Artifacts Associated with Measuring Cardiac Electrical Currents in a Post-mortem Pig Using Current Density Imaging

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ABSTRACT: After 50 years of clinical use of external defibrillation of the heart, current flow through the torso remains poorly understood. We investigated current flow in the torso of a post-mortem pig using current density imaging (CDI). CDI maps magnetic fields, produced by externally applied current, onto MRI phase images. CDI measurements were made by passing current through the tissue via defibrillation electrodes. Results of this experiment are presented followed with a discussion of artifacts associated with the CDI technique. Artifacts include nonlinear gradient image distortion, susceptibility, RF shielding, registration, high phase gradients and phase unwrapping.

INTRODUCTION: Low Frequency CDI (LF-CDI) was selected for these experiments because of its ability to measure all 3 orthogonal components of the current density vectors throughout a volume of soft tissue [1]. Spatial maps of magnetic field components are encoded in phase images as twist angles

$$\Gamma = \gamma B_J T_c \tag{1}$$

where B_J is the magnetic component parallel to the main magnetic field, B_0, generated by the applied current, T_c is the width of the square current pulse and γ is the gyromagnetic ratio. Other components of the magnetic field generated by the applied current can be measured by re-orientating the sample in the other 2 orthogonal positions. A minimum of 2 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

$$\mathbf{J} = \nabla \times \mathbf{H} \tag{2}$$

Three orthogonal orientations of the sample will result in complete measurement of all 3 components of magnetic field which allows for computation of all 3 components of current density.

An LF-CDI post-mortem pig experiment is described and some CDI results are presented. An analysis of artifacts that pertain to the pig experiment is performed. The analysis includes the effects of gradient warp, magnetic susceptibility, RF shielding, registration, high phase gradients and phase unwrapping.

METHODS: A 3 kg pig was selected because its length, from nose to tail, could fit across the 55 cm diameter MRI bore. The pig was anesthetized and euthanized 1 hour prior to the experiment. The lungs were inflated to minimize movement of the heart. The pig was mounted on an acrylic frame, shown in fig. 1, and held in position by an evacuable bean cushion and straps. Two pediatric-sized defibrillation electrodes (Philips Medical Systems - Heartstream) were placed in a lateral-lateral position similar to human defibrillation procedures.

To measure image distortions caused by nonlinear gradients, a phantom with a periodically spaced 3D rectangular array of spheres, was imaged. To demonstrate the effects of magnetic susceptibility and RF shielding caused by the electrode, an electrode was disassembled into its components and each component was imaged against a slab of homogeneous gelatin. MRI signal losses and gains are easy to visually detect within the gelatin. One of the data processing steps in LF-CDI requires accurate registration of two different images from two different orientations of the sample. An experiment using a length of copper wire with a 90° bend set on top of a slab of homogeneous gelatin was used to demonstrate the worst case errors.

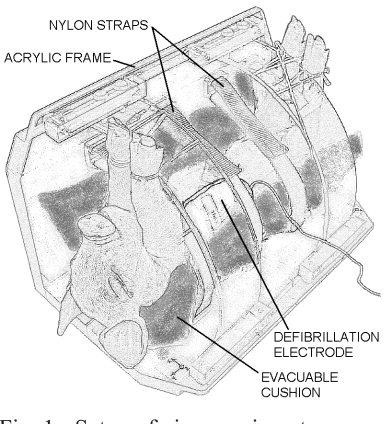

Fig. 1 - Setup of pig experiment.

RESULTS: Fig. 2 shows a view of the pig's chest using a transparent isosurface to represent the MRI data. Streamlines, computed from the CDI vector data, clearly display some pathways of current through the chest and heart. Several streamlines show current pathways from one electrode to the other. Streamlines inside the heart show the dominant direction of current flow along the length, head to tail, of the pig's body. Streamlines inside the heart do not continue through the airspaces of the lungs where there is no MRI/CDI signal.

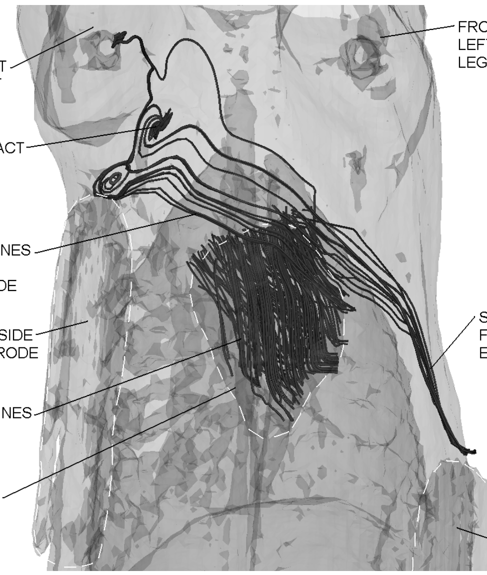

Fig. 2 - Streamlines showing current flow through pig's torso.

DISCUSSION OF CDI ARTIFACTS: "Rubber sheet" type distortions occur in MR images due to nonlinear gradients. The distortion is corrected by translating distorted data points to their respective known points. Known points come from gradient coil specifications or by imaging a phantom with known points. Data between known points is corrected using interpolation. Magnitude image correction requires an intensity adjustment that corresponds to the Jacobian of the transformation. Phase image correction does not require this adjustment. Distortion increases with distance away from the MRI's isocenter.

Susceptibility artifacts are known to exist in some tissues such as the apex of the heart. A severe case of this artifact occurs within a few cm of copper electrodes. MR signal tends to be over/under emphasized along the frequency encoding direction of a spin echo sequence near the electrode. Electrodes dissipate MR signal energy leading to the RF shielding artifact. Overall, CDI is difficult to achieve within about 3 cm of the electrodes.

LF-CDI requires registration of 3 image sets corresponding to the 3 orientations. Image misalignment in regions where high magnetic gradients exist causes substantial CDI errors. To demonstrate, a length of wire carrying 30 mA with a 90° bend was suspended over a slab of gel to create high magnetic gradients within the gel. LF-CDI data sets were acquired. Misaligning the images by only half a pixel in each of the x and y directions caused erroneous CDI values near the 90° bend. These errors exhibited a region of +10 A/m^2 adjacent a to another region of -10 A/m^2 where the entire region was expected to have 0 ± 1 A/m^2.

From this, the CDI artifact shown in fig. 2 can be explained: Gradient warp has a different effect on the 3 image sets because they were acquired with different orientations of the pig. This difference makes proper image registration impossible several cm from the center of imaging space. Susceptibility artifacts further complicate registration near electrodes. The result is a circular current pattern that appears as a source/sink of current in fig. 2. Techniques for eliminating and/or reducing these artifacts are now being developed.

REFERENCES:

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