Spline-Based Temperature Probe Registration for MRThermometry Validation in Head and Neck Hyperthermia Phantoms

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Purpose: MR thermometry (MRT) can be used to enhance the temperature information available in head and neck (H&N) hyperthermia (HT) treatments by providing multi-dimensional temperature information with high spatial resolution over large regions of interest. However, to ensure the accuracy of MR temperature maps, MRT validation experiments must be performed in a H&N clinical setup [1,2]. Given the nonlinear trajectory of H&N temperature probe (T probe) catheters [1], a spline fitting method has been previously devised to reconstruct the layout of catheters in MR image coordinate space and thereby extract the coordinates of the temperature locations [3]. In this work, we (i) utilize the spline-fitting technique and present an effective approach for T probe sensor localization in phantoms to mitigate temperature probe localization errors and (ii) provide a means of more accurate proton resonance frequency (PRFS) thermal coefficient (alpha) characterization, which corrects for systematic over- or underestimation of temperature with MRT.

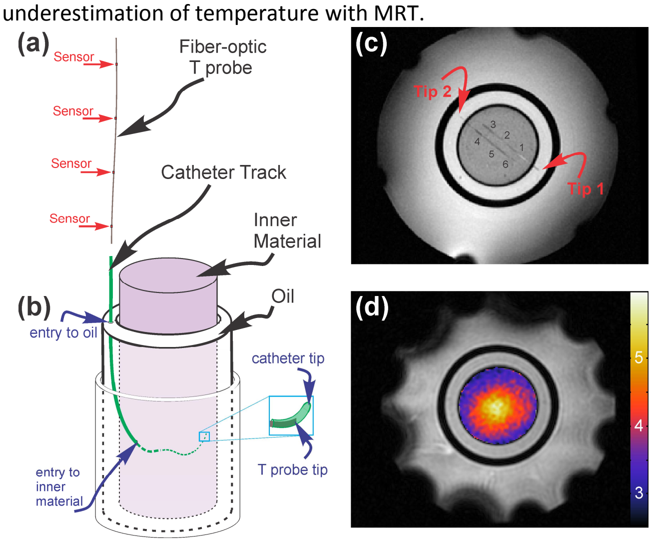

Fig 1 (a) Fiber-optic T probe strand containing four equi-spaced temperature sensors distributed along its length. (b) Illustration of phantom setup: (a) is inserted into the catheter track which has a non-linear trajectory through the phantom. (c) Axial FSPGR image showing catheters in phantom and approximate T probe sensor locations. (d) Axial MRT map.

Methods: Phantoms had an inner cylinder (diameter = 100mm) of a TX-151 (superstuff)/agar-based formula, or a gelatin interior (cylinder dia=100mm), and oil exterior (outer layer, with dia=135mm), as shown in Fig. 1b [4]. Brachytherapy delivery catheters (W. Cook, P4.1-CE-50-SFT-NS-0, ID = 0.89±0.03mm) were inserted through the phantoms. Catheters were imaged with a 3D FSPGR sequence (Fig. 1c, TE = 3.3ms, TR = 6.9, θ = 8°, FOV 33cm, 512x512, NEX 2, axial, 2mm thick). Fiber-optic temperature probe filaments (Fig. 1a) were inserted through the catheters (FISO, FOT-NS-577C, OD = 0.8±0.05mm, ±0.1ºC) to provide reference temperature readings during heating experiments. Cubic spline-curve fitting was performed on the extracted MR coordinates from images like Fig. 1c and used to generate a 3D trajectory of the catheter/T probe path according to the procedure outlined by Tarasek et al. [3].That result was utilized as a way to constrain a positional sweep in MR coordinate space for the selection of MRT voxels. T probe sensor registration was achieved by a linear correlation between all sensor points located along each temperature probe (given that the sensors were located in the heating region). Here, linearity of PRFS phase change (Δ□) as a function of temperature for all sensor points along a given T probe indicates correct localization. In particular, the Pearson product-moment correlation coefficient (R^2) for all sensor points plotted together, was maximized by performing a positional sweep along the spline curves. An $R^2 > 0.995$ threshold provides sufficient correlation, as depicted in Fig. 2a-b. Heating experiments were performed with the MRlabcollar HT applicator [2], and a spoiled gradient-echo (SPGR) imaging sequence (TE = 19.7ms, TR = 110ms, Flip 29°, FOV 40cm, Matrix 128x128, axial slice 10mm) was used to generate PRFS MRT maps as depicted in Fig. 1d. All MR images were acquired on a 1.5T GE MR450w scanner (GEHC, Waukesha, WI), and post-processing was performed with Matlab (Mathworks, Natick, MA).

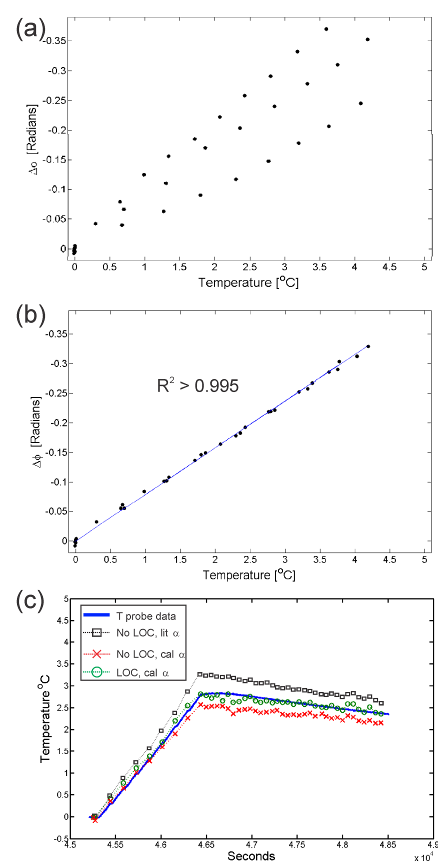

***Fig. 2** (a) PRFS phase as a function of ground-truth temperature for sensors 1-3 from Fig. 1b, non-localized (R^2<0.90). (b) PRFS phase as a function of ground-truth temperature for all sensors localized. (c) Heating experiment showing MRT data for non-localized (both with literature and calibrated α) and localized (with calibrated α) sensors plotted with reference T probe data.*

Results: Fig. 2a shows the Δ□ versus temperature plot of sensors 1-3 from Fig. 1b at a non-localized position along the spline. Once the sensor positions are localized, the Δ□ versus temperature plots merge into a single curve as shown in Fig. 2b. In addition, the slope of the curve in Fig. 2b is the α parameter of the material. This plot becomes less disperse (thus more accurate) when sensor points are properly localized. Heating experiments were performed to assess localization/α-characterization methods, where the difference between the MRT temperature and the sensor point temperature (ΔT) was used as the metric of accuracy. Fig. 2c plots the temperature during heating vs. time for a sensor point in the heating region for *localized*: calibrated α (green circle) and *non-localized*: incorrect/literature α (black squares), and calibrated α (red triangle). In general for all sensors in this setup, the localization/α-calibration method reduced average error, giving ΔT < 0.15°C with a maximum error of ΔT ~ 0.25°C compared to MRT data without sensor localization/α-calibration, which yielded an average error of ΔT > 0.75°C with a maximum error of ΔT ~ 1.51°C.

Conclusions: Using the spline-sweep method for temperature sensor registration, we can correct for errors in localizing the T probe sensors, and get more accurate verification of the PRFS temperature coefficient (α) in specific materials, i.e., gradient of fitted curve in Fig. 2b versus Fig. 2a. Overall, this method is feasible and beneficial for MRT validation and provides a useful benchmark method to maximize MRT accuracy in any similar setup.

References: [1] Paulides et al. Phys Med Biol 2010;55:2465-80, [2] Paulides et al. IJH 2007;68:2, [3] Tarasek et al. ISMRM 21;2013, [4] Pellicer et al. ESHO 2013