Imaging of dynamic MR–derived tissue models containing optical voids

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Abstract: The occurrence of optical voids can introduce model inconsistencies into diffusion–based imaging methods. For this report, we have investigated the ability to measure various features of dynamic behavior from a time–varying image series, using tissue–like models containing an optical void. Results show that whereas such structures can significantly influence image results from time–averaged measurements, measures of dynamic features are much less influenced.

OCIS codes: (170.6960) Tomography; (170.5280) Photon migration

1. Introduction

An important goal in developing any imaging method is optimization of the quality of information that is retrievable. This is influenced by many parameters, including approximations made in the physical model, limits on numerical methods, and choice of the data collection method. In the case of optical imaging, all are issues currently unresolved. For instance, with regard to data collection, it is unclear whether the principal diagnostic information lies with a discrete or time–averaged measurement, or with a dynamic measurement. While physiological arguments favor dynamic studies, is it not at all certain that improved diagnostic information could be derived. Of the many reasons that could be cited for this, the two already mentioned are the approximations made in the physical model and the limitations of numerical methods. Here we have focused on the influence that the former has on image quality and its information content. Specifically, we recognize that whereas most model–based imaging methods adopt a diffusion approximation, it is understood that tissue not infrequently contains structures whose optical properties seriously violate the assumptions invoked by this approximation [1]. To investigate this we have explored the influence that an optical void has on our ability to detect a simulated tumor embedded in an anatomic model of the breast obtained from an MR measurement. This was examined for two different measurement conditions: a time–averaged measurement and a dynamic measurement. Dynamic behavior was modeled by introducing time–harmonic variations in the absorption properties of the tissue. The derived image series was subsequently evaluated using time–series analysis methods. This produced maps of measures of the time–varying optical properties. The quality of images obtained from the two data sets was compared for their ability to detect the embedded tumor.

2. Methods

MR–Breast Tissue Model: Figure 1 shows a segmented finite element MR map of the breast extended to a circular geometry [2]. Indicated are three different tissue types (adipose in red, parenchyma in green and tumor in blue). Optical properties corresponding to a dual–wavelength measurement (760 and 840 nm) were assigned to each tissue in a manner that would model variations in tissue blood volume (2.5–10%) and its oxygenation level (30–100%). The tissue scattering properties also were varied, over a range of 5–15 cm^{-1}. In addition, the blood volume levels within each tissue type were made to vary in time by ±10% about its mean value, and each tissue type was modulated at a different beat frequency (0–0.4 Hz). Thus, the described model was intended to represent a more realistic hemodynamic model of tissue contrast [3]. In each experiment, 105 sets of detector readings were computed at intervals of 0.5 s in the modulation cycle. Also evaluated was a second medium whose structural, hemodynamic and optical properties were identical to the preceding, except that a region containing an essentially clear fluid cyst was introduced in place of the parenchyma "island" nearest the "12 o'clock" position in Fig. 1.

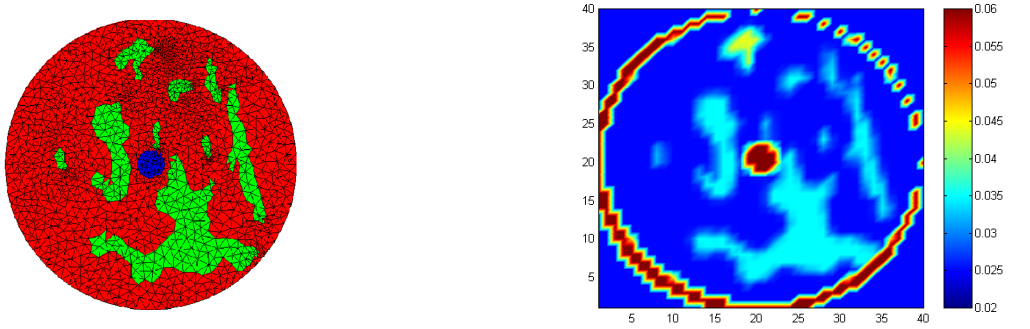


Fig. 1. (a) Segmented MR map of breast,first target medium; (b) mean true (adipose, parenchyma, and tumor tissues) or apparent (cyst) fractional blood volume, second target medium.

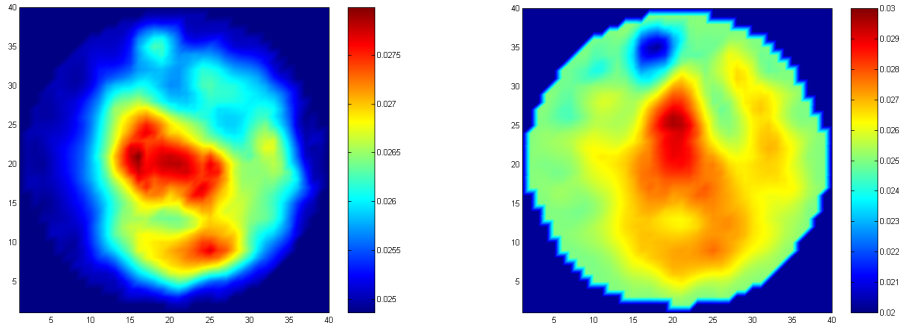
Forward Modeling: For computation of detector readings, the optical property map was transferred to a regular Cartesian grid, and a discrete ordinates code (DANTYS – diffusion accelerated neutral particle transport system) [1] was used to solve the radiation transport equation for each of six isotropic point sources located inside the target media at a depth of one mean free pathlength. The sources were placed at 60º central angle intervals about the medium, with the first at the "12 o'clock" position in Fig. 1. The detectors, lying at the same depth as the sources, were located at 20º intervals, for a total of 108 detector readings per set. For each contrast map explored, 105 sets (one for each time point) of detector readings were computed [3].

Image Recovery: Image reconstruction was accomplished by solving a linear perturbation model using a previously described CGD method limited to the first–order Born solution. Reference detector readings and the Jacobian matrix were computed using a FEM solution to the diffusion equation [4].

Time–Series Image Analysis: Maps revealing the amplitude and phase of the Fourier spectrum were derived from each image series by computing the frequency spectrum for every pixel in the image map. Similar analyses were performed for measures of temporal correlation and its frequency spectrum (*i.e.*, cross–spectral density and coherence) [3].

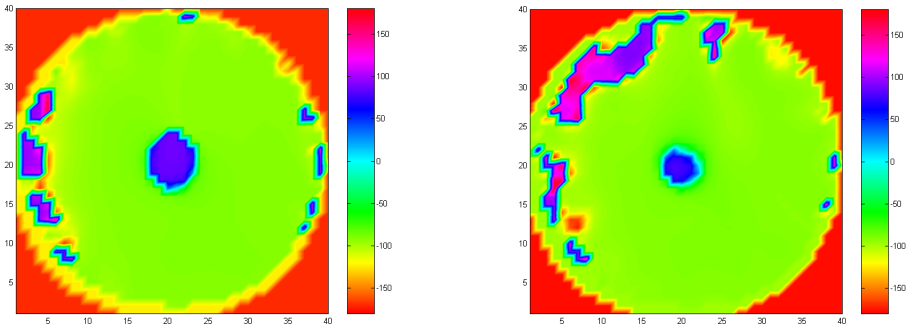
3. Results

Examples of time–averaged image maps of blood volume computed from the tissue models containing the tumor, with and without the added cyst, are shown in Figure 2a and b, respectively. In both cases, the quality of the blood volume image is relatively poor, and the presence of the central tumor is not evident. Comparison of the two images reveals that whereas the presence of the cyst is revealed, its presence has a significant impact on the contrast features of the more deeply buried structures. Also seen is a region of enhanced blood volume between the center location, where the tumor actually resides, and the edge at 12:00. This feature, however, is an artifact (*cf.*, Figure 1). In contrast, as shown in Figure 3, analysis of the two time series of images correctly locates the tumor in both cases. Shown are phase maps computed at the parenchyma beat frequency. Significantly, these results were obtained without the use of any prior knowledge of the tumor's presence or location. Figure 4 shows that an image of similar quality is obtained from a map of inter–pixel coherence.



(a) (b)

Fig. 2. Maps of position–dependent mean blood volume, deduced from reconstructed images of μ_a at two wavelengths.



(a) (b)

Fig. 3. Fourier transform phases, at f = 0.4 Hz, from reconstructed images of time–varying blood volume.

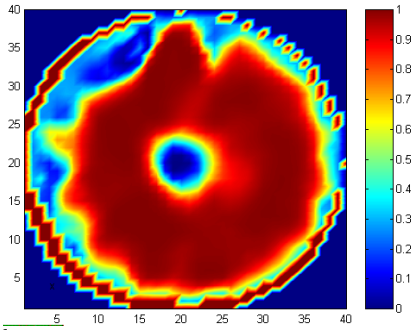


Fig. 4. Inter–pixel coherence, at f = 0.35 Hz, from reconstructed images of time–varying blood volume, for the target medium containing both tumor and cyst.

4. Summary and conclusions: The influence of an inclusion whose optical properties violate the assumptions made by the diffusion approximation to the radiation transport equation on image quality computed using time averaged and time–varying data has been explored. We observe: i) improved tumor detection is achieved from analysis of time series image data; ii) tumor detection and localization are minimally influenced by presence of a feature whose optical properties significantly violate the assumptions invoked in diffusion theory.

5. References:

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