Specialty area: High Field Imaging

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Title: Exploring the potential of high field MRI magnets

Highlights:

- Benefits of operating at higher magnetic fields include increased signal-to-noise ratio (SNR) and enhanced contrast mechanisms.
- These advantages may be exploited for higher resolution anatomical imaging, more localized functional imaging and improved spectroscopic imaging. Multinuclear imaging also benefits from increased SNR.
- Higher fields may be used to visualize subtle anatomical abnormalities associated with disease; reveal spatially varying metabolite ratios between smaller structures; isolate functional signal that is more tightly coupled to underlying neuronal activity; and image microvasculature and blood products in greater detail.
- There are several technical and physical limitations associated with high-field imaging, such as field inhomogeneity and increased RF power deposition in tissues, which need to be overcome before adaptation to the clinic.
- Fortunately some specialized RF pulse and pulse sequences as well as hardware solutions such as parallel transmit systems may be used to combat these issues.
- There are still many open problems, but high field multi-modal imaging offers great potential to visualize the human body in unprecedented detail and improve diagnosis and treatment of diseases.

Target audience:

Clinicians and basic scientists who want to familiarize themselves with the benefits and pitfalls of MR at high field strengths.

Outcome/objectives:

Learners will be able to utilize the capabilities of high field scanners by gaining knowledge on: 1) sequences and applications that are best suited to high field strengths; 2) The information that is best visualized/revealed by operating at these field strengths; 3) Clinical applications that may benefit from MRI at 7T and 4) Technical limitations associated with high fields and some of the solutions and workarounds for these issues.

Motivation to Operate at Higher Field Strengths:

Since SNR and susceptibility effects scale with field strength, higher resolution MRI is possible at greater field strengths, elucidating finer anatomical detail and leading to increased conspicuity and more accurate characterization of abnormalities in the brain and other regions of the body. Increased SNR also enables higher resolution spectroscopic imaging. The chemical shift differences among metabolite resonances are directly proportional to field strength. The combination of increased spectral separation

and SNR translates to higher resolution or faster MR spectroscopic imaging (MRSI) and improved spectral quantification. Increasing the field strength also provides opportunities for new and enhanced contrast mechanisms. The sensitivity to susceptibility effects scales with field strength making it possible to depict irregular microvasculature and smaller calcifications in greater detail. This increased sensitivity to deoxygenated blood results in enhanced blood oxygenation level-dependent (BOLD) contrast which may be used for higher resolution functional MRI. The component of the BOLD signal arising from smaller blood vessels, which is more spatially correlated to the underlying functional activity, also scales with field strength. Greater SNR provides a signal boost to nuclei other than protons, such as sodium and carbon, which provide a means to probe important cell processes, different metabolic pathways and new relaxation mechanisms.

Technical and Physical Limitations:

Unfortunately, several technical issues such as inhomogeneity of the applied RF field (B_1 field) and the main magnetic field (B_0 field), chemical shift localization (CSL) errors, and increased RF power deposition result in artifacts for imaging as well as spectroscopy and limit the utility of current 7T scanners.

One of the most difficult problems to overcome at high magnetic fields is the severe B_1 inhomogeneity over the volume of interest. As the B_0 field increases to 7T, The RF operating wavelength becomes comparable to the diameter of the human head, resulting in a severe reduction of B_1 strength in the brain periphery as compared to isocenter. At 7T, this reduction can be as great as 45%. Standard pulse sequences utilizing conventional RF pulses for excitation and refocusing are very susceptible to changes in B_1, resulting in spatially varying contrast and SNR in structural and spectroscopic images. B_0 inhomogeneity also scales with field strength. In MR imaging, it results in distortion of both geometry and intensity of images. Single or few-shot rapid acquisition schemes such as echo planar imaging (EPI) or spiral imaging are particularly susceptible to geometric distortions due to susceptibility effects. In MR spectroscopy, to first order, B_0 inhomogeneity manifests itself as spectral shifts. As a result, frequency-selective pulses, including those for water and lipid suppression are less effective. To second order, field inhomogeneity also broadens the metabolite peaks. To combat this effect, robust referencing schemes, shimming and decreased voxel volumes are required.

RF power deposition, usually measured as the Specific Absorption Rate (SAR) increases as the square of B_0, limiting the number of applied RF pulses in a given repetition time (TR). For MR pulse sequences that utilize many closely spaced high-flip angle RF pulses, such as Fast Spin Echo (FSE), this severely limits the number of slices that may be acquired.

Relaxation constants change as a function of field strength. T_1 values lengthen and converge for most tissues as the field strength increases. T_2* values decrease significantly resulting in enhanced contrast due to contrast agents or blood, but also increased signal loss due to tissue interfaces on gradient recalled echo (GRE) images. Apparent T_2 values also shorten for spin echo sequences due to diffusion effects. Sequence timing must be changed to account for these effects and achieve the desired contrast.

Most spectroscopic imaging sequences excite a localized volume using three RF pulses, each selective along a single spatial dimension. However, for spins at different chemical shifts (e.g., Cho and NAA which are separated by 1.2 ppm or 360 Hz at 7T), the slices selected by conventional RF pulses are shifted in space with respect to each other. This spatial shift, called the chemical shift localization error, is linearly proportional to field strength, thus becoming a significant problem at 7T, resulting in reduced usable volume containing signal from all metabolites of interest.

Solutions:

Specialized RF pulses and creative pulse sequence design may be used to overcome these limitations so that the full signal gain and enhanced contrast afforded by the 7T can be exploited. In many of these techniques, we use variants of two types of RF pulses, adiabatic and spectral-spatial (SPSP) pulses, either in combination or fused into a single excitation.

Adiabatic pulses are a special class of RF pulses that, above a certain amplitude called the "adiabatic threshold", uniformly rotate magnetization, independent of B_1-field variations. Thus, these RF pulses may be used provide uniform flip angles in the presence of a non-uniform B_1 field.

SPSP pulses are comprised of an RF envelope sampled by several short spatial subpulses. The spatial profile is dictated by the sub-pulses, while the spectral profile is dictated by the RF envelope. In this way, simultaneous, independent, spectral and spatial selectivity may be achieved. For the selected spectral band, the selected slice remains largely invariant with respect to frequency, resulting in greater chemical shift immunity, or reduced CSL error.

Parallel imaging may be used to speed up acquisition times in order to overcome some of the SAR limitations. Lower flip angle schedules that produce similar contrast for pulse sequences that use trains of high flip angle RF pulses, such as the Fast Spin Echo (FSE), may also help reduce the amount of deposited RF energy.

Multi-transmit systems with custom RF pulses that utilize the "spokes" excitation kspace trajectory have been shown to achieve very uniform transmit B_1 profiles [1-3]. However, the heterogeneous SAR profiles resulting from multiple RF transmission are not fully understood, currently limiting flip angles to very small values in order to remain within safety limits. Furthermore, such an approach requires acquisition of subject-specific field maps in order to generate the custom RF pulses and requires the scanner to be equipped with parallel transmit hardware. Thus it remains valuable to have single-channel solutions for uniform B_1-insensitive, slice-selective RF excitation.

Discussion and Clinical Applications:

There are several powerful applications of high-field MRI in the brain. High resolution structural imaging at 7T may be used to improve detection and characterization of subtle abnormalities associated with a wide range of neurological diseases and disorders. These include Alzheimer's disease, dementia, brain tumors, epilepsy, neuropsychiatric disorders and multiple sclerosis [4-9]. MRSI provides complementary information about metabolic alterations associated with neuronal loss and/or dysfunction. High

resolution MRSI at 7T may be used to differentiate metabolite ratios between smaller structures in the brain. Neurotransmitters such as glutamate and glutamine are more effectively measured using MRS at high fields due to increased SNR and spectral separation. SWI may be used to detect small calcified lesions within tumors, vascular malformations or infections [10]. High-resolution SWI has also been shown to elucidate abnormal microvasculature associated with gliomas [11]. Since sensitivity to susceptibility effects scales with field strength and SWI sequences use small flip-angle excitation pulses which are inherently more robust to B_1 inhomogeneity and SAR limitations, SWI is an ideal application for high-field magnets. With respect to functional imaging, specificity, sensitivity, and contrast of the BOLD response to neuronal activity have also been shown to increase with field strength resulting in improved functional localization [12-14].

Outside of the brain, musculoskeletal applications, such as ultra-short echo time (UTE) imaging and sodium imaging of cartilage also benefit from the increased SNR offered by higher field strengths [15].

Conclusion:

By utilizing novel RF pulse and pulse sequence designs, we can overcome the technical barriers confounding ultra-high field MR, and fully exploit the SNR advantage and enhanced contrast to visualize the human body in unprecedented detail. The combination of high-resolution anatomic, spectroscopic and functional MR imaging at 7T has the potential to be a powerful, noninvasive toolset for improved localization and treatment of disease.

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