Renal 4D CEST-MRI under free breathing

Quan Tao[a,b,c], Zelong Chen[d], Yizhe Zhang[b,c], Wenyan Zhang[b,c], Yikai Xu[d], Yanqiu Feng*[a,b,c]
[a]Department of Rehabilitation Medicine, Zhujiang Hospital, Southern Medical University, Guangzhou, China; [b]School of Biomedical Engineering, Southern Medical University, Guangzhou, China; [c]Guangdong Provincial Key Laboratory of Medical Image Processing & Guangdong Province Engineering Laboratory for Medical Imaging and Diagnostic Technology, Southern Medical University, Guangzhou, China; [d]Medical Imaging Center, Nanfang Hospital, Southern Medical University, Guangzhou, China
* Corresponding author: foree@163.com

ABSTRACT

Introduction: Respiration-induced motion can lead to artifacts in chemical exchange saturation transfer (CEST) images, and inaccurate quantization of CEST signals. The aim of this study was to develop a motion-insensitive renal 4D (extra motion dimension) CEST imaging technique for clinical use during free breathing.

Methods: We utilized a 3D turbo filed echo (TFE) sequence with in-plane golden-angle radial sampling and out-plane Cartesian sampling (stack of stars) to acquire renal CEST images from three normal volunteers under free breathing. The respiration states were separated, and XD-GRASP was used to reconstruct the CEST images. The efficacy of this method in suppressing motion artifact was evaluated.

Results: The renal Z-spectrum demonstrated distinct CEST peaks, and no motion artifacts were observed in the CEST images. This motion-insensitive sequence proved to be reliable for renal CEST imaging.

Conclusion: 4D CEST-MRI provides a motion in-sensitive CEST imaging approach for renal imaging in clinical nephropathy patients under free breathing, this may improve the accuracy of nephropathy detection.

Keywords: Renal CEST-MRI, stack of stars, motion correction, free breathing

1. INTRODUCTION

The kidneys are vital organ responsible for urine production, playing a crucial role in maintaining the body's osmotic pressure balance, as well as the reabsorption and elimination of metabolic waste. They ensure the stability of the body's internal environment and support normal metabolism. Nephropathy encompasses various abnormal changes in the kidneys, including acute kidney injury [1], diabetic nephropathy [2], IgA disease [3], and others. Without intervention, many kidney diseases may progress to the terminal stage. Therefore, early diagnosis is essential as it provides valuable information for doctors to initiate appropriate treatment strategies [4].

CEST is an innovative metabolic MRI imaging technique [5]. CEST induces the MR signal decreasing of water protons by saturation, which transferred from the saturated protons in exchangeable protons in bio macromolecule. This mechanism allows for the reflection of the types and concentrations of metabolic molecules in the body, providing valuable information about the internal environment. Metabolic CEST has emerged as a promising MRI technique with sensitive to nephropathy, including acute kidney injury [6], diabetic nephropathy [7], and more. However, respiratory motion is the major obstacle in clinical renal imaging of CEST technique, because it may induce the kidney displacement, blurring, and artifacts in images, potentially leading to inaccuracies in CEST signal quantification.

Many previous studies were focused to reduces the impact of respiratory movements during imaging. Breath hold is an effective method to suppress motion artifact, however, it increases the acquisition time and bring uncomfortable experience to patients [8]. Navigation echo technology also increases scanning time [9]. Traditional rigid or elastic image registration method cannot register the blurred images, and interpolation will alter the signal values [10]. Non-Cartesian sampling methods include radial or spiral have been shown to be less sensitive to respiratory motion, and with the self-gate property, have been approved to be effective for CEST imaging of brain and liver [11,12].

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In this study, we aimed to develop a reliable 4D CEST-MRI method by introducing an extra motion dimension to guide k-space reconstruction and then acquired the motion-correction clinical renal CEST imaging under free breathing.

2. METHOD

Sequence Design: Each CEST module contains a 30 ms Gaussian-shape saturation pulse, followed by a spoiler gradient and thirty turbo filed echo (TFE) readout, and the k-space was filled by golden-angle (111.25°) radial in plane, and Cartesian sampling between planes (stack of stars). The k-space were continuously filled without pause between each frequency offset.

MRI: This experiment was approved by local Institutional Review Board. Written informed consent was obtained for all participating subjects. MRI data were acquired in three (n = 3) healthy volunteers under free breathing on a Philips 3.0 T scanner (Ingenia, Philips Healthcare, Best, The Netherlands) equipped with 32 channels torso coil. The CEST parameters were: FOV = 384×384×90 mm^2, acquisition matrix size = 128×128×3, reconstruction matrix size = 256×256×3, repetition time/echo time/saturation time/(TR/TE/ST) = 4.4/1.9/30 ms, saturation power = 1.5 μT. The frequency offsets were from -5 to 5 ppm with 0.25 ppm interval (Mz), and the other image at 200 ppm was acquired as reference (M0). The total acquisition time is 11 min and 48 s.

Data Analysis: All data were analyzed using MATLAB (MathWorks, Inc., Natick, MA, USA). After the 1DFFT to the centers of k lines along kz direction (k_x=k_y=0), the principal component analysis (PCA) was used to separate the respiratory motion (0.1-0.5 Hz), according decomposition of the breathing state guides the sorting of the k-space data. The reconstruction of MR images was according to extra-dimensional golden-angle radial sparse parallel MRI (XD-GRASP) from Feng Li and et al [13]. The non-local means (NLMs) were used to image denoising. The CEST data was interpolated to a 0.01 ppm interval using spline interpolation, and followed by B_0 inhomogeneity correction, and the magnetization transfer ratio (MTR), asymmetry analysis of MTR (MTR_{asym}) at -3.5 ppm and 3.5 ppm were calculated. The CEST signal were showed as mean ± std. We showed the maximum coronal slice of kidney, and the Z-spectra was showed by the average of two renal cortex.

3. RESULT

Figure 1 shows the centers of k space (DC component) were processed FFT along the k_z dimension, PCA was used to separate the breath motion, and then divided to be four states to guide the reconstruction of raw data.

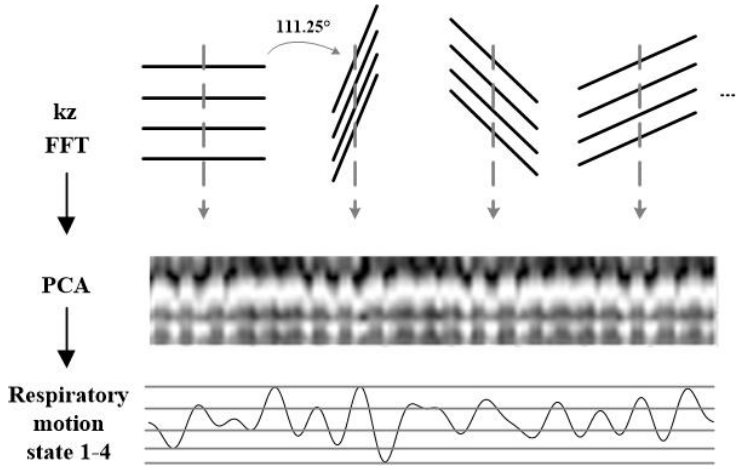

Figure 1. The k space readout and extraction of self-gating signal.

Figure 2 shows a typical CEST image on 3.5 ppm by original motion average in scanner and separated four motion states. Compared with the image of motion average, it is obvious that the liver blurring was removed, and with clearer boundaries (red arrow) in the image of motion state 2. The abdominal movement caused by breathing can be characterized (white line). The renal motion artifact also be removed. These results mean this method is effective in suppressing artifacts caused by respiratory motion.

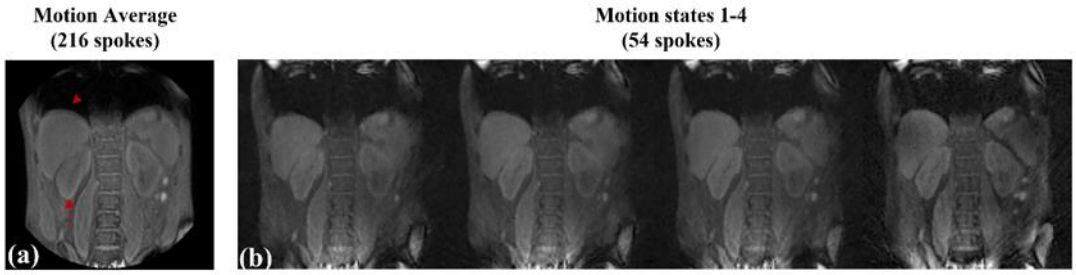

Figure 2. a: The CEST image on 3.5 ppm with motion average from scanner; b: The according reconstructed CEST image at four motion states.

Figure 3 shows the CEST results after re-sortation. The cortical Z-spectra of motion average and motion state 2 were shown in Fig. 3a. The Z-spectrum of motion average showed obvious fluctuate due to motion and difficult to quantized CEST signal, the Z-spectrum of motion state 2 is more stable, and showed obvious CEST peaks on 3.5 ppm from amide, 2.2 ppm from amine, and another three relied nuclear Overhauser (rNOE) effects (marked with asterisks). The T1w, MTR_{asym} maps on 3.5 ppm and 2.2 ppm, and MTR map on -3.5 ppm, 3.5 ppm, and 2.2 ppm were showed in Fig. 3b. There was no clear boundary between the cortex and medulla. The quantized cortical MTR_{asym} value on 3.5 ppm and 2.2 ppm were -0.14% ± 0.20 and -0.65% ± 0.43 (n=3). The MTR value on -3.5 ppm, 3.5 ppm, and 2.2 ppm were 4.25% ± 3.67, 3.55% ± 1.27, 5.86% ± 3.25 (n=3).

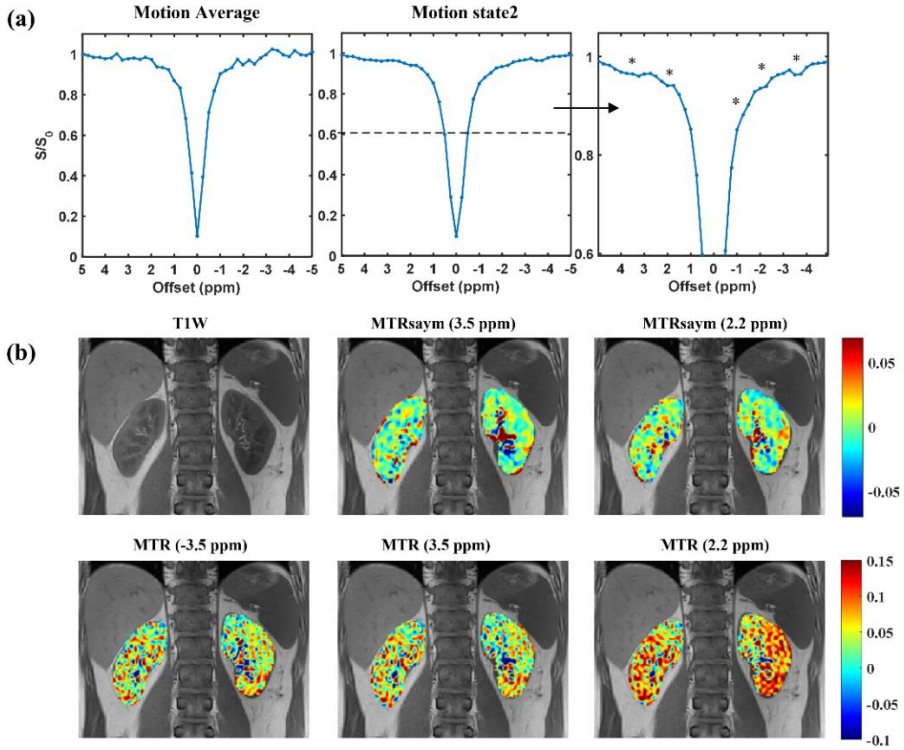

Figure 3. a: The cortical Z-spectra of motion-average images and motion state 2; b: The MTRasym on 3.5 ppm and 2.2 ppm, MTR on -3.5 ppm, 3.5 ppm, and 2.2 ppm.

4. DISCUSSION

CEST is a non-invasive MRI technique, which has limitations for clinical diagnosis due to its low signal-to-noise ratio and sensitivity to motion. In this study, we design the steady-state CEST sequence, and used stack of start to filled the k-space, introduced a motion dimension to correct the respiratory motion and obtained a stable CEST images.

Non-Cartesian sampling and separation of respiratory transitions have advantages in abdominal imaging. Golden angle radial sampling provides uniform k-space coverage, and self-gate information for motion correction. XD-GRASP ensure the image quality after k-space split. Combined with the continuous short saturation RF with small power, the conventional magnetization transfer, direct saturation, and another pollution effect were reduced, the Z-spectra showed obvious CEST effect even on 3T scanner, this may potentially be used to detection clinical nephropathy more accurately. Using more respiratory motion states may more effective in inhibiting the motion effect, however, this influence the image quality. The balance between number of motion states and image quality showed been considered.

The origination of CEST signal in kidney is complex, particularly in the disease state. The amine CEST signal is generally stronger than amide signal, which may be due to urine accumulation. This could potentially serve as a renal-specific biomarker, as abnormal changes in urine often occur when the kidney is diseased.

However, there are a few limitations in this study. Firstly, the prolonged acquisition time required to adequately cover various motion states poses a significant challenge. Additionally, acquiring more slices would provide more precise information on respiratory movement, but would further increase the overall acquisition time. Some acceleration methods can be applied to address this issue, like CS-SENSE. Secondly, it is crucial to include more volunteers to evaluate the stability of the technique, as well as to assess its sensitivity in the detection of renal diseases. Lastly, the data on different breathing states were not effectively utilized in this study, resulting in a missed opportunity to fully leverage the available data and enhance image quality. Further research should aim to comprehensively utilize these data to improve image quality.

5. CONCLUSION

In this study, we employed continuous TFE readout to acquire CEST images, re-sorted the k-space according to different motion states to mitigate motion artifacts. The in-vivo results demonstrated the effectiveness of this method. Overall, 4D CEST-MRI with extra motion dimension provides a reliable technique for renal CEST imaging under free breathing, offering improved image quality and motion suppression.

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