Correlation between Histopathology and Signal Loss on Spin-Echo T2-Weighted MR Images of the Inner Ear: Distinguishing Artifacts from Anatomy

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ABSTRACT

BACKGROUND AND PURPOSE: MR imaging of the inner ear on heavily T2-weighted sequences frequently has areas of signal loss in the vestibule. The aim of the present study was to correlate the anatomic structures of the vestibule with areas of low signal intensity.

MATERIALS AND METHODS: We reviewed T2-weighted spin-echo MR imaging studies of the internal auditory canal from 27 cases and cataloged signal intensity variations in the vestibulum of inner ears. Using a histologic preparation of a fully mounted human ear, we prepared 3D reconstructions showing the regions of sensory epithelia (semicircular canal cristae, utricular, and saccular maculae). Regions of low signal intensity were reconstructed in 3D, categorized by appearance, and compared with the 3D histologic preparation.

RESULTS: The region corresponding to the lateral semicircular canal crista showed signal loss in most studies (94%). In the utricle, a focus of signal loss occurred in the anterior-cranial portion of the utricle and corresponded to the location of the utricular macula and associated nerve on histopathologic specimens (63% of studies). Additional areas of low signal were observed in the vestibule, corresponding to the fluid-filled endolymphatic space and not to a solid anatomic structure.

CONCLUSIONS: Small foci of signal loss within the inner ear vestibule on T2-weighted spin-echo images correlate with anatomic structures, including the lateral semicircular canal crista and the utricular macula. More posterior intensity variations in the endolymphatic space are likely artifacts, potentially representing fluid flow within the endolymph caused by magneto-hydrodynamic Lorentz forces.

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Our aim in this retrospective study was to classify these foci of low signal intensity within the vestibulum according to their topography and to determine whether they correspond to anatomic structures.

MATERIALS AND METHODS
Research Design and Patients/Subjects
In this retrospective study, we reviewed T2-weighted SPACE sequence MR images from patients who were examined at the Department of Otolaryngology, Karl Landsteiner University Hospital Krems, Krems an der Donau, Austria, between January 1, 2019, and June 30, 2020. The study had been authorized by the Bioethics Committee of Lower Austria (GS4-EK-4/676–2020). All patients were older than 18 years of age, and in all cases, the radiologic evaluation showed normal high signal intensity representing the fluid-filled spaces of the inner ear, including the cochlea, vestibule, and semicircular canals.

MR Imaging Data Acquisition and Processing
The SPACE technique consists of a 3D-fast (turbo) spin-echo acquisition using very long echo-train lengths (typically 100–250 echoes), ultrashort echo spacing (typically 3–4 ms), nonselective refocusing pulses, and reduced flip angles. The examinations used a Magnetom Verio 3T MR imaging system (Siemens) with the following sequence parameters: TR, 1000 ms; TE, 135 ms; section thickness, 0.5 mm; bandwidth, 289 Hz/pixel; flip angle, 120°; echo spacing, 6.84 ms.

The MR imaging SPACE sequences were evaluated independently by 2 investigators for foci of low signal intensity in the vestibule without any processing using the DICOM viewer MagicView DANUBE (Siemens). Images were exported as JPEGs, and a scalar volume was created using Slicer (Version 4.10.2; http://www.slicer.org). The areas of low signal intensity in the vestibule were manually defined and registered in Slicer. The MR images were then threedimensionally reconstructed (as illustrated in Fig 1A).

Processing of the Histology Sections
One normal ear (left side) from the temporal bone collection of the Otopathology Laboratory at the Massachusetts Eye and Ear Infirmary was examined (National Institute on Deafness and Other Communication Disorders National Temporal Bone Registry; institutional review board ethical commission permission number: 92–04-017X). The

FIG 1. Demonstration of a morphologic fitting procedure, which was applied to search for correlations between MR images and anatomy observed in histologic sections. A, Inner ear fluid-filled spaces (right ear) as seen in the SPACE images were reconstructed in 3D (the 3D reconstruction has been mirrored to fit the anatomy of the left ear). Red: Note 2 landmarks in the MR images: an indentation in the region of the lateral canal crista (green arrow) and a diamond-shaped area of low signal (blue arrow). B, 3D reconstruction of the histologic sections (left ear) showing the lateral canal crista (LC), utricular macula (UM), and saccular macula (S). C, The two 3D reconstructions (MR imaging and histology) are fitted together according to their outer (perilymphatic) fluid boundary. D, Results of the fitting (green: histologic endolymphatic space of the utricle and semicircular canals). E, The composite fitted MR imaging and histologic 3D compartments are resectioned in the plane of the MR imaging sections to create a virtual MR image based on histology in which the regions with low signal intensity are embedded. In this image, the indentation in the region of the lateral canal crista on MR imaging (red) is colocalized with the same structure from histology (blue) and the diamond-shaped area shown in red projected more cranially to the utricular macula (blue).
donor was a 71-year-old man, and the specimen was acquired 14 hours postmortem. The ear was horizontally sectioned (ie, in the axial plane) with a section thickness of 20 μm and mounted. The histologic slides were scanned using an Aperio AT2 scanner and viewed using Aperio ImageScope (Leica Biosystems). The ROIs were captured using a resolution of 3264 × 1836 and stored in JPEG format. Anatomic details such as the lateral canal crista, utricular macula, and saccular macula were manually defined and registered in Slicer. The 440 images were manually aligned using Fiji ImageJ (National Institutes of Health, Bethesda) and three-dimensionally reconstructed using Slicer (as illustrated in Fig 1B). By means of Blender 2.82 (https://www.blender.org/download/releases/2-82/), a composite 3D model of the temporal bone histology including membranous spaces was built and virtually re-sectioned in the plane of the MR image sections. This process was necessary because the histologic sections are much thinner than the MR image slices, and the radiologic plane differed from the plane of the histologic sections.

Preliminary Fitting of the MR Images to the Histology

After the 3D reconstruction of the histologic sections was completed, the 3D MR imaging and 3D histology were scaled and fit. Using Blender, the location of the areas of low signal intensity on MR imaging were compared with the anatomic details from the reconstructed histology of the inner ear (Fig 1). After patterns of low signal intensity were identified, to focus on normal anatomy, we excluded patients with a diagnosis of a peripheral vestibular disorder from the final analysis.

Statistical Methods

The frequency of observation of areas of low signal intensity was compared between the left and right inner ears using a Fisher exact test. Statistical analyses were performed using GraphPad Prism, Version 5.03 (GraphPad Software). A P value < .05 was considered statistically significant.

RESULTS

Originally 43 cases were identified that met the inclusion criteria. After a preliminary examination of the MR images for regions of low signal intensity, 5 patterns of low signal intensity in the vestibule were identified (Fig 2): 1) a focus near the anterior takeoff of the lateral semicircular canal; 2) the anterior-cranial part of the vestibule we called the utricular root; 3) a rhomboid or diamond-shaped filamentous area of decreased signal within the middle portion of the vestibule; 4) a focus near the saccule (saccular region); and 5) a focus in the posterior vestibule. The MR imaging SPACE sequences were evaluated independently by 2 investigators and the interrater agreement for identifying the regions of low signal intensity for the 2 examiners was 97.9% (Cohen k = 0.907).

After the classification of these ROIs, 5 cases with the clinical diagnosis of vestibular neuritis, 3 cases with Ménière disease, and 8 cases with benign paroxysmal positional vertigo were excluded from the analysis because we intended to focus on normal peripheral vestibular anatomy. Ultimately, scans from 27 patients (13 women, 14 men) were processed (average age, 63 years; range, 35–89 years). Clinical diagnoses were hypertensive crisis (n = 3), idiopathic sudden hearing loss (n = 12), tinnitus (n = 2), central downbeat nystagmus (n = 1), minor cerebral hemorrhage
In this study, by comparing conventional spin-echo T2-weighted images with a detailed 3D histologic reconstruction of inner ear anatomy, we found 2 inner ear anatomic structures that can be identified frequently by reduced signal intensity and 2 areas of low signal that do not correspond to a solid anatomic structure. An indentation is found consistently on both right and left inner ears at the anterior attachment of the lateral semicircular canal to the vestibule, corresponding to the anatomic position of the lateral semicircular canal crista. More medially and somewhat caudal from the crista, foci of low signal intensity were observed in more than half of the cases on both sides approximately at the anatomic position of the root of the utricular macula. The bulk of the utricular root spreads over 400 μm along the z-axis (ie, 20 histologic slices), and the section thickness of the MR images was 500 μm, which means that this tiny tissue mass protruding into the fluid-filled vestibule may have been missed due to partial volume averaging, with the high signal intensity of the surrounding fluid perhaps accounting for its being found only in 63% of the ears.

The frequency by which the root of the utricular macula could be seen was exactly the same on the left and right sides, supporting the hypothesis that the signal loss corresponds to an anatomic structure.

The additional 2 areas of low signal intensity within the vestibule did not correlate with solid anatomic structures but rather corresponded to regions of the endolymph-filled space of the vestibule on histology. The inner ear houses a thin membranous labyrinth that contains potassium-enriched fluid called endolymph and is surrounded by sodium-enriched perilymph. The sensory epithelia of the inner ear are located within the endolymph-filled space of the membranous labyrinth. The composition of these fluids is like water, indicating that endolymph and perilymph ought to have similar proton density and therefore a similar signal intensity on T2-weighted spin-echo images. The loss of signal within this space is likely an artifact.

An advantage of T2-weighted spin-echo sequences like SPACE over T2*-weighted gradient-echo sequences is fewer magnetic susceptibility artifacts. T2-weighted TSE sequences like SPACE, however, are especially susceptible to movement artifacts. The imaging characteristics of CSF cause it to manifest as space. However, CSF is relatively fluid, and the section thickness of the MR images was 500 μm, which means that its being found only in 63% of the ears.
FIG 3. Cartoon presentation of the hypothetical mechanism of asymmetric turbulent fluid movements in the left and right ears caused by Lorentz forces. The Lorentz force (red arrow) is evoked, the direction determined by the right-hand rule, by the combination of the magnetic field (yellow arrow) and the utricular current (green arrow) as described in Roberts et al.\textsuperscript{16} The anterior part of the utricle and lateral semicircular canal viewed from posterior on the left (A) and right (B) side. 3D reconstruction of the endolymphatic space from the histologic specimen. UM indicates utricular macula; LSSC, lateral semicircular canal crista in the ampulla. C and D. Original axial histologic section of the left inner ear across the utricular macula. Image C was mirrored horizontally to create the impression of the right inner ear. UM indicates utricular macula; SM, saccular macula; red arrows, magneto-hydrodynamic Lorentz force; blue arrows, hypothetical turbulent endolymph movements.

A limitation of the study is that only 1 normal cadaveric temporal bone was fully processed and reconstructed to compare with MR images of the study population. Observations from the cadaver may not correlate perfectly with findings in the imaged patients. The spatial resolution of a 3D reconstructed, fully processed cadaveric specimen exceeds that of standard histologic preparations, and due to the time-intensive process of digitizing and manually aligning the specimen, few fully processed specimens have been reported in the literature.\textsuperscript{19,20} Nevertheless, on the basis of the appearance of normal labyrinthine fluid spaces from other lower-resolution specimens, we are confident that the specimen used in this study represents a typical distribution of the different scalar volumes in a normal specimen.

In this study, we excluded cases in which pathology may have affected the peripheral vestibular system. The aim was to describe the findings in the normal inner ear; however, the included participants all had a clinical indication for the imaging study that may have affected the frequency of the observed findings. Nevertheless, the findings may have implications for patients who could demonstrate different patterns of low signal intensity, as in the single case in which low signal was seen near the saccule in an individual with ipsilateral benign paroxysmal positional vertigo but in none of the cases without a peripheral vestibular disorder. In cases with utricular endolymphatic hydrops, flow void artifacts may appear differently compared with normal ears. Changes in inner ear signal intensity, for instance in cases with dysfunction of the utricular macula (vestibular neuritis) or intralabyrinthine schwannoma, could benefit from more precise localization of affected inner ear structures. More precise localization of signal abnormalities can aid clinicians treating patients with inner ear abnormalities.

CONCLUSIONS

In this study, we identified foci of low signal intensity in the vestibule in T2-weighted spin-echo MR images. While some areas of low signal corresponded on histology to structures like the lateral semicircular canal crista and the utricular macula, others corresponded to the fluid-filled endolymphatic space of the utricle. We hypothesize that these latter areas are artifacts caused by fluid movements in the endolymphatic space and could result from magneto-hydrodynamic Lorentz forces.

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