

Abdominal and Pelvic Imaging at 3T

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Overview

3 Tesla magnets are no longer just a research tool used almost exclusively for brain imaging. Clinical 3T imaging of the abdomen and pelvis is now feasible and being performed worldwide. There is a huge push particularly from the industry to “upgrade” to 3T with units designed for whole body imaging. While in theory, 3T imaging offers higher signal to noise, increased spectral separation and improved image contrast, can these advantages be realized in the setting of the busy clinical practice? If so, is 3T imaging better than 1.5 T for body imaging?

In order to grasp the potential advantages of body imaging at 3T, it is important to understand what changes at 3T when compared to 1.5 T and how does it impact protocol. Sequence parameters at 1.5T should not be applied to 3T without making some basic modifications in order to optimize imaging quality. While some adjustments are straightforward such as altering TR and TE to improve image contrast, others may require new sequence design and technical improvements in magnet and coil designs which are actively being pursued. It is the goal of this lecture to introduce the audience to body imaging at 3T and address not only the challenges but the potential opportunities.

Objectives

1. Basic safety at 3T
2. Review potential advantages and disadvantages of abdominal/pelvic imaging at 3T.
3. Discuss the impact of 3T on routine abdominal/pelvic imaging protocols
4. Discuss potential future applications of 3T for body imaging

Safety concerns at 3.0T

Short-term exposures to static magnetic fields have not been shown to result in harmful biological effects in humans. The FDA has categorized clinical MR systems with a static magnetic field of up to 8 T as posing “non-significant risk” for patients over 1 month old. (Current FDA guidelines can be found at their website: www.fda.gov). In general, most devices that are safe at 1.5 T are proving also to be safe at 3 T.[1] Several continuously updated internet websites may be used for reference in specific cases (www.radiology.upmc.edu/MRsafety, www.mrisafety.com, for example).

Specific absorption rate (SAR) is a measure of the rate at which the body absorbs radiofrequency energy. Radiofrequency (RF) energy deposition and absorption must be carefully monitored to avoid excess heating. It is related to the square of the main magnetic field, so that at 3T, RF energy deposition is four times greater than at 1.5 T. The US Food and Drug Administration limits SAR based on concerns regarding the potential for tissue damage cause by excessive heat exposure.

Pros and Cons of Body Imaging at 3T

Field (B_0) Homogeneity:

Increasing field strength from 1.5 to 3 T leads to more susceptibility effects (local alterations in the magnetic field caused by placing a body in the magnet).

B_0 inhomogeneity leads to shortened $T2^*$ relaxation times and leads to greater signal loss at a given echo time at higher field strength. Such an effect may be favorable in abdominal and pelvic imaging and improve sensitivity to iron deposition for example in patients with hemochromatosis. Also, greater sensitivity to iron-containing contrast agents may prove advantageous. This also may be useful for certain sequences such as blood oxygenation level dependent (BOLD) which rely on the susceptibility effects of deoxyhemoglobin.

Susceptibility effects can also distort the local field and can also lead to image distortion and this effect can be problematic in body imaging because of signal loss at the interface between air and soft tissue (bowel, heart/lungs) or around implanted metallic clips or prostheses

Solutions: Better shimming, decreased voxel size (minimize intravoxel dephasing), shorten echo times (TE). Note that in order to shorten TE, higher bandwidth may be required resulting in a decreasing signal to noise (SNR).

Radiofrequency / (B_1) Homogeneity

B_1 describes the magnetic field that is associated with RF excitation, necessary to tip magnetic moments of protons temporarily away from their alignment with the main magnetic field. B_1 heterogeneity causes imperfect excitation and consequently areas of low signal, typically referred to as the **dielectric effect**. Inhomogeneous RF excitation due to B_1 inhomogeneity, results in visible inhomogeneity across the image that can obscure visualization of certain parts of the body, such as the left lobe of the liver. This is especially a problem in body imaging at 3 T in thin individuals.

Solutions: Use of extra padding over the abdomen and pelvis. New pulse sequences, new RF excitation pulses that can generate more uniform excitation and/or new phased array transmit coil designs that permit customized excitation pulses for uniformity.[2] Many of these are under investigation and rapidly evolving.

SAR

When scanning human subjects, RF power deposition is constrained by SAR limitations. Some of the simplest solutions reduce SAR but at the expense of decreased image quality. For example, lower flip angles for both types of sequences reduce image contrast and SNR. Alternatively, shortened echo train lengths, increased interecho spacing, or lengthened TR tend to lengthen acquisition times. This can be undesirable in chest and abdominal applications where breath hold imaging is favorable.

Solutions: For RARE sequences, lower flip angles can be used for refocusing, but at the expense of introducing a $T1$ dependence of the signal.[3] Variable flip angle sequences have recently been implemented that use a flip angle evolution during the echo train resulting in predictable patterns of signal intensity and desired image contrast with lower RF deposition.[4]

Variable-rate selective excitation (VERSE) methods, first described almost two decades ago, are also seeing a resurgence at higher field strengths.[5] VERSE techniques combine a time-varying gradient waveform with a modified RF waveform to provide the same excitation profile with less RF deposition. These pulses can be used to achieve high flip angles without exceeding SAR limits.

By reducing the necessary number of phase-encoding steps, parallel imaging techniques can help decrease RF exposure.

Signal to Noise ratio (SNR)

One of the major advantages of high field imaging is the potential increase in signal to noise ratio (SNR). Increasing field strength from 1.5 to 3 T leads to a theoretical two-fold increase in signal while noise remains relatively unaffected by field strength.

In human subjects, the theoretical increase in SNR may not be completely realized because of other factors. At high field strength, longitudinal relaxation T1, chemical shift and susceptibility effects increase, while T2 relaxation times decrease. To optimize tissue contrast, higher bandwidths are often required thereby decreasing the overall SNR. SAR limitations may reduce imaging efficiency or image quality.

Solutions: Parallel imaging strategies can potentially compensate for the limitations of SAR and maximize the potential gains in SNR at higher fields.

Chemical Shift

Given the higher Larmor frequency at 3T, there is (2X) greater chemical shift between compounds. This greater spectral separation and combined with greater SNR, provides great promise for MRS at high fields. The greater chemical shift between fat and water, equaling about 440 Hz at 3 T, compared with 220 Hz at 1.5 T, has several implications for conventional sequences such as in and out of phase T1 gradient echo and frequency selective fat suppressed sequences. Echo times at which fat and water protons are in-phase and opposed phase become much more closely spaced at 3 T.

Given the greater separation of fat and water at 3 T, chemical shift artifact due to mismapping of the frequency-encoded signal of fat into water voxels, occurs at higher bandwidths.

However, greater spectral separation lends itself to more successful frequency selective fat suppression.

T1 and T2 Relaxation Times

The magnetic field-dependence of tissue relaxation times is well-documented in the brain and musculoskeletal system. [6-9] De Bazelaire et al. calculated relaxation times of abdominal organs of human volunteers at 1.5 T and 3 T and showed an overall increase in T1 relaxation times and a slight decrease in T2 relaxation times at 3 T when compared to 1.5 T, depending on the organ.[10]

Owing to the lengthening of T1 relaxation times for most abdominal organs, there is a potential reduction of T1 contrast. Consequently, for gradient echo imaging, the TR should be longer, acquisition bandwidths should be larger, and the flip angle should be adjusted in order to optimize the image contrast and SNR. T1 relaxation times for

gadolinium contrast agents, however, are less affected at higher field strengths. This may result in greater image contrast on gadolinium-enhanced images at 3 T compared with 1.5 T.

Because of faster T2 relaxation, the rapid acquisition relaxation enhancement (RARE) sequences such as fast spin echo (FSE) or turbo spin echo (TSE) can be more affected by blurring artifacts at 3 T than at 1.5 T. [11] Consequently, a shorter TE and a shorter echo train length may be necessary and attained by use of parallel imaging.

Optimizing routine body imaging protocols at 3T

T1-Weighted Gradient Echo Imaging

- The greater chemical shift between fat and water at 3 T means that echo times at which fat and water protons are in-phase and opposed-phase are more closely spaced at 3 T. An efficient method for acquiring in-phase and opposed-phase images that also ensures image registration is dual-echo gradient echo imaging. High receiver bandwidths may be necessary to allow for sampling of two separate echoes following each RF excitation.
- In general, it is desirable to for the opposed-phase acquisition be performed at a shorter TE than the in-phase so that signal loss on the opposed image can be attributable to fat-water signal cancellation, rather than to T2* decay, such as due to iron deposition.
- The TR should be selected depending on the number of imaging slices desired for the acquisition, where Number of slices is typically just less than TR/TE₂. Flip angles may need adjustment to obtain acceptable T1-weighted image contrast.

T2-Weighted Fast Spin Echo

- For routine liver imaging, T2-weighted FSE sequences are typically performed with suppression of fat signal to enhance lesion conspicuity. Options include STIR imaging and frequency-selective FSE.
- For inversion recovery methods, the inversion time at 3 T should be adjusted slightly, although the change in T1 relaxation of time for fat at 3 T is modest.
- Frequency-selective FSE techniques tend to be more robust at 3 T given the greater spectral separation between fat and water.
- One challenges of RARE imaging at 3 T is related to SAR limitations. Several approaches can be used to reduce the RF deposition as discussed above.

Single-Shot Fast Spin Echo (HASTE)

- Commonly used in pancreatic and biliary imaging, these sequences are also challenged by the greater energy deposition of the repeated RF refocusing pulses at 3 T compared with 1.5 T. Strategies described above also pertain to HASTE sequences.

3D Gradient Echo Imaging

- Volumetric imaging of the abdomen and pelvis typically uses a fat-suppressed interpolated 3D gradient echo sequence.
- For gadolinium-enhanced MRA, non-fat-suppressed interpolated 3D gradient echo sequences are similar at 3 T compared with 1.5 T.

- Potential for parallel imaging in both phase-encoding directions resulting in reductions in acquisition time of 4 -6 at 3 T

Sample guidelines for protocols will be provided during the lecture.

Future applications of 3T for body imaging?

- Improved SNR and spectral separation will likely lead to more robust clinical MRS, particularly in applications such as prostate and breast cancer
- Pulse sequence designs such as VERSE and variable flip angle methods may overcome many SAR issues.
- Novel coil designs may help increase parallel imaging factors that can be realized at 3 T and lead to higher temporal and spatial resolution imaging.
- Some sequences may performed better at 3T such Diffusion, ASL (arterial spin labeling) and BOLD imaging
- Gd-contrast may be more robust at 3T and other contrast agents may perform better at 3T such as iron containing agents.

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References:

1. FDA. Guidance of Industry and FDA Staff: Criteria for significant risk investigation of MR Diagnostic Devices. <http://www.fda.gov/cdrh/ode/guidance/793.html>, 2003.
2. Lee RF, Giaquinto RO, Hardy CJ. Coupling and decoupling theory and its application to the MRI phased array. *MRM* 2002; 48:203-213.
3. Hennig J, Scheffler K. Easy improvement of signal-to-noise in RARE-sequences with low refocusing flip angles. Rapid acquisition with relaxation enhancement. *MRM* 2000; 44:983-985.
4. Hennig J, Weigel M, Scheffler K. Multiecho sequences with variable refocusing flip angles: optimization of signal behavior using smooth transitions between pseudo steady states (TRAPS). *MRM* 2003; 49:527-535.
5. Hargreaves BA, Cunningham CH, Nishimura DG, Conolly SM. Variable-rate selective excitation for rapid MRI sequences. *MRM* 2004; 52:590-597.
6. Duewell SH, Ceckler TL, Ong K, et al. Musculoskeletal MRI at 4 T and at 1.5 T: comparison of relaxation times and image contrast. *Radiology* 1995;196:551-555.
7. Duewell S, Wolff SD, Wen H, Balaban RS, Jezzard P. MR imaging contrast in human brain tissue: assessment and optimization at 4 T. *Radiology* 1996; 199:780-786.
8. Jezzard P, Duewell S, Balaban RS. MR relaxation times in human brain: measurement at 4 T. *Radiology* 1996; 199:773-779.
9. Wansapura JP, Holland SK, Dunn RS, Ball WS, Jr. NMR relaxation times in the human brain at 3.0 tesla. *JMRI* 1999; 9:531-538.
10. De Bazelaire CM, Duhamel GD, Rofsky NM, Alsop DC. MR imaging relaxation times of abdominal and pelvic tissues measured in vivo at 3.0 T: preliminary results. *Radiology* 2004; 230:652-659.
11. Constable RT, Gore JC. The loss of small objects in variable TE imaging: implications for FSE, RARE, and EPI. *Magn Reson Med* 1992; 28:9-24.