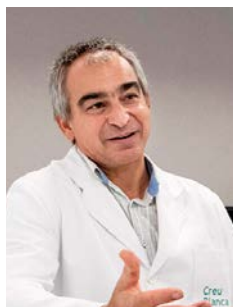


Combination of Compressed SPEEDER and Advanced intelligent Clear-IQ Engine (AiCE): A clinical evaluation on knee pathologies



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Introduction

Magnetic Resonance's popularity in the clinical environment is continuously increasing due to the technological developments made over the last decades, which allow the non-invasive acquisition of a wide variety of contrasts and clinical applications. Nowadays, the challenge is shifting from contrast improvement and development of new techniques to acceleration and ultra-high resolution.

The goal for all sequences is to achieve high image quality with the highest resolution as possible, achieved by matrix increase and slice thickness reduction, for the lowest scan time. However, it is necessary to find a balance between acceleration and resolution in order to ensure enough SNR and to maintain consistent clinical information.

Recently, Canon has developed Advanced intelligent Clear-IQ Engine (AiCE) and Compressed SPEEDER, two advanced solutions that, although having different purposes and mechanisms, can be combined to significantly improve the relationship between signal to noise ratio (SNR) and scan time and, therefore, allow high-resolution and fast imaging. This can be particularly useful in a clinical environment to accelerate the workflow while providing high-quality images.

This study focused on understanding of AiCE and Compressed SPEEDER while, evaluating the potential of the combining these two different technologies acquired during knee examinations with known pathology.

Compressed SPEEDER

Compressed SPEEDER is an acceleration technique based on k-space undersampling, allowing faster acquisition time while reducing the compromise of image detail with respect to other speeding techniques such as the parallel imaging approach.

Compressed SPEEDER is based on the compressed sensing sequence¹ and it follows its three requirements:

- **Incoherent undersampling**

The acceleration part is provided by undersampling approach, which consists of filling only a part of the whole k-space during image acquisition. Based on the compressed sensing theory, this undersampling needs to be random, introducing incoherent noise to the image (Fig. 1, top line). In comparison, parallel imaging k-space undersampling follows patterns, resulting in coherent noise, which is harder to remove and associated with fold-over artifacts (Fig. 1, bottom line).

• **Transform sparsity**

In the frequency domain, incoherent noise can be easily differentiated from real signal (containing useful information), as incoherent data presents more different frequency patterns than coherent information. Therefore, the noise introduced by k-space undersampling can be largely removed by performing a wavelet transform on the image and properly applying a threshold (Fig. 2), keeping only the sparse data above it. The denoised output image is then obtained by applying an inverse wavelet transform on this data.

• **Non-linear iterative reconstruction**

It is important to reach a balance between noise reduction and data consistency. The goal is to remove

as much noise as possible, while remaining a maximum of useful information. The denoising process explained previously is iteratively repeated until the optimal balance is achieved.

In the iterative reconstruction process, Compressed SPEEDER uses multiple reference maps to assist in the reconstruction of the intermediate images (Fig. 3). These maps are generated from the acquired data itself. Compressed SPEEDER k-space undersampling is random except for the k-space center, which is fully acquired. This central data will be used to generate these reference maps for each coil element, allowing a better quality of the reconstruction process.

As described in Figure 3, two factors can be adjusted during the Compressed SPEEDER process:

• **CS Factor**

Determines the acceleration speed, which can be applied up to x4. This value needs to be selected wisely to find a balance between time reduction and SNR. The higher CS Factor, the lower the SNR of the acquired data. Therefore, if the CS Factor is set too high, some of the signal coming from body tissues will not be strong enough to be differentiated from noise, leading to a loss of critical information (Fig. 4, top line).

• **Regularization Factor**

Determines the amount of signal that is removed from the original image (Fig. 2). Selecting the right value is key to an optimal performance of Compressed SPEEDER. If it is too high, the noise will be removed but other useful data might be affected as well, leading to a blurry image and information loss (Fig. 4, bottom line). If too low, noise will not be completely removed and image quality will be poor.

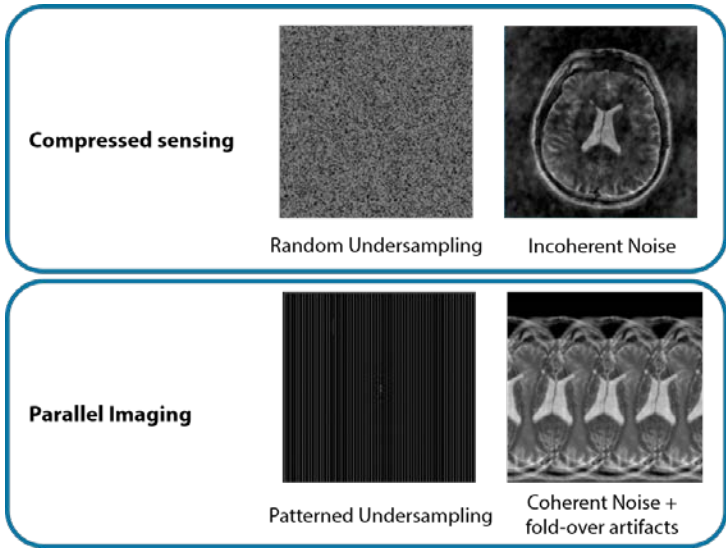


Figure 1 Illustrative k-space representations and corresponding reconstructed images including noise patterns for different k-space undersampling approaches: compressed sensing (top) and parallel imaging (bottom) techniques.

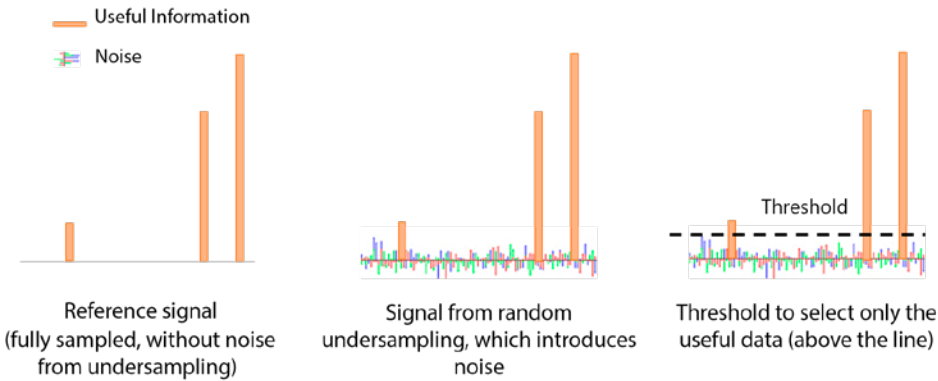


Figure 2 Representation of noise introduction in the frequency domain due to k-space undersampling, and of the threshold used to eliminate it.

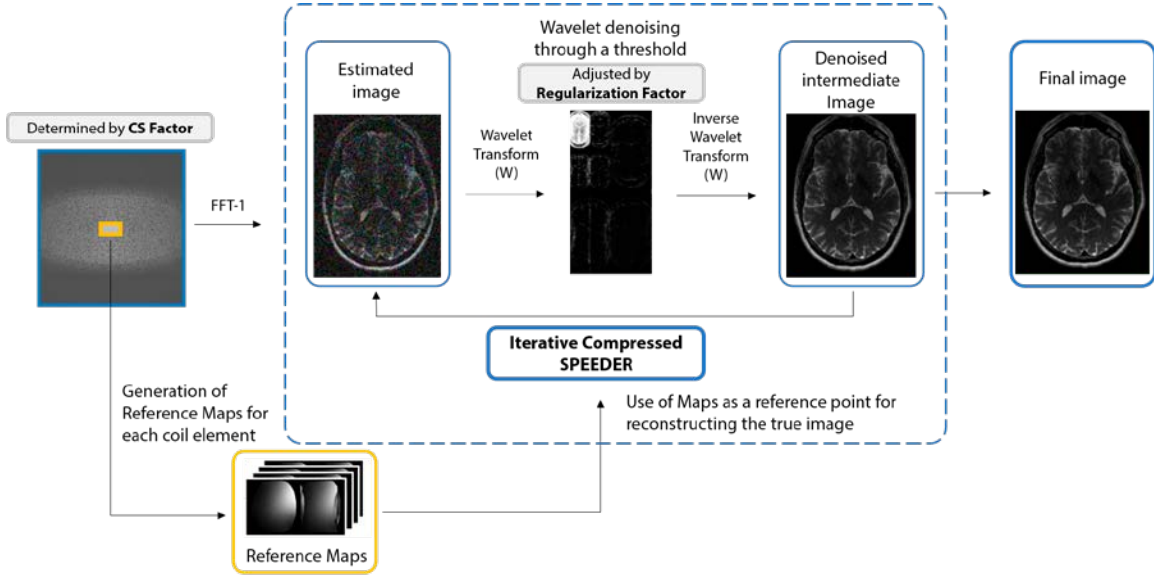


Figure 3 Diagram of the Compressed SPEEDER process. Acceleration is achieved by k-space undersampling and determined by the CS Factor. The introduced noise is reduced through an iterative process averaging coherent signal and reducing incoherent one and thanks to a threshold adjusted by the Regularization Factor.

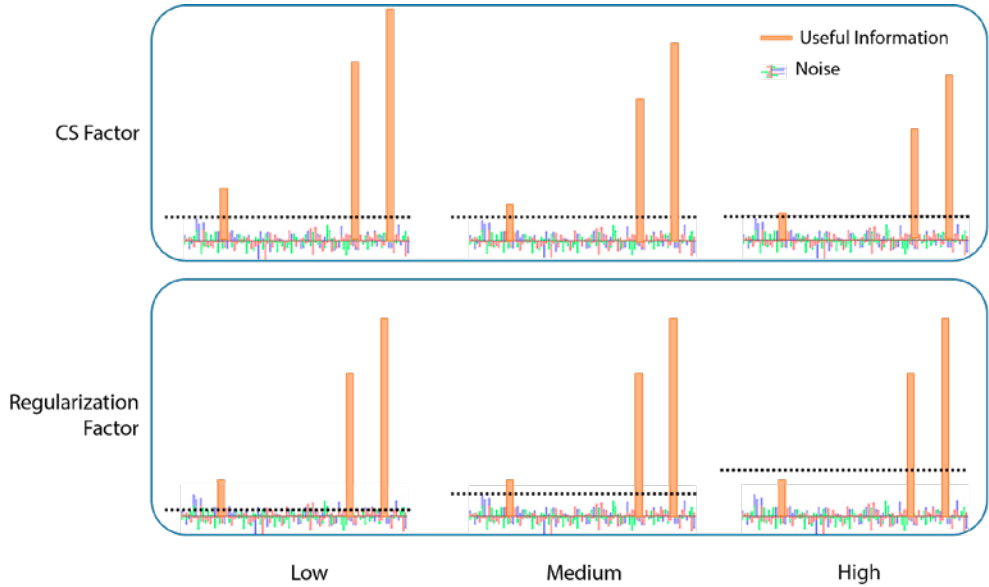


Figure 4 Representation of the Compressed SPEEDER parameters effects on the signal. The CS Factor impacts the differentiation between real signal and noise (top line), while the Regularization Factor defines the signal quantity to cut-off (bottom line).

Advanced intelligent Clear-IQ Engine (AiCE)

AiCE relies on deep learning reconstruction to achieve high SNR images by selectively removing noise, allowing to reach ultra-high resolution images and acquisition acceleration without compromising image quality^{2,3,4}.

AiCE denoising only acts on high-frequency data, which corresponds to the noisy components of the image, to ensures that tissue contrast information, related to low-frequency data, remains untouched.

Figure 5 summarizes AiCE’s mechanism. With the information acquired during the coil sensitivity mapping (MAP), the noise is also measured. AiCE uses this information to automatically estimate and adjust the denoising process accordingly on the high frequency components of the image. It also allows further manual optimization if wanted by the user.

Finally, there is an option to use an additional filter to improve the edge sharpness.

This process results in denoised images where the useful information remains intact. Although all the steps are automatized, AiCE allows the user to adjust some parameters, explained hereafter, in order to adapt the resulting image to their preferences.

- **AiCE Adjust**

It determines which percentage of the automatic noise estimation calculated by the algorithm is applied (Fig. 5, step 3). If it is set to 1, 100% of the estimation will be applied. Therefore, it defines how strong the denoising is.

- **d0x Factor**
- Image sharpness is adjusted using d0x Factor. The range of values goes from d01 (weak enhancement of image smoothness with strong retention of natural sharpness) to d05 (strong enhancement of image smoothness with weak retention of natural sharpness).
- **Edge Enhancement**
- When Edge Enhancement is turned “ON” (Fig. 5, step 6), the edges are sharpened through an additional unsharp masking process.

Combination of AiCE and Compressed SPEEDER

These two tools provide many benefits independently, but their potential is even higher when they are combined. They complement each other and can maximize resolution and time reduction⁵.

On the one hand, Compressed SPEEDER allows acquisition time reduction while auto-compensating for the noise introduced due to k-space undersampling. On the other hand, AiCE is a noise reduction tool that improves SNR, enabling higher resolution and faster acquisitions without sacrificing image quality.

It is important to note that Compressed SPEEDER and AiCE do not impact the signal and the noise in a same way:

- Compressed SPEEDER uses a Regularization Factor which is a threshold keeping only the signal above and removing the signal below it. This factor must be well adjusted to remove a maximum of noise without touching too much the real signal.

- Due to this deep learning technology, AiCE denoising only suppresses conventional MR noise without touching real signal. Therefore, AiCE will achieve a high image quality, free of noise, as long as real signal from tissues is present enough in the native data.

For this reason, it is recommended to adjust the acquisition parameters (e.g. slice thickness, matrix size, CS Factor) to get enough real signal, and to fine tune the reconstruction parameters (AiCE and CS Regularization Factors), to remove the noise and to recover a high SNR.

According to the user’s requirements, these two tools combined can be adjusted to benefit in two different contexts: a resolution increase with the same or even lower acquisition time, or a faster scanning without resolution loss. This article focuses on the first scenario, where AiCE and Compressed SPEEDER allow increasing in-plane and through plane resolutions for lower scan times, while counteracting the added noise.

SPEEDER, a higher resolution, thinner slices and lower scan times (Protocol 2). The acquisition and reconstruction parameters are summarized in Table 1.

For both protocols, resulting images were blindly analyzed by a radiologist and image quality was scored on seven diagnostic criteria for all patients: internal and external meniscus, anterior cruciate ligament, femoro-tibial cartilage, meniscal lesion, patellar cartilage and bone edema. Study results are summarized in Figure 6.

Results concluded that AiCE and Compressed SPEEDER protocol systematically presented a similar or a higher score for all of the seven evaluated criteria, despite a 2:31 min gain compare to the standard one, representing 22% of the total acquisition time.

Therefore, AiCE and Compressed SPEEDER were able to improve the overall image quality, helping the diagnostic of healthy cases and knee-related pathologies, while reducing the examination time.

Improve the diagnostic capability with higher resolution and lower scan times

We evaluated the potential of these tools on 30 patients, consulting for a MR exploration following knee concerns. These patients were scanned on a Vantage Orian 1.5T System (Canon Medical Systems), and we compared a standard high-resolution protocol including three sequences: sagittal PD fat sat, coronal PD and axial PD fat sat (Protocol 1), with a second protocol including the same sequences and using AiCE and Compressed

“Shorter scan times are not only important for productivity increase; they also contribute to a better patient comfort and motion artifact reduction, which are some of the main causes of poor image quality in MR nowadays.”

Xavier Alomar, M.D.

Table 1 Sequence parameters from Standard protocol (protocol 1) and AiCE and Compressed SPEEDER protocol (protocol 2).

	SAG PD FS		COR PD		AX PD FS	
	Protocol 1	Protocol 2	Protocol 1	Protocol 2	Protocol 1	Protocol 2
Slice thickness (mm)	3	2	2.5	2	2.2	2
Resolution (mm²)	0.2 × 0.2	0.1 × 0.1	0.2 × 0.2	0.1 × 0.1	0.2 × 0.2	0.1 × 0.1
AiCE adjust/Edge enh	–	1/On	–	1/On	–	1/On
AiCE d0x	–	d04	–	d03	–	d04
SPEEDER/CS Factor	PE 1	CS 3	PE 1	CS 3	PE 1.6	CS 3
CS Regul. Factor	–	2	–	1.6	–	2.2
Duration	4:23	3:08	3:14	2:30	3:40	3:08
Time reduction	-28.5%		-22.5%		-14.5%	

Figure 5 Diagram of AiCE denoising process including the parameters that can be adjusted by the user to optimize the outcome.

Improve confidence in ruling out pathology

Although both protocols obtained good results regarding image quality, the one using AiCE and Compressed SPEEDER generated images with a higher resolution and an improved delineation of structures and contours, leading to a better and more reassuring diagnosis, not only for pathological cases, but also in ruling out pathology.

Figure 7 and 8 show typical images from two different patients with normal external and internal menisci respectively. In both cases, meniscal edges and chondral surfaces, especially for the femoral cartilage, are better defined with the AiCE and Compressed SPEEDER protocol. This definition increase allows visualizing the structures in detail and discarding pathology with more confidence.

“The protocol using AiCE and Compressed SPEEDER makes me feel more comfortable when ruling out pathology for a patient.”

Xavier Alomar, M.D.

• Achieve a better definition for pathological diagnosis

This higher overall detail also allows analyzing the pathological structures with more precision. Figures 9 and 10 illustrate typical images from patients with an external meniscus degenerative tear (Fig. 9, white arrow) and a medial meniscus lesion that extends towards the tibia (Fig. 10, white arrow).

On both cases, lesion visualization has been improved on the AiCE and Compressed SPEEDER protocol images because of a better structural separation.

The Figures 9, 10, 11 and 12 show typical images of cartilage-related pathologies on different patients. The cartilage irregularity (Fig. 9, red arrows) and the small fissure in the patellar cartilage (Fig. 11, green arrows) are more easily distinguished on the AiCE and Compressed SPEEDER protocol images, due to their higher resolution. For both cases, the anterior cruciate ligament fibers appear sharper and fascicles are better defined. Bone edemas and surrounding structures can also be observed in more detail when AiCE and Compressed SPEEDER are used. This is especially significant in Figure 11 where both femoral (white arrows) and subchondral (red arrows) bone edemas are better visualized. Finally, a patellar cartilage thinning has been observed in a patient (Fig. 12, red arrow), but it has been detected with the AiCE and Compressed SPEEDER protocol only, while it goes unnoticed in the standard protocol.

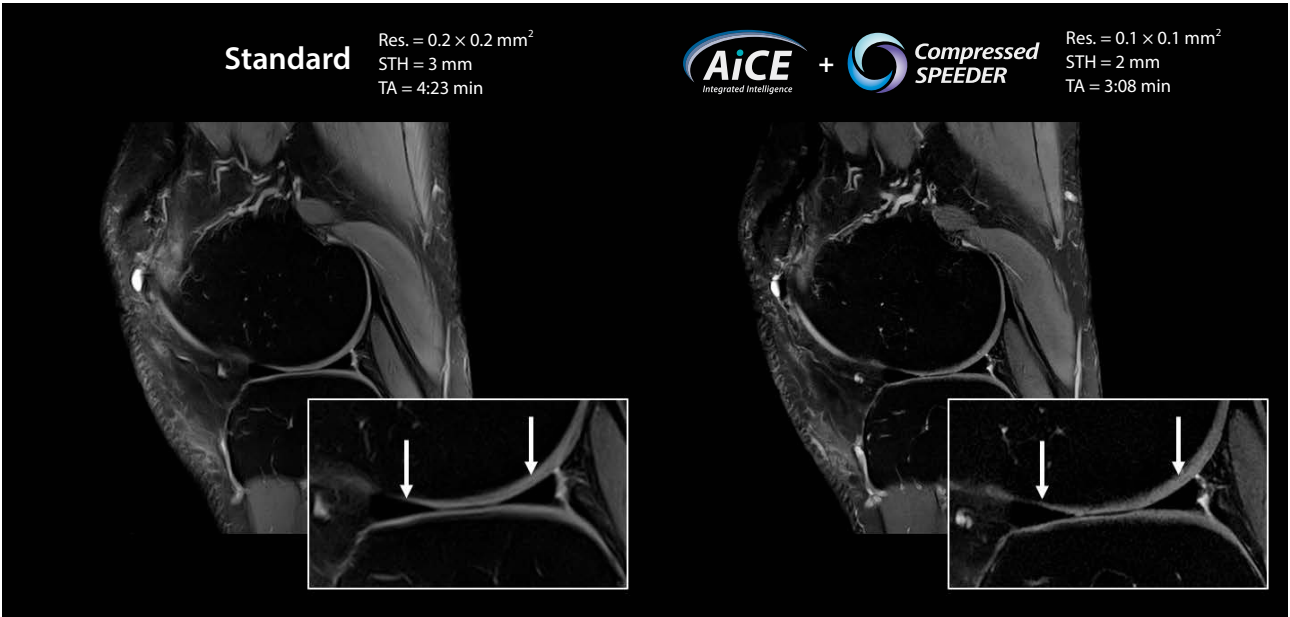


Figure 7 Typical SAG PD FS images of a patient with a normal external meniscus (white arrows). Standard protocol (left) has been performed with a Resolution = 0.2 × 0.2 mm²; Slice thickness = 3 mm; Acquisition time = 4:23 min. AiCE and Compressed SPEEDER protocol (right) has been performed with a Resolution = 0.1 × 0.1 mm²; Slice thickness = 2 mm; Acquisition time = 3:08 min.

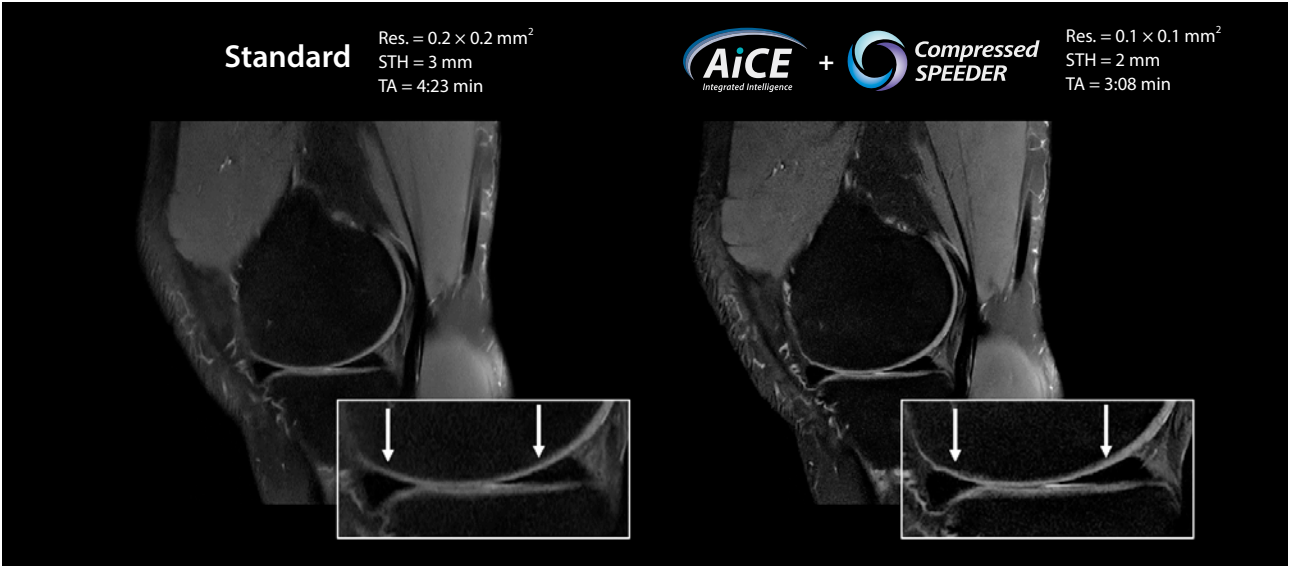


Figure 8 Typical SAG PD FS images of a patient with a normal internal meniscus (white arrows). Standard protocol image (left) is compared to AiCE and Compressed SPEEDER protocol (right).

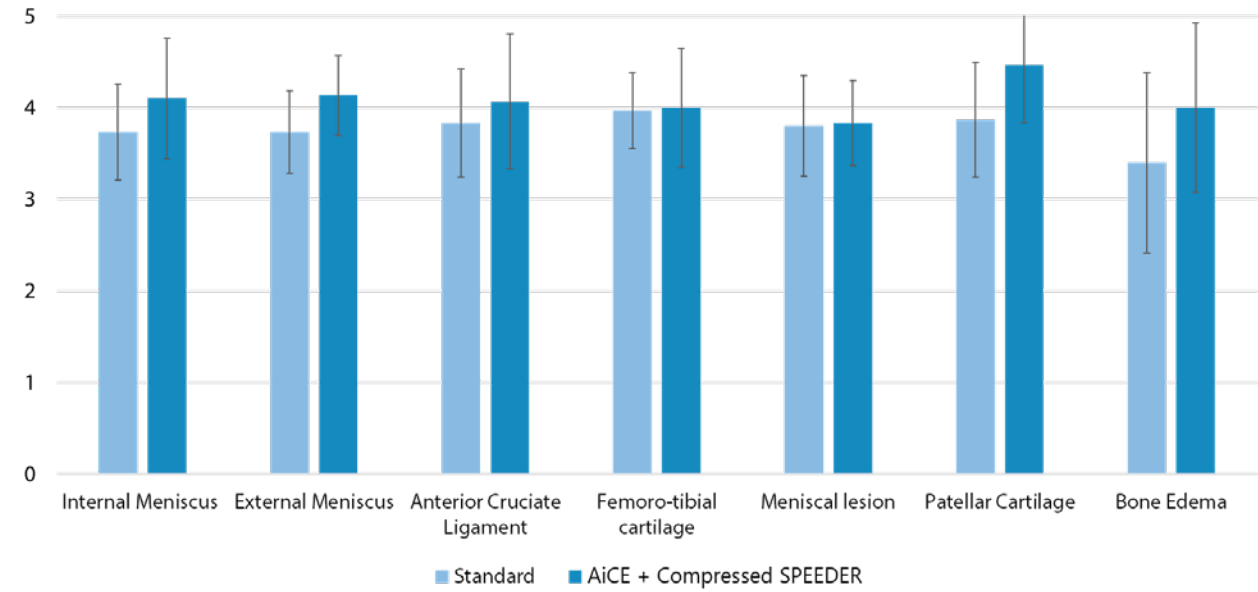


Figure 6 Results of the clinical evaluation of the images. The score correspondence was the following: 1: Non acceptable, 2: Acceptable, 3: Good, 4: Very good, 5: Excellent.

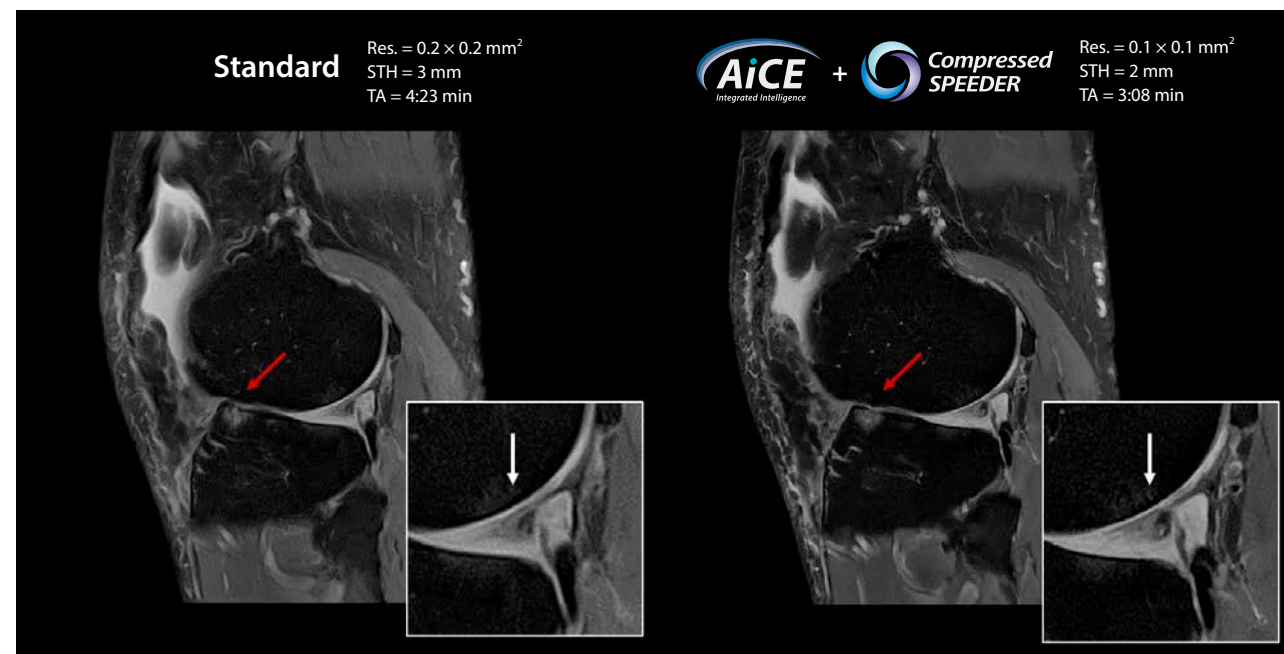


Figure 9 Typical SAG PD FS images of a patient with an external meniscus degenerative tear (white arrows). Irregularity in the cartilage can be observed due to a subchondral bone edema in the tibia (red arrows). Standard protocol image (left) is compared to AiCE and Compressed SPEEDER protocol (right).

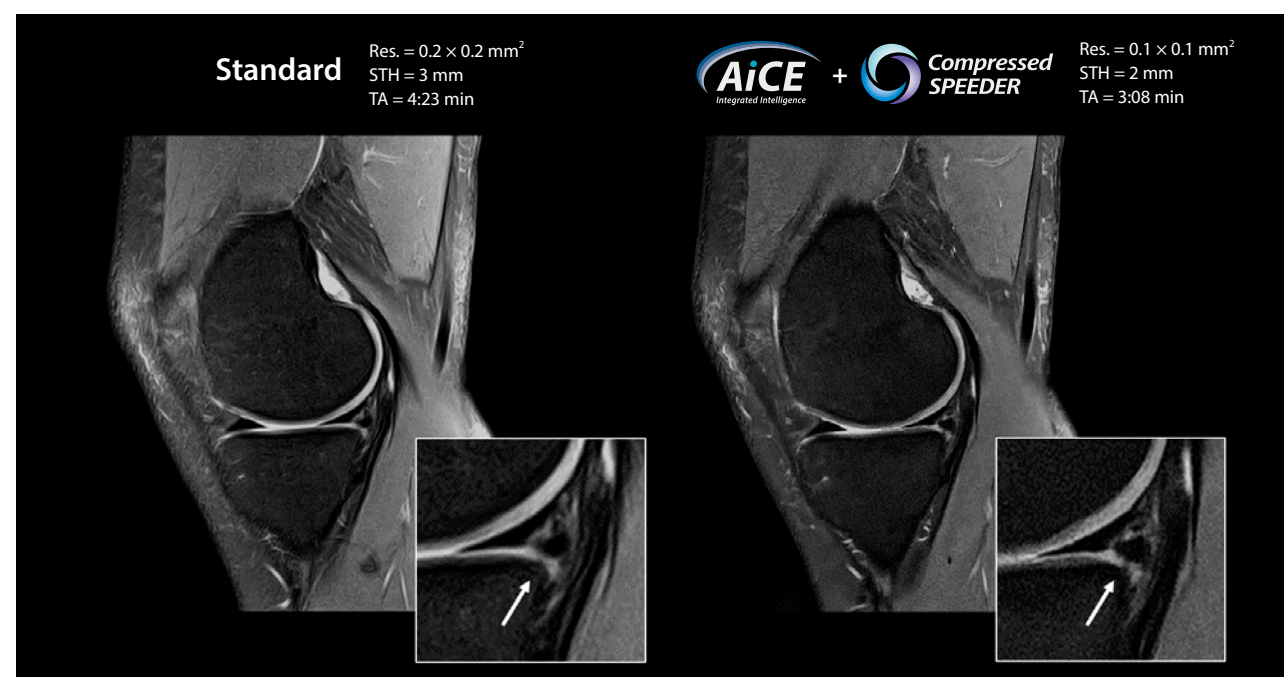


Figure 10 Typical SAG PD FS images of a patient with a medial meniscal tear of the inferior horn with extension to the tibial surface (white arrows). Standard protocol image (left) is compared to AiCE and Compressed SPEEDER protocol (right).

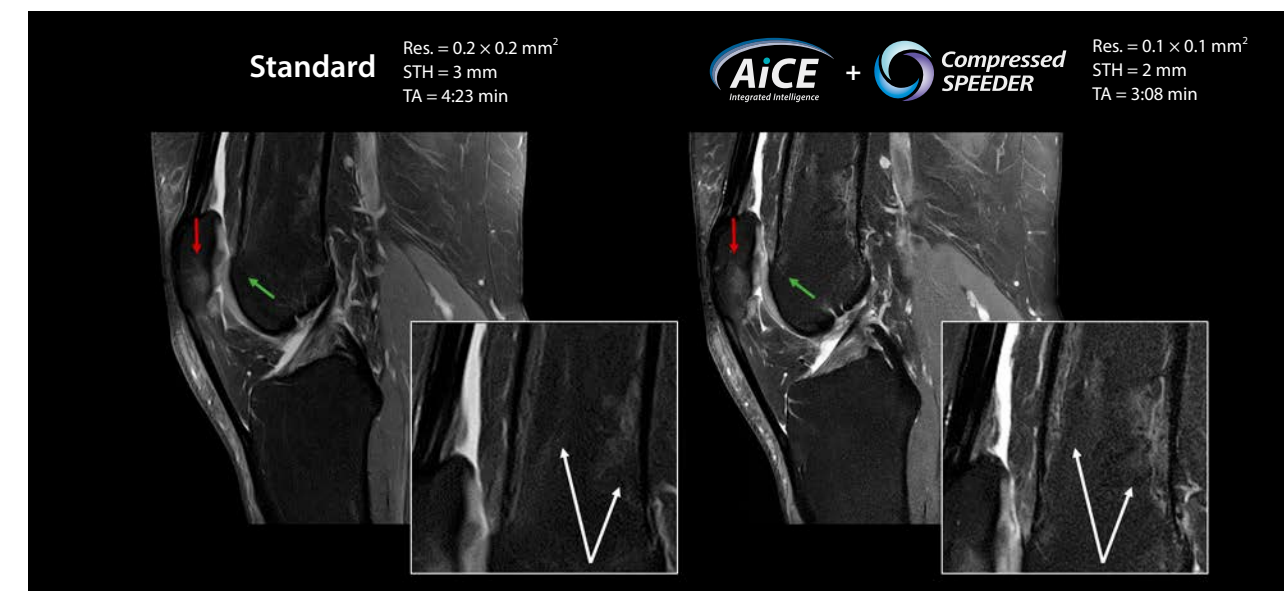


Figure 11 Typical SAG PD FS images of a patient with a subcortical femoral edema (white arrows), a subchondral bone edema in the inferior pole of the patella (red arrows) and a small fissure on the patellar cartilage (green arrows). Anterior cruciate ligament fascicles can be depicted one by one on the AiCE and Compressed SPEEDER protocol image (right), while this is not possible with the standard one (left).

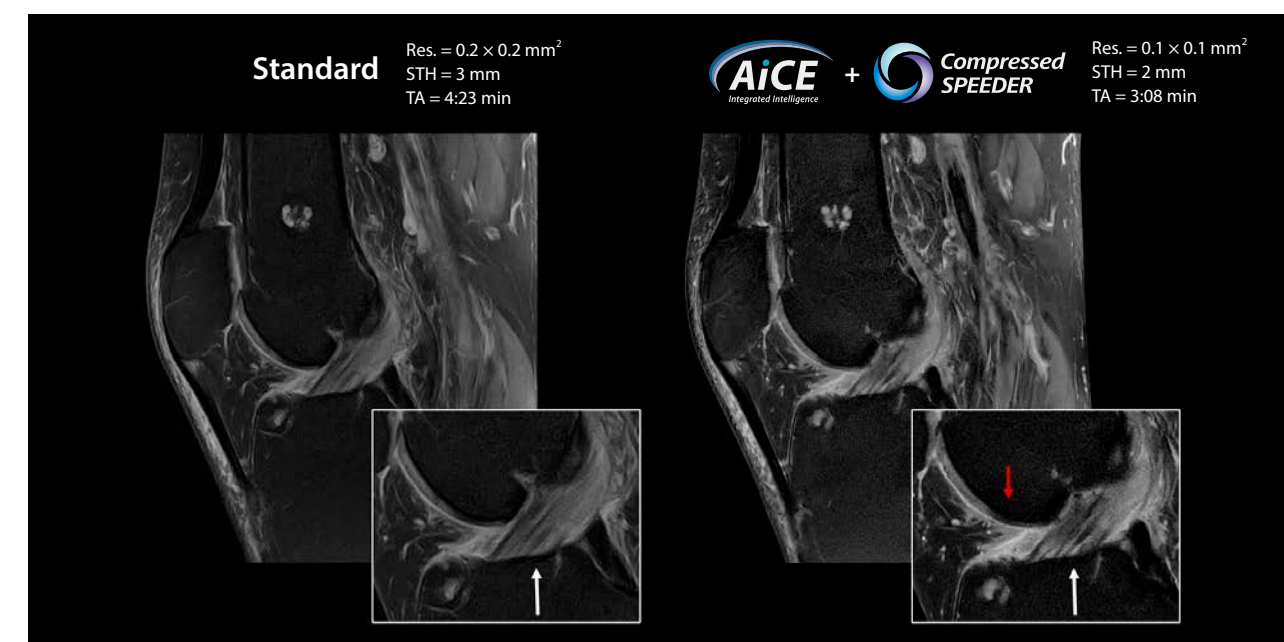


Figure 12 Typical SAG PD FS images of a patient with an inflammatory affection of the synovial fluid surrounding the anterior cruciate ligament (white arrows). The patellar cartilage is thinner, and this thinning is only seen on the AiCE and Compressed SPEEDER protocol image (right, red arrow), while this is not possible with the standard one (left).

Conclusions

Acquisition time and image quality are directly related and represent the main challenge of clinical MR departments. Therefore, the development of tools such as AiCE and Compressed SPEEDER can have a significant impact on the daily user activity.

In this study, we showed that the combination of AiCE and Compressed SPEEDER improves the relationship between SNR and acceleration, allowing the acquisition of ultra-high resolution examinations within shorter scan times than usual. This can lead to an important improvement of the diagnostic capability associated with a throughput increase.

“AiCE and Compressed SPEEDER represent a real revolution in the Magnetic Resonance field because they allow both image quality improvement and scan time reduction.”

Xavier Alomar, M.D.

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MWPMR0009EAA 2021-06 CMSC/Produced in Japan

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