CNS Aneurysms & Vascular Malformations: Physics Perspective

Specialty Area:

Multi-Disciplinary Neuroradiology
CNS Aneurysms & Vascular Malformations

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Highlights:

- Rapid blood flow and small features make the neuro-vasculature highly challenging to image.
- Standard MRA techniques are challenged by flow based errors (Time of Flight) and the slow speed of MRI (Contrast Enhanced MRA).
- Next generation neurovascular MRI may include improved inflow based MRI techniques, faster contrast enhanced MRI, and alternative flow based metrics vessel wall health.

Target Audience: Students, scientists, physicists, engineers, and clinicians interested current and prospective methods for the evaluation of intracranial vascular disease.

Objectives: This talk aims to provide insights into solution for current challenges and elicit thoughts for potential changes in the neuroangiography imaging landscape. At the end of this talk, participants should:

- Be able to identify limitations of the current MR vascular imaging paradigm and how these techniques compare to state-of-the-art angiographic techniques across modalities
- Contemplate how potential new assessment tools may change the imaging landscape

Purpose: Excluding limitations due to logistical and economic factors, MRI is a superior method for comprehensive assessment of the brain. This has been largely spurred by the diverse contrast mechanisms available to probe pathology. However, the assessment of the small vascular structures remains challenging. In this lecture, we explore the limits of current MR imaging techniques and techniques in development to enhance MRI evaluation of intracranial vascular disease.

Current Imaging Landscape: Current clinical diagnosis of vascular lesions is largely based on "lumenographic" techniques that depict the lumen of vessels and veins. From these images and prior studies relating geometry and filling patterns to prognosis, treatment actions are considered. The parameters required depend on the disease in question. For aneurysms, this includes the size, location, growth, and appearance of blebs; requiring high spatial resolution (much greater than 1mm). For arteriovenous malformations (AVMs), this includes the identification of filling and draining pattern; requiring high temporal resolution (less than 1s). In providing these metrics universally, X-ray digital subtraction angiography (DSA) is the clear gold standard. Modern DSA systems provide high frame rate dynamic images (>10 fps) and 3D images with exceptionally high spatial resolution (< 0.25mm). This impressive performance is in addition to vessel selective capacities. Current MRA techniques do not provide the same level of lumenographic detail and thus can miss important details required for surgical planning or diagnosis. Common occurrences include overestimation of stenosis percentage, poor visualization of small aneurysms structures, and incomplete visualization of arteriovenous malformation filling and draining. However, the complimentary information provided by anatomical and functional measures and a minimal safety risk make them viable alternative in most cases.

Advances in Inflow based MRA: Inflow based angiography is currently the most commonly technique for the assessment of intracranial vessels. While a variety of techniques have been proposed, time-of-flight (TOF) is dominantly used clinically. TOF is a simple T1 weighted sequence optimized to maximize an existing inflow based contrast. With the development of multi-slab excitation [1], use of magnetization transfer background suppression [2, 3], and use of 3T scanners TOF has improved dramatically over the years. In healthy volunteers, TOF can be used to produce exquisite depiction of the intracranial vascular. However, TOF is quite insensitive to slow flowing blood. To examine this, please define the time-of-arrival (TOA) as the time required for blood to enter the slab and reach a given location. Given the strong background signal from grey and white matter, a TOF sequence is only sensitive to vessels with TOA less than ~500ms. That is if it takes longer than 500ms to travel from outside to slab, the signal from background signal will be higher than that of blood. This poses a significant problem if examining aneurysms, stenosis, and AVMs which often have slower flowing components of interest due to recirculation zones and venous drainage. These limitations have created recent interest in alternative inflow based imaging techniques which more specifically target inflow blood via Arterial Spin Labeling (ASL). In this imaging paradigm, blood is specifically tagged during a preparation module and subsequently imaged. This decoupling of imaging and preparation allows background free intracranial MRA via subtraction of images collected with and without the preparation module. Thus unlike TOF, ASL imaging techniques are solely limited by noise and it is relatively easy to produce images of vascular structure with TOA less than 3s. With this substantial reduction in flow sensitivity, single slab inflow MRA images are feasible [4, 5] with better depiction of anatomy with complex or tortuous flow. Of perhaps greater interest, by taking multiple images with different tagging durations, time resolved images can be created [5, 6]. Unlike contrast enhanced MRA and CTA techniques, these dynamic images can be acquired with better than 100 ms resolution and are not subject to bolus dispersion associated with intravenous injection. Furthermore, small modifications to the pulse sequence allow vessel selective tagging [6], bringing complete feature set of DSA to MRA. Despite these promises, the ASL angiography landscape is far from unified. There is currently great variety of ASL tagging schemes in question (i.e. PCASL, FAIR, STAR, etc) and the readout options (i.e. gradient echo vs. bSSFP/TrueFISP, Cartesian vs. Non-Cartesian). Further studies are required to determine true clinical efficacy.

Advances in Contrast Enhanced MRA: When Contrast Enhanced MRA (CE-MRA) was introduced; it made incredible inroads to almost every vascular territory. Currently, CE-MRA is by far the most dominant method for MR angiography outside the head. This is largely due to improved scan efficiency and greatly improved insensitive to errors related to slow filling vessels. The use of CE-MRA in the intracranial vasculature is unfortunately far more challenging and is thus heavily reliant on high resolution images acquired with alternative techniques. This is namely due to the demand for both high temporal and spatial resolution. A temporal resolution of 1s with 0.5mm spatial would be sufficient to detect most abnormal filling patterns and prevent most significant errors from venous and perfusion overlap. However, this leads to an estimated required acceleration >100x. This is far greater than what is achievable with common acceleration techniques such as parallel imaging. Thus for the past decade, CE-MRA techniques have either ignored dynamic information entirely or relied on clever schemes to accelerate image acquisition (i.e. TRICKS [7],CAPR [8], TWIST, etc). Subsequent CE-MRA images often have substantial artifacts, most often at vessel edges, which must be carefully interpreted to prevent misdiagnosis. With recent developments in reconstruction algorithms, an incredible opportunity exists to more explicitly harness assumption regarding CE-MRA. These techniques, which will often be labeled “compressed sensing” and “low rank approximation”, provide opportunities to provide substantially higher accelerations and/or reduced imaging artifacts[9, 10]. All of these techniques exploit known

assumption about the underlying structure (i.e. few vessels, similar temporal dynamics). With these techniques, required acceleration factors of 100x may be possible in the near future.

Alternative Measures of Vascular Health: It is important to note that while lumenography is the most dominant method of assessing large vessel vascular disease, many prevalent diseases are due to abnormal endothelial response and subsequent remodeling. Thus alternative measures of the vessel wall health may be of much greater prognostic value than lumenographic techniques alone. The vascular endothelium is sensitive to flow conditions, due to the residence time of locally produced factors and local forces on the wall itself. For example, endothelial cells align with the flow direction and abnormal flow leads derangement. This is especially true for aneurysms which have been shown to have flow sensitive growth and rupture risk [11]. With recent advances flow fields can now be directly probed with 4D Flow MRI (ecg gated, 3D phase contrast)[12]. This provides a new opportunity to more directly measure the local hemodynamic conditions and how they may be altered to either reduce disease. The interpretation of this information is still highly speculative and like the formation of AVM and Anuerysms, still poorly understood.

Discussion/Conclusions: The assessment of intracranial malformations is highly challenging. From a technical perspective, the flow is fast enough to be challenging for CE-MRA and yet slow enough to create artifacts in in-flow based techniques. Furthermore, pathologic structures are often small (anueysms, stenosis) or rapidly filling (AVMs). These features have challenged existing MRA protocols, more so than respective computed tomography techniques which have benefited from the emergence of dual energy techniques and larger detectors. However, new MRA techniques are emerging that may substantially improve imaging performance. More importantly, it is likely that "lumenographic" techniques may become insufficient to grade vascular lesions with advances in pharmaceutical treatment. Here MRI holds potential to become a dominant and comprehensive technique, providing proxy measures of vessel wall health and status of the downstream parenchyma.

References:

1. Parker, D.L., C. Yuan, and D.D. Blatter, *MR angiography by multiple thin slab 3D acquisition.* Magn Reson Med, 1991. **17**(2): p. 434-51.
2. Pike, G.B., et al., *Magnetization transfer time-of-flight magnetic resonance angiography.* Magn Reson Med, 1992. **25**(2): p. 372-9.
3. Edelman, R.R., et al., *Improved time-of-flight MR angiography of the brain with magnetization transfer contrast.* Radiology, 1992. **184**(2): p. 395-9.
4. Wu, H., et al., *Noncontrast dynamic 3D intracranial MR angiography using pseudo-continuous arterial spin labeling (PCASL) and accelerated 3D radial acquisition.* J Magn Reson Imaging, 2013.
5. Robson, P.M., et al., *Time-resolved vessel-selective digital subtraction MR angiography of the cerebral vasculature with arterial spin labeling.* Radiology, 2010. **257**(2): p. 507-15.
6. Okell, T.W., et al., *Vessel-encoded dynamic magnetic resonance angiography using arterial spin labeling.* Magn Reson Med, 2010. **64**(2): p. 430-8.
7. Korosec, F.R., et al., *Time-resolved contrast-enhanced 3D MR angiography.* Magnetic Resonance in Medicine, 1996. **36**(3): p. 345-51.
8. Haider, C.R., et al., *3D high temporal and spatial resolution contrast-enhanced MR angiography of the whole brain.* Magn Reson Med, 2008. **60**(3): p. 749-60.
9. Trzasko, J.D., et al., *Sparse-CAPR: highly accelerated 4D CE-MRA with parallel imaging and nonconvex compressive sensing.* Magn Reson Med, 2011. **66**(4): p. 1019-32.
10. Lustig, M., D. Donoho, and J.M. Pauly, *Sparse MRI: The application of compressed sensing for rapid MR imaging.* Magn Reson Med, 2007. **58**(6): p. 1182-95.

11. Cebral, J.R., et al., *Characterization of cerebral aneurysms for assessing risk of rupture by using patient-specific computational hemodynamics models.* AJNR Am J Neuroradiol, 2005. **26**(10): p. 2550-9.
12. Hope, T.A., et al., *Evaluation of intracranial stenoses and aneurysms with accelerated 4D flow.* Magn Reson Imaging, 2010. **28**(1): p. 41-6.