Endocavitary phased array applicator of therapeutic ultrasound with an integrated opposed-solenoid coil for high resolution MRI-guided thermotherapy: an in vivo study

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Introduction. Minimally invasive treatment using endoluminal high intensity contact ultrasound (HICU) is being suggested as an alternative cancer therapy in esophagus, colon or rectum [1]. This ablative technique uses the acoustic energy delivered by an ultrasound transducer introduced in the lumen, close to the target tissue. A successful therapy requires an active control of the energy deposition pattern, which can be reached under MRI guidance. The objective of this study was to offer high resolution MRI guidance for accurate spatial targeting, combined with active feedback control of the temperature. For this purpose, local RF coils integrated with a therapy ultrasound probe within a single endoscopic device were built for rectal application. The improvement of the image quality and temperature monitoring and control using this device has been investigated *in- vivo.*

Methods. The endorectal ultrasound probe (Imasonic, Besancon, France) was a 1D phased array cylindrical applicator (64 parallel elements, active zone length: 20 mm, outer diameter: 14 mm, frequency: 3.57 MHz, tip cooling balloon with degassed water circulating in a closed circuit). The phased array geometry of the probe allowed an electronic rotation of the ultrasound beam with an angular step of 5.6°. A MR-compatible impedance matching unit was used in order to optimize the power transfer. The electrical driving system (multi-channel generator, 64 power amplifiers and micro-controller) was operated outside the magnet room. This system provided an independent control of the signal amplitude and phase for each element, up to a maximal effective power of 5 W/element.

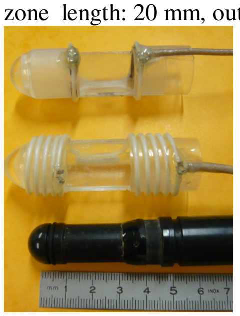

Fig.1. Transducer, 5 - turn coil and single-turn coil. Note the acoustic window opened in front of the active zone of the ultrasound probe.

The geometry of the RF receiver-only coil consisted of an opposed-solenoid made of polytetrafluoroetylene-coated copper wire (total outer diameter of wire and isolator layer: 1.67 mm) with the active HICU elements lying in the coil gap (see Fig.1). The normal operation position of the device was parallel to the Bo field. Two different coil configurations with one and respectively five turns were initially investigated *ex-vivo* on a clinical Philips Achieva 1.5T scanner, equipped with the DRIN real time data sender. Morphological (T1-w, T2-w, IR-T1-w) and thermometry (PRF shift method, segmented EPI, RF spoiled gradient echo) images were further acquired *in-vivo* on three healthy pigs (female, 35 kg body weight). The integrated coil was compared versus a standard 4-element phased array extracorporeal coil with respect to the available standard deviation in temperature measurements (SDT). Finally, active temperature control experiments were conducted *in–vivo*, in axial plane. Since no tumor model was available, the peri-rectal muscles represented the target region. Temperature feedback control was based on the Fourier transform solution of the Bio Heat Equation. Assessment of temperature controller performance was based on the correlation between a predefined target curve and the experimentally obtained temperature evolution.

Results. No susceptibility or RF-related artifacts were found to corrupt the MR signal. The Q values measured in water/ tissue environments were 53.9/ 20.5 for 5-turn coil and, respectively, 58.5/ 53.2 for single-turn coil. The 5-turn coil had lower Q values when operating in tissue, showing strong sensitivity to the loading environment, while the single-turn coil showed less important sensitivity. Hence, the *ex-vivo* muscle thermometry data (voxel: 0.63x0.63x8mm^3, 30 dyn, 2s/dyn) obtained with the single-turn coil showed better sensitivity, i.e. the limit of 1°C STD was reached at 18 mm distance from the tip balloon, instead of 13.5 mm with the 5 - turn coil. The *in-vivo* comparison between endocavitary (single turn) and external standard coils, with voxel size of 0.88 x 0.88 x 8 mm^3 and 4s/dyn, showed a sensitivity gain up to a factor 4 at the limit of the cooling balloon. High resolution morphological images (voxel size 0.4 x 0.4 x 5 mm^3) and accurate thermometry data (voxel size 0.75 x 0.75 x 8 mm^3, 2s /image, see Fig.3a) were acquired during *in-vivo* experiments. The endoscopic device was operated under automatic feedback control of the temperature, demonstrating accurate performance (4.35 % SD, 0.3 % error of mean value, see Fig.3b).

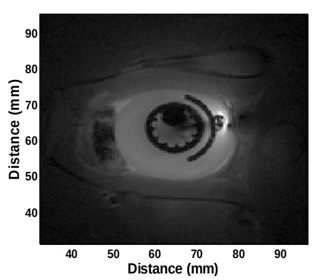

Fig. 2. *T2-w image (axial plane) of in-vivo porcine pelvis.* *<u>Data parameters:</u> FOV= 128x 128 mm², TE/TR = 60/ 1250 ms, rec. matrix =256 x 256, thickness 4.9 mm, flip angle = 90°, acq. time= 82 s.*

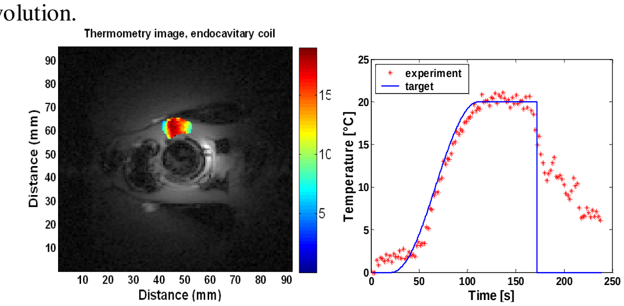

Fig. 3 a).Thermometry image for an in-vivo heating experiment. <u>Data parameters</u>: EPI factor = 11, FOV = 96 x 96 mm², TE/ TR = 17.5/ 180 ms, rec. matrix = 128 x 128, thickness 8 mm, flip angle = 45°, 2s/ dynamic, acq. time= 243 s.
b).Time course of the temperature evolution under active PID control (same experiment).

Discussion. The home built, receiver-only RF coils were designed to meet both anatomical and technical constraints. The assembling of the coil and the transducer was mounted into the cooling balloon. The balloon offered important advantages (biocompatibility, RF pulse heating prevention). A fundamental advantage of this local coil was the capability to acquire images with high resolution (small FOV), without possible phase wrapping from other regions. This phase wrapping problem appears usually when using external coils and the strategies to eliminate it are generating of extra acquisition-time. Flow artifacts due to tip cooling water could be shifted out of the region of therapeutic interest by changing the phase encoding direction. Unlike the homogeneous sensitivity of extracorporeal coil, the endocavitary coil had a significant sensitivity gradient. However, a sufficient SDT (up to 1°C) still could be achieved at 20 mm distance, on a vertical profile, from the cooling balloon. An optimal SDT (< 0.5°C) was limited at a distance of 6.5 mm around the cooling balloon. In conclusion, two technological issues were successfully investigated in this *in-vivo* study. First, an endoscopic HICU device for digestive applications was combined with a local receiver-only RF coil. Second, this combined device was coupled to an automatic temperature controller. Infra-millimeter resolution became feasible for fast MR thermometry while providing excellent SDT.

References. 1. D. Melodelima et al *Mag. Res. Med*, 2005, 54: 975 – 982; 2. M. Rata et al *Phys. Med. Biol,* 2008, 53**:** 6549-6567.