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MRI and MR Angiography Evaluation of Pulsatile Tinnitus: A Focused, Physiology-Based Protocol

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Abstract

Pulsatile tinnitus (PT) is the subjective sensation of a pulse-synchronous sound, most often due to a cerebrovascular etiology. PT can severely impact quality of life and may indicate a life-threatening process, yet a timely and accurate diagnosis can often lead to effective treatment. Clinical assessment with a history and physical examination can often suggest a diagnosis for PT, but is rarely definitive. Therefore, PT should be evaluated with a comprehensive and targeted radiographic imaging protocol. MR imaging provides a safe and effective means to evaluate PT. Specific MR sequences may be used to highlight different elements of cerebrovascular anatomy and physiology. However, routine MR evaluation of PT must comply with economic and practical constraints, while effectively capturing both common and rarer, life-threatening etiologies of PT.

In this state-of-the-art review, we describe our institutional MR protocol for evaluating pulsatile tinnitus. This protocol includes the following dedicated sequences: Time-of-Flight Magnetic Resonance Angiography; Arterial Spin Labeling; Spoiled gradient recalled acquisition in the steady state; Time-Resolved Imaging of Contrast-Kinetics; diffusion weighted imaging, and 3D-Fluid attenuated inversion recovery. We describe the physiologic and clinical rationale for including each MR sequence in a comprehensive PT imaging protocol, and detail the role of MR within the broader evaluation of PT, from clinical presentation to treatment.

Keywords

Pulsatile tinnitus; MRI; angiography; cerebrovascular

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Introduction

Pulsatile tinnitus (PT) is the sensation of pulse-synchronous sound in the absence of an external stimulus. PT can negatively impact quality of life and mental health,[1,2] leading to secondary conditions such as insomnia[3] and depression.[4] In contrast to non-pulsatile tinnitus, PT frequently (though not always) has a vascular etiology.[5] Therefore, in addition to impact on quality of life, PT may be associated with life-threatening conditions such as dural arteriovenous fistulas (DAVFs) or internal carotid artery stenosis.[6] The diagnostic workup of PT is anchored by a thorough history and physical examination, but judicious use of diagnostic imaging is nearly always necessary to confirm a clinically suspected etiology. Previous work has proposed clinical and imaging protocols for PT based on CT and CT angiography.[5-9] By contrast, our institution has developed an alternate strategy using MRI rather than CT. The purpose of this article is to present the rationale and advantages (as well as limitations) of a targeted, physiology-based MR protocol for the evaluation of PT comprising five core sequences: 1) Time-of-flight MR angiography without contrast, 2) arterial spin-labeled (ASL) perfusion, 3) craniocervical Time-Resolved Contrast-KineticS (TRICKS), and spoiled gradient recalled acquisition in the steady state (SPGR) volumetric sequences 4) without and 5) with contrast.

Pre-Imaging Evaluation: History and Physical Examination

Prior to selecting an imaging approach, a targeted history and physical examination are necessary to establish pre-test probability of the causative vascular lesion. PT most frequently has a subjective quality which may be described as ‘whooshing’, ‘buzzing’, ‘ringing’, or ‘whistling’, synchronized with the heartbeat. Qualitative pitch assessment may differentiate venous (low-pitch) from arterial (high-pitch) mechanisms.[10] Auscultation of the anterior neck, orbits, and periauricular region may identify a bruit (objective PT), which on cranial auscultation is a specific finding for DAVF.[11,12] Conversely, improvement of tinnitus with compression of the ipsilateral jugular vein or ipsilateral head rotation usually implicates the jugular venous system as causal in PT.[13,14] Specific diagnoses may also be evident from clinical context: an otherwise healthy woman with an elevated body mass index and findings of chronic headache and papilledema, suggestive of idiopathic intracranial hypertension (IIH).[15] (Figure 1 demonstrates the MR workup and subsequent treatment of a patient with IIH). Non-vascular pathologies can occasionally mimic vascular PT. Otoscopic evaluation is necessary in most patients, and is essential to diagnose pathology of the temporal bone, such as advanced otosclerosis, paraganglioma, or cholesteatoma.[6] Audiometric testing may further identify conductive or sensorineural hearing loss (sometimes in a highly specific pattern) that can narrow the diagnosis and even suggest treatment.[16]

MRI Evaluation of Pulsatile Tinnitus: Rationale

Early imaging protocols for PT focused on computed tomography (CT). In 2009, Mattox and Hudgins proposed an algorithmic imaging approach to PT based on CT angiography (CTA).[5] In 2014, Ahsan et al proposed an imaging protocol for unilateral PT that prioritized CTA for most suspected etiologies, with MRI/MRV (MR venography) reserved for suspected IIH.[9] Although the majority of studies have historically recommended CT-

based imaging protocols, recent work has demonstrated the benefits of MR-based imaging for PT. A systematic review by Greierson et al concluded that modern MR imaging has a higher pooled sensitivity than CT imaging for diagnosis in PT.[11] In addition to higher sensitivity, MR-based imaging for PT may be a safer option for those with contraindications to iodinated contrast agents; spares the use of radiation; and provides a safer, less invasive option for initial imaging compared to traditional angiography [Table 1].[11,17] For these reasons, an MR-based imaging protocol is used for most patients seen at our pulsatile tinnitus clinic at the University of California, San Francisco (UCSF), where we evaluate over 120 new patients with PT each year.

Physics of Magnetic Resonance Imaging

MRI generates interpretable images principally through localization of protons and tissue characterization of their environs. A comprehensive review of MR physics is beyond the scope of this study, but a fundamental understanding of MR physics is necessary to design, apply, and understand the role of MRI in imaging the cervicocerebral vasculature. Biologic tissues are exposed to a static magnetic field (B0) that aligns the ‘spin’ of some of the protons in a low-energy state, parallel to the B0 field. Upon excitation with a pulsed radiofrequency (RF) field that is perpendicular to B0, the spin of protons transiently aligns in the transverse xy-plane, thus becoming energized. As protons subsequently transition back to the low-energy state, parallel with the B0 field, they emit this energy, which is ‘detected’ by the scanner. Relaxation in the longitudinal z-axis corresponds to the time constant (“T1”), while relaxation in the transverse xy-plane corresponds to “T2”. The three-dimensional localization of an elicited signal is achieved by manipulating the phase and frequency of the RF pulse. By modulating characteristics of the applied RF pulse, detectors, and tissue being sampled, MR imaging can be focused to assess particular elements of cerebral vascular physiology, or provide clear visualization of specific anatomic or pathological entities. The following discussion of specific MR sequences greatly oversimplifies the complexity underlying these methods, but is intended to provide a summary of their purpose in clinical practice.

The UCSF Pulsatile Tinnitus protocol is structured on a backbone of five sequences, each selected to capture physiologic or anatomic information germane to the differential diagnosis of PT. The first goal of the protocol is to reliably detect the most dangerous causes of pulsatile tinnitus, including vascular etiologies prone to rupture and structural causes such as tumors. Thus, inclusion of axial diffusion-weighted imaging and volumetric 3D fluid attenuation inversion recovery sequences may detect acute processes such as cerebral edema or hemorrhage. The additional sequences described collectively provide a comprehensive screening protocol for other common and rare causes of PT. In practice, the typical acquisition time is 22-26 minutes, with all studies performed on 3T GE Systems (Signa Premier). The following describes our institutional MR sequencing protocol for PT, driven by multiple years of experience with over 1,000 patients in our PT-specific clinic.

Time-of-Flight Magnetic Resonance Angiography

Time-of-flight (TOF) MR angiography (MRA) is among the most popular MR methods to perform cerebral vascular imaging. In essence, TOF-MRA without contrast creates a 'subtraction' image where only protons in motion (i.e. arterial blood) generate signal while all other tissues are suppressed. This is achieved with 'saturation' of protons within a select plane (or volume) of tissue in which there is equal spin aligned in both directions of the plane, giving zero net magnetization. As a consequence of the saturation pulse, only 'new' protons (flowing blood) that enter the selected plane generate signal; all static tissues having been negated in the first step.[18] Of critical importance, TOF-MRA derives signal using blood as an endogenous tracer; thus, intravenous contrast is to be avoided. The addition of intravenous contrast, while it facilitates the visualization of the dural venous sinuses, dramatically reduces sensitivity for identifying DAVF. Several parameters can be adjusted to amplify the signal of flowing, arterial blood including the use of magnetization transfer pulse, increased slice thickness, selection of echo time, and the use of ramped tip angle.[18] As with all MR sequences, there is inevitably a tradeoff for higher fidelity signal, usually in the form of protracted scan time. However, recent technical advances such as compressed sensing TOF-MRA, which capitalizes on the mathematical 'sparsity' of information (vessels vs. background), enabling accurate diagnosis of arteriovenous (AV) shunting with sequence time of 2.5 min.[19]

TOF MRA may reliably identify a number of vascular etiologies of PT, most critically dural arteriovenous fistulas (DAVFs).[20] Some DAVF can have an annual risk of intracranial hemorrhage in excess of 24%. TOF-MRA without contrast is probably the most sensitive and specific noninvasive method for diagnosing DAVF.[21,22] In addition, increased signal intensity of TOF-MRA within cortical veins may also help identify DAVFs at a high risk for rupture [23]. TOF MRA is also quite effective at diagnosing arterial aneurysms (sensitivity >90% and specificity >80%)[24,25] and stenoses (sensitivity: 95.5% and specificity: 87.2%).[26] For diagnosing severe carotid artery stenosis as a cause of PT, TOF MRA has a sensitivity and specificity approaching 100%.[27,28]

Arterial Spin Labeling: Principles and Rationale

Arterial spin labeling is a relatively newer MR sequence, developed as an alternative to Positron Emission Tomography (PET)/CT as a method of quantifying cerebral blood flow. Unlike other forms of MR perfusion imaging, ASL does not require intravenous contrast agents; instead, ASL generates MR signal using arterial H20 as an endogenous tracer by 'tagging' the molecules using RF pulses and gradients to induce T1 signal (longitudinal relaxation).[29] The 'tagging' (labeling) phase is performed in an axial slab of tissue perpendicular to the direction of blood flow, typically in a slab of tissue below the skull base, above the carotid bifurcation. After a prescribed delay period known as the post-label delay, the labeled arterial blood is imaged during the capillary phase of transit, allowing quantifiable estimation of tissue perfusion. Overall scan acquisition time using parameters is typically 4-5 minutes.[30]

Initially developed as a tool for brain tumor imaging as an alternative to PET, early investigations noted the sensitivity of ASL for detecting arteriovenous shunts. Because ASL signal decay (T1 relaxation) is typically much shorter than capillary bed transit time, ASL signal should not contaminate veins in normal physiology. Le et al. reported 78% sensitivity and 85% specificity for venous-ASL signal for shunt detection in a small series of patients with DAVF and small cerebral arteriovenous malformations (AVM).[31] Although not yet widely used in clinical practice, ASL has robust reproducibility and several advantages over other MR perfusion techniques, including being unaffected by variable blood-brain barrier permeability.[32] ASL may improve sensitivity and specificity for DAVFs over TOF-MRA alone (and reduce dependence on reader performance),[33] and specifically improves detection of small shunts that may be missed by conventional MR angiography.[34] Figure 2 demonstrates the ability of ASL to capture Still, ASL is vulnerable to numerous artifacts, including false-positive AV shunting due to venous reflux which requires context during interpretation.[35]

Spoiled gradient recalled acquisition in the steady state

Three-dimensional spoiled gradient recalled acquisition in the steady-state (3D-SPGR) is a T1-weighted MRI sequence used for a number of diagnostic applications and, in our experience, is a critical sequence for the evaluation of PT. Long considered a standard sequence in the workup of intracranial tumors, 3D-SPGR, and other volumetric, T1-weighted sequences (BRAVO, Magnetization Prepared Rapid Acquisition Gradient Echo) enable multiplanar (e.g. coronal, axial, oblique) reformatting.[36] ‘Spoiling’ refers to the cancelation of all transverse components of magnetization at the end of each RF excitation, eliminating the T2 component of an MR signal and emphasizing T1 contrast. There are a few different methods by which spoiling may be accomplished. Along with most other modern methods of MR spoiling, SPGR utilizes RF-spoiling, by which the RF phase is varied in relation to detector phase via a predefined formula (either linear or quadratic).[37] RF-spoiling accomplishes T1-weighted images with a short repetition time , thus decreasing overall scan time compared to older methods of T1-weighted imaging.[38] Of note, 3D-SPGR (GE) is equivalent to methods by other manufacturers, including volumetric interpolated brain examination (VIBE, by Siemens, a type of fast low angle shot magnetic resonance imaging or fast low angle shot) and T1-fast field echo imaging (by Philips).[39,40]

In the UCSF PT protocol, a 3D-SPGR sequence is performed pre- and post-contrast, with fat-saturation applied in the post-contrast acquisition. This sequence effectively screens for neoplasms that may cause PT in the neck, skull base and temporal bones, as well as throughout the cranial vault. While a “whole brain” acquisition, 3D-SPGR obtained and reformatted using 1mm isovoxels can be very effective at identifying even very small intracochlear schwannomas as well as larger paragangliomas.[41,42] An additional advantage of post-contrast SPGR is the ability to produce strong intravascular signal while attenuating CSF.[37] This advantage allows direct visualization of many vascular causes of pulsatile tinnitus using 3D-SPGR, such as a double-lumen indicating vertebral artery dissection.[43,44] Although contrast-enhanced SPGR sequences are not formally considered ‘venography’, clear visualization of the contrast in the dural venous sinuses allows post contrast SPGR to be one of the most effective “MR venography” sequences outperforming time-of-flight and

phase-contrast techniques in characterization of the dural sinus pathology.[45,46] While SPGR sequences do not reflect flow characteristics (see TRICKS below), we find this sequence provides excellent visualization of sinus anatomic and pathological variants associated with PT, including high-riding jugular bulb, sigmoid sinus diverticulum, and both intrinsic sinus stenoses caused by arachnoid granulations or encephaloces and extrinsic stenoses caused by tentorial deflection.[47]

Time-Resolved Imaging of Contrast-Kinetics

While the previously described MR sequences demonstrate cerebral anatomy in the static state, some vascular causes of PT require imaging that captures their dynamic physiology. Time-Resolved Imaging of Contrast-KineticS MR can resolve temporal characteristics of vascular flow between the arterial, capillary, and venous phases. As such, TRICKS is particularly useful for diagnosing disease entities with aberrant flow between arterial and venous networks, including arteriovenous malformations, cranial and cervical DAVFs, and symptomatic cranial venous drainage patterns as well as excellent visualization of the course and contour of the cervical arteries and veins. While still limited in temporal and spatial resolution compared to digital subtraction angiography (DSA), TRICKS serves as a non-invasive analogue to DSA without the risks of ionizing radiation[48] or invasive procedural risks.[49]

TRICKS is a particular implementation of contrast-enhanced MRA , which uses gadolinium contrast to demonstrate vascular flow.[50] TRICKS uses an algorithm in which the k-space is overlapped between scans across time points. As the k-space is moved across the tissue being sampled over time, the periphery of the k-space is overlapped between scans, while the center of the k-space is more frequently updated. The center of k-space carries low spatial frequency data, which will produce the course outline of an image. The periphery of k-space carries high spatial frequency data, which will produce the fine details of an image.[51] Therefore, by overlapping the periphery of k-space between scans (rather than shifting the entire k-space between scans, as in other MR methods), high spatial resolution is preserved while increasing the speed of data acquisition, increasing temporal resolution. The alternative temporal k-space sampling scheme used in TRICKS can reduce the acquisition time of traditional high-resolution CE-MRE from 20-30 seconds down to sub-second speed with parallel acquisition, allowing the temporal resolution necessary to capture the rapid vascular flow of structures such as cavernous (c)DAVFs and AVMs.[52] We also modify the field of view anterior to posterior to extend from anterior to the carotid bifurcation to posterior to the torcula, and from cranial to caudal from above the circle of Willis to the aortic arch. This expanded field of view not only allows full visualization of the cervical arteries, but bilateral dural venous sinus outflow pathways from the torcula to the superior vena cava.

A number of studies have shown TRICKS performs similarly well compared to that of DSA for both cDAVFs and AVMs.[53] Meckel et al documented 100% accuracy with TRICKS for 13 DSA-identified patent cDAVFs, compared to just 56% and 88% sensitivity with T2-weighted MRI and TOF MRA, respectively.[54] Farb et al documented 93% accuracy of TRICKS interpretation for both the presence and grade of 42 suspected cDAVFs.[55] For

brain AVMs, a number of studies have found strong correlation between DSA and TRICKS findings: 17/19 (89.5%) by Machet et al; 19/19 (100%) by Cuong et al.[56,57] Similarly excellent performance by TRICKS has been shown for nidus identification (88%) and venous drainage (88%) in extracranial AVMs, compared to DSA.[58,59] Therefore, TRICKS offers a safe, effective alternative to DSA for temporal imaging for cDAVFs and AVMs in patients with PT.

Our experience supports these data; we find that high-flux shunting lesions are typically (though not always) visible on TRICKS. TRICKS is also complimentary to SPGR for characterizing dural sinuses; while the spatial resolution is superior with SPGR, one can identify sinus dominance, reflux, and pathological craniocervical venous drainage patterns seen in IIH or venous Eagle's syndrome (Figure 3). We also utilize the TRICKS sequence to better identify extracranial fistulas in the scalp, where TOF MRA can sometimes be signal-starved. A combination of TOF-MRA, ASL and TRICKS allows for a robust noninvasive screening for AVM or DAVF.[60-62] Figure 4 demonstrates how the described comprehensive MR protocol may be used to support an etiology of PT. Table 2 summarizes the applications and limitations of each MR sequence.

Discussion

In summary, we present a physiologically-driven, pragmatic MRI protocol for the initial evaluation of patients with PT. Following an appropriate history and physical exam, this comprehensive MR protocol for PT allows careful selection for more invasive procedures, including lumbar puncture (LP), angiography, and venography. Findings of transverse sinus stenosis on SPGR may have sensitivity and specificity over 84% and 94% for idiopathic intracranial hypertension, indicating the need for a lumbar puncture.[63] The described comprehensive MR screening protocol that captures not only the common, but more importantly is tuned to screen for the most threatening causes of PT. This approach reassures patients and prevents the expense and anxiety of further testing.

MR is also complementary to the temporal bone CT, which can effectively demonstrate osseous lesions responsible for PT including otosclerosis, enlarged vestibular aqueduct syndrome, fibrous dysplasia, large jugular paragangliomas and Paget disease.[64] Temporal bone CT may also help identify some of the more rare but benign vascular causes of PT such as aberrant internal carotid artery, which can be a challenging diagnosis with MRA due to dephasing of spins in a tortuous vessel.[65]

Limitations

It is critical to identify the limitations of any proposed universal imaging protocol. Among the limitations of our suggested MR protocol for PT are the technical specifications of individual scanners and personnel expertise. For example, implementation of ASL sequences may not be possible with older commercial MR scanners, often from lack of proper acquisition and analysis software.[29] Lower field MR scanners (<3T) may also be inadequate for ASL, due to low signal-to-noise ratio .[29,66] For implementation of this MR protocol, an MR technologist may also need to identify anatomic variations to select the proper field-of-view and acquisition orientation. If the long axis of a vessel lies coplanar with

acquisition, the vessel may be missed.[67] A common example of anatomic variation for which this applies is in venous imaging, as there is significant anatomic variability in the course of the torcular herophili and dural venous sinuses that may be missed without proper MR parameters.[67,68]

The high cost of MR may a barrier to the implementation of a PT protocol. However, in the context of overall cost-effectiveness, it is not clear that MR is inferior to other approaches. As described, an adequate physical examination may expedite diagnosis and avoid unnecessary MR imaging. For instance, Lyu et al proposed an algorithm which prompts vascular imaging only if internal jugular vein compression fails to mitigate symptoms of PT.[7] When a definitive diagnosis is not clear, the high sensitivity of MR can help avoid significant costs associated with missed diagnoses and can obviate the need for repeat testing and potentially avert DSA. Early detection of a cerebral aneurysm, DAVF, or AVM causing PT may offset significant costs to the healthcare system associated with rupture,[69,70] not to mention the benefit to the individual patient. Future work on quantitative cost-effectiveness of MR imaging for PT would help serve to justify use of MR for PT.

As overall utilization of MRI in the United States continues to increase,[71] available scanner time remains an additional constraint on the utilization of MR for PT. Advances in MR technology, such as motion analytics and parallel imaging, offer to reduce scanning time, thus increasing access to MR while reducing costs.[72,73] A streamlined protocol of MR sequences specific to PT would further increase access, reduce costs, and facilitate efficient diagnosis.

Some patients will be ineligible for MR imaging due to ferrous materials near the eye or spinal cord, or implanted devices including pacemakers. MR also has the limitation of claustrophobia in some patients in addition to increased time cost for patients as compared to CT. Widespread clinical applicability of the described MR protocol may also be limited by the relatively low number of specialized pulsatile tinnitus centers.

Lastly, it should be reiterated that some etiologies of PT, albeit rare and low-risk, may not be optimally detected by MR despite the technical advances discussed above. While continuing to improve in detection of superior semicircular canal dehiscence,[74] MR remains inferior to CT for evaluating some of the osseous structures of the petrous temporal bone. MR signal is vulnerable to artifacts at air-bone interfaces.[75] Specifically, several conditions associated with PT that present with subtle bony abnormalities, including fibrous dysplasia, Paget disease, enlarged vestibular aqueduct syndrome, and dehiscence of the carotid canal or sigmoid plate may elude detection on MRI (see Figure 5).[64,76] While we estimate the diagnostic yield of the described PT MR protocol to be over 75%, a complete sensitivity and specificity has yet to be determined.

Conclusion

Pulsatile tinnitus can be a debilitating condition for patients and may be associated with life-threatening cerebrovascular diseases. However, many causes of PT can be effectively diagnosed and treated with the proper workup. PT should be evaluated with targeted,

physiology-based MR sequences which have evolved substantially in recent years but are not yet incorporated into standards and guidelines.[77] With focused protocol design, we argue that MR has the potential to achieve high-yield, cost-effective diagnosis without added time or ionizing radiation. Future work should evaluate the sensitivity and specificity of these sequences in the context of alternate imaging tools.

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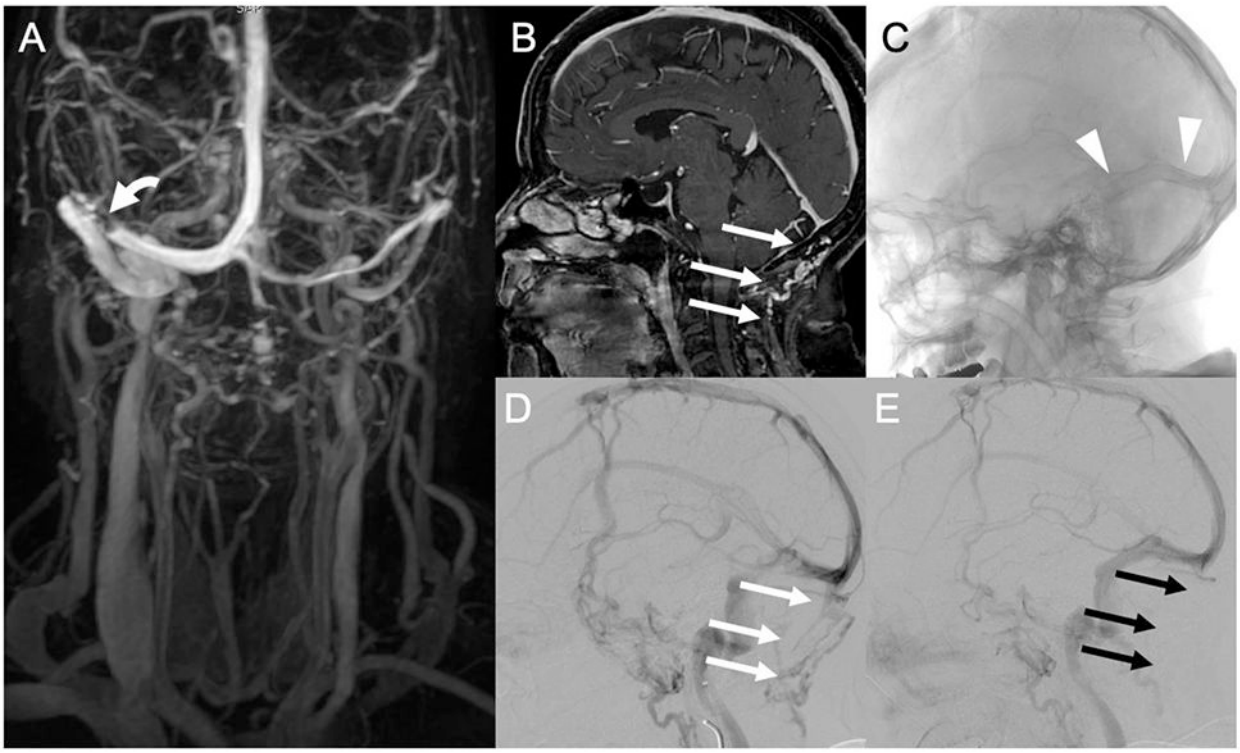

Figure 1: MR imaging and treatment of idiopathic intracranial hypertension causing pulsatile tinnitus

The most common etiology of venous pulsatile tinnitus (PT) is idiopathic intracranial hypertension, which is well-characterized with the PT protocol MRI/MRA. A 52-year-old woman with idiopathic intracranial hypertension (CSF opening pressure 25cm of water (H20)) despite acetazolamide therapy was evaluated. Craniocervical time-resolved imaging of contrast-kinetics (A) shows right-dominant jugular venous drainage and focal severe stenosis (curved arrow) of the transverse sinus. Sagittal reformat of post-contrast spoiled gradient recalled acquisition in the steady state (B) showed alternate pathway venous egress via an occipital emissary vein, (white arrows), a known secondary mechanism of PT in idiopathic intracranial hypertension. These findings were confirmed on digital subtraction angiography (D, white arrows = occipital emissary vein). A physiologic pressure gradient was present across the stenosis and the patient was treated with overlapping venous sinus stents (C, white arrowheads). Post-stent angiography revealed ‘normalization’ of venous flow and disappearance of emissary vein drainage (black arrows). Symptoms, resolved, acetazolamide was discontinued, and CSF opening pressure decreased to 13cm H20 post-treatment.

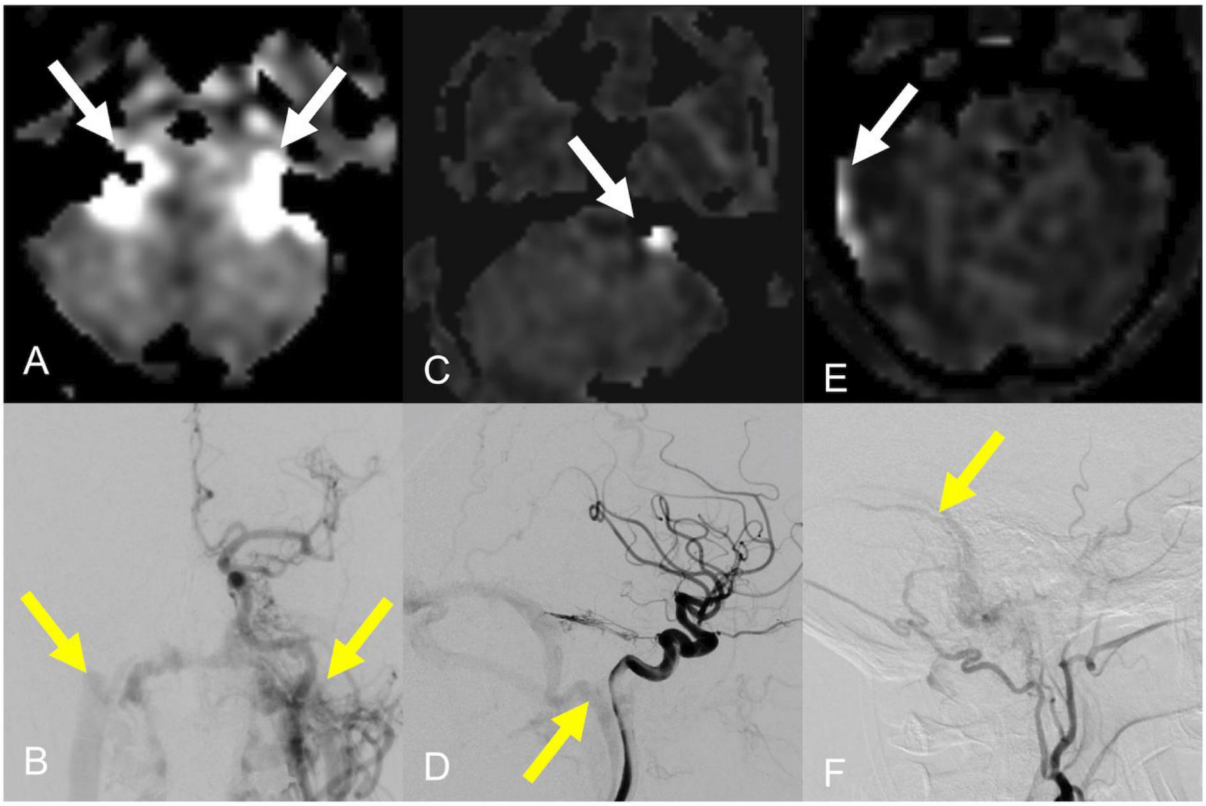

Figure 2: Spectrum of abnormal arterial spin labeling (ASL) in patients who initially presented with pulsatile tinnitus

Abnormal MR ASL sequences in three different patients (A, C, E) indicate venous accumulation of arterial ‘spins’, highly suggestive of shunting. The corresponding digital subtraction angiography appearances are shown in B, D, and E. Yellow arrows indicate shunted blood corresponding to the region of ASL signal abnormality (white arrows in A, C, and E).

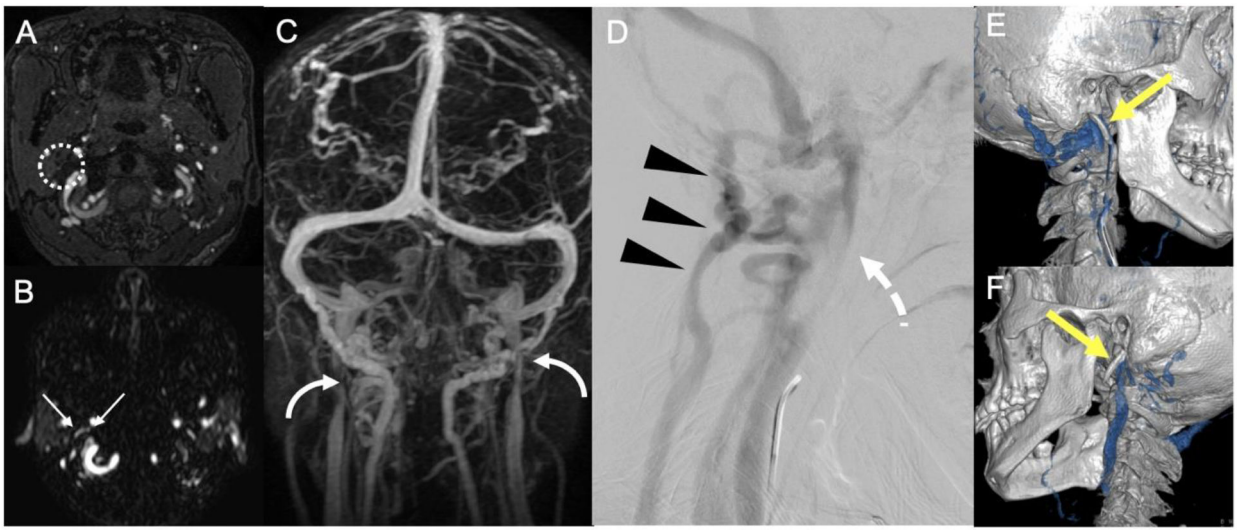

Figure 3: MR imaging of styloid process compression causing pulsatile tinnitus

The targeted University of California, San Francisco pulsatile tinnitus (PT) MR protocol includes sequences that provide complementary physiologic data. A young woman with constant, low-pitch PT had normal time-of-flight MR angiography of the right skull base (dashed circle) (A) but a careful review of the same imaging plane in a reconstructed axial time-resolved imaging of contrast-kinetics (TRICKS) image (B) shows severe compression of the internal jugular vein (white arrows) at this level. Coronal craniocervical TRICKS maximum intensity projection image (C) confirmed functional stenosis of the bilateral (co-dominant) jugular veins just below the skull base (curved arrows). Subsequent angiography confirmed the jugular stenosis (dashed arrow) with significant redirection of cranial blood via the posterior condylar (emissary) vein (arrowheads), a known cause of PT. Reconstruction of digital subtraction angiography images identified extrinsic compression due to styloid process compression (yellow arrows), known as ‘venous’ Eagle syndrome.

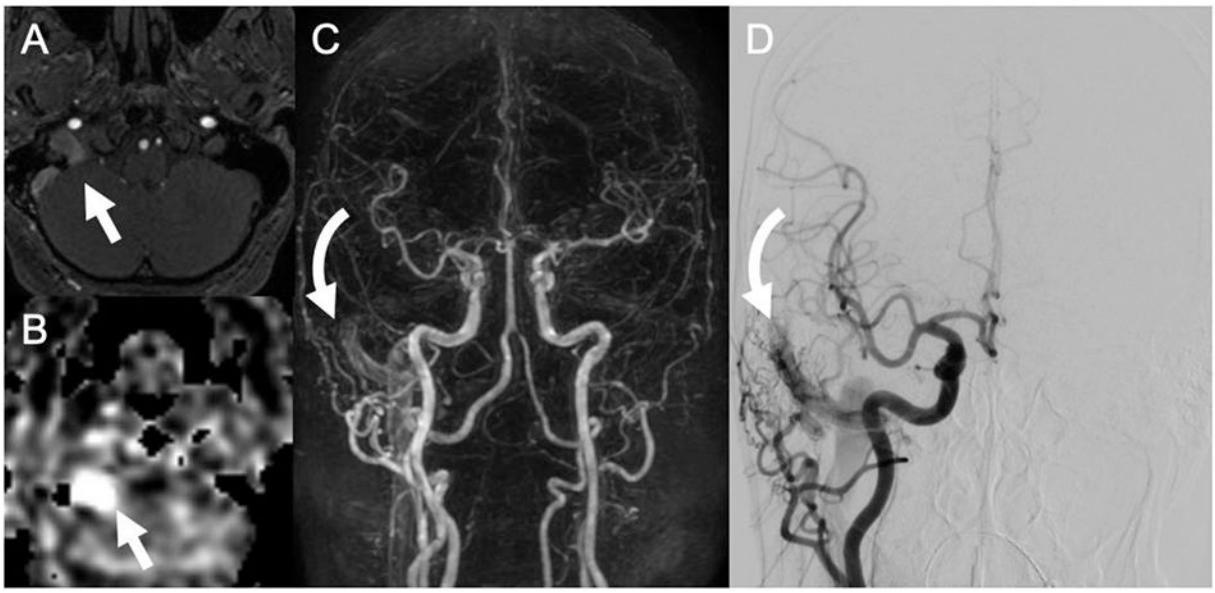

Figure 4: MR imaging of an arteriovenous fistula causing pulsatile tinnitus

A 62-year old patient with right-sided, high-pitch pulsatile tinnitus. Time-of-flight MR angiography (A) identified high-intensity signal in the right sigmoid sinus (white arrow). The correlative signal on arterial spin labeling (B) indicates accumulation of arterial blood within the sinus (white arrow), supporting the diagnosis of arteriovenous fistula. Craniocervical time-resolved imaging of contrast-kinetics (C) confirmed shunting and shows low-risk, unrestricted outflow via the jugular vein (curved arrow). Subsequent digital subtraction angiogram (right common carotid injection) precisely mirrors the findings on pulsatile tinnitus protocol MR (curved arrow = shunt site in sigmoid sinus wall).

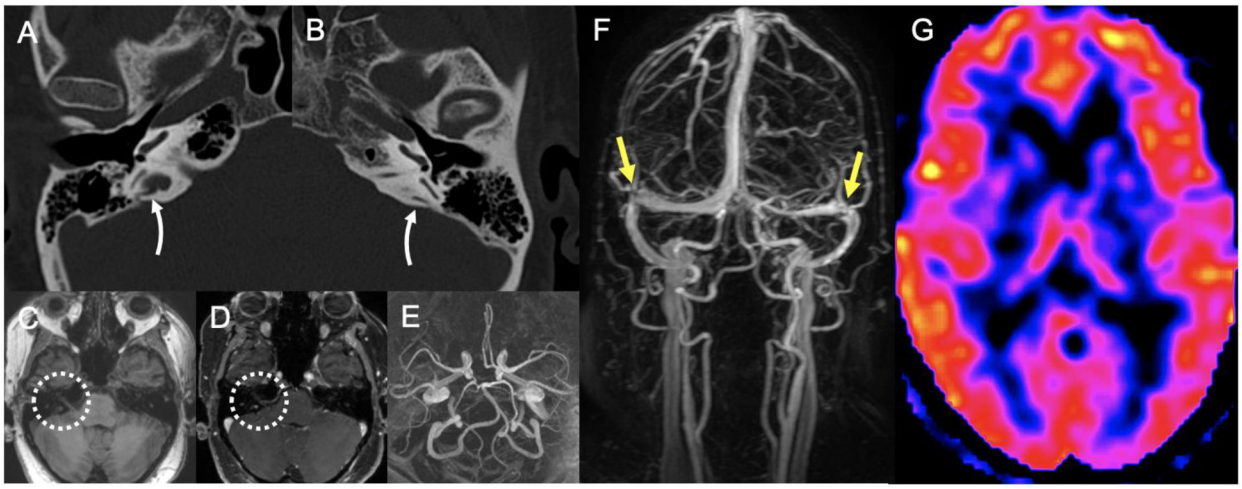

Figure 5: Temporal bone CT captures right vestibular aqueduct syndrome causing pulsatile tinnitus missed with MR imaging

Rare, non-vascular etiologies of pulsatile tinnitus (PT) can be missed with the PT MR protocol. In a 75-year old with mild, intermittent PT and right-sided sensorineural hearing loss was diagnosed with enlarged right vestibular aqueduct syndrome on temporal bone CT (A); contrast with the normal side (B). This osseous abnormality is not clearly seen on MR sequences (C = T1 spoiled gradient recalled acquisition in the steady state (SPGR) pre-contrast, D = T1 SPGR). Craniocervical time-resolved imaging of contrast-kinetics (F) showed very mild bilateral transverse sinus stenosis (yellow arrows), suggesting idiopathic intracranial hypertension physiology but clinical evaluation, including lack of change in PT with jugular compression, argued against this as the etiology of PT. Time-of-flight MR angiography (E) and arterial spin labelling (G) sequences were normal in this patient.

Table 1:

Comparison of imaging modalities for pulsatile tinnitus

	MR/MRA	CT/CTA	Temporal Bone CT
Advantages	-Greater pooled sensitivity for diagnosis than CT.[11]	-No tradeoff between temporal and spatial resolution.[78]	-First-line imaging in presence of a middle ear mass.[79] -Best modality for osseous pathology,[9] offers highest spatial resolution of bone.[80] -Can identify some vascular pathologies (fistula of semicircular canal).[81]
Disadvantages	-High cost -Time of scanning -Dephasing of tortuous vessels.[65]	-Radiation exposure -Iodinated contrast -Lower sensitivity than MR.[11]	-Cannot identify most vascular causes of PT

Table 1 provides the advantages and disadvantages of different imaging modalities for pulsatile tinnitus, comparing MR/MR angiography (MRA), CT/CT angiography (CTA), and temporal bone CT. PT: pulsatile tinnitus

Table 2:

Rationale and limitations of MR sequences for pulsatile tinnitus

MR Sequence	Strengths/Use	Limitations	Typical Sequence Acquisition Time
TOF-MRA	-Excellent spatial resolution -Can diagnose intracranial and high cervical arterial etiologies (fibromuscular dysplasia, carotid stenosis, variant anatomy). -Most powerful sequence for DAVF diagnosis.	-Motion-sensitive -Limited use in low-flow vascular shunts. -Does not interrogate venous system.	3.5 min (3:40)
ASL	-High sensitivity for detecting shunted blood flow. -aids in detection of DAVF -Unaffected by variable blood-brain barrier permeability -Improves detection of low flow vascular shunts.	Vulnerable to technical failure (failed labelling) and artifact from carotid stenosis, venous reflux. -Requires post-processing -Generally requires 3T MRI scanner	4.5 min (4:42)
TRICKS	-Provides dynamic blood flow with DSA. -Excellent visualization of course and contour of cervical arteries. -Allows full visualization of the venous outflow pathways bilaterally.	-Requires intravenous contrast -FOV must be adjusted by patient habitus to include torcular herophili and skull base veins. -Limited sensitivity for low-flux shunting lesions.	1 min (1:11)
SPGR (w and w/o contrast)	-Sensitivity for neoplastic causes of PT. -Provides intravascular signal while attenuating CSF Most sensitive MR Venogram sequence.	-Does not provide flow characteristics of vascular pathologies. Chronic thrombus can be difficult to identify.	Pre (3:45) Post (4:11)
DWI	-Versatile sequence for detecting a range of cerebral pathologies including choleastatoma.[82]	-Lower resolution image -Motion-sensitive,[83] (effect limited by high speed of acquisition).	2 min (2:20)
3D FLAIR	-Versatile sequence performed to screen for other parenchymal pathology (e.g. multiple sclerosis, or lesion in Heschel's gyrus).	-Generally not useful for vascular pathology, but can identify edema or hemorrhage secondary to a vascular etiology.	5.5 min (5:45)

Table 2 provides the uses and limitations of each MR sequence in imaging for pulsatile tinnitus, including the typical acquisition time for each sequence. ASL: arterial spin labeling; TRICKS: time-resolved imaging of contrast-kinetics, TOF: time-of-flight;, MRA: MR angiography; FLAIR: fluid attenuated inversion recovery; DWI: diffusion-weighted imaging; SPGR: spoiled gradient recalled acquisition in the steady state; w: with; w/o: without, PT: pulsatile tinnitus; DAVF: dural arteriovenous fistula; DSA: digital subtraction angiography; FOV: field-of-view