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Three-dimensional fluid pressure mapping in porous media using magnetic resonance imaging with gas-filled liposomes

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Abstract

This paper presents and demonstrates a method for using magnetic resonance imaging to measure local pressure of a fluid saturating a porous medium. The method is tested both in a static system of packed silica gel and in saturated sintered glass cylinders experiencing fluid flow. The fluid used contains 3% gas in the form of 3-μm average diameter gas filled 1,2-distearoyl-*sn*-glycero-3-phosphocholine (C18:0, MW: 790.16) liposomes suspended in 5% glycerol and 0.5% Methyl cellulose with water. Preliminary studies at 2.35 T demonstrate relative magnetic resonance signal changes of 20% per bar in bulk fluid for an echo time T_E=40 ms, and 6–10% in consolidated porous media for T_E=10 ms, over the range 0.8–1.8 bar for a spatial resolution of 0.1 mm^3 and a temporal resolution of 30 s. The stability of this solution with relation to applied pressure and methods for improving sensitivity are discussed.

Keywords: Microbubble; Porous medium; MRI; Pressure; Contrast agent; Liposome

1. Introduction

The pressure of a fluid saturating a porous medium can be measured nondestructively by conventional means only at the surface of the sample. This surface pressure yields insufficient information to determine the internal pressure of a heterogeneous sample. A method has been previously developed to measure the local fluid pressure of a gas flowing in porous media with magnetic resonance imaging (MRI) [1]. This was, however, found to be unsuitable for media with high permeability such as sandstone.

It has been shown [2], using MRI, that a gas encapsulated within suspended micrometer-sized phospholipid monolayer spheres (liposomes) causes changes in nuclear magnetic resonance (NMR) signal intensity, as a result of fluid pressure changes.

This article presents preliminary results in the application of such a contrast agent to the understanding of the fundamental properties of fluid flow through porous media exhibiting permeability and pore size distributions similar to those of sandstone.

2. Theory

The difference in magnetic susceptibilities ($\Delta\chi$) between the suspending medium and the gas encapsulated by the liposome causes local perturbations in the static magnetic field according to Eq. (1) [3]:

$$\frac{\Delta B_z(r,\theta)}{B_0} = 1/3 \cdot \Delta\chi \cdot \left(\frac{R}{r}\right)^3 \cdot \left(3\cos^2\theta - 1\right), \quad (1)$$

where R is the liposome radius and r is the radial distance from the centre of the liposome at angle θ from the direction of the static magnetic field of strength B_0.

It is not known how the gas filled liposome's radius varies with pressure, but the ideal gas law can be assumed to hold for the gas bubble. Because the spatial extent of the polarising field perturbations are dependent on the bubble radius, a change in the size of liposome due to a change in pressure results in a change of field perturbation. As protons diffuse around a liposome, they sample different magnetic field strengths as a result of the perturbations. Therefore, a hypothetical proton experiencing an identical diffusion path relative to the liposome will sample different field strengths if the liposome has experienced a change in external pressure. This effect is demonstrated in Fig. 1. The greater the field perturbations sampled by the proton, the greater the dephasing, yielding

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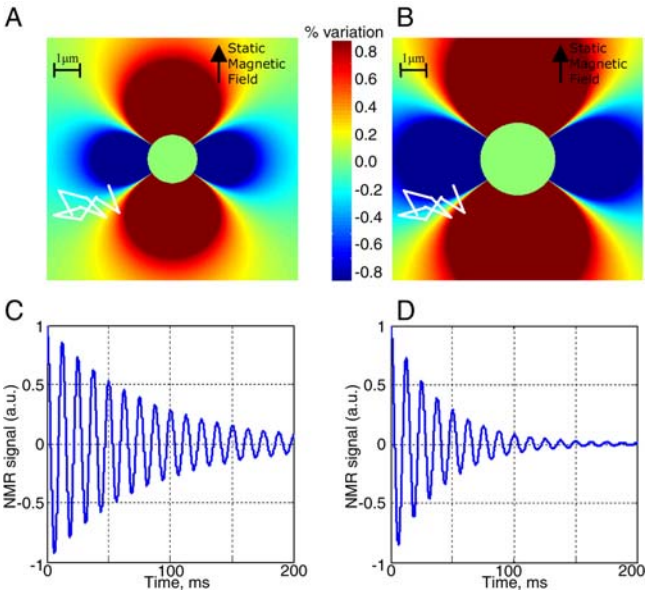

Fig. 1. Schematic colour-coded plot of the relative magnetic field perturbations caused by gas-filled liposomes (central discs) in a static field at 3 T produced from Eq. (1) for liposome radii of 2 (A) and 3 μm (B) both with plots showing the path of a proton undergoing the same random walk (white path). (C and D) Sketch of the free induction decay measured in the presence of the gas-filled liposomes above.

image contrast to fluid pressure for signal intensity through the change in relaxation rate. Extensive work has been published both on the theoretical elements and numerical simulations of the system. For spin echo sequences, it has been shown [4] that each liposome size has a corresponding theoretical echo time for which maximum effective spin-spin relaxation rate R_2^{eff} is seen. Numerical simulations have also been published, which model the system [5], although the experimental studies which are available to date offer insufficient data to conclude upon the applicability of these two theoretical works.

3. Materials

Initial experiments are conducted using a hollow extruded acrylic cell of internal diameter 39 of mm and length 52 mm, packed with silica gel saturated with the above fluid and attached at one end to a dual barrel syringe pump.

Sintered glass cylinders (AM Glassware, Aberdeen, Scotland) are used for the remaining experimental work as they are resilient to fluid flow. These cylinders have a structure very similar to that of sandstone, with the advantages that the homogeneity and pore size distribution are well known while maintaining a sample with minimal paramagnetic impurities.

These cylinders are produced from borosilicate glass in two standard porosities: 150–200 and 90–150 μm with 33-mm diameter and 50-mm length. To prevent bypass flow, these are coated in a layer of epoxy resin and embedded in an extruded acrylic tube. Two extruded acrylic end plates fitted with Swagelok connectors are then attached to either end with 5-mm clearance from the sample acting as a distribution cap.

The gas-filled liposomes are prepared by dissolving desiccated 1,2-distearoyl-*sn*-glycero-3-phosphocholine in water and cooling the solution below the phase transition temperature $T_C \approx 60^\circ C$. This results in a solution containing laminar lipid bilayers. The mixture is then homogenised with a high sheer mixer [6], which causes the laminar lipid sheets to form monolayers around the gas liquid interface at the surface of bubbles introduced in this process [7]. This produces gas-filled liposomes of 1–6 μm. For simplicity in production, all of the experiments presented herein use air as the encapsulated gas.

The gas-filled liposomes are diluted to a concentration of 3% gas by volume in a solution of 0.5% Methyl cellulose (viscosity 1500 cP, 2% in H_2O) with 5% glycerol in water. The Methyl cellulose is used to increase the viscosity sufficiently that the gas-filled liposomes do not rise too rapidly to the surface of the suspension while ensuring a substantial pressure gradient of at least 0.2 bar is produced for flow rates less than 2 ml/min. The glycerol is mixed with the liposome preparation before they are introduced into the Methyl cellulose, resulting in a more homogeneous solution than if the liposomes are added suspended in water.

4. Method

The silica gel–packed cell is attached to two interconnected 50-ml gas-filled syringes in a syringe pump via a length of Methyl cellulose filled tubing. The volume of the syringes is continuously swept to apply pressures which vary between 0.8 and 1.2 bar while imaging is performed. The MRI system is a 2.35-T Bruker Biospec small animal scanner (Bruker Instruments, Billerica, MA, USA). The sequence used is Multi Slice Multi Echo (MSME), which is a spin echo sequence that minimises susceptibility artefacts between the silica or glass and the liposome fluid.

A mixing cell with a magnetic stirrer is used for the flow experiments to ensure a homogeneous mixture is achieved for all preparations. This is initially filled with Methyl cellulose in water at a concentration of 0.5%.

The liposomes are mixed with five thirds their volume of glycerol and are injected into the cell using a syringe pump. Once the liposome mixture has been added, the syringes are refilled with Methyl cellulose, which is used to force the mixed fluid out of the cell and into the sample via a short section of Swagelok tubing. The other side of the sample is

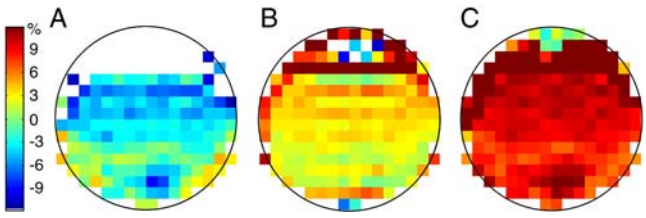

Fig. 2. Relative MR signal intensity deviation from 1 bar, averaged over all slices, in silica gel sample at static pressures of (A) 0.8, (B) 1.0 and (C) 1.2 bar. Note the increase in signal towards the upper portion of the images indicating the accumulation of liposomes in the bulk fluid.