Unlocking the Potential of Arterial Spin Labeling at 7T: Overcoming Challenges and Advancing Clinical and Neuroscience Applications

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Among the various functional imaging techniques, arterial spin labeling (ASL) has emerged as a powerful tool, not only in neuroscience and cognitive research but also in clinical practice. By using water as an endogenous tracer, ASL delivers quantitative perfusion information with high spatial specificity. Over the years, ASL has demonstrated its clinical value in diagnosing and monitoring a range of neurological conditions, from stroke and brain tumors to neurodegenerative disease, and has been extensively practiced at 3T and 1.5T [1]. Today, ASL is routinely practiced in numerous hospitals and research institutes worldwide. In 2017, the MAGNETOM Terra 7T scanner (Siemens Healthineers, Erlangen, Germany) received FDA approval for clinical use [2]. The advent of ultra-high-field (UHF) 7T in clinical practice has opened new opportunities for ASL while also presenting significant technical challenges [3]. The Laboratory of Functional MRI Technology (LOFT) at the University of Southern California (USC) has spearheaded the development and optimization of 7T ASL, which was applied to clinical studies through the collaboration with the PLA General Hospital (PLAGH), paving the way for its large-scale clinical adoption and for neuroscience applications.

The promise and challenges of ASL at 7T

ASL operates by magnetically labeling arterial blood water, which then serves as an endogenous tracer. After labeling, a delay is introduced to allow the labeled blood to flow into the tissue, generating perfusion contrast. The amount of labeled blood accounts for 1%–2% of the total tissue volume, making ASL a technique with an intrinsically low signal-to-noise ratio (SNR). Additionally, during the waiting period, the labeled water undergoes T1 relaxation, which further reduces the SNR [4]. In theory, higher field strengths like 7T offer significant advantages for ASL. The increased SNR and prolonged T1 relaxation times at 7T promise a huge improvement in perfusion measurement. This has led to high expectations for ASL at UHF [5]. However, the road to realizing these benefits has been far from straightforward.

UHF MRI presents its own set of challenges. Increased magnetic field strength accentuates B0 and radio frequency (RF) field inhomogeneities, increases specific absorption rate (SAR), and markedly reduces transverse relaxation time (T2). These challenges, which are less pronounced at 3T or lower fields, demand systematic innovations and modifications to the ASL sequence to ensure robust and reliable performance at 7T. In 2009, a review article titled "Arterial spin labeling at ultra-high field: all that glitters is not gold" summarized the hurdles for the translation of ASL to UHF [6]. The title aptly reflects the difficulties.

Collaboration between USC and PLAGH

LOFT at USC has long been at the forefront of advancing ASL for clinical applications. USC was the first site in North America to install a MAGNETOM Terra scanner following FDA approval, and the lab has played a pivotal role in the development and optimization of ASL techniques at ultra-high fields. A series of publications from USC has documented the iterative improvements in ASL at 7T, addressing challenges such as B0/B1 field inhomogeneities, SAR limitations, and T2/T2* relaxation penalty [7–9]. For example, the RF and gradient in the labeling unit of pseudo-continuous ASL (pCASL) were optimized for 7T to achieve robust labeling in the presence of B0/B1 field inhomogeneities. Additionally, the widely used turbo-gradient and spin-echo readout at 3T was replaced with turbo gradient echo to mitigate transverse relaxation penalties and image distortions. The end product is a robust, whole-cerebrum, distortion-free 3D pseudo-continuous ASL sequence for 7T perfusion imaging with high resolution and quality [7, 10], as shown in Figure 1,

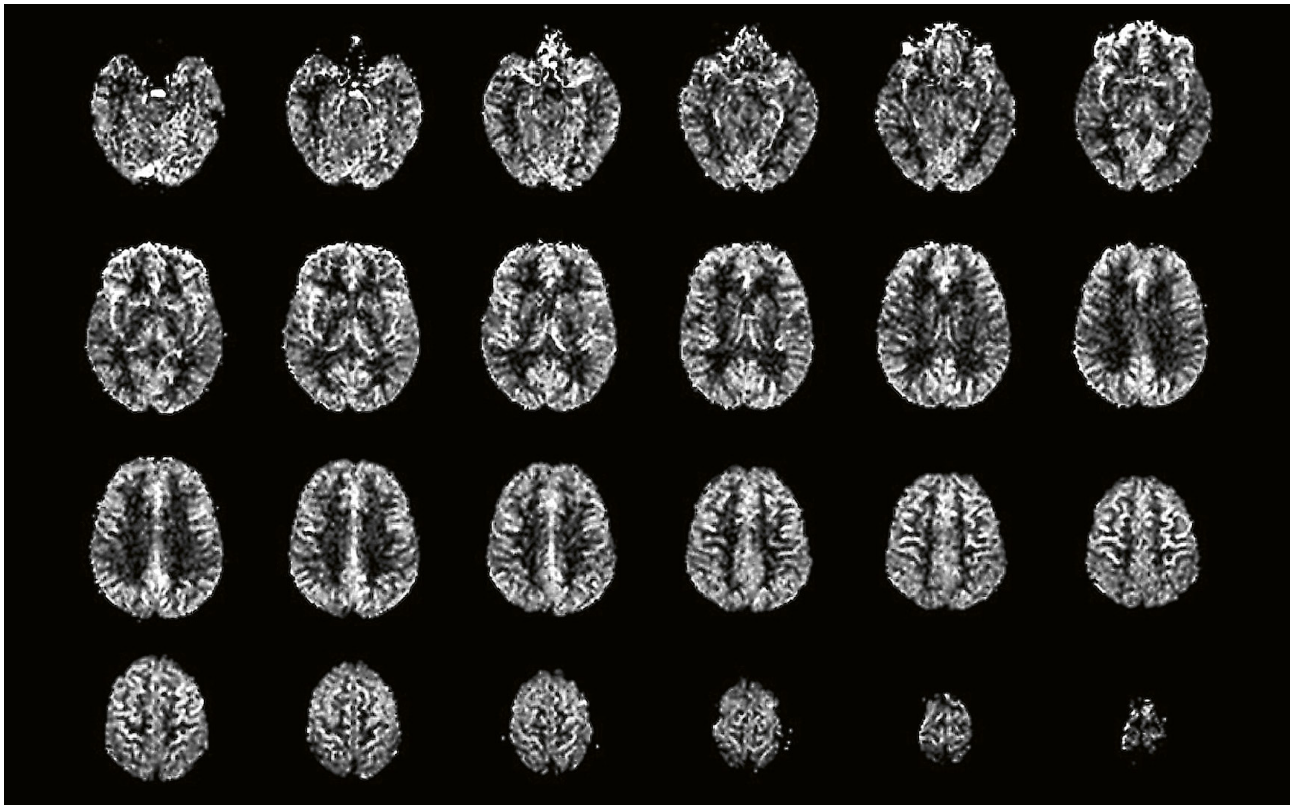
and the sequence can be acquired from the C2P exchange platform.

PLAGH was one of the first hospitals to deploy a 7T MRI scanner for clinical research in China. It played a critical role in evaluating the optimized 7T ASL sequence in clinical use and providing valuable feedback to USC for further refinement. In 2021, after the installation of the MAGNETOM Terra, a prototype ASL sequence was installed at PLAGH via a C2P agreement to explore its clinical utility in patients with moyamoya disease, brain tumors, and other neurological disorders. This collaboration, also supported by the collaboration team from Siemens Healthineers, led to the refinement of ASL at 7T for clinical applications, achieving spatial resolution as fine as 2.0 mm isotropic or even higher – a significant improvement over the 3.5 to 4.0 mm isotropic resolution typically achieved on conventional clinical scanners. This advancement allows for the clear visualization of small lesions and enhances the conspicuity of important imaging markers, such as arterial transit artifacts (ATA), as shown in Figure 2, which are clinically useful in identifying collateral perfusion in cerebrovascular disorders [4, 11].

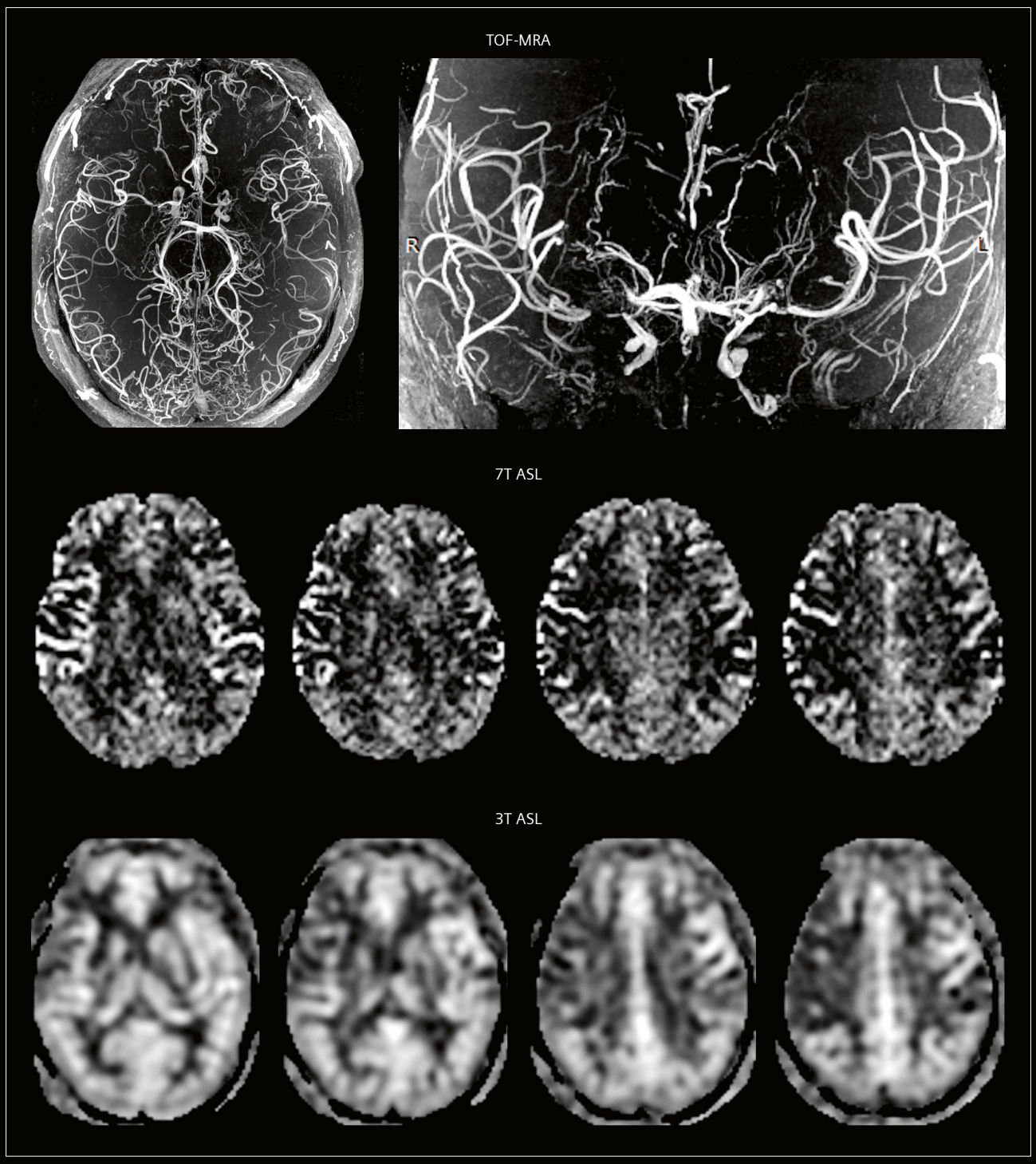
In 2022, at the ISMRM Perfusion Study Group virtual meeting, Dr. Lou, director of the Radiology Department at PLAGH, shared the preliminary findings on the clinical applications of 7T ASL in a talk titled "Clinical Translations of UHF ASL Perfusion MRI" [12]. This presentation highlighted the advantages of 7T ASL, including its ability to provide higher spatial resolution and more accurate perfusion maps, offering clinicians unprecedented insights into cerebral blood flow alterations in a number of brain disorders.

While the clinical applications of ASL at 7T are pioneering, its potential in neuroscience research is equally compelling. The enhanced SNR and resolution at 7T enable researchers to delve deeper into the laminar functional activity of the cortex, uncovering subtle changes in perfusion across cortical layers. This capability opens new avenues for studying brain function and connectivity. For example, LOFT has been using 7T ASL to investigate hemodynamic parameters, such as perfusion and arrival time, across cortical layers in task functional MRI [13]. These advancements not only enhance our understanding of the brain's functional organization, but also hold promise for addressing complex neurological and psychiatric disorders.

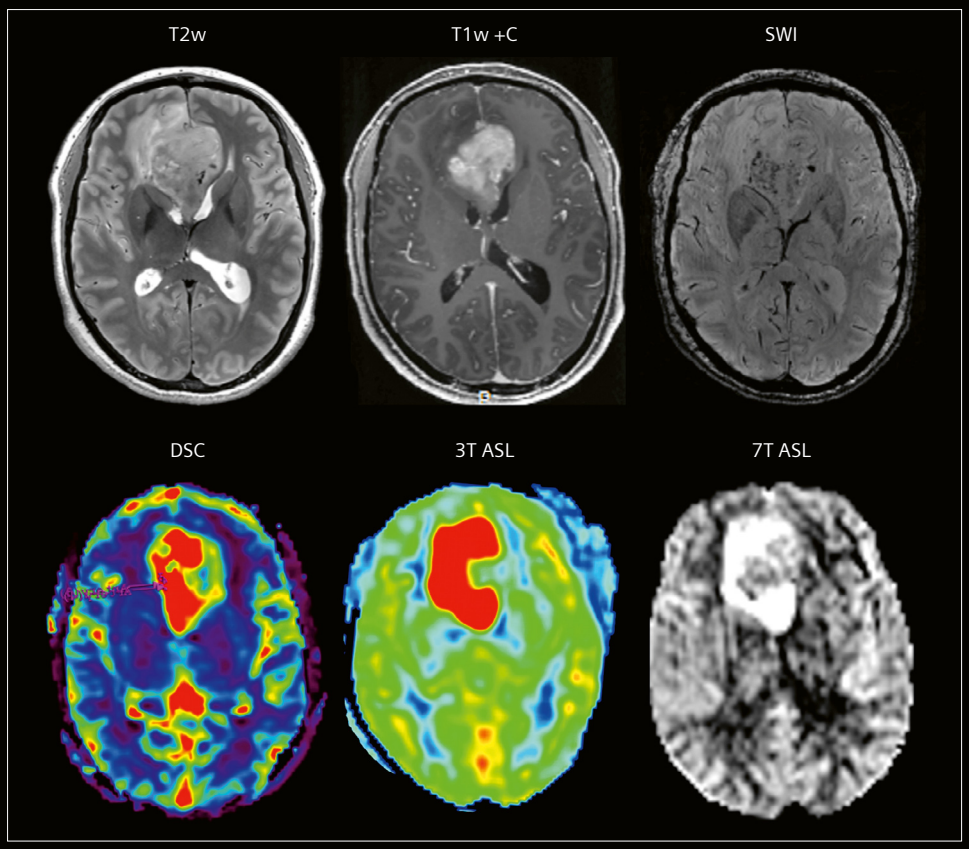
Below are several examples showcasing the advantages of UHF ASL.



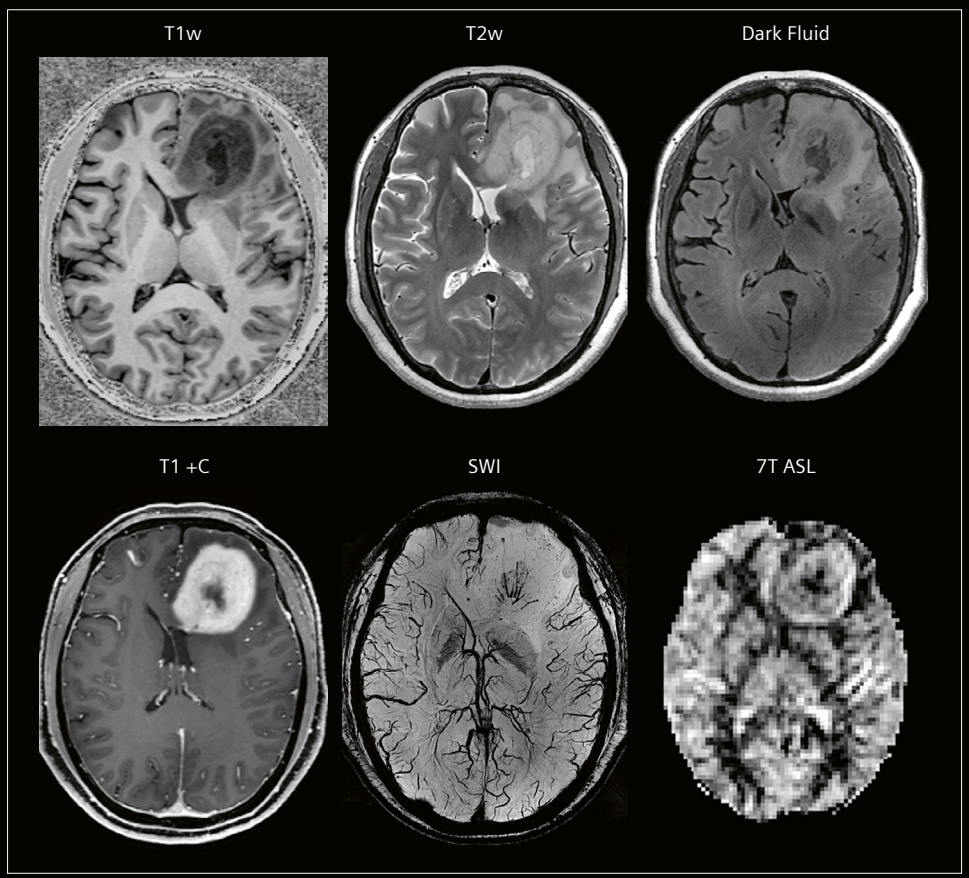
1 7T high-resolution (iso-2.0 mm) 3D TFL pCASL at 7T acquired with the following parameters: effective TR = 6.0 s, labeling duration = 1.0 s, post-labeling delay (PLD) of 2.0, TE = 1.65 ms, FOV = 224 × 192 × 112 mm^3, matrix size = 112 × 96 × 56, FA = 8°, in-plane resolution = 2 × 2 mm^2, slice thickness = 2.0 mm, 56 slices, centric ordering, bandwidth = 490 Hz/pixel, 2 OPTIM background suppression (BS) pulses, 2D-CAIPIRINHA undersampling (R = 2 × 2) with GRAPPA reconstruction, number of repetitions = 24, and scanning time = 10 min [7].



2 A 67-year-old female patient diagnosed with moyamoya disease. The 7T ASL imaging demonstrates a pronounced arterial transit artifact (ATA), whereas no significant ATA expression was detected on the 3T ASL images [11]. The in-plane resolution is 2.2 × 2.2 mm^2.



3 This is a 45-year-old woman with pathologically confirmed oligodendroglioma. A mass with predominantly mild heterogeneous hyperintensity on T2-weighted imaging (T2w) was observed in the right frontal lobe, extending into the knee of the corpus callosum, with small areas of hypointensity. Susceptibility-weighted imaging (SWI) sequences revealed signs of bleeding or calcification within the mass, and significant enhancement was noted. ASL sequences demonstrated hyperperfusion in most regions of the lesion.



4 A 56-year-old female patient with pathologically confirmed glioblastoma. Masses were observed in both frontal lobes, exhibiting low signal on T1-weighted imaging (T1w) and high signal on T2-weighted imaging (T2w). Necrosis was noted in the center of the left frontal mass, which showed low signal on the dark fluid sequence. The SWI sequence revealed microbleeding and dilated venous vessels within the lesion, along with marked enhancement after contrast administration. ASL demonstrated hypoperfusion in the necrotic areas and hyperperfusion in the solid portion corresponding to enhanced portion.

Conclusion

The journey to harness the full potential of ASL at 7T has been marked by both challenges and breakthroughs. Thanks to the collaborative efforts of USC, PLAGH, and Siemens Healthineers, significant progress has been made in overcoming technical barriers, enabling the clinical translation of ASL at UHF and its application in neuroscience research. The theme of the 2022 ISMRM Perfusion Study Group meeting was aptly formulated: "Ultra-High Field Perfusion MRI: Reality, Not Fantasy." As a workhorse for perfusion imaging, ASL has undergone advancements that have transformed it into a practical and powerful tool for both clinical and research applications at 7T. Undoubtedly, there is much to be expected for UHF ASL in the future.

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References

1 Woods JG, Achten E, Asllani I, Bolar DS, Dai W, Detre JA, et al. Recommendations for quantitative cerebral perfusion MRI using multi-timepoint arterial spin labeling: Acquisition, quantification, and clinical applications. Magn Reson Med. 2024;92(2):469–495.
2 U.S. Food & Drug Administration. FDA clears first 7T magnetic resonance imaging device [Internet]. FDA; 2017 Oct. 12 [updated 2018 Mar 2022; cited 2025 Mar 26]. Available from: https://www.fda.gov/news-events/press-announcements/fda-clears-first-7t-magnetic-resonance-imaging-device
3 Shao X, Yan L, Ma SJ, Wang K, Wang DJJ. High-Resolution Neurovascular Imaging at 7T: Arterial Spin Labeling Perfusion, 4-Dimensional MR Angiography, and Black Blood MR Imaging. Magn Reson Imaging Clin N Am. 2021;29(1):53–65.
4 Alsop DC, Detre JA, Golay X, Günther M, Hendrikse J, Hernandez-Garcia L, et al. Recommended implementation of arterial spin-labeled perfusion MRI for clinical applications: A consensus of the ISMRM perfusion study group and the European consortium for ASL in dementia. Magn Reson Med. 2015;73(1):102–16.
5 Zuo Z, Wang R, Zhuo Y, Xue R, Lawrence KSSt, Wang DJJ. Turbo-FLASH Based Arterial Spin Labeled Perfusion MRI at 7 T. PLoS One. 2013;8(6):e66612.
6 Teeuwisse WM, Webb AG, Van Osch MJP. Arterial spin labeling at ultra-high field: All that glitters is not gold. Int J Imaging Syst Technol. 2010;20(1):62–70.
7 Zhao C, Shao X, Shou Q, Ma SJ, Gokyar S, Graf C, et al. Whole-Cerebrum distortion-free three-dimensional pseudo-continuous arterial spin labeling at 7T. Neuroimage. 2023;277:120251.
8 Wang K, Ma SJ, Shao X, Zhao C, Shou Q, Yan L, et al. Optimization of pseudo-continuous arterial spin labeling at 7T with parallel transmission B1 shimming. Magn Reson Med. 2022;87(1):249–262.
9 Wang K, Shao X, Yan L, Ma SJ, Jin J, Wang DJJ. Optimization of adiabatic pulses for pulsed arterial spin labeling at 7 tesla: Comparison with pseudo-continuous arterial spin labeling. Magn Reson Med. 2021;85(6):3227–3240.
10 Zhao C, Guo F, Shou Q, Shao X, Li Y, Huang S, et al. Iso-1.25mm Whole-cerebrum pCASL at 7T for Mapping Depth-dependent Cortical Gray Matter and Tract-specific White Matter Cerebral Blood Flow. In: Proc Intl Soc Mag Reson Med. 2024 In Toronto, ON, Canada; [cited 2025 Mar 15]. Abstract #1264 [cited 2025 Mar 15]. Available from: https://archive.ismrm.org/2024/1264.html
11 Lyu J, Duan Q, Duan C, Bian X, Wang D, Zhao C, et al. Pseudo-continuous arterial spin labeling evaluation of collateral circulation at 7T and 3T MRI in Moyamoya disease. In: Proc Intl Soc Mag Reson Med. 2023. Abstract #0887 [cited 2025 Mar 15]. Available from: https://archive.ismrm.org/2023/0887.html
12 Lou X. Clinical Translations of UHF ASL Perfusion MRI. ISMRM & ISMRT Virtual Meeting Archives [Internet]. ISMRM.org [cited 2025 Mar 15]. Available from: https://www.ismrm.org/virtual-meetings/archive/
13 Shao X, Guo F, Shou Q, Wang K, Jann K, Yan L, et al. Laminar perfusion imaging with zoomed arterial spin labeling at 7 Tesla. Neuroimage. 2021;245:118724.