Rapid EPR Oximetry using Sparse Spin Distribution

S. Som[1], L. C. Potter[2], R. Ahmad[3], D. S. Vikram[4], and P. Kuppusamy[3]

[1]Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH, United States Minor Outlying Islands, [2]Department of Electrical and Computer Engineering, The Ohio State University, Columbus, OH, United States, [3]Davis Heart and Lung Research Institute, Department of Internal Medicine, The Ohio State University, Columbus, OH, United States, [4]Davis Heart and Lung Research Institute, Department of Internal Medicine, The Ohio State University, Colmbus, OH, United States

Abstract

A method is presented to use continuous wave electron paramagnetic resonance (EPR) imaging for rapid measurement of oxygen partial pressure in three spatial dimensions. A particulate paramagnetic probe is employed to create a sparse distribution of spins in a volume of interest. Data is acquired by varying the orientation and strength of the magnetic field gradient. Reduction of unknown parameters is achieved by using a parametric forward model and exploiting the sparsity of spin distribution. This leads to an order of magnitude reduction in data acquisition time as compared to tradition spectral-spatial imaging. The proposed oximetry method is experimentally demonstrated for a lithium octa-*n*-butoxy naphthalocyanine (LiNc–BuO) probe using an L-band EPR spectrometer.

Introduction

There are two widely used techniques for EPR oximetry. In the first method, paramagnetic material is diffused in the entire volume of interest and four dimensional spectral-spatial imaging is done on the entire field of view (FOV). This technique does not require any assumption about sparseness of spins but the data acquisition time is huge. The second method known as "multi-site oximetry" uses a single favorable gradient direction for which the spectrum of each of several isolated discrete implants is resolved to some extent. The key assumption is that lineshapes are resolved with a single, one-dimensional magnetic field gradient. Thus, this method localizes pO_2 measurements in one dimension.

Method

A two step method is employed to estimate the pO_2 at the discrete isolated probe sites. These probes can be implanted anywhere in three dimensional space and the lineshapes in the acquired projections need not be resolved.

Step 1 (Sparse Initialization): Assuming fixed linewidth in the entire FOV, an approximate linear forward model in spin density is used to obtain sparse spin locations. Computation of sparse solutions to underdetermined linear equations has been a topic of considerable recent interest [1]. For simplicity, we adopt the technique of Gradient Projection Sparse Reconstruction [2]. From the reconstructed spin density map, we use the "clusterdata" routine from Matlab7.1 to cluster the voxels into candidate regions corresponding to the individual implants. The centroid of each region is used to identify candidate nonzero voxels; specifically, voxels inside a sphere with radius twice the maximum extent of an implanted probe are detected for further processing. Thus, the sparse initialization serves merely to safely discard many voxels with zero spin, thereby dramatically reducing the dimensionality and complexity of the nonlinear curve fitting task.

Step 2 (Gradient Descent): After obtaining a sparse spin map a nonlinear parametric model [3] is used to estimate the linewidths at the various probe locations. A nonlinear least-squares fit is computed using the "lsqnonlin" routine from Matlab 7.1; note that the derivative of the model with respect to each parameter is readily computable from parametric forward model, and used in "lsqnonlin" to provide a gradient descent method.

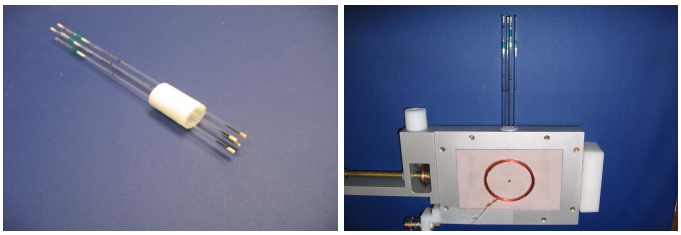

Fig. 1: Phantom and the resonator.

Results

Experiment Design: A phantom using capillary tubes was constructed (Fig 1). Each capillary tube was filled with LiNc–BuO up to a height of 3–5 mm. Variations in linewidths were obtained by using different amounts of sodium hydrosulfite ($Na_2S_2O_4$) and water, a combination known for changing the oxygen concentration to which the sample will be exposed. A total of 18 capillary tubes were prepared, out of which 4 were used to construct the phantom. The four tubes were selected to provide both a large range of linewidths and a subset of closely matched linewidths. Projections were acquired at 24 different angles generated using 4D uniform distribution of points over a hypersphere.

Results: In the initialization stage sparse $16 \times 16 \times 16$ spin density maps were estimated. Then four regions were identified by clustering. For the second stage a $32 \times 32 \times 32$-voxel reconstruction was computed. The spin density and linewidths were estimated for the four spherical regions with radius of 3 voxels. Final spin density and linewidth estimates are shown in Fig 2. The RMS error is 6.5 mm Hg.

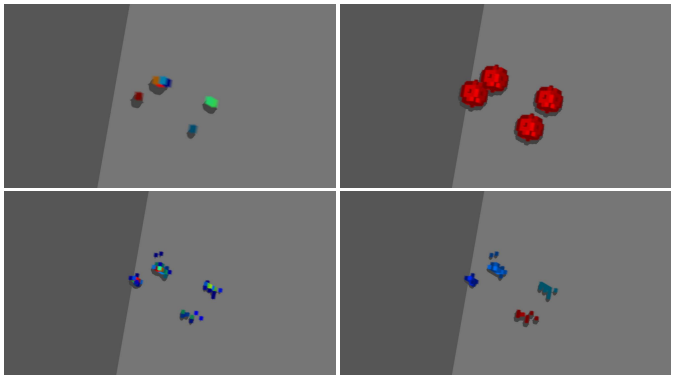

Fig. 2: Top-left: Sparse spin map from step 1. Top-right: Spherical regions around the detected and clustered probe locations selected for step 2. Bottom-left: Spin density map from step 2. Bottom-right: Linewidth map from step 2.

Conclusion

This technique enabled us to reduce the data acquisition time by a factor of more than 50:1 as compared to the tomographic techniques. It also overcomes the strict condition of resolvability of lineshapes in multi-site oximetry.

Reference:

1. D.L. Donoho, M. Elad and V.N. Temlyakov, Stable recovery of sparse over complete representations in the presence of noise, *IEEE Trans. Inform. Theory* 52 (1) (2006), pp. 6–18.
2. M.A.T. Figueiredo, R.D. Nowak and S.J. Wright, Gradient projection for sparse reconstruction: application to compressed sensing and other inverse problems, *IEEE J. Select. Topics Signal Process.* 1 (4) (2007), pp. 586–597.
3. S. Som, L.C. Potter, R. Ahmad and P. Kuppusamy, A parametric approach to spectral–spatial EPR imaging, *J. Magn. Reson.* 186 (2007), pp. 1–10.