Ultra-High Field Magnetic Resonance Imaging Techniques in Interdisciplinary Neuroscience

Yumen Wu1, Song Xuemei2,3,*, Chan-Ying Zheng2,3,*

1Western Reserve Academy, Hudson, OH, 44236
2Interdisciplinary Institute of Neuroscience and Technology, School of Medicine, Zhejiang University, Hangzhou 310029
3Key Laboratory of Biomedical Engineering of Ministry of Education, Zhejiang University, Hangzhou 310029

Corresponding author:
Chan-Ying Zheng
Interdisciplinary Institute of Neuroscience and Technology, School of Medicine, Zhejiang University, Hangzhou 310029, Key Laboratory of Biomedical Engineering of Ministry of Education, Zhejiang University, Hangzhou 310029
E-mail: zhengchanying@zju.edu.cn

Song Xuemei
Interdisciplinary Institute of Neuroscience and Technology, School of Medicine, Zhejiang University, Hangzhou 310029
E-mail: songxuemei@zju.edu.cn

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Magnetic Resonance Imaging (MRI) is an imaging generating system that provides anatomical tissue information when radio frequency pulses excite the protons in tissues. Compared to other commonly used medical imaging tools, such as computed tomography (CT) and positron emission tomography (PET), MRI is non-invasive and avoids radiation exposure to patients.[1] It provides physicians with better contrast of different types of soft tissues and a clearer anatomical view between air, bones, cartilage, organs, etc. Since its invention in the 1970s,[2] MRI has gone through huge technological developments. To achieve higher spatial and temporal resolution, scientists worked hard to create MRI scanners with higher magnetic fields, which are measured in Teslas (T). For animal imaging, MRI with up to 2T magnetic fields has been achieved. For human studies, MRI with 7T magnetic field is the highest magnetic field that has been approved by the FDA for clinical use.[3] MRI scanners with 7T or higher magnetic fields are considered ultra-high field (UHF) scanners. UH MRI opens a new imaging world for both researchers and physicians. 7T scanners can produce in-plane resolution up to 0.2 mm by providing higher signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) than 3T scanners. This increased spatial and temporal resolution enables researchers to visualize previously unseen small anatomical details and subtle pathological structures.

Improvements in the components of MRI systems have steadily influenced the advancement of MRI imaging. MRI hardware includes a magnet, gradient coils, radio frequency (RF) coils, and shim coils, as well as cooling, electronic, and computer systems. As the name indicates, the magnet is an essential part of MRI and is critical for spatial resolution. Each improvement of the field level has been challenging: from less than 0.5T to 1-1.5T, then to 3T. Improving MRI imaging from 3T to ultra-high magnetic field has not been an exception.[4,5] UHF MRIs use a superconducting magnet for their main magnet coil, which is cooled to zero Kelvin to provide a powerful and stable static magnetic field. Three sets of gradient coils, which generate static magnetic fields along three orthogonal directions, x, y, and z, adjust imaging volume orientation and transfer MRI signals into images. RF transmission coils transmit RF energy into the bodies of patients; it is critical for patients' safety. RF receive coils act as an antenna to detect RF signals from the patient's body, it is highly contributes to the SNR of the output images.[6] Shim coils can increase the homogeneity of the system to produce images of better quality with less distortion. In recent years, cutting-edge MRI technologies have been developed to enable higher spatial and temporal resolution imaging, with whole brain coverage. These include parallel imaging methods which utilize multi-channel RF coils to simultaneously receive MRI signals from different distances and orientations around the imaged area, and provide many novel, fast data acquisition schemes known as sequences.

Traditional high field MRI, often around 1.5 to 3 T, is mainly utilized in clinical studies, including anatomical and functional imaging for brain, body, and musculoskeletal disorders.[7] In particular, UHF MRI, such as 7T, is currently applied for brain injuries caused by tumors, stroke, multiple sclerosis, epilepsy, cerebrovascular diseases, and neurodegenerative diseases. Neuroscientists work closely with physicians and experts from other fields, such as optics, information science, brain-computer interface, and image processing. Together they commit to interdisciplinary research and build bridges for medicine, neuroscience, engineering, and other science areas. Thanks to the collaboration among various fields, including radiology, physics, biology, engineering, and even computer science, the innovation and improvements in MRI flourishes, and in turn leads to more in-depth probing into the structure of the human brain and related fields of neuroscience.[4] Neuroscientists recognize that much more detailed information can be discovered from in vivo human brain utilizing interdisciplinary MRI technologies in UHF.

Applying functional MRI (fMRI) to neuroscience exploration has resulted in great achievement in the fields of cognition, motor behavior, emotion, and sensory research. Brain activities depend on neural activation in functional brain regions. Increasing neural activation requires an extra supply

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of oxygenated venous-blood flow. The technique of fMRI is able to detect minor blood flow changes in active brain regions using magnetic imaging, because oxygen-carrying hemoglobin has different magnetic characteristics before and after binding oxygen. The blood oxygenation level dependent (BOLD) technique maps brain activity by demonstrating oxygen influx with MRI. Such a technique has clear advantages for investigating brain networks and neuron plasticity, as it is non-invasive and does not require intravenous contrast medium injection. Combining UHF fMRI with deep brain optical stimulation produces a fast, high spatial resolution method for in vivo brain columnar mapping. This combination helps us to understand not only anatomical brain structures, but also functional brain networks within, and between, different brain areas. After collecting extensive brain network datasets and then developing a topological model of these networks, with mathematical and computational techniques, scientists have established mathematical theory of functional brain connection patterns. In addition, functional optical stimulation and imaging methods, such as focused ultrasound methods with variable frequency capability and electroencephalogram (EEG), can be combined with MRI methodologies and new computational methods for evaluating the human brain network in high spatiotemporal resolution. These interdisciplinary neuroscience methods are now being tested for both animal and human studies.

Recent innovative MRI techniques extend UHF MRI research to the neuronal and molecular level. Membrane channel gating is tightly associated with neuronal activity. Channel opening affects water cycling, which can be measured by MRI methods. Recently, a hybrid optical MRI system was developed, combining a single-sided MRI system and a wide-field fluorescence microscope. This technique provides a non-invasive method to study the modulation of neuronal activity in vivo. Furthermore, many advanced MRI techniques, such as diffusion-weighted imaging (DWI), diffusion tensor imaging (DTI), magnetic resonance spectroscopy (MRS), chemical exchange saturation transfer (CEST), and quantitative susceptibility mapping (QSM) are also being used in pre-clinical brain research. Within 7T or higher magnetic fields, technologies such as MRS and CEST are expected to reveal critical information for plasticity mechanisms and neurotransmitter changes during brain dysfunction. Scientists dedicate themselves to developing cutting-edge new technologies for clinical therapeutics and bioengineering research. Taking advantage of UHF MRI technologies, neuroscientists work closely with physicians and engineers to transfer basic scientific knowledge into new products and push them into industry. For instance, for the human brain to be studied by UHF MRI scanners with up to 20Tmagnetic fields, it is non-invasive and does not require intravenous contrast medium injection. Dynamic MRI, with three-dimensional (3D) coverage and knowledge into new products and push them into industry. For instance, taking advantage of UHF MRI technologies, neuroscientists work closely with physicians and engineers to transfer basic scientific knowledge into new products and push them into industry. 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Taking advantage of UHF MRI technologies, neuroscientists work closely with physicians and engineers to transfer basic scientific knowledge into new products and push them into industry. For instance, combining focused ultrasound with MRI techniques can be used to deliver a targeted drug across the blood–brain barrier for central nervous diseases. Dynamic MRI, with three-dimensional (3D) coverage and high spatial resolution, has been used in phonetic application and might be further investigated for potential interdisciplinary studies. Virtual reality imaging technology, which can turn 2D MRI slices to 3D images through a computer program, provides surgeons with 3D visualization and a better view into patient anatomy (Echopixel, Inc., Mountain View, CA). In addition, artificial intelligence-based MRI segmentation and analysis modeling can provide accurate information and real-time diagnosis. Wearable MRI devices, which show tissue and bones moving, are expected to contribute significantly to anatomical studies and physicians’ diagnoses. MRI also benefits from theories originating from big-data, such as deep learning to rapidly analyze massive data sets, identify biomarkers, and build patient-specific anatomical models to help determine abnormalities. The fast development of technology might soon enable the human brain to be studied by UHF MRI scanners with up to 20Tmagnetic fields. According to the rapid development of MRI, it is reasonable to assume that there will be additional accomplishments and innovations in this field in the future.

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REFERENCES
