Initial Clinical Experience with an Iterative Denoising Algorithm Applied to Reduced-data 2D Turbo Spin Echo Acquisitions

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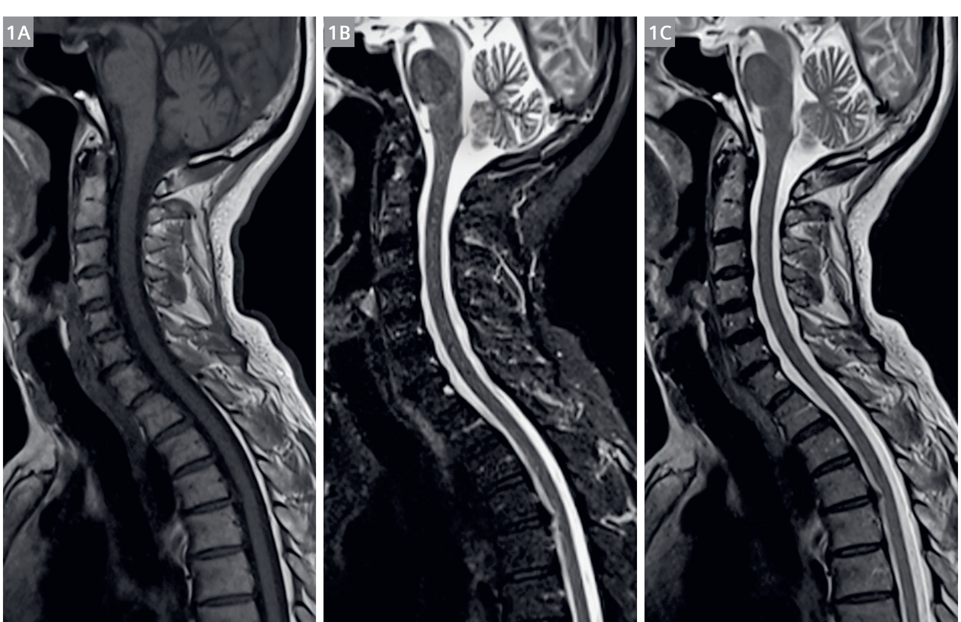
Introduction

Magnetic Resonance Imaging (MRI) with standard 2D Turbo Spin Echo (TSE) sequences is a trusted technique to guarantee excellent soft tissue contrast in musculoskeletal (MSK), neurological, and abdominal imaging. The signal and contrast behavior are well understood and appreciated by the reading radiologist and referring physicians alike. The acquisition time of these 2D TSE sequences is in the order of several minutes, hence has always been a point of attention. With the introduction of parallel imaging [1], acquisition times could be sped up, typically by an acceleration factor (p) of two or three, by only acquiring a fraction of the data lines in *k*-space and calculating the missing data lines taking into account the coil-sensitivity profiles. The well-known standard 2D TSE soft tissue contrast behavior is not affected by this acceleration. However, as a rule of thumb, higher acceleration factors do induce some noise in the image by a factor of $\sqrt{p}*G$ where G stands for geometry factor (G is close to 1 in a perfect system), limiting the practical acceleration factor to two or three. Note that it is common practice to combine parallel imaging and multiple averages, since motion effects can be minimized by the shorter acquisition times of the former, while regaining SNR with the latter, which has advantages over un-accelerated acquisitions of the same duration.

At the same time elaborate denoising methods have been developed which have to balance noise removal and preservation of details [2]. A recently introduced acceleration technique with strong data under-sampling, allowing for significantly higher acceleration factors, for example five or higher, is Compressed Sensing (CS) [3]. CS works best in combination with random undersampling of multidimensional data, and the reconstruction algorithm can achieve both image restoration and denoising. Pushed to the limit, the CS images may appear unnatural, so that both radiologist and referring physician need to get used to this new sequence, to gain experience with a new



1 Parallel imaging p2: halving acquisition time with acceleration factor 2 comes with a signal loss by $\sqrt{2}*G$, best noticeable in the T2 stir images; acquisition time 46 seconds T1 TSE **(1A)**, 47 seconds T2 STIR TSE **(1B)**, and 68 seconds T2 TSE **(1C)**.

signal and contrast behavior, a new look and feel of the soft tissue contrast. Regular 2D TSE data does not seem to be optimal for CS reconstruction.

Image reconstruction based on artificial intelligence (AI) / deep learning (DL) is the latest development capable of denoising [4]. These techniques, however, require large amounts of training data, which was beyond the scope of this study.

Iterative denoising (ID) is a technique which uses similar noise-suppressing operations as Compressed Sensing, but which is specifically designed to be combined with standard parallel imaging and other standard imaging techniques, allowing for shorter scan times and/or higher resolution while compensating for the resultant SNR loss [5]. First applications focused on volumetric acquisitions [6]. This study presents initial experience with this technique applied to standard 2D TSE data in multiple body regions.

Methods and materials

The goal of this study was to investigate whether the new iterative denoising technique can compensate for the resultant SNR loss when using higher acceleration in standard 2D TSE imaging. To make this comparison between images with higher acceleration versus standard acceleration as accurate as possible, instead of rescanning patient with higher acceleration factors, higher acceleration was simulated by discarding one average from the raw data sets. By applying this simulated acceleration, it was possible to obtain datasets that are – except for the virtual acceleration – completely identical.

Eleven clinical data sets from the perineum, uterus, prostate, l-spine, and sacroiliac joint were acquired on a 1.5T clinical MR scanner (MAGNETOM Sola, Siemens Healthcare, Erlangen, Germany) with the standard turbo spin echo (TSE) sequence. Raw data allowing retrospective image reconstruction with subsets of the originally acquired averages was collected from regular patient examinations so that no additional or modified scans had to be performed. Informed consent from patients was obtained to reprocess anonymized data for clinical research. All raw data sets featured Parallel Imaging under-sampling and comprised two or more signal averages.

Data processing was performed offline and with the help of a prototype implementation of the ID algorithm as described in [4], integrated into the image reconstruction pipeline. Quantitative noise measurements were drawn from the system's adjustment framework. Taking into account all noise-modifying operations, a noise map was calculated which describes the spatial noise distribution in coil-combined, complex-valued images after the parallel imaging reconstruction [7, 8]. Then the wavelet thresholding is automatically adjusted for MMSE-optimal noise removal according to "Stein's Unbiased Risk Estimator" (SURE) [9]. This automated parameter selection allows the algorithm to adapt to both the noise and signal characteristics of each individual image and to generalize to multiple body regions and scan protocols without additional manual tuning. Some edge enhancement was applied after the ID to compensate for perceived loss in sharpness.

From each multi-average raw data set three different versions of the images were reconstructed. The first version (called "original") used all available averages and corresponds to the regular reconstruction; it does not use the denoising algorithm. To simulate accelerated acquisition, the second reconstruction version discarded one signal average from the raw data sets, e.g. one out of two; it also did not use the iterative denoising algorithm and is called "accelerated". The third reconstruction version discarded the same signal average from the raw data sets, and additionally applied the described iterative denoising algorithm. These images are called "accelerated + ID".

The versions "accelerated" and "accelerated + ID" simulate accelerated acquisition by lowering the number of averages. With this simulation approach the three versions are based upon as similar data sets as possible so that they can be directly compared. They derive from the same acquisition so that all variations between repeated scans can be avoided. However, the data is not identical because version two and three only use a subset of the data. Hence effects like physiological motion still can have a different effect on the different versions – especially if the motion happens during the discarded part of the raw data.

The described versions of the images were viewed side-by-side on an open source DICOM viewer (Horos™) and ranked by an experienced radiologist according to image quality in terms of perceived signal to noise ratio as well as noticeable artifacts like blurring. Any non-diagnostic image quality was marked. Given the obvious differences between the image versions, no effort at blinding was made.

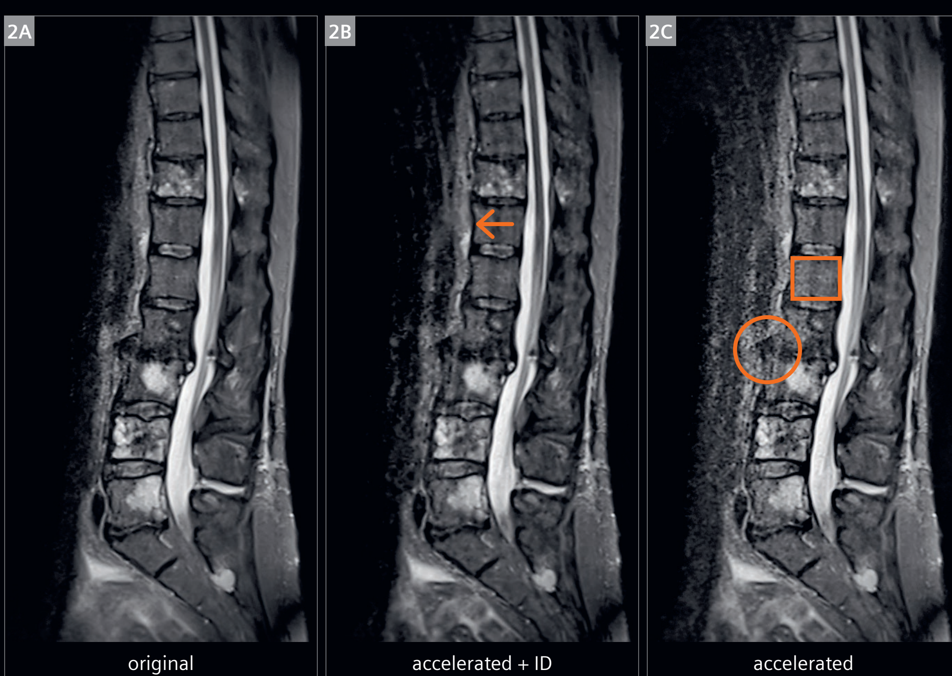
Results

Table 1 lists the ranking results. In 10 out of 11 cases (91%), the "original" version was ranked best. Of the "accelerated" versions, study 2 (Figs. 2, 3) is no longer diagnostic (marked as X). All "accelerated + ID" versions were ranked better than the "accelerated" versions, and all were diagnostic. In study 5 (Fig. 5) the image quality in the "accelerated + ID" version equals the image quality of the "original" version. In study 11 (Figs. 7, 8) the image quality of the "original" is less than the image quality of both the "accelerated + ID" images and "accelerated" images. Example image features are described in the figure captions.

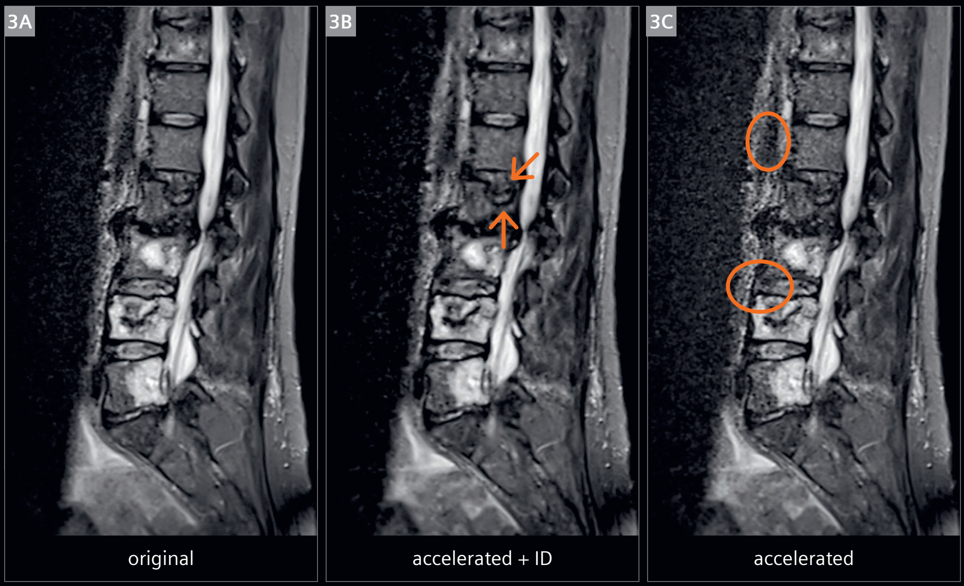
study #	contrast	# of averages, [timesaving]	best image	2nd best image	3rd best image
1	STIR SI joint, cor	2 [50%]	“original”	“accelerated + ID”	“accelerated”
2	STIR L-spine, sag	2 [50%]	“original”	“accelerated + ID”	“accelerated” (X)
3	T1 L-spine, sag	2 [50%]	“original”	“accelerated + ID”	“accelerated”
4	T1 L-spine, sag	2 [50%]	“original”	“accelerated + ID”	“accelerated”
5	T2 uterus, cor	3 [33%]	“original” = “accelerated + ID”	“accelerated”	–
6	T2 prostate, ax	3 [33%]	“original”	“accelerated + ID”	“accelerated”
7	STIR SI joint, cor	2 [50%]	“original”	“accelerated + ID”	“accelerated”
8	STIR SI joint, cor	2 [50%]	“original”	“accelerated + ID”	“accelerated”
9	STIR SI joint, cor	2 [50%]	“original”	“accelerated + ID”	“accelerated”
10	T2 uterus, sag	2 [50%]	“original”	“accelerated + ID”	“accelerated”
11	T2 perineum, ax	4 [25%]	“accelerated + ID”	“accelerated”	“original”

Table 1: Results from the side-by-side reading of an experienced radiologist.

Study 2

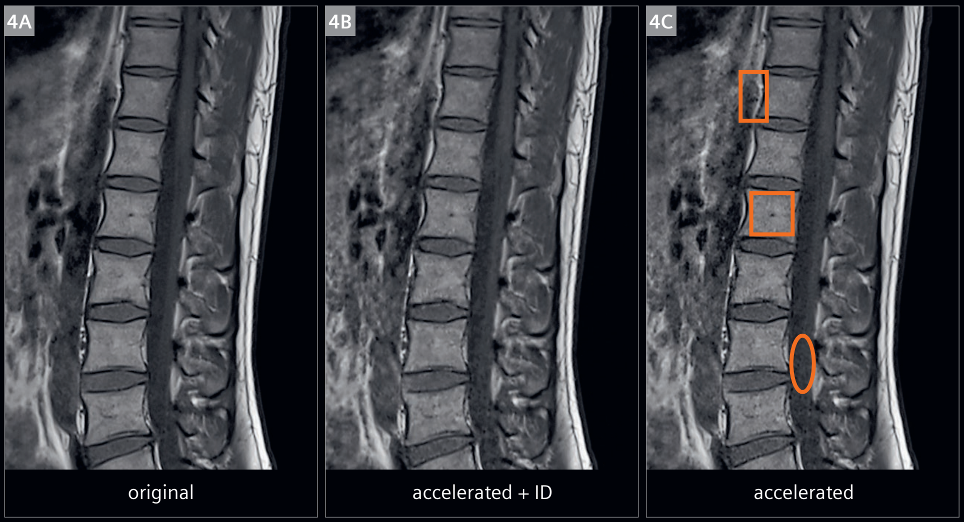


2 The “original” version **(2A)** with two averages has the best image quality since two averages are effectively averaging out the ghosting artifact. On top of the ghosting, version “accelerated” **(2C)** has a very low SNR with a "grainy unsharpness" e.g. in the body of vertebra L1 (square box) or prevertebral space (red circle) and intervertebral space level L2–L3 making this image non-diagnostic. In version “accelerated + ID” **(2B)** the "grainy blurriness" is effectively removed (arrow points to substantial SNR gain in prevertebral space). This leads to a still challenging but more diagnostic image quality resembling the morphology and contrast of the “original” version, e.g. in the endplates L2–L3. Simulated acquisition time saving: 50%. Scanning parameters: TE 99 ms, TR 4570 ms, TI 140 ms, duration for original (two averages) 1:17 min.



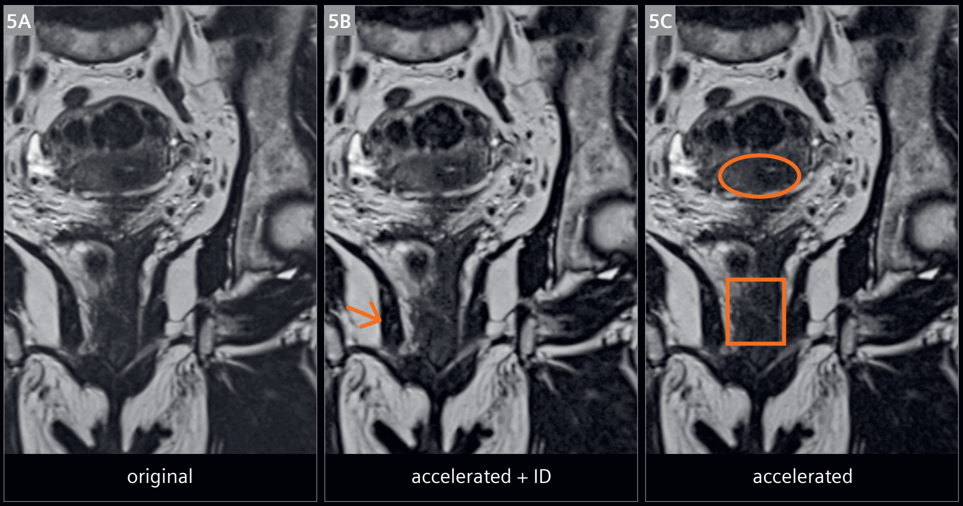
3 Same patient as Figure 1. Image zoomed in and slightly off midline. Version "accelerated" **(3C)** is severely impaired by both low SNR and ghosting artifact. The exaggerated noise level makes it of questionable diagnostic value (red circles indicate low SNR).Version "accelerated + ID" **(3B)** still suffers from ghosting artifact, however the ID algorithm processing of the image effectively removes the grainy pattern over the vertebral bodies and prevertebral fat plane. The resulting image quality improvement makes it easy to delineate the intravertebral disc herniation (red arrows).

Study 3



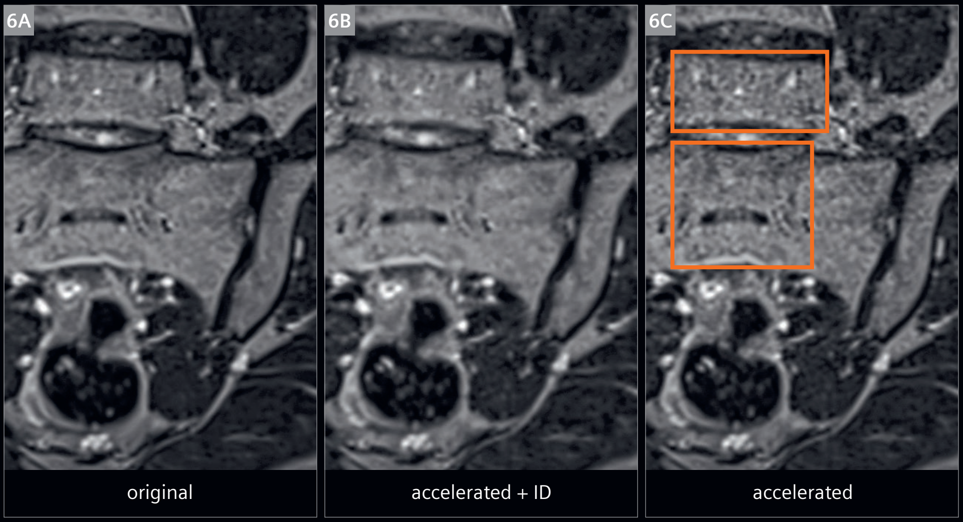
4 The "original" version **(4A)** with two averages has crisp image quality in this "perfect patient". Version "accelerated" **(4C)** features an exaggerated noise level in comparison to the "original" (red squares). The SNR of version "accelerated + ID" **(4B)** is still lower than in the "original" version; however, in comparison to the "accelerated" version SNR is clearly higher. Simulated acquisition time saving: 50%. Scanning parameters: TE 8 ms, TR 603 ms, duration for original 1:38 min.

Study 5



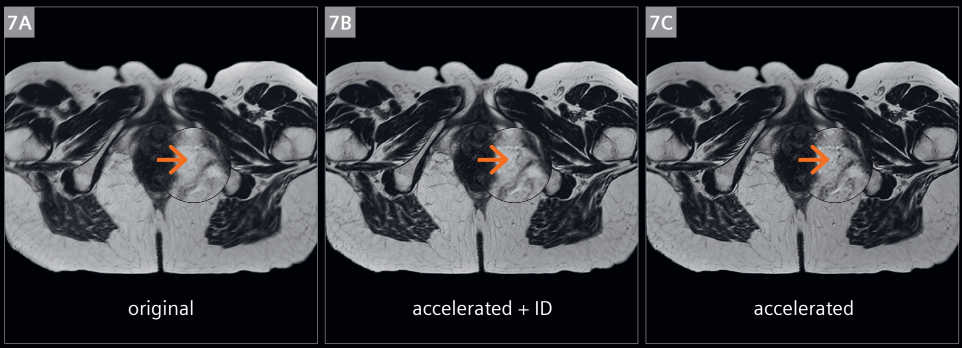
5 All three images are of diagnostic quality with high signal. Some graininess indicating lower SNR is present in the "accelerated" image **(5C)** over the uterus (red oval) and vagina (red box). This grainy superposition is removed after ID in version "accelerated + ID" **(5B)**. The resulting image in version "accelerated + ID" (center) matches very closely the image quality of the "original" version **(5A)**. The version "accelerated + ID" (center) has the highest overall SNR without graininess. Taking a closer look at details e.g. the fatty streaks in the right ischiococcygeal muscle (red arrow): these small fatty streaks are depicted with the same confidence as on the original image, indicating that no image detail is lost during ID. Simulated time saving: 33%. Scanning parameters: TE 132 ms, TR 7780 ms, duration for original 1:25 min.

Study 7

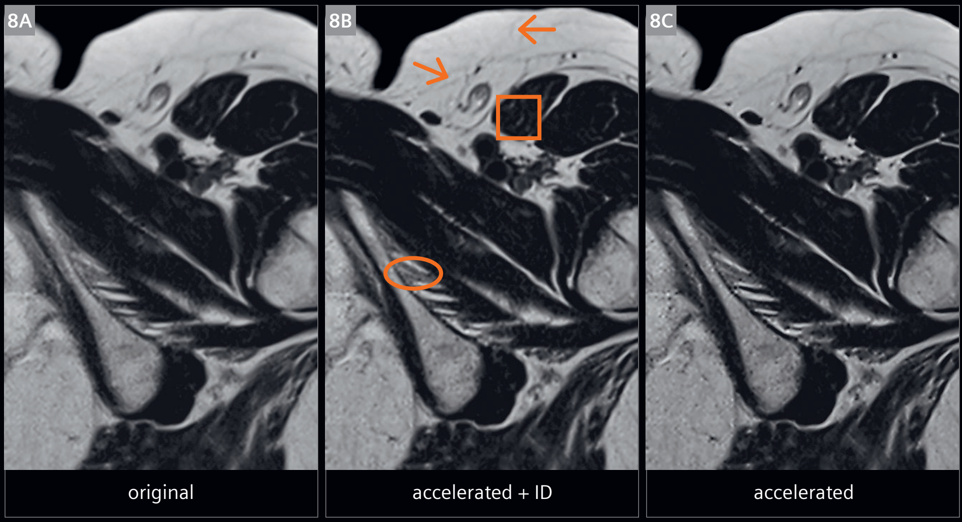


6 The "original" version **(6A)** with two averages has the best image quality. Version "accelerated" **(6C)** has a low signal to noise with impressive "graininess" (square boxes) over the fifth lumbar and first sacral vertebra. In version "accelerated + ID" **(6B)** the overlying "graininess" is effectively removed resulting in an image with SNR resembling the "original" version. Simulated acquisition time saving: 50%. Scanning parameters: TE 87 ms, TR 3400 ms, TI 140 ms, duration for original 0:52 min.

Study 11



7 Version “original” **(7A)** has abundant signal, however, some blurring is present. Version “accelerated” (right) and “accelerated + ID” **(7B)** have less blurring since less measurement time leads to less patient movement, but still have abundant signal. This abundance in signal results in an image quality where for instance the veins in the ischiorectal fossa are better depicted in both versions “accelerated” **(7C)** and “accelerated + ID” (center) than on the original version. Although high enough SNR is present in version “accelerated” (right), ID further enhances the image quality in “accelerated + ID” (center) image: the small venous bifurcation (red arrow, magnifying glass) in the left ischiorectal fossa is better depicted after ID (center). Simulated time saving: 25%. Scanning parameters: TE 106 ms, TR 814 ms, duration for original 4:12 min.



8 Same study as Figure 7: In version “original” **(8A)** the small fibrous strands in subcutaneous fat are hard to depict even though they are clearly present on the “accelerated” version **(8C)** and really stand out on the “accelerated + ID” version (red arrows). The fatty streaks (red circle) in between the muscle fibers of the external obturator cannot be seen on the “original” version, they are however visible on the “accelerated” version and really stand out on the “accelerated + ID” version **(8B)**. The ID algorithm does not only increase SNR but also enhances image details, for example the fatty streaks in the iliac muscle (red box). The internal structure with fat-containing hilum of the left inguinal lymph node (between the red arrow and red box) is again best depicted on the “accelerated + ID” version. Simulated time saving: 25%. Scanning parameters: TE 106 ms, TR 814 ms, duration for original 4:12 min.

Discussion

Acquiring a dataset that is substantially accelerated (by reducing the number of averages) leads to a discernible drop in signal to noise ratio. This is rendering the resulting images grainy and harder or even sometimes impossible to interpret, with an obvious drop in image quality in comparison to the "original" images. The results of this small-scale study provide evidence that the process of ID as described above can compensate for the drop in signal to noise ratio in substantially accelerated 2D datasets.

In this study the perceived gain in image quality after ID was obvious in images which are already by design inherently lower in signal to noise ratio like e.g. Short-TI Inversion Recovery (STIR) imaging. Studies 7 and 8 with coronal STIR imaging of sacroiliac joints demonstrate the benefit from the ID bringing image quality back to the standard imaging quality. Apparently, ID is reducing the noise level in the signal and image quality thereby approaches the image quality of the "original" images.

Less intuitive, even in images with abundant signal, the image quality of "accelerated + ID" can be as good (study 5) or even better (study 11) than the original. A plausible explanation is that by removing an average also removes the blurring that can occur due to slight patient movement between multiples averages.

Iterative denoising, in contrast to conventional noise-removing image filters, has the advantage of supplementary quantitative noise distribution information, which would otherwise have to be estimated from the images themselves. Consequently, over- or under-filtering is inherently avoided. In combination with the SURE-optimizing iteration, this is especially important for preserving small image details and sharpness, although some additional edge enhancement appears to be beneficial. Preserved image details and sharp edges are striking in study 11 (Figs. 7) where the small venous bifurcation in the left ischiorectal fossa is clearly sharper delineated in the "accelerated + ID" image than on the images without denoising. Figure 8 is another excellent example that no over-filtering occurs: the small septae in the subcutaneous fat are better depicted on the accelerated images with denoising when compared to the accelerated version as well as to the original version. This can be seen in the fatty streaks in the external obturator muscle.

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Conclusion

Image quality in standard 2D MRI sequences, accelerated in simulation beyond the threshold of standard acceptable noise levels, can be substantially improved by applying an ID algorithm using supplementary information about the image noise level. It is expected that standard 2D MRI can profit from ID when natively scanning with lower numbers of averages and hence shorter acquisition times. More clinical studies with different clinical perspectives are required to show if ID could become as indispensable a tool in MRI as iterative reconstruction is in CT.

Acknowledgements

The authors are grateful to Dr. Boris Mailhe for developing the core of the iterative denoising technique and Dr. Carmel Hayes for her support in algorithm implementation and data processing.

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