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Utility of Microwave Radiometry for Diagnostic and Therapeutic Applications of Non-Invasive Temperature Monitoring

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***Abstract* — This paper describes the use of microwave radiometry for several diagnostic and therapeutic applications that can benefit from accurate non-invasive measurement of volume average temperature of tissue regions extending 4cm or more into the body. Design features are summarized for an appropriate high sensitivity long term stable system with 2.5 and 7 cm diameter receive antennas and integral 1.35 GHz total power radiometer electronics. Radiometer performance is characterized with electromagnetic and thermal simulations and experimental measurements in realistic models of two typical clinical applications. Results demonstrate sufficient sensitivity to track clinically significant changes in temperature of deep tissue targets for applications like the non-invasive detection of vesicoureteral reflux and monitoring brain "core" temperature during extended hypothermic surgery.**

***Index Terms* — Microwave radiometry, thermal sensors, microstrip antennas, biomedical telemetry.**

I. Introduction

There are numerous diagnostic and therapeutic applications for non-invasive monitoring of deep tissue temperature. Potential high impact diagnostic applications include: i) early detection of breast cancer by probing for small regions of elevated temperature to distinguish benign calcification from aggressive tumor growth [1]; ii) monitoring of critical deep brain temperature during extended hypothermic surgery or following severe head trauma [2, 3]; iii) long term monitoring of brown adipose tissue (BAT) to assess effect of interventions that stimulate BAT metabolism for control of obesity and diabetes [4, 5]; and iv) monitoring of rheumatoid arthritis following treatments for reduction of inflammation. Many other diagnostic applications are poised to benefit from reliable non-invasive deep temperature measurement, such as monitoring of muscular exercise in rehabilitation medicine, assessment of therapeutic interventions for spinal cord injury, thyroid disease, and tissue changes after radiation and/or chemotherapy.

There are also potentially high impact therapeutic applications for safe and effective non-invasive radiometry such as: i) tumor temperature monitoring for realtime feedback control of hyperthermia therapy for cancer [6-9], and ii) feedback control of warming bladder urine as stimulus for radiometric detection of temperature rise in kidneys when diagnosing vesicoureteral reflux (VUR) in children [10, 11].

This report describes the use of passive microwave radiometry for non-invasive thermal sensing of tissue targets located moderately deep in the body using a miniature microwave antenna sensor to be held securely in place on the skin under an elastic strap. With continued miniaturization of the sensor, this approach should be suitable for new clinical applications that benefit from fixation of the sensor under a thin adhesive patch. The following sections briefly describe the current radiometer sensor and readout electronics, electromagnetic and thermal simulations of possible sense regions, phantom models used to evaluate the system, and radiometer performance in terms of accuracy and long term stability of deep tissue sensing in two representative tissue monitoring applications.

II. Radiometry system

The basic configuration of our high-sensitivity 500 MHz bandwidth 1.35 GHz center frequency microwave radiometry system is shown in Fig.1. Several configurations of radiometer electronics have evolved and specifics will be published elsewhere. The common goal has been to provide maximum sensitivity by placing a high gain low noise amplifier immediately adjacent to the receive antenna to eliminate EMI pickup and interconnection losses. The circuit also provides continuous reading of signal from tissue while providing calibration to known temperature references through parallel rather than time-sequenced amplification, using dual matched amplifier first stage.[12] The radiometer consists of four components: i) a miniature skin contacting sensor with receive antenna and printed circuit with temperature references, RF switches, filters and first amplification stage (+15db) to raise the extremely small signal from tissue above environmental noise, ii) electronics chassis with second stage amplification (+40db), more filtering, and conversion to a digital signal proportional to received power, iii) computer display with signal processing software for temporal averaging, drift correction, and calibration of the algorithm converting received power to equivalent tissue temperature, and iv) 12V battery.

The tissue contacting radiometric sensor integrates the critical first amplification stage and preliminary signal filtering onto a miniature printed circuit that is mounted on the back side of a high directivity receive antenna, both encased in EMI-shielding that seals to lossy tissue surface

around the sensor perimeter. A thick substrate log spiral microstrip antenna was designed with HFSS (Ansys Corp) for maximum penetration into various target tissues. Optimization parameters included the number and winding of spiral turns, and thickness and dielectric properties of the substrate and matching layer. A 7cm tapered log spiral was determined most appropriate for recording temperature rise in kidney located 3-5cm below the skin [13, 14], and a 2.6cm diameter tapered log spiral was found to maximize coupling through the human skull into brain.[15]

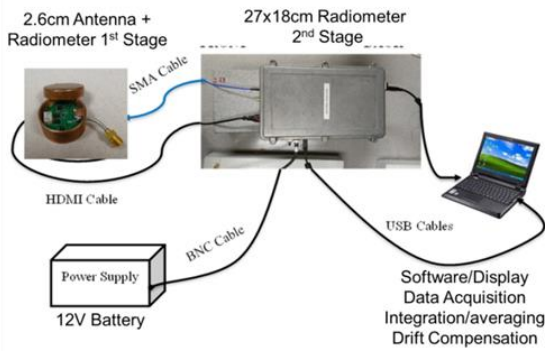

Fig. 1 Basic configuration of high-sensitivity microwave radiometry system.

III. Radiometer Performance

Performance of the radiometry system is characterized in both simulated and experimental multilayer phantom models of two representative clinical measurement sites: A) human brain underlying intact scalp and skull, and B) kidney located 3-5cm deep in the torso. In each case, the experimental models include layers of circulating tissue-mimicking liquids controlled at different temperatures to characterize our ability to quantify small changes in target temperature at depth under normothermic surface tissues.

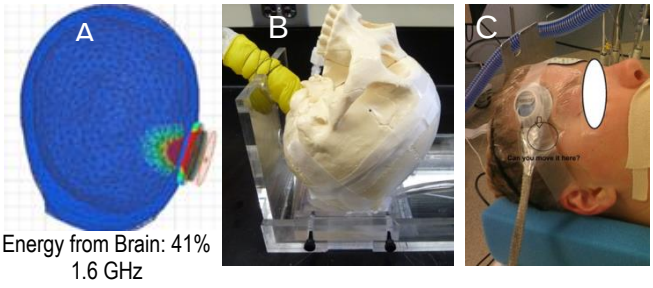

Fig. 2 A) HFSS-simulated receive pattern at 1.6 GHz for a 2.5cm log spiral antenna on B) multilayer head model with temperature-controlled circulating scalp and brain tissue compartments. C) IRB approved brain temperature monitoring of patient during surgery.

A. Monitoring Brain "Core" Temperature

As simulated with Ansys HFSS, Fig. 2A shows the SAR pattern at 1.6 GHz of a high directivity 2.6cm dia thick substrate tapered log spiral microstrip antenna in the layered head model of Fig. 2B. While the highest power deposition rate occurs in the thin superficial scalp layer, the simulations demonstrate minimal power deposition (and received energy) from low electrical conductivity skull bone and a significant percentage of total signal (41%) received from brain. In practice, the radiometer collects a signal integrated from all tissue that is a weighted average of SAR patterns of all frequencies within the sensing band (1.1-1.6 GHz).

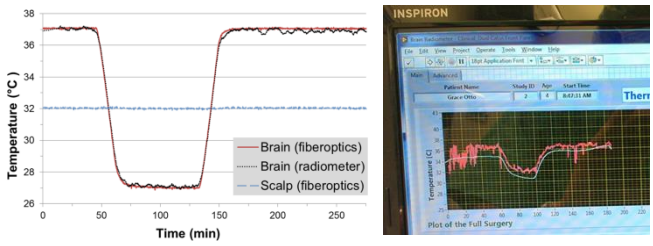

Fig. 3 A) Radiometric signal (black) and fiberoptic measured brain temperature agree within 0.4°C over 4 hour experiment with Fig.2B model. B) Close correlation of core temperature measures from brain radiometer (red) and nasopharyngeal (white) while monitoring Fig. 2C patient during two hour hypothermic surgery.

B. Detection of Vesicoureteral Reflux

Our team is investigating a non-invasive approach to detecting VUR that minimizes trauma by eliminating the Foley catheter.[10, 11, 13] This application requires radiometric monitoring of temperature rise in kidney while controlling MW heating of bladder urine with radiometry.

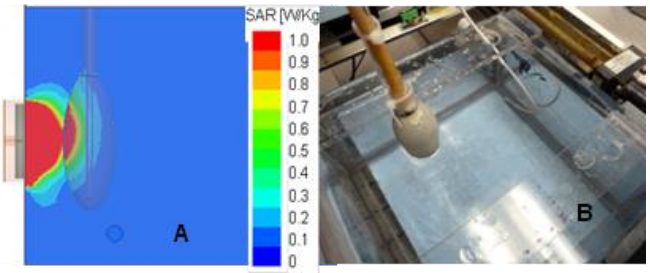

Fig. 4 A) HFSS simulation of receive pattern of 5cm log spiral looking through Mylar window into the muscle-kidney phantom, showing significant received energy (red) from within the "kidney" 3-5cm deep in muscle. B) Photo of experimental model with temperature-controlled "kidney" at 3-5cm depth in circulating muscle-equivalent phantom at separately controlled temperature.

To test our ability to detect elevated kidney temperature underlying normothermic fat and muscle, a phantom model was constructed from 25x25x15cm Plexiglas container filled with circulating 35°C liquid "muscle" surrounding a saline filled latex balloon "kidney" (Fig.4). The "kidney" was positioned at variable distance (1-5cm) from a 7cm dia. radiometric antenna contacting a 0.010" thick Mylar film on one side of box. "Kidney" temperature was varied to produce a range of surface/deep temperature gradients to determine radiometer sensitivity as a function of target volume, depth, and temperature difference to surrounding muscle. Radiometer measurements during a transient 3.5 or 5°C increase of kidney temperature are shown in Fig. 5.

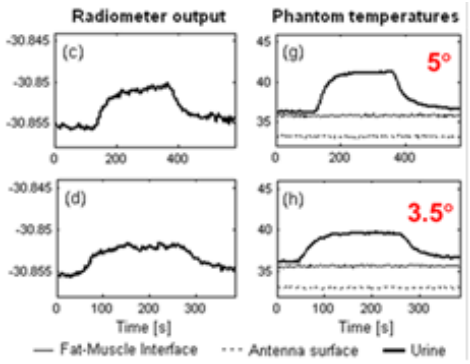

Fig. 5 Left panels show radiometric received power as a function of time measured in the Fig. 4B kidney phantom when the saline circulating inside the 30 ml balloon was raised either 3.5 or 5°C above the surrounding 35°C "muscle", as measured with a fiberoptic sensor (right panels) inside the balloon.

IV. Conclusion

This paper briefly describes a 1.1-1.6 GHz single band radiometry system for measuring volume average temperature of tissue targets at moderate depth in the body. Computer modeling and experimental phantom model tests are described for two typical clinical applications for this technology. Current software with temporal averaging and drift correction provides a stable radiometric signal for accurate monitoring of temperature to at least 5 cm depth. These results demonstrate that passive microwave radiometry is now poised to emerge as an accurate and affordable noninvasive thermometry approach for many applications in monitoring subsurface tissue temperature.

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