Important Updates for Advanced Imaging Topics, with a Perspective on Improved Patient Throughput

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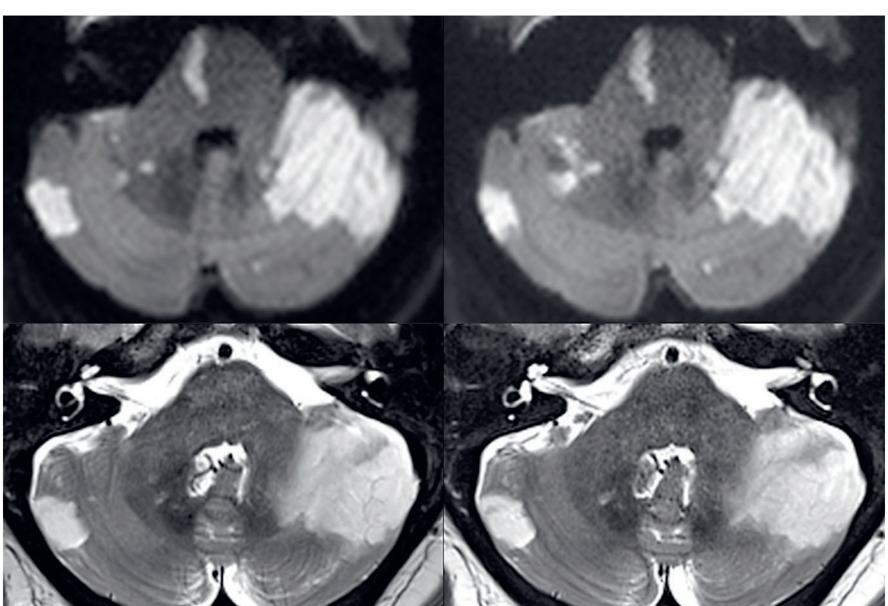
Introduction

Five important relatively recent innovations involving MR scan techniques and the approach to the patient are described. These include specifically simultaneous multi-slice (SMS), compressed sensing, GRASP (and its variants), respiratory sensing (using a sensor embedded into the patient table), and monitoring cardiac contraction employing a Pilot Tone[1] (as opposed to the ECG). Each offers potentially major time savings relative to any patient's exam time, impacting in a positive way patient throughput.

[1] *Work in progress: the application is currently under development and is not for sale in the U.S. and in other countries. Its future availability cannot be ensured.*

Simultaneous Multi-slice (SMS)

In simultaneous multi-slice (SMS) technique, multiple slices are excited at the same time, with each slice subsequently individually reconstructed. This is a major innovation in scan acquisition that occurred in the past decade. By use simply of an acceleration factor of two – the most common implementation clinically, scan times for applicable sequences can be reduced nearly in half. The physics involved is somewhat complex, with the details not important for clinical application. To give a brief summary of how such scans can be acquired, blipped CAIPIRINHA is applied during the echo train (minimizing *g*-factor-related SNR loss) – with for example two non-adjacent slices excited.



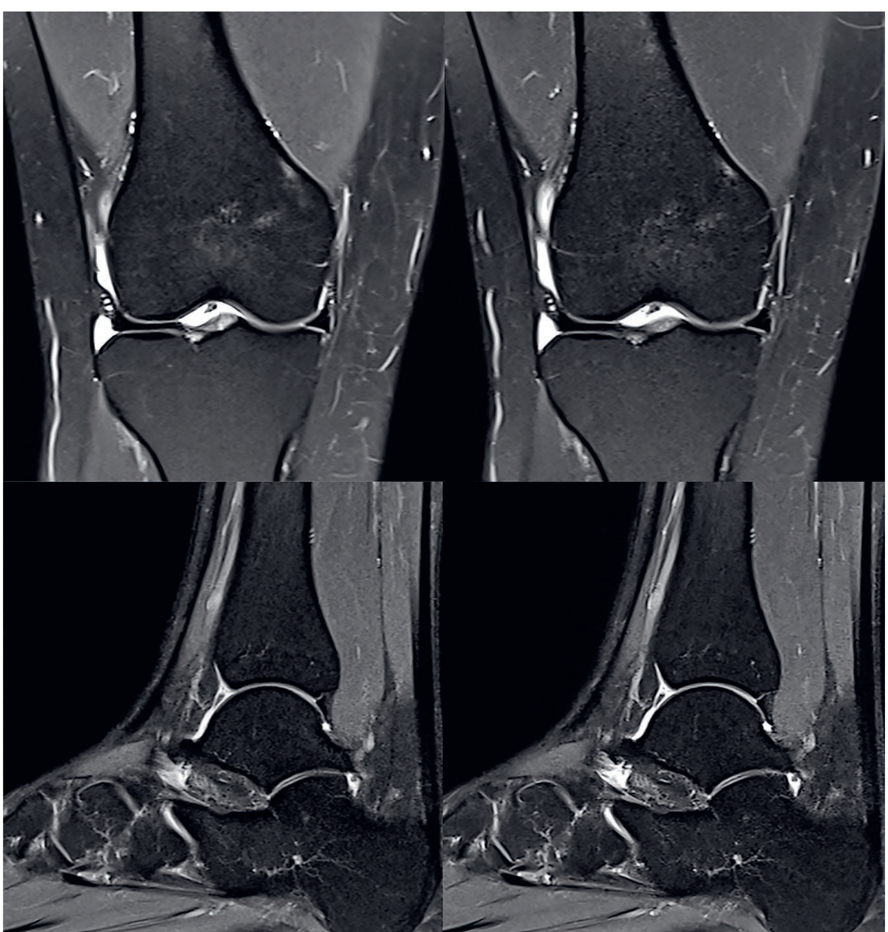
1 Multiple early subacute cerebellar infarcts with high signal intensity on both DWI and TSE T2-weighted scans. The conventionally acquired scans are on the left, the SMS scans on the right. The scans were acquired at 3T, with 2x (for DWI) and 3x (for TSE) acceleration factors employed using SMS. *Adapted with permission from Invest Radiol 2019;54:383-95.*

Reconstruction of the images is then accomplished by first applying slice GRAPPA-based unaliasing, and subsequently in-plane GRAPPA-based unaliasing. Otherwise the single reconstructed image would represent the sum of the two slices [1].

There is an important difference between parallel imaging and SMS. Both are commonly used to reduce scan time, however with parallel imaging SNR is markedly decreased (but not with SMS). In parallel imaging, fewer *k*-space lines are acquired, the cause of the reduction in SNR. The fundamental basis of parallel imaging is the use of coil sensitivity information (from a multichannel coil) to reconstruct missing *k*-space lines. The loss in SNR with parallel imaging is proportional to both the coil specific geometry (g) factor and the square root of the acceleration factor. The *g*-factor is a noise amplification factor that varies across the image volume, a result of the estimation process of the unwrapping algorithm. Because blipped CAIPIRINHA is employed in SMS, the *g*-factor loss is minimized. And, since there is no reduction of acquired *k*-space lines, there is no related SNR penalty.

An important clinical tip when employing SMS is to use the receiver coil with the highest coil density available. For example, given the choice between a 20-channel and a 64-channel head coil, the latter should be chosen. Higher coil density specifically when using SMS generally provides a higher signal-to-noise ratio.

SMS can be utilized with both echoplanar and turbo spin echo (TSE) scan sequences (Fig. 1) [2]. The technique was first introduced for diffusion-weighted imaging, and then subsequently for TSE. Important applications of SMS single-shot (ss) EPI DWI include scan time reduction for liver imaging, due to the number of slices needed, and, although it might not be immediately evident, in a similar fashion for scan time reduction in imaging of the prostate – due to the thin sections required. In another DWI application, SMS is commonly employed at 3T with readout-segmented EPI scans (rs-EPI, RESOLVE). RESOLVE offers reduced geometric distortion and blurring at 3T, which leads to poor image quality when using single shot EPI. Susceptibility artifacts, such as those caused by the air filled sinuses, are also decreased substantially by the use of RESOLVE. However, an important limitation of RESOLVE is the longer scan time when compared with ss-EPI. Thus, SMS is used routinely today for scan time reduction with RESOLVE. This is achieved by reducing the



2 Proton density-weighted, fat suppressed, TSE scans at 1.5T of the knee (upper row) and ankle (lower row). The conventional acquisitions are displayed on the left, the SMS acquisitions on the right. In both instances 2x acceleration was employed, resulting in scan time reductions respectively of 45% and 32%. In clinical practice SMS scans are often preset with minor variations in other parameters, to achieve the best combined image quality and slice coverage, thus leading to less reduction in scan time than a factor of 2 (a 50% reduction) – for instance with the ankle scan presented. *Adapted with permission from Invest Radiol 2019;54:383-95.*

TR in combination with the application of SMS. Another application of rs-EPI is acoustic noise-optimized DWI (reducing the noise of the scan for increased patient acceptance). In this application, echo spacing is increased and thus the noise due to the reduced gradients. On the negative side, image distortion and bulk susceptibility artifacts are increased – which can be countered by the use of readout-segmented EPI.

Following the successful implementation of SMS for DWI, this innovation was extended to TSE technique. SMS TSE is not restricted to any one tissue contrast, but can be used with proton density-, T1-, and T2-weighted imaging. SMS TSE is implemented for scans that would otherwise need multiple concatenations to acquire the required number of slices. SMS with a factor of 2 allows in essence twice the number of slices to be sampled within the same TR, thus making possible the number of concatenations to be halved and thus also scan time. It is used in certain instances for brain and soft tissue neck imaging, and in particular for musculoskeletal imaging.

SMS was first introduced at 3T, and subsequently extended to 1.5T systems (Fig. 2). It has excellent applicability at both fields, with little difference in terms of efficacy – specifically in terms of reducing scan time. In regard to next generation low-field (0.55T) MR units, SMS will also likely play an important role [3]. However, this will be different than what it is applied for at 1.5 and 3T, which is mainly to decrease scan time. At 0.55T SMS is likely to be implemented to increase SNR while maintaining scan time, due to the lower intrinsic SNR at 0.55T.

Compressed Sensing (CS)

Compressed sensing has been available clinically now for several years for specific applications, leading to a substantial reduction in scan time. The time required for image reconstruction was originally quite long with this technique. However, this process has been streamlined, and new hardware introduced, making reconstruction times suitable for routine clinical use of CS scan sequences.

The compressed sensing variants of VIBE, including GRASP-VIBE, XD-GRASP[1], CS-VIBE and XD-VIBE[1], will be discussed in the next section. These scans have specific applicability for liver imaging. These also allow liver perfusion calculations to be made from a free-breathing dynamic post-contrast scan, thus eliminating an additional contrast injection and not further prolonging exam time. XD-GRASP deserves special note, with this scan technique providing free breathing motion-resolved reconstructions, thus making available diagnostic quality multiphase images following contrast administration.

Compressed sensing magnetic resonance cholangiopancreatography (MRCP) enables a major reduction in scan time for this specific application. At 1.5T when applied to a conventional sequence, CS enables imaging in as little as 1/3rd of the original scan time. At 3T, diagnostic quality single breath-hold MRCP scans are a very viable clinical alternative (Fig. 3) [4]. Given the long scan time of conventional MRCP scans and the associated motion artifacts, CS MRCP exams are advocated for improved diagnosis and reduced exam time.

In cardiac imaging, compressed sensing variants are available for myocardial perfusion and CINE imaging. Single breath-hold 3D CS CINE imaging of the left ventricle is also available, offering an alternative to conventional 2D CINE with multiple breath-holds. Acceleration using CS is also possible for first-pass cardiac perfusion, providing quantification of myocardial blood flow while allowing increased anatomic coverage and higher spatial resolution.

In musculoskeletal imaging, CS versions of SEMAC have made high quality metal artifact reduction clinically feasible. SEMAC was previously limited by its long scan times, with CS permitting a marked acceleration of the ac-

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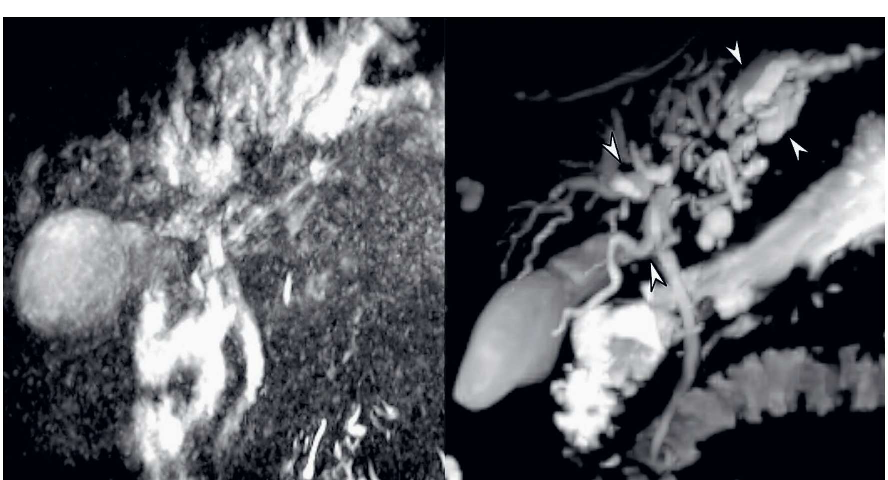


3 Magnetic resonance cholangiopancreatography (3D acquisition), cholangiocarcinoma invading the portal hilum, comparison of a conventional seven minute acquisition and a breath-hold (16 second) compressed sensing (CS) exam. There is marked degradation of the conventional scan due to breathing artifacts. Note the substantial improved depiction of dilated intrahepatic ducts (arrowheads) on the CS exam. *Adapted with permission from Invest Radiol 2017;52:612-9.*

quisition with excellent resultant image quality. Scan times of 2 to 6 minutes are now routine with this technique.

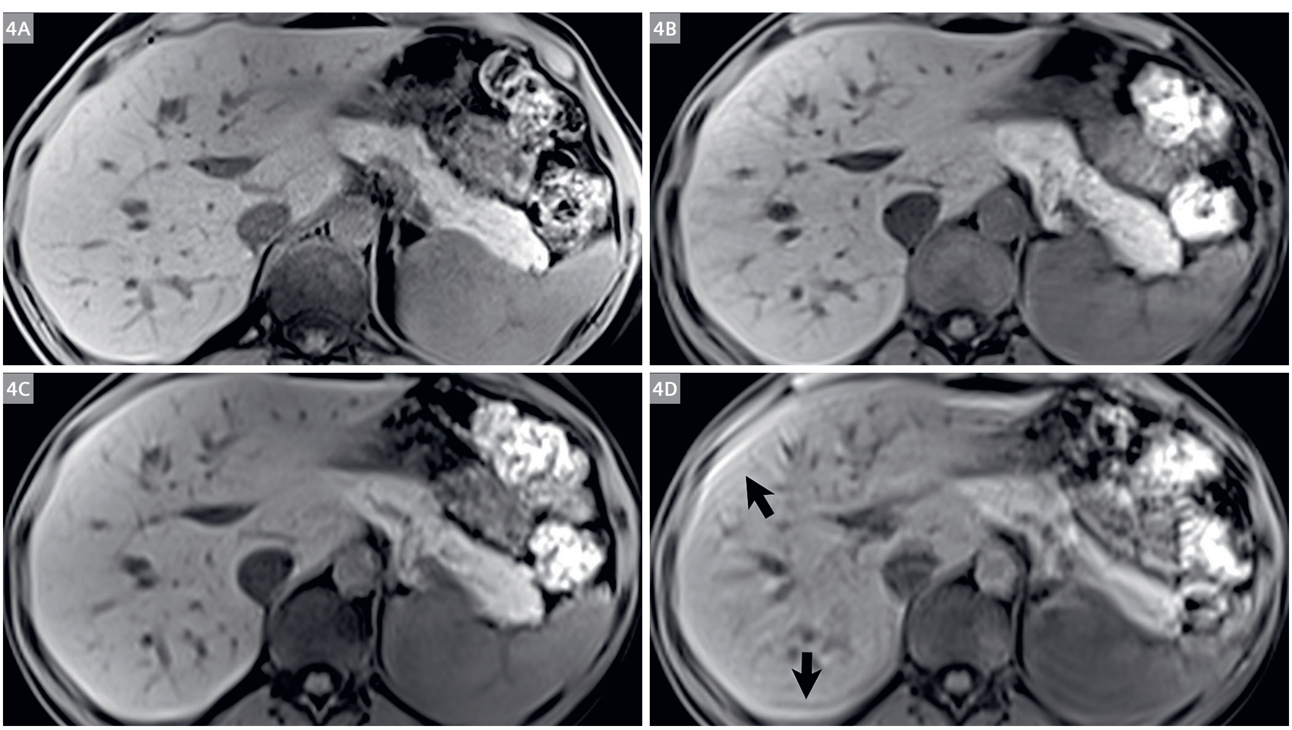
Compressed sensing applications have even been demonstrated for the brain, where specialty exams with a lengthy scan time are candidates. Double inversion recovery, which finds clinical use in multiple sclerosis (for improved detection of cortical lesions), can be acquired with compressed sensing, reducing scan time in half (down to about 3 minutes). Time of flight MRA is another lengthy scan technique where the application of compressed sensing has been demonstrated, halving scan time yet providing equivalent diagnostic information.

GRASP (Golden-angle radial sparse parallel imaging)

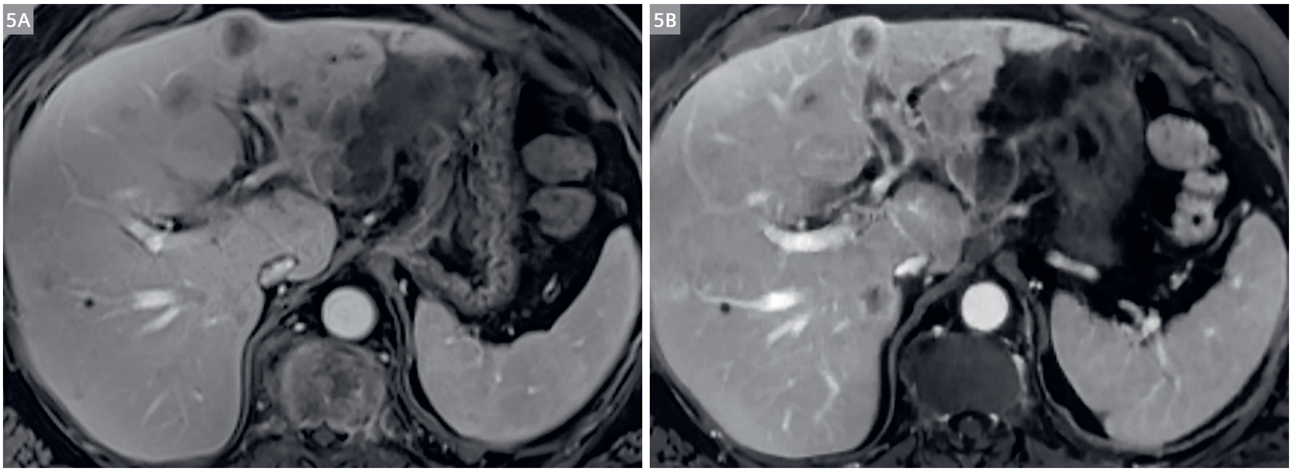
StarVIBE employs radial acquisition in-plane in combination with a fat-suppressed spoiled gradient-echo sequence. Extending this to 3D, with Cartesian sampling in the *z*-direction, this approach is known as a stack-of-stars (*k*-space trajectory). In-plane the acquisition is radial, through-plane it is Cartesian. The scan sequence can tolerate moderate under-sampling and is motion robust. StarVIBE was first used in liver imaging ten years or so ago. Today it has applicability in many different body regions, for example the orbits, the head and neck, the chest, the abdomen and the bowel, as well as in pediatric imaging[2]. When acquired with golden-angle radial sampling, retrospective gating is possible and the sequence itself can provide the respiratory signal (self-gating). Self-gated isotropic radial scans have been used for example following Eovist/Primovist injection to demonstrate the hepatobiliary excretion of the contrast agent. The image quality is superior using this approach to conventional StarVIBE.

With golden-angle radial sampling, the consecutively acquired spokes cover *k*-space almost uniformly when the total spokes constitute a Fibonacci number (a series of numbers in which each is the sum of the two preceding). Temporal resolution can likewise be adjusted. Using this sampling approach, data acquisition is not repetitive over the whole scan but instead can be considered temporally incoherent, a necessary condition for compressed sensing. StarVIBE thus evolves, in combination with the use of compressed sensing reconstruction, to GRASP-VIBE (Fig. 4).

[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.



4 Comparing breath-hold VIBE and GRASP during normal breathing for liver imaging. High-resolution VIBE **(4A)** is compared with a slightly lower resolution GRASP scan **(4B obtained during free-breathing)**, a VIBE scan with resolution close to that of the GRASP scan **(4C)** and the VIBE scan obtained without breath-holding **(4D)**. Respiratory artifacts (arrows) markedly degrade VIBE scans when acquired during normal breathing, or as common in certain patient populations, without a good breath-hold. Scan times were all within the range used normally for breath-hold scans (10–20 sec). As expected, GRASP and the breath-hold VIBE scan with matched voxel size are of equivalent image quality. The high resolution breath-hold VIBE scan offers the best image quality in the current comparison (due to the spatial resolution and the excellent breath-hold), although this is not achievable in many elderly patients. *Adapted with permission from Invest Radiol 2019;54:383-95.*



5 Free-breathing scans can provide image quality comparable to breath-hold scans, a time-saving strategy that makes post-contrast imaging feasible for patients who cannot hold their breath. This is illustrated with the comparison of breath-hold VIBE **(5A)** and free-breathing XD-VIBE **(5B)** scans, both in the venous phase. Multiple liver metastases from colorectal cancer are visualized by both exams, with XD-VIBE superior in this instance due to better contrast timing. XD-VIBE is a Cartesian acquisition that enables motion state reconstruction. It provides during free breathing excellent image quality, good temporal resolution, and accurate lesion detection.
Adapted with permission from Invest Radiol 2017;52:708–714.

Free-breathing contrast-enhanced multiphase liver MR becomes possible, with flexible spatiotemporal resolution tailored to clinical needs. Self-gating is an integrated part, reducing the impact of respiratory motion.

GRASP-VIBE (which is also referred to as simply GRASP) is extremely useful in dynamic abdominal MR for patients who cannot cooperate with breathing instructions or who have difficulty holding their breath. Using this free breathing approach, liver perfusion metrics (including specifically total plasma flow, portal venous flow, arterial perfusion fraction, mean transit time and hepatocellular uptake rate – the latter if Eovist/Primovist is administered) can also be acquired, without an additional contrast injection or additional scan time. Outside of the liver, GRASP-VIBE finds many other applications, due to its inherent robustness to motion, including the female pelvis and prostate/rectum.

By including respiratory motion state resolved reconstruction GRASP-VIBE further evolves to XD-GRASP.[1] Instead of including only data from a certain motion window, the data is binned into multiple different motion states which are then likewise reconstructed. This approach can further improve image quality. Arterial phase reconstructions with XD-GRASP, acquired in free-breathing, can potentially surpass conventional breath-hold Cartesian acquisition in terms of image quality. Breath-hold scans can suffer due to limitations imposed by balancing temporal and spatial resolution with the need for anatomic coverage and also from the transient dyspnea seen with Eovist/Primovist.

Compressed sensing variants have been developed as well for Cartesian *k*-space sampling strategies. CS-VIBE is the Cartesian counterpart to respiratory gated GRASP. XD-VIBE[1] is the Cartesian counterpart to XD-GRASP. Both CS-VIBE and XD-VIBE allow dynamic, self-gated data acquisition with free-breathing [5]. Like their radial counterparts, CS-VIBE uses data from the dominating motion state for a given gating acceptance, whereas XD-VIBE bins the data into different motion states and provides motion state resolved images (Fig. 5). Both approaches have been shown to be useful clinically.

Respiratory Sensing

Today, patient respiration is automatically monitored by a coil that lies within the patient table (and is more specifically part of the spine coil insert). This represents a major innovation, providing substantial time savings. Respiratory monitoring with a bellows type device, allowing respiratory gating for image acquisition and reconstruction, has a long history in MR. It was first suggested in 1984 [6], but requires substantial setup time and offers a poor solution for efficient respiratory gated scan acquisition. Navigator echoes were subsequently invented, and are still in use today, but have the disadvantages of requiring operator setup, being prone to misplacement, and requiring time within the scan sequence.

In contrast to these older approaches, using a respiratory sensor embedded in the table requires no setup, is automatic, and provides a reliable, reproducible respiratory trace. The signal itself is generated from a single simple, transmit/receive loop coil. To allow the signal to be differ-

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6 The location of the two transmit/receive coils used for respiratory sensing are indicated on the surface of the patient table/spine coil by the lung icons (at the top and bottom). The patient can be positioned head or feet first, with the diaphragm thus lying close to one of these two coils, for detection of respiration.

entiated from that used for imaging, the coil operates at 30 MHz for 1.5 and 3T systems, far away from the Larmor frequency. Respiration causes a change in the coil loading, which leads to current changes in the coil that can be detected and monitored. A small current is fed into the coil, and the resulting current output takes the form of the respiratory cycle, with slightly higher current during inhalation and lower during exhalation.

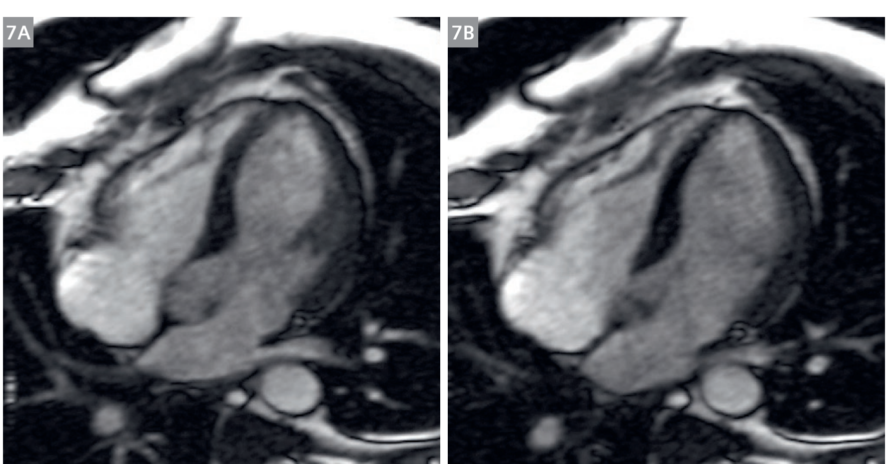
Because the coil for respiratory sensing needs to be placed near the diaphragm of the patient, there are in reality two such coils (Fig. 6). One coil is located in the appropriate place for patients positioned head first in the scanner. The other coil is used for feet-first studies, as well as for exceptionally tall or short individuals and pediatric patients.

The respiratory signal is detected and displayed as soon as the patient is placed on the scanner table, regardless of whether the patient is inside or outside of the magnet bore. In addition to its use with scan acquisition (for respiratory-triggered scans), the respiratory sensor plays an important role for patient monitoring and as a quality control measure for breath-hold scans, allowing the technologist to monitor the patient's ability to hold their breath for the duration of the scan.

Monitoring Cardiac Contraction (the Pilot Tone[1])

In the future, the ECG – as a monitoring and triggering device for MR – is likely to be replaced by direct monitoring of heart motion, using a reference radiofrequency signal described in telecommunications as a Pilot Tone[1] [7]. Such a sensor design would allow automatic capture/monitoring of the cardiac cycle, to some extent like that provided today but using different principles by the respiratory sensor. There are many negatives to the use of the ECG. These include the difficulty and time consumed for placement of the leads, the poor signal sometimes obtained, and the artifacts contaminating the observed signal. Particularly at higher field strengths, the MR gradients and the magnetohydrodynamic effect cause artifacts in the ECG, leading to poor triggering. Blood, a conductive fluid, when flowing through a magnetic field induces a voltage – a well-known phenomenon in fluid mechanics, the magnetohydrodynamic effect. This causes a change in the observed ECG – which can interfere with gating as well as masking cardiac ischemia in the observed ECG, when the patient is in an MR scanner, and is greater at 3T when compared to 1.5T.

For MR, a small magnetic field generator embedded in an anterior coil generates the Pilot Tone. That signal is then modulated by heart motion, more specifically the changes



7 Early-diastolic images, comparing that triggered by the use of the Pilot Tone **(7A)** vs the ECG **(7B)**, from a cardiac cine scan, courtesy of Mario Bacher (Siemens Healthineers).

in conductive geometry, and sampled using local receive coils. This signal correlates well with the ECG, is detectable during free breathing, and can be used to acquire high quality images of the heart. The frequency used for the Pilot Tone is just outside that employed for image reconstruction (the Larmor frequency). This design should generate a much more robust signal than that from the ECG. Flexible trigger time point placement is also possible, unlike with the ECG, triggering for example at maximum cardiac contraction. This single device will also provide both cardiac and respiratory signals, as both influence the Pilot Tone. Figure 7 shows good correlation between images acquired with the Pilot Tone and the ECG. Whether this additional way to observe respiration will be further developed lies in the future.

In terms of clinical utilization, receive coils are already available containing the necessary hardware, with implementation of the Pilot Tone sensor system ongoing in next generation MR systems.

A potential advantage of Pilot Tone navigation – in addition to the ease of use – is that cardiac volume is measured directly as opposed to observation of the electrical activity of the heart (by the ECG). Any trigger time point can also be used, during the cardiac cycle, as previously noted. Pilot Tone navigation can be employed with any scan sequence, and unlike navigator echoes does not require the use of additional RF pulses.

Summary

Five important innovations for MR scanning are described, all with a very positive affect upon patient throughput. Simultaneous multi-slice offers with many scan techniques a method to halve scan time. Compressed sensing also offers a major reduction in scan time, by utilizing the concept of data sparsity and a sophisticated algorithmic approach. Its applicability is widespread in terms of types of patient studies, including brain, cardiac, abdominal, and musculoskeletal exams. Compressed sensing further makes possible many advanced imaging techniques including GRASP and its variants. This scan sequence group has its major impact in abdominal and pelvic imaging. Extremely important as well are two major hardware advances – automatic respiratory sensing and, using the Pilot Tone[1], cardiac monitoring/gating, both enabling from a clinical perspective a major reduction in set up time. Also achieved is excellent image quality and access to scan techniques that require high quality physiologic input.

Acknowledgment

Portions of the text as well as the figures are adapted with permission from "The Physics of Clinical MR Taught Through Images", 5th edition and reference #1.

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