Radiance-based monitoring of the extent of tissue coagulation during laser interstitial thermal therapy

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Received October 23, 2003

Optical monitoring relates the dynamic changes in measured light intensity to the extent of treatment-induced coagulation that occurs during laser interstitial thermal therapy. We utilized a two-region Monte Carlo simulation to elucidate the nature of the changes in interstitial radiance and fluence that result from the formation of a volume of thermal coagulation surrounding a cylindrical emitter. Using simulation results, we demonstrate that radiance sensors are more sensitive than traditional fluence sensors to coagulation-induced scattering changes. Radiance measurements take advantage of directional detection angles that are more receptive to the onset and passing of the coagulation boundary. We performed experiments with albumen phantoms to demonstrate the practicality of the radiance method for monitoring interstitial laser thermal therapy. © 2004 Optical Society of America

OCIS code: 000.3860.

Laser interstitial thermal therapy (LITT) is a minimally invasive medical treatment modality that uses optical energy delivered via thin, flexible fibers that are typically inserted under ultrasound guidance directly into tissue to thermally destroy solid tumors.[1] In regions heated to greater than ~55 °C, irreversible coagulative cell death occurs that is manifested immediately and grows outward from the source fiber(s) as treatment progresses. The primary goal of LITT is the complete thermal destruction of the target tumor while sparing the surrounding healthy tissue. Monitoring of LITT is important for providing real-time information regarding the size and location of the damage boundary throughout the course of this dynamic treatment.

Point temperature measurements with thermocouples or fluoroptic temperature probes currently offer a practical and feasible minimally invasive means of monitoring LITT treatments.[2] However, temperature sensors are unable to sense coagulation directly and instead rely on thermal damage models to infer its extent.[3] Such models require tissue-specific information that is often unavailable. Optically based methods are currently under investigation for LITT that may potentially provide direct monitoring of the coagulation front.[4,5]

Optical monitoring takes advantage of the significant increase in tissue optical scattering that occurs as a result of coagulation,[6] which is manifested visually as a demarcated whitening of the tissue.[7] During LITT, the change in optical properties results in a dynamically changing light distribution that can be detected in real time by use of point optical fluence-rate sensors.[4] The increased scattering of coagulated tissue about a treatment fiber acts as a light trap, producing a drop in detected fluence for sensors located outside the coagulated region and a rise in fluence inside the coagulation boundary.[5] Hence, feedback from fluence-rate sensors positioned at the margins of a targeted region may indicate when to terminate treatment, based on a sharp increase in signal. In this Letter we demonstrate by Monte Carlo (MC) modeling and phantom experiments the utility of radiance measurements for sensing the formation and growth of a coagulation volume surrounding a cylindrical light source.

We adapted a previously described MC model[5] of photon propagation in a scattering and absorbing medium and used it to examine changes in local fluence, $\Phi(\rho)$, and in radiance, $L(\rho, \hat{\Omega})$, within and outside concentric ellipsoidal volumes of native and coagulated tissue centered about a 1.5-cm optical line source (geometry, inset in Fig. 1). Here, ρ is the radial distance from the center of the optical line source, and Ω is the solid angle. The fluence is obtained by integration of the radiance over all solid angles: $\Phi(\rho) = \int L(\rho, \Omega)\mathrm{d}\Omega$. The ray-tracing algorithm to determine photon crossing between concentric ellipsoidal regions is similar to that used previously for spherical volumes,[5] except that the equations that we used to determine photon intersection between regions were scaled along the z axis to account for the length of the ellipsoid.

Validation of the MC results was performed in well-characterized, tissue simulating albumen-based gel phantoms whose optical properties change in

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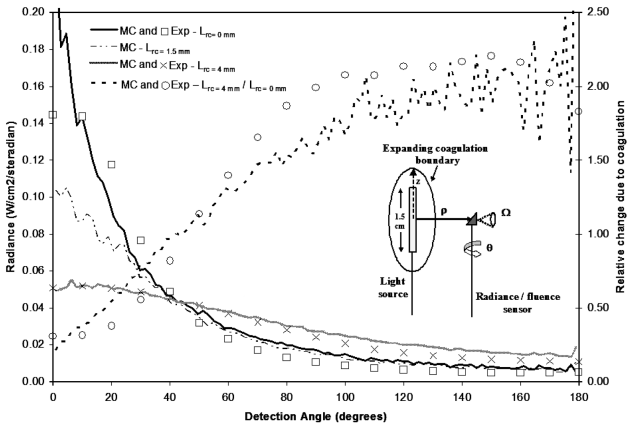

Fig. 1. MC and phantom measurements of radiance at $\rho = 2.85$ mm before LITT ($r_c = 0$) and with the coagulation boundary inside ($r_c = 1.5$ mm) and beyond ($r_c = 4$ mm) the radiance detector location. Also plotted is the relative change, $L_{rc=4\,\mathrm{mm}}/L_{rc=0\,\mathrm{mm}}$. Optical properties are given in text. Inset, modeling geometry.

a known way as a result of coagulation.[8] At a wavelength of 805 nm, the native gel had absorption coefficient $\mu_a = 0.5\ \mathrm{cm}^{-1}$ and reduced scattering coefficient $\mu_s' = 2.7\ \mathrm{cm}^{-1}$, whereas the coagulated properties were $\mu_a = 0.7\ \mathrm{cm}^{-1}$ and $\mu_s' = 13.1\ \mathrm{cm}^{-1}$. These property changes are similar to those of biological tissues.[9] As the anisotropy factor, g, was not previously characterized, it was assumed to be 0.9, which is typical for biological tissues,[9] in the MC simulations. India ink was used as an absorber, with μ_a determined by spectrophotometry. The radiance sensors were constructed in house, by the method of Dickey *et al.*[10] The sensor was not enclosed by a glass sheath, as significant perturbation of the light field was observed during preliminary experiments. The radiance sensor was held tightly in an optical fiber chuck and mounted on a rotational stage (Thorlabs, Inc.) that we turned to vary detection angle θ. A fluence sensor (Resonance Optics) and a radiance sensor were fed through an acrylic template and positioned radially at 2.8 ± 0.3 mm on opposite sides from the center of the active length of a 1.5-cm-long diffusing line source (Medlight). During heating, the laser output was delivered at ~4 W, and fluence and radiance signals were converted to photovoltage readings by use of a PDA55 photodiode (Thorlabs, Inc.) and read into a PC via a Gen2000 data acquisition system (Labmate Sciemetrics). Before and after heating, radiance distributions were measured at a noncoagulative power of ~0.4 W.

Figure 1 shows an example of the way in which native radiance at 2.8 mm changes in albumen phantoms as a result of coagulation volumes of radius $r_c = 1.5$ or $r_c = 4$ mm, i.e., sensor inside or outside the coagulation volume. Here r_c is the ellipsoid radius perpendicular to the midpoint of the source fiber axis. Before the damage front ($r_c = 1.5$ mm) passes the sensor position, a drop in the entire distribution occurs, particularly at the forward detection angles (approximately 0°–30°), where ballistic and snake photons dominate. Thus a sharp drop in the forward radiance near the beginning of a LITT treatment signals the onset and growth of a coagulation volume. Moreover, the contribution of diffuse photons collected at 90°–180° increases significantly after the coagulation boundary ($r_c = 4$ mm) has passed the sensor position because of a light-trapping effect that results from the increased scattering inside the coagulated volume. Plotting the relative radiance change, $L(2.8\ \mathrm{mm}, \theta)_{r_c=4\,\mathrm{mm}}/L(2.8\ \mathrm{mm}, \theta)_{\mathrm{native}}$, shows that the greatest increase in radiance signal occurs at approximately 100°–160°. Fluence sensors integrate the intensity of light over all detection angles (i.e., the total area under the radiance distribution) and hence lose their inherent angular sensitivity to coagulation-induced changes.

Following LITT, the phantom was sliced along the center plane, where the resultant lesion was visually observed to be 7 mm in radius and was composed of a brighter, completely coagulated 4-mm-radius inner region and a lighter, partially coagulated 3-mm outer region. As shown in Fig. 1, experimental measurements (symbols) in albumen phantoms agree well with the $r_c = 4$ mm radiance MC results. For comparison, the experimental measurements have been normalized to the MC radiance value at 10°. Two prominent features predicted by the model are evident: (1) The crossover point at ~40° where the radiance distribution for a 4-mm coagulated volume rises above the native distribution and (2) the steady increase followed by the slight decrease in $L(2.8\ \mathrm{mm}, \theta)_{r_c=4\ \mathrm{mm}}/L(2.8\ \mathrm{mm}, \theta)_{\mathrm{native}}$ for detection angles of 150°–180°.

To demonstrate the improved clinical utility of radiance sensors compared with fluence sensors, Fig. 2 shows representative experimentally measured dynamic changes in both at ~2.8 mm during LITT. A total of six experiments in different albumen phantoms (not shown) were performed to ensure the repeatability of these results. Error bars are estimated from the percent standard deviation of the optical data at the end of heating. All optical measurements are normalized to the native reading at $t = 1$ s. As shown in Fig. 2(a), before coagulation the fluence remains relatively constant, whereas the radiance rises slightly, possibly because of slight asymmetries in coagulation formation early during heating. At ~410 s, both fluence and forward sensing radiance, $L(0°)$, drop, indicating the onset of coagulation. Following the initial decrease, $L(0°)$ shows improved sensitivity to the approaching coagulation boundary, with the signal decreasing almost 2× faster than the fluence reading from 550 to 1500 s. However, although $L(0°)$ readings offer improved sensitivity to an approaching coagulation boundary, they are relatively insensitive to the passing of the thermal lesion. After ~1500 s the fluence signal increases, indicating passage of the coagulation boundary, whereas the $L(0°)$ sensor, as predicted in the MC simulations, remains relatively constant. In this experiment the resultant lesion was observed to pass both sensors by almost ~4 mm [photograph inset in Fig. 2(a)], allowing enough of a light-trapping effect to produce a noticeable fluence increase. However, at locations where the coagulation boundary just reaches

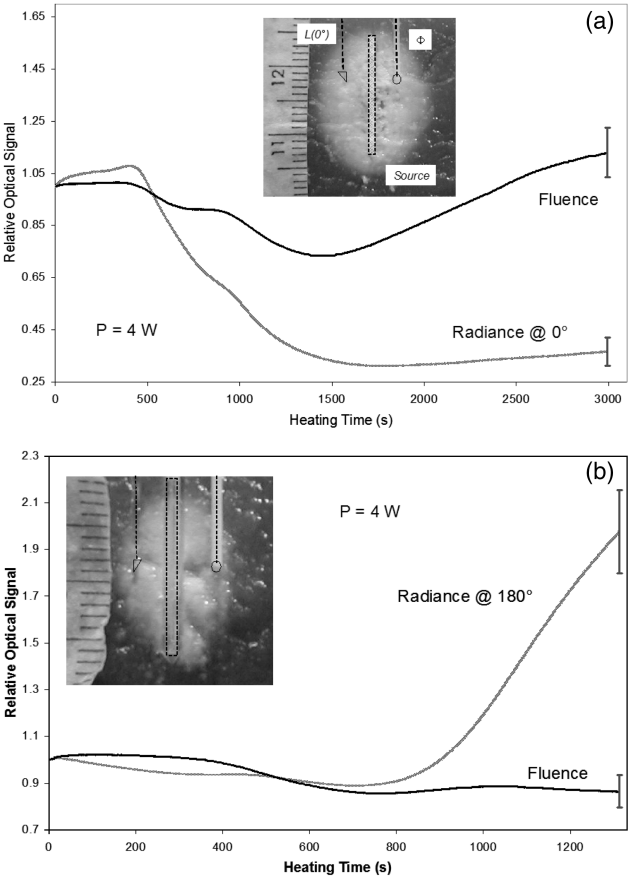

Fig. 2. (a) Experimentally measured changes in radiance at 0°, $L(0°)$, and fluence, Φ, as a function of heating time. For clarity a schematic diagram has been overlaid on the photograph. (b) Experimentally measured changes in radiance at 180°, $L(180°)$, and fluence, Φ, as a function of heating time.

an optical sensor, greater sensitivity is necessary. In such cases, the backward-sensing radiance probe will likely prove useful. To demonstrate the sensitivity of the backward radiance, $L(180°)$, to the passage of the coagulation boundary we conducted additional experiments in which the final coagulation volume was observed to pass the optical sensors by only 0.5–1 mm, as shown in Fig. 2(b). In this case the fluence increases minimally following passage of the coagulation boundary at ~800 s, whereas the 180° radiance reading increases by ~2× compared with the native (no coagulation) reading.

These results indicate a useful clinical approach for monitoring thermal coagulation by use of radiance sensors during LITT. Before treatment, the positioning of a radiance sensor array (relative to the treatment source) may be determined by use of diffusion-theory-based strategies.[11] On heating, forward radiance measurements can be used to determine the onset and approach of a growing coagulation boundary. Following a plateau of the forward signal, the sensor would be rotated to the backward detection angles to monitor the passing of the coagulation boundary and subsequent termination of the treatment.

In summary, we have demonstrated a novel directional light-intensity (radiance-) based method for monitoring thermally induced coagulation during LITT that provides significant improvements in sensitivity compared with integrated light-intensity measurements (fluence). The method takes advantage of the radiance directions that are most sensitive to the onset, approach, and passing of a coagulation boundary. A possible strategy for clinical implementation of radiance monitoring of LITT has been suggested.

Financial support for this research was provided by the National Cancer Institute of Canada (with funds from the Canadian Cancer Society) and the Natural Sciences and Engineering Research Council of Canada. The authors thank Sean Davidson (Ontario Cancer Institute, Toronto) for his early editing of the manuscript and Dwayne Dickey and John Tulip (University of Alberta) for advice on radiance sensor construction. L. C.-L. Chin's e-mail address is chinl@uhnres.utoronto.ca.

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