Simultaneous Multi-Slice – a Concise Review Covering Major Applications in Clinical Practice

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Introduction

When MR was originally introduced clinically, only single slice acquisition was possible. Rapidly thereafter, 2D multislice imaging was developed. This has remained a clinical standard for the last 30 years, being used in almost every patient exam. The term multislice however is somewhat misleading, since data for the individual slices is actually acquired sequentially during each TR. True simultaneous multislice (SMS) imaging was only recently introduced [1–3], and can be and is often combined with conventional 2D multislice imaging. SMS is likely the most significant technical development for clinical MR imaging in the current decade, enabling in its current implementation scan time to be reduced by a factor of two to three.

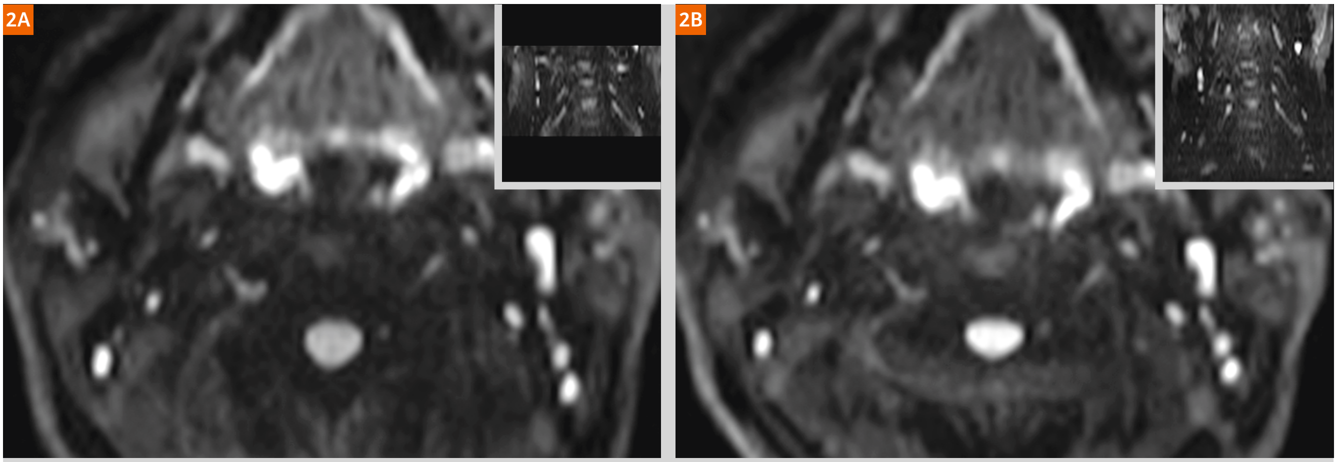
The technique was originally introduced for echo-planar imaging, but has subsequently been expanded as well to turbo spin echo (TSE) imaging. From a scientific point-of-view, higher order acceleration is also possible, with research currently focused in this area. As with many such developments in MR over the past decades, the application of the technique should be viewed more generally, for example in terms of providing higher SNR/time, as opposed to simply enabling scan time to be reduced. The higher SNR per unit time can be used to either shorten scan time (Fig. 1), acquire more slices in situations where these are limited by TR (Fig. 2), and/or to acquire high-resolution images (with complete anatomic coverage) in a reasonable scan time (Fig. 3).

no SMS
2:41 min
5 mm

SMS2
1:38 min
5 mm

SMS2
2:54 min
3 mm
complete liver
(cc) coverage

Figure 1: SMS in liver diffusion imaging, general principles. As illustrated, SMS in this instance can be used either to decrease scan time or to provide thinner sections with near equivalent image quality in a similar scan time.

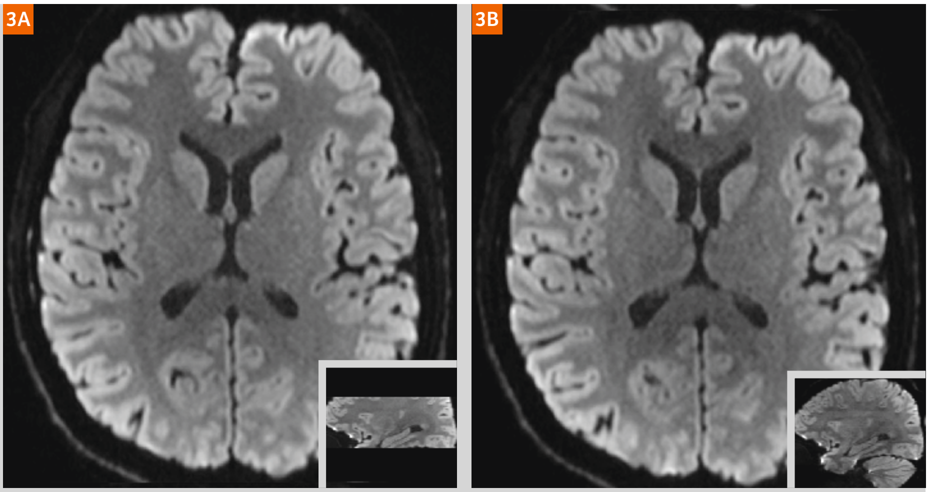


ss-EPI, b800, 3T, 1:45 min

SMS2 with increased cc coverage, 1:54 min

Figure 2: Application of SMS in head and neck diffusion-weighted imaging to provide complete anatomic coverage.

Figure 3: For brain thin section diffusion-weighted imaging, SMS can make complete anatomic coverage possible in a reasonable scan time. 2D ss-EPI DWI thin section scans are illustrated, with the sagittal reformats (inserts) revealing the anatomic coverage achieved without and with SMS.



no SMS, 0.6 x 0.6 x 0.8 mm^3, 5:03 vs

SMS2, 5:15 (TA)

SMS would not have been possible without prior important technological advances in both MR hardware and software, including specifically multicoil arrays, CAIPIRINHA and slice-GRAPPA reconstruction. It also can be, and typically is, implemented clinically in combination with more conventional parallel imaging. Its implementation in 2D echo-planar imaging (EPI) sequences is possible because diffusion encoding, which requires a significant portion of the acquisition time, is performed for the whole imaging volume with each single slice excitation. Because fewer total slice excitations (with the simultaneous excitation of two or three slices each time) are needed to cover the anatomic area of interest, TR can be reduced and thus the scan accelerated. SMS has been implemented for both single shot (ss) EPI and readout segmented (rs) EPI [4]. The latter implementation is particularly important because of the longer scan time required for rs-EPI when compared to ss-EPI. Subsequent to its implementation for EPI, SMS was extended to turbo spin echo sequences. Here, like with EPI, if TR can be shortened, SMS can be implemented in this way to accelerate the scan. However, another perhaps more important application is for TSE scans in which two or more concatenations are required to obtain the necessary number of slices. In this instance, SMS can be used to acquire the desired number slices in a single concatenation, and thus a reduction in scan time.

Several important advances in pulse sequence design were necessary to make SMS a clinical reality. Improved unaliasing of the simultaneously acquired yet closely spaced slices was required. This was made possible, for example for single shot sequences, by the use of a blipped CAIPIRINHA approach [5] which avoids the high g-factor (SNR) penalty and blurring associated with previous techniques. Specialized reconstruction techniques are also used to reduce signal contamination between the simultaneously acquired slices. The multiband RF pulses, which allow for simultaneous excitation and refocusing of multiple slices, also increase specific absorption rate (SAR). Implementation with low SAR variable-rate selective excitation (VERSE) pulses provides adequate SAR reduction.

The applicability of SMS to routine clinical practice is broad and includes almost every anatomic region [6, 7]. The scans in this article were all acquired at 3T. In the head, SMS can increase throughput by reducing scan times, at the same time decreasing the impact of inadvertent patient motion (Fig. 4). If the thin sections are desired through the entire brain, whether with diffusion-weighted or T2-weighted scans, SMS makes this clinically feasible, with reasonable scan times (Fig. 5). In breast imaging, SMS reduces the scan time needed for diffusion imaging, which is required today in evaluations for breast cancer (Fig. 6) [8]. In body imaging the acquisition of axial diffusion-weighted scans is now routine, for example in the liver, with SMS enabling a decrease in scan time [9]. However, depending on the area of interest and the required coverage in the z-dimension, both the application of SMS to reduce slice thickness (yet maintain coverage and image quality) as well as the application to cover larger regions in the z-dimension are important (Fig. 7). Not yet mentioned in regard to diffusion-weighted imaging, the image quality of ADC maps is maintained with SMS, being largely a reflection of SNR and potential artifacts (Fig. 8). For musculoskeletal imaging, in many instances high-resolution images are desired, with SMS permitting their acquisition in a more reasonable scan time (Figs. 9, 10). However, often there are time pressures, due to either the condition of the patient or throughput needs, with the application of SMS in this situation geared to making scans faster (Fig. 11).

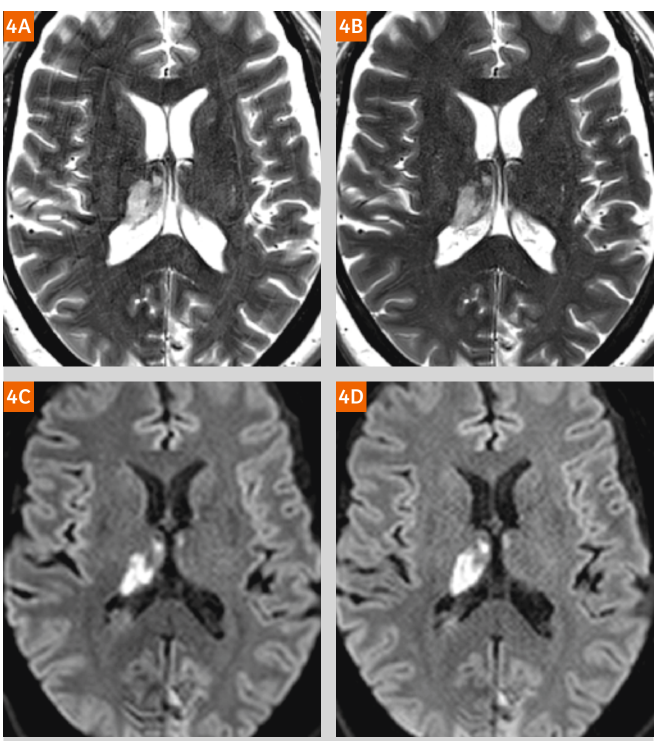


Figure 4: Thalamic infarct, **(4A, B)** T2-weighted TSE and **(4C, D)** diffusion-weighted ss-EPI scans. **(4A, C)** Conventional acquisition compared to **(4B, D)** SMS, the T2-weighted scan with an acceleration factor of three and the DWI with a factor of two. Note the ghosting and image degradation on the conventional T2-weighted scan due to the longer acquisition time. The SMS T2-weighted scan in this instance is superior and the SMS DWI scan equivalent in terms of image quality to the scans acquired in a conventional fashion.

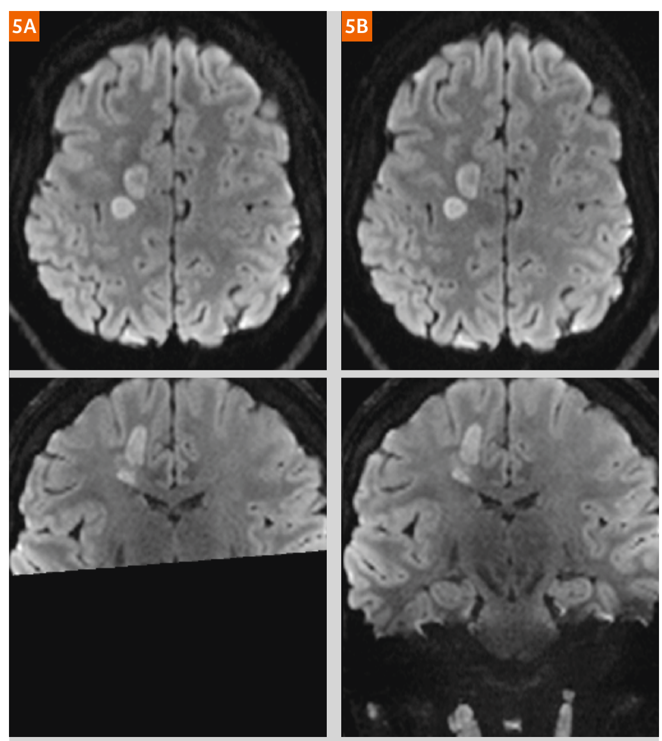


Figure 5: Multiple sclerosis, thin section high resolution 2D ss-EPI DWI without **(5A)** and with SMS **(5B)**. The specific techniques used and scan times are similar to that of Figure 3. Note that SMS permits complete coverage of the brain, as illustrated by the reformatted coronal sections.

Figure 6: Breast imaging, utilizing SMS for decreased scan time in the acquisition of diffusion-weighted images. A spiculated, hyperintense lesion **(6A**, orange arrow) highly suspicious for malignancy is noted on the T2-weighted scan in the right breast. **6B**, The conventional single-shot DWI sequence acquired with a selective field-of-view (zoomed), for faster speed and decreased susceptibility artifacts as well as geometric distortion, is compared with **(6C)** the SMS (acceleration factor of 2) rs-EPI diffusion-weighted scan. The tumor, with restricted diffusion (high signal intensity) is similarly depicted, with scan time decreasing from 5:52 to 3:17 min. On the rs-EPI scan, the metastatic lymph node in the right axilla (white arrow) can also be visualized, which is not depicted in 6B due to residual susceptibility issues/ geometric distortion.

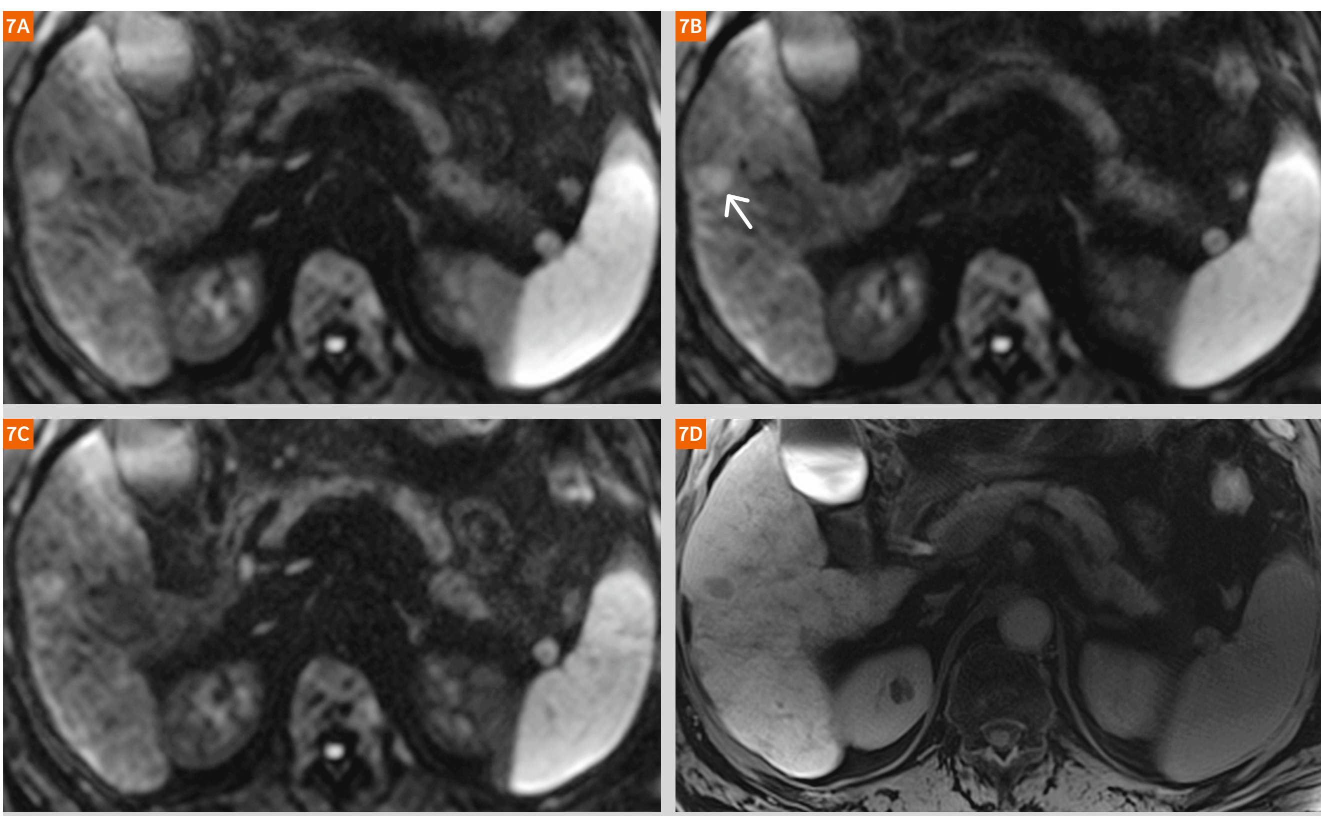


Figure 7: 2D ss-EPI DWI SMS in the liver for shorter scan acquisition or alternatively thinner sections. DWI scan times were **(7A)** 2:41 min (non-SMS), **(7B)** 1:38 min, and **(7C)** 2:54 min (both SMS with a 2 fold acceleration). The slice thickness in 7A and B was equivalent (5 mm), with 7C performed using a thinner slice (3 mm), and complete liver coverage with all scans. A small HCC with restricted diffusion (arrow) is noted. The lesion is also well seen on delayed imaging after gadoxetic acid administration, in **(7D)** a non-breath-hold 2-minute acquisition radial VIBE scan.

SMS can be applied today to both DWI and TSE techniques, with great utility. Immediate applications include brain, axial spine, breast, abdomen, whole body and musculoskeletal imaging. An important decision tree in terms of its specific use in any patient is whether to employ the technique to decrease scan time, or to provide high-resolution images without significantly prolonging scan time, or to enable a larger number of slices to be acquired.

Acknowledgment

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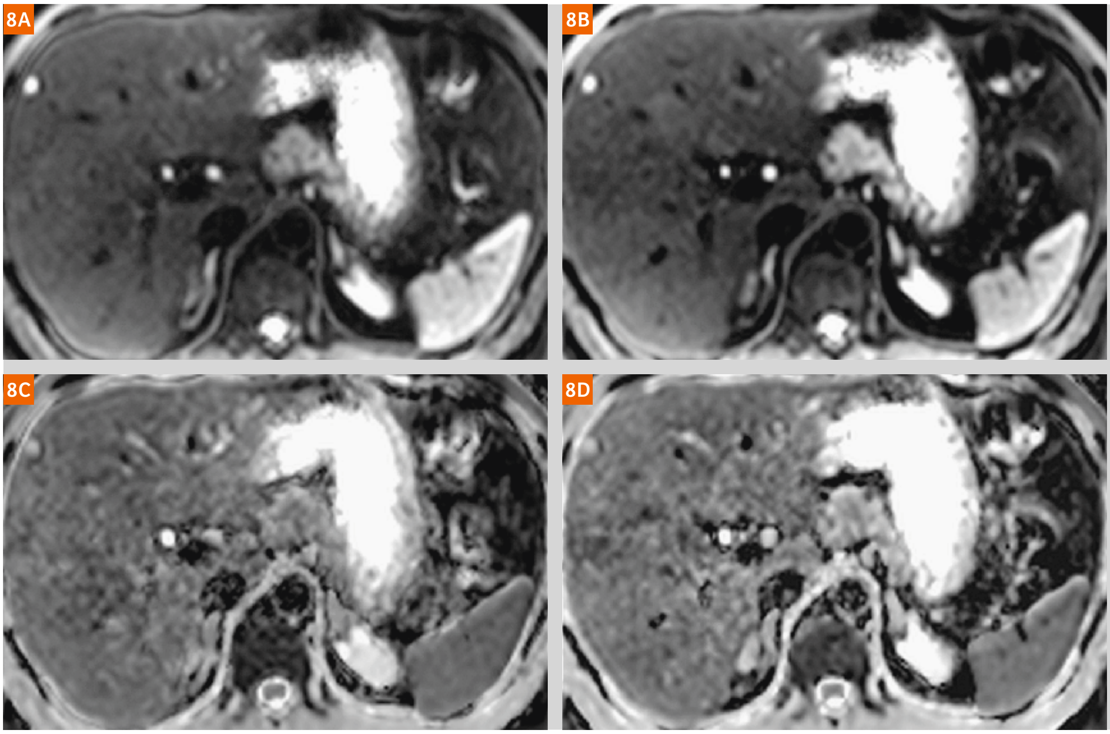

Figure 8: Small hepatic cysts. Liver DWI, **(8A, C)** no SMS in comparison to **(8B, D)** SMS 2, b-value 800 s/mm² top, ADC bottom. Scan times were 4:14 vs 2:31 min, with the same anatomic coverage (number of slices) for both scans and complete liver coverage (using a 4 mm slice thickness).

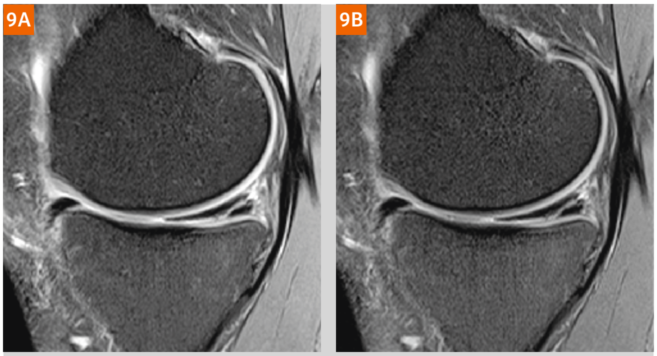

Figure 9: Sagittal proton density-weighted images of the knee demonstrate a horizontal tear of the posterior horn of the medial meniscus on high resolution images (**9A**) without and (**9B**) with SMS (2 fold acceleration). Image quality and SNR are essentially equivalent, with a reduction in scan time from 6:36 to 3:27 min.

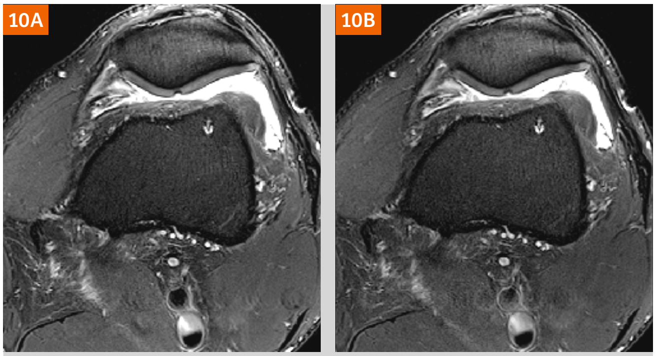

Figure 10: Axial TSE T2-weighted scans of the knee at 3T depicting patellar cartilage damage, in a patient with prior medial collateral ligament and anterior cruciate ligament surgery, on images **(10A)** without and **(10B)** with SMS (2 acceleration). Image quality is equivalent, with SMS allowing a reduction in scan time from 7:14 to 3:48 min. In plane resolution is 0.4 x 0.4 mm².

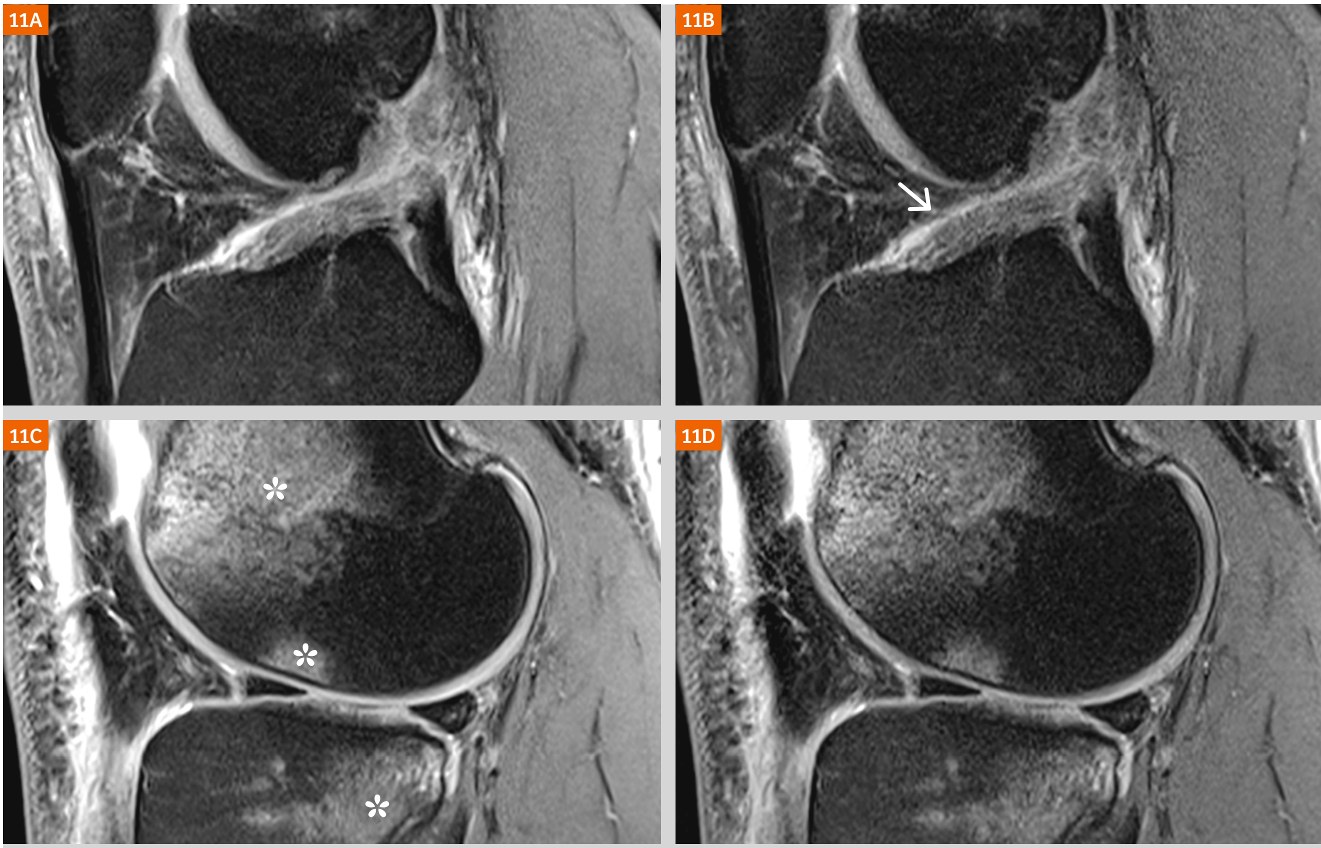

Figure 11: The use of SMS for short scan times in a trauma patient. A ruptured anterior cruciate ligament (arrow) is seen on **(11A and B)** sagittal proton density-weighted images acquired at 3T, together with **(11C and D)** bone marrow edema (asterisks) of the distal femur, lateral femoral condyle, and posterolateral tibial plateau. Depiction is essentially equivalent on the scans **(11A and C)** without and **(11B and D)** with SMS. The SMS scan, due to use of 2 accelerations, required only 1:34 min for acquisition, approximately half that for the non-SMS scan.

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