Motion-insensitive susceptibility weighted imaging

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Purpose: To enable SWI that is robust to severe head movement.

Methods: Prospective motion correction using a markerless optical tracker was applied to all pulse sequences. Three-dimensional gradient-echo and 3D EPI were used as reference sequences, but were expected to be sensitive to motion-induced $B_0$ changes, as the long TE required for SWI allows phase discrepancies to accumulate between shots. Therefore, 2D interleaved snapshot EPI was investigated for motion-robust SWI and compared with conventional 2D EPI. Repeated signal averages were retrospectively corrected for motion. The sequences were evaluated at 3 T through controlled motion experiments involving two cooperative volunteers and SWI of a tumor patient.

Results: The performed continuous head motion was in the range of 5–8° rotations. The image quality of the 3D sequences and conventional 2D EPI was poor unless the rotational motion axis was parallel to $B_0$. Interleaved snapshot EPI had minimal intraslice phase discrepancies due to its small temporal footprint. Phase inconsistency between signal averages was well tolerated due to the high-pass filter effect of the SWI processing. Interleaved snapshot EPI with prospective and retrospective motion correction demonstrated similar image quality, regardless of whether motion was present. Lesion depiction was equal to 3D EPI with matching resolution.

Conclusion: Susceptibility-based imaging can be severely corrupted by head movement despite accurate prospective motion correction. Interleaved snapshot EPI is a superior alternative for patients who are prone to move and offers SWI which is insensitive to motion when combined with prospective and retrospective motion correction.

Keywords: echo planar imaging, interleaved snapshot EPI, movement correction, prospective motion correction, susceptibility weighted imaging
Sensitivity to tissue susceptibility can be encoded into the magnitude and phase of gradient-echo (GRE) images with the use of long TEs. In T2*-weighted images, only the magnitude information is used, whereas the key feature of SWI is to also exploit the image phase for increased sensitivity. This lends SWI the excellent ability to depict veins and makes it useful for the detection of calcifications and iron deposition, including cerebral microbleeds.

Unfortunately, the blessing of susceptibility contrast is also a curse, as the same susceptibility-sensitizing phase renders these images particularly sensitive to motion. The reason for this is that the susceptibility-induced phase is not rotation-invariant, at least not if the head orientation is changed relative to the B0 field. Prospective motion-correction techniques adjust the imaging gradients to follow the motion in real time, but cannot compensate for this residual motion-induced phase. Figure 1 and Supporting Information Videos S1–S4 illustrate how the image phase is affected by motion, despite prospective correction. Motion during the acquisition of an image may therefore induce phase changes that interfere with the spatial encoding and cause ghosting artifacts, even if the acquisition was perfectly prospectively motion-corrected. The motion sensitivity of SWI may restrict its availability for patients who are inclined to move, such as children who would otherwise benefit from this technique.

Susceptibility-weighted imaging is typically based on spoiled 3D-GRE acquisitions. However, the SNR efficiency of these acquisitions is rather low due to the idle time between the excitation pulse and the long TE required for susceptibility sensitivity. The SNR efficiency can be greatly improved using 3D EPI, in which any gaps in the pulse sequence are used to sample additional k-space lines. Many drawbacks of single-shot EPI, such as distortion from field inhomogeneity, can be moderated using multishot 3D-EPI sequences, in which each plane in k-space is acquired with multiple interleaved shots. The remaining spatial distortions at some locations are often tolerable, as these locations would suffer from signal dropout anyway, due to intravoxel dephasing. Multishot 3D EPI offers SWI with increased spatial resolution without excessive scan time. Alternatively, the high SNR efficiency can be used to shorten acquisition time by an order of magnitude. Even if multishot 3D EPI is sensitive to motion for the same reasons as 3D GRE, this smaller temporal footprint of k-space improves the situation, as there is simply less time for motion to occur.

In this work, we investigate the efficacy of prospective motion correction for SWI using a markerless optical motion-tracking system. We explore the motion sensitivity of SWI based on 3D GRE and fast multishot 3D EPI. Furthermore, we revisit 2D interleaved snapshot EPI in the context of SWI. In this sequence, all shots of a given slice are acquired consecutively, which reduces the temporal footprint by a factor equal to the number of slices, greatly decreasing the sensitivity to motion. Unfortunately, the TR will also be reduced by the same factor, having the effect of restricted T1 relaxation, hence imposing lower SNR. To improve SNR, imaging is made in the transient state using a variable flip-angle train tailored to the TR and number of shots. Further SNR is gained by acquiring the...
multiple signal averages, which also enables retrospective motion correction between the averages before combining them. Conventional interleaved 2D EPI is included for comparison. The sequences are evaluated at 3 T by controlled motion experiments involving 2 cooperative volunteers. Lesion conspicuity is assessed by SWI of a tumor patient.

2 | METHODS

Images were acquired using a 3 T Signa Premier MR system and a 48-channel head coil (GE Healthcare, Milwaukee, WI). All pulse sequences were prospectively motion-corrected by updating the FOV and slice/slab position and orientation before each excitation pulse, according to the latest available rigid-body motion estimate. These were provided by a research version of a markerless optical motion-tracking system (Tracoline TCL3.1m; TracInnovations, Ballerup, Denmark). The setup of the tracking system was done as described elsewhere, but the scanner/tracker cross-calibration image volume was acquired using an anthropomorphic phantom before the subject entered the scanner. The experiments were performed under local ethical approval, and informed consent was obtained from both volunteers and the patient. All pulse sequences were developed in-house using the KS Foundation framework. The vendor’s reconstruction routine was used for 3D GRE without SWI processing. The 3D-GRE-SWI reconstruction and the EPI reconstruction were developed in-house in C++ and Matlab (The MathWorks, Natick, MA), respectively.

2.1 | Prospectively corrected EPI

Because each EPI shot was prospectively updated, zero and first-order phase alignment between odd and even lines was done separately for each shot, referred to as “dynamic ghost correction.” This was enabled by acquiring four navigator lines without phase encoding immediately after each excitation pulse. Intershot zero and first-order phase alignment was then made based on the even navigator lines of each shot and a reference shot. Echo-time shifting and RF spoiling with hexagonal gradient spoiling was used in all EPI sequences. For 2D EPI, GRAPPA acceleration was enabled by a leading 6.4-s calibration volume based on the fast low-angle excitation echo-planar technique, acquired with a 96 × 96 matrix with three interleaves, flip angle (FA) = 5°, TE = 18 ms, and TR = 44 ms. The calibration volume was also prospectively updated and ghost-corrected by four navigator lines.

The images shown in Figure 1 and Supporting Information Videos S1–S4 were acquired using a prospectively corrected single-slice and single-shot GRE-EPI sequence without GRAPPA acceleration. The sequence playout was repeated continuously to enable cine imaging during rotational motion about each of the gradient axes. Frames corresponding to 10° rotation about each axis were extracted for the figure. Imaging parameters were as follows: square 240-mm FOV, 96 × 96 matrix, 4-mm slice thickness, FA = 15°, TE = 35 ms, and TR = 79 ms.

2.2 | Interleaved snapshot EPI

In standard multishot 2D EPI, each shot is acquired for all slices before acquiring the next shot. The sequence was modified to optionally enable the acquisition of all shots for a given slice before proceeding with the next slice, denoted as “interleaved snapshot EPI.” Repeated averages were acquired after all shots and slices of the preceding average had been acquired. Note that this effectively yields two TR intervals: an inner TR (time between shots) and an outer TR (time between averages). In Figure 2, the loop ordering of standard EPI and interleaved snapshot EPI are illustrated. Following McKinnon, a variable flip angle (VFA) train was calculated based on the number of shots, the inner TR, and an assumed T1 relaxation time (T1 = 1 s was used as a middle ground between white and gray brain matter). No dummy shots were played. It can be noted that interleaved snapshot EPI has also been referred to as consecutive multishot EPI and VFA fast low-angle excitation echo-planar technique.

To avoid signal fluctuation between shots due to deviations from the assumed T1 and prescribed flip angle, the flip angle train was calculated for a larger number of excitations than actually played out. An experiment was performed comparing VFA trains calculated with zero, one, and two extra shots. In addition, constant flip-angle imaging was done at the Ernst angle, which was 18° for an inner TR of 58 ms. The theoretical SNR was calculated for all FA trains. A single average with 12 k-space interleaves was acquired with a GRAPPA acceleration factor R = 3, resulting in four acquired shots. Other imaging parameters were as follows: square 240-mm FOV, 36 slices of 4-mm thickness, 288 × 288 matrix, FOV bandwidth = ±250 kHz, and TE = 26 ms.

2.3 | Motion experiments

The sequences were compared in three different scan sessions with intentional head motion. To reproduce the motion patterns with and without prospective correction, the volunteer was guided by movies played back on a functional MRI screen visible through the coil-mounted mirrors and instructed to aim at the moving cross-hairs with their nose.

The first scan session aimed to evaluate 3D techniques in the presence of continuous head motion, combined with prospective motion correction, and to investigate the effect of TE. Therefore, short-TE 3D-GRE, long-TE 3D-GRE, and
long-TE 3D-EPI acquisitions were made, all with RF spoiling. Each sequence was repeated without intentional motion, with yaw motion (rotation axis parallel to B₀, ~5 cycles/minute), and with pitch motion (rotation axis perpendicular to B₀, ~4 cycles/minute). The acquisitions with motion were each repeated with prospective correction on and off. The whole brain was covered by 48 slices of 3-mm thickness. The 3D-GRE acquisitions were flow-compensated in the readout and slab-selection directions. A 240 × 192 mm FOV with 384 × 320 matrix was collected with $R = 2$, 16 GRAPPA autocalibration lines, and elliptical k-space. Imaging parameters for the short/long TE acquisitions were as follows: TE = 4.9/20 ms, TR = 9.1/29 ms, FA = 10°/15°, and FOV bandwidth = ±41.7/13.9 kHz. The total acquisition time was 52 seconds/2:43 minutes. The 3D-EPI acquisitions were made with a 100-mm inferior spatial saturation band, as the flow compensation of the EPI train appeared to be insufficient. A square 240-mm FOV with $320 \times 320$ matrix was collected with 16 interleaves and $R = 2$, resulting in eight shots per $k_z$ plane, but the 16 centermost planes were fully sampled with 16 shots to enable GRAPPA autocalibration. Other imaging parameters were as follows: TE = 29 ms, TR = 71 ms, FA = 18°, and FOV bandwidth = ±125 kHz. The total acquisition time was 39 seconds. No SWI processing was performed.

In the second scan session, the purpose was to compare prospectively corrected SWI using interleaved snapshot 2D EPI to standard interleaved 2D EPI, 3D EPI, and 3D GRE. All sequences were acquired without intentional motion, as well as with and without prospective motion correction during continuous circular motion (drawing a circle with the nose, ~6 cycles/minute). The imaging parameters of the 3D sequences were identical to the first scan session. The imaging parameters of the 2D-EPI sequences were the same as for the VFA experiment, except 48 slices of 3-mm thickness were acquired with four signal averages. The standard 2D EPI used one dummy shot, FA = 90°, and TR = 2.8 seconds. The snapshot 2D EPI used a VFA train without dummies and had an outer TR of 11.2 seconds. The total acquisition time was 51 seconds. The SWI processing as described by Reichenbach et al. was performed for each average separately after adaptive coil combination, but before retrospective motion correction and RMS combination of the averages.

The effect of head orientation on SWI processing was investigated in the third scan session. A second volunteer was instructed to change head pose between acquisitions of interleaved snapshot EPI. The SWI images were then reconstructed by combining and aligning one average from each of the four poses, as well as for each pose separately. The image-acquisition parameters were identical to the previous scan session.

A 52-year-old tumor patient was imaged to assess the lesion conspicuity of interleaved snapshot EPI. The acquisition parameters were identical to the previous scan sessions. For reference, 3D EPI was also acquired with identical scan conditions.
coverage. The TE and spatial resolution were matched to the interleaved snapshot EPI.

3 | RESULTS

The motion estimates from the first scan session are shown in Figure 3. The timing and magnitude of the motion were similar for the acquisitions repeated with prospective motion correction on and off. The performed motion was in the range of 5°–8°. Figure 4 shows the same slice from each of the acquisitions. Although the motion severely degraded all uncorrected acquisitions, the prospectively corrected yaw motion resulted in acceptable image quality for all sequences. In contrast, for the prospectively corrected pitch motion, the image quality was acceptable for the short-TE acquisition only.

The VFA trains calculated with zero, one, and two extra shots were [31°, 37°, 47°, 90°], [28°, 32°, 37°, 47°], and [25°, 28°, 32°, 38°], respectively. The corresponding SNRs were 54%, 49%, and 45% relative to the SNR of standard 2D...
EPI, whereas the SNR for Ernst-angle excitation was 30%. Reconstructed images from the VFA experiment are shown in Figure 5. The VFA train without extra shots corresponds to an effective total FA of 90°, and therefore had the highest SNR. However, it was also more sensitive to mismatch between the prescribed and achieved FAs, as well as between the assumed and actual T1 values. This mismatch results in signal variation between the shots, which leads to ghost artifacts. Using two extra shots in the VFA train calculation appeared to be a good compromise between artifact level and SNR. Imaging at the

**FIGURE 4** Motion experiments comparing 3D GRE with short and long TE, and 3D EPI. Prospective motion correction works quite well for all sequences in the case of rotation about the B0 field (yaw motion, third column). However, prospective correction of rotation perpendicular to B0 (pitch motion, last column) works only if the TE is short.

**FIGURE 5** Comparing different RF excitation strategies for interleaved snapshot EPI. The image SNR is maximized with the use of a variable flip angle train (VFA), tailored to the TR and an assumed T1 relaxation time. Deviation from the assumed T1 yields signal variation between the shots, which causes ghost artifacts (arrows). The sensitivity to T1 errors can be decreased by calculating the flip-angle train for a greater number of shots than prescribed. Using two “extra” shots resulted in an acceptable ghost level, while still providing a significant SNR advantage compared with a constant flip angle corresponding to the Ernst angle, which is SNR-optimal for steady-state imaging.
Ernst angle resulted in significantly lower SNR. Therefore, VFA calculated with two extra shots was used in the following interleaved snapshot EPI acquisitions.

Motion estimates from the second scan session are shown in Figure 6. Again, the timing and magnitude of the motion matched well between acquisitions with and without prospective motion correction. The range of the circular motion was about 8°.

A slice reconstructed without SWI processing for the 2D-EPI acquisitions is shown in Figure 7. For the standard 2D EPI, the acquisitions with motion showed severe artifacts, regardless of the application of prospective and retrospective motion correction. The consecutive shot order of interleaved snapshot EPI made the sequence much less sensitive to motion, as demonstrated by the uncorrected acquisition, which was greatly improved, albeit still blurry. This blur was considerably reduced by retrospective correction alone, and even more by prospective correction alone. The benefit of adding retrospective correction to the prospectively corrected acquisition was typically subtle, as demonstrated in Figure 7, although a greater improvement was seen in a few slices, presumably due to inaccuracies of the prospective correction. The combination of retrospective and prospective motion correction resulted in similar image quality as for the acquisition without motion.

Figure 8 shows images from the third scan session, demonstrating the effect of head pose on the SWI processing. The slices from the different acquisitions with different head poses were well aligned, as they were prospectively motion-corrected using the same reference position. Even though the varying head poses induced large phase differences between the acquisitions, the effect on the SWI filter was limited, as the low spatial frequencies had been removed. One SWI-processed average from each head pose was aligned with retrospective motion correction and combined with magnitude averaging (Figure 8B). The quality of the combined SWI image was similar to a corresponding motion-free image (Figure 8C), even though the head poses spanned 11.7°. The combined image demonstrated a subtle loss of sharpness seen in the frontal portion of the brain.

Another slice from the second scan session is shown in Figure 9, where SWI with interleaved snapshot EPI is compared with 3D EPI and 3D GRE. The 3D sequences did not tolerate the motion well, even when prospectively corrected. In contrast, interleaved snapshot EPI demonstrated much greater robustness to the motion. With both prospective and retrospective motion correction applied, the image quality of interleaved snapshot EPI was comparable with and without motion.

Figure 10 shows several slices from the tumor patient, comparing interleaved snapshot EPI to 3D EPI with matching spatial resolution. The patient did not move significantly in either acquisition (< 0.2°). The sequences display an evident difference in image contrast; although the interleaved snapshot EPI is purely T₂*-weighted, the 3D EPI shows additional T₁ weighting due to the combination of TR and FA. Both sequences appeared equally sensitive to susceptibility changes, and the lesion conspicuity was equal. Interleaved snapshot EPI showed more ghost artifacts in some slices.
4 | DISCUSSION

This work has investigated the potential of prospective motion correction for susceptibility-based imaging. It was shown that applying prospective correction alone to 3D imaging techniques is insufficient in the presence of rotational motion perpendicular to the B0 field (Figure 4). This applies for long-TE GRE imaging—the very same conditions that enable susceptibility contrast. Prospective motion correction has previously been combined with quantitative susceptibility mapping, but only small or involuntary motion was examined in the context of 7 T high-resolution imaging.6 The present study investigated more challenging motion patterns with the aim of enabling diagnostic SWI for patients who are likely to move.

When 3D SWI fails due to motion, a common clinical workflow is to acquire a (low-resolution) single-shot 2D-EPI T2*-weighted image instead. Such images are very motion-robust due to the snapshot quality of single-shot EPI, but are less sensitive to lesions such as cerebral microbleeds.3 This motivated us to aim for the motion robustness of single-shot EPI, the spatial resolution of multishot EPI, and the increased sensitivity of SWI. Our proposed solution is SWI based on 2D spoiled GRE interleaved snapshot EPI, which effectively averts motion-induced phase discrepancies by greatly reducing the temporal footprint of the acquisition of each slice. Interleaved snapshot EPI has previously been used for T1-weighted and T2*-weighted imaging,17 functional MRI,15,22,24 diffusion MRI, 25 and parallel imaging calibration,18 but not for SWI, to the best of our knowledge. The present work demonstrates that interleaved snapshot EPI in combination with prospective motion correction (aided by dynamic ghost correction) yields sharp SWI in the presence of large continuous motion. The sequence is, however, motion robust in itself, and therefore suitable for routine clinical imaging even when prospective motion correction is not available. A further advantage is that the sequence does not require any additional complicated reconstruction routines. The minimization of the temporal footprint requires a short (inner) TR to be used, which leads to low FA and low SNR for steady-state imaging. Therefore, it was found to be beneficial to use transient state imaging with a variable flip angle train,16 which aims to distribute all of the available longitudinal magnetization equally over the shots. Assuming some “extra” shots in the VFA train calculation poses a more conservative approach with lower artifact level at the expense of SNR (see Figure 5). Two extra shots were found to be a good trade-off, in agreement with the advice of McKinnon.16 Even with VFA transient state imaging, the SNR efficiency of interleaved snapshot EPI is significantly lower than for
standard 2D EPI and 3D EPI. The SNR could be further improved by signal averaging, which also enabled retrospective motion correction that could compensate for prospective correction flaws, as demonstrated in Figure 7. The long outer TR increases the probability of motion-induced phase mismatch between the averages, but this appeared tolerable, as the SWI processing was performed for each average separately before magnitude combination (Figure 8). We also implemented the option to acquire all averages for a slice before proceeding to the next slice, with a VFA train over all shots and averages. This, however, defeats the purpose of averaging, as the same amount of available longitudinal magnetization must be shared between the averages with only a minor SNR gain from $T_1$ recovery during the VFA train (results not shown).

An alternative sequence is short-axis propeller EPI, which has been proposed for motion-robust 3D SWI. The idea is that the amount of motion within each volumetric blade will be limited, but the duration of these “3D snapshot” is an order of magnitude longer compared with those of 2D interleaved snapshot EPI. Short-axis propeller EPI also suffers from lower scan efficiency due to frequent gradient ramping, and $B_0$ distortions that rotate with the blade angle.

Another approach to cope with motion is to simply acquire images faster. This reduces the opportunity for motion to

**FIGURE 8** Susceptibility-weighted image processing was performed separately for each signal average. A, The columns correspond to interleaved snapshot EPI averages, each acquired with a different head pose. The numbers indicate the estimated rotation about the x-, y-, and z-axes, relative to the reference pose in the leftmost column. Prospective motion correction assured consistency across acquisitions for the signal magnitude (first row), but the phase (second row) varied with head pose. Despite this, the SWI filter (third row, inverted contrast) remained quite consistent, as it only keeps the high spatial frequency content of the phase image. This resulted in consistent SWI-processed averages (last row). B, The SWI-processed averages shown in (A) combined with RMC. C, The combination of four SWI processed averages all acquired at the reference pose.
Even if shorter acquisition time is desirable in itself, this is not a satisfying solution, as devastating motion may still happen during the short acquisition (see, for example, the 39-second 3D EPI in Figure 9). Three-dimensional multislab SWI is also less motion sensitive, only by virtue of its shorter total acquisition time. In contrast, the sequence proposed here is fast, but can be prolonged without affecting its motion robustness. If, for example, thinner slices are acquired, the SNR loss can be compensated by adding more averages. Unlike for 3D imaging, the minimum slice thickness will be limited by the RF pulse. If a higher in-plane resolution is needed, it is probably useful to add more shots to keep a desired TE, although this will slightly increase the sensitivity to motion from intershot phase errors. In addition, the VFA train will need to distribute the available longitudinal magnetization over more shots, to the disadvantage of the SNR efficiency. This could be compensated by more averages, increasing the acquisition time.

For the prospectively corrected interleaved EPI sequences, artifacts related to intershot mismatch were observed. This can manifest as ghosting or more subtle shading, as seen in Figure 7. If this is due to imperfect ghost correction, improved algorithms could be used, or the problem could be avoided by prospectively updating the interleaved snapshot EPI once per slice rather than each shot, at the cost of increasing the prospective update interval from 0.05 seconds to 0.2 seconds. Another possibility is that the mismatch is an effect of the nonrectangular slice profile, accumulating an error over the course of the VFA train. Deeper investigation of this issue, however, was considered to fall outside the scope of this work.

An evident difference in image contrast can be noted when comparing the interleaved snapshot EPI to the other sequences (Figure 10); most conspicuously, fluid appears much brighter. This is explained by the absence of $T_1$-weighting; not much $T_1$ contrast builds up during the 0.2-second RF
train, whereas full $T_1$ recovery is permitted during the 11-second outer TR. Although not investigated in detail here, the contrast between fluid and soft tissue may impair the conspicuity of vessels or lesions at fluid/soft tissue interfaces, due to partial-volume effects. In the tumor patient, the lesions were equally well depicted by interleaved snapshot EPI and 3D EPI, despite this difference in contrast. If desired, an SWI contrast similar to the other sequences can be achieved by acquiring the slices in several concatenations to lower the outer TR, or by suitable magnetization preparation pulses. Both approaches would result in an SNR reduction.

Beyond bulkhead movement, phase errors due to spatio-temporal field changes may also be induced by other movements or physiological motion such as breathing. Although the proposed snapshot SWI approach primarily avoids these phase errors by minimizing the temporal footprint, the dynamic ghost correction also inherently provides zero-order and first order-phase correction in the frequency-encoding direction. Several alternative approaches have been developed, primarily for susceptibility-based imaging at 7 T, in which respiratory-induced field changes are significant. The field changes may be measured using multichannel FID navigators, respiratory signal correlated to a reference scan, NMR field probes, navigator echoes, image navigators, or the mismatch between image data and coil-sensitivity profiles. Correction may then be implemented by real-time shimming or retrospectively during reconstruction. Although, many of these approaches are limited to low-order spatial correction, which has been suggested to be insufficient to counter the effects of head movement. The volumetric navigator approach by Liu et al enables phase correction at 4-mm isotropic resolution every 0.5 seconds, which could retrospectively correct involuntary motion and intentional stepwise motion for $T_2$*-weighted 3D GRE at 7 T. However, volumetric navigators may require complex reconstruction schemes, and would significantly increase the acquisition time if combined with an EPI-based main sequence. Alternatively, intershot phase errors can be incorporated into advanced parallel-imaging reconstruction algorithms such as multiplexed sensitivity encoding, which has previously been successfully combined with prospectively motion-corrected DWI.

A different approach is to predict field changes based on the estimated motion to correct the image retrospectively. This is feasible if a susceptibility map of the subject is available, although this is generally not the case. There are also sophisticated approaches to estimate motion-induced field changes from the actual data. This has been demonstrated for distortion correction of diffusion-encoded data, but relies on estimating field changes between volumes rather than between shots, and is therefore not applicable to the problem at hand.

**FIGURE 10** A 52-year-old patient with a previously operated and radiated oligodendroglioma was imaged with resolution-matched SWI based on 3D EPI and interleaved snapshot EPI, respectively. The interleaved snapshot EPI had no $T_1$-weighting, which made the operation cavity seen in the left frontal lobe on the top two rows appear hyperintense. The extension of metal artifacts from the craniofix (signal void) is similar for both sequences, and their depiction of tumor calcifications in the basal ganglia and septum pellucidum (arrows, second row) is equal. The conspicuity of punctate radiation-induced microhemorrhages in the cerebellar hemispheres (bottom row, solid arrows) is also equal, although ghost artifacts are seen for interleaved snapshot EPI (dashed arrows).
5 | CONCLUSIONS

The present study showed that susceptibility-based imaging can be severely corrupted by motion-induced phase errors caused by spatiotemporal $B_0$ field changes. Therefore, prospective motion correction alone is insufficient for SWI in the presence of substantial head motion.

These errors can be avoided by interleaved snapshot EPI, as the temporal footprint of each slice is short compared with the rate of spatiotemporal $B_0$ field changes, even in the presence of continuous head motion. This makes interleaved snapshot EPI robust to motion with fast acquisition and simple image reconstruction, and therefore offers improved availability of susceptibility contrast for patients prone to move, even when prospective motion correction is not available. When combined with prospective and retrospective motion correction, interleaved snapshot EPI enables SWI insensitive to motion. Although the snapshot property is gained at the expense of SNR and the minimum slice thickness will be limited for 2D sequences, interleaved snapshot EPI is a superior alternative for susceptibility-based imaging of patients inclined to move.

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**SUPPORTING INFORMATION**

Additional Supporting Information may be found online in the Supporting Information section.

**VIDEO S1** Prospectively corrected real-time single-slice single-shot gradient-echo EPI (TE = 35 ms). The corresponding rotational motion estimates are shown on the left with the current frame indicated by the vertical line. The center panel shows the phase-difference image relative to a reference frame in cyclic pseudo-color, and the magnitude image is shown on the right. In this acquisition, there was no intentional motion.

**VIDEO S2** Like Supporting Information Video S1 but with intended “pitch” motion (rotation about the x-axis). The large motion induced strong phase fluctuation, primarily in the anterior–posterior direction.

**VIDEO S3** Like Supporting Information Video S1 but with intended “roll” motion (rotation about the y-axis). The large motion induced strong phase fluctuation, primarily in the left–right direction.

**VIDEO S4** Like Supporting Information Video S1 but with intended “yaw” motion (rotation about the z-axis). In this case, the phase fluctuations were smaller, as the head orientation relative to the B0 field was relatively intact.

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