T1-FLAIR imaging during continuous head motion: Combining PROPELLER with an intelligent marker

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Purpose: The purpose of this work is to describe a T1-weighted fluid-attenuated inversion recovery (FLAIR) sequence that is able to produce sharp magnetic resonance images even if the subject is moving their head throughout the acquisition.

Methods: The robustness to motion artifacts and retrospective motion correction capabilities of the PROPELLER (periodically rotated overlapping parallel lines with enhanced reconstruction) trajectory were combined with prospective motion correction. The prospective correction was done using an intelligent marker attached to the subject. This marker wirelessly synchronizes to the pulse sequence to measure the directionality and magnitude of the magnetic fields present in the MRI machine during a short navigator, thus enabling it to determine its position and orientation in the scanner coordinate frame. Three approaches to incorporating the marker-navigator into the PROPELLER sequence were evaluated. The specific absorption rate, and subsequent scan time, of the T1-weighted FLAIR PROPELLER sequence, was reduced using a variable refocusing flip-angle scheme. Evaluations of motion correction performance were done with 4 volunteers and 3 types of head motion.

Results: During minimal out-of-plane movement, retrospective PROPELLER correction performed similarly to the prospective correction. However, the prospective clearly outperformed the retrospective correction when there was out-of-plane motion. Finally, the combination of retrospective and prospective correction produced the sharpest images even during large continuous motion.

Conclusion: Prospective motion correction of a PROPELLER sequence makes it possible to handle continuous, large, and high-speed head motions with only minor reductions in image quality.

KEYWORDS
brain, motion correction, magnetic resonance imaging, PROPELLER, T1-FLAIR, wireless radiofrequency triggered acquisition device
1 | INTRODUCTION

Fast spin-echo– (FSE-) based $T_1$-weighted fluid-attenuated inversion recovery ($T_1$-FLAIR) is one of the key contrasts used to image the central nervous system. Its suppression of signal from cerebrospinal fluid and strong contrast between gray matter (GM) and white matter (WM) improves anatomical assessments.

However, in the clinical setting, patient motion is a recurrent challenge, especially for pediatric and uncooperative patients. Motion (and flow) artifacts can be mitigated by acquiring the $T_1$-FLAIR images using the PROPELLER\(^1\) (periodically rotated overlapping parallel lines with enhanced reconstruction) method,\(^2\)-\(^8\) which has retrospective motion correction (RMC) capabilities. However, a problem for PROPELLER is out-of-plane motion, which cannot be fully corrected.\(^9\) Additionally, an issue for 2-dimensional (2D) inversion sequences, in general, is that motion causes a mismatch between the inverted slice and the imaged slice. This creates spin history effects that can undo the contrast and cause signal loss.

To acquire $T_1$-FLAIR images during rapid and large head movements, and alleviate the issues of out-of-plane motion, as well as slice mismatches, we propose combining the RMC of the PROPELLER method with prospective motion correction (PMC), using a wireless radiofrequency triggered acquisition device (WRAD)\(^10\),\(^11\). The idea being that the PMC would take care of a majority of the motion, and the RMC could then deal with residual errors. Such a combination of RMC and PMC has previously proven to be synergistic.\(^12\)-\(^15\)

The PMC updates were integrated into the sequence using 3 different approaches and the combination of RMC with PROPELLER and PMC using the WRAD was evaluated on 4 volunteers with a variety of motion patterns.

Furthermore, to facilitate efficient acquisitions of the $T_1$-FLAIR PROPELLER sequence, at 3T, its specific absorption rate (SAR) penalties were avoided using a variable refocusing flip-angle scheme.

2 | METHODS

2.1 | The wireless radio-frequency triggered acquisition device

The WRAD is a small battery-powered device that can be attached to the subject to measure rigid body motion. For the experiments presented here, the WRAD was mounted to a small sled that rests on the bridge of the subject’s nose, as illustrated in Figure 1.

A short navigator lasting 4.2 ms was used to encode the pose of the WRAD. As previously described in van Niekerk et al,\(^10\) each navigator consists of a series of short sinusoids that are played out sequentially on the x-, y-, then z-gradient axes (Figure 1; WRAD module). The WRAD measures these waveforms through induction, using a 3D pickup coil, and

![Figure 1](image-url)
then combines them with an observation of the direction of the static magnetic field, obtained from a 3D magnetometer, to compute its instantaneous position and orientation.\textsuperscript{10} The longer duration of 4.2 ms used here, as compared with 880 $\mu$s in Niekerk et al.,\textsuperscript{10,11} consists of 3 cycles of each sinusoid at a reduced frequency of 3.9 kHz. This reduced variance in the pose estimates allowed the motion updates to be applied directly (unfiltered) with negligible “measurement” latency.

Each WRAD module, or block, starts with 2 small opposed phase radiofrequency (RF) pulses (Figure 1; WRAD module). These pulses are detected by the WRAD using an RF detection circuit and used to synchronize its analog-to-digital converters to the MRI scanner hardware.\textsuperscript{10} The pose measurements produced by the WRAD are, therefore, synchronous to the pulse sequence allowing a fixed update latency that is well-defined with respect to when the imaging data were acquired.

For the present work, it was important to determine the time required for an update to be available to the pulse-sequence-generation software. This is because, in some cases (as discussed in the following section), it was necessary to wait for the most recent pose update (effectively inserting dead time into the pulse sequence). Minimizing this period, therefore, reduces the impact on the pulse sequence duration and improves update accuracy through reduced latency, particularly in the case of continuous motion.

To this end, a counter on the WRAD was incremented each time an RF pulse was detected. This value was appended to each motion measurement sent to the pulse sequence. Similarly, the pulse sequence was programmed to keep track of the number of RF pulses played-out up to that point. The dead time was then decreased until there was a mismatch between the 2 RF pulse counters (the point at which the feedback was too slow). Successful feedback within 1.5 ms was achieved. This did, however, result in the scanner crashing for some protocols: It was particularly sensitive to changes in the echo train length (ETL). A compromise of 3 ms was found robust to changes in the protocol and allowed a margin for a reattempt of lost transmissions (after 500 us of not receiving an acknowledgement after transmitting a motion measurement) over the wireless link. This value was used for the remainder of this text.

The $T_1$-FLAIR PROPELLER and WRAD pulse sequences were implemented using the KS Foundation framework.\textsuperscript{16}

### 2.2 Sequence updating strategy

The pulse sequence can be divided into 3 main building blocks: the readout block (including excitation), the WRAD block, and the adiabatic inversion block. In this case, the inversion blocks were interleaved between the readout blocks.\textsuperscript{17}

The WRAD sequence blocks were incorporated into the sequence employing 3 approaches listed from largest to smallest impact on the pulse sequence duration:

A. A WRAD block was inserted before each inversion block and readout block. Additional dead time was added after the WRAD block to allow field of view (FOV) updates to come back and be applied to the coming block, whether it is the inversion or the readout block (Figure 2A).

B. A WRAD sequence block, including dead time, was inserted only before each inversion block, and updates were applied to the immediate inversion block and the

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**FIGURE 2** Depicting 3 strategies to insert the wireless radiofrequency triggered acquisition device (WRAD) module into the sequence. The blocks are depicted to scale. Arrows show where the WRAD updates are applied. A. Strategy A, where the inversion and readout blocks are updated with minimal delay between estimation and application. B. Strategy B, where one WRAD module produces estimates for both the following inversion and readout block. C. Strategy C, where the inversion block is used to wait for the estimations, instead of adding extra dead time. This prolongs the time between measuring and applying motion estimates (red arrow) for the inversion block. D. The sequence without any addition of WRAD modules. Note that the slice position of the inversion and the following readout is different.
readout block after it (Figure 2B). This provides a compromise between update frequency and prolonging the total scan time.

C. The WRAD block was inserted before each inversion block, and the FOV updates were applied to the next readout block and the following inversion block, using the inversion block just after the WRAD block as wait time for the feedback loop (Figure 2C). This removes the dead time needed for the updates to come back. Nevertheless, it prolongs the time between estimating the head position and updating the inversion slice position by one readout block.

The three approaches are depicted in Figure 2.

2.3 | The echo train

Each PROPELLER blade was acquired in a single shot, avoiding shot-to-shot differences in FOV and phase accumulation, thus making the individual blades as robust against artifacts as possible. To keep the echo time (TE) low enough for $T_1$-weighting, the PROPELLER acquisition was accelerated without the use of ACS lines similar to Holmes et al., except each blade was reconstructed using an orthogonal blade (ie, a blade with an angle differing by 90°) for generalized autocalibrating partially parallel acquisitions (GRAPPA) calibration, instead of acquiring additional data. Although both blades, in an orthogonal pair, were undersampled in their respective phase-encoding direction, their frequency-encoding directions provide fully sampled k-space points in each other’s undersampled directions. This can be utilized to calibrate the respective GRAPPA kernel weights. This maximizes the effective in-plane acceleration, while avoiding calibration overhead. The orthogonal blades were acquired consecutively, minimizing the time, and therefore also the risk of motion, between calibration data and target data.

2.4 | Avoiding specific absorption rate constraints

Interleaved inversion recovery sequences employing adiabatic inversion pulses and acquired with FSE are often limited by SAR constraints because many high-power RF pulses are generated back-to-back. Dead times can be inserted to decrease heating; however, this increases total scan time and the risk of patient movement during the scan. Another option to reduce SAR is to lower the refocusing flip angles (FAs). A common strategy is a constant FA train preceded by a ramp. Another option, which can preserve more signal-to-noise ratio (SNR), is to use the transitions between pseudo-steady-states (TRAPS) method.

Here, we used the TRAPS design with sinusoidal ramps. The TRAPS FA scheme starts with a ramp down, then up again to the center echo, and then it ramps down again (Figure 3A). It can be described by 6 parameters; $n_1$, $n_2$, $n_4$, $\alpha_1$, $\alpha_2$, and $\alpha_4$. Where the $n$s set the turning points and the $\alpha$s are the FAs at the corresponding turning points. By changing these parameters, the signal response and the SAR of the FA scheme can be controlled. The TRAPS parameters in this work were heuristically chosen to produce a SAR that did not limit the sequence (eg, no dead times needed).

![Figure 3](image_url)
2.5 | Reconstruction

A PROPELLER trajectory covers k-space by acquiring rectangular stripes (ie, blades) rotated about the k-space center. Because all blades cover the k-space center, it is possible to correct for motion between them, before combining them into a single image.

The reconstruction starts with parallel imaging and phase-correction stages. The phase correction entailed the removal of the low-frequency phase using a triangular window as described in the study by Pipe.24 Next, the multichannel data were combined using the adaptive coil combination method.25 Rigid-body motion correction between the blades and a reference was then performed in image space, independently within each slice. As a reference, the blade slice (eg, a slice within a blade-angle-slice stack) that deviated the least from the mean of all blade slices was chosen. A sum-of-squares metric was used with a registration algorithm taken from the SPM5 (statistical parametric mapping 5) package,26 with the motion estimates restricted to 3 parameters; x and y translations and z rotation. Care was taken to initialize the search function with the blade angles incorporated in the rotational matrix. The blades were then resampled, using B-spline interpolation, to their new positions and orientations, retaining their rectangular pixels. This was followed by data rejection, where blade slices that were either corrupted by artifacts or not aligned properly are discarded. Such blade slices were found by measuring their structural similarity27 to a reference, with a threshold set to 0.6. Just as the previous reference, the blade slice that deviated the least from the mean of all blade slices was chosen. Care was taken not to discard blade angles in a way that would create empty wedges at the edges of k-space and a limit on the number of discarded blade slices was set close to 25%. Finally, the remaining blade slices were Fourier-transformed back to k-space for the final gridding of the data into a single full-resolution image volume.

2.6 | EXPERIMENTS

2.6.1 | Refocusing flip-angle schemes

For the TRAPS FA scheme used in the subsequent experiments with an ETL of 15, the parameters were: \( n_1 = 3 \), \( n_23 = 8 \), \( n_4 = 15 \), \( \alpha_1 = 65^\circ \), \( \alpha_{23} = 115^\circ \), and \( \alpha_{4} = 70^\circ \). This scheme was simulated in MATLAB (MathWorks Inc, Natick, MA) using an extended-phase graph (EPG)28 algorithm developed by Weigel.29 The initial magnetization, at excitation, was calculated using the Bloch signal equations. The FAs were simulated for GM and WM relaxation times: \( T_{1GM} = 1331 \) ms, \( T_{1WM} = 832 \) ms,30 \( T_{2GM} = 122 \) ms, and \( T_{2WM} = 92 \) ms31; also including the relative proton density: \( k_{GM} = 1.0 \) and \( k_{WM} = 0.9,32 \).

The SAR relative to an IR sequence employing a refocusing FA scheme consisting of only 180° refocusing pulses (\( \Phi_{SAR} \)) can be estimated using the following equation22:

\[
\Phi_{SAR} = \frac{1}{3.8 + 0.25 + ETL} \cdot \left( 3.8 + 0.25 + \sum_{i=1}^{ETL} \left( \frac{\alpha_i}{180^\circ} \right)^2 \right)
\]

where ETL is the echo train length and \( \alpha_i \) is the refocusing FA number \( i \) in the train. The adiabatic IR pulse used in the sequence had a power deposition 3.8 times higher than one 180°-refocusing pulse (the excitation pulse had a lower power deposition of 0.25 times). The TRAPS scheme was compared with a constant FA train with the same SAR and one with higher FAs, 82° and 120°, respectively. The results are presented in Figure 3B.

2.6.2 | Imaging during motion

Four volunteers were included in the study under a ethical approval issued by the Swedish Ethical Review Authority. They were imaged both laying still and moving their heads, with and without applying PMC. To get repeatable motion patterns, they were instructed to follow a moving crosshair displayed on a screen, observed through a mirror mounted on the receive coil.

The \( T_1 \)-FLAIR PROPELLER data sets were acquired in 3 acquisitions, using a standard interleaved slice order. This allowed the inversion slice thickness to be wider than the imaged slice, thereby saturating the signal from flowing cerebrospinal fluid.33 The inversion slice thickness was, however, only increased by 50% for this purpose. The remaining space was used to create a buffer, avoiding unnecessary saturation of neighboring slices when rapid motion occurs between PMC updates.

2.6.3 | Evaluating the update strategies

To compare the 3 update strategies, 1 volunteer was imaged 4 times, in each case with a different strategy, but repeating the same movement pattern, 3 times with FOV updates and 1 without. The subject was instructed to move according to a circulating crosshair, effectively drawing a circle in the air with their nose. To clearly see the effects of update latency, the speed of the crosshair was set to 1 revolution every 5-second interval. A reference was also acquired while the volunteer lay still, without FOV updates. The resulting images are presented in Figure 4.

Relevant sequence parameters and settings were: \( TE = 52 \) ms, number of blades = 22, acceleration factor = 3, ETL = 15, slice thickness = 4 mm, and pixel size = 0.7 × 0.7.
A detailed description of all sequence parameters can be found in Supporting Information Table S1. Update strategy A resulted in a pulse repetition time (TR) of 2103 ms with a total scan time of 2:25 minutes, whereas update strategy B resulted in a TR of 1967 ms and a total scan time of 2:15 minutes. Finally, update strategy C led to a TR of 1922 ms and a total scan time of 2:13 minutes. Without any WRAD modules inserted, corresponding to Figure 2D, the TR was 1857 ms with a scan time of 2:08 minutes.

2.6.4 | High-resolution acquisition

To investigate if PMC with the WRAD could potentially degrade image quality when the subject is still, a higher resolution T1-FLAIR PROPELLER data set was acquired with (Figure 5B) and without PMC (Figure 5A) and reconstructed with and without RMC. Update strategy A was used in this case. The enlarged versions of the results are presented in Figure 5C. Relevant sequence parameters and settings were: TI = 842 ms, TR = 2108 ms, TE = 51 ms, number of blades = 38, acceleration factor = 3, ETL = 13, slice thickness = 3 mm, pixel size = 0.5 × 0.5 mm², and a scan time of 4:19 minutes. Remaining sequence parameters can be found in Supporting Information Table S2.

2.6.5 | Different motion patterns

Three volunteers were imaged while performing 1 of 3 movement patterns intended to produce large head movements, in each case following the crosshair across the screen. For each type of motion, 2 images were acquired: one with PMC on and the other with PMC updates off. The 3 movement patterns were:
1. Yaw: A continuous left–right motion where the crosshair moved back and forth across the screen every fifth second. It was used to compare the PROPELLER RMC with the PMC. The pattern was designed to minimize the occurrence of out-of-plane motion because the RMC cannot correct for it.

2. Stepwise: Every third second the crosshair moved to a new unpredictable position anywhere on the screen. The same positions and ordering were used for each repetition of this pattern. This pattern was used to evaluate the RMC and PMC combination during large translation and rotational motion along and around all directions.

3. Circular: The crosshair continuously moved in a circle with one revolution every 5-second interval. The same pattern was used for the evaluation of the update strategies. This pattern was designed to push the limits of the proposed motion correction approach, both in terms of speed and range of motion.

All acquisitions employed update strategy A, using the same sequence parameters and settings described for the evaluation of the update strategies. A reference was acquired while the volunteer was lying still, with PMC updates turned off. The resulting images and the corresponding PMC estimates are displayed in Figures 6, 7, and 8.
FIGURE 6  Results from the yaw motion experiment. A, Images acquired with prospective motion correction (PMC), with and without retrospective motion correction (RMC), and the corresponding PMC motion estimates. B, Reference images acquired when the subject was still. C, Images acquired without PMC updates, with and without RMC. Also, the motion estimates reported by the wireless radiofrequency triggered acquisition device (WRAD). D, Enlarged views of the resulting images. The pink arrows point to a fold that is identical on all images.

FIGURE 7  Results from the stepwise motion scans. A, Images acquired with prospective motion correction (PMC) updates (with and without retrospective motion correction [RMC]) and the motion estimates to the left. B, Reference image acquired when the subject remained still. C, Images acquired without PMC updates (with and without RMC) and the corresponding motion estimates. D, Enlarged images, showing the external capsule. The pink arrows point to anatomical differences between the RMC only image and the rest.
The experiments were carried out with a GE 3T SIGNA Premier MR system (GE Healthcare, Waukesha, WI), employing a 48-channel head coil.

3 | RESULTS

3.1 | Refocusing flip-angle scheme

The $\Phi_{\text{SAR}}$, defined in Equation 1, was 0.4 for the TRAPS and the constant 82° schemes; it was 0.58 for the constant 120° scheme. If the 120° scheme was to be used with the set-up used in the motion experiments, it would lead to a scan time of 3:50 minutes, a 59% increase caused by SAR penalties. In the simulation, the TRAPS scheme produced higher signal amplitudes around the central echoes than both constant schemes (Figure 3B).

3.2 | Evaluating the update strategies

The increase of scan time for update strategies A, B, and C were: 17 seconds (13%), 7 seconds (6%), and 5 seconds (4%), respectively.

The readout block was 125-ms long and the inversion block was 13 ms. This means that with update strategy C the inversion got a 142-ms old-motion estimate, whereas with update strategy B the readout block got a delayed estimate of only 16 ms.

Using strategy B produced slightly blurry images (Figure 4B) compared with the reference (Figure 4D) and the SNR was lower. With strategy A (Figure 4A), the sharpness is almost the same as the reference, nevertheless, the SNR was reduced to the same level as B. The delay of strategy C (Figure 4C) caused a large loss of contrast predominantly in the front of the brain. Some GM–WM matter contrast remains in the posterior to the frontal plane, closer to the center of rotation. The structures in the brain are, however, as sharp as when using strategy B.

The PROPELLER RMC rejected 24% of the blade slices acquired with strategy A, 26% with strategy B, and 27% with strategy C. In total, there were 858 blade slices in each acquisition and 27% (eg, 6 of 22 blade angles) was the upper limit for the rejection rate. The rejection rate of strategy C reached 27%, regardless of the upper limit.

Update strategy A was used for the remaining experiments presented in this work as the 17-second time penalty seemed reasonable for the added sharpness compared with strategy B.

3.3 | High-resolution acquisition

Even though the motion estimates were applied unfiltered, the high-resolution images show that PMC with the WRAD does not notably degrade the image quality. The level of detail appears to be the same for all images. The RMC performed similarly to the PMC in this case and had no visible effect on the already prospectively corrected images.
3.4 | Different motion patterns

In all cases, the repeated motion patterns resulted in equivalent motion estimates, suggesting that the volunteers were able to repeat the same motion with the help of the moving crosshair. To better visualize the amount of movement in each case, the motion estimates were applied to a 3D-head model, together with the movies showing the moving crosshair. This movie is provided as Supporting Information Video S1.

3.5 | Yaw

For the yaw (left–right) motion, the subject moved in a range of 13° according to the WRAD motion parameters. The translation range was merely 2 mm in the z direction. Moreover, the WRAD, at its position on the nose, was moving at a root-mean-squared speed of 6.9 mm/s throughout the acquisition.

The PROPELLER RMC (Figure 6C) was able to recover the image just as well as the PMC (Figure 6A) for this type of motion, both indistinguishable from the reference (Figure 6B). Showing that for this particular case the PROPELLER and the WRAD produce equivalently accurate motion estimates. The combination of RMC and PMC did not improve the images significantly, which can be appreciated in the enlarged images of Figure 6D. In both cases (PMC on and off) the PROPELLER RMC rejected 4% of the blade-slices. As before, there were 858 blade-slices in total for each acquisition, and 27% was the upper limit for the rejection rate. All blade-slices that make-up the images of Figure 6 are shown in Supporting Information Figure S1. The motion estimated by the PROPELLER RMC is shown in Supporting Information Figures S2 and S3.

3.6 | Stepwise

In the stepwise motion case, the motion updates to the FOV showed a range of motion close to 17-mm translation and 20° rotation. Moreover, it moved at a root-mean-squared speed of 13.4 mm/s.

Here, the RMC image remains largely blurry and anatomy from different slice positions have been mixed into the slice (pink arrows in Figure 7C). On the contrary, the PMC retained much more image sharpness (Figure 7A). Still, the PMC and RMC combination was able to add some additional detail, bringing it close to the quality of the reference (Figure 7B). This can also be observed in Figure 7D, where the external capsule regained sharpness. The PROPELLER RMC rejected 27% of the blade slices acquired without PMC and 10% for the PMC case. All blade slices that make-up the images of Figure 7 are shown in Supporting Information Figure S4.

The residual motion estimated by the PROPELLER RMC is shown in Supporting Information Figure S5.

3.7 | Circular

Finally, the continuous circular motion pattern caused a range of motion between 16° rotation and 7-mm translation of the FOV. The WRAD reported a root-mean-squared speed of 20.3 mm/s at its position on the bridge of the nose.

In this severe case, the RMC alone failed (Figure 8C), whereas the PMC was able to regain most of the image sharpness (Figure 8A). In each case, the best result was with a combined RMC plus PMC approach (Figure 8D). Nonetheless, the motion in this case also caused some signal loss in the front of the brain and parallel-imaging artifacts, compared to the reference (Figure 8B). The PROPELLER RMC rejected 27% of the 858 blade slices in both cases (with and without PMC). The blade slices making-up the images in Figure 8 are shown in Figure 9, where the level of degradation can be appreciated. The residual motion estimated by the PROPELLER RMC is shown in Supporting Information Figure S6.

4 | DISCUSSION

We have, in this work, combined the PROPELLER technique with prospective motion correction using the WRAD. T1-FLAIR images were acquired using a TRAPS refocusing FA scheme that eliminated the need for wait periods in the sequence caused by SAR limits. We evaluated how and when to insert the WRAD block and apply its FOV updates. The results showed that as often and with as short a delay as possible, update strategy A produced the sharpest images while increasing scan time by only 13%. Three large motion-pattern types were used to evaluate this new sequence, showing that imaging during extreme continuous motion resulted in only minor artifacts and SNR losses, in relation to the amount of motion.

4.1 | The update strategies

The complete loss of GM–WM contrast in the T1-FLAIR images, when using update strategy B, shows how important the update latency of PMC is when the subject is moving quickly. The FOV updates applied to the inversion slice were only 142-ms old, but saturation of the neighboring slice positions or misalignment between the inverted slice and the imaged slice still occurred. This is in agreement with Frost et al., where an increased PMC update frequency was shown to significantly improve the motion correction quality during continuous movement.
In some cases, PMC has been shown to improve image quality for long acquisitions. However, we see no clear improvement here, either with RMC, PMC, or RMC and PMC combined, most likely because the PROPELLER trajectory has an inherent tolerance to motion because the center of k-space is heavily oversampled. Also, the involuntary motion was slightly larger for the image acquired without PMC.
4.3 Retrospective motion correction and prospective motion correction

The RMC on its own was able to correct for in-plane movements; however, as soon as there was any out-of-plane motion, the resulting images consisted of a mix of several different slice positions and substantial loss of contrast. Rejecting blade slices could not remedy this; there were too many different head poses during the acquisition and only a few (27%) blade slices could be rejected, while avoiding empty wedges at the edges of k-space. However, in combination with PMC, the RMC successfully improved the image sharpness for the stepwise and circular motion scans. These results are in agreement with earlier exploits.14,15

During these high-speed movements (13.4 and 20.3 mm/s), a considerable amount of movement (a few millimeters and degrees) between the WRAD’s estimation of the head position and the head position when central k-space was acquired, is to be expected. This seems to roughly correspond to the range of residual motion corrected by the RMC, implying accurate WRAD estimates.

Looking at the residual motion estimates of Supporting Information Figures S3, S5, and S6, slices at the very top of the head produced lower quality estimates. Here, any through-plane motion has the largest impact because these slices are far from the center of rotation. Therefore, the RMC tries to compensate for the small unavoidable out-of-plane motion. Furthermore, at the top of the head, fewer anatomical structures can be used to drive the optimization algorithm.

4.4 Prospective motion correction and GRAPPA

For PMC scans, the goal is to keep consistent anatomy within a slice even when the subject is moving. In contrast, when updating the position of the FOV to follow the anatomy, the receive coil and the corresponding coil sensitivities appear to move instead. This can complicate parallel imaging reconstructions because they rely on the coil sensitivities being the same for the calibration data and the accelerated data.37

The orthogonal blade GRAPPA calibration has the benefit that the calibration and accelerated data are acquired closely in time, and therefore with a similar set of coil sensitivities. Nonetheless, the blades contributing to each slice are separated in time by one TR (around 2 seconds in this case) and it is possible that the subject has moved a significant amount during this time. This could result in differing coil sensitivities between the slices in the orthogonal blades and in turn suboptimal GRAPPA reconstruction.

In the case of the circular motion scan, the speed was high enough for this effect to cause increased noise and fold-in artifacts. There were fold-in artifacts in the stepwise-motion dataset as well, however, to a much lower degree (see Supporting Information Figure S4). Fortunately, the phase-encoding direction is different for all blades in a PROPELLER acquisition, and the artifacts were spread out across the FOV (Figures 8 and 9). This issue has previously been addressed by incorporating the applied PMC updates into the GRAPPA reconstruction and resampling the calibration data.37 For a PROPELLER trajectory, this could be done with an external calibration volume or blade, instead of the orthogonal blade GRAPPA calibration.18,38 Nevertheless, the orthogonal calibration is deemed to be sufficient for most naturally occurring motion patterns.

4.5 Signal-to-noise loss caused by motion

Refocusing using low FAs has been shown to lose more signal because of flow and motion during the echo train than higher refocusing FAs.39 This is because the signal relies partly on stimulated echo pathways to converge, and if the tissue is flowing or moving during the refocusing train the pathways are broken. However, the FAs used in this work were high enough for this effect to be small and the ETL was short compared with the 3D rapid acquisition with relaxation enhancement (RARE) sequences where this effect has been observed. In any case, there is a visible signal loss on the images acquired during the circular motion. During this motion pattern, the forehead would be the fastest moving part of the brain (around 20.3 mm/s) and it is in this region that the signal loss is the most obvious. The signal loss could also come from a discrepancy between the excited slice and the slice being refocused. A final reason for signal loss could be magnetization history effects from previously misaligned RF pulses. However, it is not clear if the loss of SNR is caused by suboptimal GRAPPA reconstruction, also caused by the fast motion (as discussed above), excitation and refocusing slice mismatch, magnetization history, broken echo pathways, or a combination of these effects. By looking at how the signal is lost in segments with straight edges (green arrow points out an example in Figure 9D), the most likely reason is the misalignment of excitation and refocusing slices. This could be mitigated by increasing the slice width of the refocused relative to the excited slice.

4.6 TRAPS

The SAR limitations were effectively removed by using the TRAPS refocusing FA scheme. The scan time saved reduces the probability of motion to occur during the scan, as well as shortening the overall protocol in which it will be included.
This is important for patient groups that typically have a hard time keeping still for a long time (e.g., children).

4.7 | Data rejection

The faster movements, stepwise and circular, damaged the data enough for the RMC to discard the maximum number of blade slices. Employing PMC reduced the rejection rate from 27% to 10% for the stepwise case. But the movement speed of the circular motion was high enough that the number of blade slices damaged remained above the threshold of 27%, even with PMC. In the case of the yaw pattern, there was no out-of-plane motion for the PMC to correct; therefore, the rejection rate was low (4%) and the same for PMC on and off.

The rejection algorithm could potentially benefit from information about how much motion occurred during each shot, which can be obtained from the WRAD estimates. Consequently, this could be an additional utility of combining PMC with RMC.

4.8 | Outlook on the future

The presented technique could easily be extended to include all contrasts acquired with FSE-based PROPELLER trajectories for example; T2-weighted and T2-weighted FLAIR and all contrasts acquired with FSE-based PROPELLER trains might benefit from intratrain FOV updates.

The combination of retrospective and prospective motion correction, with PROPELLER and the WRAD, could enable imaging of patient groups that are otherwise excluded. Most notably, children could potentially be imaged while watching a movie and be allowed to move almost freely within the confines of the receive coil.

5 | CONCLUSION

In this work, we have shown that sharp T1-FLAIR images can be acquired during extreme head motion by combining prospective and retrospective motion correction, for example, using the PROPELLER method together with the WRAD. Estimating the position of the head and applying the FOV updates before each inversion and excitation (update strategy A) produced the best results. The T1-FLAIR PROPELLER sequence was efficiently acquired by the use of a TRAPS refoCUSing FA scheme, which removed any SAR penalties to the scan time.

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**SUPPORTING INFORMATION**

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

**FIGURE S1** Showing all blade-slices making up the images of Figure 6, acquired during the yaw-motion pattern. (A) Acquired without PMC and RMC. (B) Acquired without PMC, with RMC. (C) Acquired with PMC, without RMC. (D) Acquired with PMC and RMC. (E) Reference acquired while the subject was still. Red crosses mark blade-slices that were discarded.

**FIGURE S2** Showing the PROPELLER RMC estimates for all the blades for each slice. The data corresponds to the RMC image in Figure 6C, which shows the images acquired during the yaw-motion without PMC updates. The mean range of translation estimated by the RMC was 12 mm and the mean range of rotation was 11°. The top slice has been excluded since it was acquired above the head and contained only noise. Each slice has its own reference blade, marked with a cross, which all other 21 blades (in that slice) are registered to.

**FIGURE S3** Showing the residual PROPELLER RMC estimates for all the blades for each slice. The data corresponds to the PMC+RMC image in Figure 6A, which shows the images acquired during the yaw-motion with PMC. The mean range of translation estimated by the RMC was 1 mm and the mean range of rotation was 1°. The top slice has been excluded since it was acquired above the head and contained only noise. The y-axis range was chosen to match that of the plots in Figure 6. Each slice has its own reference blade, marked with a cross, which all other 21 blades (in that slice) are registered to.

**FIGURE S4** Showing all blade-slices making up the images of Figure 8, acquired during the stepwise motion pattern. (A) Acquired without PMC and RMC. (B) Acquired without PMC, with RMC. (C) Acquired with PMC, without RMC.
(D) Acquired with PMC and RMC. (E) Reference acquired while the subject was still. Red crosses mark blade-slices that were discarded. The pink arrow points to a blade-slice that would have been discarded because of its signal loss. However, since the neighboring blade-slices have even worse artifacts, and therefore score, discarding them all would have caused an empty wedge at the edge of k-space

**FIGURE S5** Showing the residual PROPELLER RMC estimates for all the blades for each slice. The data corresponds to the PMC+RMC image in Figure 7A, which shows the images acquired during the stepwise-motion with PMC. The mean range of translation estimated by the RMC was 4 mm and the mean range of rotation was 3°. The three topmost slices have been excluded since they were acquired above the head and contained only noise. The y-axis range was chosen to match that of the plots in Figure 7. Each slice has its own reference blade, marked with a cross, which all other 21 blades (in that slice) are registered to

**FIGURE S6** Showing the residual PROPELLER RMC estimates for all the blades for each slice. The data corresponds to the PMC+RMC image in Figure 8A, which shows the images acquired during the circular-motion with PMC. The mean range of translation estimated by the RMC was 3 mm and the mean range of rotation was 3°. The four topmost slices have been excluded since they were acquired above the head and contained only noise. The y-axis range was chosen to match that of the plots in Figure 8. Each slice has its own reference blade, marked with a cross, which all other 21 blades (in that slice) are registered to

**TABLE S1** Parameters and settings for the T1-FLAIR PROPELLER acquisition using update strategy A

**TABLE S2** Parameters and settings for the high-resolution T1-FLAIR PROPELLER acquisition using update strategy A

**VIDEO S1** Video demonstrating the different motion-patterns. Created from the motion estimates reported by the WRAD, applied to a 3D head model. It also shows the animated moving crosshair that helps the volunteer repeat similar movement patterns

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