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Imaging inert fluorinated gases in cracks: perhaps in David's ankles

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Abstract

Inspired by the challenge of determining the nature of cracks on the ankles of Michelangelo's statue David, we discovered that one can image SF_6 gas in cracks in marble samples with alacrity. The imaging method produces images of gas with a signal-to-noise ratio (SNR) of 100–250, which is very high for magnetic resonance imaging (MRI) in general, let alone for an image of a gas at thermal equilibrium polarization. To put this unusual SNR in better perspective, we imaged SF_6 in a crack in a marble sample and imaged the lung tissue of a live rat (a more familiar variety of sample to many MRI scientists) using the same pulse sequence, the same size coils and the same MRI system. In both cases, we try to image subvoxel thin sheets of material that should appear bright against a darker background. By choosing imaging parameters appropriate for the different relaxation properties of SF_6 gas versus lung tissue and by choosing voxel sizes appropriate for the different goals of detecting subvoxel cracks on marble versus resolving subvoxel thin sheets of tissue, the SNR for voxels full of material was 220 and 14 for marble and lung, respectively. A major factor is that we chose large voxels to optimize SNR for detecting small cracks and we chose small voxels for resolving lung features at the expense of SNR. Imaging physics will cooperate to provide detection of small cracks on marble, but David's size poses a challenge for magnet designers. For the modest goal of imaging cracks in the left ankle, we desire a magnet with an approximately 32-cm gap and a flux density of approximately 0.36 T that weighs <500 kg.

Keywords: Historic preservation; Statue; Gas MRI; SF_6; Michelangelo; Lung imaging

1. Introduction

During the last 25 years that Michelangelo's renowned statue David was outdoors in Piazza della Signoria, Florence, people documented cracks on the back of his ankles [1]. A theory on how they formed stated that the pedestal had shifted so that the statue was leaning forward, putting the back of the ankles under considerable tension. Even good sculpture-grade marble is weak in tension and prone to cracking. While this theory is good for explaining how the cracks started, it does not explain why they stopped. A crack of such origin in a rigid brittle material would propagate all the way through.

Importantly for conservation, we do not know how deep the cracks are and whether they compromise David's structural integrity. In 1873, the statue was transferred to the Accademia delle Arti e del Disegno, where it has since been sheltered and standing upright in proper balance. Existing records indicate that the cracks have not gotten worse since 1873. To date, attempts to image the cracks with X-rays have been unsuccessful.

Inert gas is a choice material for imaging because it has no surface tension to aggravate mechanical problems and it will not dissolve the marble. SF_6 is a good choice because it is inert, it has fast relaxation, ^{19}F is a good NMR nucleus and there are six ^{19}F nuclei per molecule. In a laboratory study, Kuethe and Scholz [2] imaged SF_6 gas in a cracked sample of marble and demonstrated that, by using the coarsest voxel size that is practical for the purpose (e.g., 44 pixels across a 44-mm object), one can detect cracks down to 5 μm thick. They calculated that, by imaging SF_6 gas, one could detect 23-μm cracks on David's left ankle using a 0.36-T magnet and 5.1-mm voxels with an imaging time of approximately 12.8 h. The keys to making such a useful image with gas at thermal equilibrium polarization are (a) an appropriate choice of gas and (b) the use of a large voxel size to achieve a very high signal-to-noise ratio (SNR). The SNR Ψ for voxels full of gas is approximately 200, and the crack width that can be detected is $\Delta x/\Psi$, where Δx is the voxel dimension. The higher is Ψ, the smaller is the crack that one can detect. Two hundred is an unusually high SNR for

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magnetic resonance imaging (MRI) and it seems especially so considering that these are images of a gas at thermal equilibrium polarization. To put the method in better perspective, this paper will compare an image of SF_6 gas in a crack in marble to an image of the lung tissue of a rat, both made with the same pulse sequence and with similar equipment.

In both cases, we try to image thin sheet-like objects that are thinner than voxel size and that should appear as bright objects against a darker background. In the case of cracks in marble, we expect the cracks to be relatively isolated so that any brightness in a voxel that is distinguishable from the background noise indicates that a crack is present and that the marble at that location is mechanically compromised. To detect the smallest cracks possible, we want the highest SNR and, thus, the largest voxels that yield practical spatial localization. In the case of lung imaging, we try to distinguish from one another as many voxels of lung tissue as possible, so we use the smallest voxels possible, purposely seeking the lowest SNR compatible with practical image quality.

Lung tissue imaging is regarded as difficult, primarily because of inhomogeneous broadening. The trick is to collect signals rapidly before they decay. Normal gas imaging is regarded as difficult, primarily because of low spin density with concomitant low SNR. A trick is to use a gas with very fast NMR relaxation, so that one can average signals extensively, but fast relaxation also leads to fast-decaying NMR signals. Both samples can yield good images, but with the very different voxel SNR ratios, in accordance with the different goals. Interestingly, the gas image is the one with high SNR and the one that puts fewer constraints on NMR hardware by virtue of minimal dynamic range requirements and longer-lasting NMR signals.

2. Methods

We imaged a crack in Colorado Yule marble, similar to the one in Kuethe and Scholz [2] and with similar methods, although the pulse sequence was directly modified from the one designed for imaging rat lung tissues. The parameters used for imaging the lungs of a live rat and SF_6 in a marble crack appear in Table 1. The rat was deeply anesthetized and mechanically ventilated according to procedures approved by our animal care committee. The 44-mm-diameter cylindrical marble sample was cracked by drilling a 6.4-mm, 24-mm-deep hole with two 1.6-mm, 7-mm-deep holes on either side and by tightening an expansion screw into the 6.4-mm hole until cracks opened but did not propagate all the way through. The five holes were directed at the axis of the cylinder.

We used free induction decay (FID) projection imaging. Broadband radiofrequency (RF) pulses were given in the presence of an imaging gradient, and data were collected as soon as possible after the receiver dead time. We collected data for 54,000 projections. Each requires data from two FIDs collected with gradients in opposite directions so that there were 108,000 gradient directions. We spaced k-trajectories as evenly as possible by mathematically placing 54,000 points approximately evenly on half a sphere along with their antipodes and by treating them all as repulsive charges. Then in an iterative calculation, we moved each in proportion to the net force from all the others, similar to that in Bak and Nielsen [3]. We sorted gradient directions so that each is at least 70° different from the prior two in the pulse sequence to spoil residual magnetization.

Acquisition of rat lung data was timed with a ventilator that held the lungs at constant inspired volume for 40% of the 1-s ventilatory cycle. We collected data for 30 gradient directions during the constant volume period and transferred the data during breathing motion. Crack data were also collected in groups of 30 FIDs.

The longitudinal relaxation time constant T_1 of lung tissue and the signal decay time constant T_2* are 1.2 s and 0.8 ms, respectively, in our 1.89-T, 30-cm bore magnet. The T_1 and T_2* values for SF_6 gas in the marble sample at 1 atm and 20°C are 2 and 1 ms, respectively. The repetition time T_R and flip angles (Table 1) were adjusted accordingly. The acquisition time T_{acq} was chosen for good point discrimination for the lung image and for good SNR for the crack image. The crack image was also processed with and without a line-broadening filter that further increases SNR at the expense of minor point spread. For both samples, the SNR was measured by making a second image through an identical procedure, dividing the two and measuring the variance of the resulting image [4].

We used a shielded gradient coil set (240-mm outer diameter and 120-mm inner diameter; Resonance Research, Billerica, MA). For the imaging of lung tissue, we used a 55-mm-inner-diameter bird cage RF coil (Morris Instruments, Ottawa, Ontario) with a fused quartz coil form and Teflon superstructure to eliminate background proton signals. For SF_6 gas, we used a fluorine-free coil by the same manufacturer and of the same size and design. For both images, we used two tuned Advanced Receiver Research (Burlington, CT) preamps in series, but for lung

Table 1
Parameters for imaging SF6 gas in a cracked sample of marble and for imaging the tissue of a rat's lungs

	T_R (ms)	Flip angle (°; Ernst)	Data acquisition time (min)	Total scan time (h)	T_{acq}[a] (ms)	Gradient strength (mT/m)	NMR frequency (MHz)
SF_6 gas in crack	3.00	77	259	6.0	1.6	15.6	75.6
Rat lung	3.50	6.7	25.2	1.0	1.1	80.0	80.3

[a] Twice the FID acquisition and dead time.