2014

Monitoring brown fat metabolic activity using microwave radiometry: antenna design and frequency selection

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Recommended Citation

Monitoring brown fat metabolic activity using microwave radiometry: antenna design and frequency selection

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Abstract — **This paper describes the use of microwave radiometry for monitoring brown fat metabolism (mBAT). The radiometric frequency band and receive antenna were optimized for coupling to 2-6 ml BAT depots in the supraclavicular region. Radiometric signal variations induced by higher metabolic activity resulting from a cold stimulus were calculated with electromagnetic and thermal simulations in a segmented computational model of the human neck including BAT. A 2.5 cm dia. log spiral antenna was selected as optimum using a 500 MHz bandwidth and center frequency 2.75 GHz. Results suggest sufficient sensitivity to track sub-surface temperature variations during long term mBAT monitoring for potential use in obesity and diabetes research.**

Index Terms — **Brown fat metabolism, log-spiral antenna, microwave radiometry, noninvasive monitoring, 3D multiphysics modeling.**

I. INTRODUCTION

Brown adipose tissue (BAT) plays an important role in whole body metabolism and could potentially mediate weight gain and insulin sensitivity [1]. Although imaging techniques are available to detect BAT, there are currently no methods for long term monitoring of BAT metabolic activity (mBAT) to assess the effect of interventions.

Positron emission tomography–computed tomography (PET-CT) have proven most effective for locating BAT due to its high uptake of 18F-FDG [1, 2]. These studies are expensive however and risks associated with radiation exposure prevent repetitive scanning. Magnetic Resonance Imaging has also been used, but is similarly expensive and poorly-suited to repetitive scan investigations [3]. Infrared thermography has demonstrated feasibility in locating BAT, but is not sufficiently sensitive to quantify small changes in thermogenesis of subsurface BAT [4].

In order to facilitate mBAT studies that might lead to new approaches in control of obesity and diabetes, there is a need for new technology that is painless, non-toxic, reliable, and inexpensive enough for repetitive use to quantify long term changes in mBAT in large patient studies. Microwave radiometry fits these requirements since it allows non-invasive collection of thermal radiation from deep tissue and can be calibrated to convert received power into a volume-averaged measure of absolute temperature.

Our group recently developed a 2.5 cm dia. sensor that consists of a log-spiral antenna integrated with a miniature radiometer. The sensor was optimized for sensing changes in brain temperature in the 1.1-1.6 GHz band [5]. The present study is focused on the redesign and optimization of the antenna and radiometric band to sense small changes in temperature at depth in the neck as a result of increased mBAT, which can be activated by a cold stimulus [2].

II. METHODS

A. Log-spiral antenna design

Log-spiral antennas exhibit frequency-independent properties over a wide band limited by the finite physical dimensions of the antenna [5]. The most critical parameters of the log-spiral geometry are the diameter, number of spiral turns (N), dielectric properties and thickness of the substrate and matching layer coverlay, all of which are chosen to provide optimum coupling to the BAT target.
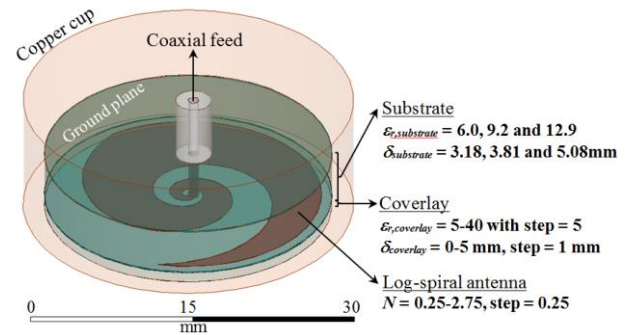

Fig. 1. Radiometric receive antenna: microstrip log-spiral patch design with tapered ends. The parameters in italic bold define the optimization strategy based on a parametric analysis, where the parameter δ represents thickness.

The microwave antenna measures an equivalent temperature (T_B) determined from the weighted volumetric average temperature within the sense region of the antenna. The power collected by the antenna (P_{ant}) is directly proportional to T_B and is given by $P_{ant} = Gk_BT_B\Delta f$, where k_B is the Boltzmann constant and G is the radiometer total gain. Defining $T(r)$ as the physical temperature in the human tissue located at position r within a sense volume V, and S_{11} as the power reflection coefficient due to mismatch at the antenna/load interface, the temperature measured by the radiometer is given by:

$$T_B^j \propto \left(1 - \left|S_{11}^j\right|^2\right) \int_V W^j(\mathbf{r}) T(\mathbf{r}) dV, \quad W^j(\mathbf{r}) = \frac{SAR^j(\mathbf{r})}{\int_V SAR^j(\mathbf{r}) dV} \quad (1)$$

where W is a weighting function given by the power collection pattern which, by reciprocity [5], is the same as the specific absorption rate (SAR = $\sigma|E(\mathbf{r})|^2/2\rho$), which is a function of electric conductivity σ, density ρ and the electric field $\mathbf{E}$ inside the sense volume V. The superscript j indicates that radiometric observations can be implemented over multiple frequency bands.

The design optimization is based on a parametric analysis (range parameters are defined in italic bold in Fig. 1) that aims to maximize the bandwidth (Δf) of the receive antenna and efficiency (η), which is evaluated here in terms of the ratio of power received from the brown fat (BAT) to the total power received by the antenna. Besides efficiency, the band is chosen based on the constraint $S_{11} \leq -10$ dB in order to minimize mismatch (S_{11}) between the antenna and tissue. Frequency bands allocated by the Federal Communications Commission (FCC) are specifically avoided.

B. Computational model

A 3D computational model of the human neck and chest was created in HFSS (Ansys Inc., Canonsburg, PA), from PET-CT images that were used to establish realistic volumes and locations of BAT (Fig. 2). PET-CT scans indicate volumes up to 20 ml in lean people and approximately half that size in overweight humans. BAT regions were segmented in the supraclavicular region with a volume of 2-6 ml underlying a superficial layer of 1.5 mm skin and 3-10 mm of subcutaneous white adipose tissue (WAT). The depth of these depots ranged from 4.5-20 mm.
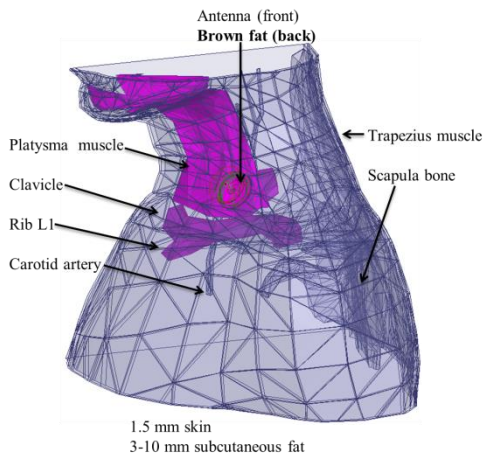

Fig. 2. Location of the antenna and 3D computational model of the neck and chest region: skin, WAT, BAT as well as relevant muscle and bone structures.

The simulation of power received by a surface antenna required thermal simulations. Heat transfer was simulated using the FEM-based software COMSOL Multiphysics (COMSOL, Inc., Burlington MA), which solves the bioheat equation [6] that accounts for heat transfer due to conduction, blood perfusion and metabolism:

$$\rho C_p \frac{\partial T}{\partial t}(\mathbf{r},t) = k\nabla^2 T(\mathbf{r},t) + \omega_b C_{pb}(T_a - T(\mathbf{r},t)) + Q_m \quad (2)$$

where C_p is specific heat capacity, k is thermal conductivity, ω_b is volumetric blood flow rate, T_a is arterial temperature, Q_m is metabolic heat rate and the index b stands for blood. Human tissue properties were retrieved from the literature [7]. The boundary condition at the skin surface was defined by a convection heat transfer coefficient $h_{air} = 5$ W/m^2/K and room temperature $T_{air} = 25$°C in thermoneutral conditions. The simulated power received by the antenna was characterized as a function of frequency and using different levels of mBAT under cold stimulation: $T_{air} = 15$°C.

III. RESULTS AND DISCUSSION

A. Antenna optimization

Simulations of S_{11} and efficiency (η) showed only minor dependence on coverlay permittivity and thickness in the analyzed ranges. Thus simulations were performed using $\varepsilon_{r,coverlay} = 30$ and $\delta_{substrate} = 1$ mm due to ready availability. Simulations also showed that thicker substrates with lower dielectric permittivity provided better efficiency and larger bandwidth at the expense of larger antenna size. The same results could be obtained using thinner structures with higher dielectric permittivity providing a trade-off between efficiency and antenna size. Our strategy was to determine the optimal combination of $\varepsilon_{r,substrate}$, $\delta_{substrate}$ and N.
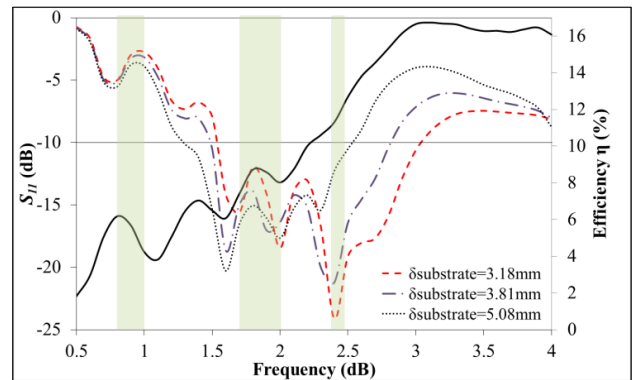

Fig. 3. Parametric analysis of substrate thickness to improve efficiency and S_{11}. The shaded regions represent FCC bands.

Fig. 3 shows the antenna reflection coefficient of the log-spiral antenna over 0.5-4 GHz for different substrate thicknesses. All signals present good reflection coefficients ($S_{11} \leq -10$dB) over a wide band as typical of log-spiral configurations. The best combination of parameters was: $\varepsilon_{r,substrate} = 12.85$, $\delta_{substrate} = 3.18$ mm and $N = 2$, which

yielded the frequency band 2.5-3.0 GHz with an average efficiency of 15%, *i.e.*, 15% of the power is collected from the sub-surface BAT depot tissue. Fig. 4 shows the antenna radiation pattern simulated in HFSS for the optimized configuration, where we can observe that the antenna sense region penetrates beyond the BAT tissue region.
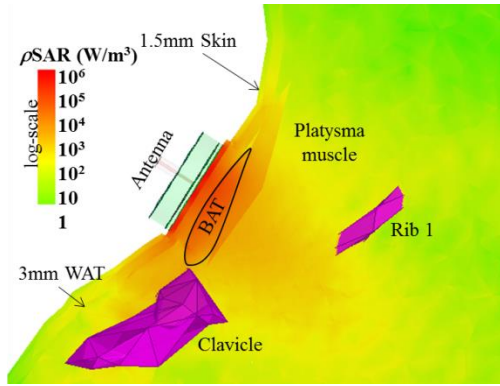

Fig. 4.   Simulated radiation (receive) pattern in neck model using optimized antenna parameters and a BAT volume of 6 ml.

B. Thermal modeling of BAT metabolism

The simulated temperature and SAR were combined to compute the theoretical power received by the antenna. Fig. 5 shows the variation of received power induced by increasing mBAT up to 25-fold with a mild cold stimulus, *i.e.*, using T_{air} = 15°C. It is clear that received power is dependent on the metabolic activity of different BAT depot volumes (2-6 ml) and WAT thicknesses (3-10 mm). Above a 15-fold change, the received power shows less dependency on mBAT, but so far literature only describes variations in this range [1]. The correspondent average BAT temperature variation within the analyzed mBAT variation (5 to 25-fold) was 0.33-1.47°C.
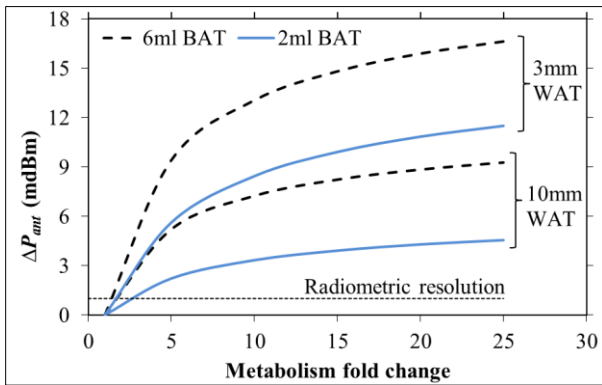

Fig. 5.   Parametric simulations to assess radiometic sensitivity to mBAT variation during mild cold simulation (15°C).

The minimum power variation is 2.2 mdBm for a 5-fold increase in mBAT (2 ml BAT volume below 10 mm WAT thickness), which is detectable using current microwave

radiometry techniques [5, 8]. Our previous device [5] was designed for a larger and deeper target region (brain); it demonstrated mdBm sensitivity over an optimized frequency band of 1.1-1.6 GHz. The redesigned antenna discussed in this work is currently being implemented for operation at higher frequencies (2.5-3.0 GHz) since BAT is more superficial than brain.

IV. CONCLUSIONS

We presented a computational model to optimize a radiometric antenna for monitoring BAT metabolism and to estimate radiated power from typical supraclavicular BAT depots. The optimized frequency band for a 2.5 cm dia. thick substrate tapered log-spiral antenna was 2.5-3.0 GHz. The antenna produced good S_{11} coupling and an average receive efficiency of 15% from the BAT volume. These characteristics are sufficient to detect thermal radiation from small volumes (2-6 ml) of BAT located 4.5-20 mm deep and to monitor small changes (<0.5°C) in BAT temperature associated with increased metabolism during mild cold exposure. The miniature sensor and a 2.75 GHz radiometer appear suitable for non-invasive long term monitoring of BAT metabolism, enabling future experimental investigation of the role of BAT in mediating obesity and diabetes.

V. REFERENCES

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