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Boldly Going Where No One Has Gone Before – The Roadmap to 10-fold Accelerated Routine Musculoskeletal MRI Exams

"One man cannot summon the future."
– Lt. Cmdr. S'chn T'gai Spock

"But one man can change the present!"
– Capt. James Tiberius Kirk

Have you ever wondered about the excitement that Captain James T. Kirk, Kathryn Janeway, Jonathan Archer, Jean-Luc Picard, and their crews felt onboard a brand-new starship equipped with disruptive new technologies, ready to embark on a pioneering mission to *boldly go where no one has gone before?*

The Star Trek saga is built on quantum-leap-type technological advances that symbolize gatekeepers and door openers to new horizons in space and time. With every technological advancement, such as fusion reactor plasma-driven impulse engine, spacetime continuum-distorting warp-field drive, or organic displacement-activated mycelial spore network propulsion – Starfleet and the United Federation of Planets overcame boundaries, crossed distant frontiers, and reached new horizons.

The evolution of MRI has notable similarities. Multiple significant technological advancements have overcome technological boundaries and have successfully translated into clinical MRI applications that have continuously improved patient care. In terms of hardware, these advances include 3T field strength, high-gain receiver chains, high-performance gradients, fast radiofrequency pulse techniques, multi-channel technology, and high-density surface coil technologies [1]. In terms of pulse sequences, they include fast and turbo spin-echo acquisition techniques [2], parallel imaging acceleration [3], and simultaneous multi-slice acquisition [4].

While time and the time-space continuum are constants for us, a deep dive into the building blocks of the value of MRI identifies scan efficiency as central to almost every value component. MRI efficiency is a cornerstone for growing the availability and accessibility of MRI worldwide, improving the tolerability for patients undergoing MRI scans, limiting degrading motion artifacts on MR images, reducing the need for sedation and anesthesia in pediatric patients[1], decreasing contact and patient dwell times during the COVID-19 pandemic, and augmenting throughput for busy academic institutions and private centers [5].

At the dawn of this new decade image reconstruction and post-processing techniques artificial intelligence (AI) and machine learning mark the next technological breakthrough and affect almost every aspect of MRI [6] (Fig. 1).

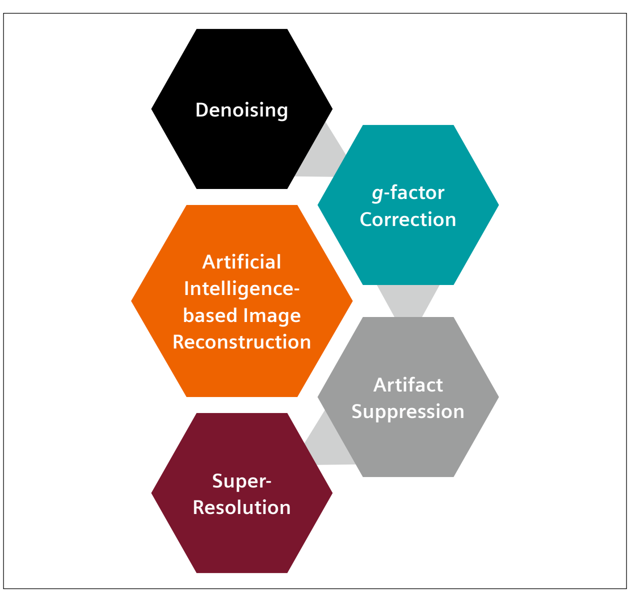
Particularly machine-learning-based image reconstruction and post-processing technologies will permit never-before-seen gains in scan-time efficiency and image-quality enhancements and further potentiate synergies with existing acceleration strategies, including echo-train compaction, parallel imaging, and simultaneous multi-slice acquisitions [5, 7].

Musculoskeletal MRI has achieved extraordinary gains in efficiency and image quality over the past decade with substantial contributions coming from the now widely used 3T field strength, high-performance surface coils, and the combined use of advanced acceleration techniques with fast and turbo spin-echo pulse sequences, which are essentially part of every musculoskeletal MRI protocol [1]. Effective and optimized use of these technologies is fundamental to maximizing the gains of machine-learning-based MRI.

For example, the optimized combined use of parallel imaging and simultaneous multi-slice now permits clinically available 4-fold accelerated musculoskeletal turbo spin-echo MRI in any contrast variation [4, 8]. This includes T1-weighted, proton density-, intermediate-, and T2-weighted tissue contrast, and multiple fat suppression techniques, including spectral, Dixon, and inversion-recovery fat suppression. Combining the above techniques with machine-learning-based image reconstruction will unlock multiple synergies, with 8-fold and even 10-fold accelerated turbo spin-echo pulse sequences in stellar image quality as the next breachable frontier – which could reduce 20-minute MRI exams to under 3 minutes (Table 1).

Imaging scientists and radiologists alike have already embarked on a momentous journey to new horizons in musculoskeletal MRI with unprecedented MRI efficiencies and acquisition speeds. It is my distinct honor to be a crew member on this journey – and even more so to editorialize this fine RSNA edition of MAGNETOM Flash. In addition to shining a spotlight on what is ahead, the purpose of this editorial is to highlight key components for the journey to 10-fold accelerated musculoskeletal turbo spin-echo pulse sequences and to sub-5-minute musculoskeletal MRI exams.

So, in the spirit of Captain Jean-Luc Picard: "Engage!"



1 Deep neural networks for artificial intelligence-based image reconstructions can include various components based on their training and intended use.

Acceleration Factor	Protocol Time [mm:ss]	Pulse-Sequence Time [mm:ss]
unaccelerated	20:00	04:00
2-fold	10:00	02:00
3-fold	06:40	01:20
4-fold	05:00	01:00
5-fold	04:00	00:48
6-fold	03:20	00:40
7-fold	02:51	00:34
8-fold	02:30	00:30
9-fold	02:13	00:27
10-fold	02:00	00:24

Table 1: Effect of acceleration factor on the acquisition times of MRI protocols and pulse sequences.

[1] *MR scanning has not been established as safe for imaging fetuses and infants less than two years of age. The responsible physician must evaluate the benefits of the MR examination compared to those of other imaging procedures.*

Resistance is futile: Artificial intelligence-driven image reconstruction

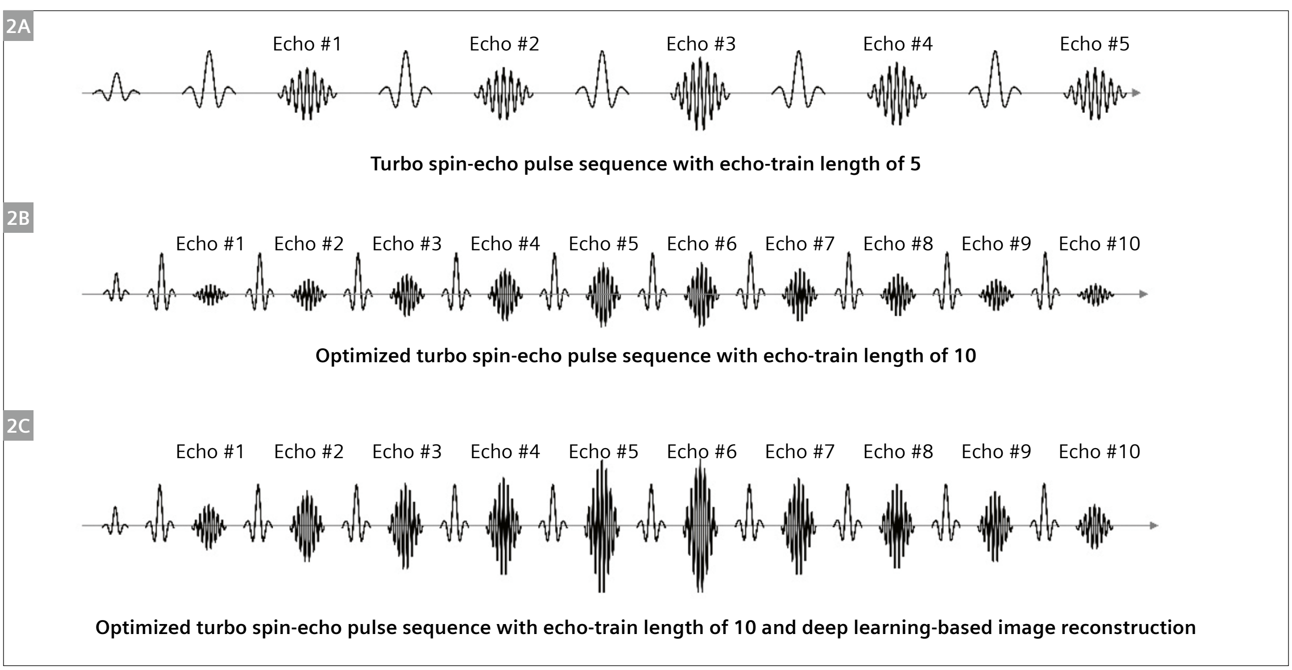
Deep neural networks used for artificial intelligence-based image reconstruction can include various components based on their training and intended use, such as denoising capabilities and *g*-factor corrections to increase the signal-to-noise ratio, artifact suppression techniques to correct aliasing artifacts of parallel imaging and interslice leakage of simultaneous multi-slice acquisition, as well as super-resolution techniques to increase image detail (Fig. 1) [9].

Make it so: Preparing pulse sequences for new frontiers

Regardless of whether one employs conventional or advanced acquisition schemes, image reconstruction techniques, or post-processing methods, using optimally designed pulse sequences for a specific application (such as a knee MRI protocol) remains fundamental to achieving the fastest scan times (Fig. 2).

In fact, pulse-sequence optimization before applying advanced techniques becomes even more important and rewarding as time savings arising from an optimally played pulse sequence multiply and could even potentiate when applying and combining higher-level acceleration techniques, such as parallel imaging, simultaneous multi-slice acquisition, elliptical scanning, and compressed-sensing-based undersampling. For example, a 10-second time saving achieved through careful optimization of the echo train could multiply to 80 seconds with subsequent 8-fold acceleration.

For musculoskeletal MRI, turbo spin-echo pulse-sequence techniques may be considered the *Bird of Prey*, as their versatility, technical performance, and diagnostic accuracy are unrivaled. Turbo spin-echo pulse sequences are a perfect target for next-generation acceleration because of their ability to generate true T1- and T2-weighted contrasts, and to combine favorably with many techniques, such as 2D and 3D acquisition schemes [10, 11], spectral, Dixon, and short-tau inversion recovery (STIR) fat suppression [12], high-bandwidth, view-angle-tilting (VAT), and SEMAC metal artifact suppression[2] [13], as well as acceler-



2 Effects of echo-train compaction of a turbo spin-echo pulse sequence and deep learning-based image reconstruction.
(2A) Turbo spin-echo pulse sequence with an echo-train length of five, acquiring five signals for every repetition time.
(2B) Optimized turbo spin-echo pulse sequence via echo-train compaction with fast radiofrequency pulses, high-performance gradients, and high receiver bandwidth permits acquiring ten signals for the same echo-train duration, which constitutes a factor two acceleration compared to the top row sequence.
(2C) The application of deep learning-based image reconstruction effectively results in higher visible signal gains, simplified here as relative gains of echo amplitudes.

[2]The MRI restrictions (if any) of the metal implant must be considered prior to patient undergoing MRI exam. MR imaging of patients with metallic implants brings specific risks. However, certain implants are approved by the governing regulatory bodies to be MR conditionally safe. For such implants, the previously mentioned warning may not be applicable. Please contact the implant manufacturer for the specific conditional information. The conditions for MR safety are the responsibility of the implant manufacturer, not of Siemens Healthineers.

ation methods including parallel imaging, simultaneous multi-slice acquisition [4], and compressed sensing-based sampling [11, 14].

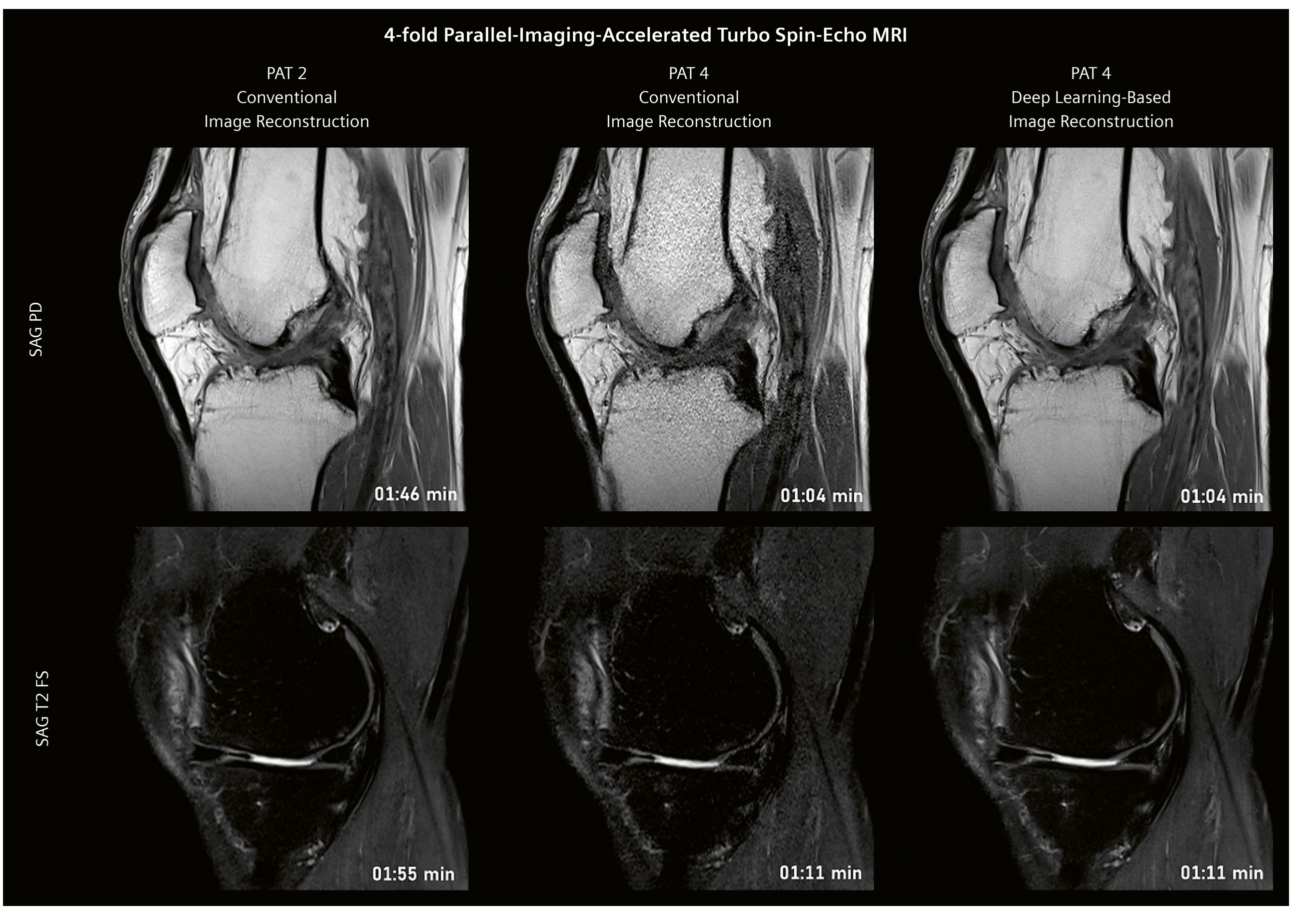
Proton density and intermediate-(PD)-weighted turbo pulse sequences with and without fat suppression are frequently used in musculoskeletal MRI due to their ability to maximize signal gain, to display fluid brightly for reliable detection of edema, inflammation, and collections, and to achieve high-contrast differentiation of ligaments, tendons, and articular and fibrocartilage, which naturally have lower concentrations of protons, and long T1 and short T2 constants.

Creating compact echo trains is crucial for optimal turbo spin-echo pulse sequences. Echo-train compaction describes a concept based on optimizing pulse-sequence parameters so that the maximum number of refocusing echoes can be applied in the shortest length of time needed to complete the echo train, resulting in the sampling of higher signal echoes and minimizing the introduction of image blur (Fig. 2).

The shorter the time between neighboring echoes (echo spacing), the more echoes can be sampled per time unit and within a certain length of time of an echo train. Shortening echo spacing will permit sampling of more echoes in the same length of time, or of the same number of echoes in a shorter time.

The three most important parameters for compacting echo trains are a fast radiofrequency pulse, maximum gradient performance, and high receiver bandwidth. All three factors substantially affect the baseline acquisition time, although they might not be specifically mentioned in commonly used pulse-sequence time equations.

Modern scanners allow users to choose how fast radiofrequency pulses will be executed within a turbo spin-

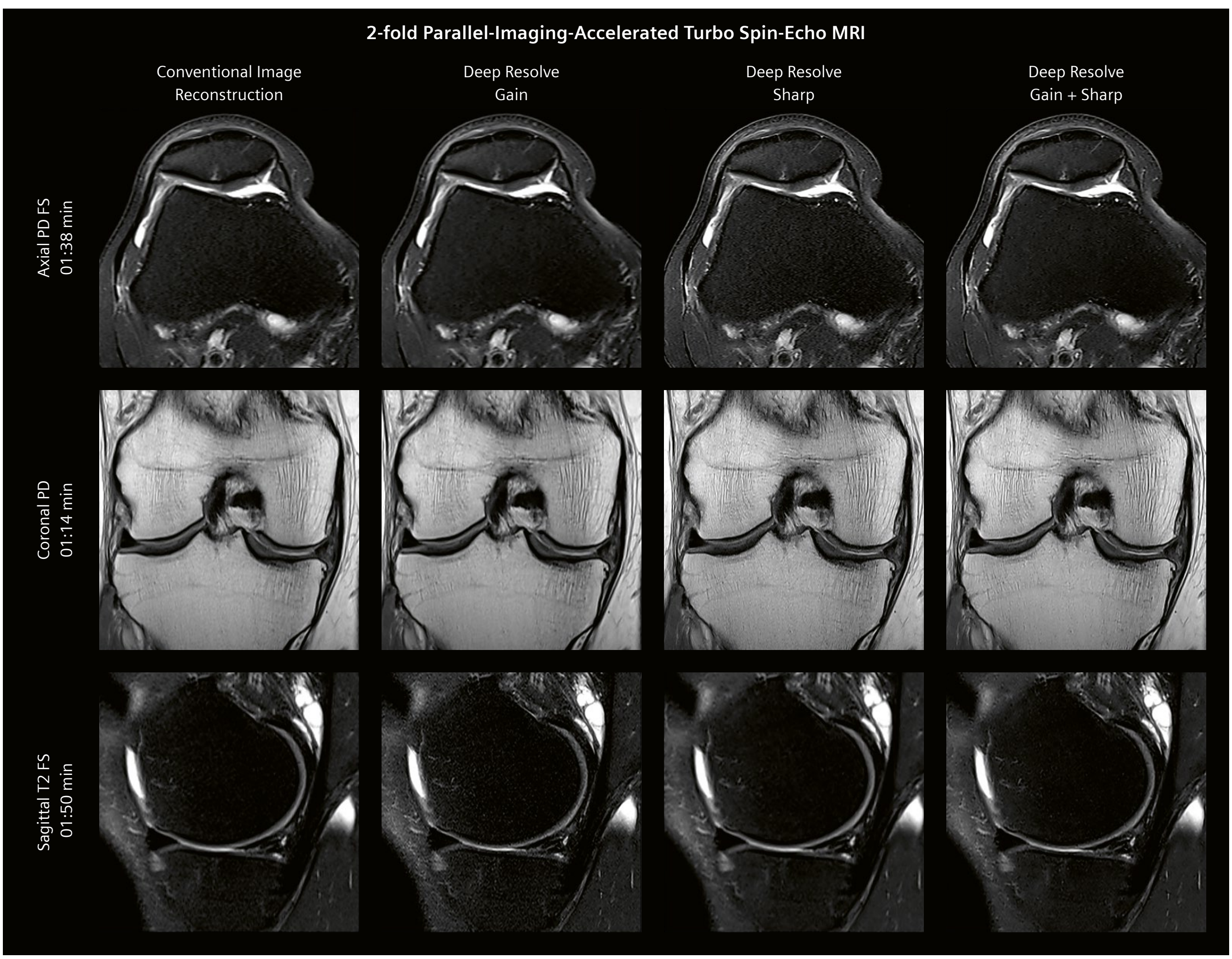


3 3-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using 2-fold and 4-fold parallel imaging acceleration (PAT) and conventional and deep learning-based image reconstructions. Application of deep learning-based image reconstruction using an algorithm developed by Facebook AI Research (FAIR) and NYU Langone Health [17] achieves similar or better image quality with 4-fold parallel-imaging-accelerated datasets than 2-fold parallel-imaging-accelerated datasets using conventional image reconstruction. The sagittal PD MR images show a partially torn anterior cruciate ligament. The sagittal fat-suppressed T2-weighted MR images show a torn anterior meniscus segment and high-grade articular cartilage loss of the central femoral condyle. The MR images were obtained with a 3 Tesla MAGNETOM Skyra MRI system and a 1-transmit-channel-15-receiver-channel knee coil. PD = proton density weighting, T2 FS = fat-suppressed T2-weighting, PAT= parallel acquisition technique using GRAPPA (GeneRalized Autocalibrating Partial Parallel Acquisition) echo pulse sequence. Radiofrequency pulses with shorter durations occupy less time, shorten echo spacing, and result in faster sampling. Compared to slower modes, faster radiofrequency pulses may impart more energy and increase the specific absorption rate (SAR).

The quality of a gradient system is indicated by the gradient speed (slew rate, [T/m/s]) and gradient strength [mT/m], which indicate how quickly and how powerfully gradient effects can be achieved [15]. Modern clinical MRI scanners with slew rates of 150–200 T/m/s and gradient strengths of 35–80 mT/m permit executing turbo spin-echo pulse sequences much faster than previous generations. Gradients have no direct effects on the SAR but may induce nerve-stimulating effects, which are usually well tolerated during musculoskeletal MRI. The "performance" gradient mode now gives users access to the highest gradient performance.

High receiver bandwidths enable faster sampling of MR signals and can therefore substantially contribute to short echo spacing and echo trains. Additional effects that are especially favorable to musculoskeletal MRI and the detection of small abnormalities are reduced chemical shift artifacts and improved sharpness of MR images. High receiver bandwidth results in overall lower strength of the MR signal and reduced SNR. However, the associated shortening of echo spacing leads to an earlier sampling of stronger MR signals, limiting signal losses.

The combined use of high-performance gradients, fast radiofrequency pulses, and high receiver bandwidth can substantially shorten the echo spacing of turbo spin-echo pulse sequences. Short acquisition times translate to shorter possible minimum required repetition times and higher possible echo-train lengths, which lays the foundation for multiplying and potentiating gains with advanced



4 3-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using 2-fold parallel imaging acceleration (PAT) and conventional and Deep Resolve image reconstructions. Application of Deep Resolve Gain reduces perceived image noise. Deep Resolve Sharp increases image detail. The MR images show a patellar cartilage fissure and complex meniscus tear. The MR images were obtained with a 3T MAGNETOM Skyra MRI system and a 1-transmit-channel-15-receiver-channel knee coil. Parallel imaging acquisition was performed with GRAPPA (GeneRalized Autocalibrating Partial Parallel Acquisition). PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting techniques. Carefully optimized turbo spin-echo pulse sequences that employ echo-train compaction can often yield a 2-fold acceleration factor.

Live long and prosper: Artificial intelligence-driven parallel imaging

Parallel imaging has proven to be one of the most effective and easy-to-use methods of accelerating turbo spin-echo pulse sequences. Based on sensitivity profile encoding of multi-element receiver coils, parallel imaging permits the undersampling of time-consuming phase-encoding steps. Effectively, parallel imaging saves acquisition time by sampling only every second (2-fold acceleration), third (3-fold acceleration), or even fourth (4-fold acceleration) phase-encoding step while keeping the field-of-view, matrix size, and spatial resolution unchanged. The number of omitted phase-encoding steps is proportional to the acceleration factor and will directly reduce the acquisition time (Table 1).

The SNR of an MR image will reduce proportionally to the square root of the acceleration factor. Hence, with conventional image reconstruction, acceleration factors above two often result in a detrimental increase in image noise and additional aliasing artifacts depending on the coil geometry (Fig. 3). Considering *g*-factor-related effects, 2-fold, 3-fold, and 4-fold parallel imaging accelerations result in approximately 29–36%, 41–48%, and 50–58% less SNR in musculoskeletal structures, respectively [7].

Deep Resolve is an artificial intelligence-based reconstruction method that combines targeted denoising and deep learning-based image reconstruction by incorporating noise maps acquired with the original data in a time-neutral fashion [16]. Deep Resolve Gain applies advanced denoising by extracting individually heterogeneous noise distributions, regaining SNR to better advantage than conventional denoising techniques. Deep Resolve Sharp utilizes a deep neural network to increase the sharpness of the reconstructed image (Fig. 4).

As a rule of thumb, aliasing artifacts and visible heterogenous noise enhancement are expected to occur when the acceleration factor exceeds the number of coil elements across the phase-encoding direction of the pulse sequence. For example, a parallel imaging acceleration factor of four will likely overwhelm the geometry of an 18-channel knee coil consisting of three rings in head-to-foot direction, and will therefore result in additional aliasing artifacts (Fig. 3).

Deep learning-based image reconstruction techniques that combine intelligent denoising and aliasing correction can reconstruct 4-fold accelerated MR image datasets with higher quality than achieved by conventional image reconstruction algorithms reconstructing 2-fold parallel-imaging-accelerated datasets [17] (Fig. 3).

Beam me up, Scotty: Artificial intelligence-driven simultaneous multi-slice acceleration

Simultaneous multi-slice acquisition of turbo spin-echo pulse sequences is a key technology for achieving artificial intelligence-based ultrafast musculoskeletal MRI as it favorably combines with parallel imaging acceleration and elliptical scanning, thereby multiplying acceleration factors [4].

While conventional turbo spin-echo pulse sequences obtain slice signals one after the other, simultaneous multi-slice acquisition techniques can acquire signals from multiple slices at the same time. Sharing some similarities with parallel imaging, dedicated deconvolution algorithms such as CAIPIRINHA [18] separate the mixed MR signals from the originating slices, using coil-sensitivity profiles, field-of-view shifts, and gradient encoding.

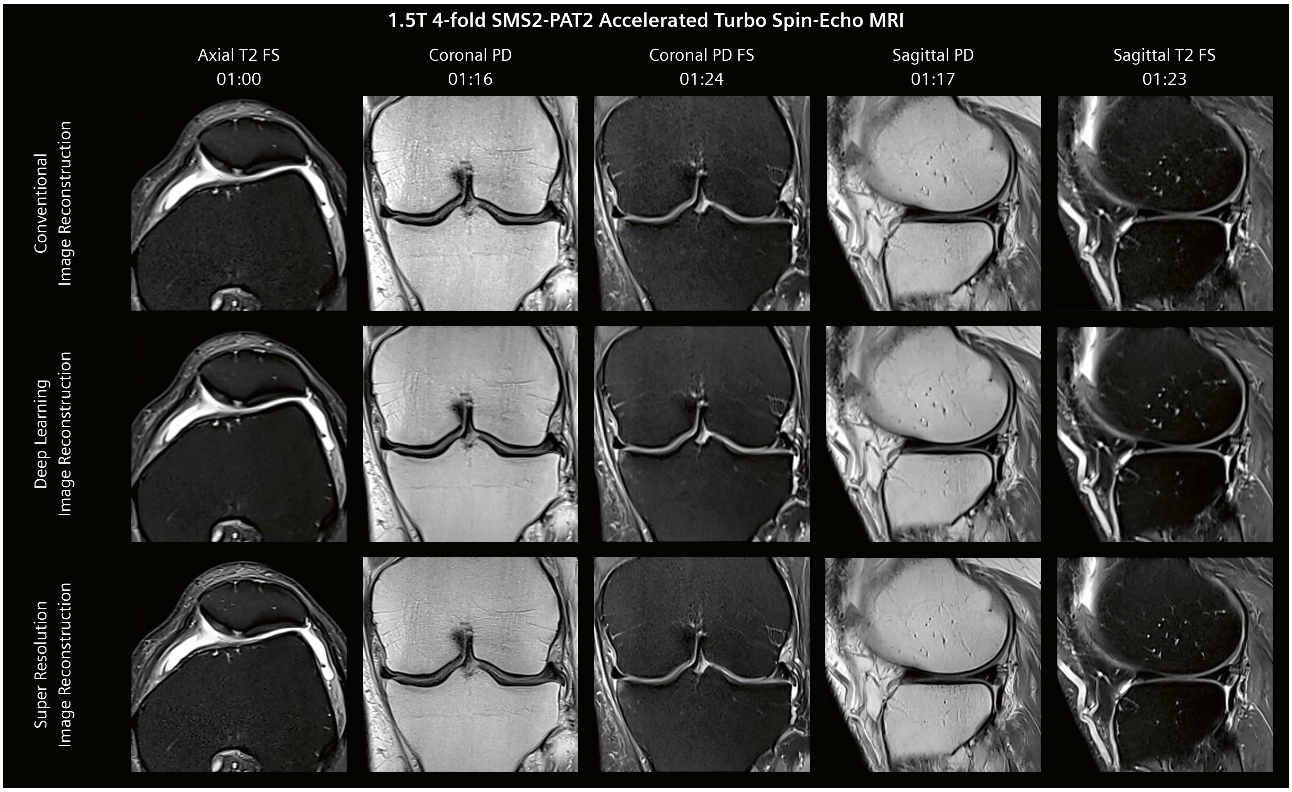
Simultaneous multi-slice acquisition effectively reduces the total repetition time of a multi-slice turbo spin-echo pulse sequence, which translates into direct and indirect time savings, including shorter possible repetition times, obviating concatenations and permitting longer echo trains, simultaneous acquisition of in-phase and opposed-phase echoes within Dixon-based acquisitions, as well as time-neutral use of a higher number of slices or reduction of interslice gaps, and repetition of time-consuming SPAIR fat suppression.

Simultaneous multi-slice acquisition synergizes favorably with parallel imaging acceleration [4]. In contrast to parallel imaging acceleration, simultaneous multi-slice acquisition is linked only to *g*-factor-associated signal loss, which is a fraction of the SNR loss of parallel imaging. On the other hand, SMS may result in higher SAR values because of the sum of simultaneously imparted radiofrequency pulses. However, dedicated radiofrequency pulse designs, flip angles of 125–150 degrees, and local transmit coils can substantially reduce SAR levels in peripheral joints.

When used in combination, the acceleration factors contributed by each technique multiply. For example, the combined use of simultaneous multi-slice acquisition and parallel imaging acceleration enables artifact-free, 4-fold accelerated turbo spin-echo acceleration for rapid 5-sequence knee MRI at 1.5T (Fig. 5 and Table 2), and at 3T (Fig. 6 and Table 3) with a much higher average SNR than 4-fold accelerated parallel imaging [8]. Combining deep learning-based image reconstruction with 4-fold accelerated simultaneous multi-slice acquisition and parallel imaging results in substantial SNR gains (Figs. 5, 6)[3].

Since deep neural networks have already been shown to reconstruct 4-fold parallel-imaging-accelerated datasets with image quality exceeding a conventionally recon-

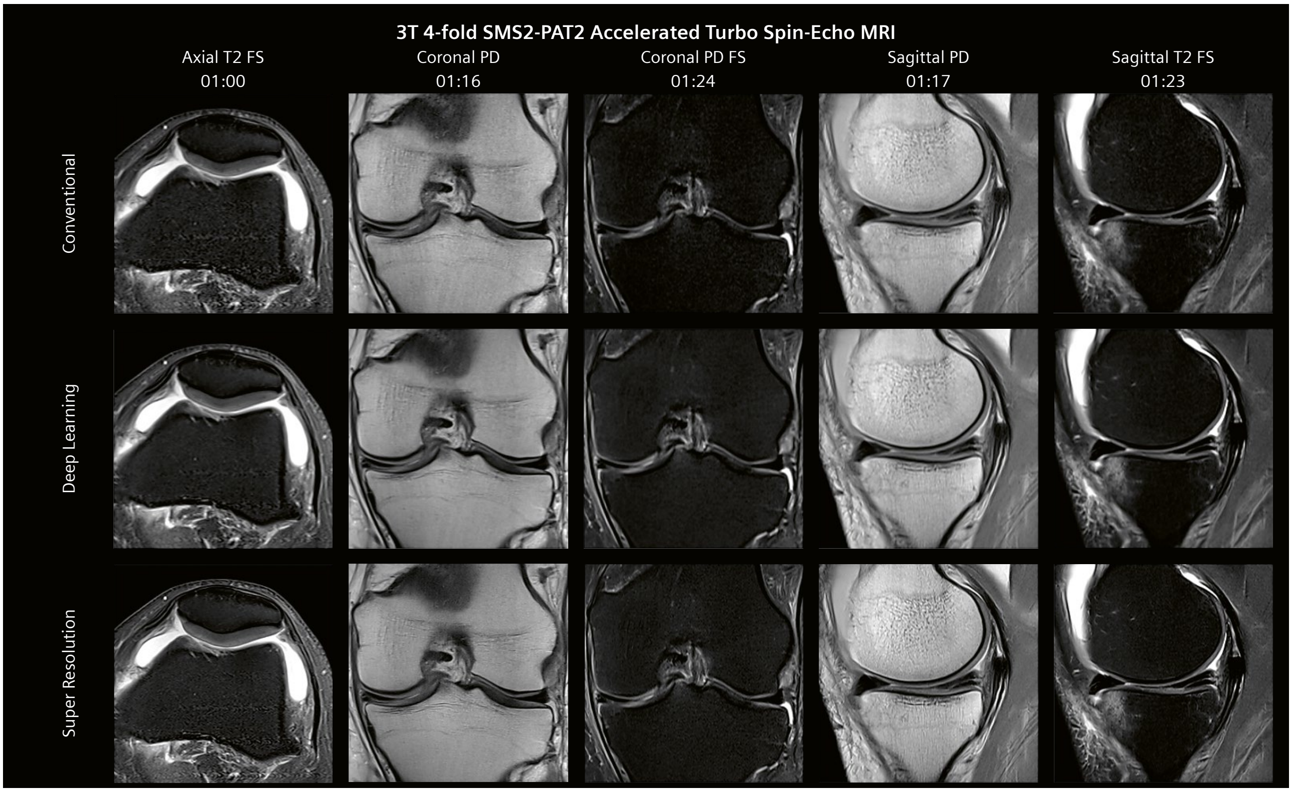
[3] *Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*



5 1.5-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using combined 2-fold parallel imaging and 2-fold simultaneous multi-slice acquisition acceleration and conventional and deep learning image reconstructions[3]. Application of deep learning-based image and super-resolution reconstruction substantially decreases image noise, increases perceived signal and contrast, and increases image detail. The MR images show a patellar cartilage defect and lateral meniscus tear with a displaced fragment in the inferior meniscosynovial recess. The MR images were obtained with a 1.5T MAGNETOM Sola MRI system and a 1-transmit-channel-18-receiver-channel knee coil. The MRI protocol is given in Table 2. PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting

Parameter	Ax T2 FS	Cor PD	Cor PD FS	Sag PD	Sag T2 FS
Repetition/echo time [ms]	4000/54	4000/37	3500/31	4000/37	4000/53
PI	2	2	2	2	2
SMS / FOV shift	2/2	2/2	2/2	2/2	2/2
Echo-train length	14	11	11	15	14
Bandwidth (Hz/px)	159	200	159	200	159
Echo spacing [ms]	10.8	9.31	10.3	9.31	10.6
FOV [mm]	160 × 160	160 × 160	160 × 160	160 × 160	160 × 160
Voxel size [mm]	0.55 × 0.69 × 3.0	0.45 × 0.56 × 3.0	0.56 × 0.69 × 3.0	0.45 × 0.56 × 3.0	0.56 × 0.69 × 3.0
Slices	40	40	40	36	36
Concatenations	1	1	1	1	1
Phase direction	right-to-left	right-to-left	head-to-foot	head-to-foot	head-to-foot
Acquisition time [mm:ss]	00:58	00:55	01:18	01:18	01:11

Table 2: NYU 1.5-Tesla 4-fold SMS2-PAT2 accelerated knee MRI protocol.
Ax = axial, Cor = coronal, sag = sagittal, PD = proton density weighted, FS = fat suppression, PI = parallel imaging acceleration factor, SMS = simultaneous multislice acquisition acceleration factor, TSE = turbo spin-echo, FOV = field-of-view



6 3-Tesla MRI of the knee with echo-train compacted turbo spin echo pulse sequences using combined 2-fold parallel imaging and 2-fold simultaneous multi-slice acquisition acceleration and conventional and deep learning image reconstructions[3]. Application of deep learning-based image and super-resolution reconstruction substantially decreases image noise, increases perceived signal and contrast, and increases image detail. The MR images show intact patellar articular cartilage and a nondisplaced horizontal medial meniscus tear. The MR images were obtained with a 3 Tesla MAGNETOM Vida MRI system and 1-transmit-channel-18-receiver-channel knee coil. The MRI protocol is given in Table 3. PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting

Parameter	Ax T2 FS	Cor PD	Cor PD FS	Sag PD	Sag T2 FS
Repetition/echo time [ms]	3600/57	4000/23	4000/35	4000/23	3700/56
PI	2	2	2	2	2
SMS / FOV shift	2/2	2/4	2/4	2/4	2/4
Echo-train length	11	11	11	11	9
Bandwidth (Hz/px)	296	354	301	354	301
Echo spacing [ms]	7.51	7.05	8.03	7.05	8.03
FOV [mm]	140 × 140	140 × 140	140 × 140	140 × 140	140 × 140
Voxel size [mm]	0.5 × 0.6 × 3.0	0.4 × 0.5 × 3.0	0.5 × 0.6 × 3.0	0.4 × 0.5 × 3.0	0.5 × 0.6 × 3.0
Slices	38	36	36	38	38
Concatenations	1	1	1	1	1
Phase direction	right-to-left	right-to-left	head-to-foot	head-to-foot	head-to-foot
Acquisition time [mm:ss]	01:00	01:16	01:24	01:17	01:23

Table 3: NYU 3-Tesla 4-fold SMS2-PAT2 accelerated knee MRI protocol.
Ax = axial, Cor = coronal, sag = sagittal, PD = proton density weighted, FS = fat suppression, PI = parallel imaging acceleration factor, SMS = simultaneous multislice acquisition acceleration factor, TSE = turbo spin-echo, FOV = field-of-view

structured 2-fold parallel-imaging-accelerated dataset [17], the door is now open to teaching deep neural networks to reconstruct SMS2-PAT3, SMS3-PAT3, SMS2-PAT4, and SMS3-PAT4, which may exceed a total acceleration factor of 10 (Fig. 9)[3].

Set phasers to stun: Artificial intelligence-driven matrix interpolation and super-resolution images

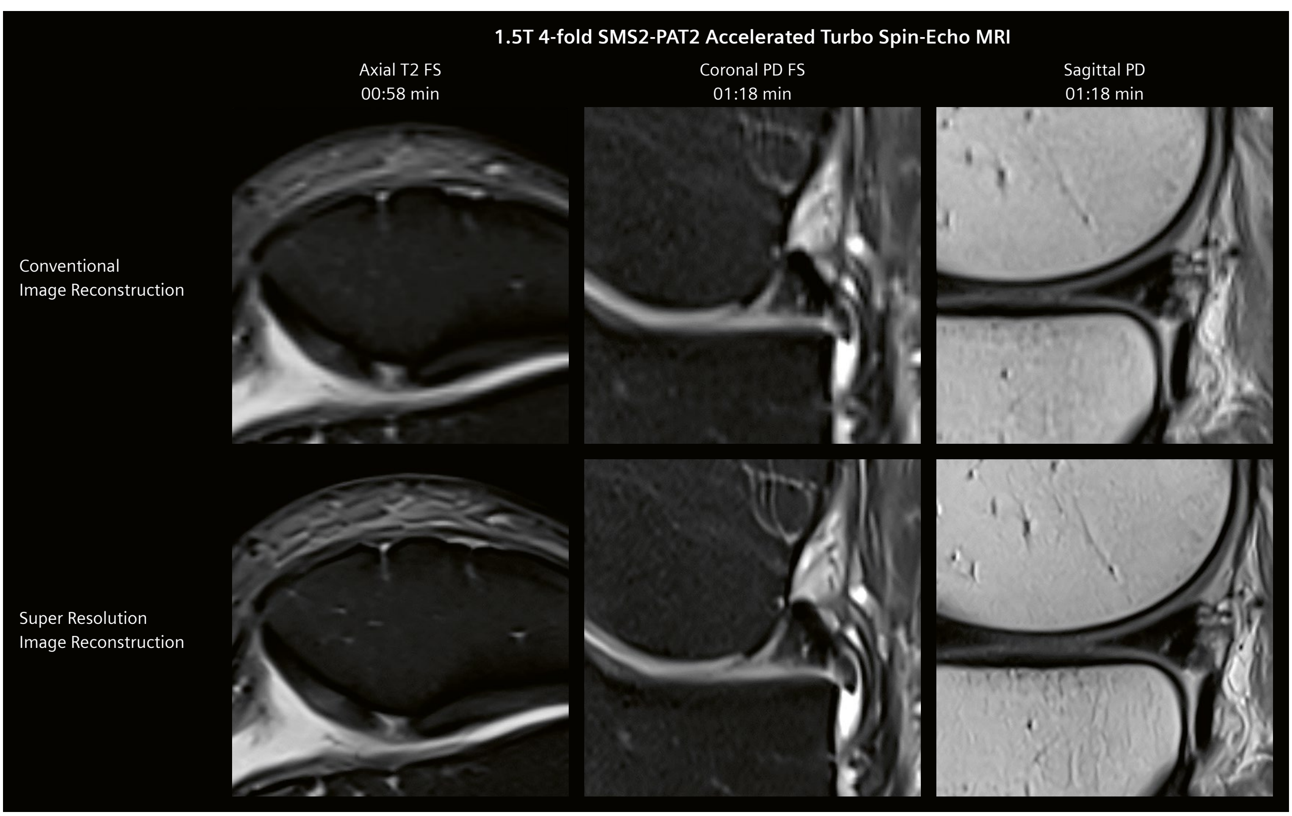
Acquiring MR images with higher spatial resolution to resolve small musculoskeletal structures and abnormalities with greater detail is a costly endeavor because of the inverse square-root relationship between increasing spatial resolution and SNR loss.

Hence, technologies that can accurately convert MR images from an acquired lower resolution to calculate or predict higher spatial resolutions could substantially increase scan efficiency [5]. MRI datasets could then be acquired with lower matrix resolution in shorter acquisition times. Conversely, higher image quality could be achieved without the need for longer scan times.

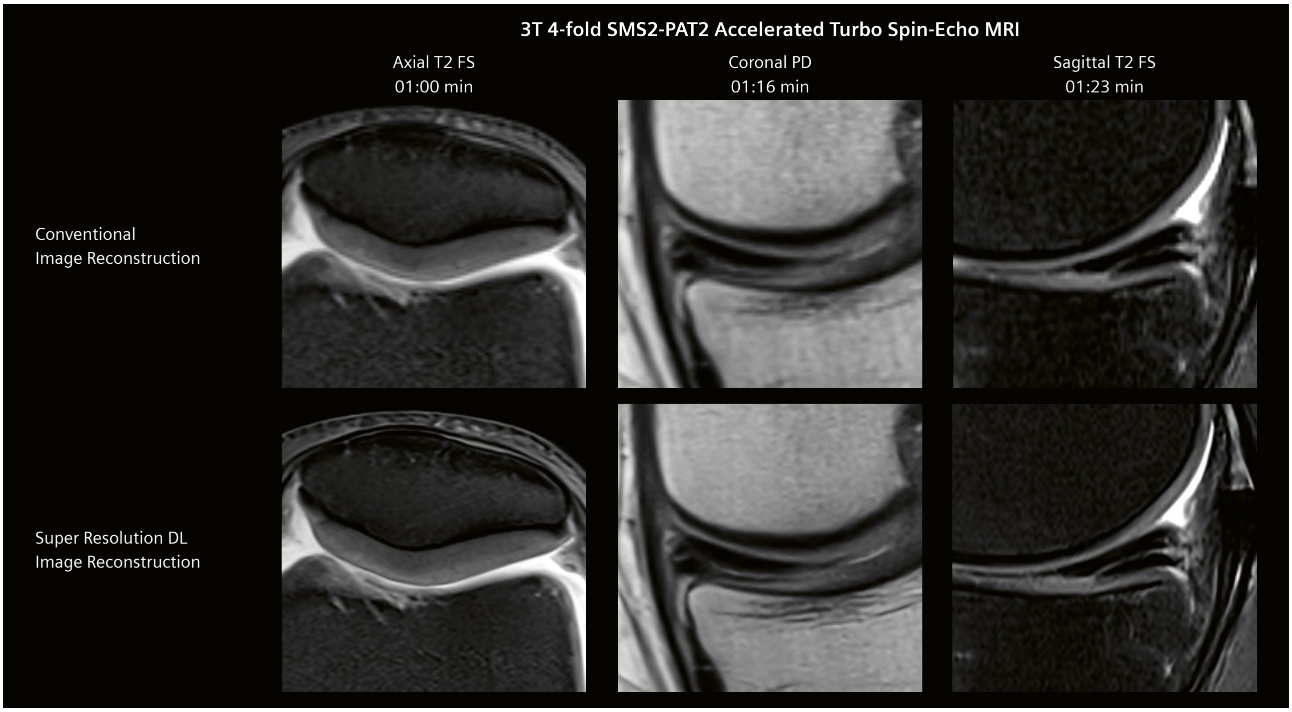
Various conventional *k*-space- and image-domain-based matrix interpolation techniques have been applied in the past, including adding empty data (zero filling) or mathematically estimated data. While basic interpolation techniques may not add information, improved edge sharpness and reduced partial volume effects have been achieved in some cases.

Deep Resolve Sharp is a super-resolution algorithm based on deep neural networks that increases image detail and sharpness of MR images acquired with various pulse sequences and image contrast [16]. The algorithm combines matrix expansion and accurately predicts higher spatial resolution information based on its extensive training with many pairs of low-resolution and high-resolution MRI datasets.

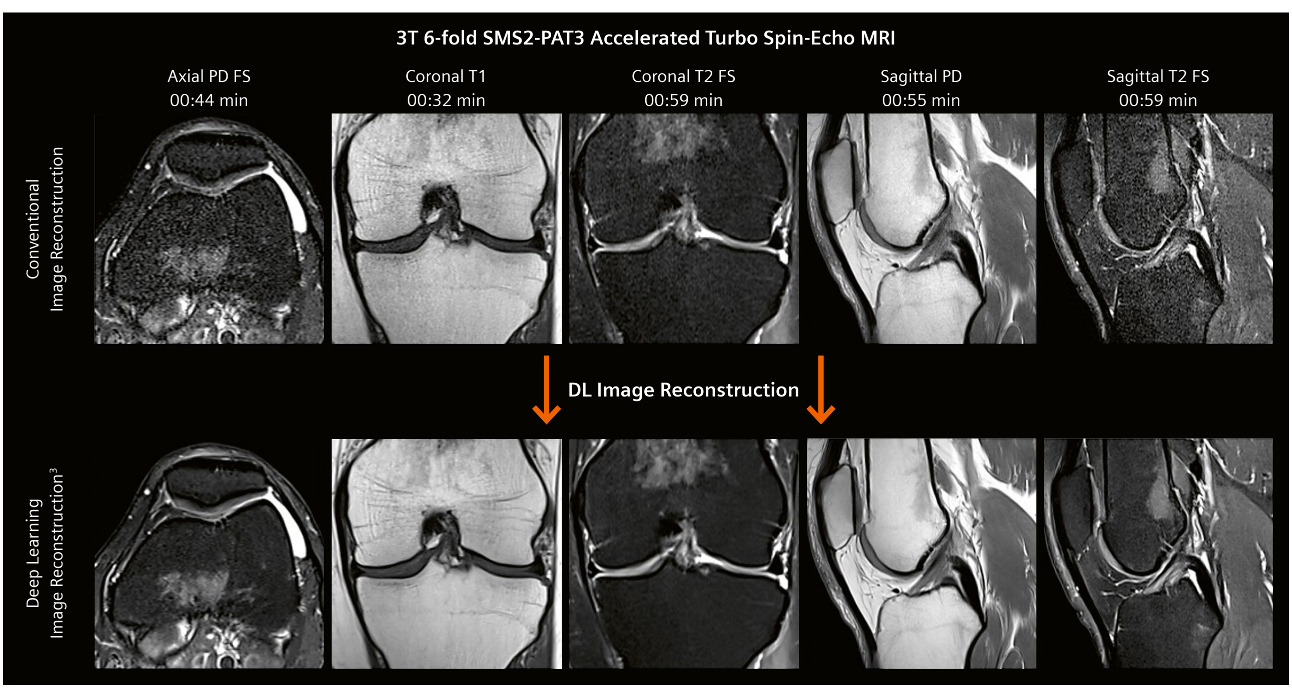
Deep Resolve Sharp can be combined with other deep learning-based image reconstruction algorithms and acceleration techniques, such as combined parallel imaging and simultaneous multi-slice acquisition with, indeed, *stunning* increases in sharpness, detail, and overall image quality (Figs. 7, 8).



7 1.5-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using combined 2-fold parallel imaging and 2-fold simultaneous multi-slice acquisition acceleration and conventional and deep learning image reconstructions. The application of Deep Resolve Sharp super-resolution reconstruction greatly increases the detail of the patellar cartilage defect and the displaced lateral meniscus tear. The MR images were obtained with a 1.5T MAGNETOM Sola MRI system and a 1-transmit-channel-18-receiver-channel knee coil.
PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting



8 3-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using combined 2-fold parallel imaging and 2-fold simultaneous multi-slice acquisition acceleration and conventional and deep learning image reconstructions. The application of Deep Resolve Sharp super-resolution reconstruction greatly increases the detail of the intact patellar articular cartilage and nondisplaced horizontal medial meniscus tear. The MR images were obtained with a 3T MAGNETOM Vida MRI system and a 1-transmit-channel-18-receiver-channel knee coil. PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting



9 3-Tesla MRI of the knee with echo-train-compacted turbo spin-echo pulse sequences using combined 2-fold simultaneous multi-slice acquisition and 3-fold parallel imaging acceleration and conventional and deep learning image reconstructions[3]. The application of deep learning image reconstruction permits artifact-free MR image reconstruction with high signal, low noise, and high anatomical detail. The MR images were obtained with a 3T MAGNETOM Vida MRI system and a 1-transmit-channel-18-receiver-channel knee coil. PD = proton density weighting, PD FS = fat-suppressed proton density weighting, T2 FS = fat-suppressed T2 weighting

Things are only impossible until they're not: Conclusion

Driven by synergies of high-performance scanner technologies, advanced acceleration techniques, and artificial intelligence-based image and super-resolution reconstructions, we are already well on our way to new horizons and to crossing new musculoskeletal MRI frontiers with acceleration factors that no one believed were possible. Each parsec of the journey will add a value component to MRI, ultimately benefiting patients, institutions, and societies in multiple ways. *We are, indeed, boldly going where no one has gone before!*

Live long and prosper 🖖,

Jan Fritz

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