Optimizing SwiftMR™ Protocols for Diverse Applications

Geunu Jeong, MD, Head of SwiftMR™ Research at AIRS Medical Inc

Magnetic Resonance Imaging (MRI): Game of Balance Between Image Quality and Scan Time

Key features of MR image quality include signal-to-noise ratio (SNR), resolution, artifact, and contrast. It is well known that these features have a trade-off relationship with scan time – meaning that compromise from at least one of these features is necessary to reduce scan time. Similarly, achieving improvement on one of the four factors without increasing scan time would also require the expense of other three parameters. This relationship was the standard on which the industry and the clinic revolved around – before SwiftMR™*.

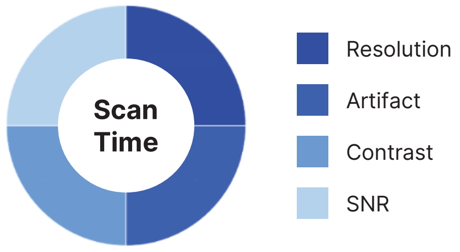

Figure 1. The trade-off between MR image quality and scan time

Introducing SwiftMR™: Enhancing MR Image Quality Without Compromise

SwiftMR™* is a deep learning-based technology which allows the user to break the conventional rule of the trade-off. SwiftMR™ is capable of enhancing the SNR and spatial resolution of MR images without extra scan time, and without sacrificing contrast or introducing artifacts.

SwiftMR™ can be utilized to address various clinical needs. However, protocol setting strategies tailored to meet these specific needs must be established beforehand. The guiding principle is: “adjust the parameters to achieve desired outcomes by willingly sacrificing either SNR or spatial resolution. SwiftMR™ will compensate for any loss in SNR or spatial resolution."

Next, different strategies for SwiftMR™-optimized protocol settings under various clinical needs will be illustrated.

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* Jeong, Geunu, et al. "All-in-One Deep Learning Framework for MR Image Reconstruction." arXiv preprint arXiv:2405.03684 (2024)

* The intended use may vary by country

Scan Time Reduction

Naturally, scan time reduction is the most common, unanimous need in modern MR imaging. Here, we will talk about strategies for a common 2D fast spin echo (FSE) or turbo spin echo (TSE) pulse sequences. The scan time of the 2D TSE pulse sequence is determined by the following formula:

$$TR \times \#\ TSE\ shots \times \#\ Averages \times \#\ Acquisitions$$

$$\#\ TSE\ shots = \frac{\#\ Phase\ Encoding\ Steps}{Echo\ Train\ Length}$$

where TR stands for repetition time, # TSE shots and # Phase Encoding Steps each refer to the numbers used per slice per average, # Averages indicates the number of averages and # Acquisitions denotes the number of slice sets in multi-slice imaging. From this formula, several strategies can be taken to reduce scan times.

First approach is to decrease the number of averages. This will directly reduce scan time at the expense of SNR, which SwiftMR™ is capable of recovering. While it is the simplest method to implement, factors such as worsening motion/flow artifact and free induction decay (FID) artifact should be accounted for.

Parallel Imaging (PI) is another method that reduces scan time by decreasing the number of phase encoding steps. This sacrifices SNR. While the SNR sacrifice from reducing the number of averages is constant at $\sqrt{scan\ time\ reduction\ ratio}$, the SNR sacrifice from using PI is equal to or more severe than reducing the number of averages and varies depending on the imaging scenario. There are primarily two conditions related to scan parameters that can minimize the SNR sacrifice (i.e., bring it closer to $\sqrt{scan\ time\ reduction\ ratio}$). The first is whether the phase encoding direction and the receiver coil element arrangement are parallel. For instance, when using a knee coil which surrounds the anatomy, having the phase encoding direction as Right-Left (RL) or Anterior-Posterior (AP) is much more advantageous than Head-Foot (HF). The second is whether the phase acquisition field-of-view (FOV) is sufficiently large. This refers to a phase FOV that considers phase oversampling, and the larger this value, the more advantageous it is for PI. Aside from scan parameters, another important factor is whether the number of channels available in the receiver coil is sufficient. With these conditions met (or favorable), it is possible to achieve an SNR sacrifice close to $\sqrt{scan\ time\ reduction\ ratio}$ with a higher PI factor, which SwiftMR™ could recover. However, using PI should also take into account the possibility of residual aliasing artifacts.

Another strategy would be to decrease the phase oversampling, which also reduces the number of phase encoding steps, thereby shortening scan time. This sacrifices SNR, which SwiftMR™ can recover. Reducing phase oversampling beyond the point where small FOV aliasing artifact occurs should be avoided.

> Note: In fact, PI and phase oversampling are closely related. Both adjust the spacing between samples along the phase encoding axis in k-space (phase Δk). When using PI, adjusting phase oversampling allows for the control of the effective PI factor. A PI factor of 2 with a phase oversampling factor of 1 is equivalent in k-space sampling to a PI factor of 4 with a phase oversampling factor of 2. Implementing a PI factor of 3 with a phase oversampling factor of 1.2 achieves an effective PI factor of 2.5 (=3/1.2). Increasing phase oversampling reduces the effective PI factor, while decreasing phase oversampling raises the effective PI factor.

Another method of reducing scan time is to increase the receiver bandwidth and reduce the repetition time (TR). Increasing the receiver bandwidth sacrifices SNR. However, it reduces echo spacing, thereby lowering the minimum TR, which makes it possible to reduce the TR. Lost SNR could be recovered by SwiftMR™ during the post-processing stage. However, change in TR may result in change in image contrast so proper precautions should be taken to maintain intended contrast.

Next is increasing the echo train length (ETL). This method requires increasing the receiver bandwidth to reduce the echo spacing, thereby controlling the echo train duration (=echo spacing×ETL). This control is crucial because an increase in echo train duration can make the images blurry. Moreover, simply increasing the ETL without controlling the echo train duration often does not shorten the scan time, as it may lead to an increase in the minimum TR. Increasing the receiver bandwidth sacrifices SNR, which can be recovered by SwiftMR™.

On the other hand, image resolution may also be set as an expense by which acceleration is achieved. Decreasing phase acquisition matrix, as one of the methods to reduce the number of phase encoding steps, will sacrifice spatial resolution – which SwiftMR™ is also capable of recovering. However, this approach should be considered less if high image quality is desired.

Additionally, adjustments to RF mode, gradient mode, B1 amplitude, and refocusing flip angle can be made depending on the scanner vendor to modify echo spacing and minimum TR, allowing their effective use in reducing scan time.

Although scan time reduction strategies for 2D TSE have been introduced, appropriate strategies can be devised for other pulse sequences as well based on their respective scan time formulas. Depending on the type of the pulse sequence, 2D TSE-specific strategies described above may be equally applicable, may not be applicable, or there may be separate dedicated strategies.

Spatial Resolution Improvement

Improving spatial resolution of an image is also a common need. Here, strategies for the 2D TSE pulse sequence will be introduced. Although the term “resolution” typically refers to the acquisition voxel size, it will be used in a broader and practical sense to denote 'the ability to distinguish closely spaced structures' in the following sections.

By default, without making any changes or expenses during the acquisition, SwiftMR™ will always improve the spatial resolution of the input image.

Intuitive method of increasing spatial resolution would be to increase the frequency acquisition matrix. However, this will come at the cost of SNR and requires increasing the receiver bandwidth to control the increased echo spacing. Or, phase acquisition matrix may be increased instead. This will also sacrifice SNR and, because it increases the number of phase encoding steps, it will also increase the scan time. Therefore, if an increase in scan time is undesirable, strategies for reducing scan time must accompany this change.

Another method would be to decrease the slice thickness at the expense of SNR. This will also require the number of slices to increase, if maintaining slice FOV coverage is required. This may lead to more acquisitions or an increase in minimum TR, potentially resulting in longer scan times. Again, if this increase in scan time is undesirable, strategies for reducing scan time must be devised as well.

Increasing the receiver bandwidth will also work, but at the cost of SNR. This results in shorter echo spacing, ultimately leading to a reduced echo train duration, which can decrease phase-direction blurring. Moreover, frequency-direction blurring may also be reduced due to the shorter signal readout duration. Similarly, decreasing the echo train length may also be considered. This will shorten the echo train duration, thereby reducing blurring. Additionally, this decreases minimum TR, allowing minimal scan time increase.

Lost SNR from the strategies described above can be compensated by SwiftMR™.

SNR Improvement

Also by default, SwiftMR™ will improve the SNR of any input image without any change in the acquisition parameters. However, for images with extremely low SNR, sacrificing spatial resolution to secure SNR may be beneficial. Lost resolution can be recovered by SwiftMR™.

Figure 2 is a good example where scan time reduction, spatial resolution improvement, and SNR improvement were achieved simultaneously. For scan time reduction, the number of averages were decreased. For resolution improvement, the frequency acquisition matrix was increased. SNR was increased via SwiftMR™ by default, without any change in the acquisition parameters.

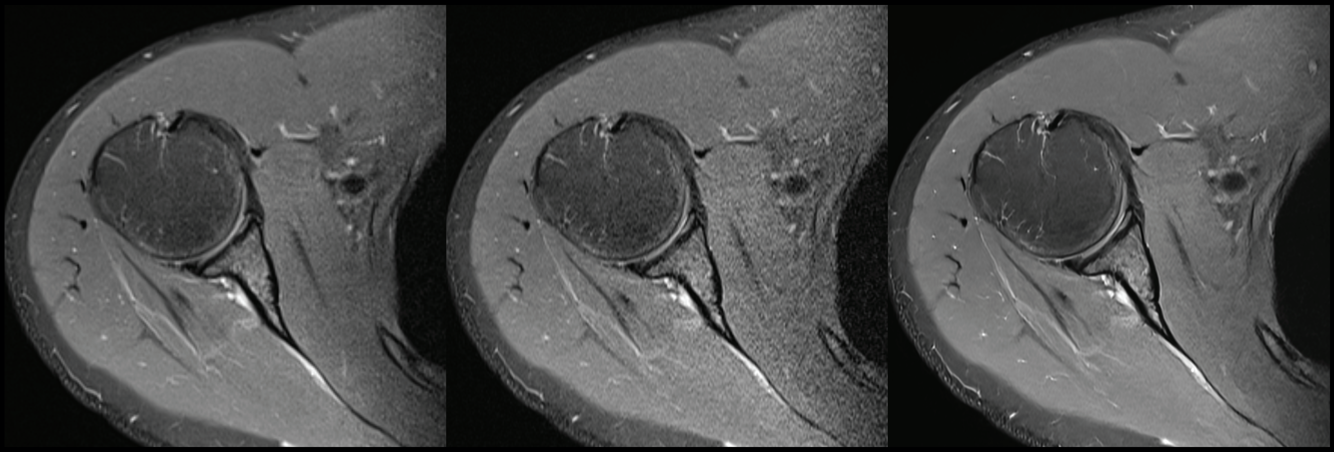

Figure 2. An example of achieving scan time reduction, spatial resolution improvement, and SNR improvement simultaneously in shoulder proton density weighted image with fat suppression (PDWI FS). (Left) conventional image, 2D TSE, 0.6 x 0.8 x 3.0 mm, number of averages=2, scan time=2m 51s (Middle) conventional image with modified scan parameters, 2D TSE, 0.5 x 0.8 x 3.0 mm, number of averages=1, scan time=1m 27s (Right) SwiftMR™ reconstructed image from (Middle).

Artifact Improvement [1]

There are numerous types of MR artifacts, many of which can be improved through SwiftMR™-enabled scan parameter modifications. Here are some examples.

First example is the geometric distortion artifact in echo planar imaging (EPI). EPI pulse sequences are vulnerable to these artifacts in anatomical locations prone to B0 field inhomogeneity. Reducing echo spacing or increasing phase Δk can mitigate this distortion. **Figure 3** shows an example of increasing PI factor to increase phase Δk and mitigate distortion. Although this will decrease the SNR, SwiftMR™ has compensated the loss.

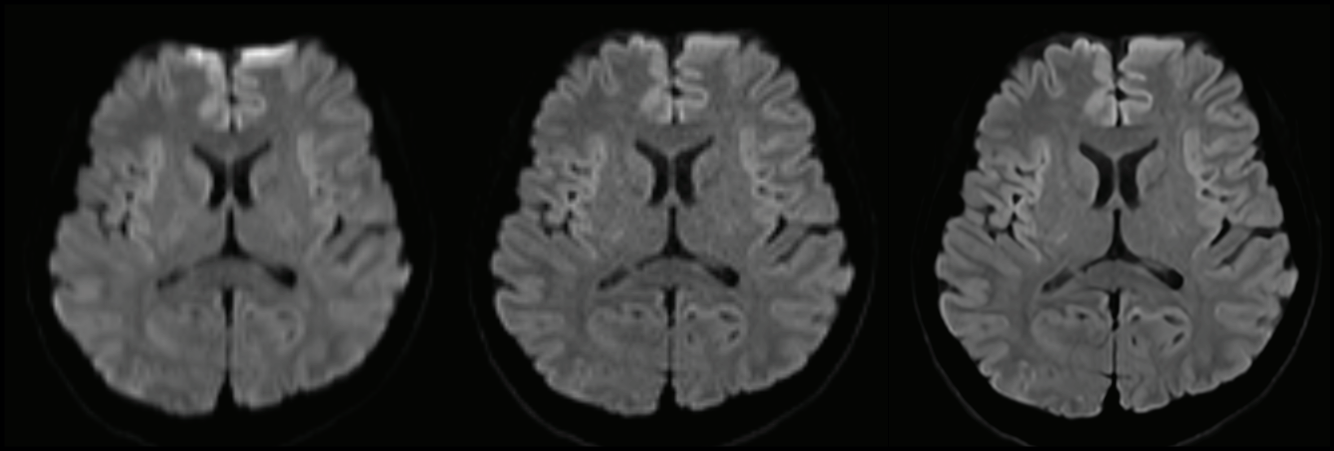

Figure 3. An example of achieving improvement in EPI geometric distortion artifact in brain diffusion weighted image (DWI). (Left) conventional image, 2D EPI Diffusion, 1.5 x 1.9 x 3.0 mm, PI factor=2, scan time=1m 30s (Middle) conventional image with modified scan parameters, 2D EPI Diffusion, 1.5 x 1.9 x 3.0 mm, PI factor=4, scan time=1m 30s (Right) SwiftMR™ reconstructed image from (Middle).

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[1] Not within the FDA-cleared indications for use of SwiftMR™

Cerebrospinal fluid (CSF) flow artifacts are frequently seen in brain 2D fluid-attenuated inversion recovery (FLAIR) images, which may be mistaken for subarachnoid hemorrhage (SAH). 3D FLAIR, employing a non-spatially selective inversion pulse for CSF suppression, is a good alternative but requires longer scan time for equivalent resolution. This issue can be resolved if the image acquisition is accompanied by scan time reduction strategies. **Figure 4** shows an example of transitioning from 2D to 3D FLAIR with the same scan time to mitigate CSF flow artifacts. Again, although this is achieved at the expense of SNR, SwiftMR™ compensates for this loss.

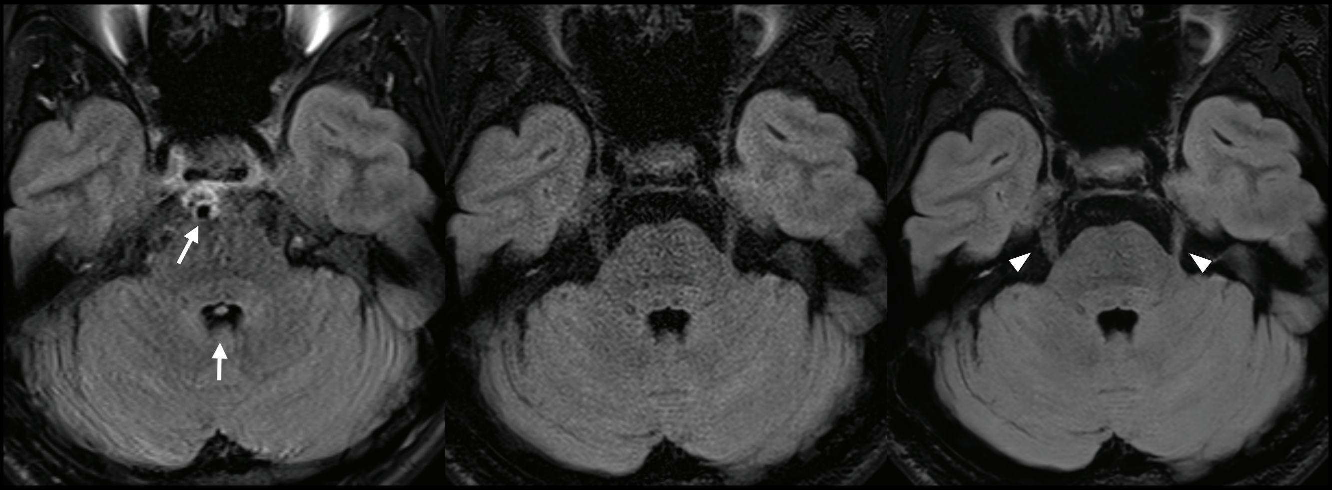

Figure 4. An example of achieving improvement in CSF flow artifact in brain FLAIR image. (Left) conventional image, 2D TSE, 0.6 x 0.8 x 4.0 mm, scan time=1m 15s (Middle) conventional image with modified pulse sequence, 3D SPACE, 0.7 x 0.8 x 3.0 mm, scan time=1m 15s (Right) SwiftMR™ reconstructed image from (Middle). CSF flow artifacts are visible in 2D FLAIR (arrows) but not in 3D FLAIR image. Cranial Nerve Ⅴ is clearly delineated in 3D FLAIR image due to the absence of these artifacts (arrowheads).

Contrast Improvement [2]

A representative example is in brain T1-weighted images (T1WI), where it is important to clearly differentiate between gray matter and white matter but is particularly challenging in the cerebellum. In the 3D magnetization-prepared rapid gradient echo (MPRAGE) pulse sequence, reducing the number of excitation pulses per inversion pulse while maintaining the interval between inversion pulses, or keeping the number of excitation pulses per inversion pulse constant while increasing the interval between inversion pulses, improves T1 contrast. This essentially provides more recovery time but also leads to an increase in scan time. Therefore, strategies for reducing scan time must accompany this. **Figure 5** illustrates an example where T1 contrast is improved while maintaining the scan time. SwiftMR™ has compensated the lost SNR.

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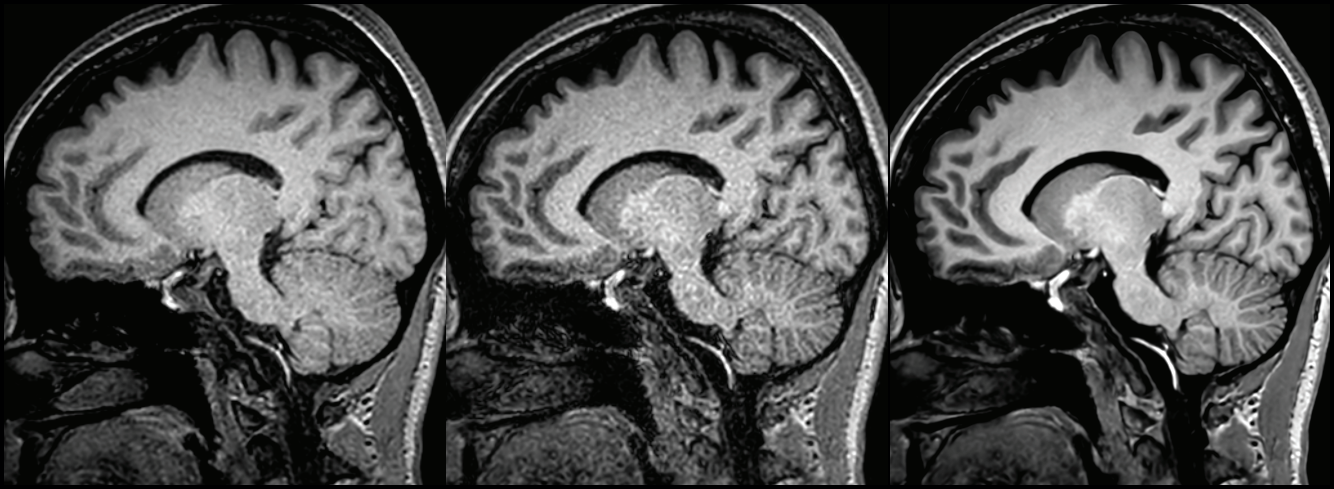

Figure 5. An example of achieving improvement in T1 contrast in brain T1WI. (Left) conventional image, 3D TFE, 1.0 x 1.0 x 1.0 mm, number of excitation pulses per inversion pulse=250, inversion pulse interval=2000 ms, PI factor=4, scan time=1m 10s (Middle) conventional image with modified scan parameters, 3D TFE, 1.0 x 1.0 x 1.0 mm, number of excitation pulses per inversion pulse=250, inversion pulse interval=3250 ms, PI factor=6, scan time=1m 10s (Right) SwiftMR™ reconstructed image from (Middle).

Temporal Resolution Improvement [3]

For dynamic or multi-phase imaging, including cine imaging, high temporal resolution is required to meet each specific imaging purpose. Scan time reduction strategies allow for a decrease in scan time per phase, leading to higher temporal resolution. Sacrificed SNR and spatial resolution of each phase image can be restored by SwiftMR™.

Basic Scan Parameter Settings for Maximum SwiftMR™ Compatibility

Regardless of specific clinical needs, there are universally recommended basic scan parameter settings to maximize SwiftMR™ compatibility. These are related to conventional filters and interpolation.

- Turning off the smoothing filter and sharpening filter options available on the scanner console is recommended.
- Setting the truncation removal k-space filter to its minimum intensity is recommended. SwiftMR™ will enhance the spatial resolution and alleviate truncation artifacts.
- For 3D pulse sequences, setting the slice interpolation factor to a value near 2 (making the slice reconstruction voxel size approximately half the slice acquisition voxel size) is recommended. This enables SwiftMR™ to improve spatial resolution in the slice direction as well.
- If the scanner console is equipped with a vendor-specific DL/AI-based reconstruction option, it is recommended to turn it off and let SwiftMR™ process it exclusively.

Summary

SwiftMR™ is a deep learning-based technology that enhances the SNR and spatial resolution of MR images. It can address various clinical needs, including the reduction of scan time and the improvement of image quality. The single guiding principle for setting the SwiftMR™-optimized protocol is illustrated again: "adjust the scan parameters to achieve desired outcomes by willingly sacrificing either SNR or spatial resolution. SwiftMR™ will compensate for any loss in SNR or spatial resolution." This article will serve as a guide in solving your clinical needs through SwiftMR™.

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[3] Not within the FDA-cleared indications for use of SwiftMR™.

contact@airsmed.com
T: +1 847-306-8731
airsmed.com/en

Chicago Office
475 North Martingale Rd. Suite 710
Schaumburg, IL 60173