and limbs.

Finally, the major outcomes of the investigations carried out on different types of horn antennas and conformal antenna applicators terminated in a bio-medium/bio-media are presented in chapter 6. The major conclusions drawn on the basis of the study are summarized. The future scopes and extension of the present work are also outlined in this chapter.

At the end, the references are intended to include the significant source of reference material for different types of horn/planar applicators for hyperthermia related to present work.