Feasibility and Challenges of Dual-Modality Pinhole SPECT / MRI Systems

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Introduction: The combination of a superconducting magnetic resonance imaging (MRI) scanner with other, complementary scanning modalities presents many technical problems. High strength magnetic fields interfere with devices used in nuclear imaging, most notably photomultiplier tubes (PMTs). MRI offers an excellent view of the structure of a subject; it is, however, less proficient at the tracking of individual cells or chemicals. Nuclear imaging, on the other hand, excels in tracking the progress of a chemical through the body. One needs only to attach a radioactive isotope of any number of common elements to the substance in order to facilitate tracking. The major downfall of nuclear imaging is that it cannot report on the physiological structure through which the tracking agent moves. For small animal imaging pinhole-collimated single positron emission computed tomography (pinhole SPECT) is often used as it can achieve sub-millimetre resolution.

In combining these two scanning modalities and executing them simultaneously, several benefits arise. The co-registration of structural and functional images becomes straightforward. The need to account for nonlinear organ shifting drops away because the subject is not being moved between scanners. Information regarding timing is preserved since the two scans are happening simultaneously. Attenuation correction, based on the anatomical data acquired, can be used to improve the resolution of the pinhole SPECT image. [1]

Both of these modalities possess qualities not conducive to the success of the other. These challenges, to be overcome in the combined design, as well as proposed solutions involving a novel, field-cycled MRI system are outlined presently.

SPECT Challenges: The most obvious difficulty in attempting to perform pinhole SPECT in a magnetic field is that of PMT operation. As these devices depend on electron cascades to operate, they are susceptible to Lorenz forces. It has, however, been shown [2] that certain designs, such as the mesh PMT, suffer only a loss of gain when subjected to external magnetic fields. In addition, other solutions exist to channel the light away from the scintillator blocks to PMTs in a protected area.

The less obvious, but potentially more damaging problem is that of line-of-sight. Photons emanating from the subject must be able to reach the collimator opening. Even if the magnet and the gradient coils are designed with a gap in the middle to allow access to the subject, there remains the problem of the shim coils and RF coil; ideally, neither of these items should be constructed with a gap. 511 keV gamma rays, as used in positron emission tomography (PET) are capable of penetrating a thin copper shield in high enough numbers for imaging. [3] Photon energies employed in SPECT are generally lower and may have a greater problem escaping such a shield.

A third issue emerges in the interaction of emitted photons with the surrounding bulk of the MRI scanner itself. The scanner will be constructed out of relatively high atomic weight elements, most notably copper. This will mean that the chance of a photon scattering is quite high. Photons that Compton scatter through low angles or those that scatter coherently have a chance at reaching the detector and without having lost enough energy to be rejected via an energy windowing technique. These photons will increase the noise of the pinhole SPECT image compared to the same image taken without an MRI scanner surrounding the subject.

MRI Challenges: The quality of an MRI image depends on, among other things, the field uniformity during acquisition. Pinhole SPECT requires the use of large cone-shaped collimators composed of high atomic weight material, such as lead, positioned as close as possible to the subject [fig. 1]. These collimators, which have a high magnetic susceptibility, would interfere greatly with the homogeneity of the fields surrounding the subject. By arranging multiple collimators symmetrically about the subject, the field perturbation is mitigated, somewhat. [4] Regardless, extra measures such as specifically designed shim coils will need to be taken in order to counteract this effect. To make matters more complicated, the SPECT collimators and cameras may need to be rotated about the subject, which would require continuously updated field shimming during a scan.

By requiring an open system design to facilitate line-of-sight to the gamma cameras, the difficulty in engineering the magnet is increased. Whatever solution decided upon to correct for the field inhomogeneities must place a minimum amount of material in the gap created in the magnets.

MRI Approach: A proposed field-cycled MRI scanner [5] lends itself to this application. This technique involves polarizing a subject with a relatively high (~1 T) magnetic field for a period on the order of a second and then switching off this magnet and acquiring an image using a lower field (~0.1 T). This design has several important advantages when trying to address the problems outlined above. The alternating periods of high and low field create a window in which a PMT will suffer a much-reduced gain penalty [fig. 2]. At the decreased readout field, distortions due to susceptibility are greatly reduced. The polarizing magnet need not be uniform, only strong. This means that for the purposes of polarization, the pinhole collimators will have little effect. In addition, creating a strong, relatively inhomogeneous polarizing magnet with a gap in the centre is not a difficult proposition.

Investigation: We are designing a combined field-cycled MRI and pinhole SPECT system. In order to explore the first half of this problem, that of the interference with the magnetic fields required for MRI, we are employing finite-element analysis of the proposed system geometries. Since the motion of the pinhole SPECT cameras is slow in comparison with the acquisition of an MRI image, the field perturbations will be functionally static and will be minimized using shim coils.

In exploring the twofold effect of scatter and attenuation we are using a Monte Carlo simulation via the GEANT4 architecture. This allows for simulation of acquisition of entire SPECT images, in turn allowing an exploration of the change in quality and creation of artefacts produced by different geometries of shim coil and RF coil.

We are exploring both of these fronts in tandem in order to reach a design that represents the optimal compromise between these two competing modalities. As dose is a fixed factor limiting image quality, the most emphasis will be placed upon the optimization of the pinhole SPECT acquisition efficiency.

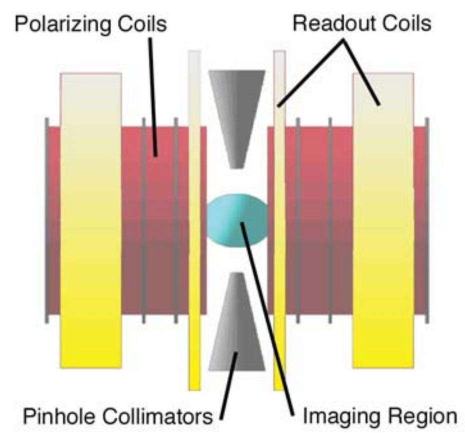

Figure 1: Approximate position of pinhole SPECT collimators relative to field-cycled MRI hardware. RF coil is not shown.

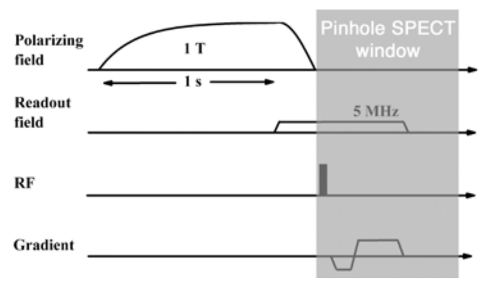

Figure 2: Field-cycled pulse sequence prototype and proposed opportunity for pinhole SPECT imaging

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