Radial FLASH with segmented saturation for ungated, preclinical cardiac CEST-MRI

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INTRODUCTION: Traditionally, cardiac CEST-MRI acquisitions utilize electrocardiograph (ECG) and pneumatic signals for cardiac and respiratory gating to minimize motion artifacts[1,2]. While significant work has been done to progress self-gated and real-time acquisitions for anatomical imaging, these methods have yet to be translated for use with CEST imaging[3].
In high-resolution preclinical imaging scenarios, scan times can become significantly long, and inconsistencies in cardiac and respiratory rates can manifest as differences in the z-magnetization from offset to offset (Fig. 1a). Furthermore, as saturation powers are increased for intermediate exchanging CEST pools (e.g., creatine), ECG signals become degraded by RF interference and become unusable (Fig. 1b).
We propose a new method utilizing a segmented saturation scheme and radial FLASH readout, which enables CEST imaging of the murine myocardium without the need for cardiac and respiratory gating.
METHODS: The proposed method consists of a segmented saturation module with a radial FLASH readout and golden angle progression. Animals are oriented in the prone position to minimize diaphragmatic motion. Because center k-space is sampled repeatedly, steady-state saturation dominates contrast during gridding and reconstruction. Multiple saturation powers were tested to optimize for creatine and APT contrast.

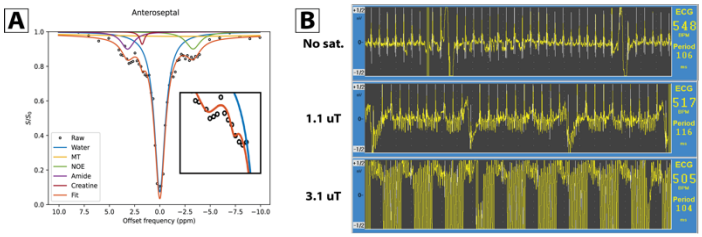

Fig. 1 ECG signals with no saturation, 1.1uT saturation pulses, and 3.1uT saturation pulses (b). ECG trigger delays introduce inconsistencies in z-magnetization (a).

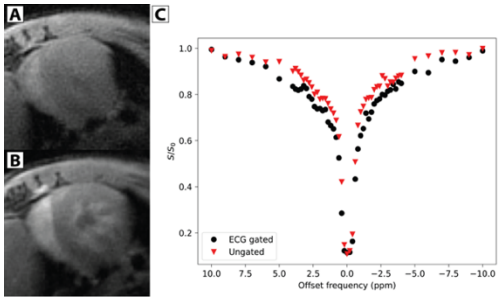

Fig. 2 Representative reference images acquired using the proposed method with (a) and without (b) cardiac and respiratory gating, with corresponding z-spectra (c).

To avoid ECG signal degradation, we compare ECG/respiratory gated images (Fig. 2a) with ungated images (Fig. 2b) and corresponding z-spectra using a saturation power of 1.1uT (Fig. 2c). We also compare creatine, APT, and rNOE contrasts using saturation powers between 1.1 and 3.1uT. All analyses are performed on the anteroseptal segment[4] of the myocardium to minimize susceptibility artifacts and B_1 inhomogeneities.
RESULTS: Myocardial contrast is preserved without significant motion artifacts. Z-spectral analysis suggests more consistent z-magnetization at off-resonance offset frequencies (i.e., no inconsistencies introduced ECG by trigger delay).
We observe broad interscan agreement per CEST contrast at 1.1uT (σ^2 = 0.57, 2.32, 3.92 for APT, creatine, and rNOE respectively) in the ungated scenario. The interscan agreement is significantly worse in the ECG-gated scenario (σ^2 = 10.07, 2.36, 19.44 for APT, creatine, and rNOE, respectively), as missed ECG and respiratory triggers and trigger delays cause inconsistencies in the z-magnetization between individual readouts and frequency offsets. When poorly gated acquisitions are excluded (<25% missed or extraneous triggers during a predefined observation period), we see good agreement in the variance in APT (σ^2_{ECG} = 0.45, $\sigma^2_{Ungated}$ = 0.57) and creatine pools (σ^2_{ECG} = 2.55, $\sigma^2_{Ungated}$ = 2.32) between the ungated and ECG gated acquisitions.
A saturation power of 1.1uT optimizes for APT and creatine contrasts without introducing substantial water direct saturation and magnetization transfer effects; additionally, higher saturation powers lead to peak broadening, which makes decoupling APT and creatine contrasts difficult (Fig 3).

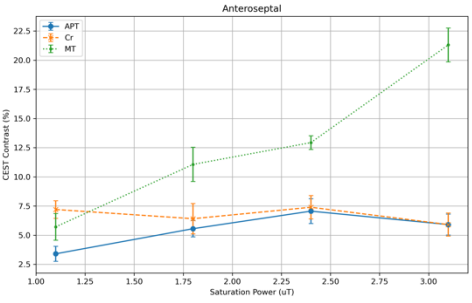

Fig. 3 Comparison of APT, creatine, and MT contrast at saturation powers between 1.1 and 3.1uT. Error bars represent standard error.

DISCUSSION: This ungated approach enables more consistent z-spectral analysis. Myocardial contrast is improved, and motion artifacts are minimized when the duration of each readout segment (T_{seg}) approximately matches the cardiac period, this must be balanced so that the relationship $T_{seg} << T_1$ is maintained, and steady-state saturation is preserved.
CONCLUSION: This work takes important steps towards the standardization of preclinical cardiac CEST protocols and establishes a consistent method for quantifying APT and creatine contrasts in the murine myocardium. Notably, this method also enables the extraction of cardiac and respiratory signals from raw k-space data, which could be applied to retrospectively self-gated reconstructions.
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