Hybrid MRI/RF-Heating at 7.0 Tesla and 11.7 Tesla: Electro-Magnetic Field Simulations, Temperature Simulations/Measurements, Dipole Antenna Design and Heating Experiments

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Target audience: Basic researchers and clinical scientists interested in novel MR technology and thermal therapy applications at ultrahigh fields (UHF), in particular at 7.0T and 11.7T MR frequency.

Purpose: Magnetic Resonance Imaging (MRI) is of proven diagnostic value with an ever growing number of applications that support interventional procedures and therapies [1-2]. The clinical value of regional RF hyperthermia as an adjunctive therapy to radiotherapy and chemotherapy has been demonstrated [3-4]. A recent study showed that dedicated MR hardware can be used to meet the needs for imaging, MR thermometry (MRTh) and controlled targeted RF heating at 7.0T in a single device [5-6]. Numerical simulations showed that RF wavelength reduction benefits sharpening and focusing of RF heating induced temperature hot spots [7]. Realizing this opportunity this work examines controlled RF induced heating at 7.0T and 11.7T. For this purpose EMF simulations, temperature simulations, dedicated antenna development, RF heating experiments and MRTh are performed using a frequency of 300 MHz and 500 MHz.

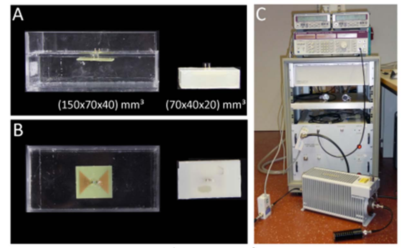

Figure 1 Hardware for RF-Heating experiments at 500MHz. A-B) Bowtie antennas C) Custom build 2-channel RFPA

Methods: EMF and temperature simulations solving Pennes Bioheat equation were conducted in phantoms and voxel models “Ella” and “Duke” from the virtual family (ITIS Foundation, Zurich, Switzerland) at frequencies of 300MHz and 500MHz. Two antenna configurations with dimensions (150x70x40)mm³ and (70x40x20)mm³ were built and evaluated for 500MHz consisting of an bowtie antenna and a dielectric resonator ($D_2$0 for 300MHz and deionized water for 500MHz) as shown in Fig. 1A,B. To perform RF heating experiments at 500MHz a two channel broadband (100-500MHz) Class A Linear RF Power Amplifier (RFPA) was implemented (Fig. 1C) which is capable to apply an RF power of 2x140W at 500MHz. A power signal generator (SMGL, Rhode Schwarz, Munich, Germany) was used to supply a rectangular pulse to the RFPA. Two power reflection meter were used to calibrate the input power (70W) at the antennas feeding cable and to monitor forward and reflected power during the RF heating experiments. MRTh applying the proton resonance frequency method (PRF) was performed at 7.0T [8]. A fiber optics system (Omniflex, Neoptix, Quebec, Canada) was used to validate MRTh. A cylindrical agarose phantom was utilized to emulate the electrical properties of brain tissue (l=25cm, ⍰=18cm, ε=75, σ=0.72S/m).

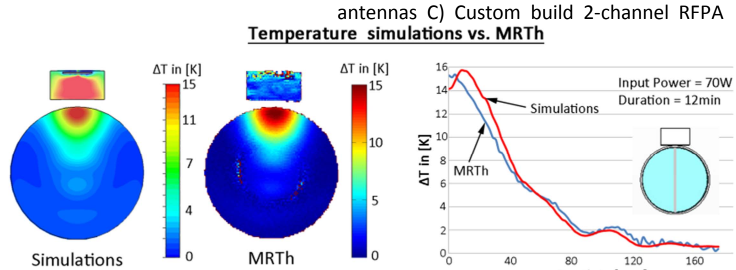

Figure 2: Comparison of the results of the simulated temperature distribution of a single antenna at 500MHz in an axial slice of a cylindrical phantom versus MRTh measurements for 70W input power and an RF-Heating duration of 12 minutes.

Results: EMF and temperature distributions resulting from the simulations show a match with MRTh as demonstrated in Fig. 2. After 12 min and an input power of 70W a temperature increase of 15K was achieved in the phantom. The bowtie antenna designed for 500MHz (150x70x40)mm³ showed improved focusing abilities versus the 300 MHz equivalent as illustrated in Fig. 3 for an 8 channel array. The 90% iso-SAR hotspot in the axial plane was (18x18)mm² for 300MHz vs (10x10)mm² for 500MHz. A decrease in volume of the dielectric substrate by a factor of >7 has no implications on the hotspot size, however the surface SAR values show an increase by a factor of ~2. The B_1/√kW distribution is decreasing when moving from 300MHz to 500MHz as shown in Fig 3. Temperature simulations in the voxel model “Ella” derived from a healthy volunteer [9] demonstrated the feasibility of targeted RF heating using the proposed 300MHz and 500MHz bowtie antenna configurations. For the center of the brain temperatures of 46°C and larger were induced while the surface temperature remained below 42°C as demonstrated in Fig. 4. The 90% iso-Temperature hotspot in the axial plane has the dimensions of (38x47)mm² at 300MHz and (32x33)mm² at 500MHz.

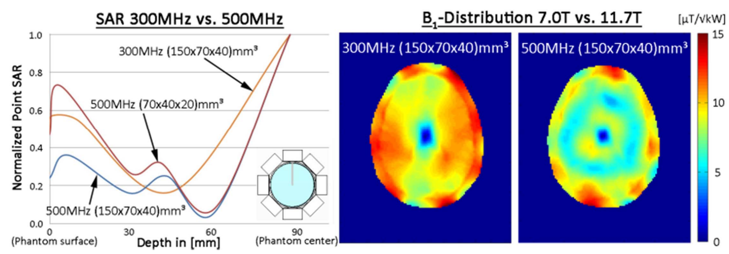

Figure 3: Comparison of the target RF-Heating capabilities of three 8ch hardware configurations at 300MHz and 500MHz (left). Comparison of the B1 distribution at 7.0T and 11.7T with an in-phase phase setting (right).

Discussion: The presented setup consisting of a custom built RFPA, multichannel bowtie antenna arrays and MR thermometry demonstrates the feasibility of targeted RF heating. Our preliminary results indicate that the RF heating shown here holds the promise to suit the needs of RF hyperthermia applications and/or targeted drug delivery. Our RF heating results are to be expected to continue to drive RF antenna developments at 500 MHz (and beyond) and are a motivating force to move apace to MR at 11.7 T. Notwithstanding the progress shown here a significant increase in losses (cables, dielectric, B1) was observed while moving from 300 MHz to 500MHz; a behavior that needs to be considered for RF heating applications.

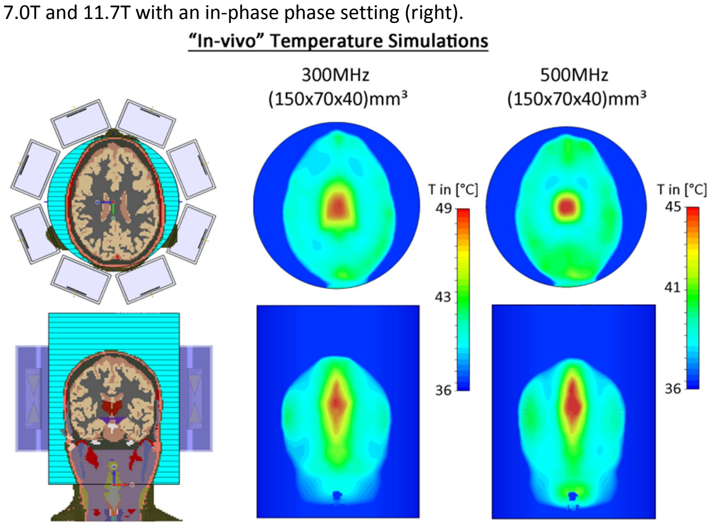

Figure 4: Temperature increase induced by a 300MHz and a 500MHz 8 channel bowtie antenna array after 5min of 50W avg power per channel. Temperature change is shown for an axial **(top)** and coronal **(bottom)** slice of “Ella”. A water bolus was used for cooling purposes and EMF coupling to the brain.

Conclusion: The presented antenna configurations both for 7.0T and for 11.7T are suitable for MR imaging, MRTh and targeted RF heating. Temperature simulations show that the generation of a hotspot in the human brain is feasible and the hotspot dimensions are further reduced while increasing the RF frequency.

References: [1] Lewin JS, et al., AJNR, 1999 [2] Lewin JS, et al., Radiology, 2004 [3] Issels RD, et al., Lancet Oncol, 2010 [4] Overgaard J, et al., Lancet, 1995 [5] Winter L, et al., ISMRM Proc., 2012 [6] Özerdem C, et al., ISMRM Proc., 2012 [7] Winter L, et al., ISMRM Proc., 2012 [8] Wonneberger U, et al., MRM, 2010 [9] Christ A, et al., Phys Med Biol, 2010