MR Temperature Imaging for Development and Validation of 3D Light Propagation Models in the Presence of Gold-Silica Nanoshells for Thermal Therapy Treatment Planning

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Introduction:

Laser Induced Thermal Therapy (LITT), when used in conjunction with Gold-silica nanoshells (a class of nanoparticle tuned to absorb strongly in the near infrared) has proven to be an effective method for effecting thermal therapy of tumors[1]. Accurate treatment planning is necessary for safe and efficient delivery of thermal therapy in the presence of these nanoshells. This requires fast, high quality modeling of the interaction between the photons and the nanoshell impregnated tumor to accurately determine the therapeutic temperature distribution. Traditionally the Standard Diffusion Approximation (SDA) is used for modelling optical photon transport in tissue but this is known to be inaccurate for turbid media with low transport albedo[2], which is the case for gold-silica nanoshells in turbid media. For this work we utilize the spatiotemporal temperature distribution as measured by Magnetic Resonance Temperature Imaging (MRTI) to validate the delta-P1 approximation[3] as a more accurate alternative for modeling thermal interaction of infra-red photons with nanoshells in phantoms. Finite Element Modeling (FEM) was used to compare both these models against experimental results obtained form MRTI.

Methods:

All experiments were performed in a 1.5T clinical MR scanner (Signa, GEHC, Milwaukee, WI). MRTI was performed using a 2D fast, rf-spoiled gradient-echo sequence with parameters: flip angle 30°, FOV= 12cm, slice thickness 3.0mm, encoding matrix of 256x128, TR/TE = 74.5-ms/15-ms and a 3-inch receive only surface coil. Agar gel phantoms containing nanoshells of various sizes, optical properties and concentrations were prepared (Nanospectra Biosciences Inc, Houston, TX). The cylindrical gels (23mm diameter x 69mm high) were positioned in the MR scanner so that collimated output of a diode laser fiber (808 nm wavelength) could be reproducibly positioned to irradiate gels, thus keeping the beam intensity and beam width constant across the experiments. Each phantom was irradiated for 3 minutes at different laser powers and a spot size of 5mm diameter and allowed to cool under MRTI guidance. FEM was carried out using a commercial Finite Element package (Comsol® Inc. CA U.S.A). The first photon transport model tested was the SDA, which is characterized by an isotropic diffuse fluence component and an anisotropic radiant flux component of the diffuse light field. The second model uses the delta-P1 approximation where the radiance function is split into a ballistic component, representing photons that are not scattered and a diffusive component that is the same as the SDA. This model is well suited to a highly directional photon source (laser) in a highly forward scattering medium[2] (tissue like phantom).

Results:

Figure 1 shows MRTI experimental temperature distribution within a cylindrical phantom containing nanoshells with a 180nm core diameter and a transport albedo of 0.54. The reduced scattering coefficient and absorption coefficient for the phantom were 0.89 cm^{-1} and 0.71cm^{-1} respectively; the laser power used was 1.0W. Figure 2 shows the temperature change as a function of depth down the center of the phantom. The observed maximum temperature increase is 14.6°C for a laser power of 1.0W and a 20.7°C for a laser power of 1.5W, which is more than adequate for LITT. Before the temperature peak is reached at 1.8cm both SDA and delta P1 accurately model the temperature change for both laser power settings. Beyond 1.8cm SDA predicts a faster fall off in temperature than is measured experimentally with MRTI, the correlation coefficient for SDA and experiment beyond 1.8cm is 0.990. Delta P1 models the experimental data effectively over the entire range of depths shown, the correlation beyond 1.8cm in this case was 0.996.

Conclusions:

MRTI is an effective imaging technique for measuring the temperature distribution of nanoshell enhanced LITT and is therefore useful for verifying models designed to describe temperature distributions under experimental conditions. Future treatment planning will require tissue specific models of greater accuracy than the commonly used SDA. The delta P1 is one such possible model but further development is needed in vivo. MRTI promises to be an extremely useful tool in refining and verifying these models.

References:

1. L.R. Hirsch et. al. PNAS 100 (23) pages 13549-13554 (2003)
2. J.S. You et. al. Physical Review E (72) 021903 (2005)
3. S.A. Carp et. al. J. Biomed. Optics 9(3), 632-647 (2004)

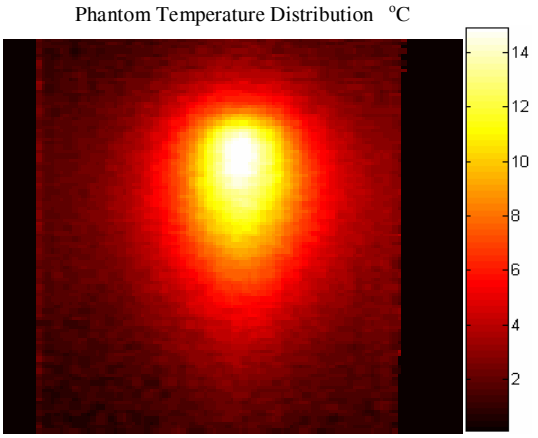

Figure 1: Temperature distribution within experimental phantom. Because MRTI measures relative temperature differences room temperature appears as zero on the temperature bar.

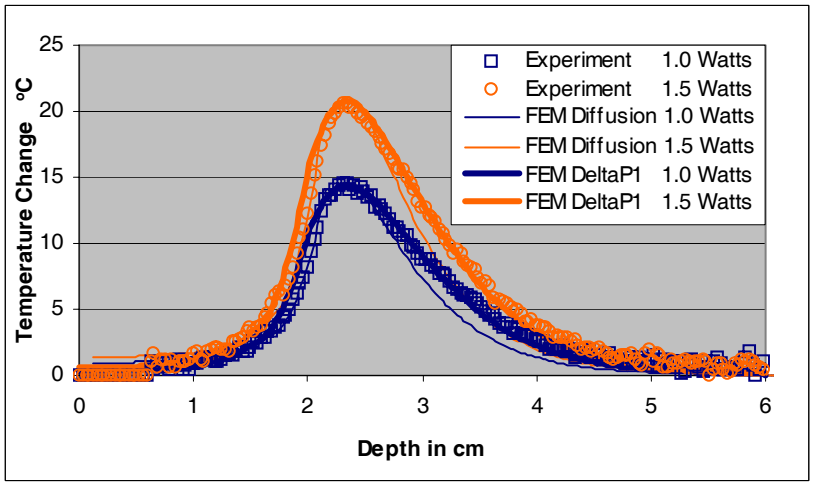

Figure 2: Change of phantom temperature with depth as measured using MRTI for two laser power settings of 1.0W and 1.5W. SDA and DeltaP1 are shown respectively as the light and heavy solid lines.