Published in final edited form as:

Magn Reson Med. 2018 August ; 80(2): 655–661. doi:10.1002/mrm.27056.

Artifact-reduced imaging of biopsy needles with 2D multi-spectral imaging

Hans Weber, Brian A Hargreaves, and Bruce L Daniel

Radiology, Stanford University

Abstract

Purpose—MR-guidance for biopsy procedures requires high intrinsic soft-tissue contrast. However, artifacts induced by the metallic needle can reduce its localization and require low susceptibility needle materials with poorer cutting performance. In a proof-of-concept, we demonstrate the feasibility of 2D multi-spectral-imaging (2DMSI) for both needle tracking and for needle artifact reduction for more precise needle localization and to enable the usage of needle materials with higher susceptibility.

Method—We applied 2DMSI for imaging of MR compatible biopsy needles, conventional stainless-steel needles and mixed-material needles and compared it to conventional techniques. In addition, we exploited intrinsic off-resonance information for passive needle tracking.

Results—2DMSI achieved a stronger reduction of the needle artifact compared with conventional techniques. For the mixed-material needles, the artifact was reduced to a level below that for MR compatible needles with conventional imaging. The passive tracking also improved the ability to pinpoint the needle.

Conclusion—2DMSI is promising for both needle tracking and artifact-reduced imaging of biopsy needles for a more precise needle localization. 2DMSI may be particularly promising for needles inducing large distortions or for targeting of small lesions. In addition, it may enable the use of needle materials with higher susceptibility and potentially better sampling performance.

Keywords

multi spectral imaging; distortion correction; metallic implants; metal artifacts; metal-induced distortions; susceptibility artifact

Introduction

MRI enables guidance of biopsy procedures with high intrinsic soft-tissue contrast. Providing additional signal-to-noise ratio, 3 T high-field MRI even allows for targeting of submillimeter structures such as small nerves [1]. However, the metallic needle can induce field inhomogeneities, resulting in artifacts such as distortions or signal void [2, 3]. These effects are more pronounced at 3 T compared to 1.5 T [4]. Though the signal void may aid in detecting the needle, it prevents pinpointing the exact needle location and thus reliable

targeting of smaller lesions. In addition, in-plane and through-plane distortions can misguide the needle path, as lesions might appear at a different position on imaging with respect to their actual location. Low susceptibility materials such as cobalt-chromium, nickel-chromium or nickel-titanium can reduce these artifacts and are therefore used in needles specifically designed for utilization in MR-guided procedures. Typically, these needles are referred to as MR compatible. However, these low-susceptibility materials are a significant compromise for biopsy, as they cannot be ground as sharply as stainless-steel, resulting in a poor cutting performance and sample quality [5, 6].

Several MRI techniques can be applied to reduce needle artifacts. Spin-echoes compensate for dephasing. High readout bandwidth decreases in-plane distortions. Inversion of the slice selection gradient between excitation and refocusing excludes signal from the off-resonance region that suffers from through-plane distortions [7]. Building on these techniques, the recently introduced 2D multi-spectral-imaging (2DMSI) approach aims for fast, artifact-reduced imaging of the off-resonance region by segmenting it into spatially and spectrally limited regions (“bins”) that, individually, can be imaged with minimal artifact [8]. With an increasing number of acquired frequency “bins”, coverage of the off-resonance region and thus visualization of the region close to the metal increases. Compared to conventional, 3D-based multi-spectral-imaging approaches such as SEMAC, MAVRIC or hybrid methods [9–11], 2DMSI can limit the acquisition to a few slices and therefore achieve significantly shorter acquisition times, while offering similar artifact correction. This is particularly attractive for interactive needle placement during procedures where the surgeon uses repeated frequently updated images of the needle progress, without having to wait for lengthy scans to be performed.

The goal of this work is to explore the feasibility of 2DMSI for both needle-artifact reduction and needle tracking at 3 T. To demonstrate proof-of-concept, we perform three experiments: First, we apply 2DMSI to MR-compatible needles to virtually remove the needle artifact for improved pinpointing of the needle. Second, we apply 2DMSI to conventional, “non-MR-compatible” stainless-steel needles as well as custom-made mixed-material needles to reduce the needle artifact to a level comparable to imaging of MR compatible needles with conventional techniques. Third, we exploit the 2DMSI-intrinsic off-resonance information for passive needle tracking.

Methods

2D Multi-Spectral Imaging (2DMSI)

2DMSI is a spin-echo train based imaging technique that enables fast, artifact-reduced imaging in the presence of high off-resonance. Its underlying concept is illustrated in Fig. 1. It is based on the segmentation of the slice to be imaged into spatially and spectrally limited regions (“bins”) that can be imaged individually with minimal artifact (Fig. 1a). An individual bin is selected by inverting the slice gradient between excitation and refocusing pulses (Fig. 1b). The overlap between the excitation and the refocusing profile defines the bin profile, which is located within the desired, undistorted slice. For maximum speed, k-space is acquired using a single-shot readout with half-Fourier undersampling. Adjacent bins for one slice are acquired by repeating the process with an identical shift of the radio

frequency modulation on excitation, refocusing and reception, which excites off-resonance and reduces in-plane distortion. Each bin image is reconstructed individually and the composite 2DMSI image is formed by combination of the individual bin images (Fig. 1c). For single-shot 2DMSI, the acquisition time scales linearly with both the number of bins and slices.

Data Acquisition

All experiments were performed on a 3 T whole-body MRI system (Discovery MR750, GE Healthcare, Waukesha, WI, USA). The biopsy needles were mounted in a 3D printed rectangular grid and immersed in doped water (1.0 mmol/l CuSO_4). The grid had a cube length of 15 mm and the bars had a thickness of 2 mm. The needles were oriented perpendicular to the static magnetic field to maximize artifact. Imaging data was acquired with a 6-channel surface coil wrapped around the setup. Processing of the DICOM images for the needle tracking was performed off-line in Matlab (MathWorks, Natick, MA).

Experiment 1: Artifact-Reduced Imaging of MR-Compatible Biopsy Needles

To demonstrate the ability of 2DMSI for improved visualization of MR compatible, low-susceptibility biopsy needles, we acquired axial images of both a 14G nickel-chromium (NiCr) biopsy needle (MRI BioGun, E-Z-EM, Westbury, NY, USA) and a 16G cobalt-chromium (CoCr) biopsy needle (MRI Biopsy Handy, Somatex, Teltow, Germany) with single-shot 2DMSI, conventional imaging and alternative artifact reduction techniques. The axis of both needles was aligned with the grid as shown in Fig. 2. The needles were chosen to reflect the spectrum of commonly used needle diameters for biopsy. Supporting Table S1 in the online supporting material summarizes the details of the 3D gradient-echo (3D GRE), 2D spoiled-gradient-recalled-echo (SPGR), 2D fast-spin-echo (FSE) and 2DMSI sequences. FSE imaging was repeated with increased readout bandwidth and inverted slice selection gradient. 2DMSI images were acquired with 1 bin (covering off-resonances from -0.6 kHz to $+0.6$ kHz) and 12 bins (-5.7 kHz to $+6.6$ kHz). As an indicator for the artifact reduction performance, we roughly estimated (± 1 mm) the width of the artifact perpendicular to the needle axis both at the top part of the needle and at the tip. The artifact width was defined by the accompanying signal loss and marked with a red line.

Experiment 2: Artifact-Reduced Imaging of Mixed-Material Biopsy Needles

We also investigated the ability of 2DMSI to enable MR-guidance with conventional, “non-MR compatible” biopsy needles, typically made of stainless steel (SS) with a higher susceptibility. Reducing the needle artifact to an acceptable level might allow use of these needles to benefit from their better cutting performance. Imaging experiments were performed with pairs of a 14G and a 18G needle made of a) CoCr, b) 304 SS and c) a combination of both materials (all Somatex, Teltow, Germany). For the latter, we disassembled the original needles and created mixed-material needles, consisting of a CoCr inner stylet and a SS cutting cannula. For each pair, we acquired 3D GRE, 2D SPGR, 2D FSE with high readout bandwidth and 12 bin 2DMSI images as outlined in Supporting Table S1 in the online supporting material. Supporting Figure S1 shows scanning electron microscope (SEM) micrographs of both a CoCr and a SS cutting cannula. The 1500x

magnification enables visualization of smooth edges for the CoCr needle and sharper edges for the SS one.

Experiment 3: Passive Needle Tracking Using Off-Resonance Bin Information

The individual 2DMSI bin images contain valuable information about the magnitude and the sign of the needle-induced off-resonance and thus about the location and orientation of the needle. As the field map in Fig. 1a indicates, a shift of the needle with respect to the slice normal would change the ratio of positive to negative off-resonance volume within the slice. To evaluate the potential of the 2DMSI-intrinsic off-resonance information for passive needle tracking, we color-coded the signal originating from bins with higher off-resonance in a 12 bin 2DMSI image of the two MR compatible needles from experiment 1. A mask of each bin was automatically created by thresholding the individual bin images using a threshold of 60 % with respect to the maximum signal intensity in the corresponding bin image. For both positive and negative off-resonance, the masks of the bins with frequency 2.7 kHz and higher were combined and the composite 2DMSI image was color-coded based on these masks. We applied this color-coding to a series of 2DMSI images acquired while inserting the needles into the phantom.

Results

Experiment 1: Artifact-Reduced Imaging of MR-Compatible Biopsy Needles

Figure 3 shows the axial images of the 14G NiCr and the 16G CoCr biopsy needles acquired with the different sequences and artifact reduction strategies. With all imaging techniques, both needles are visible, although the ability to pinpoint them varies considerably. The 3D GRE image (a) produces an easily visible needle axis, but hypo- and hyper- intense signals surround the needle, obstructing the surrounding grid structure. For the 14G NiCr needle, the artifact extends about 31 mm at the top part and about 18 mm at the narrower tip. For the 16G CoCr needle, the extent is about 25 mm at the top and about 7 mm at the tip. In the SPGR image (b), the slightly reduced needle artifact is dominated by signal void. In comparison, FSE (c) compensates for signal void, revealing the distortions visible as signal pile-up surrounding the needle. Increasing the readout bandwidth (d) reduces the in-plane distortions and the through-plane distortions become more distinct. Inverting gradients (e), successfully suppresses the signal from the distorted off-resonance region, identifying the unbiased signal. Single-bin 2DMSI (f) reveals a similar result, although higher-bandwidth radio frequency pulses cause a better region selection. Adding off-resonance bins reveals the signal regions close to both needles without distortions (g).

For 2DMSI with 12 bins (g), the uncovered region at the needle top is less than 30% of that for the artifact in the commonly used SPGR sequence and very close to the actual extent of the needle of 2 mm (14G NiCr needle) and 1.6 mm (16G CoCr needle). At the needle tips, the artifact is almost completely removed.

Experiment 2: Artifact-Reduced Imaging of Mixed-Material Biopsy Needles

Figure 4 compares the imaging results of the MR-compatible, pure CoCr needles (top), the conventional, pure SS needles (middle) and the combined CoCr and SS needles (bottom).

The CoCr needles reveal a behavior similar to that of the MR-compatible needles in experiment 1, with 12 bin 2DMSI (d) again almost completely removing the needle artifact. For the SS needles, the artifact is massive in both GRE-based images (e & f). Although FSE with high readout bandwidth reduces signal void and in-plane distortions, the in-plane extent of the through plane distortions – revealed by the missing grid bars – is comparable to the artifact extent in the GRE-based images. 2DMSI with 12 bins (h) considerably reduces the extent of the artifact to about 35 mm (18G CoCr needle) and 38 mm (14G CoCr needle), though it is still rather large. The signal intensity variation surrounding the signal void regions originates from the variation in slice thickness at the bin intersections (compare Fig. 1c).

Combining a CoCr inner stylet with a SS cutting cannula results in a slightly larger artifact compared to the pure CoCr needles but a strongly reduced artifact compared to the pure SS needles for all sequences. However, whereas for the conventionally used SPGR sequence (j) the artifact extent for the mixed-material needles of about 19 mm (18G needle) and 22 mm (14G needle) is still about 60 % larger than for the pure CoCr needles, 2DMSI (l) allows reduction of the artifact for the mixed-material needles to about 5 mm (18G needle) and 7 mm (14G needle), respectively. Thus, even for the mixed-material needles with an expected better cutting performance, 2DMSI achieves considerably better artifact reduction than conventionally used SPGR imaging does for pure CoCr needles.

Experiment 3: Needle Tracking Using Off-Resonance Bin Information

As an example for needle tracking using the 2DMSI bin off-resonance information, Fig. 5 shows the 12-bin 2DMSI image of the two MR-compatible needles from experiment 1 without (a) and with automatic color-coding applied (b). Signal in the tip of the left needle is due to partial volume effects. The tip of the 16G CoCr needle (right) does not trigger color-coding, as the thin needle does not induce sufficient off-resonance. As the image comparison for the thicker 14G NiCr needle reveals (left), the color-coding increases the ability to pinpoint the needle.

Figure 5c shows three selected frames of a series of 2DMSI images acquired while inserting the needles into the grid with the inner stylet retracted. The full series is plotted in Supporting Figure S2 in the online supporting information. Moving the needles out the imaging plane changes the ratio between positive and negative off-resonances. Thus, in addition to a better localization of the needle, the color coding also provides feedback on the change in needle orientation with respect to the imaging plane for a moving needle.

Discussion

In this work, we explored the potential of fast, 2D multi-spectral imaging for both artifact-reduced imaging and passive tracking of biopsy needles. The ability of 2DMSI to provide imaging in regions exhibiting high off-resonance enables a more precise localization of MR compatible needles and visualization of needles made of higher-susceptibility materials on a level comparable approaching that of MR compatible needles with conventional imaging.

Artifact-Reduced Imaging of MR-Compatible Biopsy Needles

Compared to the conventional techniques, 2DMSI clearly enabled a stronger reduction of the needle artifact. With 12 bins, the off-resonance coverage ranging from -5.7 kHz to 6.6 kHz was sufficient to remove most of the needle artifact at the needle tips. Adjusting the number of bins allows for choice of coverage around the needle as a tradeoff between needle conspicuity as well as acquisition speed and ability to pinpoint its location. The application of 2DMSI for MR guidance with MR compatible, low susceptibility needles is particularly promising for targeting of smaller lesions in cases where visualization of sensitive structures close to the lesion or to the needle path is crucial. The short acquisition time of a few seconds per slice allows for the acquisition of multiple slices in an acceptable time, comparable to the FSE-based artifact reduction techniques. As MR guidance usually requires only a few slices surrounding the needle path, 2DMSI is expected to achieve a higher temporal resolution than highly accelerated 3D-based multi-spectral imaging techniques, which must acquire a larger volume [12].

Besides artifact reduction, sufficient image quality and contrast to visualize the lesion and sensitive structures surrounding the needle path is crucial for MR guidance. Although this work focuses on the artifact reduction, in vivo application of 2DMSI for implant imaging [8] has shown promising results with respect to image quality and contrast. 2DMSI with single-shot readout - as applied in this work - results in a long spin-echo train and thus a T2 weighting. Combination of 2DMSI with an inversion-recovery preparation pulse [13] allows for T1 weighting and/or fat suppression. Alternatively, a multi-shot readout would enable T1 weighting or proton-density weighting, perhaps reducing image blurring as well.

Artifact-Reduced Imaging of Mixed-Material Biopsy Needles

The ability of 2DMSI for artifact-reduced imaging in the presence of high off-resonance may also enable the use of needle materials with higher susceptibility and potentially better cutting performance. In this work, we showed that we could considerably reduce the artifact from a conventional, pure SS biopsy needle, although the needle artifact might be still too large for most applications (Note that for thinner needles the artifact reduction may be o.k.). The acquisition of additional bins would further reduce the artifact extent. However, the increasing steepness of the needle-induced off-resonance reduces the area covered per additional bin and thus reduces the efficiency of this approach.

Whereas the outer cannula cuts the sample, it is the inner stylet that primarily contributes to the needle artifact due to its larger volume. Therefore, mixed-material needles - composed of a low susceptibility inner stylet and a sharper, higher susceptibility cutting cannula - potentially offer an optimized combination of overall limited susceptibility to ensure restricted attraction by the magnetic field and high cutting performance. Whereas conventional imaging won't be able to facilitate the use of these optimized needles, 2DMSI shows great potential of reducing their artifact even below the extent for MR compatible needles with conventional imaging. Although we noticed little force for the pure stainless steel needles after removing the spring and negligible force for the combined needles, clinical application of mixed-material needles would still require both dedicated engineering

for careful balance of materials and comprehensive testing to address safety concerns in the presence of the magnetic field.

Needle Tracking Using Off-Resonance Bin Information

The 2DMSI-intrinsic off-resonance information can be easily exploited to highlight the off-resonance region and thus to further improve the needle localization. As demonstrated, the discrimination between positive and negative off-resonance sharpens the otherwise blurry transition between signal void at, and/or next to the needle and the surrounding signal. During needle movement, the color coding also reveals the change in negative and positive off-resonance. This also enables estimating the change in needle orientation with respect to the imaging plane to further improve guidance. The individual acquisition of bins in 2DMSI also offers the possibility to acquire only off-resonance bins and to use the information to highlight the off-resonance areas in a separately acquired anatomical image with potentially more suitable contrast.

Conclusion

2DMSI revealed promising results for both artifact-reduced imaging of biopsy needles for a more precise needle localization and for needle tracking, justifying pre-clinical and clinical investigations for MR guidance. 2DMSI might be particularly promising for biopsy needles that induce large distortions or for targeting of small lesions. In addition, it may enable use of a wider range of needle materials, with potentially better sampling performance.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The authors like thank Jan Rieger and Marilu Sanz from Somatex GmbH for providing needle samples, Dr. Lydia-Marie Joubert from the Stanford Cell Sciences Imaging Facility for acquiring the SEM micrographs and Dr. Roger Goldman for discussions. This work was supported by NIH (R01 EB017739, R21 EB019723, P01 CA159992, P41 EB015891) and GE Healthcare.

Abbrev

MRI	Magnetic Resonance Imaging
MSI	Multi Spectral Imaging
GRE	Gradient-Recalled Echo
SE	Spin Echo
NiCr	nickel-chromium
CoCr	cobalt-chromium
SS	stainless-steel

References

1. Fritz J, Dellon AL, Williams EH, Belzberg AJ, Carrino JA. 3-Tesla High-Field Magnetic Resonance Neurography for Guiding Nerve Blocks and Its Role in Pain Management. *Magn Reson Imaging C*. 2015; 23:533–545.
2. Lewin JS, Duerk JL, Jain VR, Petersilge CA, Chao CP, Haaga JR. Needle localization in MR-guided biopsy and aspiration: Effects of field strength, sequence design, and magnetic field orientation. *Am J Roentgenol*. 1996; 166:1337–1345. [PubMed: 8633445]
3. Ladd ME, Erhart P, Debatin JF, Romanowski BJ, Boesiger P, McKinnon GC. Biopsy needle susceptibility artifacts. *Magn Reson Med*. 1996; 36:646–651. [PubMed: 8892221]
4. Penzkofer T, Peykan N, Schmidt K, Krombach G, Kuhl CK. How MRI compatible is “MRI compatible”? A systematic comparison of artifacts caused by biopsy needles at 3.0 and 1.5 T. *Cardiovasc Inter Rad*. 2013; 36:1646–1657.
5. Fraunhofer JA von, Storey RJ, Masterson BJ. Characterization of surgical needles. *Biomaterials*. 1988; 9:281–284. [PubMed: 3408803]
6. Frick TB, Marucci DD, Cartmill JA, Martin CJ, Walsh WR. Resistance forces acting on suture needles. *J Biomech*. 2001; 34:1335–1340. [PubMed: 11522313]
7. Butts K, Pauly JM, Daniel BL, Kee S, Norbash AM. Management of biopsy needle artifacts: Techniques for RF-refocused MRI. *J Magn Reson Imaging*. 1999; 9:586–595. [PubMed: 10232519]
8. Hargreaves BA, Taviani V, Litwiller DV, Yoon D. 2D multi-spectral imaging for fast MRI near metal. *Magn Reson Med*. 2017; doi: 10.1002/mrm.26724
9. Lu W, Pauly KB, Gold GE, Pauly JM, Hargreaves BA. SEMAC: Slice Encoding for Metal Artifact Correction in MRI. *Magn Reson Med*. 2009; 62:66–76. [PubMed: 19267347]
10. Koch KM, Lorbiecki JE, Hinks RS, King KF. A multispectral three-dimensional acquisition technique for imaging near metal implants. *Magn Reson Med*. 2009; 61:381–390. [PubMed: 19165901]
11. Koch KM, Brau AC, Chen W, Gold GE, Hargreaves BA, Koff M, McKinnon GC, Potter HG, King KF. Imaging near metal with a MAVRIC-SEMAC hybrid. *Magn Reson Med*. 2011; 65:71–82. [PubMed: 20981709]
12. Sonnow L, Gilson WD, Raithel E, Nittka M, Wacker F, Fritz J. Instrument visualization using conventional and compressed sensing SEMAC for interventional MRI at 3T. *J Magn Reson Imaging*. 2017
13. Weber H, Taviani V, Yoon D, Ghanouni P, Pauly KB, Hargreaves BA. MR thermometry near metallic devices using multispectral imaging. *Magn Reson Med*. 2017; 77:1162–1169. [PubMed: 26991803]

2D Multi-Spectral Imaging (2DMSI)

Figure 1.

Illustration of the 2DMSI technique: a) The slice is segmented into spatial-spectral regions ("bins") that can be imaged with minimal artifact. b) For bin selection, the slice selection gradient is inverted between excitation and refocusing pulses. Repetition of the acquisition with different radiofrequency modulations results in imaging of adjacent bins. c) The final 2DMSI image is built up by root-sum-of-squares combination of the individual bin images. By increasing the number and extent of frequency bins, visualization of the region close to the metal increases.

Figure 2.

Photograph of the MR compatible biopsy needles investigated in experiment 1, showing their arrangement with respect to the phantom grid. The 14G NiCr needle consists of a cutting cannula and an inner stylet. The 16G CoCr needle consists of a coaxial cannula, a 18G CoCr cutting cannula and an inner stylet. For both needles, the inner stylet exceeds the tip of the cannula, exposing the specimen chamber.

MR Guidance with MR-Compatible Biopsy Needle

Figure 3.

Results experiment 1: Axial slice containing the MR-compatible NiCr and CoCr biopsy needle, comparing conventional imaging (a & b), alternative artifact reduction techniques (c, d, e) and 2DMSI (f & g). Frame h) shows the grid phantom without needles as a reference. All images were acquired in the axial plane with readout oriented in left-right and the field-of-view was cropped. The red bars mark the extent of the needle artifact with the estimated values in mm. Whereas the reference techniques suffer from signal void and distortions, 2DMSI with 12 bins also enables artifact-reduced visualization of the off-resonance regions close to the needles and thus more precise needle localization.

Figure 4.

Results experiment 2: Axial slice containing CoCr biopsy needles (first row), conventional, non-MR-compatible SS biopsy needles (middle row) and a combination of CoCr inner stylets with SS cutting cannulas (bottom row). For all needles, the inner stylet was retracted. 2DMSI clearly reduces the extent of the needle artifact. For the combined needles (l), the artifact is even smaller than for the MR-compatible needles with conventional imaging (b).

Needle Tracking with Off-Resonance Bins (MR-Compatible Needle)

Figure 5.

Results experiment 3: Tracking of the MR compatible needles using the 2DMSI-intrinsic off-resonance information. The red mask indicates signal intensity in the negative off-resonance bins, the blue mask in the positive off-resonance bins, respectively. Compared to the raw 2DMSI image (a), the masking overcomes windowing issues and localizes the needle even more precisely (b). Selected frames of a time series (c) capture the insertion of the needles in the phantom (inner stylet retracted). The ratio of positive and negative off-resonance bin signal is also sensitive to the orientation of the needle with respect to the slice plane. The full series is shown in Fig. A in online supporting information.