INITIAL EXPERIENCE WITH A MICROWAVE IMAGING SYSTEM FOR MONITORING TEMPERATURE CHANGE IN AN ANIMAL MODEL

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***Abstract* -We are developing a microwave system for non-invasively monitoring temperature distributions in human tissue during thermal therapy. Central to our approach is a microwave antenna array and switching matrix which allows tomographic data collection over a wide range of frequencies (300 MHz - 1 GHz). The measured field values are processed by a reconstruction algorithm that creates electrical property maps which vary with temperature and show changes in temperature as a function of time through difference imaging. Initial phantom investigations suggested that our imaging device was sufficiently sensitive to thermally induced electrical property changes to expand the studies to animal models. The results presented here are from our initial experiments conducted with a saline-coupled microwave imaging system on a 5-day old live piglet. The heating was accomplished using a heated tube of water surgically implanted in the piglet's abdomen. Fiber optic temperature sensors were inserted at various positions for comparison with recovered conductivity values and the entire experiment was performed in a CT scanner to facilitate localization of the probes with respect to the heating tube, piglet geometry and microwave antenna array.**

***Keywords* – Microwave imaging, thermal monitoring, animal model**

I. INTRODUCTION

Clinical hyperthermia treatment in conjunction with radiation therapy has been demonstrated in Phase III clinical trials to significantly improve complete response rates when compared with radiation alone [1,2]. However, deployment of this approach has been hindered by the limited thermal data that can be collected at time of therapy for the purposes of assessing thermal dose delivery and subsequent treatment planning. Availability of a noninvasive temperature monitoring technique coupled with a therapy device would be an important step towards making this approach appealing. Microwave imaging is a potentially attractive modality largely because of the thermal sensitivity of the tissue electrical conductivity [3]. We have previously reported results from our laboratory scale 2D thermal phantom studies where we have demonstrated 1º C temperature sensitivity [4]. Translation of this technology into the clinic is a challenging task given the difficulties of integrating the monitoring apparatus with a therapy device and because of the more demanding problems associated with imaging in vivo anatomical structures.

We present preliminary results from experiments on a live piglet in our saline coupled microwave imaging system. Heating of the internal tissue is achieved with a temperature controlled tube of saline surgically inserted into the abdomen. The entire experiment was performed in the bore of a CT scanner which provided structural information on the location of temperature sensors with respect to the heating tube, antenna array and animal geometry, as well as prior information for the image reconstruction process. While the results have not been quantitatively analyzed to date, the sequence of microwave images produced strongly suggests that the technique can accurately distinguish the heating zone within the torso and that the recovered property changes reflect temperature variations which occurred during the experiment. This experimental configuration will facilitate accurate assessment of the microwave thermal imaging approach in an animal model which is an important precursor to integration with a practical therapy device.

II. METHODS

Initial experiments to test a microwave thermal-monitoring system were carried out on a 5-day-old piglet. A source for controlled heating of the target, fiberoptic sensors for monitoring internal temperatures, and a CT scanner for registering the location of the target and sensors were integrated with the microwave imaging system. The 18 cm diameter, 16 monopole antenna array coupled with the microwave switching network and transceiver circuitry provided electric field data over a frequency range of 300 MHz to 1 GHz [5]. Images were sequentially reconstructed using a two-dimensional, Gauss-Newton algorithm [6] in 10 iterations which required under 3 minutes on an IBM 270 workstation. The antenna array was fixed at one end of a 76 cm x 38 cm x 38 cm tank. The piglet was centered in the array and the tank was filled with 0.9% saline at room temperature. The 2.2 cm diameter heating tube (0.5 mm wall thickness) was surgically implanted in the abdominal cavity next to the spine and extended from just under the sternum through the pelvis of the animal. The intestines were packed around the tube, and the abdomen was sutured closed. The piglet was intubated to permit delivery of oxygen and anesthesia while completely submerged during the experiments. Fiberoptic temperature sensors were placed either in catheters adjacent to the heating tube or in microtubing attached to the heating source. Measurements

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Abstract

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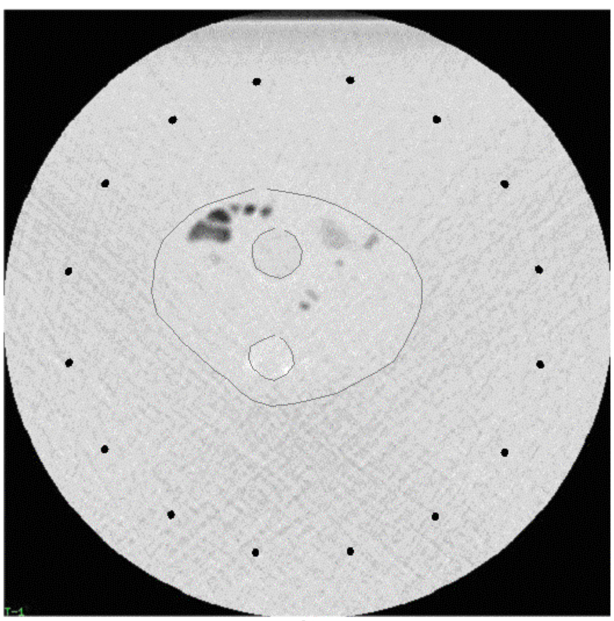
were recorded directly with a PC for continuous monitoring in the region nearest the heating tube. Figure 1a shows the experimental configuration with the microwave illumination tank removed from the CT bore. The intubation tubes, fiber optic measurement system and microwave cables feeding the antennas are visible. The heated zone was created by pumping 0.9% saline through the tube implanted in the pig

(a)



(b)

Fig. 1. (a) Experimental set-up showing the illumination tank with microwave cables, heating tubes, intubation tubes and fiber optic measurement system, (b) CT scan of piglet showing the outline of the pig and saline tube with respect to the monopole antenna array.

let under temperature control. Thermocouples were inserted into the tubing upstream and downstream of the heated region (outside the animal and microwave illumination zone) measured the temperature drop across the target. These were connected to digital thermometers that were read manually. Another digital thermometer was inserted approximately 1” into the rectum to provide core temperature readings. The piglet core temperature dropped from roughly 34 °C to 28 °C when first placed in the room-temperature water tank and subsequently stabilized over a narrow temperature range for the remainder of the experiment. Figure 1b shows a CT scan of the imaging region with the antennas, tube, spine and air pockets identified. The CT image quality was generally poor because of the large amount of water and the plastic tank bottom plate which were located outside of the CT image field-of-view and therefore were not properly reconstructed.

III. RESULTS

For the reconstructions shown here, the implanted tube was heated to five temperatures: 33 °C, 36 °C, 39 °C, 42 °C and 45 °C. This sequence was then repeated by decreasing the temperature to 42 °C, 39 °C, 36 °C and 33 °C (designated with a “d” for decreasing temperatures next to the temperature headings in Figure 2). For each of these settings, heated saline was pumped through the tubing system until temperature measurements upstream and downstream of the target remained stable for two minutes. At that point, data for the microwave image was acquired at 12 frequencies between 300 MHz and 1 GHz. Data acquisition time was roughly 90 seconds at each temperature and the time between acquisitions was approximately 20 minutes. The parameter reconstruction mesh [7] containing 142 nodes was transformed to an ellipse that encompassed the pig abdomen with a 2 cm buffer.

During the experiment air was not completely removed from the line until the heated tube temperature reached 45ºC after which the temperature-decrease portion of the experimental protocol was performed. Consequently, the contents of the tube for the first five temperature time-points were largely composed of air. While not an intended outcome, the resulting images from the heat-up period are nonetheless quite informative. The first five temperature cases were not repeated with the tube completely filled with saline at the end of the cool-down phase because of concern for the limited duration of the pig's viability.

In the absolute images in Figures 2a there is a distinct low permittivity zone in the first five image sets corresponding to the tube location. The fact that the permittivity values do not reach unity is a consequence of the small size of the tube and the spatial filter in the reconstruction algorithm that tends to average image properties. Between the 45ºC and 45dºC data acquisitions, the pumping direction of the saline was rapidly reversed back and forth which successfully removed the air from the line. The difference between these images is significant with the 45d-33 difference image (Figure 2b) exhibiting considerable increases in permittivity and conductivity which is consistent with the contents of the tube changing from air to heated saline.

Even with the air in the line for the first half of the experiment, the conductivity images reveal a progressive increase near the tube location. While the conductivity of the air would not be expected to change, that of the surrounding tissue would be altered and the resultant increases in conductivity shown in the difference images are probably representative of a property change which is an average of the air and surrounding tissue. The permittivity change is minimal during this sequence. The latter part of the difference image sequence utilized the 45dºC case as the baseline since this was the first image acquired with little or no air in the tube. These reconstructions demonstrate a progressive decrease in conductivity at the tube location which is consistent with cooling saline. There is also a slight permittivity increase at this site which would also be predicted for cooling saline.

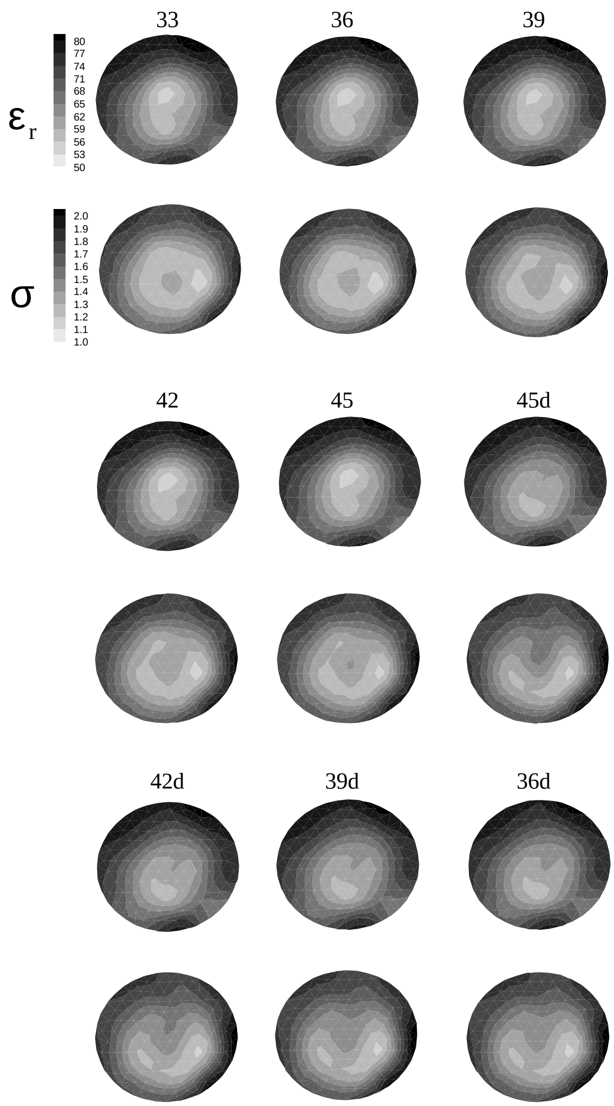


Figure 2.a 900 MHz 2D reconstructed permittivity and conductivity images for a piglet submerged in 0.9% saline with an 2.2 cm diameter heating tube inserted in its abdomen. Absolute images as a function of temperature – first 5 image pairs have air in the heating tube; second 4 image pairs have the air removed with heated saline

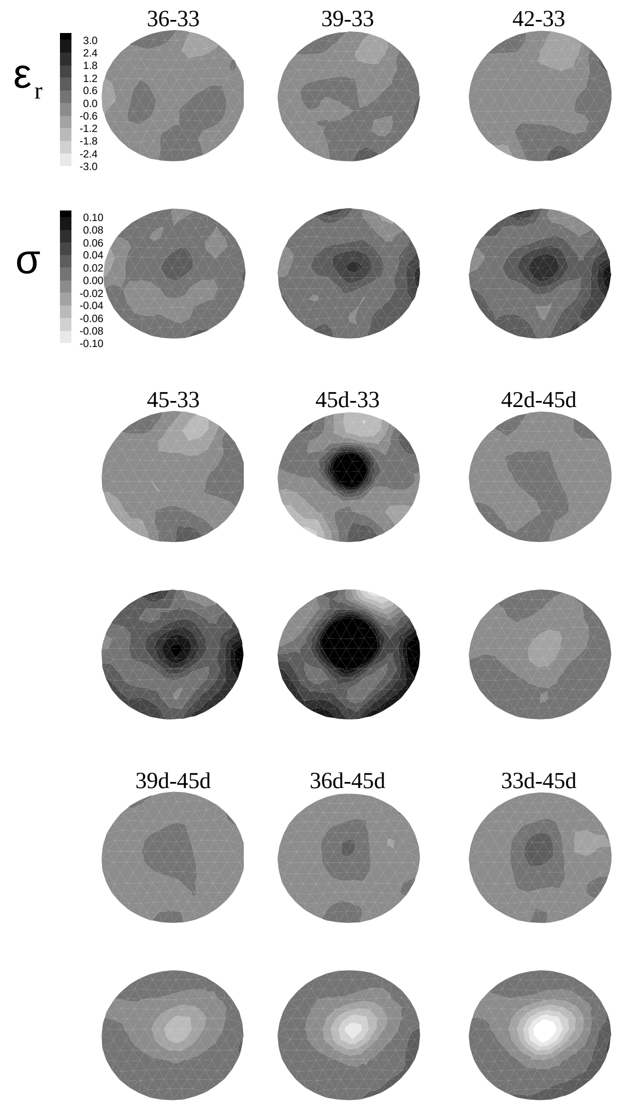


Figure 2.b 900 MHz 2D reconstructed permittivity and conductivity images for a piglet submerged in 0.9% saline with an 2.2 cm diameter heating tube inserted in its abdomen. Difference images – first 5 image pairs utilize the 33 °C image as the baseline while the last 4 use the 45d °C image as the baseline

V. DISCUSSION AND CONCLUSIONS

Integration of microwave imaging with CT scanning has been realized in order to conduct well-documented thermal imaging experiments in an animal model. To date, we have established the feasibility of the approach which includes temperature-controlled heating in the abdomen of a piglet using a saline tube, independent temperature monitoring with implanted fiberoptic probes that can be radially translated away from the heat source, and coregistered microwave and CT images for thermal tracking and anatomical modeling. In the experiment reported here all of these systems functioned appropriately to provide a rich data set for subsequent analysis. Both heat-up and cool-down periods were monitored from body core temperature (approximately 33ºC once the animal was immersed in the room-temperature coupling fluid) to temperature elevations of 45ºC. During the heat-up the saline tube heating source contained a substantial amount of air that was removed for the cool-down phase of the experiment.

While quantitative comparisons between recovered conductivity changes and measured temperature rises in and around the saline tube remain to be completed, semi-quantitative analysis of the initial microwave images acquired during the experiment are encouraging. The effect of the air-filled tube is clearly evident in both the absolute conductivity and permittivity images obtained during heat-up as well as their difference images with the baseline. Removal of the air and its replacement with heated saline (45ºC) is also immediately obvious in absolute and difference images. The effect of saline cool-down from its 45ºC peak back to near baseline is tracked as a definite localization of decreasing conductivity in proportion to the temperature drop as expected. Interestingly, the permittivity exhibits a slight increase with temperature decrease which is also anticipated, although the effect is far less pronounced in agreement with the negative permittivity temperature coefficients of saline and tissue. Overall, these results suggest that the experimental protocol and microwave imaging technique is ready for a thorough evaluation of its in vivo performance in this animal model system.

ACKNOWLEDGEMENTS

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