A Volume Saddle Coil for Hyperpolarized ^{129}Xe Lung Imaging

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Target Audience: Researchers and engineers interested in hyperpolarized gas imaging and coil design for pulmonary applications

Purpose:

Traditional proton MRI of the lungs is challenging due to the low density and rapid T_2* relaxation (~ 2 ms) of the pulmonary tissues. Fortunately, the challenges inherent in ^{1}H lung MRI can be overcome using hyperpolarized (HP) gases. Moreover, HP gases allow the regional distribution of lung microstructure and function (e.g., ventilation) to be visualized directly[1]. Although ^{3}He has long dominated the field of HP gas MRI, ^{129}Xe is of increasing interest, because it is readily available and because of its unique physical and MR properties[2]. Specifically, ^{129}Xe is moderately soluble in tissues (Ostwald Solubility 10% or greater) and possesses an in vivo chemical shift range of >200 ppm, allowing regional pulmonary gas exchange to be assessed in human subjects[3-6]. Unfortunately, practical hardware constraints make clinical implementation of HP ^{129}Xe MRI far from trivial. That is, ^{129}Xe MR coils must operate at low frequency (~25% that of ^{1}H) and uniformly excite the entire chest cavity. Ideally, ^{129}Xe coils will also be mechanically flexible enough to accommodate a range of subject sizes and also the volume changes inherent to the breathing cycle, while still maximizing coil filling-factor. Due in part to these practical challenges—and the cost of the commercial hardware needed to overcome them—^{129}Xe MRI can only be performed routinely at a handful of research sites around the world. To expedite the dissemination of HP ^{129}Xe MRI, we present a design for a simply constructed, mechanically robust, and low cost coil that is suitable for routine HP ^{129}Xe lung MRI in both adults and pediatric subjects. Additionally, to facilitate clinical implementation of this coil design, we have created an electromagnetic model that allows coil homogeneity and SAR values to be evaluated prior to coil fabrication.

Materials and Methods:

Physical Design: To accommodate the large size of the adult human lung, the coil was constructed with a saddle configuration by connecting two, 30.5cm wide squared copper loops through an RG 8 coaxial cable (Figure 1). To minimize inductance and avoid self-resonance of these large loops, traces were constructed from 254µm thick, 7.6cm wide copper strips. By connecting the two halves of the coil saddle with coaxial cable, asymmetries in the coil's electromagnetic field pattern were minimized. In the center of the coaxial cable, a feeder board was added to enable circuit matching and to connect the coil to the MR system's T/R switch. Each coil loop was constructed with 4 cuts: 1 to accommodate the coaxial cable and 3 to accommodate tuning capacitors. To provide robust mechanical support for subjects, while protecting electronic components, each loop was housed in a lightweight, polycarbonate frame. To perform final tuning and matching, the coil was loaded with an elliptical phantom having a dielectric constant of 77.53 and a conductivity of 0.7S/m. Additionally, two air-filled cylinders were placed in the center of the phantom to replicate the lungs. For bench top testing this entire setup was placed in an RF shield that replicated the RF shield of a 3T body coil. The overall coil setup (Figure 2) was constructed with a total materials cost of less than $1,000.

Coil Simulation: To ensure safe operation during imaging, the transmit profile and local SAR of the coil was simulated using HFSS software (Ansys Inc.). Simulated loop coils were constructed identically to the physical implementation described above. The coaxial cable was modeled as a rigid structure on the side of the coil housing (Figure 3). A tuning of -16.6dB was achieved when excited with a continuous 1W, 50Ω source.

In Vivo MRI. Isotopically enriched xenon (86% ^{129}Xe) was polarized to 24% using a commercial polarizer (XeMed LLC, Durham, NH). Axial, multi-slice GRE images (flip angle=11º,TE/TR=4.49/9.36ms, BW=15.9kHz, Matrix=100x100, voxel size= 3x3x15mm^3, 1 average) were acquired from healthy volunteers in a single breath hold (<10s) using a Philips 3T Achieva™ scanner (Philips Healthcare, Best, Netherlands).

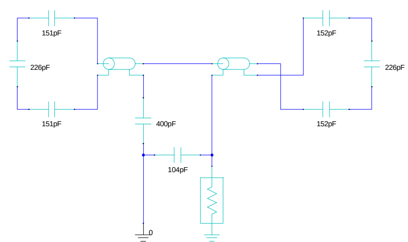


Figure 1: *^{129}Xe saddle coil schematic. The resistor was used to simulate RF drive currents during simulation. In the physical coil, the resistor is replaced with a connection to the T/R switch.*

Figure 2: *Xenon saddle coil implementation.*

Results: Based on simulations, he B1$^+$ distribution in the center planes of the phantom (Figure 4) includes a large, homogeneous region that encompasses both the right and left lungs. The unloaded Q factor for this design was 160 with a matching of -28dB and a loading factor (unloaded to loaded ratio) of 6:1 Simulations showed that using a 31.76W continuous wave excitation a local SAR limit of 10 W/kg is reached, with a small "hot spot" being located towards the anterior corner of the coil (Figure 3). Average SAR maximum with these settings results in a maximum of 8.92W/kg average SAR, offset 3cm superior of the central axial plane. A maximum B_1^+ of 3.6µT was found in the center of the phantom with these settings in the simulation.

Using this coil, single-breath, HP ^{129}Xe ventilation images were successfully acquired in healthy, adult volunteers (e.g., Figure 5). These images demonstrate that, despite its simplicity, of the robust design of the coil generated sufficiently homogenous signal intensity to be diagnostically useful. Moreover, the SNR of these images was ~30, which is more than sufficient for quantitative analysis of ^{129}Xe ventilation.

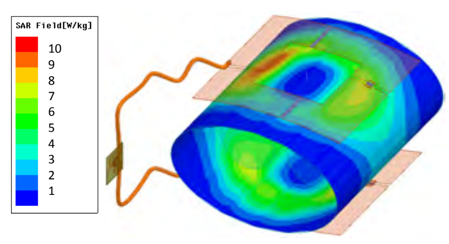
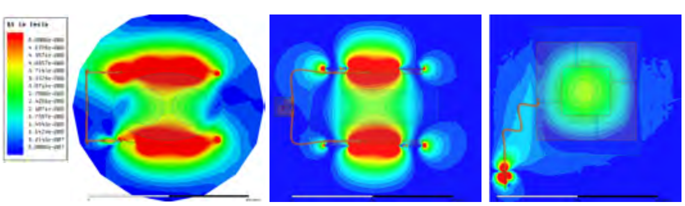


Figure 3: *Local simulated SAR on torso phantom*

Conclusion and Discussion: Simulations and safety tests showed that this coil design is a safe for hyperpolarized ^{129}Xe imaging. Further, simulations and in vivo imaging demonstrated its relative homogeneity. The flexible RG 8 coaxial cable allowed for comfortable subject breathing and made the coil robust for positioning for a large range of volunteer sizes, while also contributing to a low loss design that minimized asymmetries in the RF field. With straightforward, robust designs such as this, volume ^{129}Xe coils can be custom-built in the laboratory at low cost and high performance for routine clinical research applications.



a) b) c)

Figure 4: *B1$^+$ in the **a)** axial center plane **b)** in the sagittal center plane, and **c)** in the coronal center plane of the phantom.*

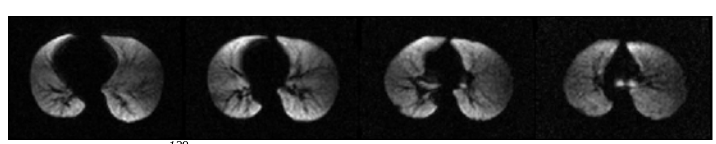


Figure 5: *In- vivo ^{129}Xe ventilation images(SNR ≈ 30).*

References: **[1]** LL Walkup and JC Wood, *NMR Biomed*., DOI: 10.1002/nbm.3151 (2014). **[2]** JP Mugler and TA Altes, *J Magn Reson Imaging* 37 (2), 313-331 (2013) **[3]** ZI Cleveland, et al., *Plos One* 5 (8), e12192 (2010). [4] JP Mugler, et al., *PNAS* 107 (50), 21707-21712 (2010). **[5]** K Qing, et al, *J Magn Reson Imaging* 39 (2), 346–359 (2014). **[6]** SS Kaushik, et al., *J Appl Physiol* 115 (6), 850-860 (2013).