Limitations to SV Determination from APT Images

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ABSTRACT

Recently, *in vivo* Applied Potential Tomography (APT) images showing cardiac related changes in the electrical resistivity distribution within the human thorax have been produced [1]. From these images a stroke volume (SV) index can be expressed in terms of the temporal variation of local resistivities. However, several limitations exist. In this experimental study, the limitations related to the position dependent point response function (PRF) of the APT system are determined.

INTRODUCTION

Electrical impedance imaging is used to determine the spatial distribution of conductivity of a volume conductor from a knowledge of voltage and current conditions at the boundary. Reviews showing a recently growing interest can be found in [2] and [3]. First, *in vivo* impedance images have been produced with an Applied Potential Tomography (APT) system. Although the APT images are 2-dimensional (2D) the third dimension contributes significantly because of volumetric current flow. APT images of the human thorax showing the ejection of blood from the ventricles, lung perfusion, and dilatation of great vessels have been produced [1], volume variation indices may be determined from these images. However, the causes of the differences between individuals are yet to be explained. Although they may be due to differences in stroke volumes (SV) of different subjects, they may also well be a result of 3-dimensional (3D) PRF of the APT system. In this study, the 3D distribution of the PRF is measured. The slice thickness of the APT's field of view and the spatial resolution are determined from these measurements. Effects of these parameters on the reconstructed image are discussed.

THE APPLIED POTENTIAL TOMOGRAPHY

The data acquisition hardware and the reconstruction algorithm of the APT system are explained in detail elsewhere [4-5]. Here, a brief description of the data acquisiton and the image reconstruction is given. APT uses an array of 16 electrodes attached on the surface of the volume conductor. A 50kHz current with approximately 5mA peak to peak amplitude is applied in turn to all adjacent pairs of electrodes (drive pairs). For each drive pair, a set of voltages between adjacent electrode pairs other than the drive pair (receive pairs) is measured. The principles of superposition and reciprocity apply to the measurements, yielding 16*13/2 = 104 measurements, which will be referred to as a "data cycle". Several data cycles can be averaged to improve the signal-to-noise (S/N) ratio.

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A linear backprojection method used for image reconstruction assumes equally spaced electrodes around a circular (2D) homogeneous and isotropic conducting medium, surrounded by an infinitely resistive medium. Two data sets are used to reconstruct an image. One of the two data sets is a reference data set g_{ref}, measured from a uniformly assumed resistivity distribution, and the other data set g_m is measured after a change has occurred in the conductivity distribution. Then, the normalized change

$$\Delta g_n = (g_m - g_{ref}) / g_{ref}$$

is calculated. The relation between the measurements on the surface and the conductivity distribution is given by

$$\Delta g_n = \mathbf{W}\, \Delta\sigma ,$$

where Δg_n is a (M,1) vector with entries representing the normalized changes in the boundary voltage measurements, $\Delta\sigma$ is a (M,1) vector of voxel conductivity changes, and **W** is a (M,M) weighting matrix. M is the number of independent measurements. To determine $\Delta\sigma$, the inversion is approximated by a filtered back-projection, $\mathbf{W}^{-1} = \mathbf{F}\,\mathbf{B}$, where **B** is a weighted backprojection operator and **F** is an empirically determined enhancement filter operator as explained in [4]. Backprojection is done along curved equipotential lines calculated for a uniform and isotropic conductivity distribution.

EXPERIMENTAL SET-UP

The volume conductor is modelled by a perspex cylindrical tank, 170mm in diameter and 520mm in height. The cylinder is filled with saline solution having resistivity 5.0Ωm at 20°C. 16 brass electrodes, each having an 8mm diameter, are equally spaced around the tank and are located 260mm from the bottom of the tank. The point response function (PRF)'s for a brass conductor ball and an insulator ball, made of vacuum sealing compound, with a diameter 0.1 of the array diameter were measured at different spatial locations. An xyz micro-manipulator was used to position the balls.

A reference data set g_{ref} was measured with only saline in the tank, and a data set g_m is measured for each position of the balls. Ten data cycles were averaged to improve the S/N ratio. Angular symmetry is assumed. Therefore, the balls were moved only in radial and longitudinal directions. Measurements were taken at 10mm intervals (0.1176 of the array radius) over a total distance of 60mm (0.7 of the array radius) from the center. The micro-manipulator could not position the ball closer than 10mm to the surface. In the longitudinal direction, the ball was moved up to a level measuring 0.824 of the array radius (70mm) from

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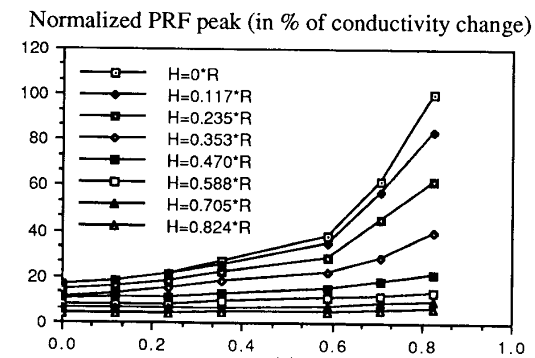
the plane of the electrodes.

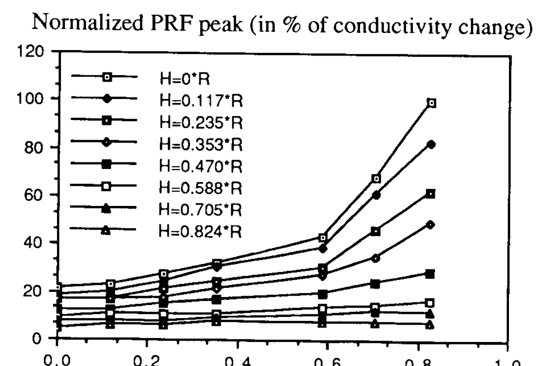
RESULTS OF THE PRF MEASUREMENTS

Conducting and insulating anomalies perturb the current flow differently. For the conductor object, the PRF has a higher peak value and a narrower profile than for the insulator object. The width of the PRF is directly proportional to the distance from the electrodes. The peak of the PRF decreases as the width increases.

Spatial variations of the peak value of the PRF for the conductor and the insulator balls are given in Figure 1 (a) and (b), respectively. These plots are normalized to the maximum values at 0.7 of the array radius from the center in the plane of the electrodes. At the center the peak value of the PRF's for the conductor and the insulator balls degrades by 15.8dB and 13.4 dB, respectively. For the conductor ball, at a radial point 0.7 of the array radius from the center and 0.3 of the array radius from the plane of electrodes, the peak of the PRF degrades by 6dB from the maximum. For the insulator ball, the same drop occurs at 0.35 of the array radius from the plane of the electrodes. At the center, a 6dB drop occurs at a point approximately 0.7 of the array radius from the electrode plane for both of the objects. The degradation of the sensitivity with longitudinal movement is less at the center, but the sensitive volume is greater closer to the surface. Therefore, resistivity variations from a significantly larger volume are integrated into the image if the region is closer to the surface.



(a)



(b)

Figure 1. Spatial distribution of PRF (a) for the conductor ball, (b) for the insulator ball. The horizontal axis represents the radial distance from the center normalized to R. H is the distance from the electrode plane, and R is the radius of the electrode array.

An off-plane object produces an image similar to the one which would be produced by an object in the plane of the electrodes at a radial position falling into the same equipotential surface passing through the off-plane object.

The spatial resolution of the APT is determined as the full-width-at-half-maximum (FWHM) of the PRF. For off-center points, PRF does not have the same FWHM in the radial direction and the tangential direction, i.e. perpendicular to the radial direction. The FWHM in both directions increases towards the center. This increase in the tangential FWHM is less than the increase in the radial FWHM. The maximum FWHM at the center is approximately 24% of the array diameter for both the conductor and the insulator.

The minimum FWHM for the conductor object is 12.7% of the array diameter in the radial direction, but the tangential FWHM at the same point is 21% of the array diameter. The minimum FWHM for the insulator object is 14.5% of the array diameter in the radial direction, but the tangential FWHM at the same point is 22% of the array diameter. The FWHM resolution is better for the conductor than for the insulator as expected because of the different perturbation of the current flow lines.

To obtain comparable images from different subjects, a uniform spatial resolution across the image is desired. However, in our case the spatial resolution is strongly dependent on position, being a minimum at the center.

CONCLUSIONS

These results shows that the sensitive slice thickness is not uniform across the image plane and that the PRF is strongly dependent on position. Therefore, the appearance of localised resistivity changes in the images is a function of their position relative to the electrodes in 3D space. The same amount of SV at different spatial locations is therefore not reconstructed the same. Hence, an accurate calculation of an index of cardiac volumes is complicated, and calibration is needed. A uniform sensitivity distribution across the image plane would result in more reliable volume indices.

The FWHM resolution is position dependent and is a function of the conductivity change, being poorest at the center of the field. Spatial resolution of 12.7% of the array diameter at a point 0.7 of the array radius from the center is sufficient to resolve the two sides of the heart but not sufficient to yield the detail within the heart.

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