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Original contribution

# Alternate update of shifted extended keyholes (AUSEK): A new accelerating strategy for interventional MRI

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ABSTRACT

Real-time or near-real-time acquisition plays a key role in providing immediate image guidance for interventional magnetic resonance imaging (iMRI). However, the requirement of accurate needle tip localization has made several accelerating techniques, like Keyhole imaging or sliding window reconstruction, difficult to be applied to iMRI. The purpose of this work was to further explore the possible ways of applying view sharing techniques to iMRI. Inspired by Keyhole imaging, we present an easy-to-implement accelerating strategy called "Alternate update of shifted extended keyholes (AUSEK)". In this method, the keyhole views are not only extended but also shifted towards either high-frequency edge to form two divisions in k-space. The divisions which are mirrored to each other along the center are alternately updated following a reference scan. By using simulations and experiments, we demonstrate that AUSEK could effectively preserve the spatial resolution of the image, especially of the needle, at a temporal acceleration rate of about 2.5. AUSEK was implemented online in an open-configuration low-field MR imaging system.

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## 1. Introduction

Over the years, the demand for MR-guided minimally invasive surgeries keeps growing and the techniques of interventional MRI (iMRI) have advanced rapidly. High tissue contrast, no risk of ionizing radiation, multiple contrast mechanisms, arbitrary plane orientation and temperature sensitivity seem to have made MRI the perfect modality for image guidance in interventional procedures. IMRI has been used in procedures like spinal injection [1–3], joint puncture and arthrography [4–6], liver tumor ablation [7–9], breast cancer therapy [10,11] and so on. Although many improvements have been made on the gradient system, the acquisition speed of MRI is still slower compared with other imaging modalities such as computed tomography (CT) or ultrasound. This is especially true for low-field scanners.

The spatial redundancy in k-space could be exploited to design an efficient sampling scheme. And for many interventional procedures, especially when the interventional device is pretty close to the target, freeze mode, that is images are continuously updated with a fixed FOV, is used [4]. In cases like this, the temporal redundancy in k-space could be exploited, too. View sharing methods, like Keyhole imaging [12,13] or sliding window reconstruction, are used to improve temporal resolution of MRI for many years [14–16]. But their applications to iMRI seem not very straightforward. Interleaved multi-turn radial sampling was used with sliding window reconstruction for real-time MRI in [16]. But for iMRI, sliding window reconstruction with multiple intermediate images may be inherently not suitable for iMRI. Take the needle insertion as an example. During the interventional procedure, the needle is almost always moving, usually at a speed of 2 mm/s. So for sliding window reconstruction, the reconstructed needle image of current update would overlay the one of previous updates. But only the current update contains relevant information of the true current needle tip position. There would be several intermediate darkness levels at the tip part of the needle if multi-turn sliding window reconstruction was used and the darkness level of the tip would be the lowest among them. If too many turns were used, the tip might be too obscure to be noticed. The application of Keyhole imaging to iMRI was studied by Jeffrey L. Duerk in [14,17]. When the phase encoding direction is perpendicular to the needle shaft, the spatial resolution, especially the width resolution of the needle shaft would be inadequate for conventional keyhole method which repeatedly updates the center 25% of k-space. When the phase encoding direction is parallel to the needle shaft, although the width resolution is excellent, the ringing artifacts at the tip would make the conventional keyhole method difficult to be applied to iMRI. From another perspective, the contradiction of using conventional Keyhole imaging is that only updating the low-frequency part would lose too much critical high-frequency information about the

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needle. Hence, we were inspired by [14–17] and proposed a simple updating scheme called "alternate update of shifted extended keyholes (AUSEK)".

The purpose of this study was to further explore the possible ways of applying view sharing techniques to iMRI while preserving adequate spatial resolution of the image, especially of the needle. Simulation experiments, dynamic phantom experiments and ex vivo experiments were conducted. AUSEK was implemented online in an open-configuration, low-field MR imaging system.

## 2. Materials and methods

### 2.1. Materials

A phantom was used in the experiments. The materials used for this phantom were Agarose (4%), NaCl (0.5%), $CuSO4\text{-}5H2O$ (0.05%) and distilled water. The phantom was roughly in the shape of a cuboid. The length, breadth and height of the phantom were about 16 cm, 12 cm and 8.5 cm respectively. Two tubes were placed in the phantom. The diameter of the thin one with air filled in it was about 0.5 cm. A 16-G MR-compatible needle with a 20° bevel tip was used. It was constructed of a Nickel-Titanium alloy. One pig thigh was used for needle insertion in ex vivo experiments.

All imaging was done on a 0.35 T open-configuration whole-body MR scanner (PICA, Time Medical Systems, Hong Kong, China). A receive-only quadrature knee coil was used. This coil was custom-made for intervention. The interventional MRI system consisted of the MR scanner, two in-room monitors, one infrared camera, fixed infrared reflector reference to enable frameless stereotaxy. Optical tracking was performed using the infrared navigator camera (NDI, Waterloo, Ontario, Canada), like in [18]. The simulation experiments were done using MATLAB (The Mathworks, Natick, MA). The dynamic phantom experiment required at least two people working in coordination in the scanning room. One person was performing the procedure and the other one was controlling the pulse sequences.

### 2.2. The process of simulation experiments

Inspired by the simulation study done by Jeffrey L. Duerk in [17], we designed a similar one (Fig. 1). The simulation experiments started with an axial image of the phantom. This image was reconstructed from a fully-sampled raw data which was acquired by a conventional spin echo pulse sequence (1 slice, TR 450 msec, TE 15 msec, slice thickness/interval 4 mm/2 mm, field of view (FOV) 256 mm × 256 mm, matrix 256 × 256, ETL 1, acquisition time 1 min, 55 s) on the 0.35 T scanner. As in [17], we got the original raw data by the inverse two-dimensional Fourier transform (2DFT) of the SE magnitude image. Then a two-pixel-wide simulated needle, consisting of zero-value pixels, was "inserted" into the phantom image. At the needle tip (the right end), the lower row of the needle had one more pixel than the upper row to simulate a 45° bevel tip. The simulated needle's insertion direction was set as both directly towards the target of the dark dot (the air-filled thin tube) and perpendicular to the phase encoding direction [17]. We got the raw data of this image by 2DFT and sampled a selected section of it and replaced the corresponding part of the original raw data. For different set of comparison, the specific sampling pattern may be different. After 2DFT of the updated raw data, we got the updated image with a needle in it. This concludes the first cycle. Then we replaced the original image with the updated image and advanced the simulated needle at the same time. The needle insertion rate was set as 6 pixels per cycle. An insertion cine was generated as the cycle was repeated 4 times. In addition to the cycle, in the updated image reconstructed following the k-space update, we also attached another simulated needle (same width, same length, same shape and same direction) parallel to the "insertion" location for comparison. The images with reference needles in them were only used for evaluation and were not included in the repetition cycle.

### 2.3. Simulation experiments

#### 2.3.1. Comparison between four different updating schemes

The four updating schemes (Fig. 2) were inspired by Keyhole imaging [12–14,17] and sliding window reconstruction. The first scheme (Fig. 2a) only updated one single division in k-space repeatedly (we called it "repeatedly single-division updating scheme"). This division contained 40% of the full number of views. There were two divisions which got updated alternately in the second scheme (AUSEK) (Fig. 2b). Either division contained 40% of the full number of views and was mirrored to the other along the center. In the third scheme (Fig. 2c), interleaved two-turn updating was used. The total views which got updated in two turns constituted 80% of the full number of views. In the fourth scheme (Fig. 2d), interleaved three-turn updating was used. The total views which got updated in three turns constituted 80% of the full number of views.

#### 2.3.2. Comparison between different levels of shifting

In this set of experiments, we compared the images when different levels of shifting were set in AUSEK. The percentage of either of the

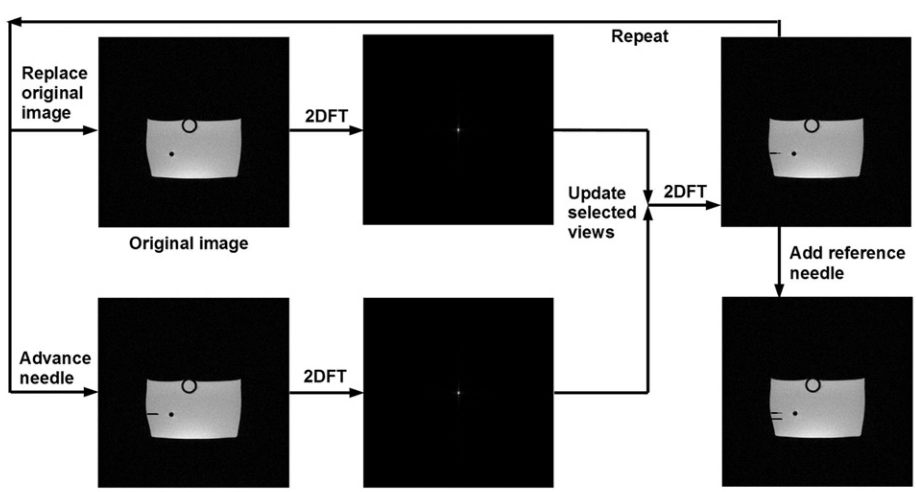


**Fig. 1.** Process of the simulation experiments. Starting with an original image, the original raw data was got by 2DFT. Then a simulated needle was "inserted". Selected views were updated and a new image was reconstructed. By replacing the original image with the updated image and advancing the needle at the same time, repetition of a cycle started. Besides, for every updated image, another simulated needle was attached for reference purpose.

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