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Review

Clinical applications of 7 T MRI in the brain

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ABSTRACT

This review illustrates current applications and possible future directions of 7 Tesla (7 T) Magnetic Resonance Imaging (MRI) in the field of brain MRI, in clinical studies as well as clinical practice. With its higher signal-to-noise (SNR) and contrast-to-noise ratio (CNR) compared to lower field strengths, high resolution, contrast-rich images can be obtained of diverse pathologies, like multiple sclerosis (MS), brain tumours, aging-related changes and cerebrovascular diseases. In some of these diseases, additional pathophysiological information can be gained compared to lower field strengths. Because of clear depiction of small anatomical details, and higher lesion conspicuousness, earlier diagnosis and start of treatment of brain diseases may become possible. Furthermore, additional insight into the pathogenesis of brain diseases obtained with 7 T MRI could be the basis for new treatment developments. However, imaging at high field comes with several limitations, like inhomogeneous transmit fields, a higher specific absorption rate (SAR) and, currently, extensive contraindications for patient scanning. Future studies will be aimed at assessing the advantages and disadvantages of 7 T MRI over lower field strengths in light of clinical applications, specifically the additional diagnostic and prognostic value of 7 T MRI.

1. Introduction

Magnetic Resonance Imaging (MRI) is a versatile technique to image changes in brain anatomy and function. Since its clinical emergence in the beginning of the eighties, magnetic field strength for clinical MRI has increased from <0.5 T to a wide use of 3.0 T in current clinical practice today. Foremost, increase in signal to noise and susceptibility induced contrast at higher field strengths is especially useful for imaging techniques that require a high signal-to-noise (SNR) and contrast-to-noise (CNR) ratio, such as functional imaging techniques (fMRI) and MR spectroscopy, but can also be used for high resolution anatomical imaging, including 3-dimensional (3D) volume imaging, within acceptable scanning time. Although not widely used clinically at this point in time, an increasing number of research sites worldwide have access to MRI scanners with a field strength of 7.0 T. Most of the current research on these 7 T MRI platforms is related to hardware- and sequence optimization to address some of the technical challenges of (ultra) high field imaging (inhomogeneous transmit field, increased susceptibility artefacts, specific absorption rate (SAR) limitations). To date only a few clinical studies have been performed at this ultra-high field strength, and there is an active debate in the MR community [1,2] if and when 7 T MRI may become the field strength of choice for certain clinical applications.

The emphasis of most (technical) developments at 7 T lies on imaging the brain. Functional imaging (BOLD) and techniques that exploit susceptibility induced contrast are among the ones that benefit most from the ultra-high field strength, and the artefacts in the brain are less pronounced than in other areas of the body. However, a widespread acceptance of ultra-high field imaging as a clinical diagnostic instrument will require high quality anatomical imaging sequences, like T_1/T_2-weighted, T_2^*-weighted, Fluid-Attenuated Inversion Recovery (FLAIR)-imaging and Magnetic Resonance Angiography (MRA). Combined with increased SNR and CNR generated at these higher field strengths, 7 T MRI may find its way to many improved and even new clinical applications.

Recently, a number of 3D anatomical sequences have been developed and optimized that make optimal use of the increased SNR at 7 T [3–6]. These sequences include FLAIR imaging, which is an important sequence in most diagnostic standard brain MRI

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protocols due to its high CNR between brain tissue lesions of any sort and the surrounding healthy brain tissue. Although not as important as the FLAIR sequence, T_2^*-weighted MRI sequences are increasingly used in clinical MRI protocols as well, for instance for the detection of microbleeds. At 7 T, the larger susceptibility effect compared to MRI at lower field strengths may result in new clinical applications of this sequence. Furthermore, T_1-weighted imaging, especially after contrast administration, can provide more detail to assess small pathology not seen as clearly at lower field strength, for instance lesions of the intracranial vessel wall. Finally, MR angiography, which is regularly used in clinical practice to assess all kinds of brain pathology, can be obtained with an ultra-high resolution for optimal assessment of even smaller arteries of the brain than at lower field strengths, like the perforating lenticulostriate arteries.

Besides increased costs and limited availability, disadvantages for clinical use of 7 T MRI include a range of imaging artefacts that to date has prevented a further widespread dissemination of ultra-high field MRI for clinical diagnosis. Moreover, we still have to learn how normal anatomy and diseases look like with the changes in contrast and resolution at high field. These could very well be the main reasons that the published literature on clinical research at 7 T has thus far been limited. The aim of this current review article is to show the clinical potential of 7 T MR high-resolution anatomical brain imaging based on the current state of the art imaging platforms and the use of (high field) dedicated pulse sequences. Advanced hardware modification (e.g. the use of multi-transmit technology), which undoubtedly will further improve the clinical performance of ultra-high field imaging, is beyond the scope of this review. Apart from a review of the current literature, a series of illustrative patient examples will be included.

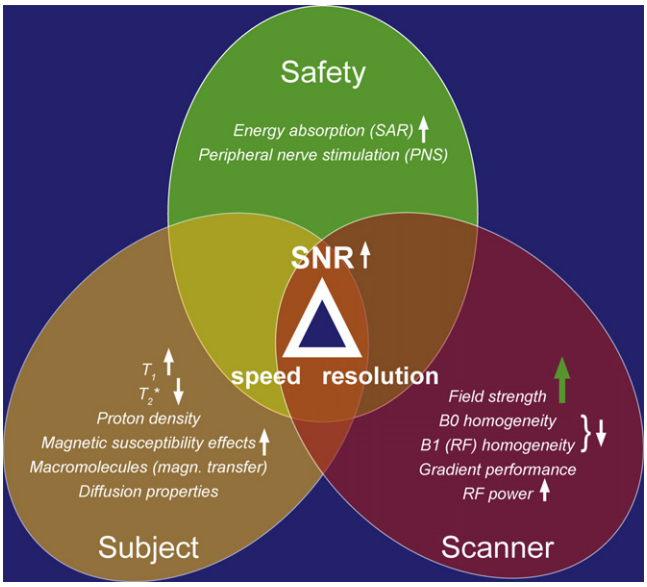

Fig. 1. Within MRI, for a certain contrast there is a central trade-off between signal-to-noise ratio (SNR), resolution and imaging speed (faster imaging comes at the cost of losing resolution and/or SNR, for example), which takes place within boundary conditions imposed by the scanner, the subject and safety considerations. This graph illustrates the changes (white arrows) that occur when the strength of the static field of the MRI scanner is increased (green arrow up). When the field strength of the MRI scanner is increased, the intrinsic SNR increases, which can be exchanged for either increased imaging speed (e.g. by acquiring less averages) or increased resolution. Since the tissue relaxation parameters and the susceptibility effects depend on the field strength, also the contrasts will change at higher field. Challenges are imposed by the increased inhomogeneity of both the main field (B_0) and the RF transmit field (B_1), together with an increase in SAR.

2. Technical aspects of high field 7 T imaging

For a given contrast, the three fundamental factors that determine the design and applications of MR imaging are: signal-to-noise ratio (SNR), imaging speed, and spatial resolution (Fig. 1). These factors are all related, and changing one of them will affect the other two parameters and vice versa. This provides flexibility to utilize the increased intrinsic SNR at high field, which rises approximately linearly with field strength. Within boundary conditions (like limits on tissue heating), the increased SNR can be used for either better lesion conspicuousness, or for increasing imaging speed to reduce motion artefacts (which facilitates imaging of unstable or less cooperative patients), or for increasing the spatial resolution to identify smaller pathological lesions. Even though many pathological processes in the brain in daily clinical routine can be detected with lower-resolution images, one can think of many applications where higher resolution could be beneficial. High-resolution imaging could make it possible to detect brain diseases in an early stage, by visualizing very small pathological changes. Furthermore, the pathological basis and development of brain diseases could be further elucidated by more detailed imaging.

High magnetic field strength also affects the relaxation times of tissues, T_1 and T_2^* in particular [7]. Fortunately, as shown by Rooney et al. [8], the increased longitudinal relaxation times still allow for sufficient contrast between grey and white matter in T_1-weighted brain imaging. Even more so, as the T_1-values for grey and white matter increase from 1.5 T to 7 T from 1188 ms and 656 ms to 2132 ms and 1220 ms, respectively [8], high field imaging can be used to generate exquisite Time-Of-Flight MR Angiography (TOF-MRA) with a high contrast-to-noise. In TOF-MRA, tissues with static spins become excited several times by radiofrequency (RF) pulses within their relaxation time T_1, and become saturated. Non-excited flowing blood that enters the exited volume, on the other hand, will be excited for only a limited number of times, depending on the chosen slab volume, resulting in a high signal. For a given pulse angle, when the T_1 relaxation times of tissues become longer, the static spins will relax less in between the RF pulses, resulting in lower signal of static tissue, and hence in a better contrast between suppressed background and flowing blood.

The shortened T_2^*-values are related to the increased magnetic susceptibility effects that scale linearly with magnetic field strength, while T_2-value changes will be not as pronounced. Also, the magnetic susceptibility effects of tissues at higher field cause more distortion of the local magnetic field in its surrounding. Especially, paramagnetic and diamagnetic substances like deoxyhaemoglobin (veins), calcium (calcified tumour), blood degradation products (like haemosiderin in microbleeds), iron-depositions and air (air-filled cavities) will exert this effect. Although these enhanced susceptibility effects may cause image distortions and/or local signal drop-outs (due to dephasing), it also gives the opportunity of creating better tissue contrast. This can be readily visualized with a T_2^*-weighted sequence sensitive for susceptibility effects.

Besides these intrinsic MR characteristics of tissue that change as a function of field strength, there are certain conditions that impose a boundary condition for the design and application for diagnostic high-field imaging protocols. Because of the larger magnetic susceptibility effects seen at high field strength, metallic objects like surgical implants, and air such as in the nasal cavities, will cause much more image distortion and artefacts (signal drop-out) than at lower field strengths for a given receive bandwidth. Possible temperature effects in conducting implant materials are another impediment for the widespread clinical use of high-field imaging. Obviously, these effects impose strict safety measures for MRI at all field strengths and, albeit much more pronounced at high field, should be taken into consideration in all MRI applications. At this point in time, it is still not clear what effect metallic