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Benefits of Accelerated MR Imaging in Daily Routine

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Introduction

Clinical development in magnetic resonance imaging in recent years has focused on decreasing scan time, an important topic because of the greater length of time required for and cost therein of an MR exam when compared to computed tomography and ultrasound. The two relevant major technical innovations in the current decade, simultaneous multi-slice imaging and compressed sensing are discussed in depth by organ system in the following article, focusing in particular on four top areas in terms of number of exams performed, the brain, upper abdomen, musculoskeletal system and breast [1]. Additional relevant new imaging approaches – which in general are specific to a single area of the body – that can lend speed to the clinical exam are also included.

Brain

In clinical brain imaging, simultaneous multi-slice (SMS) today has major impact [2]. Diffusion-weighted echoplanar and T2-weighted turbo spin echo scans are acquired in nearly every patient exam. Due to the large number of elements employed in state-of-the-art head coils, SMS is easily adapted, most commonly with an acceleration factor of two. With current technology, in limited situations, a factor of three can also be employed. In the brain, for routine clinical imaging, both single shot and readout segmented (RESOLVE) EPI DWI are widely employed, with the choice often site-specific. Single shot EPI is substantially faster, but as a screening exam with thicker sections is limited at 3T due to bulk susceptibility artifacts. Readout segmented EPI scans take substantially longer, but at many sites are favored even for screening exams. When SMS is applied to screening single shot EPI diffusion exams of the brain, the improvement is minimal due to the fact that scan time is already short. This is not the case however for readout segmented EPI[1], where a substantial savings in scan time is possible (Fig. 1). In certain situations, where thinner sections would potentially improve diagnostic yield, the use of SMS is advocated, as also illustrated, not to decrease scan time with readout segmented EPI but to enable a decrease in slice thickness to be obtained within a reasonable scan time.

An alternative approach in routine clinical brain imaging for diffusion-weighted scans is that of acquiring the entire brain with thin section (1 mm) sections. Prior to the advent of SMS, this was not practical from a scan time point of view. With state-of-the-art coils at 3T, such a scan is today possible in an acquisition time under five minutes if SMS is employed (Fig. 2). The specific diffusion technique used is single shot EPI, with the small voxel size limiting bulk

[1] SMS and RESOLVE are products. The combination of the two technologies, SMS RESOLVE is works in progress, currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

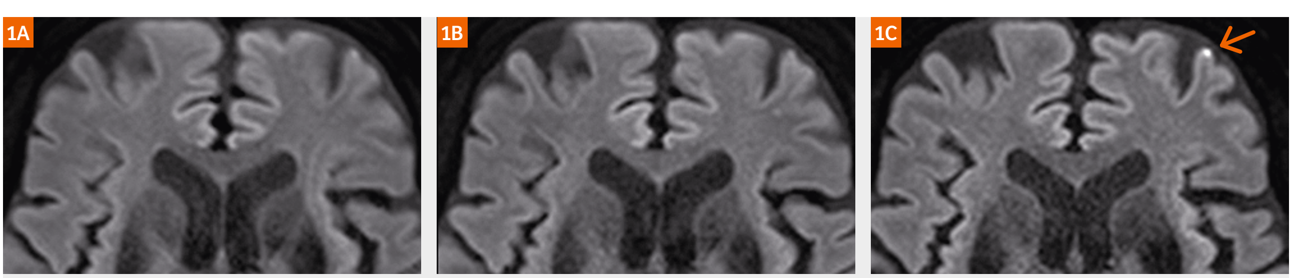

Figure 1:
The use of SMS with RESOLVE[1] for either reduced scan time or improved spatial resolution (specifically a reduction in slice thickness, while maintaining full brain coverage). A non-accelerated, 4 mm slice thickness, b 1000 RESOLVE image of the frontal lobes **(1A)** is compared to that with SMS2 (**1B**, 4 mm) and with SMS3 (**1C**, 2 mm). Scan times were 3:08 (min:sec) vs 2:06 vs 4:27. Image quality is equivalent between the conventional and SMS2 scans, however a small pinpoint cortical infarct (arrow) is visualized only with SMS3, due to the thinner slice thickness.

susceptibility artifact. Looking back at the history of the development of clinical MR, for brain screening exams, slice thickness decreased from 10 mm (initially) to 7 mm (with the advent of 1.5T) to 4 mm (with the advent of 3T). Given the possibilities offered by SMS, it is quite possible that high resolution thin section (1 mm) brain diffusion imaging will become routine in the future except for uncooperative patients.

TSE T2-weighted scans of the brain are typically fast, and thus at first glance not a likely candidate for the application of SMS. However, when thinner sections (< 4 mm) of the entire brain are desired, scan times often become substantial (over 4 minutes). This is due to the need to employ concatenations or other approaches such as extending TR in order to acquire the needed number of images to cover the entire brain. Although T2-weighted imaging is considered to be relatively robust to motion artifacts for brain imaging, this is generally a consequence of the relatively short scan time. With longer scan times, as well as with uncooperative patients, motion artifacts can be quite prominent and substantially degrade diagnostic image quality. Patients with acute ischemia are an important patient population in clinical brain MR imaging, with this population in particular benefiting by the use of SMS to achieve shorter scan times (Fig. 3).

Another approach to reducing overall exam time for a patient, specifically for brain imaging, involves the use of synthetic MRI [3]. If a specialized scan is acquired, then from this single acquisition, T1-, T2- and proton density-weighted images can be reconstructed (Fig. 4). Indeed, it is simply an issue of mathematics to calculate an image with any combination of TE and TR, or for example a FLAIR image that would for acquisition necessitate also the specification of an additional inversion pulse, and specifically TI. Likewise, parameter maps can be calculated, in the most simplistic approach

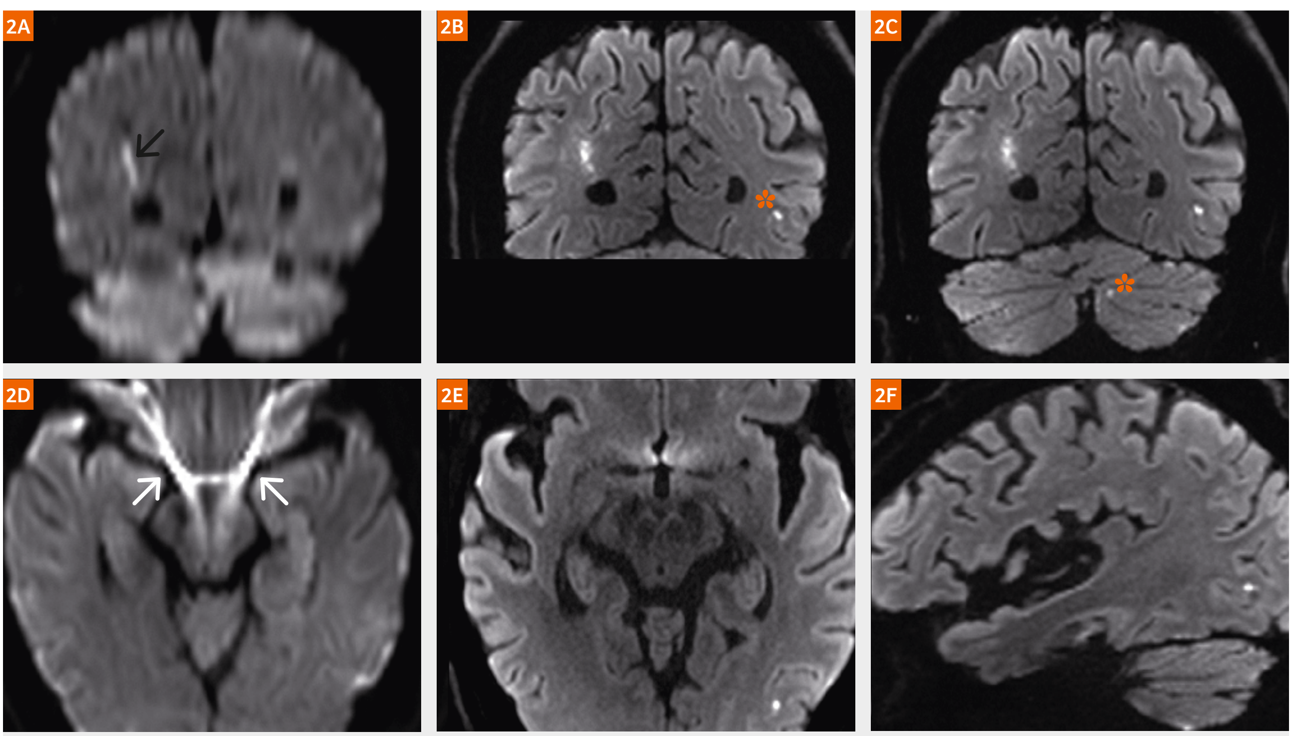

Figure 2:
Conventional 2D ss-EPI DWI (**2A, D** – 5 mm) vs thin section (1 mm), high in plane resolution (0.6 x 0.6 mm^2) scans without SMS **(2B)** and with SMS2 **(2C, E, F)**. At 3T, bulk susceptibility artifacts (white arrows) degrade substantially conventional 5 mm section ss-EPI DWI, as seen in the axial scan (2D). A coronal reformat (2A) in this patient depicts, although poorly due to the low resolution, a small watershed infarct (black arrow). By reducing slice thickness and improving in plane spatial resolution, bulk susceptibility artifacts are reduced and the infarct is well visualized on a reformatted coronal scan (2B, from a 62 image, 1 mm slice thickness, 4:24 min:sec scan). However, the entire brain cannot be scanned thus in a reasonable acquisition time. Employing SMS2, the entire brain can be imaged, with the acquisition time in this instance 4:39 min:sec, with high-resolution images and reformats possible in all planes (2C, E, F). These images reveal a pinpoint cerebellar infarct (*, 2C) in addition to the previously noted pinpoint occipital infarct (*, 2B, also visualized in 2E and F). Note also the marked reduction in bulk susceptibility artifacts in the axial plane (2E). Full brain imaging in this instance revealed multiple pinpoint acute infarcts, none visualized on the conventional 5 mm scan, and only that in the cerebral hemispheres seen on the high-resolution scan without SMS.

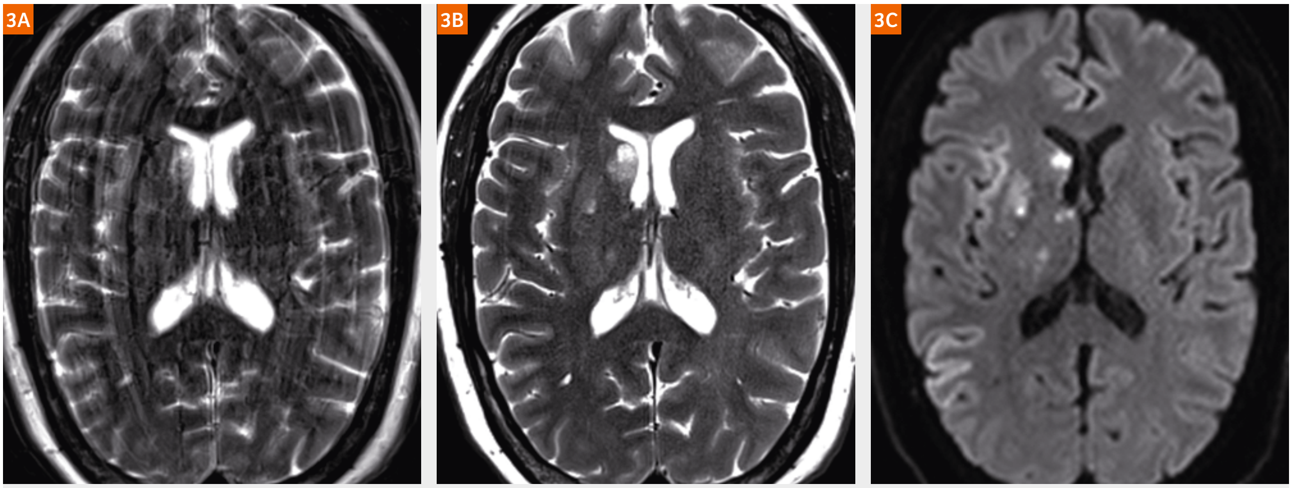

Figure 3:
Small infarcts of the caudate, putamen, and thalamus, **(3A, B)** T2-weighted TSE and **(3C)** diffusion-weighted ss-EPI scans. (3A) Conventional acquisition compared to (3B) SMS, using an acceleration factor of three. For the diffusion-weighted scan, (3C), SMS was also employed, with an acceleration factor of 2. Note the ghosting and image degradation on the conventional T2-weighted scan due to the long acquisition time, with markedly improved image quality on the accelerated SMS T2-weighted scan. The SMS DWI scan was equivalent in terms of image quality to the scan acquired in a conventional fashion (not shown).

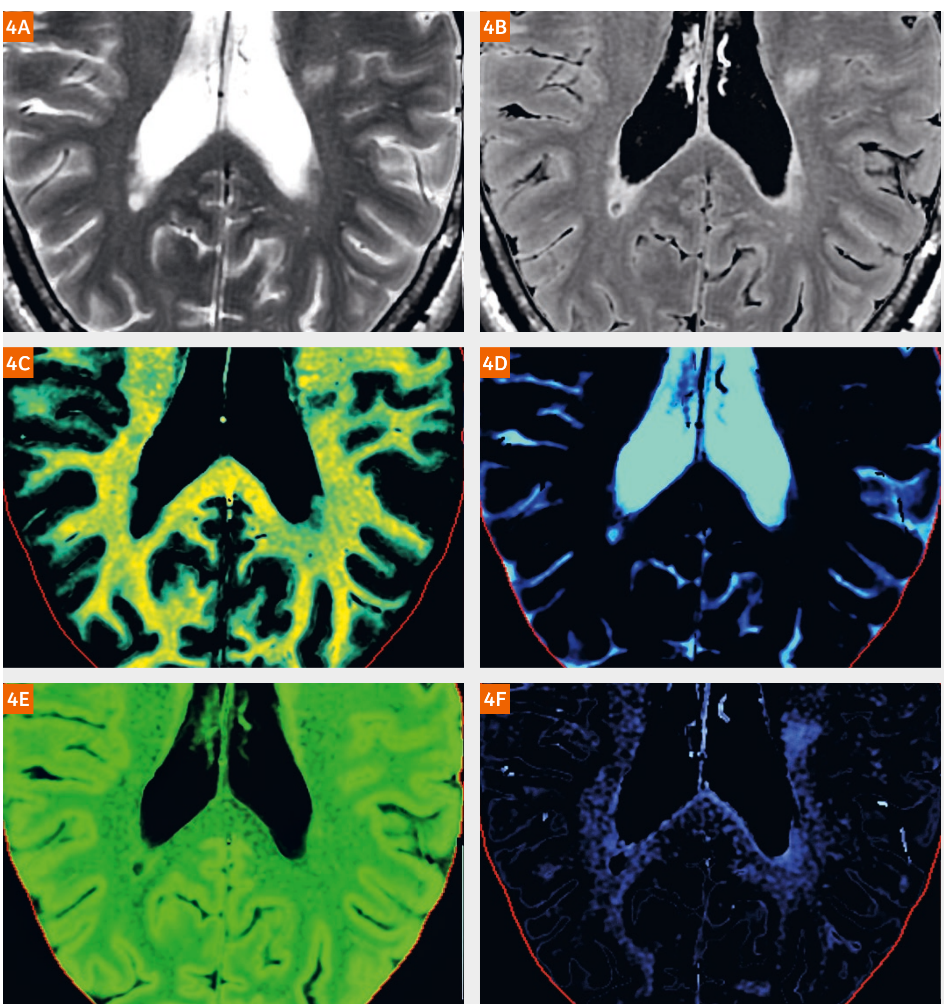

Figure 4:
Synthetic MRI, brain segmentation and myelin measurement in a patient with multiple sclerosis. From a scan requiring approximately six minutes for acquisition, R1, R2, and proton density maps are measured. This allows reconstruction of synthetic **(4A)** T2-weighted and **(4B)** FLAIR images. From the same data, myelin segmentation can be performed with calculation of **(4C)** myelin, **(4D)** free water, **(4E)** cellular, and **(4F)** excess parenchymal water partial volumes.
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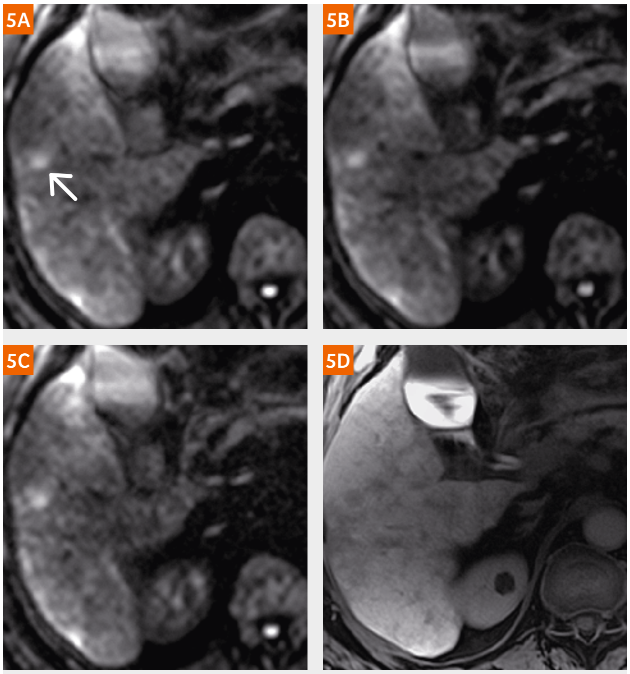


Figure 5:
SMS in liver imaging, in a patient with multifocal hepatocellular carcinoma (HCC), at 3T with 2D EPI DWI. SMS can be used, as illustrated, to either shorten scan time or acquire thinner sections without a substantial increase in scan time. Scan times were **(5A)** 2:41 (non-SMS), **(5B)** 1:38, and **(5C)** 2:54 min:sec (the latter both SMS with a 2-fold acceleration). The entire liver was covered in all scans, using a 5 mm slice thickness for **(5A, B)** and a 3 mm slice thickness for **(5C)**. A small HCC (arrow) with restricted diffusion is noted. For comparison, a delayed post-contrast scan after gadoxetic acid administration **(5D)** is also presented, using a non-breath-hold 2-minute acquisition radial VIBE scan. On the latter, the lesion is hypointense due to the lack of functioning hepatocytes.

T1, T2 and proton density maps. However, there is much more information available from such an acquisition, including volume estimations such as gray matter, white matter and ventricular volume. More sophisticated segmentation involves, as illustrated, evaluating myelin and the compartmentalization of water, which can be of value in the assessment of multiple sclerosis.

Image acquisition and reconstruction techniques that exploit data sparsity (compressed sensing) will also impact favorably brain imaging in the near future, and specifically contrast enhanced MRA and time of flight MRA – two common exams. Early clinical articles show the impact, with work in progress acquisition techniques readily available together with limited sequences for routine clinical use. Combining radial undersampling and sparse reconstruction, time resolved high-resolution contrast-enhanced MRA can be acquired, enabling improved characterization of arteriovenous malformations, for example in determination of Spetzler-Martin grade as well as assessment of venous ectasia and deep venous drainage [4]. Data undersampling can also be combined with arterial spin labeling and 3D radial acquisition to improve the detection and characterization of intracranial arteriovenous shunts. 3D TOF MRA is employed clinically for brain aneurysm detection and evaluation, providing as well detection of intracranial stenoses and occlusions. This commonly used technique is also readily combined with data sparsity approaches in order to shorten scan time. Although development of specific techniques is still in its infancy, acceleration of the scan by a factor of five appears quite feasible [5].

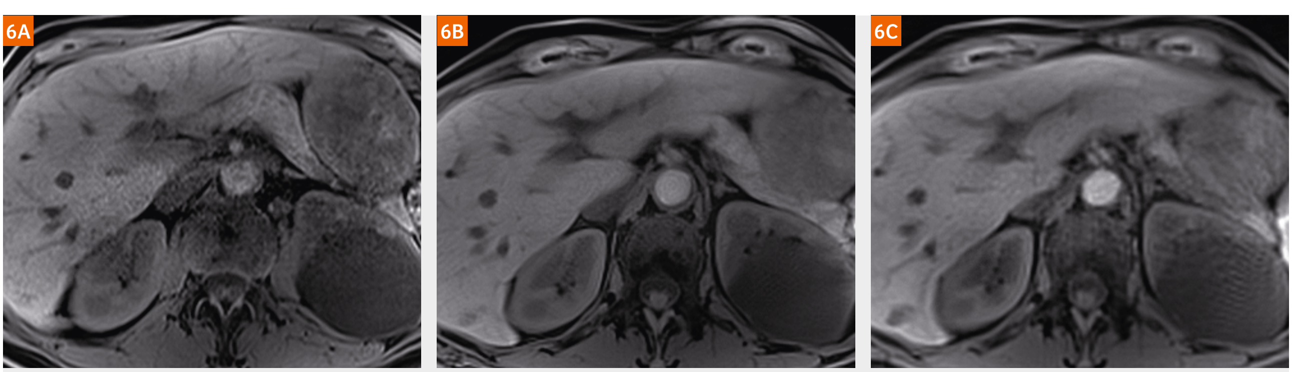
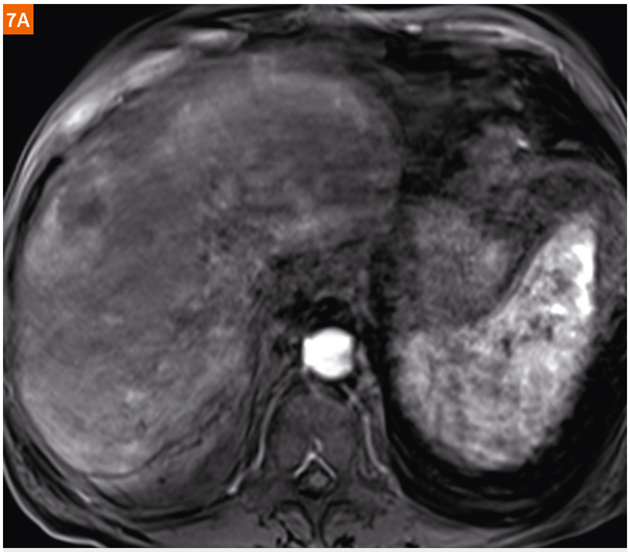


Figure 6:
Options for speed in liver T1-weighted imaging, comparison of ultrashort breath-hold and radial, free breathing, imaging. Images were acquired at 3T using a slice thickness of 3 mm without IV contrast administration. A large left renal cyst is noted. **(6A)** An ultrashort breath-hold Dixon VIBE sequence is compared to **(6B)** standard and **(6C)** scan time optimized (by restricting the number of radial views) radial VIBE scans. Scan times were 5 sec, 2 minutes, and 21 sec.



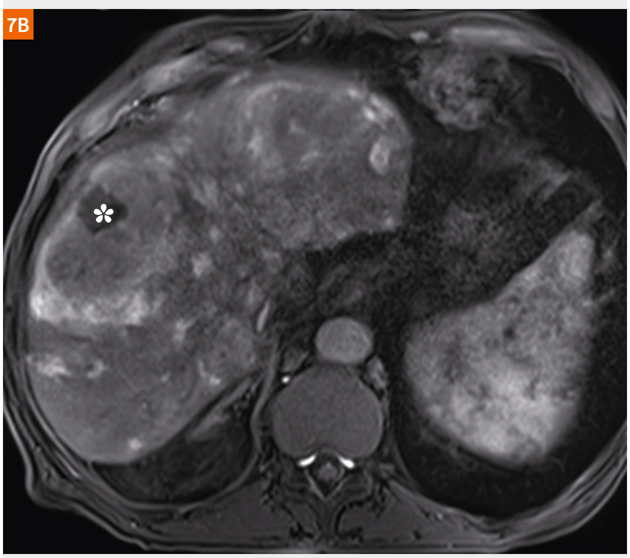


Figure 7:
Improved clinical liver imaging by utilization of ultrashort breath-hold T1-weighted imaging. Two early arterial phase T1-weighted exams in the same patient are compared. **(7A)** The first is a conventional CAIPIRINHA-VIBE sequence with fat saturation requiring an acquisition time of 16 sec. **(7B)** The second is an accelerated Dixon VIBE sequence requiring a breath-hold time of only five seconds. A large partially necrotic hepatocellular carcinoma is noted in liver segment VIII (*) in this elderly male patient. The substantially reduced acquisition time for the latter scan (7B) enabled improved patient compliance, with the result being a marked increase in diagnostic image quality.

An important additional application of radial imaging with compressed sensing is for dynamic imaging of the pituitary (implemented with GRASP), providing both the high spatial and temporal resolution necessary for this evaluation. Very high image quality has been demonstrated in initial clinical implementation, providing improved recognition on the basis of differential contrast enhancement during the dynamic phase between the normal enhancing pituitary and microadenomas [1].

Upper abdomen

Diffusion-weighted imaging today is a vital sequence for routine abdominal MRI. Acquisition is normally during free breathing, using single shot EPI technique. SMS is easily applied, by using a shorter TR yet still enabling the desired anatomic coverage (Fig. 5) [6]. Although SMS could be used to achieve thinner sections or higher in-plane resolution, the focus for use of the technique in the upper abdomen has been to decrease scan time. Motion and the lower SNR in body imaging in general dictates the use in this manner.

Motion, primarily due to breathing, is likely the clinical factor with the greatest negative impact on the quality of MRI in the upper abdomen. Over the past 20 years, sequences have been optimized and new sequences have been developed allowing shorter and shorter breath-hold times. For example, on a state-of-the-art scanner today, the Dixon VIBE sequence can be acquired in as little as five seconds (Fig. 6). Many patients have difficulty holding their breath for even 20 seconds, with such a reduction in acquisition time improving greatly patient compliance and diagnostic image quality (Fig. 7). In patients unable to hold their breath at all, e.g. pediatric patients[2], radial imaging represents a further alternative direction for sequence development to combat breathing artifacts. As compared to a Cartesian acquisition, motion artifacts are reflected in the final image in a less prominent and more benign fashion (Fig. 6). This technique can be used to acquire high-resolution 3D post-contrast images in many regions where involuntary motion occurs, for example in the oral cavity. On the downside, however, the acquisition time for a high-resolution dataset is typically in the order of 2–3 minutes. If radial scans are optimized for scan time, the same SNR limitations as in all MR acquisitions apply. However, an additional consideration when shortening radial scans is the greater prominence of streak artifacts that reflect motion, if the approach used aims to decrease the number of phase-encoding steps.

Another consideration besides breath-hold capabilities is to gain more information in dynamic contrast-enhanced imaging with faster acquisition techniques. With CT, radiologists are largely limited by radiation dose considerations in terms of acquiring additional arterial phase images,

[2] 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.

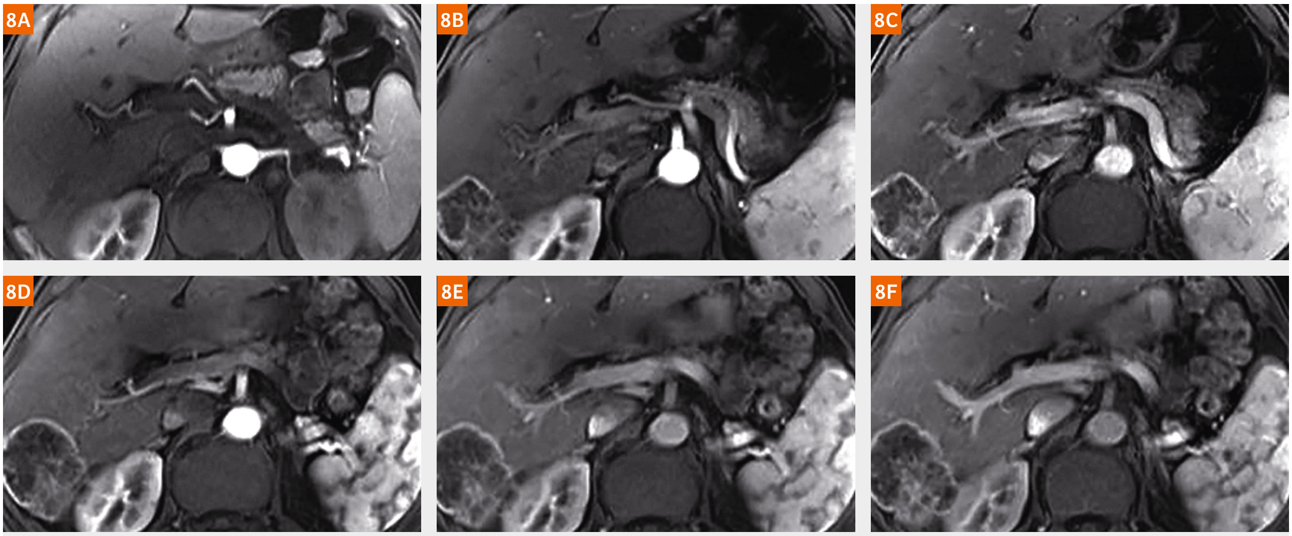


Figure 8:
Liver metastasis from rectal carcinoma, imaged with **(8A)** single phase, **(8B, C)** dual phase, and **(8D–F)** triple phase arterial acquisitions. The scans are separated in time by several months in each instance. CAIPIRINHA-VIBE with spectral fat saturation was employed for **(8A)**, CAIPIRINHA-VIBE, Dixon fat separation, and TWIST without view sharing for **(8B, C)**, and with view sharing for **(8D–F)**. Acquisition times for the three techniques per phase were 13 vs 7.5 vs 4.6 sec. Use of the dual arterial phase acquisition led to well-timed arterial phase images with low respiratory motion artifact.
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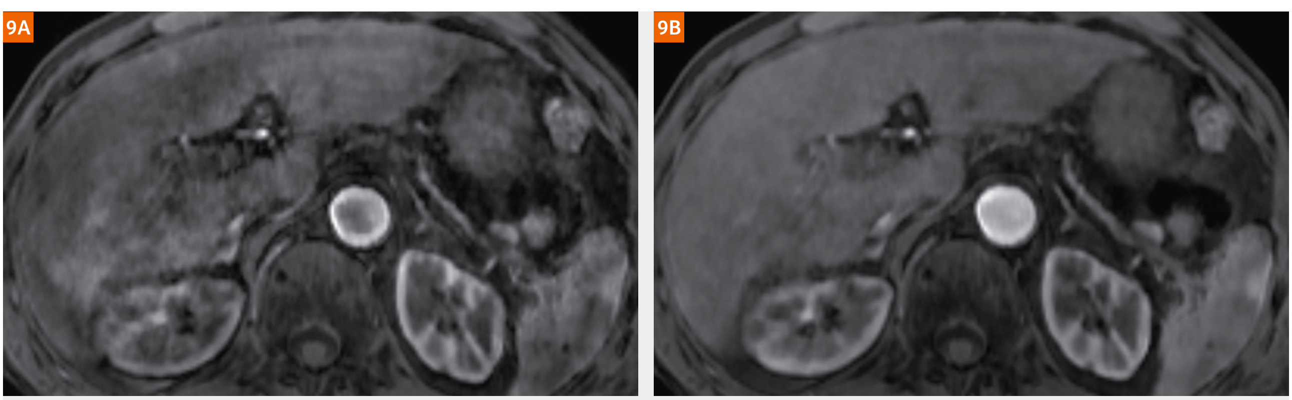

Figure 9:
Improved early arterial phase liver imaging using compressed sensing with respiratory-motion resolved reconstruction (XD-VIBE). The patient is an 81-year-old man with chronic hepatitis B and limited breath-holding capacity. The scans were acquired during free breathing. Pre-contrast, multi-arterial and portal venous phases were obtained with compressed sensing VIBE. Using a navigation signal acquired as part of the acquisition, two different image sets were reconstructed, **(9A)** the first using hard gating by either rejecting or accepting the echo train for reconstruction. For **(9B)** the second image set, with motion resolved reconstruction, the echo train was assigned to the motion state determined by the navigation signal. A substantial reduction in motion artifacts and improved image quality is achieved with (9B) XD-VIBE.
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while scan acquisition time has been the limitation in MRI. With the advent of new sequence types, however, multi-phase arterial acquisitions became possible, opening up a new diagnostic window for MRI of the upper abdomen (Fig. 8) [7]. By combining a view-sharing acquisition scheme with highly accelerated parallel imaging and fast T1-weighted 3D imaging (TWIST-VIBE), acquisition times of five seconds for imaging the entire upper abdomen are now possible. This allows for acquisition of early, mid and late arterial phase MR imagings in one 15-second breath-hold. In the past few years, many clinical studies have been published that advocate this approach and have shown the additional diagnostic information available in multi-arterial acquisitions.

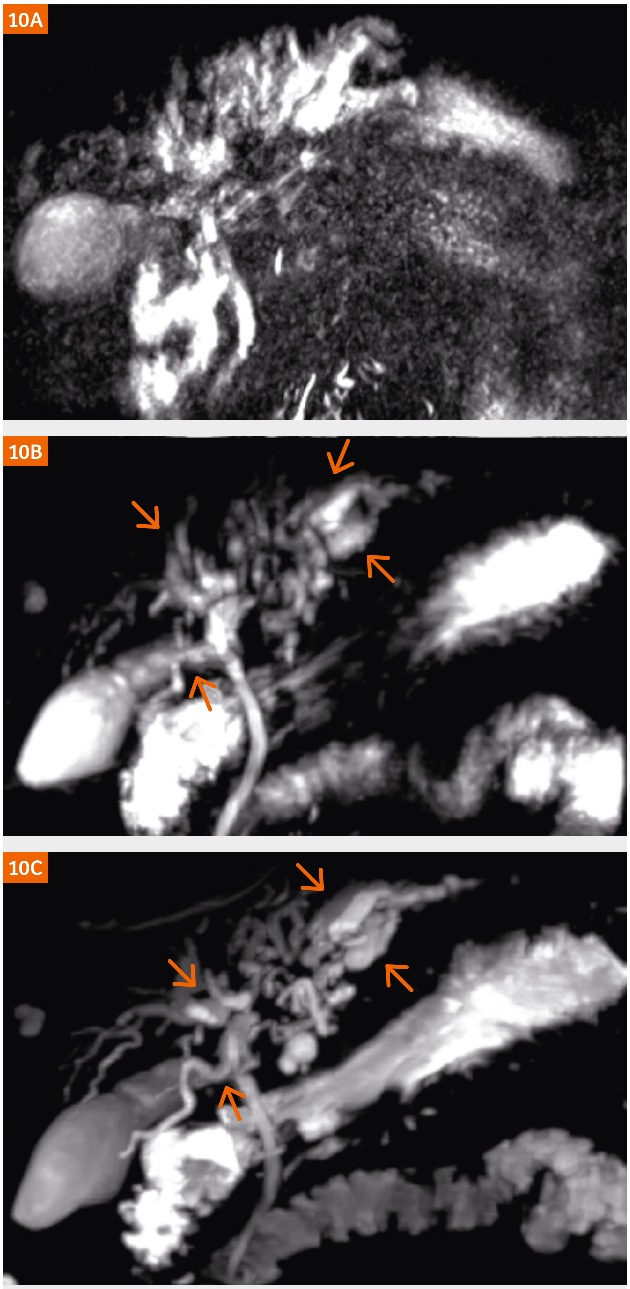

Figure 10:
3D MRCP exams of a patient with a hilar cholangiocarcinoma, comparing **(10A)** conventional and **(10B, C)** compressed sensing exams, with **(10C)** acquired during breath holding (16 sec). Conventional 3D MRCP exams require on the order of 5–10 minutes for acquisition, depending on the breathing pattern of the patient. On the conventional exam, dilatation of the intrahepatic ducts is evident, but the exam otherwise uninterpretable due to motion artifacts. Image quality with the non-breath hold compressed sensing exam is markedly improved. However, dilatation of the intrahepatic ducts and in particular second order branches (arrows) of the left hepatic duct are best visualized on the breath-hold compressed sensing exam.
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While beath-holds are still required with the TWIST-VIBE approach, the combination of radial image acquisition with compressed sensing reconstruction (GRASP-VIBE) was a seminal development in abdominal MRI in this decade. The previously mentioned streaking artifacts can be significantly reduced by introducing iterative reconstruction, thereby enabling reconstruction of 3D datasets that cover time frames of 5–10 seconds. This enables the acquisition of dynamic, contrast-enhanced scans of the liver during free-breathing in one continuous run. Studies have shown that this overcomes the timing challenges in dynamic imaging as well as limiting respiratory artifacts, expanding substantially the patient population eligible for abdominal MRI. A further improvement of image quality is achieved by applying self-gating, which recognizes the end-expiratory phase and rejects all other data.

The integration of compressed sensing into sequences optimized for imaging of the upper abdomen has already had a major impact upon clinical imaging, with further major developments anticipated in this rapidly developing field. XD-VIBE[3] is one such approach, using compressed sensing and simultaneous acquisition of a navigator signal for motion resolved reconstruction (Fig 9) [8]. With this approach, excellent image quality and lesion detectability, together with a relative lack of motion artifacts, has been demonstrated in oncologic patients with images acquired during free breathing [9].

Turning to the biliary system, compressed sensing has a major impact as well in MR cholangiopancreatography. An important scan clinically is the heavily T2-weighted 3D acquisition which is used to visualize the biliary ducts. Due to the number of breath-holds required and the long TR, acquisition time is typically in the order of 4–6 minutes. This exam, when acquired with SPACE, may also be combined with compressed sensing. Depending upon the desired result, a substantial reduction in scan time can be achieved with the exam still acquired during quiet breathing, or the scan can be further optimized to allow acquisition in a single breath-hold [10]. Initial results favor clinical use of the latter (Fig. 10), reflecting as well the historical development of upper abdominal MR imaging.

Musculoskeletal system

As in other areas of the body, simultaneous multi-slice and compressed sensing go hand-in-hand in terms of improving the clinical exam in musculoskeletal imaging. For the knee in particular, due to the cylindrical, high number of elements design of the receiver coil, SMS is

[3] WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

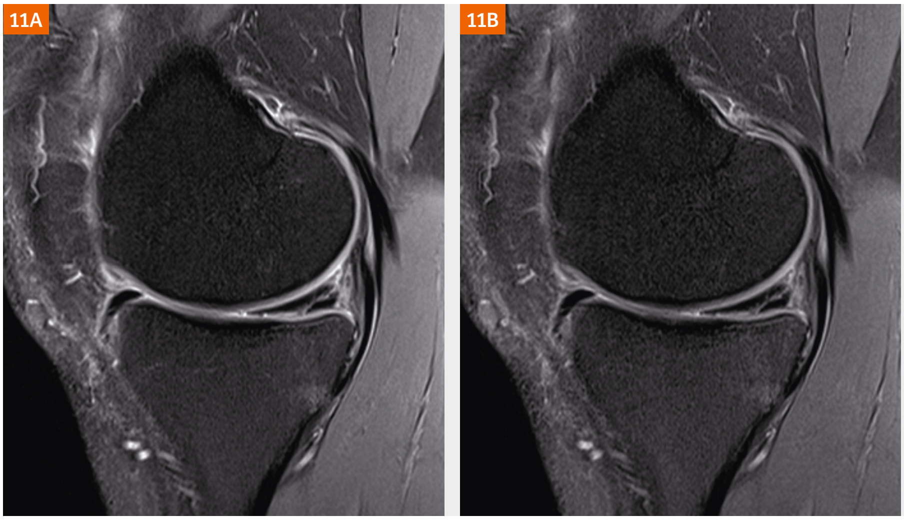

Figure 11:
High-resolution sagittal proton density-weighted images of a horizontal tear of the medial meniscus (posterior horn) demonstrating the value of SMS. Turbo spin echo exams acquired **(11A)** in a conventional fashion and **(11B)** using 2-fold SMS acceleration are compared. Voxel dimensions were 0.5 x 0.4 x 2.5 mm^3. Scan time was reduced from 6:36 to 3:27 min:sec by the use of SMS, with image quality and SNR maintained.

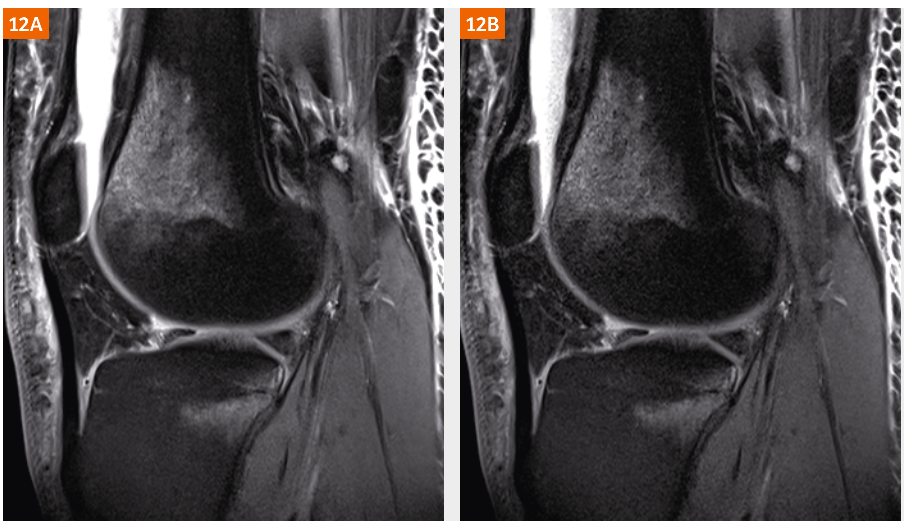

Figure 12:
SMS can be employed to markedly shorten scan time, which can be of high value either to increase patient throughput or as in the current example in the evaluation of a trauma patient. Extensive bone marrow edema (within the distal femur and proximal tibia) is seen, together with subcutaneous edema posteriorly and a large effusion within the suprapatellar bursa, on sagittal proton density-weighted images (with fat saturation) in this patient. As compared to **(12A)** the conventional scan, using **(12B)** an SMS factor of 2, the acquisition time was reduced by nearly a factor of two, to 1:34 min:sec.

highly applicable. The complex anatomy and numerous small critical components of the knee, all important for its proper function, have driven knee imaging clinically towards higher and higher resolution. The application of SMS enables a substantial reduction in scan time, making such desired high-resolution techniques viable (Fig. 11). Alternatively, if standard resolution scans will suffice for the clinical question and/or if possible patient movement limits the exam, for example in trauma patients, SMS can be critical to enable faster scans (Fig. 12). Both proton density and T2-weighted scans are commonly used in the musculoskeletal system, with SMS easily integrated in both instances. The use of two concatenations is often required, or a prolongation of TR, due to the number of slices needed to cover the structure anatomically using thin section imaging, with an SMS factor of 2 thus readily applicable.

The use of SEMAC for the reduction of metal[4] artifacts in orthopedic imaging is an ideal area for scan time reduction by the implementation of compressed sensing. Metal artifacts in many instances limit image interpretability, in particular at 3T. SEMAC corrects for metal artifacts by robust encoding of each excited slice. View angle tilting is incorporated to suppress most in-plane distortions, with *z*-phase encoding resolving the distorted excitation profiles which cause through-plane distortion. Unfortunately, the addition of *z*-phase encoding steps leads to longer scan times. To maintain feasible scan times, compressed sensing is incorporated into the SEMAC sequence. 8-fold acceleration through the implementation

[4] 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.

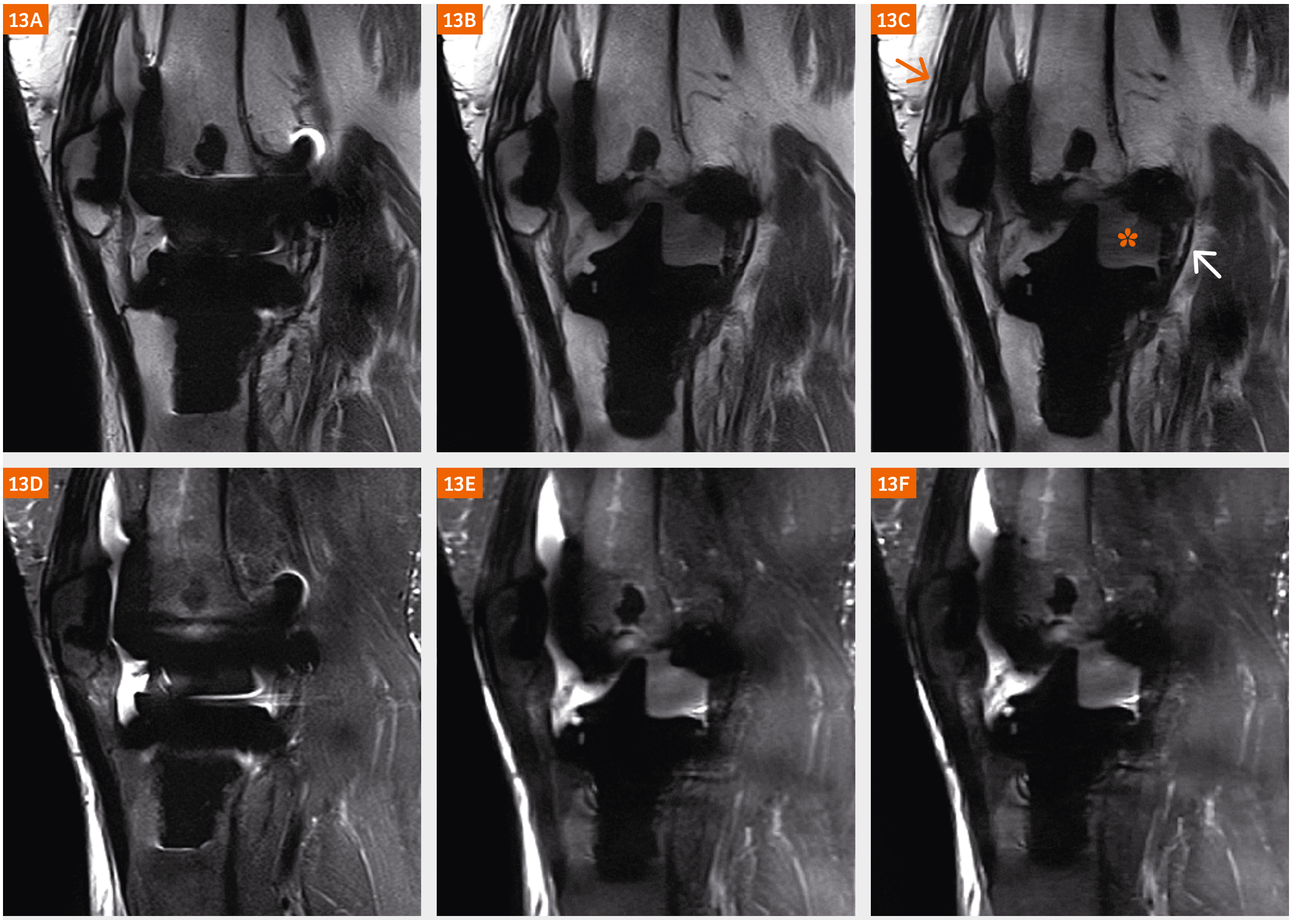

Figure 13:
Comparison of **(13A, D)** high bandwidth TSE, **(13B, E**) SEMAC TSE, and **(13C, F)** compressed sensing SEMAC TSE[3] for metal artifact reduction. The (13A–C) upper row of images is with mild proton density-weighting and the (13D–F) lower row acquired with STIR. This older man had a cobalt-chromium knee arthroplasty implant. Scan times for the high bandwidth sequences were five minutes, which with the application of SEMAC extended to 11 minutes in each instance. The application of compressed sensing allowed a reduction in scan time of the sequences with SEMAC to that of the high bandwidth sequences. The extensor mechanism (orange arrow) is well seen on all scans, however the articular structures including specifically joint fluid (*) and the posterior capsule (white arrow) are best seen on the SEMAC images.
Adapted with permission from Jan Fritz et al, Invest Radiol 2016;51: 666–676.

of compressed sensing–based incoherent *k*-space undersampling has been demonstrated, yielding improved image quality relative to the use of high-bandwidth alone and equivalent image quality to the much longer conventional SEMAC acquisition (Fig. 13) [11]. This approach enables SEMAC to be extended in clinical application to the millions of patients with metallic implants.

Breast

Today breast MRI is an integral part of screening, diagnosis, and follow-up for breast cancer. For radiographic breast imaging, the direction of development has been towards increasingly complex and expensive methods [12]. Both SMS and compressed sensing offer an excellent way to move in the opposite direction, specifically in terms of shortening the exam. The application of SMS is simplistic, simply to decrease scan time for breast diffusion-weighted imaging, a crucial part of any breast evaluation (Fig. 14).

Dynamic contrast-enhanced (DCE) MR imaging is a vital tool in the diagnosis of breast cancer. To assess tumor morphology and contrast kinetics, ideally such an acquisition would have both high spatial and temporal resolution. The use of compressed sensing (CS), specifically in combination with VIBE, permits an increase in through-plane spatial resolution in dynamic exams with comparable visual assessment of lesions as with

[3] WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

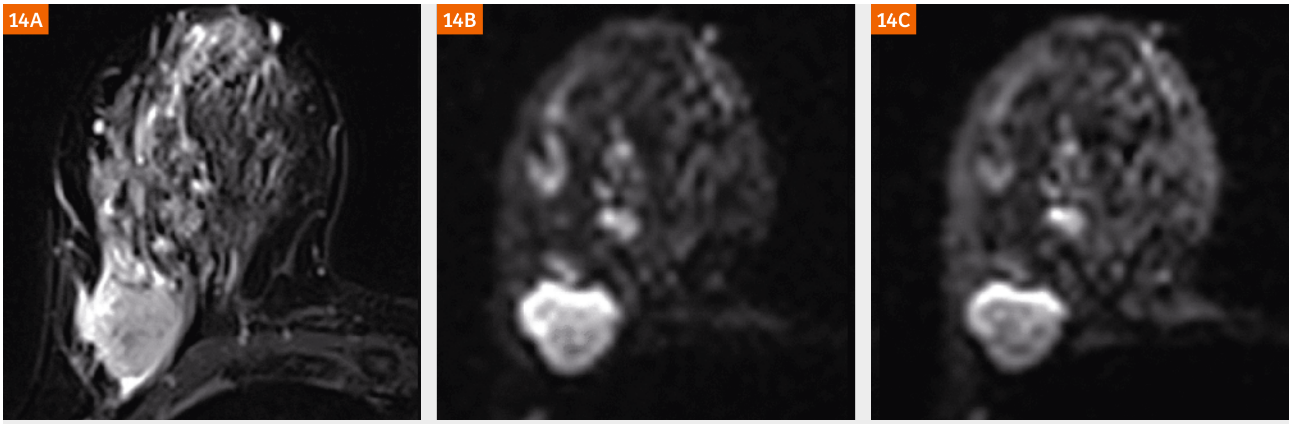

Figure 14:
The application of SMS to reduce scan time for readout segmented (rs, RESOLVE) EPI DWI in imaging of the breast. **(14A)** T2-weighted Dixon TSE and **(14B, C)** rs-EPI DWI scans of the right breast in a 45-year-old woman with invasive breast carcinoma are presented. The diffusion-weighted scans are 3 mm in slice thickness, with scan times of (14B) 7:28 and (14C) 3:17 min:sec. For (14C) a SMS factor of 2 was used.

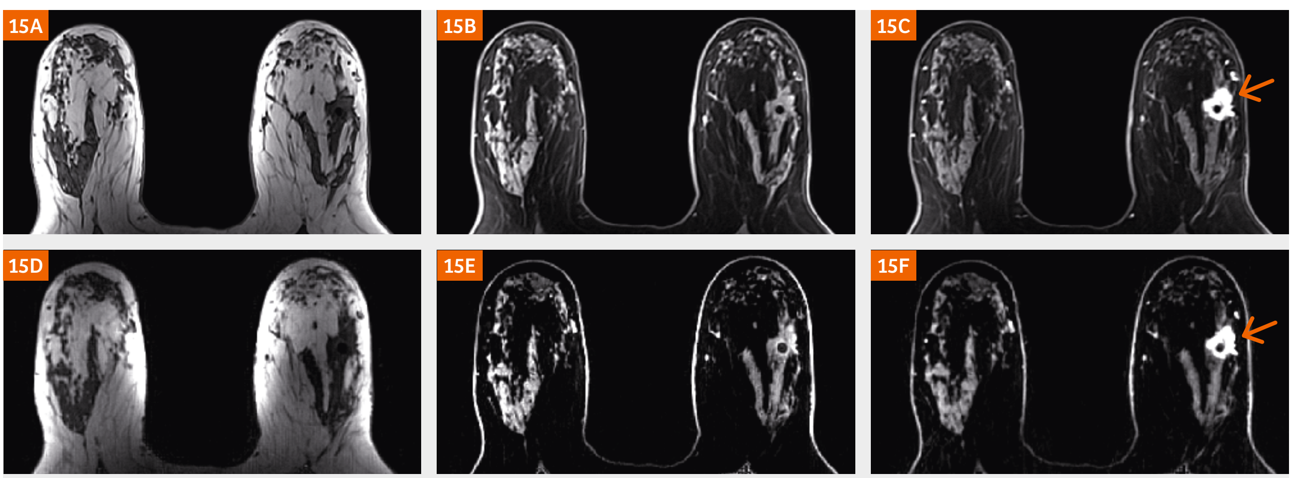

Figure 15:
Applicability of Dixon radial volumetric encoding (Dixon-RAVE) for a comprehensive 3D dynamic contrast-enhanced MR exam of the breast. Conventional T1-weighted VIBE scans pre-contrast **(15A)** without and **(15B)** with fat suppression together with a **(15C)** post-contrast fat suppressed scan are illustrated on the top row. The images with equivalent tissue contrast on the bottom row **(15D–F)**. are from a single continuous Dixon-RAVE scan performed during contrast injection, employing radial sampling and compressed sensing. This approach provides a diagnostic quality, comprehensive T1-weighted breast MR with high spatiotemporal resolution, reduced overall imaging time, and superior fat suppression. Illustrated are scans from a 61-year-old woman with invasive ductal carcinoma (arrow).
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non-dynamic techniques such as VIBE-Dixon [13]. For example, in the clinical study just referenced, acquisition time was decreased by a factor of 18 in comparison to the T1-weighted Dixon sequence, yet with morphologic assessment not significantly different. CS-VIBE is a promising technique for ultrafast MR imaging, providing high spatial and temporal resolution, with image quality comparable to non-dynamic scans, providing in distinction to prior dynamic techniques reduced temporal blurring as well as the possibility of multiplanar lesion morphology assessment.

Another application of compressed sensing for dynamic contrast enhanced 3D breast imaging is with Dixon radial volumetric encoding (Dixon-RAVE)[3] WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured. [14]. Robust and uniform fat suppression improves the clinical applicability of DCE breast MRI. Dixon-RAVE combines compressed sensing, radial

[3] WIP, the product is currently under development and is not for sale in the US and in other countries. Its future availability cannot be ensured.

sampling and excellent fat suppression – providing scans with both high spatial and temporal resolution. In addition to contrast-enhanced images, from such an acquisition pre-contrast images with and without fat suppression can be extracted, enabling a comprehensive T1-weighted DCE exam with reduced overall scan time. Dixon-RAVE thus can serve as a one-stop-shop approach for comprehensive T1-weighted imaging of the breast (Fig. 15).

Conclusion

Improving the speed of MRI is important for its continued future widespread clinical use and success. Sparse imaging (compressed sensing, CS) and simultaneous multi-slice (SMS) are the two most important developments in the current decade to achieve this goal. These build upon the foundations laid by parallel imaging, VIBE, and radial imaging as well as many other innovations. CS and SMS have very general applications in routine clinical practice, together with improving several important subspecialty exams, covering the spectrum of what clinical MRI offers today, for example from pituitary imaging on the one hand to metal artifact reduction in musculoskeletal imaging on the other. Speed also improves the robustness of the technique, with these developments fundamentally impacting clinical utilization today and further developments extending at least into the next decade.

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