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博 士 学 位 论 文

**时空编码磁共振成像和化学交换饱和转移  
成像新方法**

**Novel methods for spatiotemporally encoded single-shot  
MRI and chemical exchange saturation transfer MRI**

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## 中 文 摘 要

时空编码磁共振成像(spatiotemporally encoded MRI, SPEN MRI)是一种新型的超快速磁共振成像技术。该方法保留了回波平面成像序列快速采样的特性，并能够有效地克服不均匀磁场和化学位移引起的畸变或伪影，有着广阔的临床应用前景。由于特殊的二次相位编码机理，SPEN MRI 图像不能通过常规的快速傅里叶变换进行图像重建。超分辨率重建(super-resolved reconstruction, SR)是针对 SPEN MRI 方法提出的一种数据后处理技术，它可以在不增加采样点数的情况下，极大地提高 SPEN MRI 图像的空间分辨率。目前存在很多 SR 算法，例如共轭梯度法、部分傅里叶法、去卷积法和基于压缩感知的混合重建算法。这些算法都能有效提高 SPEN MRI 的空间分辨率，然而均未达到理论上最优的空间分辨率。

本文提出了一种最优的 SR 重建算法——SEED (super-resolved enhancing and edge deghosting)。SEED 算法充分利用 SPEN MRI 的二次相位信息，能够无损地恢复出理论上最优的空间分辨率。此外，SEED 算法还能和多扫描 SPEN MRI 结合，在减少一半采样点数的情况下恢复出与全采样质量相当的图像，从而加快多扫描的成像速度。

与笛卡尔采样相比，非笛卡尔采样具有采样效率高、采样方式灵活和抵抗欠采样混叠伪影等一系列优点，然而目前与非笛卡尔 SPEN MRI 相关的研究还非常少。本文首次提出了非笛卡尔 SPEN MRI 采样轨迹和采样梯度的设计方法，并根据 SPEN MRI 的特点提出了一种高效的非笛卡尔 SR 算法。与笛卡尔 SPEN MRI 相比，非笛卡尔 SPEN MRI 能够有效提高图像空间分辨率，减少欠采样引起的混叠伪影，获得质量更优的图像。此外，我们还针对非笛卡尔 SPEN MRI 的特性，

提出了一种非参考扫描的畸变校正技术和不均匀弛豫加权的校正技术,这些校正方法可以进一步提高非笛卡尔 SPEN MRI 的图像质量。

化学交换饱和转移 (chemical exchange saturation transfer, CEST) 磁共振成像是一种新型的分子影像技术。由于其能够无损检测活体中低浓度的蛋白质和代谢物,CEST 技术在最近十几年得到了蓬勃的发展。目前 CEST 已经成功地应用于许多领域,例如人脑神经系统疾病、动物模型的大脑局部缺血以及人体和动物模型的肿瘤。然而 CEST 方法存在一个很严峻的挑战:缺乏特异性,很难从 Z 谱中提取和定量分析特定代谢物的 CEST 信号。

为了解决 CEST 面临的挑战,本文提出一种基于偏共振延迟多脉冲的 CEST 成像新技术。结合基于 Bloch 方程的数据拟合技术,该技术可以有效地分离提取 Z 谱中快速和慢速交换质子的贡献。

此外,本文还提出一种局部洛伦茨线型拟合方法。该方法可用于分离高场下 Z 谱中的总肌酸信号。结合活体磁共振波谱技术的校正,该方法可用于定量分析大脑中的总肌酸信号,获得大脑总肌酸分布图。

**关键词:** 磁共振成像; 时空编码; 化学交换饱和转移

# **Novel methods for spatiotemporally encoded single-shot MRI and chemical exchange saturation transfer MRI**

## **Abstract**

Spatiotemporally encoded MRI (SPEN MRI) is a recently proposed ultrafast technique. Compared to EPI, SPEN MRI remains the outstanding performance in imaging speed, while possesses much better resistance to inhomogeneous  $B_0$  field and chemical shift effects. The advantages of SPEN MRI show enormous potential in clinical applications. Limited by the quadratic phase encoding, the data of SPEN MRI cannot be directly reconstructed through conventional fast Fourier transform. Super-resolved reconstruction (SR) is a data post-processing method designed for SPEN MRI aiming at improving spatial resolution without additional acquisition. To date, many SR algorithms have been proposed, such as conjugate gradient, partial Fourier transform, de-convolution algorithm and compressed sensing based reconstruction. Though these algorithms can improve the spatial resolution to some extent, the images reconstructed by these algorithms do not reach the optimal resolution in theory. In this thesis, we proposed an optimal SR algorithm SEED (super-resolved enhancing and edge deghosting). SEED algorithm can retrieve the optimal resolution in theory by fully exploiting the quadratic phase encoding information. Besides, SEED can also be applied to multi-shot SPEN MRI, which can reduce half of acquisition points without obvious degradation in image quality.

Compared to Cartesian sampling scheme, non-Cartesian sampling has a great advantage in sampling efficiency and feasibility, resistance to aliasing artifacts induced by undersampling. However, few studies relating to non-Cartesian SPEN MRI have been carried out so far. In this thesis, we firstly proposed a method to design the sampling trajectory and decoding gradient for non-Cartesian SPEN MRI. A simple and efficient non-Cartesian SR algorithm was also proposed for non-Cartesian SPEN MRI, which can greatly improve the image resolution. Compared to Cartesian



SPEN MRI, non-Cartesian SPEN MRI can yield better image quality in regard of spatial resolution and aliasing artifacts. In this thesis, we also carried out a feasibility study on referenceless geometric distortion correction and  $T_2^*$  relaxation correction for non-Cartesian SPEN MRI, which will benefit the image quality of non-Cartesian SPEN MRI.

Chemical exchange saturation transfer (CEST) MRI, as a novel molecular imaging technique, has received great attention in recent years because of its potential to detect low concentration proteins and metabolites in vivo. The technique has been successfully applied to detect pathological chemical changes in many diseases, such as neurological disorders in human brain, animal models of cerebral ischemia and cancer in both animal models and humans. Though there are many successful applications, CEST MRI suffers from the lack of specificity in the Z-spectrum of endogenous exchanging protons.

In this thesis, we proposed a new CEST technique based on off-resonance variable delay multi-pulse. Combined with the fitting based on Bloch equation, this novel method can be used to separate out the fast- and slow-exchanging components in the Z-spectrum.

Besides, we proposed a localized lorentzian line-shape fitting method to extract the creatine signal in the Z-spectrum under 11.7 T. Combined with in vivo MRS, this method can be used to quantify the creatine signal and obtain the creatine concentration. A high-resolution creatine map was obtained via this method.

**Key words:** Magnetic resonance imaging (MRI); Spatiotemporal encoding; Chemical exchange saturation transfer (CEST)

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