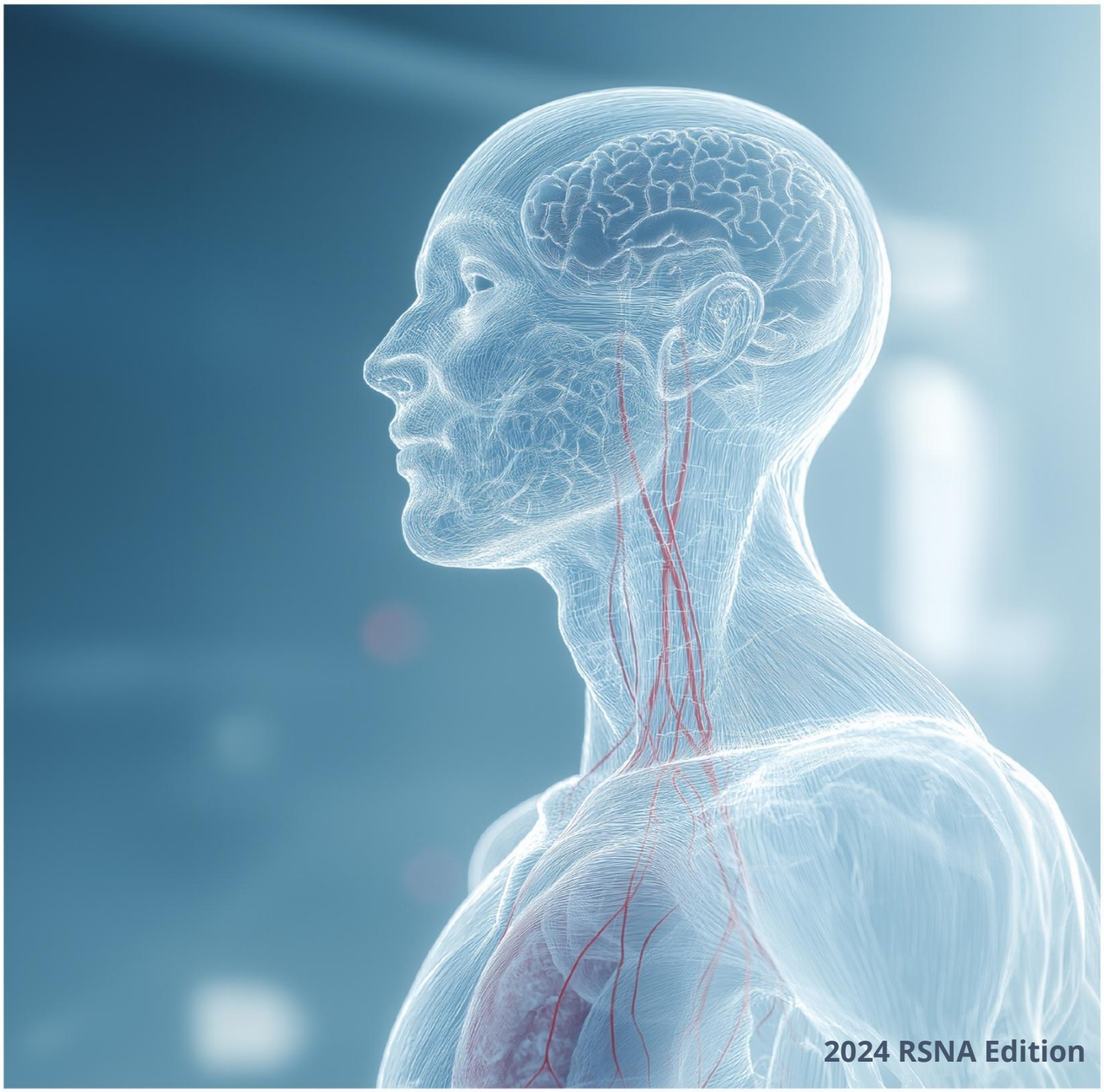
u!nnovation.

UNITED IMAGING




## Issue Highlights

## Disclaimer

The articles contained in this magazine are provided solely by the authors, and the author(s) of each article appearing in this magazine is/are solely responsible for the content thereof as well as personal data, which is used anonymously or complied with applicable data privacy laws or regulations. United Imaging Healthcare makes no representation or warranties, expressly or impliedly, with respect to the accuracy, timeliness, reliability, legitimacy, applicability, fitness, originality, or completeness of the contents of this magazine. United Imaging Healthcare assumes no legal responsibility or liability for any error, omission, or illegality with respect to the material contained within.

All articles contained in this magazine only represent the opinions and views of the authors and do not implicitly or explicitly represent any official positions or policies, or medical opinions of United Imaging Healthcare or the institutions with which the authors are affiliated unless this is clearly specified. Discussions of any brand, services, or products in the magazine should not be construed as promotion or endorsement thereof.

Articles published in this magazine are intended to inspire further general scientific research, investigation, understanding, and discussion only and are NOT intended to and should not be relied upon as recommending or promoting a specific medical advice, method, diagnosis, or treatment by physicians for any particular individual, nor to replace the advice of a medical doctor or other healthcare professional. Any individual wishing to apply the information in this magazine for the purposes of improving their own health should not do so without consulting with a qualified medical practitioner. All patients need to be treated in an individual manner by their personal medical advisors. The decision to utilize any information in this magazine is ultimately at the sole discretion of the reader, who assumes full responsibility for any and all consequences arising from such a decision. United Imaging Healthcare makes no representations or warranties with respect to any treatment, action, or application of medication or preparation by any person following the information offered or provided within or through the magazine. United Imaging Healthcare shall remain free of any fault, liability, or responsibility for any loss or harm, whether real or perceived, resulting from the use of information in this magazine.

The articles included in this magazine may contain work in progress, which represents ongoing research and development. Such technologies are not available for sale in the United States for clinical use and also may not be available for such sales in other countries around the world.

Please note that the magazine is intended to be distributed only within a limited scope instead of publication.

If you have any questions about the magazine, or simply wish to reach out to us for any other reasons, you are welcomed to contact us at the following email address: compliance@united-imaging.com

# An AI-Empowered Head-Only Ultra-High-Performance Gradient MRI System for High Spatiotemporal Neuroimaging

Liyi Kang[1] and Dan Wu[1]

[1] Department of Biomedical Engineering, College of Biomedical Engineering & Instrument Science, Zhejiang University, Hangzhou, China

## 1. Introduction

Magnetic resonance imaging (MRI) based human brain mapping is crucial for comprehending brain organization, function, cognition, and diseases, playing an increasingly vital role in global large-scale brain projects (1). Conventional MRI scanners face challenges in achieving submillimeter resolution due to physical constraints like imaging resolution, scan time, and signal-to-noise ratio (SNR). High-field MRI systems and advanced gradient systems, along with fast acquisition and AI-based methods, have been engineered expressly to push the resolution limit. The benefits of high-performance gradient for dMRI and fMRI have been nicely demonstrated in previous studies (2,3).

However, despite these advances, MRI spatial resolution remains far from the microscopic scale required for histopathological examination. Based on restricted water diffusion shaped by the local environment, dMRI is probably the only non-invasive approach to probe tissue microstructures at sub-voxel resolution (4). Advanced dMRI models are developed in both q-space (by varying diffusion gradient strength and directions) and t-space (by varying diffusion times) to reconstruct microstructural properties, such as axonal diameter, cell size, compartment fractions, and transmembrane water exchange.

High-gradient technology has experienced enormous development over the past two decades. In addition to the mainstream clinical superconducting MRI scanner that is typically equipped with a gradient system featuring maximum gradient strength (Gmax) of approximately 40 mT/m and slew rate (SRmax) of around 200 T/m/s, newly developed clinical systems with stronger gradient performance are emerging, including Siemens Prisma+ (130 mT/m, 200 T/m/s), GE Signa UltraG (114 mT/m, 260 T/m/s), etc. Furthermore, the field has endeavored to release ultra-high gradient-performance MRI systems for research purposes. (Fig. 1)

Keys in developing a high-performance head-only gradient system mainly lie in: 1) development of high-performance Gradient Power Amplifier (GPA) to supply the required voltage, current, and duty cycle; 2) optimized gradient coil design that minimizes the peripheral nerve stimulation (PNS); and 3) specialized design of the whole MRI system to adapt to the head-only gradient coil, including the miniaturized radiofrequency (RF) transmitter/receiver coils and specialized patient bed. In addition to the hardware endeavor, dedicated imaging sequences and reconstruction algorithms are also critical towards achieving high spatial and temporal resolution neuroimaging. The current surge in artificial intelligence (AI) empowered techniques opened new avenues to improve image acquisition.

In context of the previous effort, challenges, and emerging demands in neuroimaging, United Imaging Healthcare aims to develop an integrated head-only 3.0T MRI system NeuroFrontier[1] with unprecedently high Gmax of 650 mT/m and SRmax of 600 T/m/s. The proposed system features an ultra-high-power output from parallel setup of GPAs of 7MW, an optimal gradient coil design for minimizing PNS, a miniaturized high-density RF system, AI-assisted Compressed Sensing (ACS) technique for ultra-fast imaging, and a prospective head motion correction technique for motion free acquisition.

## 2. Methods

The NeuroFrontier system integrates several advanced features designed to optimize neuroimaging performance:

1. Ultra-high-power Output: The system achieves an ultra-high-power output of 7MW by running two gradient power amplifiers in parallel using a novel method that eliminates

[1] This product is not available for sale in the U.S. for clinical uses and also may not be available for such sales in other countries.

the need for a large current-sharing reactor. This setup ensures efficient current distribution and stability, enabling the system to reach a maximum gradient strength of 650 mT/m and a slew rate of 600 T/m/s along each axis.

2. Gradient Coil Design: The gradient coil design employs a two-step mechanical structure to balance forces and torques, which minimizes mechanical vibrations and peripheral nerve stimulation (PNS). The gradient coils are optimized for high efficiency and low inductance, using a ten-layer cooling tube design to enhance cooling efficiency and thicker coils to improve magnetic field shielding. (Fig. 2).

3. RF System Integration: A high-density, miniaturized radiofrequency (RF) system is integrated into the head-only setup. This includes a custom 16-ring birdcage transmit coil and a 64-channel head-only receive-array coil, designed to achieve high signal-to-noise ratio (SNR) and high acceleration factors. The RF system is shielded to minimize interference with the gradient coils, using segmented copper shielding to reduce eddy currents and resistive heat.

4. AI-Empowered Compressed Sensing (ACS): The system employs AI-assisted compressed sensing (ACS) to enable ultra-fast imaging. ACS uses convolutional neural networks (CNN) to reconstruct images from under-sampled k-space data, significantly accelerating the acquisition process while maintaining image quality. This technique allows for high-resolution imaging at reduced scan times.

5. Prospective Motion Correction: To address motion artifacts, the NeuroFrontier system incorporates a prospective head motion correction technique. This method uses a compact 3D optical tracking system to capture high-resolution 3D facial contours in real-time, which are then processed to correct for head movements during scanning. This ensures high-quality imaging even in the presence of patient motion.

6. System Design and Customization: The system is built around a 3T whole-body magnet with zero liquid helium boil-off, featuring a narrowed bore and specialized apertures for the head and body. The scanner bed is customized to accommodate these apertures, providing an optimized setup for head-only imaging (Fig. 3). The overall system design prioritizes high spatiotemporal resolution and accurate microstructural mapping, making it ideal for advanced neuroimaging applications.

# 3. Results

### 3.1 High Spatiotemporal Resolution Neuroimaging

1. Prospective Motion Correction: The information of head motion is used in real-time to update sequence RF and gradient direction in the rate of repetition time (TR), to minimize the influence of the movement of the head. (Fig. 4A)

2. AI-Assisted Compressed Sensing: The system utilizes AI-assisted compressed sensing (ACS) to accelerate image acquisition using convolutional neural networks (5,6). ACS achieved high-quality, fast imaging with minimal SNR and CNR compromise. (Fig. 4B)

3. EPI Readout and High-Resolution fMRI: The gradient system allows shorter echo times (TE), leading to higher SNR and improved image resolution. Simulations showed significant SNR improvement, especially for high-resolution imaging (Fig. 5).

### 3.2 High-Resolution dMRI

The system's high gradient performance reduces diffusion encoding duration, further reducing TE and increasing SNR. Simulations indicated substantial SNR gains for various resolutions and b-values, enhancing the capability for high-resolution dMRI (Fig. 6).

### 3.3 Neuroimaging Applications

1. Laminar Specific fMRI: The system's SNR gain supports submillimeter resolution to distinguish laminar-specific interactions in cortical regions (7).

2. Laminar Specific dMRI: High-resolution dMRI at 0.8 mm isotropic resolution revealed detailed microstructural layers in the cortex and hippocampus, which were not distinguishable at lower resolutions (Fig. 7).

3. Submillimeter Tractography: The system improved tractography accuracy, reducing false positives and enhancing the visualization of detailed fiber tracts (Fig. 8).

### 3.4 Microstructural Estimation

1. t-Space Microstructural Mapping: The system's high gradient strength enhances sensitivity to small structures

and improves the accuracy of microstructural metrics like cell diameter and intracellular fraction (Novikov et al., 2019).

2. q-Space Diffusion MRI: High b-values achievable with the system provide stronger contrast for lesion visualization and improved microstructural estimation. The system supports complex q-space models requiring high b-values and enables accelerated sampling in q-t space with deep learning-based reconstruction (Fig. 9).

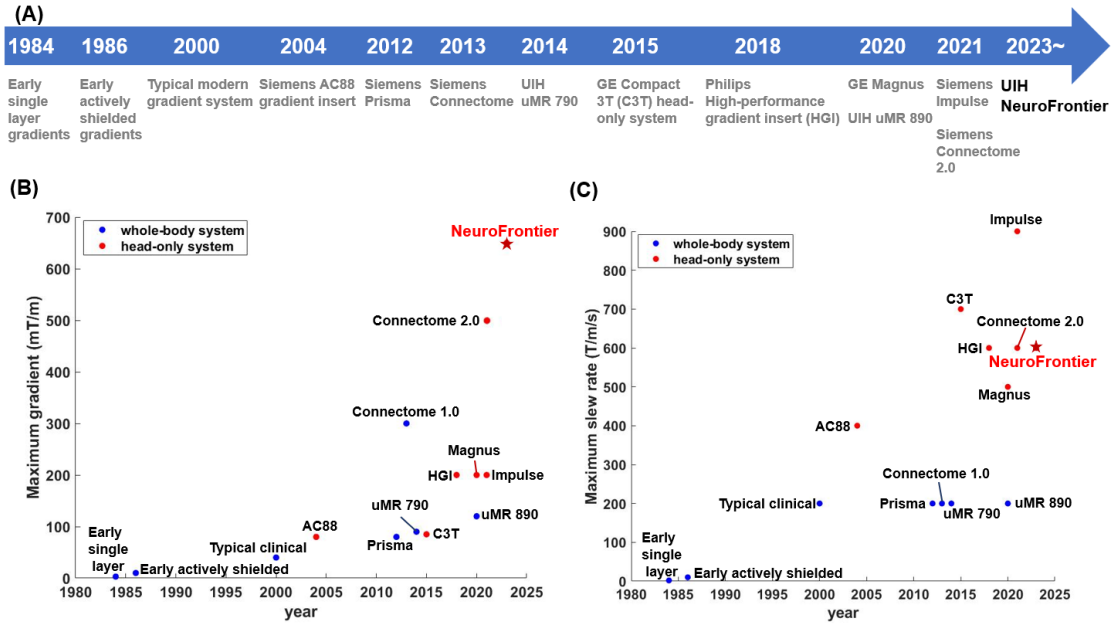



Figure 1. The history of gradient performance advances. (A) The release year of typical whole-body and head-only MRI systems. (B)-(C) The maximum gradient strength and slew rate of these systems.

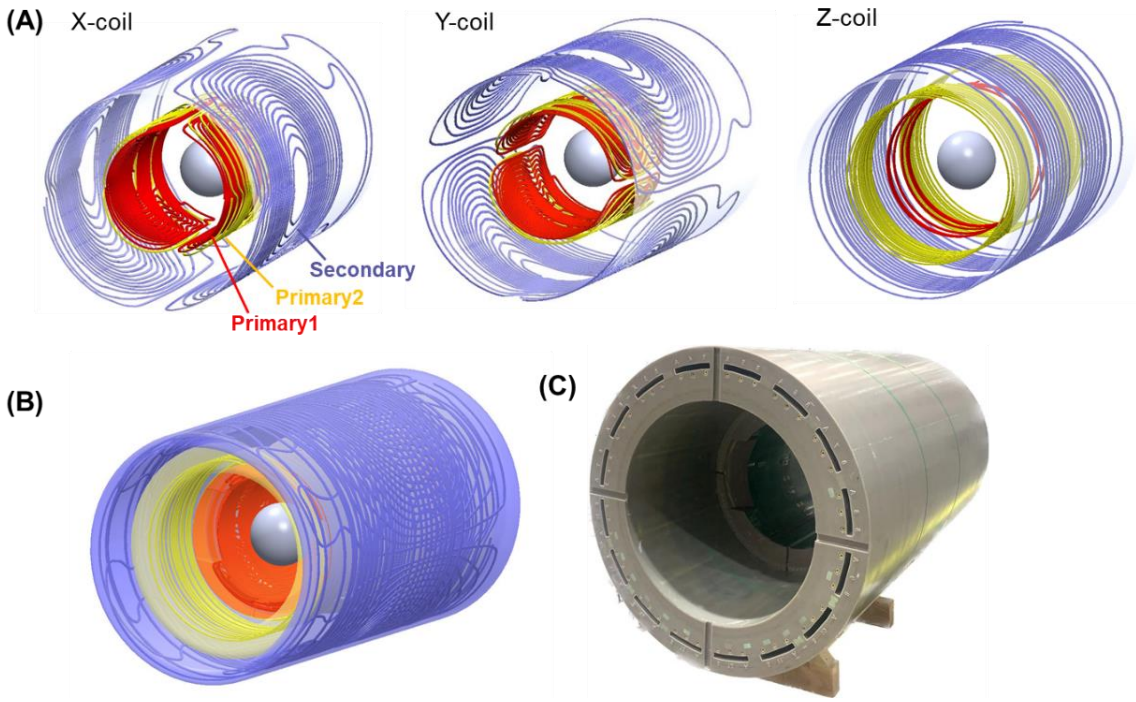
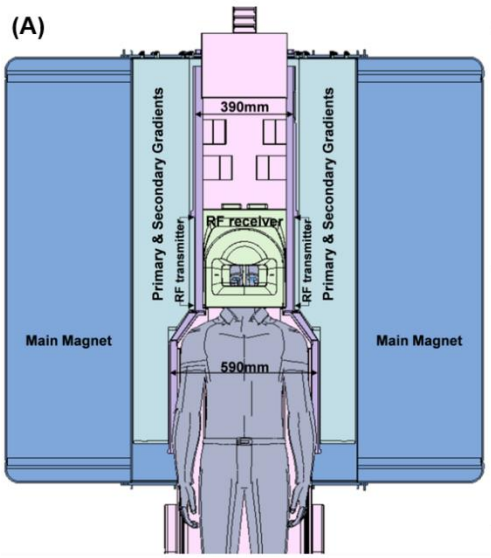



Figure 2. Gradient coils of the NeuroFrontier System. The (A) separate and (B) combined views of the two-step-structured x, y and z coils. (C) The real assembled gradient coil.




(B)

(C)

| | | |
|---|---|---|
| Magnet | B0 strength | 3.0 T |
| System size parameters | Imaging FOV | 220 mm |
| | Head aperture | 390 mm |
| | Body aperture | 590 mm |
| Gradient coil Performance | $G_{max}$ | 650 mT/m |
| | Slew rate | 600 T/m/S |
| | $G_{RMS}$ | 120 mT/m |
| | Linearity over 200-mm DSV (x, y, z) | $\leq$ 7 % |
| Radiofrequency characteristics | Number of transmit channel | 2 |
| | Number of receive channel | 64 |
| | Max B1 | 20 μT |

Figure 3. (A) The systematic overview, (B) real setup and (C) major performance parameters of the NeuroFrontier system.

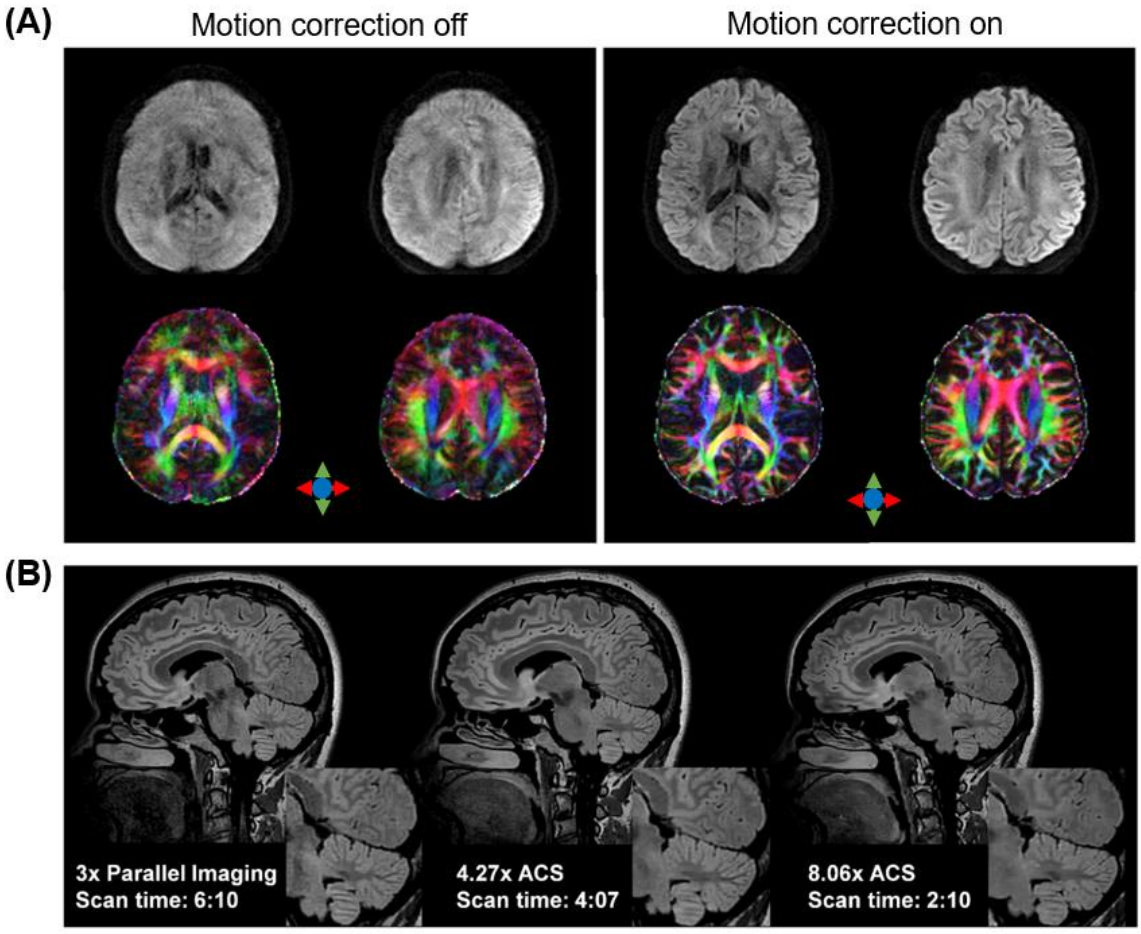



Figure 4. (A) Diffusion-weighted images and directional encoded colormaps from multi-shot dMRI acquired with prospective motion correction off and on. (B) Examples of imaging using ACS with acceleration factors of 4.27 and 8.06. Compared to the conventional parallel imaging (left), the images from ACS (middle and right) significantly reduced imaging time while achieving equivalent image quality.

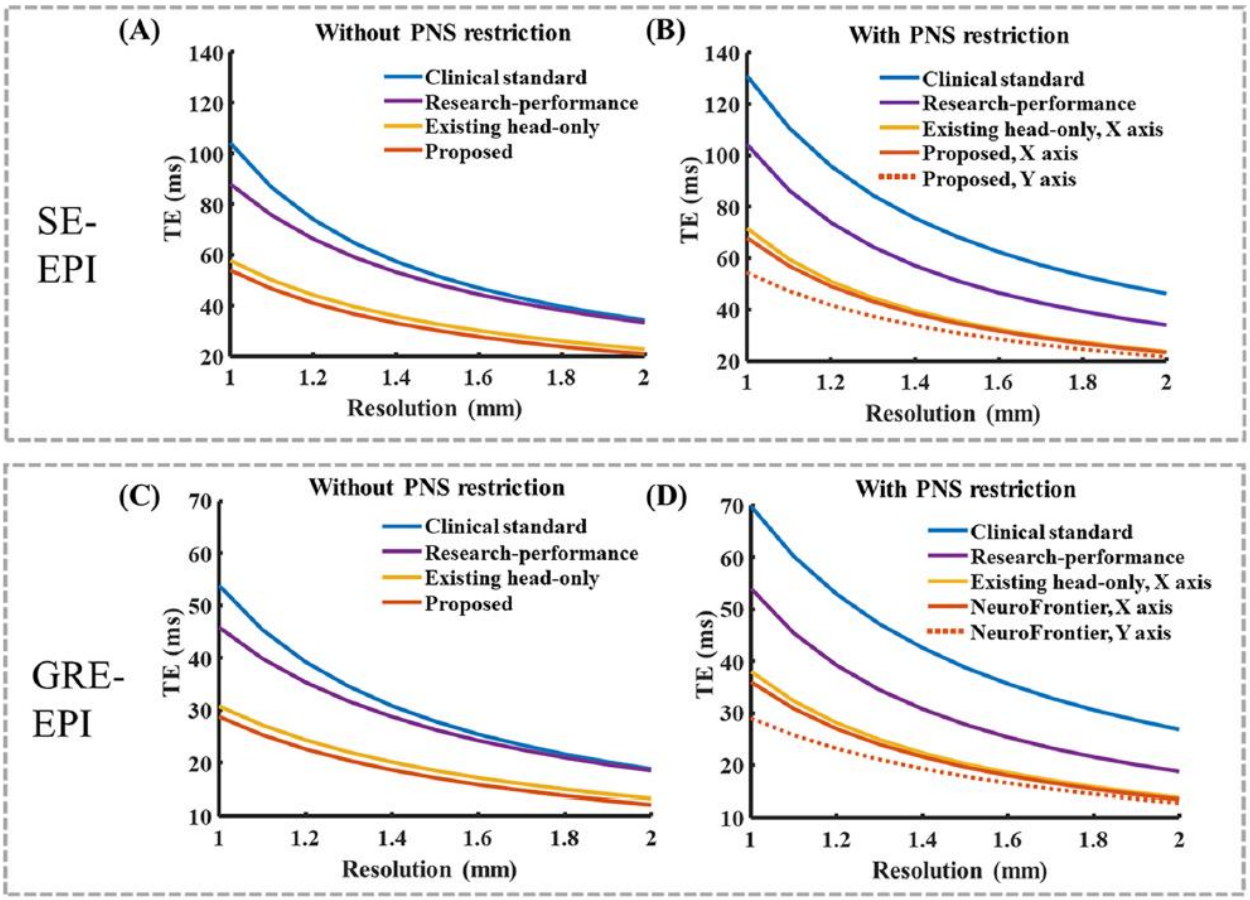



Figure 5. The minimum echo time (TE) as a function of image resolution was calculated for both standard spin-echo (SE) EPI and gradient-echo (GRE) EPI sequences. This calculation was performed with and without peripheral nerve stimulation (PNS) restrictions across various gradient systems. These systems include a standard whole-body clinical system (45 mT/m and 180 T/m/s), a research-performance whole-body system (80 mT/m and 200 T/m/s), an existing head-only gradient system (200 mT/m and 500 T/m/s), and the Neuro-Frontier system (650 mT/m and 600 T/m/s).

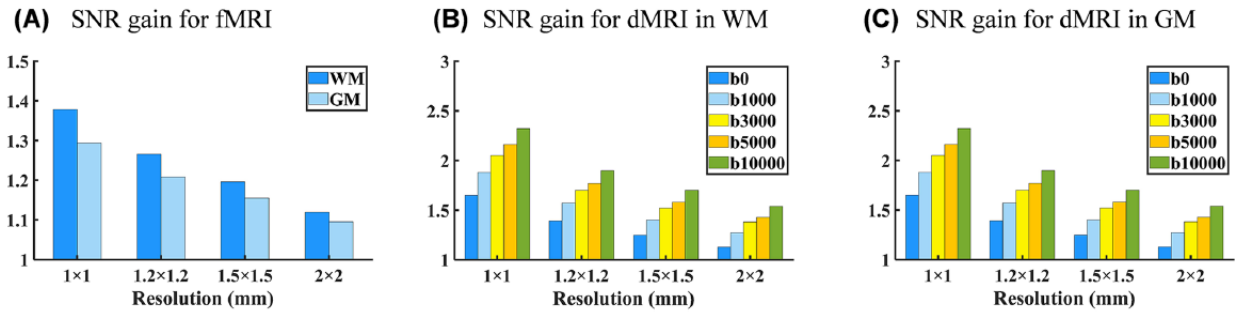



Figure 6. The signal-to-noise ratio (SNR) gain of the proposed NeuroFrontier system, com-pared to a whole-body research-performance scanner (80 mT/m and 200 T/m/s), was simulated for standard fMRI sequences using gradient-echo EPI (GRE-EPI) and dMRI sequences using spin-echo EPI (SE-EPI). The simulations were conducted at various resolutions (1 × 1 mm, 1.2 × 1.2 mm, 1.5 × 1.5 mm, and 2 × 2 mm) and different b-values (b = 0, 1000, 3000, 5000, and 10,000 s/mm²).

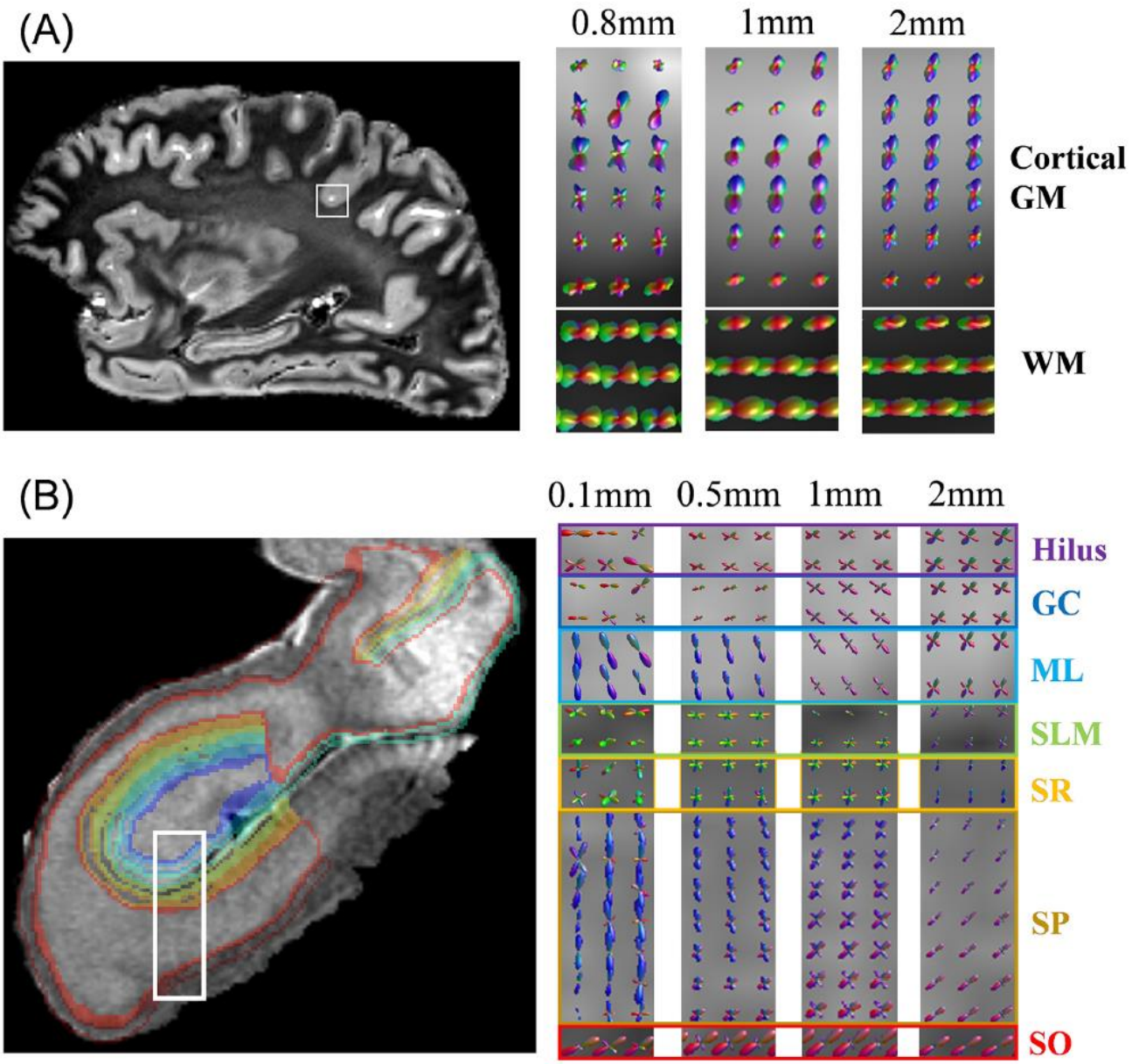



Figure 7. Layer-specific organization of fiber orientation densities (FODs) in the cortex and hippocampus of a human brain specimen was examined at various resolutions. (A) In the cerebral cortex, ex vivo MRI at 0.8 mm isotropic resolution revealed five distinct layers in the gyrus of the parietal lobe. However, as the resolution decreased to 1 mm and 2 mm isotropic (down-sampled from the original data), this layer-specific information gradually became in-distinguishable. (B) In the hippocampal sample, three layers of the dentate gyrus and four layers of CA1 were clearly identifiable at 0.1 mm resolution. This detailed structural information was progressively lost at lower resolutions of 0.5 mm, 1 mm, and 2 mm isotropic, also down-sampled from the original data.

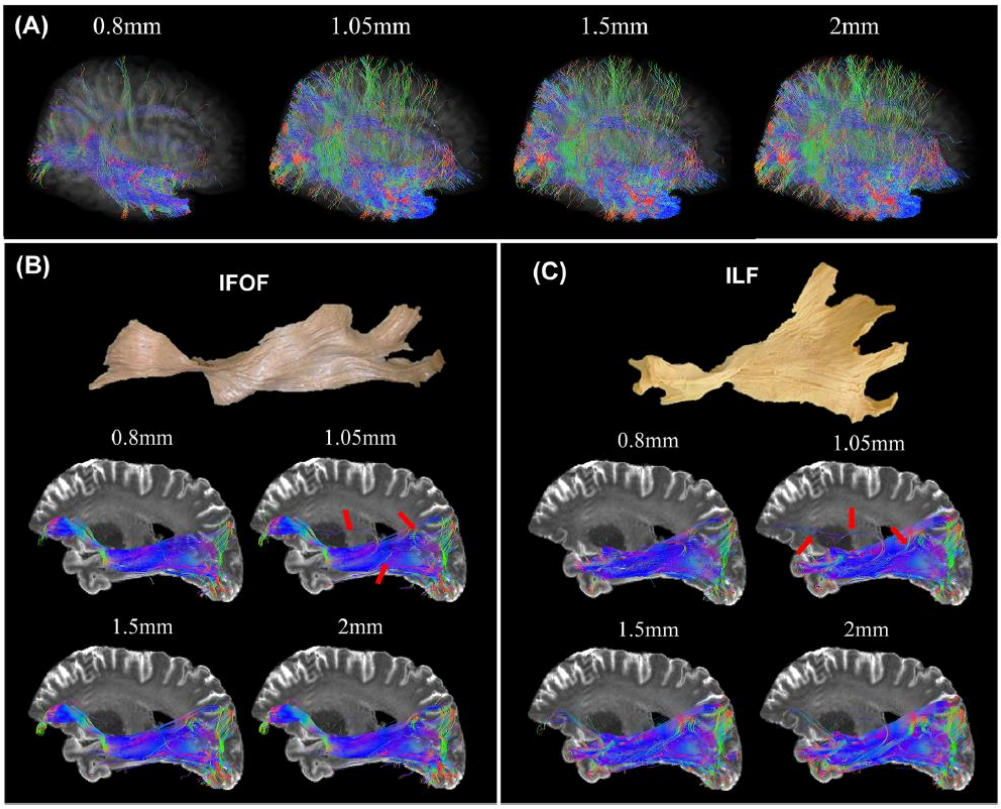



Figure 8. Diffusion tensor imaging (DTI)-based probabilistic tractography was performed at various resolutions for the whole brain (A), and for two representative association fibers: the inferior fronto-occipital fasciculus (B, IFOF) and the inferior longitudinal fasciculus (C, ILF). Red arrows indicate the presence of spurious fiber tracts.

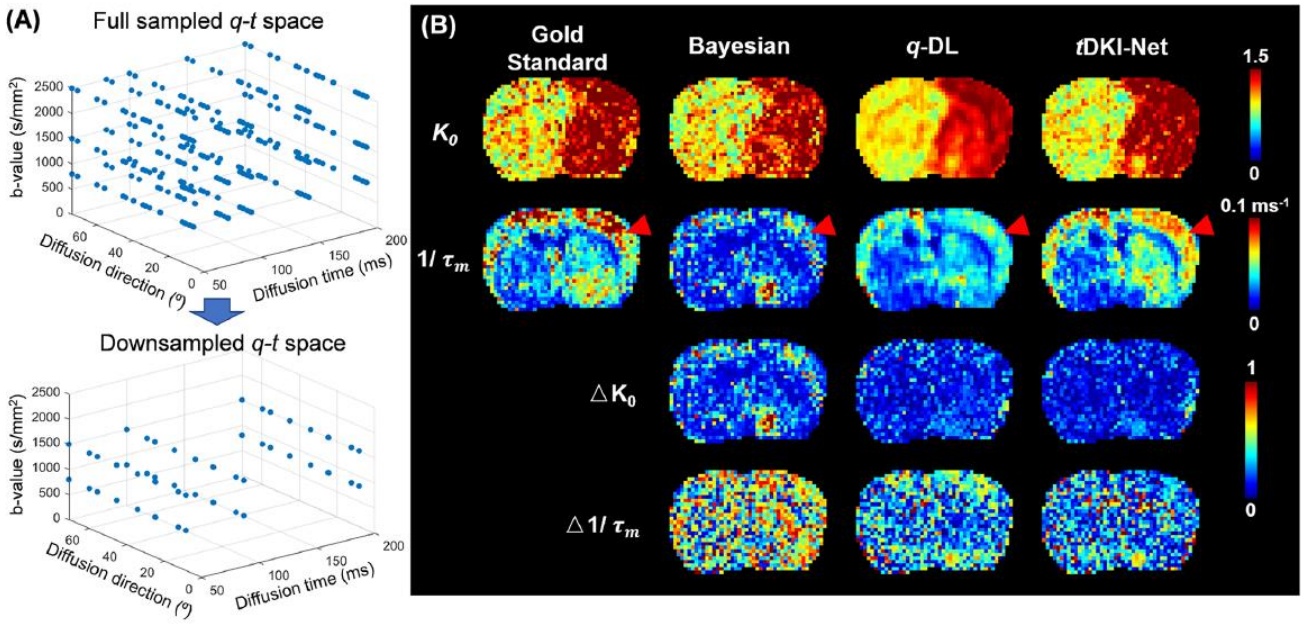



Figure 9. Accelerated q-t space acquisition with deep-learning-based reconstruction. (A) shows the fully sampled q-t space for time-dependent kurtosis imaging using the Karger model to infer transmembrane water exchange (τm), along with the downsampled q-t space used to estimate K0 and τm. Time-dependent DKI data were acquired from a mouse brain after ischemic injury using a Bruker system (Gmax = 570 mT/m and SRmax = 513 T/m/s). (B) The K0 and τm maps were estimated using the fully sampled q-t space (gold standard) and downsampled q-t space with Bayesian estimation, q-space learning, and the network used in the NeuroFrontier system.

## 4. Discussions and Conclusion

The NeuroFrontier system demonstrates significant advancements in neuroimaging capabilities, achieving high spatiotemporal resolution and improved microstructural mapping accuracy. The integration of AI techniques for fast imaging and prospective motion correction enhances the system's practicality for research and clinical applications. The system's ultra-high gradient performance facilitates detailed exploration of brain microstructures, supporting advanced neuroscience research and potential clinical diagnostics.

One of the primary advantages of the NeuroFrontier system lies in its ability to achieve high-resolution imaging with improved signal-to-noise ratio (SNR). The combination of ultra-high gradient strength and AI-assisted compressed sensing (ACS) allows for rapid acquisition of high-resolution images, making it possible to capture fine structural details within the brain that were previously challenging to visualize. This capability is particularly beneficial for studies requiring precise anatomical and functional mapping of brain regions.

The system's prospective head motion correction technique further enhances image quality by minimizing motion artifacts in real-time. This feature is especially important for functional MRI (fMRI) studies, where subject motion can significantly degrade image quality and affect the accuracy of the data. By incorporating a 3D optical tracking system, the NeuroFrontier ensures that head motion is accurately monitored and corrected, leading to more reliable and reproducible results.

Another notable strength of the NeuroFrontier system is its application in diffusion MRI (dMRI)-based microstructural mapping. The high-gradient performance enables enhanced lesion contrast at short diffusion times or high b-values, improving the estimation accuracy for cellular microstructures. This capability is crucial for studies focused on understanding the microstructural changes associated with neurological diseases and disorders.

Moreover, the system's ability to perform high-resolution tractography with reduced false positives highlights its potential for detailed connectome mapping. This application is essential for elucidating the intricate network of neural connections within the brain and understanding how these connections are altered in various pathological conditions.

In conclusion, the NeuroFrontier system represents a significant advancement in MRI technology, offering unparalleled capabilities for high-resolution neuroimaging. Its integration of ultra-high gradient strength, AI-assisted imaging techniques, and real-time motion correction positions it as a powerful tool for both research and clinical applications. The system's potential to enhance our understanding of brain structure and function, as well as its ability to improve the diagnosis and treatment of neurological conditions, underscores its importance in the future of neuroimaging.

## 5. References


1 Poo, M.M., Du, J.L., Ip, N.Y., Xiong, Z.Q., Xu, B., Tan, T., 2016. China brain project: basic neuroscience, brain diseases, and brain-inspired computing. Neuron 92 (3), 591–596.

2. Setsompop, K., Kimmlingen, R., Eberlein, E., Witzel, T., Cohen-Adad, J., McNab, J.A., et al., 2013. Pushing the limits of in vivo diffusion MRI for the Human Connectome Project. Neuroimage 80, 220–233.

3. Ugurbil, K., Xu, J.Q., Auerbach, E.J., Moeller, S., Vu, A.T., Duarte-Carvajalino, J.M., et al., 2013. Pushing spatial and temporal resolution for functional and diffusion MRI in the Human Connectome Project. Neuroimage 80, 80–104.

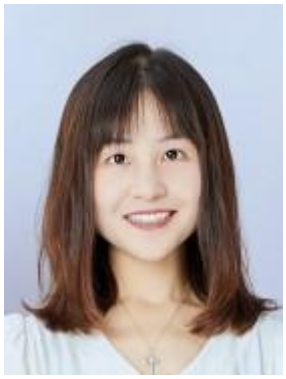
4. Xiang, L., Chen, Y., Chang, W., Zhan, Y., Lin, W., Wang, Q., et al., 2018. Ultra-fast T2-weighted MR reconstruction using complementary T1-weighted information. Med. Image Comput. Comput. Assist. Interv. 11070, 215–223.

5. Cheng, J.Y., Chen, F., Pauly, J.M., Vasanawala, S.S., 2020. Method for performing magnetic resonance imaging reconstruction with unsupervised deep learning. Google Patents, Patent No10,740,931 US Patent and Trademark Office, Washington, DC.

6. Novikov, D.S., Fieremans, E., Jespersen, S.N., Kiselev, V.G., 2019. Quantifying brain microstructure with diffusion MRI: theory and parameter estimation. NMR Biomed. 32 (4).

7. Yang, J., Huber, L., Yu, Y., Bandettini, P.A., 2021. Linking cortical circuit models to human cognition with laminar fMRI. Neurosci. Biobehav. Rev. 128, 467–478.

## Author Biography



**Dr. Dan Wu**

Department College of Biomedical Engineering and Instrument Science

Position Tenure-track Professor

Zhejiang University

Dr. Wu's research focuses on Magnetic Resoance Imaging (MRI) acquisition technqiues and neuroimage processing methods. Particularly, she is an expert on diffusion MRI, including high-resolution MRI pulse sequences and microstructural modeling methods. Her lab is also developing advanced acquisition and analytical methods for fetal and infant brain MRI to study the brain development and developmental disorders.

She has published over 60 peer-reviewed journal articles (2/3 of them are first or corresponding author papers) on top journals of the MRI field, such as NeuroImage, Magnetic Resonance in Medicine, Human Brain mpapping, etc. She has also applied 17 patients domestically and internationally (8 of them are patented).

At present, she is the PI of 6 national and provincial projects, including a Youth Project, a General Project and a Key Project (site-PI) of the National Natural Science Foundation of China, a Key Project of the Ministry of Science and Technology, an Innovation and Entrepreneurship Team Project of Zhejiang Province, and the Kunpeng Project of Zhejiang Province (total funding over ￥15,000,000). She was the PI of several NIH grants, including R01, R21 and R03 between 2016-2018.

Dr. Wu was awarded the Innovator Under 35 China by MIT Technology Review in 2019, the Young scientists of World Economic Forum in 2020, the Outstanding Young Researcher of the Chinese Socieity of Biomedical Engineering in 2020, and the Kunpeng Scholar of Zhejiang Province in 2021.

Dr. Wu is a Junior Fellow of the International Society of Magnetic Resonance in Medicine (ISMRM) since 2016, she he serves as a Annual Meeting Program Committee (AMPC) member of ISMRM, the Secretary of the Pediatic MR Study Group, the Secretary of the Placeta & Petus Study Group, and committee member of ISMRM Publication Committee and Education Committee.

# PASSION for CHANGE



If you have any questions about the magazine, or simply wish to reach out to us for any other reasons, you are welcomed to contact us at the following email address: compliance@united-imaging.com