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Benefits of Water Fat Separation Fast Spin Echo (WFS FSE) for Clinical Musculoskeletal MRI

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Introduction

The Dixon technique is a method for separating the fat and water components of an MRI signal. Since its introduction in 1984,[1] the Dixon technique has undergone continuous development[2] and is now frequently employed in musculoskeletal (MSK) MRI protocols.[3] The Dixon technique generates four sequences for review at the workstation: water-only (analogous to a fat-suppressed sequence), in-phase (analogous to a non-fat-suppressed sequence), fat-only, and opposed-phase.

There are two main components of the Dixon technique: data acquisition and post-processing. For data acquisition, the target anatomy is typically sampled two or three times ("2-point" or "3-point") with different echo times (TE). From these images, a post-processing algorithm extracts the fat and water contributions of the overall MRI signal for each voxel. This post-processing algorithm also plays a crucial role in accounting for inhomogeneities of the external magnetic (B_0) field. If improperly handled, B_0 inhomogeneities will substantially degrade the final image quality of a Dixon acquisition.[2]

Canon Medical Systems offers a two-dimensional (2D) Dixon fast spin echo (FSE) sequence entitled Water Fat Separation (WFS). The WFS FSE sequence is a two-point Dixon implementation with anatomy sampled in-phase and "partially opposed phase (POP)."[4] Post-processing is accomplished via a Tree-Reweighted Message Passing Iterative Reconstruction Algorithm.[5] Together, these features promote decreased acquisition time and effective handling of B_0 inhomogeneities. The purpose of this white paper is to present the benefits of WFS FSE, and the Dixon technique more generally, for multiple typical MSK protocols.

Acquisition Time

WFS FSE is acquisition-time-efficient on a per-sequence basis as discussed above. WFS FSE and Dixon FSE sequences can also reduce overall MRI protocol acquisition time. The typical MSK MRI protocol includes multiplanar fluid-sensitive and T1 sequences. The fluid-sensitive sequences are designed to accentuate pathology and to characterize lesions. The water-only sequences of Dixon FSE provide a direct substitute for fluid sensitive sequences. The T1 sequences of an MSK MRI protocol are used to identify normal anatomy and to assess for marrow infiltration. The in-phase sequences of Dixon FSE preserve fat signal in the images allowing for anatomic interrogation.[6,7] The fat-only images of Dixon FSE allow for accurate assessment of marrow infiltration.[8] Thus, the acquisition of Dixon FSE sequences could obviate the need to acquire T1-weighted imaging in at least one plane which would decrease overall acquisition time. The impact of this on typical MSK MRI protocols is discussed below.

Infection – Foot

One important benefit of Dixon FSE is robustness of fat suppression (FS) to B_0 inhomogeneity. This has particular relevance when imaging the feet for infection (Figure 1). A common indication for MRI of the forefoot is to assess for osteomyelitis (an infection of the marrow cavity) involving the toes in patients with diabetes. MRI of the foot has high sensitivity in this setting and can exclude osteomyelitis by demonstrating the absence of marrow edema. To accurately depict marrow edema, the normal fat signal of the marrow cavity must be suppressed.

Failure to appropriately suppress fat signal could lead to false-positive diagnoses of osteomyelitis and inappropriate medical or surgical treatment. Thus, failed FS substantially decreases the utility of MRI for assessment of osteomyelitis.

In general, radiologists favor chemical shift selective (CHESS) techniques for FS in MSK imaging because of minimal impact on acquisition time and preserved signal-to-noise ratio (SNR). However, CHESS frequently fails FS at areas of curving air-tissue interfaces, such as about the toes (Figure 1) limiting its utility in forefoot infection protocols. The short inversion time inversion recovery (STIR) sequence provides more robust FS and is frequently employed in forefoot infection protocols. However, the downsides of STIR include increased acquisition time, decreased SNR, and altered image contrast (Figure 1). STIR also cannot be utilized after gadolinium-based contrast administration as the inversion pulse nullifies not only fat signal, but also signal related to the contrast material. Finally, the STIR sequence is often added by the technologist when they identify failed FS on routine sequences which increases the overall acquisition time of the protocol.

Dixon FSE is a useful alternative to CHESS and STIR for MRI forefoot infection protocols. First, Dixon FSE demonstrates robust FS in anatomy characterized by curving air-tissue interfaces[9,10] such as the toes (Figure 1). Furthermore, failed FS with Dixon does not lead to irretrievable loss of information as occurs with CHESS and STIR. Rather, failed FS in Dixon FSE results in the "fat-suppressed" portion of the image being mapped to the fat-only images (Figure 2)[11] which are readily available for review. Second, the image contrast of Dixon FSE is similar

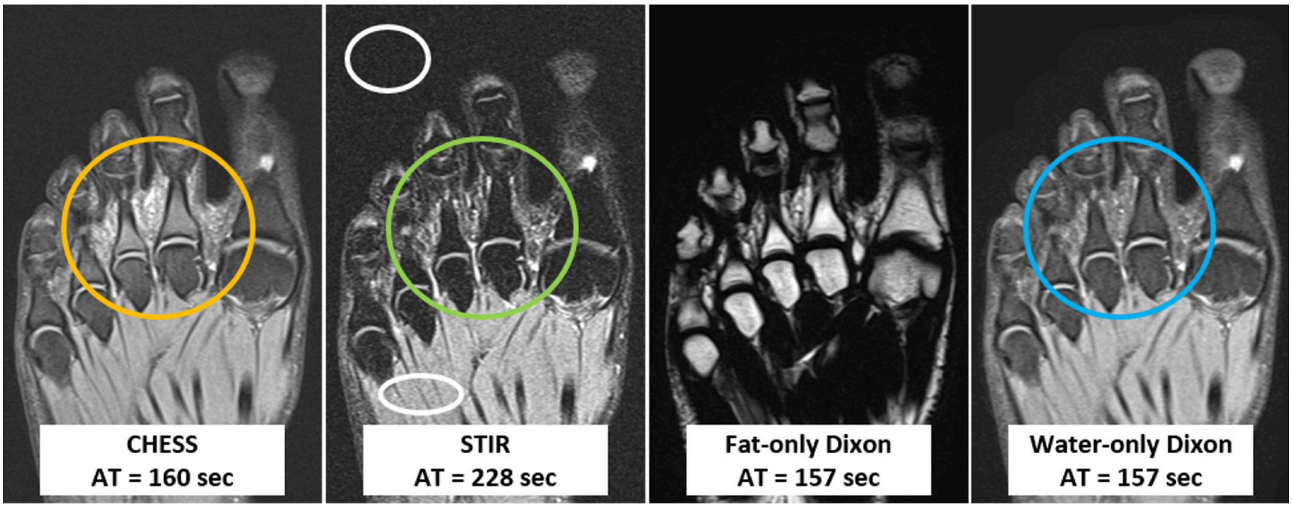

Figure 1 MR images of the forefoot in a 32-year-old man demonstrate the potential utility of the Dixon FSE sequence in the setting of forefoot infection. The typical pattern of failed FS in the marrow and soft tissues about the second and third toes on the CHESS sequence is demonstrated (gold oval). Appropriate FS is demonstrated in these regions on STIR (green oval) and water-only Dixon (blue oval). Note decreased SNR of STIR relative to the CHESS and water-only Dixon – decreased SNR is manifested by a grainy appearance of the muscles and air about the foot (white ovals). A fat-only Dixon sequence is also demonstrated which could provide additional diagnostic information. AT = acquisition time.

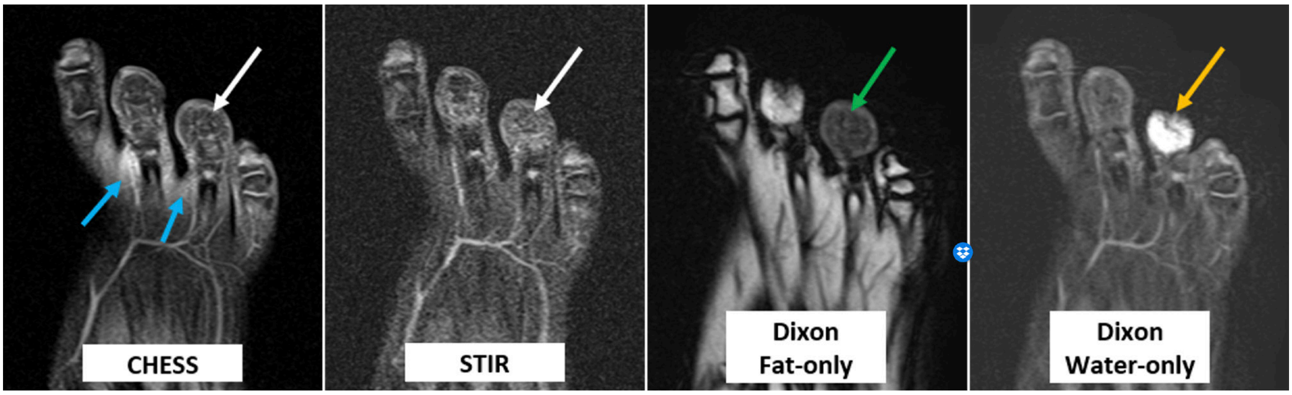

Figure 2 Fat-water swap. Fat signal has been inappropriately mapped to the fourth toe on water-only Dixon (gold arrow) while water signal has been mapped to the fat-only images (green arrow). There is appropriate FS of this region on CHESS and STIR (white arrows). Note failure of FS elsewhere about the second, third, and fourth toes on CHESS (blue arrows). There is appropriate FS in these regions on the STIR and water-only Dixon.

Current protocol		Dixon protocol	
Sequence	**Time (min)**	**Sequence**	**Time (min)**
Sag STIR	2.73	Sag STIR	2.73
Ax STIR	3.83	Ax STIR	3.83
Ax T1 Pre	3.63	Ax T1 Dix Pre	3.68
Cor T2 FS	2.48	Cor T2 FS Dix	2.48
Cor T1 Pre	2.22	Cor T1 Dix Pre	2.22
Cor T1 FS Pre	2.10		
Cor T1 FS Post	2.60	Cor T1 Dix Post	2.65
Ax T1 Post	3.93	Ax T1 Dix Post	3.83
Total time (min)	**23.53**		**21.43**
Time difference (min)	-		**2.10**
Relative savings	-		**8.9%**

Table 1 Forefoot Infection MRI without and with contrast protocol with possible time savings from the incorporation of Dixon FSE techniques. Min=minutes. Sag=sagittal. Ax=Axial. Cor=Coronal. Dix=Dixon.

to CHESS. The contrast appearance of CHESS and Dixon FSE is often preferred by radiologists over that of STIR. Third, the SNR and image sharpness of Dixon FSE are decreased relative to CHESS but are greater than STIR.[3] For an infection protocol, lower SNR is an acceptable tradeoff for more reliable FS. Fourth, unlike STIR, Dixon FSE can be used for FS after contrast administration. Fifth, the incorporation of Dixon FSE could simplify protocols. Accurate examinations would be less dependent on technologists identifying failed FS and adding a STIR. This is an important benefit as forefoot MRI infection examinations are often performed off-hours without direct radiologist supervision. Finally, the fat-only and opposed-sequences generated by Dixon FSE could lead to more accurate marrow assessment.[6]

An additional benefit of Dixon FSE is a potential reduction in the overall acquisition time of forefoot infection protocols (Table 1). Post-contrast images can be obtained with or without FS. FS increases conspicuity of enhancement but also results in lower SNR and increases potential for artifacts. Often the use of FS on post-contrast imaging defaults to the preferences of the radiologist and referring clinician. It is generally agreed that pre- and post-contrast images must be fat-suppressed similarly in at least one plane. As such, in our current protocol, we acquire an additional precontrast axial T1 FS sequence. Since Dixon FSE obtains a FS (water-only) and non-FS (in-phase) sequence in one acquisition, the precontrast axial T1 FS could be avoided. Avoiding this sequence will result in an estimated time savings of 9% or approximately 2 minutes. Forefoot infection studies are frequently performed at off-peak hours (e.g. overnight) on patients with altered mental status. Thus, any reduction in acquisition time would be advantageous. The incorporation of Dixon FSE could lead to further protocol simplifications and time savings by replacing the precontrast 2D T1 and T2 acquisitions (6 total sequences in the current protocol) with a T2 Dixon acquisition in each plane (3 total sequences) and supplementing these with a pre and post contrast three-dimensional GRE acquisitions.

Tumor – Calf

Large fields-of-view (FOV) are also characterized by B_0 inhomogeneity and consequent unreliable FS. Evaluation of bone and soft tissue tumors is a common MSK indication requiring large FOV MR imaging. These protocols usually cover an entire extremity segment for three reasons (Figure 3). First, these tumors can be large. Second, these tumors may have noncontiguous foci of involvement of the affected extremity segment ("skip lesions"). Finally, while uncommon, bone and soft tissue sarcomas can spread to regional lymph nodes which are often at the periphery of the FOV. The presence of skip lesions and lymphadenopathy can greatly impact clinical management. CHESS and STIR typically fail FS along the periphery of large FOVs which can limit or preclude the detection of these clinically important findings (Figure 3).

Dixon FSE is a useful alternative to CHESS and STIR for MRI tumor protocols. First, Dixon FSE provides more reliable FS with large FOV imaging[12–15] (Figure 3). As discussed with the foot above, when FS fails with a Dixon FSE sequence, diagnostic information is not lost. Instead the "fat-suppressed" portion of the study is mapped to the fat-only images[11] (Figures 2 and 3). Second, unlike STIR, Dixon FSE can be used to provide FS after contrast administration. Post-contrast imaging is an integral of MSK oncology protocols. Third, while SNR of Dixon FSE is less than that of CHESS, it remains satisfactory for oncologic evaluation and exceeds that of STIR (Figure 3). Fourth, the fat-only and opposed-phase images can provide additional detail regarding marrow infiltration and are acquired at no time-penalty.[6–8]

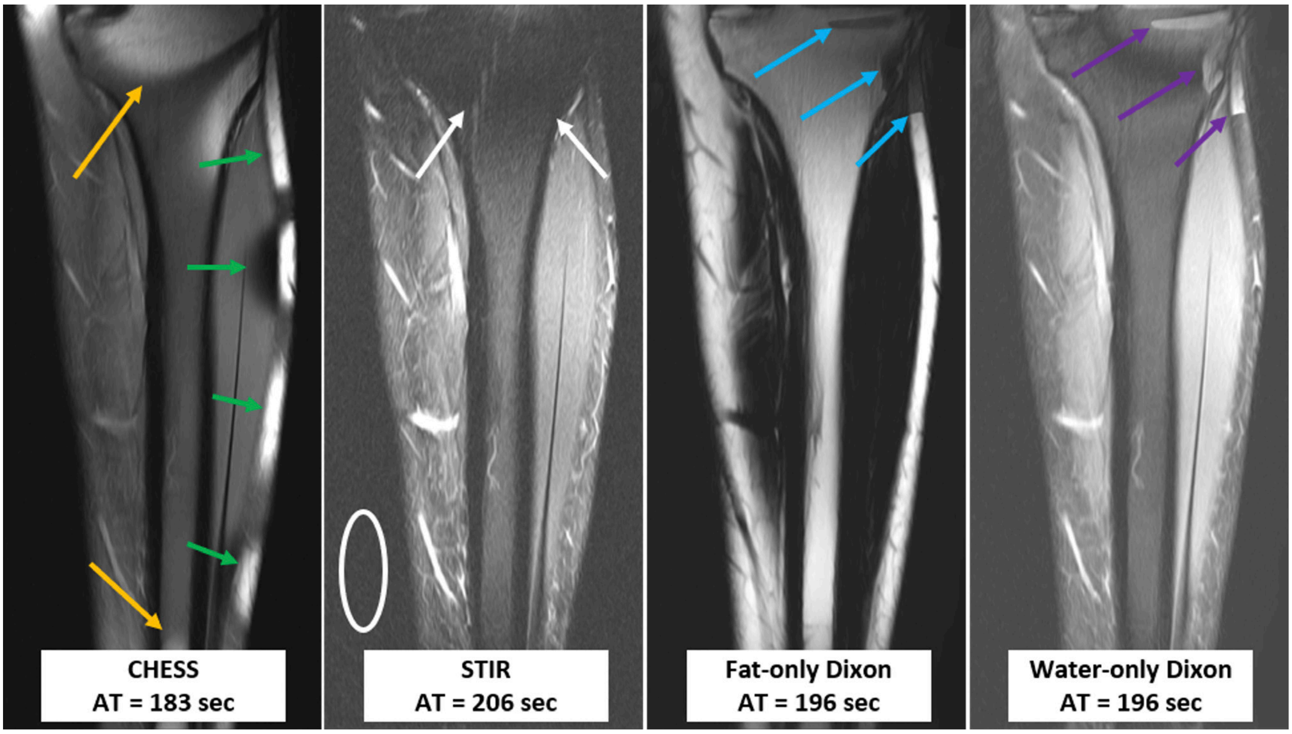

Figure 3 MR images of the calf in a 26-year-old man demonstrate the potential utility of Dixon FSE in the setting of large FOV imaging. On CHESS, the typical pattern of failed FS occurs along the superior and inferior margins of the FOV (gold arrows) and along the lateral periphery of the FOV which is furthest from magnet isocenter (green arrows). On STIR, the typical appearance of shading artifact along the superior FOV is demonstrated (white arrows). Note that the typical alternating-band appearance of failed FS on water-only Dixon (purple arrows) involves a smaller area than failed FS on the CHESS sequence. In addition, the areas of failed FS on water-only Dixon are still viewable on the fat-only images (blue arrows). STIR demonstrates decreased SNR (white oval) relative to CHESS and water-only Dixon. The fat-only Dixon sequence provides potential additional utility in marrow assessment. AT = acquisition time.

Current protocol		Dixon protocol	
Sequence	**Time (min)**	**Sequence**	**Time (min)**
Cor T1 Up	1.90	Cor PD Dix Up LFOV	2.03
Cor T1 Low	1.63	Cor PD Dix Low LFOV	1.83
Sag STIR	4.00	Sag STIR	4.00
Cor STIR	3.40		
Sag T1 Pre	2.67	Sag T1 Dix Pre	2.78
Ax T1 Pre	2.90	Ax T1 Dix Pre	2.85
Ax T1 FS Pre	3.45		
Ax T2 FS	3.05	Ax T2 Dix	3.22
Ax T1 FS Post	3.95	Ax T1 Dix Post	3.95
Sag T1 FS Post	3.97	Sag T1 Dix Post	4.02
Total time (min)	**30.92**		**24.68**
Time difference (min)	-		**6.23**
Relative savings	-		**20.2%**

Table 2 Calf tumor MRI without and with contrast protocol with possible time savings from the incorporation of Dixon techniques. Min=minutes. Sag=sagittal. Cor=coronal. Ax = axial. Up=upper. Low=lower. Dix=Dixon. LFOV=large field of view. PD=proton density.

An additional benefit of Dixon FSE is that it could reduce the overall acquisition time of MSK tumor protocols (Table 2). Like the infection protocol, a separate pre-contrast T1 FS acquisition to match the post-contrast FS sequence is no longer required. In our current protocol, we acquire an additional precontrast axial T1 FS sequence which could be avoided with a Dixon FSE acquisition. In addition, one of the long-axis STIR acquisitions (coronal STIR in our case) could be avoided. An additional benefit of Dixon FSE in the context of tumor imaging is the generation of in-phase (non-FS) T2-weighted images without time penalty. These aid in tumor characterization.[16] Overall, estimated time savings could amount to 20% or approximately 6 minutes. MSK tumor protocols tend to be among the longest of MSK studies. Thus, any time savings would be advantageous for patient comfort, to decrease motion artifacts, and to promote efficient use of limited MRI resources.

Knee

As mentioned before, the fat-only and in-phase images of Dixon FSE could obviate the need to acquire T1-weighted images (Figure 4). In our routine knee protocol (Table 3), two diagnostic sequences could be negated after the incorporation Dixon FSE. First, the coronal T1 would be replaced by the in-phase and fat-only portions of a coronal Dixon FSE. Second, the sagittal intermediate-weighted (IW) non-FS and FS sequences would now be acquired concurrently. This simultaneous acquisition removes the potential for patient motion between acquisitions. Patient motion can limit the ability to assess subtle pathology, particularly of the meniscus. Estimated time savings could amount to 36% or approximately 7 minutes. Given the ubiquity of routine non-contrast knee MRI, any systematic reduction in scan time could substantially improve daily scanner throughput.

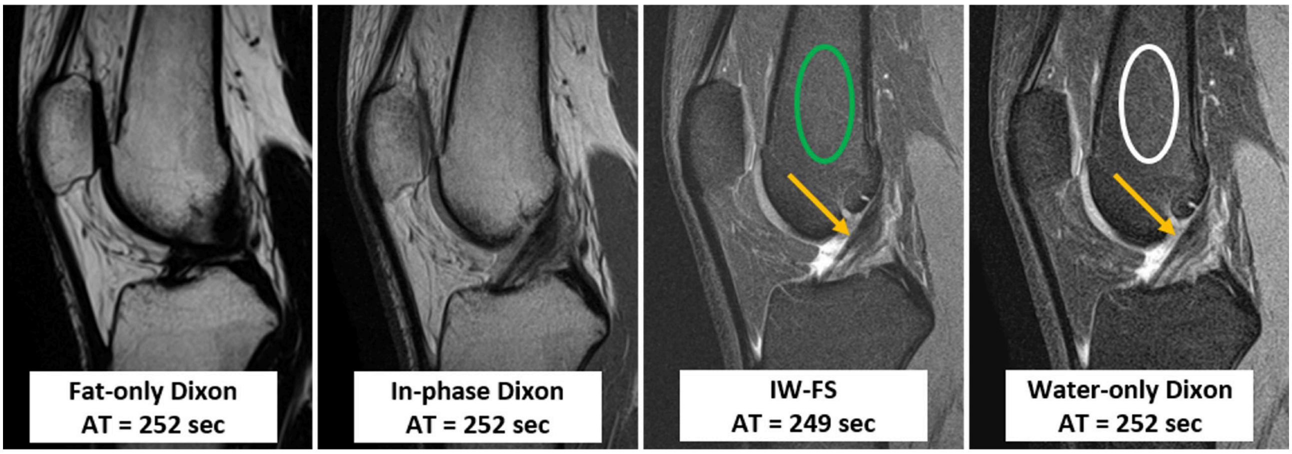

Figure 4 MR images of the left knee in a 27-year old man. Dixon generates water-only, in-phase, fat-only, and opposed-phase (not shown) images in one acquisition. Together, the fat-only and in-phase images could obviate the need to acquire T1-weighted images. Note that the water-only Dixon (white oval) has lower SNR than the FS intermediate-weighted (IW) sequence (green oval). Sharpness of the anterior cruciate ligament margin is similar on both sequences (gold arrows). AT = acquisition time.

Current protocol		Dixon protocol	
Sequence	**Time (min)**	**Sequence**	**Time (min)**
Ax IW FS	4.15	Ax IW Dix	4.20
Sag IW FS	4.15	Sag IW Dix	4.20
Sag IW FS	3.53		
Cor T1	3.80	Cor IW Dix	4.08
Cor PD FS	3.97		
Total time (min)	**19.60**		**12.48**
Time difference (min)	-		**7.12**
Relative savings	-		**36.3%**

Table 3 Routine knee MRI without contrast protocol with possible time savings from the incorporation of Dixon techniques. Min=minutes. Sag=sagittal. Ax=Axial. Cor=Coronal. Dix=Dixon. IW=intermediate-weighted. PD=proton density.

Lumbar Spine

Like tumor protocols, lumbar spine MRI requires large FOV imaging (Figure 5). Dixon FSE has shown reliable FS in the spine.[14,15] For the lumbar spine, current literature supports utilizing a single sagittal Dixon acquisition to replace three conventional sagittal sequences in patients with non-specific low back pain or lumbar radiculopathy.[17] This could result in a time savings of 34% or approximately 7 minutes (Table 4). If axial sequences were also replaced with Dixon FSE, the estimated time savings could amount to 60% or approximately 13 minutes. Like non-contrast knee MRI, routine lumbar spine MRI is extremely common and any systematic reduction in scan time would have large impact on daily throughput.

Conclusion

WFS FSE offers many benefits for MSK MRI. Because of its approach to data acquisition and its post-processing algorithm, WFS FSE can be obtained with near time-neutrality as CHESS sequences. Use of WFS FSE, and Dixon FSE in general, can decrease the overall acquisition time of MSK MRI protocols. WFS FSE demonstrates robust FS in numerous clinical MSK settings.

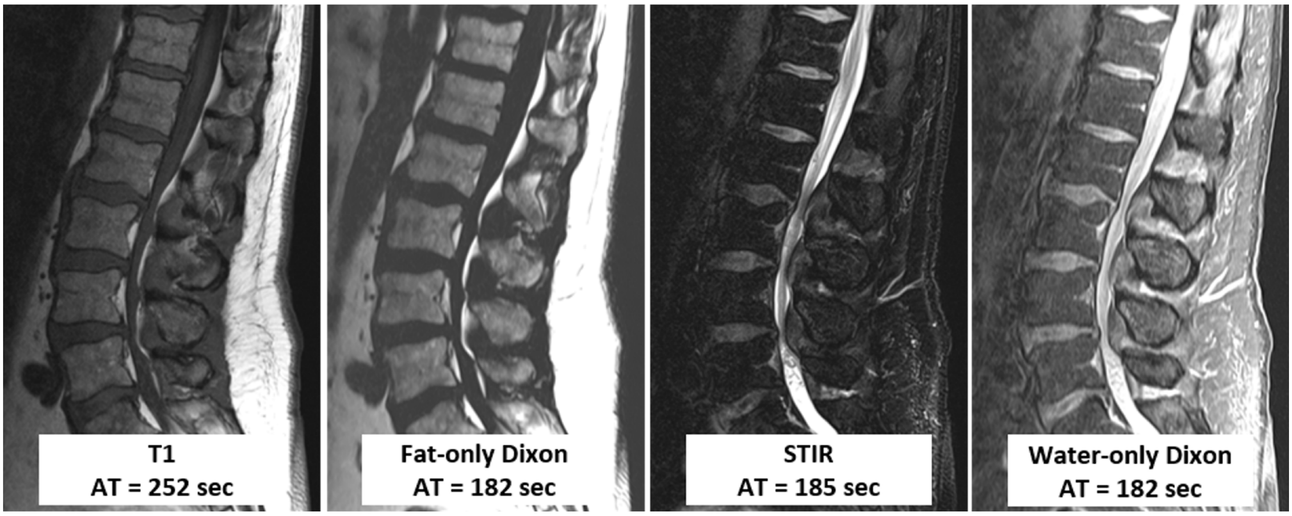

Figure 5 MR images of the lumbar spine in a 67-year-old man. Note increased SNR of the water-only Dixon relative to STIR. No areas of failed FS are evident on STIR or water-only Dixon. A fat-only Dixon is demonstrated which provides additional utility in marrow assessment. Taken together, the fat-only Dixon and in-phase Dixon (not shown) could obviate the need to acquire T1-weighted sequences. AT = acquisition time.

Current protocol		Dixon protocol #1		Dixon protocol #2	
Sequence	**Time (min)**	**Sequence**	**Time (min)**	**Sequence**	**Time (min)**
Sag T2	3.13	Sag T2 Dix	3.03	Sag T2 Dix	3.03
Sag T1	4.20				
Sag SPAIR	3.08				
Up Ax T2	2.75	Up Ax T2	2.75	Up Dix T2	2.85
Up Ax T1	2.73	Up Ax T1	2.73	Low Dix T2	2.85
Low Ax T2	2.88	Low Ax T2	2.88		
Low Ax T1	2.90	Low Ax T1	2.90		
Total time (min)	**21.68**		**14.30**		**8.73**
Time difference (min)	**-**		**7.38**		**12.95**
Relative savings	**-**		**34.1%**		**59.7%**

Table 4 Routine lumbar spine MRI without contrast protocol with possible time savings from the incorporation of Dixon techniques. Two different Dixon protocols are demonstrated: (1) utilizes a single sagittal Dixon to replace three current sequences, and (2) also utilizes two Dixon axial sequences to replace four total current axial sequences. Min=minutes. Sag=sagittal. Up=upper. Low=Lower. Dix=Dixon.

Abbreviations:

2D: Two-dimensional
AT: Acquisition time
Ax: Axial
CHESS: Chemical shift selective
Cor: Coronal
Dix: Dixon
FOV: Field-of-view
FS: Fat suppressed
FSE: Fast spin echo
IW: Intermediate-weighted
LFOV: Large field-of-view
Low: Lower
Min: Minutes
MRI: Magnetic resonance imaging
MSK: Musculoskeletal
PD: Proton density
POP: Partially opposed phase
Sag: Sagittal
Sec: Seconds
SNR: Signal-to-noise ratio
STIR: short inversion time inversion recovery
TE: Echo time
Up: upper
WFS: Water Fat Separation

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