A dynamic lesion phantom for quantitative evaluation of dynamic contrast enhanced MRI

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Introduction: There is a need for improved standardization of breast dynamic contrast-enhanced (DCE) MRI and well-characterized, anatomically realistic phantoms to quantitatively assess available protocols. Although dynamic MRI phantoms have been presented for various applications [1-3], none produces physiological washout curves or has the ability to be easily modified to mimic the variety of washout curve shapes in clinical images. In this study, we extend a previously reported anthropomorphic, static breast phantom [4,5] to include a dynamic lesion model capable of producing washout curves with similar shapes and timescales as patient washout curves [6]. In addition, the lesion is confined to a physiologically relevant space with a border shape that can be modified to mimic different lesion types.

Methods: ***Phantom design.*** Dynamic lesions consist of a hollow, plastic mold (inner dia.=10 mm) with 2 inlet and 1 outlet tubes (inner dia. = 2 mm). This mold confines the fluids to a physiological space and its shape can be modified to produce different mass-like border shapes. Spherical and lobulated versions were produced. The shape of the washout curve is controlled by adjusting the relative flow rates of tissue-mimicking and contrast agent solutions over time, which are mixed together before entering the lesion mold (total flow rate = 1 ml/s). Two lesion inlet/outlet configurations were investigated by examining the distribution of contrast agent solution in the lesion over time using the computational fluid dynamics software openFOAM (openCFD Ltd. Berkshire UK).

Truth measurements. X-ray images were acquired of the dynamic lesion versus time to measure the true dynamic behavior in the lesion. Two different curve shapes correspond to average shapes for a set of benign and malignant breast lesions [6] were investigated. X-ray data were collected for 5 identical runs of each of the two curve shapes to assess repeatability of the fluid flow. A mixture of 40:60 glycerol:water was used as the tissue-mimicking fluid and 40:60 glycerol:water + 150 mM Gd-DTPA was used as the contrast solution. The x-ray acquisition parameters were: 120 kVp, 6.4 mAs, 80 ms exposure time, 7.7 μm/pixel, single projection view. X-ray signal intensity was converted to relative Gd concentration using Beer's law. Final washout curve shapes were determined by calculating the average contrast agent concentration in a region-of-interest (ROI) that included the entire lesion area.

MRI measurements. MRI data sets of the phantom were acquired for the two curve shapes previously described using protocols with different spatial and temporal resolutions. A mixture of 40:60 glycerol:water + 5.0 mM Ni-DTPA was used as the tissue-mimicking fluid and 40:60 glycerol:water + 5.0 mM Ni-DTPA + 4.5 mM Gd-DTPA was used as the contrast solution. The scan parameters were: 1.5 T Siemens scanner, extremity coil, 3D gradient-echo, fat suppression, 10° flip angle, TE=1.58 ms, TR=4.4 ms, slice thickness = 1.5 mm, spatial/temporal res.=[0.5 mm/127 s, 0.8 mm/79 s, 1.0 mm/63 s, or 1.3 mm/47 s]. Washout curves were calculated as the mean image signal in a hand-selected ROI that contained the entire lesion. Lesion average signal values were divided by the average signal in a ROI including glandular-mimicking tissue to correct for drift in the MRI signal.

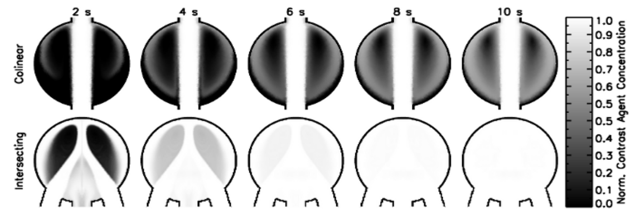

Figure 1. Fluid transfer simulations showing the distribution of contrast agent versus time for two inlet/outlet configurations (shown in the top and bottom rows). The intersecting design provides a more homogeneous distribution.

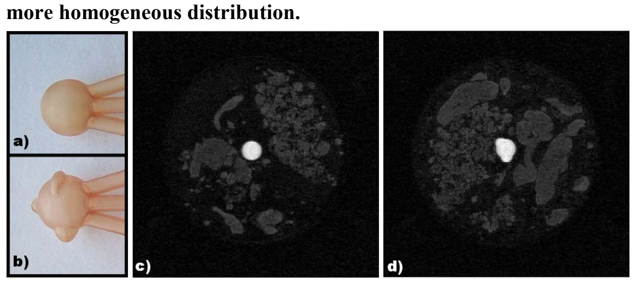

Figure 2. Photographs of spherical (a) and lobulated (b) lesion molds. Fat-suppressed, T_1-weighted, gradient-echo images (0.75 mm isotropic res., coronal slice) of a breast phantom with spherical (c) and lobulated (d) lesion molds filled with Gd-doped water.

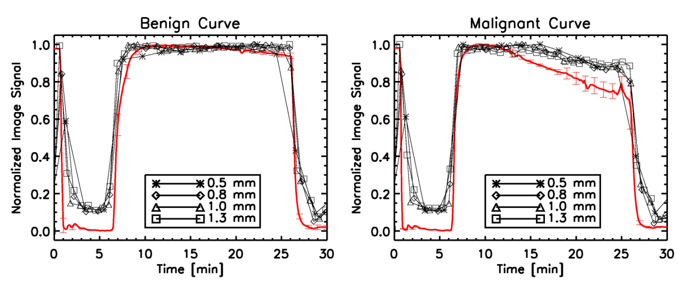

Figure 3. Comparison of truth measurements (red) and MRI results (black) for four different spatial/temporal resolution. All curves were normalized to have the same min and max value.

Results: Fig. 1 shows the results of fluid transfer simulations to determine the concentration of contrast agent versus time for two different inlet/outlet configurations. The intersecting design was chosen since it produces more rapid homogenization of the contrast agent in the lesion. Fig. 2 shows photographs and MRI images of Gd-doped water-filled lesions with spherical and lobulated border shapes. Fig. 3 shows a comparison between the x-ray and MRI measurements. As compared with the truth measurements, the MRI measurements indicate a flatter curve shape and the benign and malignant curves appear more similar.

Conclusion: We have developed a dynamic lesion model capable of producing realistic washout curves and border shapes for mass-like benign and malignant lesions, as verified by x-ray. MRI image intensity curves are flatter and less specific to lesion type than the true contrast agent concentration curves as measured by x-ray. This effect is likely due to the non-linear relationship between image signal intensity and contrast agent concentration [7]. Correcting the measured curves using reference data with known Gd concentrations, acquired using the same imaging parameters, is currently under investigation. Use of a larger flip angle or lower Gd dose could also mitigate this effect.

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