High Field Imaging

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1 Introduction

The main advantage of 3T over 1.5T is the increased signal to noise ration (SNR). However, the actual gain in SNR depends on a number of tissue and sequence parameters that have to be chosen carefully in order to achieve optimal results. Besides SNR almost all other parameters (except for the increased chemical shift) represent a drawback when compared to 1.5T. In the following we will summarize the dependence of physical parameters an the main magnetic field strength and possible implication for 3T.

2 Dependence of physical parameters on field strength and possible effects

1. *Signal-to-noise ratio (SNR).* The detected MR signal (without noise) increases quadratically with field strength given by an approximately linear increase in equilibrium spin polarization (Bolzman distribution) time a linear increase of induced currents in the receiver coil (induction law). At the same time, a linear increase in noise is observed given that noise is is originating predominantly from the patient rather than other sources, such as the coil or electronics. Therefore, in the range of clinically-used field strengths between 0.1T and 3.0T, SNR scales approximately linearly with main field B_0 (1):

$$SNR \sim B_0$$

Commonly observed effects at 3T: the full enhancement of SNR at 3T can only be observed in purely proton-density weighted sequences that do not depend on other parameters, especially on T1. A doubling of SNR as going from 1.5T to 3T can be used to reduce scan time (by a factor of 4) or to increase the spatial resolution (reduction of voxel volume by a factor of 2).

2. *RF power deposition*, as measured by the power deposited within a certain mass of tissue, or specific absorption rate (SAR in Watts per kg). In the range of clinically-used field strengths between 0.1T and 3.0T, SAR approximately scales quadratically with Larmor frequency or field strength (2):

$$SAR \sim B_0^2$$

Power deposition is mainly generated by electrical fields associated to the magnetic field (which is required for spin excitation) inducing motion or vibration of molecules, and thus heating.
Commonly observed effects at 3T: SAR will pose a limit on RF intensive sequence such as multi-spin echo (RARE, TSE, FSE, …) or SSFP using high flip angles (bFFE, TrueFisp, Fiesta, …). Either a reduction of the flip angle is required (which modifies the image contrast) or an increase in TR (which is problematic for bSSFP due to emerging banding artifacts).

3. Chemical shift. Due to different electronic shielding of protons in water molecules and, for example, lipids, the resonance frequency of these protons is different by about several ppm. The chemical shift measured in ppm is a relative unit and thus independent of field strength. The chemical shift measured in Hertz is linearly proportional to field strength (3):

$$\text{Chemical shift [Hz]} \sim B_0$$

The water resonance frequency is about 3.3-3.5 ppm higher than that of lipids. At 1.5T this corresponds to approximately (3.3-3.5 ppm) x 63.5MHz = 210-220 Hz. Therefore a frequency shift between water and lipids of 420-440 Hz can be observed at 3.0T.
Commonly observed effects at 3T: The increased frequency separation of fat and water with increasing field strength increases the spatial separation of these components along readout direction. The spatial separation depends on the readout bandwidth and may lead to an overlap or dark empty space between fat and water. A high readout bandwidth reduces this artifact, however, also decreases SNR. The fat-water shift is most severe in EPI along the slow phase encode direction making fat suppression mandatory for EPI. On the other hand, in spectroscopic application the increase chemical shift increases the spectral resolution.

4. Susceptibility effects. Different types of tissue exhibit a different magnetic susceptibility and thus produce a slightly different local magnetic field. The deviation to the main magnetic field B_0 without any material amounts to about 1-2 ppm. As a result variations in the local B_0 field arise at boundaries between different types of tissues, mainly such as air-soft tissue and soft tissue-bone. As for the chemical the frequency variation measured in Hertz is linearly proportional to field strength (4):

$$\textit{Susceptibility variation [Hz]} \sim B_0$$

Commonly observed effects at 3T: Susceptibility variation can produce signal voids due by inter-voxel dephasing, or may result in image distortion in combination with a low readout bandwidth. Again, these effects are most pronounced in EPI. For balanced SSFP (TrueFisp, Fiesta, b-FFE) that is sensitive to field inhomogeneities banding artifacts may appear more often and with closer spacing.

5. Longitudinal relaxation time T1: The longitudinal relaxation time T1 increases with main magnetic field strength. For most tissues, increase in T1 is close to linear in the range between 1.0 T and 3.0 T with an increase of about 20% (up to 40% in muscle, and 70% in the kidney), and quadratic with field strength below 1.0 T (5). An exeption is cerebral spinal fluid where T1 remains almost constant. In combination with a contrast agent, the effect of field strength on T1 is reduced. The relaxivity R of chelated gadolinium contrast agents decreases only by about 5% to 10% when going from 1.5T to 3.0T. The shortening of T1 for a given concentration of contrast agent C is given by

$$1/T1(C) = 1/T1(0) + RC$$

Where T1(0) is the relaxation time without contrast agent. Since T1 times of unenhanced tissue at 1.5T is shorter than at 3T the same dose of contrast agent often produces a stronger change in signal contrast at 3.0T than at 1.5T.
Commonly observed effects at 3T: In order to obtain identical image contrast as for 1.5T flip angle, TR and TE has to be adjusted. For balanced SSFP (TrueFisp, Fiesta, b-FFE) the decreased ration of T1 and T2 (T1 gets longer, T2 shorter) results in a decrease steady state signal, but at the same time also reduces the optimal flip angle.

6. Transverse relaxation time T2: T2 has been reported to be mostly independent of the field strength (5), although a small increase in T2 of up to 10% has been measured in certain tissues. As a result, for a certain T2 weighting the echo time has to be reduced slightly at higher fields.

7. *B_1 inhomogeniety:* At very high fields the wafelenght of the RF excitation field comes close to the dimensions of a human body. Based on the Helmholtz equation it can be shown that the B1 fields becomes progressively more inhomogeneous resulting in significant signal variations (6), and very often in signal enhancement in the center of the body. This effect can partially be compensated with complex excitation pulses or parallel transmission.
Commonly observed effects at 3T: inhomegeneous B_1 often may produce dark (abdominal imaging) or bright (brain) spots.

3 References

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