Diffusion Based Model of Contrast Agent Kinetics for Dynamic Contrast-Enhanced MRI

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Introduction

Compartmental modeling of contrast agent uptake has been explored extensively with dynamic contrast enhanced (DCE) MRI in oncology [1] and a variety of other applications including carotid atherosclerosis [2]. Such models presume that each image voxel contains a vascular compartment supplying an extracellular compartment and the total amount of enhancement depends on the combined concentration in both compartments. The assumed collocation of the compartments within the voxel makes the model inapplicable in a case where the blood supply is physically separated from the image voxel. While such a scenario is unlikely in most applications of DCE-MRI, it must be considered in atherosclerosis. Here, a large supply of blood – the vessel lumen – is adjacent to a poorly perfused region of tissue – the atherosclerotic plaque. Thus, the reported enhancement of the surface layers of plaque [3,4] must arise from contrast agent infiltration from the lumen into the plaque. The purpose of this investigation was to develop and test a model of such diffusion-based enhancement.

Theory

If we assume a uniform tissue is adjacent to a blood pool with unit concentration of a contrast agent, the agent will diffuse into the tissue over time, yielding the sequence of concentration versus depth curves in Fig 1a. Corresponding plots of concentration versus time at specific depths are shown in Fig 1b. Note increasing delay in arrival times and slower rates of enhancement at increasing depth. The behavior of these curves is dictated by the diffusion equation $\partial C/\partial t = D\partial^2 C/\partial x^2$, where C is concentration, t is time, x is depth, and D is the diffusion coefficient. Given measurements of concentration at different depths and times, a corresponding diffusion coefficient can be derived to describe contrast agent dynamics.

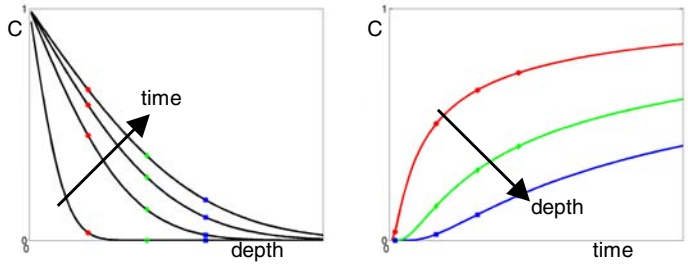

Figure 1 (a) (b)

Methods

This hypothetical process was tested in vivo using high resolution dynamic imaging of the carotid artery. A reduced field-of-view quadruple inversion recovery (QIR) technique featuring a T1-insensitive black-blood preparation [5] was used to rapidly image the artery. Sequence parameters were FOV = 12x6 cm, acquisition time = 10 sec per image, TR=500 ms, TE=10.4ms, matrix=256x112, ETL=6, thickness=2mm, and resolution = 0.5 mm. Concentration in the lumen was assumed to obey a single exponential decay. To estimate the diffusion coefficient, the juxtaluminal region was divided into three 500-μm-thick bands and the average increase in signal intensity was measured in each band at 10-20 time points. Assuming signal increase was proportional to concentration, a numerical solution of the diffusion equation yielded a single diffusion coefficient that best described the time course of enhancement in all three bands.

Results

Figure 2 shows a typical time sequence of images obtained using the reduced FOV, black-blood DCE-MRI technique. An expanding rim of enhancement (arrow) adjacent to the lumen is clearly evident. Figure 3 shows an example of the diffusion model fit to the enhancement observed in each band. The fit is good considering that all three curves are determined by a single diffusion coefficient.

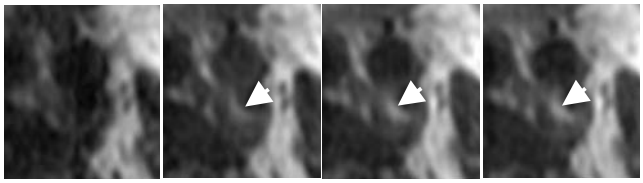

Figure 2.

Conclusions

These preliminary findings suggest that observed enhancement characteristics in the juxtaluminal layer of atherosclerotic plaque are consistent with diffusion of the contrast agent from the vessel lumen. Use of a high-resolution, reduced-FOV, black-blood DCE-MRI technique enabled the enhancement pattern to be characterized by a single diffusion coefficient. Additional studies are needed to assess the histological and clinical significance of this observation.

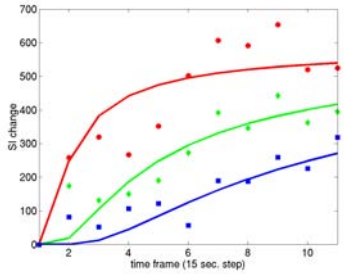

Figure 3.

References

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