Progress in Nuclear Magnetic Resonance Spectroscopy 109 (2018) 1–50

Contents lists available at ScienceDirect

Progress in Nuclear Magnetic Resonance Spectroscopy

journal homepage: www.elsevier.com/locate/pnmrs

Pros and cons of ultra-high-field MRI/MRS for human application

Mark E. Ladd [a,b,c,d,*], Peter Bachert [a,c], Martin Meyerspeer [e,f], Ewald Moser [e,f], Armin M. Nagel [a,g], David G. Norris [h,d], Sebastian Schmitter [a,i], Oliver Speck [j,k,l,m], Sina Straub [a], Moritz Zaiss [n]

[a] *Medical Physics in Radiology, German Cancer Research Center (DKFZ), Heidelberg, Germany*
[b] *Faculty of Medicine, University of Heidelberg, Heidelberg, Germany*
[c] *Faculty of Physics and Astronomy, University of Heidelberg, Heidelberg, Germany*
[d] *Erwin L. Hahn Institute for MRI, University of Duisburg-Essen, Essen, Germany*
[e] *Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria*
[f] *MR Center of Excellence, Medical University of Vienna, Vienna, Austria*
[g] *Institute of Radiology, University Hospital Erlangen, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen, Germany*
[h] *Donders Institute for Brain, Cognition and Behaviour, Radboud University Nijmegen, Nijmegen, Netherlands*
[i] *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig and Berlin, Germany*
[j] *Department of Biomedical Magnetic Resonance, Otto-von-Guericke-University Magdeburg, Magdeburg, Germany*
[k] *German Center for Neurodegenerative Diseases, Magdeburg, Germany*
[l] *Center for Behavioural Brain Sciences, Magdeburg, Germany*
[m] *Leibniz Institute for Neurobiology, Magdeburg, Germany*
[n] *High-Field Magnetic Resonance Center, Max-Planck-Institute for Biological Cybernetics, Tübingen, Germany*

Edited by David Gadian and David Neuhaus

ARTICLE INFO

Article history:
Received 6 March 2018
Accepted 7 June 2018
Available online 8 June 2018

Keywords:
MRI
MRS
Ultra-high field
7 Tesla
Human

ABSTRACT

Magnetic resonance imaging and spectroscopic techniques are widely used in humans both for clinical diagnostic applications and in basic research areas such as cognitive neuroimaging. In recent years, new human MR systems have become available operating at static magnetic fields of 7 T or higher (≥300 MHz proton frequency). Imaging human-sized objects at such high frequencies presents several challenges including non-uniform radiofrequency fields, enhanced susceptibility artifacts, and higher radiofrequency energy deposition in the tissue. On the other side of the scale are gains in signal-to-noise or contrast-to-noise ratio that allow finer structures to be visualized and smaller physiological effects to be detected. This review presents an overview of some of the latest methodological developments in human ultra-high field MRI/MRS as well as associated clinical and scientific applications. Emphasis is given to techniques that particularly benefit from the changing physical characteristics at high magnetic fields, including susceptibility-weighted imaging and phase-contrast techniques, imaging with X-nuclei, MR spectroscopy, CEST imaging, as well as functional MRI. In addition, more general methodological developments such as parallel transmission and motion correction will be discussed that are required to leverage the full potential of higher magnetic fields, and an overview of relevant physiological considerations of human high magnetic field exposure is provided.

Contents

---

* Corresponding author at: Medical Physics in Radiology, German Cancer Research Center (DKFZ), Im Neuenheimer Feld 280, 69120 Heidelberg, Germany.

E-mail addresses: mark.ladd@dkfz.de (M.E. Ladd), p.bachert@dkfz.de (P. Bachert), martin.meyerspeer@meduniwien.ac.at (M. Meyerspeer), ewald.moser@meduniwien.ac.at (E. Moser), armin.nagel@uk-erlangen.de (A.M. Nagel), david.norris@donders.ru.nl (D.G. Norris), sebastian.schmitter@ptb.de (S. Schmitter), oliver.speck@ovgu.de (O. Speck), sina.straub@dkfz.de (S. Straub), moritz.zaiss@tuebingen.mpg.de (M. Zaiss).

https://doi.org/10.1016/j.pnmrs.2018.06.001
0079-6565/

1. Introduction

Magnetic resonance imaging (MRI) is a form of nuclear magnetic resonance (NMR) that uses magnetic field gradients to generate images. In the early 1970s, Damadian published a promising report showing that the NMR characteristics of malignant tumor tissue, in particular T1 and T2 relaxation times, differed from normal tissue [1]. This led to the prospect that in some way a useful diagnostic method based on hydrogen (^{1}H) NMR might arise. The practical recording of images based on magnetic resonance was subsequently made possible by the work of Lauterbur [2] as well as Mansfield and Grannell [3]. They applied a position-dependent magnetic field (gradient) in addition to the static background magnetic field. Due to the linear dependence of the resonance frequency of the nuclear spin on the external magnetic field and with the aid of Fourier analysis, it became feasible to quickly reconstruct the spatial distribution of the spins within a slice in the form of a 2D image. For this work, which led to the birth of MRI, Lauterbur and Mansfield shared the Nobel Prize in Medicine in 2003.

Since the introduction of MRI into clinical use in the early 1980s, this technique has developed into a widespread medical