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Progressive EPR imaging with adaptive projection acquisition

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Abstract

Continuous wave electron paramagnetic resonance imaging (EPRI) of living biological systems requires rapid acquisition and visualization of free radical images. In the commonly used multiple-stage back-projection image reconstruction algorithm, the EPR image cannot be reconstructed until a complete set of projections is collected. If the data acquisition is incomplete, the previously acquired incomplete data set is no longer useful. In this work, a 3-dimensional progressive EPRI technique was implemented based on inverse Radon transform in which a 3-dimensional EPR image is acquired and reconstructed gradually from low resolution to high resolution. An adaptive data acquisition strategy is proposed to determine the significance of projections and acquire them in an order from the most significant to the least significant. The image acquisition can be terminated at any time if further collection of projections does not improve the image resolution distinctly, providing flexibility to trade image quality with imaging time. The progressive imaging technique was validated using computer simulations as well as imaging experiments. The adaptive acquisition uses 50–70% less projections as compared to the regular acquisition. In conclusion, adaptive data acquisition with progressive image reconstruction should be very useful for the accelerated acquisition and visualization of free radical distribution.

Keywords: EPR imaging; Image reconstruction; Radon transform; Adaptive acquisition; Simulation; Free radical

1. Introduction

In the last two decades, electron paramagnetic resonance imaging (EPRI) has made rapid progress [1–3] and demonstrated its unique usefulness in many branches of science including biology and medicine [4–12]. Several review articles on the development of EPRI methods and their application to biological systems have appeared in recent years [3,13–15]. While the time-domain EPRI technique has emerged recently with the advantage of significantly reduced imaging time [16,17], the continuous wave (CW) EPRI technique still dominates current applications because of its higher sensitivity and applicability to a large variety of spin probes of varied linewidths [17]. The filtered back-projection (FBP) method is commonly used for image reconstruction in CW EPRI in which an n-dimensional EPR image is reconstructed through $(n-1)$-stage back-projection operations [2,18,19]. For instance, a 3-dimensional EPR image is reconstructed in two stages, with each stage consisting of the reconstruction of a set of 2-dimensional images. The multi-stage reconstruction algorithm is easy to implement and very fast in computation speed. The use of low-computation approaches was important when advanced computational facilities (speed and memory) were not available. Despite its low requirements for computational facilities, the multi-stage image reconstruction algorithm has several limitations. First, it requires an equal-angle increment in stepping the gradient vector. The uniform angular sampling of the object space causes a non-uniform gradient density distribution on the surface of the object which considerably decreases the data

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acquisition efficiency [20,21]. Second, the image reconstruction can be performed only after all the projections are collected. During the data acquisition period, however, no information is available about the image. If the data acquisition terminates due to unexpected reasons such as a change in animal physiology, position, or environment, the previously acquired incomplete data set is no longer useful. Additionally, all the projections are by default assigned with equal importance and acquired in a nested-loop order. This content-insensitive acquisition method is not optimal in data acquisition time and/or image resolution [22].

In this work, a novel 3-dimensional progressive EPRI method with content-sensitive acquisition was developed. The inverse Radon transform [21,23] was implemented and applied to reconstruct EPR images from projections in a single stage, in which all the filtered projections are back-projected directly on to the 3-dimensional goal image. Since the image reconstruction can be done during the data acquisition process, it enables progressive reconstruction and visualization of the EPR image. The uniform gradient scanning approach [20,21] was adapted to replace the uniform angular sampling (non-uniform gradient scanning) and it was shown the data acquisition efficiency could be considerably increased. We proposed an adaptive data acquisition strategy in which all the projections are acquired in a sorted order according to their significance values derived from the previously acquired projections. The proposed progressive imaging technique with adaptive projection acquisition was implemented and tested through simulations and imaging experiments. Compared with the regular EPRI data acquisition, marked performance improvements have been realized.

2. Theory

2.1. Progressive image reconstruction using inverse Radon transform

The Radon transform of a 3-dimensional object $f(x,y,z)$ is expressed by the following equation [21,23].

$$p(s,\alpha,\theta) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f(x,y,z)\delta(x\sin\theta\cos\alpha + y\sin\theta\sin\alpha + z\cos\theta - s)\,\mathrm{d}x\mathrm{d}y\mathrm{d}z. \tag{1}$$

The inverse Radon transform of Eq. (1) is given by

$$f(x,y,z) = \int_{0}^{\pi/2}\int_{0}^{2\pi} \hat{p}(x\sin\theta\cos\alpha + y\sin\theta\sin\alpha + z\cos\theta, \alpha, \theta)\sin\theta\,\mathrm{d}\alpha\mathrm{d}\theta, \tag{2}$$

where

$$\hat{p}(s,\alpha,\theta) = -\frac{1}{8\pi^2}\frac{\partial^2 p(s,\alpha,\theta)}{\partial s^2}. \tag{3}$$

Refer to Fig. 1 for a definition of projection geometry. Image reconstruction in 3-dimensional EPRI is mathematically a 3-dimensional inverse Radon transform descried above but operated in digital domain. Therefore, the second partial derivative in the filtering operation, Eq. (3), can be approximated using a three-point digital filter [21], as

$$\hat{p}(s_i,\alpha_j,\theta_k) = -\frac{1}{8\pi^2}\left[2p(s_i,\alpha_j,\theta_k) - p(s_{i-1},\alpha_j,\theta_k) - p(s_{i+1},\alpha_j,\theta_k)\right], \tag{4}$$

where $0 \leqslant i \leqslant I-1$, $0 \leqslant j \leqslant J-1$, and $0 \leqslant k \leqslant K-1$. I is the number of data points for each projection. J and K are the sample number of the azimuth angle α and elevation angle θ, respectively. Similar to Eq. (4), the integration in Eq. (2) is approximated using summation [21],

$$\hat{f}(x,y,z) = \frac{2\pi^2}{K}\sum_{k=0}^{K-1}\sin\theta_k\frac{1}{J}\sum_{j=0}^{J-1}\hat{p}(x\sin\theta_k\cos\alpha_j + y\sin\theta_k\sin\alpha_j + z\cos\theta_k, \alpha_\mathrm{j}, \theta_k). \tag{5}$$

Eq. (5) states that, given the sample number of α and θ as J and K (then the total projection number as JK), each projection is reconstructed independent of others to obtain a 3-dimensional "basis" image. All the JK "basis" images are accumulated to obtain the final reconstruction result. Apparently, in the beginning, when only a few projections are acquired, a few "basis" images will be accumulated to obtain a low-resolution image. As more projections are collected, more "basis" images will be added to the low-resolution image to obtain a high-resolution image. Thus, a progressive image acquisition scheme is implemented based on the inverse Radon transform.

2.2. Uniform magnetic field gradient scanning

In Eq. (5), α and θ are sampled uniformly, i.e., $\alpha_j = j2\pi/J$ and $\theta_k = k\pi/2K + \pi/4K$. This is required in principle by the two-stage back-projection image reconstruction algorithm (otherwise interpolation is needed). However, the equal-increment of α and θ will result in a non-uniform gradient density distribution over the surface of the 3-dimensional object [20,21]. As shown in Fig. 2A, the gradient density near the pole (θ close to 0) is much higher than that near the equator (θ close to $\pi/2$). As will be seen later, the over-sampling near the pole seriously decreases the data acquisition efficiency. In this study, since the single stage image reconstruction algorithm is used, we will be able to implement a uniform gradient scanning path to improve the data acquisition efficiency, as reported previously.

In the uniform gradient scanning scheme, the elevation angle θ is still uniformly sampled but the sampling of the azimuth angle α is different: the increment step size of α is calculated according to the current elevation angle θ_k. The number of samples for α at θ_k is