Reconstruction-based Super-Resolution for High-Resolution Abdominal MRI: A Preliminary Study

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Synopsis

Magnetic resonance (MR) cholangio-pancreatography (MRCP) is an established specialist method for imaging the upper abdomen and biliary/pancreatic ducts. Due to limitations of either MR image contrast or low through-plane resolution, patients may require further evaluation with contrast-enhanced computed tomography (CT) images. However, CT fails to offer the high tissue-ductal-vessel contrast-noise ratio available on T2-weighted MRI. MR Super-Resolution Reconstruction (SRR) frameworks can provide high-resolution visualizations from multiple low through-plane resolution single-shot T2-weighted (SST2W) images as currently used during MRCP studies. Here, we investigate the clinical potential of using additional SST2W acquisitions in multiple directions with SRR for higher diagnostic yield.

Introduction

Magnetic resonance (MR) cholangio-pancreatography (MRCP) studies use a series of T2-weighted (T2W) MR sequences for imaging the upper abdomen and biliary/pancreatic ducts, as shown in Figure 1. Typically, single-shot T2-weighted (SST2W) images are acquired for imaging the peri-biliary (extra-ductal) and upper abdominal soft tissues. For diagnostic in-plane resolution, slice thickness is increased to maintain acceptable levels of signal-to-noise ratio (SNR)[1]. However, this can result in fine pathology such as early cancers, being overlooked entirely. Alongside those images, a heavily-T2W volume, called MRCP volume here, is acquired that allows for a high-resolution visualization of liquid-filled structures, including biliary and pancreatic ducts, but does not demonstrate peri-ductal anatomy. In our previous work[2], we explored the potential of using an MRCP-guided Super-Resolution Reconstruction (SRR) framework to create an isotropic, high-resolution (HR) volume from the motion-corrupted, low-resolution SST2W axial and coronal images that are typically available in clinical practice. If further improved, we believe that this reduces the need for contrast-enhanced computed tomography (CT) imaging required when MR data is inconclusive[3,4]. Here, we investigate the potential of using additional MR SST2W data acquired in multiple orientations to achieve high-quality HR SRR outcomes for higher diagnostic yield[5].

Methods

Abdominal MRCP data was acquired for seven healthy volunteers at University College London Hospital, as shown in Figure 2. Apart from the heavily-T2W MRCP volume and standard protocol breath-hold axial (a) and coronal (c) SST2W sequences (TR=1163ms, TE=80ms, flip angle of 90°) at 0.78x0.78x5 mm^3 resolution, we also acquired a sagittal (s) and three oblique (obl) SST2W images using the same protocol. Given the high anisotropy of about 1:6 for in-plane vs through-plane resolution of MRCP SST2W sequences, this higher anatomical oversampling combined with SRR may help counteract the partial voluming effects. To solve the SRR problem, a classical slice acquisition model[5] $y_k = A_k(x)$ is assumed that establishes the relationship between each slice y_k and the (unknown) HR volume x using a combined motion, blurring and downsampling operator A_k whereby the motion is typically unknown and needs to be estimated[5,6]. For reconstruction-based SRR, the accurate establishment of inter-slice positions is particularly important. Three SRR-methods were compared: i) a static SRR using the original SST2W data directly, i.e. without motion-correction, ii) the MRCP-guided SRR framework[2] that relies on rigid slice-to-volume (S2V) registration and in-plane deformation steps using the heavily-T2W MRCP volume as reference for motion correction, and iii) the recently proposed outlier-robust SRR framework NiftyMIC7 that leverages a two-step iterative rigid S2V-registration/reconstruction approach using the SST2W image stacks only. For data preprocessing, bias-field and intensity correction steps were performed. Quantitative experiments were conducted by evaluating the residuals $y_k – A_k(x)$ using normalized cross-correlation (NCC). Following this, a subjective qualitative assessment was made for each method. Two radiologists, blinded to the reconstruction methods, individually assessed the reconstructions side-by-side as previously[2]. Clinical usefulness was assessed based on how well common bile duct (CBD), left and right hepatic duct (LHD and RHD) were visualized and the degree of visible motion artefacts. A final consensus score was used where individual scores differed.

Results

Figure 3 illustrates that NiftyMIC produces SRRs that are of better self-consistency as measured by the slice residuals regardless of the number of input stacks. Despite the higher slice residual scores, SRRs based on fewer input stacks represent anatomically less plausible reconstructions as shown in Figure 4. Both investigated motion-correction frameworks show SRRs with improved anatomical clarity over the static approach. This is especially the case for the SRRs based on six input stacks. However, the MRCP-guided framework becomes less accurate in areas with poor MRCP contrast. The clinical evaluation in Figure 5 shows a clear preference for NiftyMIC in both quantified clinical usefulness score and radiologist's subjective preference.

Conclusions

Additional SST2W image acquisitions over the axial and coronal images currently available in upper abdominal MR protocols can substantially improve SRR outcomes. Importantly, its high anatomical fidelity relies on the accurate establishment of generally non-linearly affected, anatomical correspondences captured by different SST2W stacks acquired at different breath-holds. Two promising motion-correction and reconstruction frameworks were identified: An MRCP-guided non-linear registration approach that appears to work well in areas where MRCP volume contrast is high and an outlier-robust SRR framework based on rigid motion correction that can efficiently match (and reject if needed) image correspondences using only the SST2W image acquisitions. Further analysis is needed to evaluate the clinical value of the final HR reconstructions. Moreover, establishing the optimal number of stacks, their orientation and the balance between acquisition time and reconstruction quality remains the subject of ongoing work.

Acknowledgements

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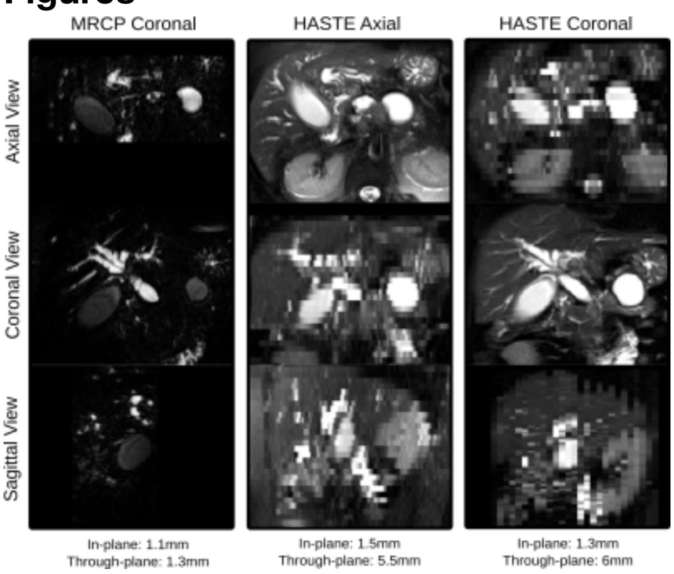
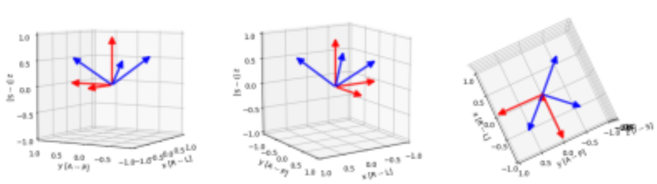
Figures



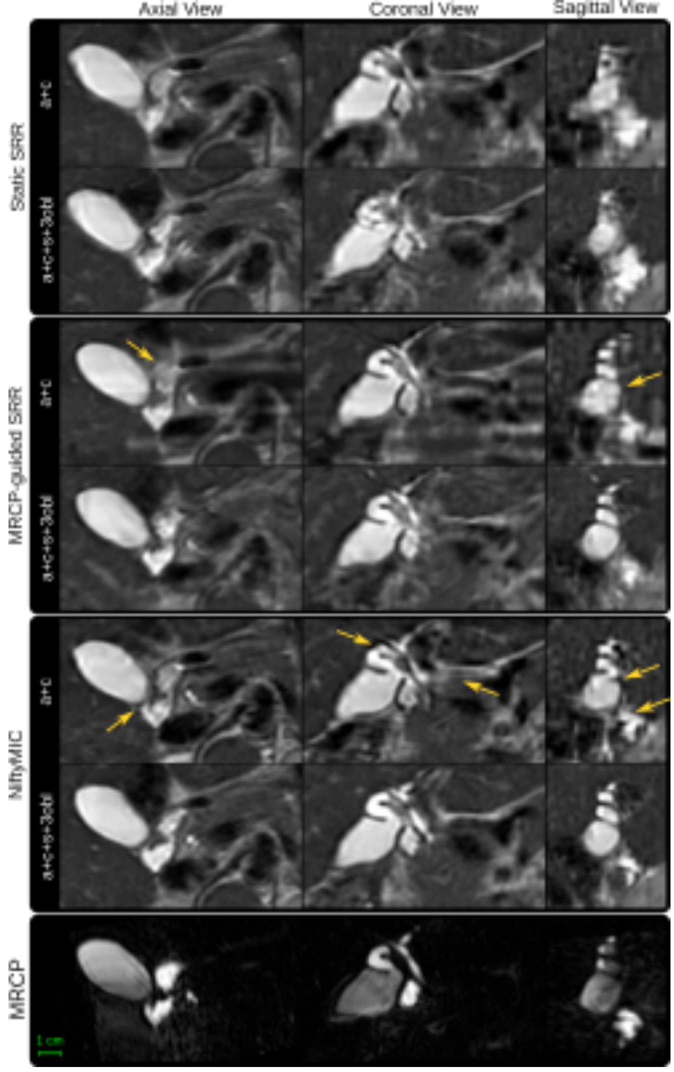
Visualization of typical MR data acquired in clinical MRCP studies around the biliary tree. The heavily T2-weighted MRCP volume has approximately five times higher resolution compared to the stack of HASTE slices (a single-shot T2-weighted acquisition) in through-plane direction. However, whereas the MRCP sequence lacks valuable contrast in the anatomy around the ducts, clinical interpretation of HASTE images is limited by its low resolution and the inter-slice motion.



Visualization of the slice-select directions of the SST2W stacks. The red arrows indicate slice-select directions of the three standard anatomical planes. In addition, three "oblique" acquisitions are performed along the directions indicated with blue arrows.

	Static SRR	MRCP-guided SRR	NiftyMIC
2 input stacks (a+c)	0.886 ± 0.087	0.878 ± 0.100	**0.942 ± 0.039**
3 input stacks (a+c+s)	0.854 ± 0.097	0.841 ± 0.137	**0.921 ± 0.049**
6 input stacks (a+c+s+3obl)	0.813 ± 0.133	0.772 ± 0.204	**0.898 ± 0.062**

Residual slice evaluation for all subjects and SRR approaches showing the associated NCC mean and standard deviations. NiftyMIC shows superior self-consistency across different number of input stacks. Importantly, SRRs based on fewer input stacks can lead to higher (measured) self-consistency but lack anatomical plausibility due do its less constrained nature during the SRR step as shown in Figure 4



Qualitative comparison between the SRR approaches using either two or six input stacks. Both motion-correction frameworks, i.e. the MRCP-guided one and NiftyMIC, achieve SRRs with visually improved anatomical plausibility. However, in areas where MRCP lacks contrast, NiftyMIC tends to produce superior results. Moreover, using six input stacks can lead to better SRR outcomes in case of adequate motion correction which is especially visible in the sagittal view. Examples for such visual improvements are indicated by arrows.

	Clinical Usefulness: Clarity of Anatomical Structures				Total Score Clinical Usefulness	Radiologists' Preference
	Common Bile Duct	Left Hepatic Duct	Right Hepatic Duct	Visible Motion		
Static SRR	1.14 ± 0.38	1.14 ± 0.38	1.14 ± 0.38	1.29 ± 0.49	4.71 ± 1.11	1.57 ± 0.53
MRCP-guided SRR	1.57 ± 0.79	1.71 ± 0.49	1.71 ± 0.49	1.43 ± 0.53	6.43 ± 1.90	1.43 ± 0.53
NiftyMIC	**2.86 ± 0.38**	**2.71 ± 0.49**	**2.71 ± 0.49**	**2.43 ± 0.53**	**10.71 ± 1.25**	**3.00 ± 0.00**

Clinical evaluation averaged over all seven subjects using six input stacks. Clarity of anatomical structures score indicates how well CBD, LHD and RHD are visualized in each image with ratings 0 (structure not seen), 1 (poor depiction), 2 (suboptimal visualization; image not adequate for diagnostic purposes), 3 (clear visualization of structure but reduced tissue contrast; image-based diagnosis feasible) and 4 (excellent depiction; optimal for diagnostic purposes). Visible motion score rates the amount of visible non-corrected motion from score 0 (complete motion) to 3 (no motion). Radiologists' preference ranks the subjectively preferred reconstructions from 1 to 3 (least to most preferred).