Control of a wireless sensor using the pulse sequence for prospective motion correction in brain MRI

Adam van Niekerk1 | Johan Berglund1 | Tim Sprenger2 | Ola Norbeck1,3 | Enrico Avventi1,3 | Henric Rydén1,3 | Stefan Skare1,3

1Department of Clinical Neuroscience, Karolinska Institutet, Stockholm, Sweden
2MR Applied Science Laboratory Europe, GE Healthcare, Stockholm, Sweden
3Department of Neuroradiology, Karolinska University Hospital, Stockholm, Sweden

Purpose: To synchronize and pass information between a wireless motion-tracking device and a pulse sequence and show how this can be used to implement customizable navigator interleaving schemes that are part of the pulse sequence design.

Methods: The device tracks motion by sampling the voltages induced in 3 orthogonal pickup coils by the changing gradient fields. These coils were modified to also detect RF-transmit events using a 3D RF-detection circuit. The device could then detect and decode a set RF signatures while ignoring excitations in the parent pulse sequence. A set of unique RF signatures were then paired with a collection of navigators and used to trigger readouts on the wireless device synchronous to the pulse sequence execution. Navigator interleaving schemes were then demonstrated in 3D gradient echo, T1-FLAIR (fluid-attenuated inversion recovery) PROPELLER (periodically rotated overlapping parallel lines with enhanced reconstruction), and T2-FLAIR PROPELLER pulse sequences.

Results: Excitations in the parent pulse sequences were successfully rejected and the RF signatures successfully decoded. For the 3D gradient echo sequence, distortions were removed by interleaving flipped polarity navigators and taking the difference between consecutive readouts. The impact on scan duration was reduced by 54% by breaking up the navigators into smaller parts. Successful motion correction was performed using the PROPELLER pulse sequences in 3 Tesla and 1.5 Tesla MRI scanners without modifications to the device hardware or software.

Conclusion: The proposed RF signature-based triggering scheme enables complex interactions between the pulse sequence and a wireless device. Thus, enabling prospective motion correction that is repeatable, versatile, and minimally invasive with respect to hardware setup.

Keywords: brain, motion correction, MRI, RF control, WRAD
INTRODUCTION

Most MR image encoding methods assume that the object under investigation is stationary for either part or the entire duration of the encoding process. The object is encoded using spectra (k-space) in the time domain, where each pixel contributes to every pixel in the decoded image. As a result, motion can result in complex artefacts such as ringing, ghosting, and/or blurring. To further complicate matters, a moving object leads to unpredictable magnetization states in the body. This is particularly relevant in 2D imaging experiments where “through-plane” motion causes a mismatch between slice selective RF pulses and results in a distribution of unknown spin states. The result is spin history artefacts that cannot be corrected retrospectively even if the exact motion path is known and no data undersampling would occur.

Motion-related artefacts can be significantly reduced by measuring any changes in the object’s pose and adjusting the encoding scheme in real time so that it appears as if it had not moved at all. This is referred to as prospective motion correction. In the case of brain imaging, it can be assumed that the head undergoes rigid body motion. One can therefore infer the position of each point of the head by measuring the precise location of a subset of points. This can be achieved by running additional NMR experiments in parallel to the imaging experiment that localize a collection of field probes rigidly attached to the patient’s head. Methods that do not use the gradient field spatial encoding have also been proposed, such as optical cameras that track the patient’s head independently of the scanner operation and FID navigators that interpret motion-induced changes in the MR signal from the sensitivity profiles of an RF receive coil array. Nongradient measurement methods require some form of cross-calibration to the gradient coil (imaging) coordinate system. This is a once-off procedure for optical-based methods or patient-specific transform in the case of FID navigators.

Recently, a new prospective motion-correction technique has been proposed that employs a wireless RF-triggered acquisition device (WRAD). The WRAD is a battery-powered “intelligent marker” that can be attached to a subject to track their pose. The WRAD detects the magnetic spatial encoding of the MR scanner’s gradient coils and therefore inherits its measurement frame from the MR scanner, similar to NMR field probe methods. The WRAD differs in that it detects the rate of change of the gradient magnetic fields through Faraday induction in a set of 3 orthogonal pickup coils. An observation of the direction of the static magnetic field is then used to interpret the voltages induced in the pickup coils and solve for the device’s pose. The process of digitising and interpreting these induced voltages is less demanding than processing an MR signal, allowing all the signal processing electronics to be built into the marker itself.

Augmenting the scanner hardware with additional sensors, such as a WRAD, is a challenge often encountered in research. This can be a simple button that a subject uses to interact with a task in an fMRI study or a more complex multi-modal experiment, such as combined MR electroencephalogram or MR ultrasound. In each case, the challenge of coexisting with the unique MR environment requires special adaptations of these sensors. Perhaps one of the most important adaptations is the ability to synchronize to the MR hardware. This way, sensors can be sampled during gradient and RF inactivity and then powered down as not to interfere with the acquisition of the MR signal. In the case of the WRAD, wireless synchronization is achieved by detecting RF pulses in the imaging sequence with a diode envelope detector circuit.

The utility of this approach has been demonstrated in a 3D gradient echo pulse sequence. The nonselective RF excitation pulses were used to synchronize the analogue-to-digital converter (ADC) on the WRAD so that it can sample the gradient spatial encoding during an 880-μs long navigator. A drawback of this technique is that the RF envelope detector circuit is unable to distinguish between different RF pulse types. The detector sensitivity is also related to the device’s orientation due to the 2D RF-pickup coil construction. If the normal of the RF pickup coil lies parallel to the B₀ field vector, almost no voltage will be detected. Extending this method of detection and synchronization to a clinical setting with different pulse sequences would require tailored responses to different RF pulse profiles, protocols, and ordering. This could make the workflow complex and sequence-specific. With a typical neuroimaging exam consisting of multiple contrasts, adapting the WRAD to each sequence could be a potential source of error.

In this work, a 3D RF-detection design is presented that reduces the effect of orientation on sensitivity. This removes any restrictions on how the device can be placed on the subject. This is achieved by using one 3D pickup coil assembly to couple to both the RF transmit and gradient coil fields. This also eliminates the need for a separate RF detection coil, which reduces the overall size of the device.

To eliminate dependencies on the pulse sequence protocol, we introduce an identifier RF-pulse type that can be interleaved with the parent pulse sequence. These pulses consist of 2 narrow opposed-phase hard pulses that are designed to have a signature significantly different from typical MR excitation pulses. The spacing between the hard pulses can also be varied to encode a pulse identity. The WRAD can then search for and decode the identity of the identifier pulses, ignoring excitation pulses in the parent pulse sequence. A successful identifier match can then trigger tasks on the WRAD synchronous to the pulse sequence execution. No prior knowledge of when or in what order these events occur is required.
Next, we explore the use of the identifiers in the context of prospective motion correction with a WRAD. A set of identifier pulses and navigators are paired to form a module collection. A prelude module is also defined that allows the sequence to send a configuration message to the WRAD using a train of RF pulses. The module collection is designed to explore the use of flipped polarity navigators to remove biases caused by eddy currents. The ability to break up navigators into smaller parts to reduce their impact on the scan duration is also included.

The identifier pulses are tuned to give reliable operation on both 1.5 Tesla (T) and 3T MRI scanners. The removal of eddy current distortions in the navigator waveforms is then demonstrated by interleaving toggling waveforms from the module collection with a 3D RF spoiled gradient echo pulse sequence. The impact of interleaving multiple smaller navigators on prospective motion-correction efficacy is then evaluated.

Finally, we show how the identifiers can be used to enable prospective motion correction in sequences with longer repetition times and complex looping structures. To this end, modules are interleaved with T1-FLAIR (fluid-attenuated inversion recovery) PROPELLER (periodically rotated overlapping parallel lines with enhanced reconstruction) and T2-FLAIR PROPELLER pulse sequences.14 The versatility of controlling the WRAD with RF identifiers is then highlighted by performing prospective motion correction with the same WRAD on 2 different MR systems with differing RF operating frequencies (1.5T and 3T).

2 | METHODS

An overview of the proposed prospective motion-correction experiment that makes use of a predetermined module collection is described in Figure 1. The MR experiment begins with the selection of the desired protocol for a custom pulse sequence that allocates time for the execution of the modules in the image looping structure (A). This is uploaded to the real-time computer that manages the generation of the waveforms that form the MR image. Once the protocol and timing are finalized, the pulse sequence is executed. The following series of events are then triggered each time an identifier (ID) pulse is played out:

1. The WRAD validates the RF signature and decodes which module in the module collection it belongs to. This information is then used to determine the timing of the ADC events (readouts on the WRAD) and how the data should be interpreted.
2. Once the WRAD has sufficient information to determine its pose, it returns the result over a low-latency 2.4 GHz wireless link to a dongle placed through the waveguide of the MR scanner room. The dongle forwards the messages to the host computer over a USB interface.
3. The host computer, running a custom script, assembles the messages and forwards the updated FOV position to the real-time computer over a UDP socket.
4. The updated FOV is used to generate the new imaging encoding waveforms either:
   a. NOW: Additional “dead time” is allocated in the pulse sequence and the current encoding step is updated.
   b. LATER: The pulse sequence execution continues and only the next encoding step is updated.
5. The updated pulse sequence encoding is played out on the MR system delayed by the time it takes to complete steps 1-4.

How updates are applied (NOW/LATER) can have a significant impact not only on the latency but on the scan time as well. 3D pulse sequences with short TR are better suited to computing the new waveforms while the next phase-encoding step is playing (LATER), increasing the latency by 1 TR. In contrast, for example, a 2D T2w PROPELLER sequence having a sequence duration of ~200 ms, delaying the FOV update to the next sequence playout, could make the latency too long to capture the head motion. Deadtime is therefore inserted into these types of sequences, and the FOV updates are executed immediately (NOW). The deadtime needs to be long enough to account for the communication latency (< 1 ms) and the time it takes the real-time computer to compute the new waveform shapes and then copy them to the hardware queue.

2.1 Combined 3D pickup coil and RF detection

The changing gradient fields are at a much lower frequency than the RF pulses, allowing the RF signal to be separated through a filtering circuit (Figure 2). The AC coupling of the detector circuits allows the RF signal to pass through to the envelope detectors, whereas the low-pass filter before the instrumentation amplifier (AMP) effectively blocks this high-frequency signal. Similarly, the AC-coupled detectors have very little influence on the much lower frequency signals induced by the gradient coils. Moreover, the modules are designed to not have RF pulses during the WRAD ADC readouts to avoid any potential sources of bias.

The envelope detection circuits are connected in series, effectively summing the voltages induced by the RF field in each of the 3 orthogonal pickup coils. The circuit therefore achieves a sensitivity greater than or equal to the maximum sensitivity of a single coil for any orientation of the pickup coil assembly. The resulting detection-voltage (Vd) is fed into
Overview: prospective motion correction feedback loop

FIGURE 1 A predetermined collection of sequence modules can be inserted into the looping structure of the parent pulse sequence. Each module has a unique ID that the WRAD can detect and decode. Each time an identifier is played out, the WRAD automatically configures itself to correctly acquire and process the readouts for the navigator that follows. The result is transmitted back to the real-time computer to generate the updated waveforms that realize the new FOV position that follows the subject’s head. ID, identifier; WRAD, wireless RF-triggered acquisition device

a high-speed comparator that is used to trigger events on the microcontroller (MCU).

The self-resonance (~80 MHz) of the printed circuit-board pickup coils were purposefully designed to avoid the Larmor frequencies of 1.5T and 3T scanners. This reduces coupling to the RF coils, limiting induced currents and interactions with the MR experiment.\(^5\) The new device that implements this configuration is shown in Figure 2.

2.2 | Bipolar identifier RF pulses

The identifiers consist of two 4-μs wide RF pulses in quick succession (Figure 3A). They are played out 180 degrees out of phase to minimize the effect on magnetization of the main pulse sequence. An important aspect of filtering out the parent sequence’s RF pulses is the ability to detect both the pulse width and spacing (time between rising edges of consecutive pulses). A pair of RF pulses are only considered to be an identifier if the width of each pulse is within an expected range and the time between the rising edges of the pulses (spacing) is less than the maximum value [n] to be encoded. In this work, the WRAD was programmed to accept 10 unique identifiers, 1 for each module, resulting in a maximum identifier pulse duration of 42 μs (Figure 3A).

Measuring the pulse width is more challenging than measuring the spacing because the charge stored on the rectifying capacitors needs to be discharged. This results in a low-pass filtering effect that smears the envelope, as shown in Figure 3B. The width is thus a function of the RF pulse amplitude/profile, comparator threshold, pull-down resistor value, and sensitivity.

2.3 | WRAD signal processing

The WRAD summarizes each sinusoidal navigator (Figure 4) by performing a single bin discrete Fourier transform, at
the sinusoid’s center frequency, over each readout for each pickup coil (in parallel). This is performed recursively with a filter-like formulation of the discrete Fourier transform, referred to as the Goertzel algorithm. The WRAD sample frequency was set to 250 kHz to match the raster period of the gradient boards. The resulting slew vector that summarizes each navigator readout is thus ready within 4 μs of the last sample of each readout.

The geometric scaling factor of the pickup coils required to relate the induced voltages to the slew rate and position was determined by displacing the scanner table in 10 mm increments (along the z-direction). A linear fit of the component of the voltages induced during the z-gradient coil play-out in the direction of the static magnetic field (z-displacement) to the table positions was then performed. This was carried out once on the 3T MRI scanner and found to be 0.00667 \( \text{mm}^2/\text{V} \). This is expected to be a 1-time device (WRAD)-specific calibration.

The WRAD was mounted to the bridge of the subject's nose using a small sled for each of the motion-correction experiments. The WRAD uses the Maxwell terms of the gradient field to determine orientation; we therefore need to consider them at the location the WRAD will be placed. The WRAD is expected to have a large positive y-displacement in the gradient coordinate system as it is placed on the subject's nose. When nodding, the WRAD will likely pass through the \( z = 0 \) plane. At small \( z \)-displacements, the direction of the slew vectors from the navigators played out on the \( x \)- and \( y \)-gradient coils are close to parallel to the direction of the static magnetic field (sensed by the 3D magnetometer). They are thus not suitable for determining the remaining degree of freedom in the WRAD’s orientation about the axis of the static magnetic field. However, the large y-displacement does mean that the slew vector sensed by the WRAD during the z-gradient coil playout will lie close to orthogonal to the static magnetic field, with a strong negative y component, making it an ideal reference for computing orientation.

Based on these observations, the WRAD was programmed to compute its pose using a closed-form analytical solution. The algorithm uses the component of each slew vector in the direction of the static magnetic field to determine the WRAD’s position. The orientation is then computed by combining the slew vector from the z-gradient coil navigator with the position vector as described in Ref. [9].

2.4 Module collection

The module collection defined for the proceeding experiments (Figure 4) consists of 10 unique modules, all comprising 1 or more sinusoidal navigator waveforms. The WRAD samples the 3D pickup coil during predetermined readout events for each navigator. Notice that the modules with IDs 0 and 8 are identical with respect to the navigator design; however, they differ in their readout event types. Nine unique
readout event types were defined to simplify the WRAD programming:

RX 1 – 3, RY 1 – 3, and RZ 1 – 3

The prefix defines which gradient coil (buffer) the readout waveform is associated with, and the number defines how the WRAD processes the incoming data stream. For the 3 processing behaviors (1-3), the incoming ADC samples are:
The ability to subtract an incoming waveform from one saved in a reference buffer is used to remove disturbances from nearby sequence elements. This is achieved by playing a navigator with a negative polarity for the reference buffer and then a positive polarity for the incoming waveform. The difference between the 2 readouts then results in a signal with twice the amplitude with the disturbances common to both readouts removed. Each module in the module collection (Figure 4) with a negative polarity reference readout (RX2, RY2, RZ2) is therefore paired with a subtraction readout (RX3, RY3, RZ3). These modules (ID1-ID8) can be interleaved with 3D pulse sequences that have short repetition times at the expense of reduced update frequency.

A prelude module was also defined that can be used to configure settings on the WRAD at the very beginning of each prospectively corrected scan. In this case, the identifier is followed by a train of RF pulses with the spacing of each pulse encoding the value of a byte in a configuration message.
This module can be used to customize the module collection. A 6 byte-long configuration message was defined:

- [1 byte]: Number of periods of the sinusoidal navigator in each readout
- [1 byte]: Number of samples per period of the navigator in each readout
- [2 bytes]: Wait period between the identifier pulse and the first readout
- [2 bytes]: Current table position

The wait period can be used to allocate time that allows the WRAD to boot from a sleeping state. This can save battery life because the WRAD can power down the magnetometer and pickup coil amplifiers at the end of each navigator. Going to sleep state reduces the current consumption from 35 mA to 12 mA. The time it takes for the WRAD to boot from this state and return stable results is approximately 600 μs. The WRAD was therefore programmed to automatically operate in this mode if the wait period was set to a value greater than 600 μs.

For the GE Healthcare (Chicago, IL) MR scanners used in this work, the system adjusts the table position before each scan so that the center of the slice stack is at iso-centre (in the z-direction) before the start of each image acquisition. The table position was therefore included in the prelude payload to allow the WRAD to incorporate this value into its pose estimates. Notice the ordering of the navigator playouts for the modules comprised of more than 1 readout (Figure 4). The z-gradient navigator is played before the y-gradient navigator. This is due to interactions between the navigators (eddy currents), discussed later. The z-gradient is used to determine orientation and therefore takes priority over the y-gradient navigator.

2.5 | Insertion into existing pulse sequences

To evaluate the proposed method a 3D RF-spoiled gradient echo (3D SPGR), a T1-weighted FLAIR PROPELLER and a T2-weighted FLAIR PROPELLER pulse sequence were modified to enable prospective motion correction (Figure 5). These pulse sequences were specifically selected due to their dissimilar looping structures and timing. The magnetization-prepared PROPELLER pulse sequences also stand to benefit most from the prospective motion-correction updates due to the long period between the inversion pulses and the readouts of each blade.

The 3D SPGR encoding loop was modified to repeat the acquisition of each phase encoding line, thereby building up two 3D k-spaces in parallel. The first repetition (of each phase encoding line) was updated prospectively, and the second was left unmodified. The sequence therefore generates 2 volumes that have been affected by the same head motion, 1 with and 1 without prospective motion correction. To explore possible uses of the module collection, 3 module insertion modes were implemented, labeled as “simple,” “toggle,” and “short” in Figure 5 (top). In simple mode, the “XYZ” module is inserted into the line encoding loop, generating an update for each line of k-space. Toggle mode interleaves modules “+XYZ” and “−XYZ.” In this mode, a pose update is generated for every second line of k-space. Short mode breaks each navigator up, playing out a sinusoid on 1 gradient coil at a time. This mode has the smallest impact on the pulse sequence duration (i.e., TR), which is important for short-TR sequences. In this mode, 6 modules are required to generate a pose update; however, for short-TR sequences the latency is still fairly short. In all cases, the pose updates received from the WRAD were applied to the following line of k-space (LATER, Figure 1).

For the PROPELLER pulse sequences, the “XYZ” module was inserted before each inversion block and each FSE block in “simple” mode. The longer repetition time in PROPELLER also meant that the pulse sequence duration was less affected by the navigator duration. The updates were therefore applied now (Figure 1) to minimize update latency, requiring a deadline of 3 ms to be inserted after each navigator module. This value was determined empirically as described in Ref. [16].

All pulse sequences and modules were designed and implemented using the KS Foundation framework for pulse programming on GE MR systems.

2.6 | Experiments

All scans involving volunteers were approved by the local ethical body. The same WRAD was used for all experiments without any changes to hardware or firmware. The maximum slew rate of each sinusoidal navigator was set to 60 T/m/s. The WRAD prelude module set the number of periods to 2 and samples per period to 40 of each navigator, resulting in a duration of 320 μs per readout of the WRAD. With these settings, the total navigator duration was 800 μs for the single readout modules [XYZ] and 1750 μs for modules comprising 3 readouts [XYZ/+XYZ/−XYZ].

2.7 | Identifier pulse width tuning

The objective of this experiment is to determine what range of RF pulse widths should be accepted for the identifier pulse design presented in Figure 3. The wider this window, the less likely the WRAD is to miss an identifier pulse—and the more likely it is to erroneously accept a pulse from the parent pulse sequence. The WRAD was therefore programmed to return the
FIGURE 5  The modifications made to each of the pulse sequences to enable prospective motion correction. The short TR of the gradient echo pulse sequence allows modules to be interleaved in different modes. The PROPELLER pulse sequences have more complex looping structures that interleave inversion pulses and blade readouts. For the PROPELLER pulse sequences, a blank “deadtime” sequence of 3 ms was added so that the current blade/inversion could be updated (NOW). PROPELLER, periodically rotated overlapping parallel lines with enhanced reconstruction.
detected pulse width for each RF pulse that exceeds a threshold-voltage of $V_c = 0.3$ V (Figure 3B). The relationship between the detected pulse width and RF flip angle was then determined by stepping through different flip angles on the 1.5 T and 3 T MRI scanners. In each case, the WRAD was specifically oriented to have its minimum detection sensitivity (i.e., 1 pickup coil with its normal in the direction of the static magnetic field). Once the desired flip angle was determined, 10 thousand prelude modules were played out on each MR scanner to test the reliability of encoding information using the spacing between the rising edges of consecutive pulses. The settings determined here were used for all the remaining experiments.

### 2.8 Removing eddy currents through readout subtractions

To measure the effect of neighboring sequence elements on the WRAD measurements and the efficacy of the proposed solution of toggling readout polarities, the WRAD was placed in the scanner at a typical location with large $y$-displacement (about where a subject’s nose would be) during the playout of the 3D SPGR pulse sequence. The WRAD was set into a state where it returns the raw data waveforms from each readout. The sequence was then played out in “simple,” “toggle,” and “short” modes—once with blank (0 amplitude) and once with sinusoidal navigators.

### 2.9 Reducing the impact on scan time in a 3D SPGR sequence

To compare prospective motion-correction efficacy when the pulse sequence interleaves modules in “simple” and “short” modes, a volunteer was asked to remain still and perform subtle circular motion and strong circular motion. A hard RF pulse stretched to 2 ms to give an excitation null point near the fat signal peak was used to improve the image contrast. A flip angle of 10 degrees, TE of 3.3 ms, and readout bandwidth of 41.6 kHz was used for all acquisitions. In “simple” mode, the TR was 9.1 ms and in “short” mode the TR was 8.1 ms due to the shorter navigator duration. This resulted in prospective update frequencies of 55 Hz and 20.6 Hz, respectively. The wait period between the first readout and identifier pulse was set to 150 μs using the prelude module. A summary of the sequence parameters can be found in Supporting Information Table S1.

### 2.10 Evaluating the proposed method in 2 different MR systems

To test the sensitivity of the 3D RF detection circuit to changes in operating conditions, it was of interest to run prospective motion experiments on 2 different MR systems at different magnetic field strengths. This experiment also gives insight into how repeatable the sinusoidal navigators are on different gradient coil systems from the same vendor. For this experiment the T1-FLAIR and T2-FLAIR PROPELLER sequences were used. Three acquisitions were made for each contrast. One scan was performed without motion and the other 2 with continuous circular motion, with and without prospective motion-correction updates applied. In-plane retrospective motion correction was also performed for each slice. The prelude message set the wait period to 750 μs for these experiments, putting the WRAD into a mode where it powers off between modules. The PROPELLER sequence parameters can be found in Supporting Information Table S2.

### 3 RESULTS

#### 3.1 Identifier pulses

The amplitude of the identifier pulses as a function of flip angle are presented in Figure 6. The exponential relationship was similar for both MRI scanners. An accepted pulse width range of 2-14 μs and a flip angle of 0.1 degrees were selected. This allows negligible impact on the magnetization, gives a factor of 2 margin for the minimum coupling to the RF coil to reach the 0.3 V threshold, and results in no restriction on the maximum coupling (due to the asymptotic relationship). The WRAD was able to successfully decode identifier pulses and the configuration data from the 10 thousand prelude modules, with a 100% success rate on both the 1.5 T and 3 T MR systems with these settings. No identifiers were falsely detected for the remaining experiments. In fact, the pulse width rejection criterion alone was sufficient to ignore all the excitation pulses in the parent pulse sequences used here.

#### 3.2 Residual signal from neighboring sequence elements

Three main effects on the WRAD readouts were observed: The first are distortions caused by neighboring sequence elements that bias the Goertzel-filtered results; thus, they can be measured irrespective of whether the navigators are ON or OFF (Figure 7, blue arrows). These were most significant in the $y$-direction (center row of the matrices) during the $x$- and $z$- navigator readouts ($RX_y$, $RZ_y$) and will not affect the position measurements that rely on the vector components in the $z$-direction. The directionality of the distortions is most likely due to the large $y$-displacement (135 mm) of the WRAD and would likely change based on location. Both “TOGGLE” and “SHORT” modes remove these distortions, resulting in readouts that more closely resemble pure sinusoids.
The second disturbance is a high-frequency ripple along the scanner bore, $z$-direction (Figure 7, green arrows). This signal is related to the switching frequency of the gradient amplifiers and is in agreement with previous results.\(^9\) It is present during all the readouts but does not appear to bias the Goertzel results. It is also effectively removed through both “TOGGLE” and “SHORT” interleaving methods.

The third disturbance is due to eddy currents caused by the navigators themselves (Figure 7, red arrows). This signal changes polarity with the navigator playouts and thus cannot be removed through the proposed waveform subtractions. It is therefore present in both “SIMPLE” and “TOGGLE” modes, where the large signal during the $z$-gradient readout in the $y$-direction ($R_{z_y}$) causes a distortion of the proceeding $y$-gradient readout in the $y$-direction ($R_{y_y}$, blue and green lines are distorted). In the case of “SHORT” mode, the different gradient playouts are separated by the sequence TR and are immune to this effect ($R_{y_y}$, the red line is closer to a pure sinusoid).

3.3 | Prospective motion correction

3.3.1 | 3D SPGR

In both “simple” and “short” modes, the WRAD successfully detected the navigator modules to give reliable pose estimates and improve image sharpness (Figure 8). For the “still” case, “short” mode performed slightly better, perhaps due to the reduced noise from toggling waveforms. For the case of slow circular motion, both methods worked well, although there is slight ringing toward the posterior of the head. Both methods begin to fail for the strong circular motion case. In “short” mode, the 54% reduction in navigator duration resulted in a total scan time penalty of 14 s per volume. This equates to a 16 s time saving per volume without significantly impacting the prospective motion-correction quality.

3.3.2 | PROPELLER

Prospective motion correction performed equally well in both MR scanners. For the 3T experiment (Figure 9), there is a slight increase in image noise for the prospectively corrected images acquired during motion (center column). However, the underlying features are accurately represented when comparing the slices to the reference. The minor improvements, when also applying retrospective correction, suggest unbiased pose estimates obtained from the WRAD. The images acquired without prospective motion correction are severely corrupted, mostly due to slice profile mismatches. For the 1.5 T images (Figure 10), these effects are slightly less pronounced due to the lower amplitude motion. This was due to a tighter fit of the subject’s head in a smaller RF receive coil, which constrained their movements.

4 | DISCUSSION

The identifier RF pulses presented in this work are particularly helpful when implementing prospective motion correction with a WRAD because the module collection can be used to adapt the navigators to the pulse sequence requirements.
The fast 3D spoiled gradient echo sequence requires navigators optimized for speed to minimize impact on the scan duration, whereas the PROPELLER sequences with blade-to-blade updates could have longer navigators optimized for precision. The number, dwell time, and digital filtering of the ADC samples acquired by the WRAD can be controlled by the identifier RF pulses, effectively allowing the WRAD to behave like a scanner hardware extension.
Perhaps the most attractive quality of this approach is that only information about the module collection is required. The WRAD requires no information about the pulse sequence, its protocol, or in which scanner it is currently placed. Moreover, the WRAD does not depend on keeping track of a state to stay synchronous to the pulse sequence execution. Its behavior is determined each time an identifier is decoded, making implementation of complex interactions robust.

In the module collection presented here, the pulse sequence could request an arithmetic subtraction of the WRAD readouts prior to processing. Navigators with flipped polarities were then played out, allowing the removal of disturbances such as eddy currents common to both readouts. This allows navigators to be placed in close proximity to elements in the main sequence. The scenario of when time is a premium in a pulse sequence was also explored. To this end, we showed how navigators could be broken up into smaller parts and then interleaved with the pulse sequence. The data from each of these parts were then reassembled to give fully constrained pose estimates. The identifier RF pulses can therefore be used to improve the precision of pose estimates as well as reduce the impact of the WRAD navigators on the pulse sequence duration.

To demonstrate the versatility of the WRAD when controlled in this manner, prospective motion correction was performed on T1-FLAIR and T2-FLAIR PROPELLER pulse sequences. The longer duration between navigators meant that the WRAD could operate in a gated mode, allowing it to reduce power consumption by a factor of 3. This can be used to increase battery life or reduce the battery size. The combination of T1-FLAIR PROPELLER with prospective motion correction has been shown to allow extremely motion robust imaging. The implementation of the identifier pulses

![Figure 7](image)

![Figure 8](image)
FIGURE 9  Example slices from the prospective motion correction experiment performed on the 3T MR scanner. The top and bottom image groups are from the T₁- and T₂-weighted FLAIR PROPELLER sequences, respectively. For each group, images are shown for when within slice retrospective motion correction is OFF (top), ON (middle). The change in orientation (euler, xyz order) of the subject, as recorded by the WRAD, is displayed on the bottom of each group. The uncorrected images (prospective off) are damaged by 2 effects. The first is mismatch in the blades when assembling a slice; the in-plane component of this can be corrected retrospectively. The second more pronounced effect is the damage to the image contrast caused by misalignments between the blades and the planes (slice profiles) of the inversion pulses.
FIGURE 10 Example slices from the prospective motion correction experiment performed on the 1.5T MR scanner. The top and bottom image groups are from the T₁- and T₂-weighted FLAIR PROPELLER sequences, respectively. For each group, images are shown for when within slice retrospective motion correction is OFF (top), ON (middle). The change in orientation (euler, xyz order) of the subject, as recorded by the WRAD, is displayed on the bottom of each group. Due to the more constrained RF receiver coil, the motion amplitudes are smaller. In this case the artefacts in the uncorrected images (prospective off) are dominated by misalignments of the blades caused by through-plane motion.
allowed this work to easily be extended to other contrasts, such as the T2-FLAIR images presented here.

5 | CONCLUSION

The simplicity of using the WRAD hardware is one of this method’s salient features. This was highlighted in an experiment in which we transferred the PROPELLER motion-correction results from the 3T to the 1.5T MRI scanner without any modifications. A subject, with the WRAD mounted on their nose, could therefore walk between the 2 systems and have prospective motion correction performed with the same device. This shows a unique independence of the MR scanner infrastructure. This quality is beneficial in a clinical setting where the scanners capabilities and room layouts can vary dramatically, ultimately allowing a bowl of WRAD devices to be used for a whole MRI department.

CONFLICT OF INTEREST

Johan Berglund and Stefan Skare receive research support from GE Healthcare. Tim Sprenger is employed by GE Healthcare.

ORCID

Adam van Niekerk https://orcid.org/0000-0001-9731-6930
Johan Berglund https://orcid.org/0000-0002-0853-9305
Ola Norbeck https://orcid.org/0000-0002-0518-5206
Henric Rydén https://orcid.org/0000-0003-3269-7482
Stefan Skare https://orcid.org/0000-0001-5403-2153

REFERENCES

1. Sipilä P, Greding S, Wachutka G, Wiesinger F. 2H transmit-receive NMR probes for magnetic field monitoring in MRI. *Magn Reson Med*. 2011;65:1498-1506.
2. Haerberlin M, Kasper L, Barnet C, et al. Real-time motion correction using gradient tones and head-mounted NMR field probes. *Magn Reson Med*. 2015;74:647-660.
3. Aranovitch A, Haerberlin M, Gross S, et al. Prospective motion correction with NMR markers using only native sequence elements. *Magn Reson Med*. 2018;79:2046-2056.
4. Zaitsev M, Dold C, Sakas G, Hennig J, Speck O. Magnetic resonance imaging of freely moving objects: prospective real-time motion correction using an external optical motion tracking system. *Neuroimage*. 2006;1038-1050.
5. Schulz J, Siegert T, Reimer E, et al. An embedded optical tracking system for motion-corrected magnetic resonance imaging at 7T. *MAGMA*. 2012;25:443-453.
6. Frost R, Wighton P, Karahanoğlu F, et al. Markerless high-frequency prospective motion correction for neuroanatomical MRI. *Magn Reson Med*. 2019;82:126-144.
7. Wallace TE, Afacan O, Waszak M, Kobert T, Warfield SK. Head motion measurement and correction using FID navigators. *Magn Reson Med*. 2019;81:258-274.
8. Maclaren J, Aksoy M, Ooi MB, Zahrneisen B, Bammer R. Prospective motion correction using coil-mounted cameras: cross-calibration considerations. *Magn Reson Med*. 2018;79:1911-1921.
9. van Niekerk A, Meintjes E, van der Kouwe A. A wireless radio frequency triggered acquisition device (WRAD) for self-synchronised measurements of the rate of change of the MRI gradient vector field for motion tracking. *IEEE Trans Med Imaging*. 2019;38:1610-1621.
10. Ives JR, Warach S, Schmitt F, Edelman RR, Schomer DL. Monitoring the patient’s EEG during echo planar MRI. *Electroencephalogr Clin Neurophysiol*. 1993;417-420.
11. Curiel L, Chopra R, Hynynen K. Progress in multimodality imaging: truly simultaneous ultrasound and magnetic resonance imaging. *IEEE Trans Med Imaging*. 2007;26:1740-1746.
12. Sebok DA, Wilkerson D, Schroder W, Mezrich R, Zatina M. Interleaved magnetic resonance and ultrasound by electronic synchronization. *Invest Radiol*. 1991;26:353-357.
13. van Niekerk A, van der Kouwe A, Meintjes E. Toward, “plug and play” prospective motion correction for MRI by combining observations of the time varying gradient and static vector fields. *Magn Reson Med*. 2019;82:1214-1228.
14. Pipe JG. Motion correction with PROPELLER MRI: application to head motion and free-breathing cardiac imaging. *Magn Reson Med*. 1999;42:963-969.
15. Ooi MB, Aksoy M, Maclaren J, Watkins RD, Bammer R. Prospective motion correction using inductively coupled wireless RF coils. *Magn Reson Med*. 2013;70:639-647.
16. Norbeck O, van Niekerk A, Avventi E, et al. T1 -FLAIR imaging during continuous head motion: combining PROPELLER with an intelligent marker. *Magn Reson Med*. 2021;85:868-882.
17. Skare S, Avventi E, Norbeck O, Ryden H. An abstraction layer for simpler EPIC pulse programming on GE MR systems in a clinical environment. In *Proceedings of the 25th Annual Meeting of ISMRM*, Honolulu, HI, 2017. p. 3813.

SUPPORTING INFORMATION

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

**TABLE S1** Parameters and settings for the 3D spoiled gradient echo acquisitions

**TABLE S2** Parameters and settings for the PROPELLER acquisitions

**How to cite this article:** van Niekerk A, Berglund J, Sprenger T, et al. Control of a wireless sensor using the pulse sequence for prospective motion correction in brain MRI. *Magn Reson Med*. 2022;87:1046-1061.  
https://doi.org/10.1002/mrm.28994