Does proton resonance frequency linearly change with temperature?

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Introduction

Proton resonance frequency (PRF) shift has been widely used for noninvasive temperature measurements as one of the popular MR thermometry methods. MR thermometry is the only FDA-approved temperature monitoring method for clinical transcutaneous High intensity focused ultrasound (HIFU) procedures. HIFU surgery, monitored by temperature sensitive MRI, is an emerging field in medical intervention and relies on accurate temperature measurements for a high temperature region. We designed and fabricated a test sample holder and conducted temperature measurements over a wide temperature range of 20 – 95 C to improve the accuracy in temperature measurements over the wide temperature region. Nonlinear relationship was monitored over the wide temperature region between proton resonant frequency and temperature in a distilled water phantom. The nonlinear relationship over such a wide temperature region has been previously reported for water temperature measurements performed by using the proton resonance frequency shift [1].

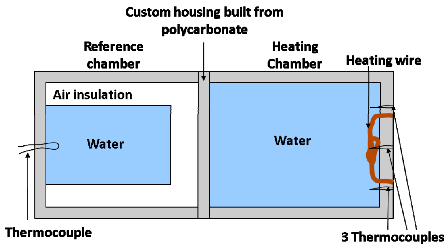

Figure 1. Test chamber comprising a reference chamber and a heating chamber.

Methods

A water-filled test chamber (Fig. 1) was designed to be placed in a 38 mm inner diameter radiofrequency (RF) volume coil (Litzcage type from Doty Scientific, Inc., Columbia, SC) and heated water uniformly to known temperatures while the proton resonance frequency (PRF) was measured in a heated slice using a gradient echo sequence (TR = 35 msec, TE = 7 msec, matrix of 64x32). Magnetic resonance imaging was conducted using a 4.7 Tesla magnetic resonance scanner with a Bruker magnet (Bruker Medical Systems, Karlsruhe, Germany), equipped with an INOVA 200 spectrometer (Varian, Inc., Palo Alto, CA).

Chamber design: To overcome problems of our previous technique [2], which pumped water through the test chamber, the heating in the final design was accomplished by running an alternating-current through a coil of NiChrome wire in a water-filled 50-mL closed cylindrical test chamber. Though there was nickel in the wire, the heating element was far enough outside the RF field to avoid distortion of the image. The heating coil shape was determined empirically so as not to vibrate in the oscillating fields produced by a RF coil. The alternating current was safer than direct current and was created by modifying the line voltage available to outlets in the lab using a Variac. Type T thermocouples were mounted in both ends of the chamber to determine actual temperature as well as also measure the uniformity of heating. The system worked reliably with temperatures from 25-95C. The water was degassed and a bellows was added on top of the chamber. The bellows permitted depressurizing of the chamber and capture of any bubbles that formed near boiling and would disrupt the image if they remained in the field of view. Degassing minimized the out-gassing into these bubbles.

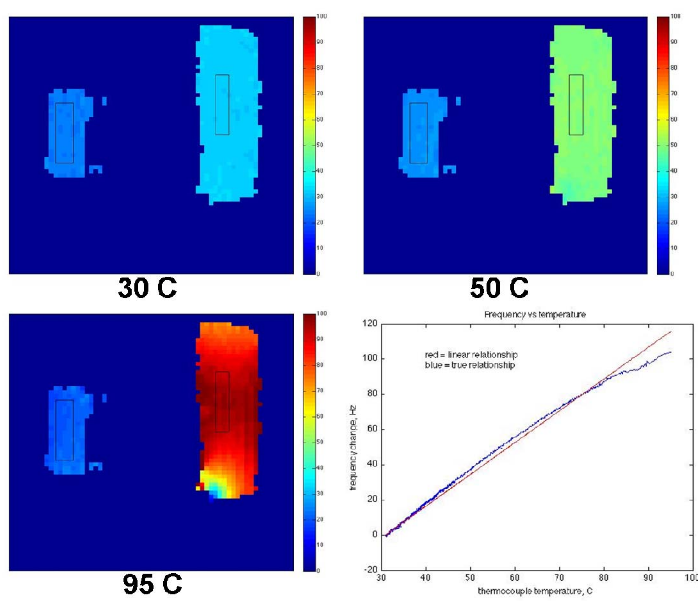

Figure 2. Temperature maps for three different values of 30, 50 and 95 C and the plot of proton resonance frequency versus temperatures.

Results and Discussion

Figure 2 shows acquired MR images converted to temperature maps during the water cool-down process. For each image, the reference chamber is on the left and the heating chamber is on the right. The cause for the artifact in the bottom left corner of the MRI image is unknown at this time. The plot in Fig.2 shows the relationship between PRF shifts and actual temperatures measured by a thermocouple during the cool-down process. Linearity shown in the red line on the plot (Fig. 2) does not seem to be effective over the entire temperature region. The standard linear relationship of 0.009 ppm/C was able to provide a limited linearity over a small temperature region ranging from 25 to 40 C. Rather, the appropriate scale factor was not the same for the higher temperature region of 85 to 95 C as it is for 25 to 40 C.

The fabricated test sample is portable and will be used for future temperature measurements at different magnetic fields such as 1.5 T, 3 T and 7T. We will also use different samples in the test chambers instead of water for the future temperature measurements.

Conclusions

We demonstrated a potential nonlinearity between PRF shift of water and actual temperatures over a wide temperature region ranging from 20 to 95 C.

References

1. Hindman, J.C. *J Chem Phys* **44**, 4582-4592 (1962).
2. 2. Khokhlova, T.D. *J Acoust Soc Am* **125**, 2420-2431 (2009).