Image Distortion and Image Mis-registration in Low Frequency Current Density Imaging

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Abstract- **Current density imaging (CDI) is a technique that uses magnetic resonance imaging (MRI) to measure volume current density distributions in tissue [1]. CDI is used to measure current pathways through tissue which adds a much needed tool to electrophysiological research such as in the area of defibrillation research. CDI maps magnetic fields, produced by an externally applied current, onto the phase images of an MRI data set. Current density is computed from the curl of the these magnetic fields. Two CDI artifacts, image distortion and image mis-registration, are studied in this article. Spatial encoding of MR images is achieved by a set of magnetic field gradients. The nonlinearity of these gradient fields causes image distortion. This article reports on the measurement of this distortion using a phantom consisting of a 3D rectangular array of point sources and the subsequent correction of this distortion using feature mapping and interpolation. Image distortion in CDI also causes mis-registration of overlying data sets. Mis-registration leads to incorrect computation of current density due to violation of Maxwell's equations. In simulation, mis-registration was also found to cause current density and the curl of current density to exhibit nonzero values in locations where proper registration gives zero current density.**

***Keywords* - Current density imaging, image distortion**

I. INTRODUCTION

In defibrillation research, current pathways through tissue are presently investigated using computer simulation techniques such as finite element methods (FEM) [2] and measurement techniques such as epicardial electrodes [3]. Unlike epicardial electrodes, current density imaging (CDI) is a non-invasive measurement technique. Low frequency CDI (LF-CDI) makes use of the spatial encoding capabilities of a magnetic resonance imaging (MRI) system to spatially map magnetic field components generated by an externally applied current waveform [1]. Spatial maps of a single component of magnetic field are encoded in phase images. Other components of the magnetic field generated by the applied current can be measured by re-orientating the sample in the other two orthogonal positions. A minimum of two orthogonal components of the magnetic field are required to compute one component of current density according to the quasi-static version of Maxwell's equation

$$\mathbf{J} = \nabla \times \mathbf{H} \tag{1}$$

Three orthogonal orientations of the sample will result in complete measurement of three components of magnetic field which is sufficient information to compute all three components of current density. In this article, two artifacts of LF-CDI are investigated. First, image distortion due to nonlinear gradient fields is measured and corrected. Secondly, the effects of image mis-registration are investigated.

A. Nonlinear Gradient Field Image Distortion

Gradient magnetic fields are used in MRI to encode spatial position information into the received signal. For an ideal linear magnetic gradient system, the fields B_x, B_y and B_z are related to positions x, y and z as

$$B_x(x,y,z,t) = xG_x(t) \tag{2a}$$

$$B_y(x,y,z,t) = yG_y(t) \tag{2b}$$

$$B_z(x,y,z,t) = zG_z(t) \tag{2c}$$

where G_x, G_y and G_z are the gradient strengths, in units of T/m, and are proportional to the amount of current passing through the X, Y and Z gradient coils, respectively. To account for the actual nonlinear relationship between gradient fields and positions, resulting from the physical geometry of the coil windings, the distortion terms δ_x, δ_y and δ_z are introduced to (2a), (2b) and (2c) as

$$B_x(x,y,z,t) = [x + \partial_x(x,y,z)]G_x(t) \tag{3a}$$

$$B_y(x,y,z,t) = [y + \partial_y(x,y,z)]G_y(t) \tag{3b}$$

$$B_z(x,y,z,t) = [z + \partial_z(x,y,z)]G_z(t) \tag{3c}$$

It is possible to measure the distortion terms by imaging a phantom of a known geometry such as a regular array of points. The distortion terms are computed from the difference between the physical locations of the points in the phantom and the distorted locations of the points in the acquired 3D volume image sets. The transformation represented by the distortion terms implies a volume change for the individual voxels or as an intensity change for individual pixels of images. The amount of intensity correction is given by the Jacobian of the transformation [4]. The intensity correction is required for magnitude images to ensure that the appropriate number of magnetic dipoles contribute to the signal, however, the intensity correction is not applicable to phase images since the information contained in phase voxels only represents the phase angle of a group of magnetic dipoles. CDI extracts information from phase images and therefore does not require the voxel volume correction specified by the Jacobian.

B. Image Registration

To compute any one component of current density requires a combination of information from the two other orthogonal components of magnetic field according to the expansion of (1) in any coordinate system. Before combining data from two separate orthogonal acquisitions, the two image sets must be registered with each other. If a directional distortion is applied to the same image set in two different orthogonal orientations, as is the case with nonlinear gradient distortion, it is not possible to register the image sets voxel for voxel. Without proper registration, Maxwell's equation

$$\nabla \cdot \mathbf{B} = 0 \qquad (4)$$

indicating that all field lines form closed loops (i.e. a magnetic pole or "charge" cannot be physically isolated in nature), is violated.

II. Methodology

To measure image distortions caused by nonlinear gradients, a simple phantom shown in Fig. 1, with a periodically spaced 3D rectangular array of spheres, was imaged. The diameter of each sphere is 8 mm and the spacing between spheres is 15 mm. The 3 x 3 x 3 sphere phantom was moved to various locations within the imaging space to cover more volume. The resulting data sets were superimposed to create a single data set containing all of the sphere locations.

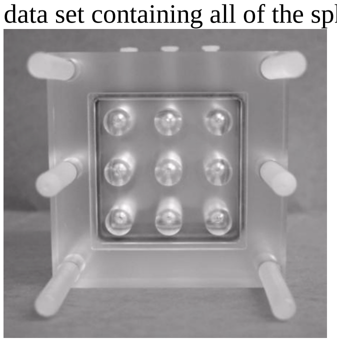

Fig. 1. Acrylic phantom with periodically spaced spheres.

The effects of mis-registration in LF-CDI were demonstrated by simulation of the geometry shown in Fig. 2. A length of copper wire with a 90° bend was set on top of a slab of homogeneous gelatin capable of producing MRI/CDI signal. A 30 mA DC current was passed through the wire to generate magnetic field gradients within the gelatin.

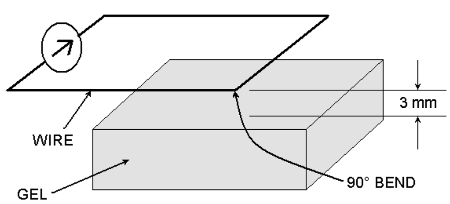

Fig. 2. Simulation geometry for mis-registration experiment.

III. Results

The resulting distorted image of the 3 x 3 x 3 sphere phantom is shown in Fig. 3(a) and the corresponding center points of the spheres are shown in Fig. 3(b). The actual sphere center locations are shown in Fig. 3(c). After mapping all of the center points from one space to the other and interpolating the remaining points, the image of Fig. 3(a) is corrected as shown in Fig. 3(d). In general, this correction can be applied to any MRI data acquired on this particular machine.

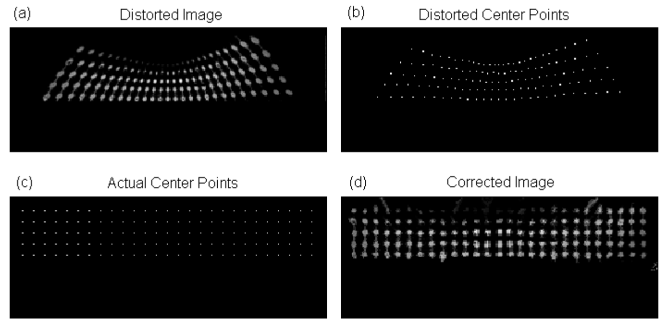

Fig. 3. (a) Distorted image of phantom. (b) Center points of spheres in distorted image. (c) Actual center points of phantom. (d) Image (a) after applying correction.

LF-CDI simulation of the geometry shown in Fig. 2 shows the current pathways indicated by the streamlines shown in Fig. 4 when the component data sets are purposely mis-registered. With proper registration, current density values are nearly zero as expected since no current flows through the gel. These 'swirls' correspond to regions of nonzero values of the current density and the curl of current density. The curl of current density may provide a possible measure of how well data sets are registered.

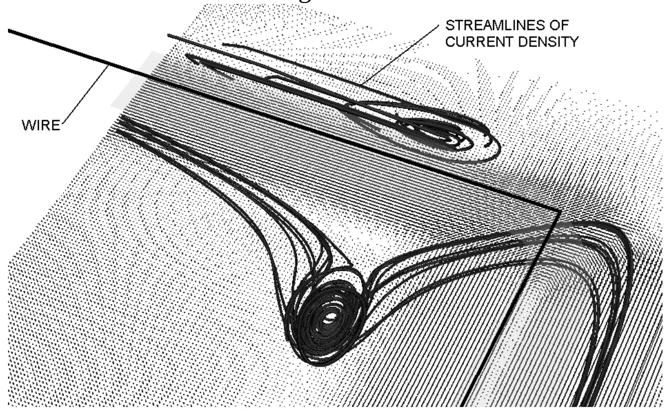

Fig. 4. Simulation results for mis-registered data sets.

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