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Ultra-High-Field Magnetic Resonance Imaging of the Human Inner Ear at 11.7 Tesla

David S. Thylur, BA^{*}, Russell E. Jacobs, PhD[†], John L. Go, MD[‡], Arthur W. Toga, PhD[§], and John K. Niparko, MD^{*}

^{*}USC Tina and Rick Caruso Department of Otolaryngology-Head & Neck Surgery, Keck School of Medicine, University of Southern California, Los Angeles, CA

[†]Biological Imaging Center, Beckman Institute, California Institute of Technology, Pasadena, CA

[‡]Department of Radiology, Keck School of Medicine of the University of Southern California, Los Angeles, CA

[§]Laboratory of Neuro Imaging, Stevens Neuroimaging and Informatics Institute, Keck School of Medicine, University of Southern California, Los Angeles, CA

Abstract

Objective—To evaluate the ability of ultra-high-field magnetic resonance imaging (UHF-MRI) at 11.7 Tesla to visualize membranous structures of the human inner ear.

Specimens—Three temporal bones were extracted from cadaveric human heads for use with small-bore UHF-MRI.

Intervention—*Ex vivo* cadaveric temporal bone specimens were imaged using an 11.7 T MRI scanner via T1- and T2-weighted-imaging with and without contrast.

Main Outcome Measure—Qualitative visualization of membranous components of the inner ear compared with reports of UHF-MRI at lower field strengths.

Results—The membranous anatomy of the inner ear was superbly visualized at 11.7 T. In the cochlea, Reissner's membrane, the scala media, and the basilar membrane were clearly shown on the scan. In the vestibular labyrinth, the wedge-shaped crista ampullaris and the maculae of both the saccule and utricle were visible. Details of the endolymphatic sac and duct were also demonstrated.

Corresponding Author: John K. Niparko, USC Tina and Rick Caruso Department of Otolaryngology-Head & Neck Surgery, Keck School of Medicine, University of Southern California. 1540 Alcazar Street, Suite 204M, Los Angeles, CA 90033. Tel: (323) 442-5790 Fax: (323) 422-5820 niparko@med.usc.edu.

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Supplemental Digital Content

Supplemental Digital Content 1, Materials and Methods

Supplemental Digital Content 2, Video. Animation of three-dimensional rendering of the human inner ear.

Supplemental Digital Content 3, Figure. Membranous anatomy of the human inner ear shown using T2-weighted imaging with contrast. (A) Reissner's membrane. (B) Crista ampullaris. (C) Macula of the saccule. (D) Macula of the utricle.

Supplemental Digital Content 4, Discussion.

Conclusion—To our knowledge, this report presents the first images of the *ex vivo* human inner ear using 11.7 T UHF-MRI, offering near-histologic resolution. Increased field strength may be particularly useful when imaging the delicate membranous anatomy of the inner ear. Further research on the use of UHF-MRI in clinical and research settings could illuminate structural changes associated with inner ear disorders.

Keywords

MRI; cochlea; inner ear; vestibular labyrinth; ultra-high-field MRI; 11.7 Tesla

Introduction

Despite tremendous advances in magnetic resonance imaging protocols in recent years, the ability to image finer details of membranous anatomy of the inner ear still lies in the domain of ultra-high-field MRI (UHF-MRI) scanners, defined here by a field strength equal to or greater than 7 T. Detailed clinical imaging of membranous components of the inner ear remains elusive due to the inability of commonly-available 3 T scanners to image the inner ear at adequate resolutions.¹ Several centers have attempted to visualize clinical inner ear anatomy with field strengths of 7 T, to varying degrees of success. Structures such as the osseous spiral lamina and the labyrinthine artery can be visualized at 7 T, but the scala media and its boundary structures are indistinct or blurry at this field strength.^{2–7}

Ultra-high-field scanners have obvious disadvantages that hinder their use, notably expense, legal barriers to clinical approval, and inadequate information about clinical safety.⁸ Despite these restrictions, ultra-high-field imaging may hold the key to help master the diagnostic dilemma found in the continuum of Ménière's disease and other inner ear disorders.¹ We endeavored to image *ex vivo* cadaveric temporal bones using a higher field strength than ever previously reported, at 11.7 T, in order to identify anatomy visible using 11.7 T UHF-MRI with its subsequent improvement to signal-to-noise ratio (SNR) over lower field strengths.

Materials and Methods

Fresh, frozen adult cadaveric heads were obtained (Science Care, Inc., Phoenix, AZ) in cooperation with the University of Southern California Anatomical Gift Program. An 11.7 T 89 mm vertical bore Bruker BioSpin Avance DRX500 scanner (Bruker BioSpin Inc., Billerica, MA) was used to image three extracted temporal bone specimens to obtain T1- and T2-weighted-imaging with and without contrast yielding 50 μ m isotropic voxels (see Supplemental Digital Content 1, Materials and Methods).^{9,10} Temporal bone histologic slides (kindly provided by Dr. Harris) were imaged using an AxioImager Z1 microscope (Carl Zeiss, Gottingen, Germany) for comparative anatomy.

Results

A three-dimensional model was rendered to demonstrate the anatomical features of the inner ear after visualization at 11.7 T with a smaller cubic voxel size (50 μ m isotropic) than ever reported in the literature for the inner ear to our knowledge (Figure 1). An animated version

of this rendering is available online (see Video, Supplemental Digital Content 2). T1-weighted imaging with contrast is shown in the following figures, while T2-weighted imaging with contrast is available online (see Supplemental Digital Content 3, Figure). Imaging without contrast did not effectively demonstrate membranous anatomy (data not shown).

Cochlea

The membranous compartments of the cochlea are clearly visualized at 11.7 T (Figure 1). Reissner's membrane can be seen emerging from the osseous spiral lamina. Reissner's membrane is not visible in all slices of the cochlea, which may represent tissue degradation during the preservation and storage process. A demarcation between the osseous spiral lamina and the basilar membrane is evident, but no details of structures on the basilar membrane, including the organ of Corti, are apparent at this resolution.

Nerve Supply

The aperture of the vestibulocochlear nerve and its subsequent divisions are robustly apparent (Figure 2). The superior branch of the vestibular nerve can be seen innervating the ampullae of the superior and lateral semicircular canals as well as the utricle, while the inferior and posterior branches of the vestibular nerve can be seen innervating the saccule and the ampulla of the posterior semicircular canal, respectively. The facial nerve is prominently visible adjacent to the cochlea.

Vestibular Labyrinth

The three semicircular canals are visible in intricate detail (Figure 1). Contrary to early depictions of the semicircular canals, each canal does not represent a perfectly flat torus but instead is warped, traversing in all three dimensions. The wedge-shaped crista ampullaris can be visualized in the ampullae of all three semicircular canals (Figure 3). In addition, both the saccular macula and utricular macula are visible on the scan.

Ducts and Sac

Detailed images of the ductus reuniens, endolymphatic duct, and endolymphatic sac were acquired (Figure 4). The ductus reuniens connects the cochlear duct to the saccule. Consistent with anatomic descriptions by Lo et al., the endolymphatic duct is composed of a proximal sinus and distal isthmus portion.¹¹ The duct then drains into the endolymphatic sac, an interlinking network of cisterns and tubules. Discerning the convergences of the utricular and saccular ducts into the endolymphatic duct remains difficult at this resolution.

Discussion

Membranous anatomy of the inner ear is inadequately distinguished at field strengths that are commonly available for use in clinical research – less than 8 T in the US at the time of this report.^{7,8} As our results using *ex vivo* cadaveric temporal bones demonstrate, contrast-enhanced UHF-MRI at 11.7 T can visualize the membranous anatomy of the human inner ear in exquisite detail, providing effective visualization of all three compartments of the cochlea – including the scala media and its boundary structures, Reissner's membrane and

the basilar membrane. In the vestibular labyrinth, the size and morphology of the crista ampullaris, the utricular macula, and saccular macula were consistently and superbly visualized. Elaborate detail of the endolymphatic duct and sac was also demonstrated.

Intricate membranous anatomy of the human inner ear was first successfully visualized at 9.4 T by Silver et al. in 2002 using *ex vivo* cadaveric temporal bones, wherein the authors reported an ability to visualize Reissner's membrane and other membranous components of the inner ear using a voxel size of $49\text{ }\mu\text{m}\times 43\text{ }\mu\text{m}\times 230\text{ }\mu\text{m}$.¹² However, the authors were only able to visualize Reissner's membrane adequately by sacrificing voxel depth, which may not provide clinically useful imaging. The membranous anatomy of the *ex vivo* human inner ear was further visualized at 9.4 T by Lane et al. in 2005, demonstrating visualization of both Reissner's membrane and to a lesser extent the crista ampullaris with a cubic voxel size of $78\text{ }\mu\text{m}$.¹³ Our report, which presents the first images of the human inner ear at 11.7 T with a cubic voxel size of $50\text{ }\mu\text{m}$, shows anatomical features that are consistent with those visible at 9.4 T. Compared with results reported using 9.4 T however, the higher field strength of 11.7 T shows clearer visualization of inner ear structures in three dimensions, in particular Reissner's membrane, the crista ampullaris, the ductus reuniens, and the maculae of both the utricle and saccule. In addition, to our knowledge, these are the first images demonstrating the saccular macula and the ductus reuniens on MRI. Moreover, the wedge-shaped morphology of the crista ampullaris only becomes apparent at 11.7 T. This improved image quality likely resulted from the improved SNR and smaller cubic voxel size of $50\text{ }\mu\text{m}$ achieved from the greater field strength. However, more intricate anatomical details, such as the organ of Corti, remain unable to be visualized even at 11.7 T. It is uncertain whether these microscopic structures, which are currently only visible using histology, will be able to be visualized with even higher field strengths.

The current frontier of *in vivo* inner ear magnetic resonance imaging, using a field strength of 7 T, has achieved the visualization of structures that were of low resolution or difficult to attain at lower magnetic fields, including the labyrinthine artery and the nerve bundle contained within the inner auditory canal.^{2,4,6,7} However, finer membranous structures such as the scala media and Reissner's membrane remain largely indistinct at this field strength.^{3,4} Although the higher field strength of 7 T carries an obvious advantage over lower fields due to the substantial improvement in SNR, higher field strengths do have limitations when imaging the inner ear. At higher field strengths, the stark contrast between bony and air-filled components of the inner ear with fluid-filled compartments contribute to increased inhomogeneities in both the main magnetic field (B0) and the radiofrequency field (B1), leading to artifact production on scans.^{4,5,7} Despite these drawbacks, optimization of MRI protocols and the use of specialized surface coils should help exploit the acquired images to improve SNR for inner ear imaging offered by UHF-MRI.⁵ It also remains to be seen whether UHF-MRI can detect pathological changes as well as it does normal anatomy – both studies that imaged *ex vivo* temporal bones at 9.4 T as well as our study at 11.7 T have used non-diseased specimens. Though UHF-MRI can produce transient vestibular dysfunction in humans, it is believed to be safe overall with technical, financial, and legislative limitations remaining the primary obstacles impeding more widespread use (see Supplemental Digital Content 4, Discussion).^{8,14–19}

UHF-MRI has the potential to provide insight into a myriad of inner ear diseases. As our report suggests, the usage of higher MRI field strengths can elucidate clinically elusive anatomy and may facilitate research across numerous inner ear disorders. However, legislative obstacles and technical challenges may continue to hinder advancement in this area. Imaging of pathological temporal bone specimens using UHF-MRI could clarify its possible contributions to the clinical management of patients with inner ear diseases as well as bridge the gap between *in vitro* and *in vivo* research in order to promote legislative support for clinical use.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Three-dimensional rendering of the human inner ear and membranous anatomy of the cochlea. (A) The cochlea in this specimen turns about the modiolus 2.5 times. The beginning of the facial nerve (asterisk) as well as the endolymphatic duct (arrow) and endolymphatic sac (pointer) are evident. The rest of the facial nerve was excluded from the rendering for visibility. As demonstrated by the rendering, each semicircular canal is not a flat torus but instead is warped into three dimensions (dotted line). (B) Reissner's membrane (arrow), the basilar membrane (pointer), and the scala media (asterisk) are shown. (C) An inverted image shows Reissner's membrane (arrow), the scala media, and the spiral ligament (dotted line) at the mid-modiolus. (D) Light microscopy of a separate temporal bone specimen demonstrates additional features of the basilar membrane not visible on MRI, such as the organ of Corti. SV: scala vestibule. ST: scala tympani. OC: organ of Corti.

Figure 2.

Nerve supply of the inner ear. A three-dimensional rendering (A) and corresponding scan segments demonstrate (B) the inlet of the cochlear nerve into the modiolus as well as (C) the division of the vestibulocochlear into the cochlea nerve, the vestibular nerve, and the facial nerve. CN8: vestibulocochlear nerve; FN: facial nerve; CN: cochlear nerve; VN: vestibular nerve.

Figure 3. Membranous anatomy of the vestibular labyrinth. Scan segments and corresponding light microscopy images from separate temporal bone specimens demonstrate (A) the crista ampullaris in the ampulla of the posterior semicircular canal, (B) the saccular macula (arrow), and (C) the utricular macula (pointer). CA: crista ampullaris. PSC: posterior semicircular canal; S: saccul; U: utricle.

Figure 4.

The ductus reuniens, endolymphatic duct, and endolymphatic sac. (A) The ductus reuniens (or reuniting duct) can be seen joining the cochlear duct to the saccule. (B) The endolymphatic duct is composed of its sinus (dotted line) and isthmus (pointer). (C) The endolymphatic sac (bounded by dotted line) is composed of a complex network of tubules and cisterns. S: saccule. C: cochlear duct. U: utricle.