The Journal of Laryngology & Otology

cambridge.org/jlo

Anatomical and imaging-based measurement of human semicircular canals: from manual morphometry to artificial intelligence-driven analysis

Jie Zhang[1,2] and Zhong Bai[1]

[1]Otolaryngology, The Second Affiliated Hospital of Kunming Medical University, Kunming, China and [2]Department of Otorhinolaryngology Head and Neck Surgery, The Affiliated Hospital of Guizhou Medical University, Guiyang, Guizhou, China

Review Article

Zhong Bai takes responsibility for the integrity of the content of the paper

Cite this article: Zhang J, Bai Z. Anatomical and imaging-based measurement of human semicircular canals: from manual morphometry to artificial intelligence-driven analysis. *J Laryngol Otol* 2026;1–9. https://doi.org/10.1017/S0022215126105593

Received: 9 March 2026 UTC
Revised: 19 June 2026 UTC
Accepted: 6 July 2026 UTC

Keywords:
semicircular canals; vestibular diseases; diagnostic imaging; artificial intelligence; deep learning

Corresponding author: Zhong Bai;
Email: bzong123@126.com

Abstract

Background. Semicircular canal morphology is fundamental to vestibular function and is implicated in disorders like benign paroxysmal positional vertigo and Ménière's disease. Manual morphometric analysis currently lacks standardisation and is labour-intensive. This review synthesises the evolution of semicircular canal morphometry, transitioning from foundational cadaveric studies to modern artificial intelligence-driven analysis.

Methods. The capabilities of high-resolution computed tomography (CT) and magnetic resonance imaging (MRI) in depicting the bony and membranous labyrinth were evaluated. The review details the shift from manual measurement to deep learning-based segmentation architectures, such as U-Net, which significantly reduce observer variability. We address the critical role of intramodality comparison registration (e.g. longitudinal CT-to-CT and MRI-to-MRI alignment) in tracking structural changes over time. Clinical evidence links specific semicircular canal geometric variations to vestibular pathologies and surgical outcomes.

Conclusion. Semicircular canal morphometry is evolving into a quantitative diagnostic tool. Future progress necessitates multi-centre data standardisation and integration of structural and functional data for precision otology.

Introduction

The semicircular canals, acting as the primary sensors of angular acceleration within the human vestibular system, form the crucial anatomical framework for the vestibulo-ocular and vestibulo-spinal reflexes.[1–3] Precise characterisation of semicircular canal geometry is vital for understanding vestibular biomechanics and elucidating the structural underpinnings of pathologies like benign paroxysmal positional vertigo (BPPV), superior canal dehiscence syndrome, Ménière's disease and congenital inner-ear malformations.[4–7] Over the past decades, the foundational understanding of semicircular canal morphology has progressed rapidly from early *ex vivo* cadaveric and micro-computed tomography (CT) evaluations[8] to high-resolution *in vivo* modalities, including high-resolution temporal bone CT, cone-beam CT and three-dimensional (3D) T2-weighted magnetic resonance imaging (MRI) sequences.[9–14]

These imaging advancements have catalysed a major paradigm shift from manual tracing toward standardised 3D co-ordinate frameworks[4–11,15–20] and, more recently, fully automated deep-learning segmentation pipelines.[21–30] Nonetheless, broad clinical translation remains constrained by heterogeneous imaging protocols, unstandardised geometric indices, a lack of large-scale multi-centre validation and a persistent separation between structural image data and functional neurotological outcomes.[4–12,16–20,30–52]

To bridge these critical gaps, this review provides a comprehensive and critical synthesis that contextualises the entire technological trajectory of human semicircular canal measurement. We systematically evaluated the transition from classical manual morphometry to state-of-the-art artificial intelligence (AI)-driven workflows, critically compared mainstream clinical imaging techniques and analysed the clinical evidence linking structural variations to vestibular disorders. Ultimately, this work aimed to outline a standardised, forward-looking roadmap for integrating automated morphometric analysis into routine clinical workflows.

Anatomy and physiology of semicircular canals

The inner ear consists of a bony labyrinth excavated within the petrous temporal bone, enclosing a corresponding membranous labyrinth. Each of the three orthogonal canals—anterior,

© The Author(s), 2026. Published by Cambridge University Press on behalf of J.L.O. (1984) LIMITED.

posterior and lateral—contains a membranous duct filled with endolymph, with sensory receptors (cristae ampullares) housed within their ampullated ends.[1–3] The non-ampullary limbs of the vertical canals join to form the common crus, while the lateral canal opens independently into the vestibule.[3] Adopting the pioneering framework by Della Santina,[4] standardised 3D multi-planar reconstructions have established that while inter-canal angles remain relatively orthogonal to optimise angular motion encoding, significant population-level variations exist in canal orientation, size and curvature across age groups, sexes and individuals.[4–6] Furthermore, comparative morphometric analyses indicate that these geometric parameters are closely constrained by primate phylogeny, craniofacial architecture and ontogenetic development.[7,8]

Physiologically, head rotation induces inertial endolymph flow that deflects the cupula and modulates vestibular afferent firing.[1–3] This intrinsic 'anatomy–hydrodynamics–symptom' pathway dictates that subtle spatial or positional shifts in the semicircular canals can disrupt normal fluid mechanics to drive distinct clinical syndromes.[4–9] Pathological alterations to this system—such as the intra-luminal displacement of otoconia in BPPV or the focal osseous defect creating a 'third mobile window' in superior canal dehiscence syndrome—fundamentally violate normal vestibular physiology. Subtle variations in canal orientation and dimensions can therefore act as anatomical determinants of disease susceptibility and dictate subsequent surgical boundaries,[9] highlighting the profound clinical requirement for precise geometric tracking.

Imaging techniques for the semicircular canals

Cross-sectional imaging enables *in vivo* visualisation of the labyrinth. The primary characteristics of current modalities are summarised in Table 1.[32–34,53–56]

Computed tomography (high-resolution computed tomography, multi-detector computed tomography and cone-beam computed tomography)

High-resolution CT and cone-beam CT constitute the reference standard for osseous labyrinth evaluation, utilising submillimetre multi-planar reformations to accurately depict canal morphology, bony dehiscence and congenital malformations.[12–20] While high-resolution CT remains indispensable for intricate surgical planning in superior canal dehiscence syndrome and cochlear implantation, cone-beam CT offers an excellent lower-radiation alternative with high isotropic resolution for pre-operative assessment. These reproducible radiological datasets serve as the primary structural inputs for downstream 3D morphometric frameworks and deep-learning segmentation pipelines.[21–30]

Magnetic resonance imaging and inner-ear magnetic resonance hydrography

Three-dimensional high-resolution T2-weighted MRI (e.g. constructive interference in steady state (CISS), driven equilibrium (DRIVE) and advanced contrast-enhanced magnetic resonance hydrography provide an exceptional membranous-level aperspective of the inner ear, capturing the soft-tissue labyrinth, vestibulocochlear nerve and endolymphatic hydrops in Ménière's disease.[13,15] This soft-tissue characterisation fundamentally complements CT-based osseous assessments.[16,20] Together, these complementary radiological modalities establish a synergistic, multi-modal imaging foundation that powers downstream 3D quantitative morphometry and automated AI analysis pipelines.

Intramodality comparison registration for longitudinal follow up

In longitudinal clinical follow up, patients must undergo repeated imaging over months or years. This is essential for monitoring the progressive erosion of the osseous labyrinth, tracking the potential expansion of bony clefts in superior canal dehiscence syndrome or evaluating post-operative bone healing and structural stability following semicircular canal-plugging surgical procedures.[57] However, variations in patient head positioning, scan angles and slice coverage across different imaging sessions introduce spatial discrepancies that make direct parameter comparison unreliable. To resolve these positioning shifts and ensure accurate longitudinal evaluation, intramodality comparison registration (e.g. CT-to-CT or MRI-to-MRI alignment) must be utilised.[58]

Intramodality registration operates under the rigid-body assumption, applying translation and rotation parameters to align follow-up scans to the baseline co-ordinate space, as the dense otic capsule is immune to soft-tissue deformation.[58] The alignment process is optimised using intensity-based similarity metrics, such as mutual information or normalised mutual information. To preserve the fidelity of fine inner-ear structures and avoid blurring from standard linear interpolation, sinc-based interpolation is preferred for image resampling, achieving sub-voxel registration accuracy.[59] CT-to-CT registration can facilitate longitudinal comparison of osseous structures across serial examinations, provided that differences in acquisition and reconstruction parameters are appropriately considered.[58] For MRI-to-MRI registration, aligning sequential 3D T2-weighted images enables precise subtraction maps that reveal microstructural deviations in the fluid-filled membranous ducts,[60] ensuring highly reproducible longitudinal morphometric assessments.

Methods for measuring semicircular canal size and spatial configuration

Canal height, width, radius of curvature and inter-canal angles

Quantitative assessment of semicircular canal geometry has evolved from direct measurements on anatomical specimens to sophisticated 3D analyses on *in vivo* CT and MRI, and more recently to fully automated pipelines based on deep learning. Current approaches differ in spatial resolution, structure of interest (bony *vs* membranous labyrinth) and suitability for large clinical cohorts. Representative morphometric studies are summarised in Table 2.

Anatomical specimens and micro-computed tomography

Historically, the quantitative assessment of semicircular canal geometry relied on cadaveric specimens and micro-CT imaging to establish foundational morphometric baselines, such as canal arc length, spatial orientation and the characteristically smaller radius of curvature observed in the lateral canal.[4,6–8]

Beyond supplying initial geometric data, these *ex vivo* studies formed the anatomical bedrock for early biomechanical models of endolymph dynamics and served as a vital 'gold standard' for validating subsequent *in vivo* measurements. However, specimen-based morphometry is inherently constrained by restricted sample

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

Table 1. Comparison of imaging modalities for semicircular canal assessment

Modality	Typical spatial resolution and/or slice thickness	Main target structures	Strengths	Limitations	Representative references
High-resolution temporal bone CT	~0.4–0.6 mm isotropic (bone algorithm)	Bony labyrinth, canal walls, middle ear, internal auditory canal (IAC)	Excellent depiction of thin bony structures; widely available; fast; essential for detecting canal dehiscence, fractures and congenital bony anomalies	Ionising radiation; limited soft-tissue contrast; less suitable for detailed membranous labyrinth or nerve assessment	12,14,16,18
Multi-detector CT	Submillimetre, multi-planar reconstructions	Bony labyrinth, temporal bone anatomy	High-quality volumetric data; flexible multi-planar reconstruction; robust pre-operative planning for temporal bone and canal-related surgery	Similar radiation concerns as high-resolution CT; soft-tissue contrast still inferior to MRI	12,16,18
Cone-beam CT	High isotropic resolution, small field of view (FOV)	Temporal bone, cochlea, semicircular canals	Lower radiation dose compared with conventional CT; high spatial resolution for osseous labyrinth; useful for cochlear implant and canal surgery planning	Limited availability; longer acquisition in some systems; motion artifacts in unco-operative patients; soft tissue poorly visualised	12,16,18
Three-dimensional high-resolution T2-weighted MRI (e.g. constructive interference in steady state (CISS), driven equilibrium (DRIVE))	~0.5–0.8 mm isotropic	Membranous labyrinth, endolymph and/or perilymph spaces, cochlear nerve, brainstem	Superior soft-tissue contrast; direct visualisation of fluid-filled canals and vestibule; evaluation of cochlear nerve, endolymphatic hydrops and central pathways	Lower spatial resolution for bone; susceptible to motion and susceptibility artifacts; longer scan time; availability and protocols vary between centres	12,14,16,19,20
Contrast-enhanced inner-ear MRI (intravenous or intratympanic gadolinium)	~0.8–1.0 mm	Endolymphatic and perilymphatic spaces, hydrops	Enables visualisation of endolymphatic hydrops and blood–labyrinth barrier integrity; useful in Ménière's disease and related disorders	Specialised protocols; off-label use in some regions; limited standardisation; primarily used in selected centres	16,19,20

CT = computed tomography; MRI = magnetic resonance imaging.

sizes, post-mortem tissue degradation, selection biases and a fundamental inability to capture dynamic structure–function relationships in living subjects. These systematic limitations have directly driven the technological transition toward the high-throughput, *in vivo* imaging-based measurement frameworks detailed below.

Computed tomography-based *in vivo* three-dimensional measurements

In vivo semicircular canal morphometry is now mainly performed on high-resolution CT or cone-beam CT datasets to reconstruct 3D configurations and define spatial orientations. Following the foundational methodology introduced by Della Santina *et al.*, 3D multi-planar reconstructions are widely utilised to fit canal planes, compute normal vectors and quantify inter-canal and canal-cranial angles within standardised cranial co-ordinate systems.[4,5]

This framework was subsequently adapted by Wu et al., who used three-dimensional CISS MRI in 55 subjects to reconstruct the semicircular canals, fit canal planes from their centre lines and quantify spatial attitude using plane normal vectors.[5] Clinically, as highlighted by Casselman, Joshi and colleagues, these standardised measurements are indispensable for surgical risk mitigation and pre-operative planning, offering critical geometric insights into canal proximity to adjacent structures, such as the facial nerve, during neurotological interventions and cochlear implantation.[14,15,18–20]

Consequently, CT-based morphometry is highly effective for delineating osseous canal configurations at the cohort level and guiding surgical decision-making. However, a major lingering challenge is that these measurements remain highly sensitive to institutional variations in CT acquisition parameters, reconstruction kernels and downstream post-processing algorithms, emphasising the critical need for cross-centre protocol standardisation.

Magnetic resonance imaging-based in vivo measurements

Three-dimensional high-resolution T2-weighted MRI directly visualises the membranous semicircular ducts and endolymphatic spaces, capturing morphometric dimensions closely tied to endolymph hydrodynamics and duct compliance. Liu *et al.*[10] proposed the W–X co-ordinate system for vestibular MRI, using the centres of the bilateral eyeballs and the vertices of the superior semicircular canals as anatomical references to quantify semicircular canal orientation.

Magnetic resonance imaging-based morphometry is particularly relevant in disorders in which membranous morphology or fluid distribution is altered, such as endolymphatic hydrops in Ménière's disease. Furthermore, MRI avoids ionising radiation and allows simultaneous assessment of the cochlear nerve and central vestibular pathways, facilitating structure–function correlation across the entire vestibular system.[9,14,16] Limitations

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

Table 2. Summary of landmark morphometric studies on human semicircular canals

Study (year)	Imaging and/or specimen type	Population and/or sample	Structures and metrics assessed	Key methodological features	Main findings (simplified)
Della Santina *et al*. (2005)[4]	High-resolution CT (*in vivo*)	22 human subjects (44 labyrinths)	Orientation of the three semicircular canals; canal plane normals; inter-canal and canal–skull angles	3D multi-planar reconstruction; definition of canal planes in a cranial co-ordinate system	Established widely used reference values for canal orientation; demonstrated approximate orthogonality of canal planes
Wu *et al*. (2021)[5]	3D-CISS MRI (*in vivo*)	55 subjects with normal inner ears	Semicircular canal spatial orientation; canal-plane normal vectors	Centreline-based plane fitting and three-dimensional coordinate analysis	Established a reproducible MRI-based method for quantifying semicircular canal spatial orientation
Lee *et al*. (2013)[6]	Micro-CT of temporal bones	40 petrous temporal bone specimens from 23 cadavers	Canal height, width, radius of curvature and inter-canal angles	High-resolution micro-CT and 3D reconstruction; direct measurement on bony canals	The lateral canal had a smaller radius of curvature than the anterior and posterior canals, and the canal planes were not exactly orthogonal
El Khoury *et al*. (2014)[7];	CT-based 3D reconstructions	137 humans, 61 bonobos and 62 chimpanzees	Semicircular canal orientation	Comparative 3D analysis	Demonstrated interspecies differences in semicircular canal orientation
Cardenas-Serna (2022)[8]	Micro-CT / 3D reconstruction	Human developmental and adult specimens	Canal shape and size	Geometric morphometrics and cross-sectional analysis	Characterised ontogenetic changes and variation in human semicircular canal form
Huang *et al*. (2024)[9]	Ultra-high-resolution CT (*in vivo*)	Patients with Ménière's disease and controls	Spatial position of semicircular canals; positional shifts relative to skull base	Intelligent segmentation and high-resolution CT; semi-automatic measurement of canal position	Indicated subtle spatial position changes in canals as a potential anatomical basis for Ménière's disease susceptibility
Liu *et al*. (2021)[10]	3D T2-weighted MRI (*in vivo*)	53 MRI and 78 CT datasets	Semicircular canal plane orientation; vestibular coordinate system	W–X coordinate system based on the bilateral eyeballs and superior semicircular canals	Established and validated an MRI-based coordinate system for measuring semicircular canal orientation
Zhou *et al*. (2024)[11]	3D-CISS MRI with deep learning-based analysis	115 subjects with normal inner-ear structures	Semicircular canal spatial orientation and plane normal vectors	Deep learning-based segmentation, 3D skeletonisation and automated plane fitting	Demonstrated automated segmentation and quantitative measurement of semicircular canal spatial orientation

CT = computed tomography; 3D = three-dimensional; MRI = magnetic resonance imaging; CISS = constructive interference in steady state

include lower spatial resolution for osseous structures compared with CT, and greater susceptibility to motion and susceptibility artifacts.

Taken together, CT- and MRI-based measurements provide complementary views of semicircular canal geometry: CT emphasises the osseous canal walls and their relationship to adjacent temporal bone structures, whereas MRI emphasises the membranous duct and fluid spaces. Harmonisation of measurement definitions and co-ordinate systems across modalities is crucial for integrating these datasets.

Deep learning-based automatic segmentation and quantitative analysis

Traditional semicircular canal measurements require extensive manual contouring or semi-manual landmark placement, which is time-consuming and subject to inter- and intra-observer variability. In recent years, deep learning-based segmentation has transformed inner-ear morphometry by enabling automated, observer-independent delineation of the bony labyrinth and fluid spaces.

On MRI, Vaidyanathan *et al.* used a 3D U-Net architecture to segment the entire inner-ear fluid space, achieving high Dice similarity coefficients and robust cross-centre performance.[21] Ahmadi *et al.* introduced IE-Vnet, a deep-learning model specifically optimised for segmentation of the inner ear's total fluid volume on MRI, which outperformed traditional atlas-based methods and operated with substantially reduced computation time.[22]

On CT, Hussain *et al.* built an auto-context convolutional neural network that automatically segments the cochlea, vestibule and semicircular canals, providing a basis for quantitative analysis of bony labyrinth morphology.[23] Li *et al.* proposed Labyrinth-Net, which uses a multi-model inconsistency constraint to improve robustness when segmenting complex labyrinthine structures on temporal bone CT.[24] Wang, Ke and colleagues extended these approaches to fully automated segmentation of adult and paediatric temporal bone CT, demonstrating high accuracy and substantial reductions in manual workload.[25,26] Lim *et al.* trained and externally validated a general U-Net model for inner-ear segmentation across multiple centres, reporting average Dice coefficients above 0.8 and highlighting clinical scalability.[27] Li *et al.* also introduced a 3D deep-supervised densely connected network tailored for small organ segmentation in the temporal bone.[28]

A recent systematic review by Li *et al.* concluded that most state-of-the-art temporal bone segmentation methods are based on U-Net-like architectures and are evolving toward integrated frameworks that combine segmentation, landmark detection and quantitative analysis.[29] In this direction, Stebani *et al.* proposed a joint segmentation and landmark detection framework that outputs voxel-wise inner-ear segmentations and geometric landmarks, enabling fully automated computation of semicircular canal curvature, arc length and plane orientation from CT or micro-CT data.[30] A scoping review on deep learning for otologic imaging further supports the feasibility of accurately segmenting small, complex structures such as the semicircular canals.[61]

Collectively, these advances indicate that deep learning-based pipelines can transform semicircular canal morphometry from a labour-intensive research tool into a high-throughput component of clinical workflows and large-scale imaging studies. By providing standardised, reproducible measurements of canal geometry, such methods pave the way for multi-centre normative databases and sophisticated structure–function analyses. The overall workflow is illustrated in Figure 1.

Clinical limitations and technical bottlenecks of artificial intelligence models

Despite the outstanding high-throughput capability of deep-learning algorithms on standardised benchmarks, several critical technical and clinical roadblocks continue to hinder their reliable translation into real-world neurotological workflows.[25] These challenges are driven by a complex interplay of spatial, algorithmic and pathology-induced factors that mandate careful methodological scrutiny.

First, severe spatial resolution constraints and inherent partial volume effects present a foundational challenge in inner-ear image analysis.[62] Because the bony and membranous semicircular canals are exceptionally narrow microstructures, they typically span a mere 2 to 3 voxels on clinical CT or MRI scans utilising standard slice thicknesses of 0.5–1.0 mm. When the fine boundaries of these thin pathways blend with the surrounding high-density otic capsule or adjacent soft tissues, pronounced voxel-level intensity blurring frequently confounds segmentation networks. This spatial degradation triggers catastrophic topological errors, including false boundary delineations, artificial lumen fusions or fragmented disconnections along the canal arc, which heavily compromise downstream hydrodynamic modelling.[62]

Beyond resolution constraints, deep-learning architectures remain notoriously hypersensitive to domain shifts across heterogeneous imaging protocols.[63] When segmentation models optimised on homogeneous, single-centre datasets are deployed across different scanner vendors, divergent magnetic field strengths or varied CT reconstruction kernels, the resulting shifts in grey-level histograms and signal-to-noise ratios typically cause a drastic decline in performance.[22] This lack of cross-vendor generalisability emphasises that without extensive multi-centre domain adaptation or transfer learning, models remain overly fragile when encountering the scanning variations typical of real-world clinical environments.

Furthermore, a profound clinical bottleneck arises from algorithmic performance failures under severe pathological conditions.[25] The vast majority of current AI tools are trained on anatomically normal templates, rendering their underlying structural assumptions vulnerable when encountering structural anomalies. In patients with congenital inner-ear malformations, such as Mondini dysplasia, these pre-configured geometric priors are completely violated. Similarly, in conditions involving intraluminal obliteration—such as fibrous tissue encapsulation or neo-ossification in labyrinthitis ossificans and advanced otosclerosis—the loss of normal MRI fluid signals and corresponding alterations in CT bone density drive massive segmentation errors. Quantitative evidence demonstrates that in such pathological ears, the Dice similarity coefficient for the labyrinth plummets from a robust 0.910 down to 0.775, while the Dice similarity coefficient for the adjacent facial nerve drops to an entirely unusable 0.506.[25]

Finally, the development of truly robust networks is severely throttled by statistical fragility in low-data regimens, largely because of the profound paucity of annotated, high-quality pathological datasets. Within these restricted data domains, marginal variations in training and testing splits can completely reshuffle different models' performance rankings.[25] This instability strongly indicates that many highly publicised 'leaderboard' superiorities on public benchmarks are frequently mere statistical artifacts of

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

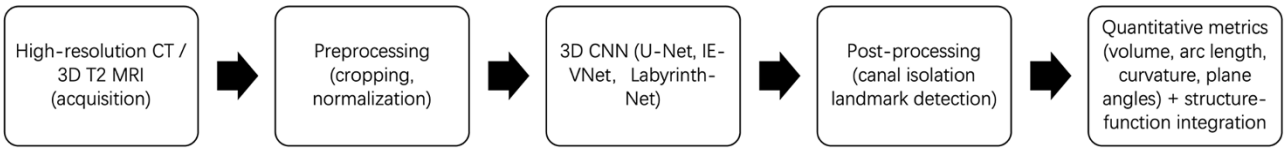


Figure 1. Deep learning-based pipeline for automated semicircular canal segmentation and quantitative morphometry. Volumetric high-resolution computed tomography (CT) or three-dimensional (3D) T2-weighted magnetic resonance imaging (MRI) of the temporal bone is first acquired. After pre-processing (cropping to the inner-ear region and intensity normalisation), a 3D convolutional neural network (CNN)—typically a U-Net–based architecture such as 3D U-Net, IE-VNet, or Labyrinth-Net—is applied to segment the inner ear. Post-processing steps (canal isolation and landmark detection) then enable extraction of semicircular canal metrics including volume, arc length, curvature and plane orientation, which can be integrated with vestibular function tests and clinical outcomes for structure–function analysis.

noise rather than reflections of genuine clinical generalisability, underlining the critical need for rigorous external validation before clinical deployment.

Morphological variation of the semicircular canals and clinical implications

Normal variation and congenital inner-ear malformations

Micro-CT and *in vivo* CT and/or MRI studies demonstrate that the three semicircular canals exhibit appreciable inter-individual variability in dimensions, curvature and spatial orientation while maintaining good bilateral symmetry of corresponding canals.[4–8] This physiological variation underpins the definition of normative ranges and may contribute to disease susceptibility in certain vestibular disorders.[5,9,10]

Congenital inner-ear malformations are a major cause of severe-to-profound sensorineural hearing loss in children, and canal malformations—such as hypoplastic, dysplastic or absent canals—are frequent components of these anomalies. Brotto *et al.* reported that about half of children with inner-ear malformations have vestibular dysfunction or delayed balance development, emphasising the importance of semicircular canal and vestibular assessment when planning cochlear implantation or other interventions.[32]

From a structural perspective, Jackler *et al.* proposed a classic embryogenesis-based classification that distinguishes common cavity, incomplete partition types and other subtypes according to the timing of developmental arrest.[34] This foundational framework was subsequently updated by Sennaroğlu and Bajin to adapt to modern management paradigms and guide cochlear implantation in severely malformed cochleovestibular systems.[35,36] Recent radiological reviews by Bhagat, O'Brien and colleagues refined imaging criteria for individual malformation subtypes and proposed algorithmic CT and/or MRI assessment workflows, which are highly relevant for pre-operative evaluation of canal anomalies.[38,39]

Histopathological studies by Monsanto *et al.* highlighted potential pitfalls of cochlear implantation in malformed inner ears, including perilymphatic gusher, aberrant cochlear or vestibular wall defects, and atypical cochlea–vestibule–canal relationships.[45] Systematic reviews by Farhood, Shah and Sennaroğlu and co-workers showed that, despite these challenges, many patients with inner-ear malformations can achieve favourable speech perception outcomes when implantation strategies are carefully tailored to the specific anatomy and vestibular status.[36,46,47] These data underscore that detailed imaging-based characterisation of semicircular canal morphology is integral to risk stratification, surgical planning and prognostication in congenital inner-ear malformations.

Semicircular canal morphology and benign paroxysmal positional vertigo

Benign paroxysmal positional vertigo, the most common peripheral vestibular disorder, is widely attributed to otoconia dislodged from the utricle that enter the semicircular canals and move with head position, abnormally stimulating the crista ampullaris. While the standardised clinical practice guidelines by Bhattacharyya *et al.*[40] and comprehensive pathophysiological updates by Swain[42] provide robust clinical frameworks for canal-specific diagnosis and canalith repositioning manoeuvres, recent neurotological interest has increasingly focused on 'structural susceptibility'. This paradigm explores whether inherent, individual semicircular canal geometry influences otoconial deposition and migration dynamics. In this context, emerging editorial perspectives by Bhandari and colleagues[49] emphasise the need for refined morphometric phenotyping of canal involvement, especially because population-level evaluations by Si *et al.*[48] demonstrated that multi-canal BPPV variants present with significantly higher recurrence rates and more complex nystagmus patterns than single-canal pathologies, pointing toward a distinct anatomical or metabolic predisposition.

Direct morphometric evidence remains limited. Yılmazer *et al.* used CT to compare semicircular canal arc lengths between BPPV patients and controls, and found significantly longer anterior and posterior canals in BPPV, proposing 'elongated canals' as a potential imaging risk marker.[64] Ping *et al.* described a short-arm variant of posterior canal BPPV in which otoconia are located in the short ampullary limb rather than the long non-ampullary limb, and showed that its clinical course and optimal repositioning strategy differ from the classic long-arm variant.[65] For lateral canal BPPV, Maia and co-workers systematically reviewed management strategies across pathophysiological forms (canalithiasis *vs* cupulolithiasis; geotropic *vs* apogeotropic nystagmus), highlighting the importance of canal orientation and ampullary position when selecting maneuvers.[50]

Overall, available data linking semicircular canal morphology to BPPV susceptibility come from small, single-centre studies with heterogeneous imaging protocols and measurement methods, and reported associations are not fully consistent. Larger, multi-centre case–control studies using standardised CT and/or MRI morphometry are needed to determine whether specific geometric features—such as increased arc length, altered curvature or canal orientation—truly increase BPPV risk or affect the likelihood of multi-canal involvement and response to treatment.

Superior canal dehiscence syndrome and canal plugging and/or occlusion surgery

Superior canal dehiscence syndrome is characterised by a focal bony defect in the roof of the superior semicircular canal, which

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

creates a third mobile window in the inner ear and leads to sound- and pressure-induced vestibular symptoms and auditory manifestations such as autophony and conductive hyperacusis. The Bárány Society consensus document by Ward *et al.* established diagnostic criteria requiring characteristic symptoms, objective vestibular or audiological signs (e.g. low-threshold vestibular evoked myogenic potentials, abnormal video head impulse test or characteristic nystagmus) and high-resolution imaging evidence of superior canal dehiscence on CT or MRI.[53] Suzuki *et al.* emphasised that CT evaluation should include oblique reformations parallel and perpendicular to the superior canal to reduce partial-volume artifacts and avoid overcalling thin but intact bone as true dehiscence.[54]

Semicircular canal occlusion, or plugging, was first introduced for refractory BPPV and has since been applied to selected cases of Ménière's disease and superior canal dehiscence syndrome. Zhang *et al.* described triple semicircular canal plugging as a novel surgical modality for intractable Ménière's disease and reported satisfactory vertigo control with partial hearing preservation in most patients.[55] Xie *et al.* evaluated triple semicircular canal occlusion combined with endolymphatic sac decompression and showed durable vertigo control with acceptable audiovestibular outcomes.[56] For superior canal dehiscence syndrome, Seiwerth *et al.* reported on transmastoid two-point superior canal plugging with preservation of the vestibulo-ocular reflex, showing that carefully planned canal isolation can effectively control symptoms while minimising long-term vestibular dysfunction.[52]

These studies support canal plugging or occlusion as a viable option for carefully selected patients; however, optimal indications, configuration of canal occlusion and long-term outcomes remain under investigation.[51–53,55,56] Precise pre-operative imaging assessment of superior canal morphology—including the size and location of dehiscence, canal curvature and relationship to adjacent structures—is therefore essential for surgical planning and for balancing vertigo control against the risk of iatrogenic vestibular hypofunction.

Future directions: standardised measurement and artificial intelligence-assisted analysis

Remaining challenges

Despite substantial advances in anatomical characterisation, imaging technology and automatic segmentation, several important challenges continue to limit the translational impact of semicircular canal morphometry.

Primarily, marked heterogeneity in multi-centre imaging and post-processing protocols—spanning divergent CT and/or MRI acquisition parameters, reconstruction kernels and reference co-ordinate systems—precludes direct cross-cohort comparisons. This is further compounded by a profound lack of standardisation in geometric indices; the absence of consensus regarding landmarks and centreline fitting strategies for core metrics (such as 'arc length', 'height' or 'canal plane') introduces methodological artifacts that heavily obscure true biological variations and complicate robust meta-analyses.

Furthermore, the field is severely limited by a paucity of large-scale, multi-centre normative databases. Most available morphometric datasets originate from modest, single-centre retrospective cohorts, leaving the compounding influences of age, sex, ethnicity and craniofacial morphology incompletely characterised. Crucially, the symbiotic integration of structural morphometry with objective vestibular function tests and patient-reported symptom severity remains sparse. Bridging this persistent structure–function gap is a critical prerequisite for establishing the definitive clinical significance and diagnostic validity of quantitative semicircular canal variations in neurotological practice.

Research priorities

The advent of automated, precise semicircular canal morphometry opens up exciting new frontiers. To realise the full clinical potential of these technologies, the research community should focus on the following strategic priorities.

First, building large-scale, standardised multi-centre databases. The single greatest limitation currently is the lack of large, diverse datasets. We advocate for a global initiative to create a federated database of high-resolution temporal bone images, coupled with standardised clinical and functional vestibular data. This resource would be indispensable for training robust, generalisable AI models and establishing normative morphometric references across different demographics.

Second, integrating structure and function. The next leap forward will come from quantitatively linking semicircular canal morphology to physiological function. Future studies must be designed to correlate geometric parameters (e.g. radius of curvature, canal non-planarity) with objective functional measures (e.g. video head impulse test (vHIT) gains and vestibular evoked myogenic potential (VEMP) responses). This will enable the development of biomechanical models that can predict an individual's susceptibility to conditions like BPPV or canal dehiscence.

Third, clinical workflow integration and prospective validation. For these tools to impact patient care, they must be seamlessly integrated into the clinical workflow. This requires the development of user-friendly, US Food and Drug Administration (FDA)-cleared software that can provide radiologists and otologists with rapid, reproducible morphometric reports. Crucially, prospective clinical trials are needed to validate the diagnostic accuracy and prognostic value of these AI-derived imaging biomarkers in predicting disease onset, progression and treatment outcomes.

Finally, exploring new morphometric biomarkers. Beyond radius and orientation, AI can uncover subtle morphological signatures of disease that are invisible to the human eye. Future research should leverage advanced techniques like radiomics and geometric deep learning to identify novel imaging phenotypes associated with vestibular migraine, Ménière's disease and age-related vestibular loss, paving the way for a new era of precision otology.

Conclusions

The semicircular canals are indispensable components of the vestibular system, and their detailed anatomy and imaging characteristics are closely linked to a broad spectrum of vestibular disorders. Advances in high-resolution CT and MRI, together with standardised co-ordinate systems, have greatly improved *in vivo* quantification of canal geometry. Deep learning-based segmentation and 3D morphometric analysis now make it possible to obtain automated, reproducible measurements of canal volume, curvature and spatial orientation across large imaging datasets.

Emerging evidence suggests that semicircular canal morphology may influence disease susceptibility and treatment response in

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

BPPV, superior canal dehiscence syndrome, Ménière's disease and congenital inner-ear malformations. However, existing studies are limited by heterogeneous methods, small sample sizes and incomplete integration of structural and functional data. Future efforts should therefore focus on harmonising imaging and measurement protocols, constructing multi-centre normative databases and combining morphometric data with vestibular function tests and clinical outcomes.

By uniting rigorous anatomical and imaging-based measurement with artificial intelligence and advanced visualisation technologies, semicircular canal metrics have the potential to become key components of precision diagnosis, surgical planning and individualised management in clinical vestibulology. In the longer term, standardised, AI-assisted semicircular canal morphometry may also provide a framework for incorporating vestibular anatomy into broader models of balance control and spatial orientation.

- Variations in semicircular canal geometry are increasingly recognised as critical factors in the pathogenesis and clinical manifestation of disorders such as benign paroxysmal positional vertigo**[Q2]**, superior canal dehiscence syndrome and Ménière's disease
- Current clinical assessment relies on high-resolution computed tomography and three-dimensional T2-weighted magnetic resonance imaging to visualise the bony and membranous labyrinths
- This review systematically synthesised the technological evolution of semicircular canal morphometry, transitioning from foundational cadaveric studies to state-of-the-art artificial intelligence-driven automated analysis pipelines
- The emergence of deep-learning architectures, such as U-Net and Labyrinth-Net, which enable reproducible, high-throughput segmentation and automated landmark detection, is detailed
- Recent clinical evidence linking specific structural markers, such as canal arc length and orientation, to disease susceptibility and surgical treatment outcomes is consolidated
- A forward-looking roadmap is proposed, emphasising the necessity of multi-centre data standardisation and the integration of structural and functional data to advance precision otology

Data availability statement. Data sharing is not applicable to this article as no new data were created or analysed in this study.

Competing interests. None declared.

Acknowledgements. In accordance with ethical publication standards, we disclose that ChatGPT was used for grammar checks and no AI tools were used for data generation or interpretation. We have ensured that the final content remains accurate and compliant with journal guidelines.

References

1 Mohamed EHS, Ibraheem WM, Gad NH. Anatomy and physiology of vestibular system: review article. *Neuroquantology* 2022;**20**:4678–89
2 Jones SM, Jones TA, Mills KN, Gaines GC. Anatomical and physiological considerations in vestibular dysfunction and compensation. *Semin Hear* 2009;**30**:231–41
3 Khan S, Chang R. Anatomy of the vestibular system: a review. *NeuroRehabilitation* 2013;**32**:437–43
4 Della Santina CC, Potyagaylo V, Migliaccio AA, Minor LB, Carey JP. Orientation of human semicircular canals measured by three-dimensional multiplanar CT reconstruction. *J Assoc Res Otolaryngol* 2005;**6**:191–206
5 Wu S, Lin P, Zheng Y, Zhou Y, Liu Z, Yang X. Measurement of human semicircular canal spatial attitude. *Front Neurol* 2021;**12**:741948
6 Lee JY, Shin KJ, Kim JN, Yoo JY, Song WC, Koh KS. A morphometric study of the semicircular canals using micro-ct images in three-dimensional reconstruction. *Anat Rec (Hoboken)* 2013;**296**:834–9
7 El Khoury M, Braga J, Dumoncel J, Nancy J, Esclassan R, Vaysse F. The human semicircular canals orientation is more similar to the bonobos than to the chimpanzees. *PLoS One* 2014;**9**:e93824
8 Cardenas-Serna M, Jeffery N. Human semicircular canal form: ontogenetic changes and variation of shape and size. *J Anat* 2022;**240**:541–55
9 Huang Y, Liu K, Tang R, Xu N, Xie J, Yang Z *et al*. Spatial position changes in the semicircular canals may be the anatomical basis of Ménière's disease: a preliminary study based on ultra-high-resolution computed tomography (CT) and intelligent segmentation. *Quant Imaging Med Surg* 2024;**14**:6060–71
10 Liu W, Chen G, Xie J, Liang T, Zhang C, Liao X *et al*. A new coordinate system for magnetic resonance imaging of the vestibular system. *Front Neurol* 2021;**12**:789887
11 Zhou M, Mao J, Li X, Li Y, Yang X. Intelligent analysis and measurement of semicircular canal spatial attitude. *Front Neurol* 2024;**15**:1396513
12 Lane JI, Lindell EP, Witte RJ, Delone DR, Driscoll CL. Middle and inner ear: improved depiction with multiplanar reconstruction of volumetric CT data. *Radiographics* 2006;**26**:115–24
13 Benson JC, Carlson ML, Lane JI. MRI of the internal auditory canal, labyrinth, and middle ear: how we do it. *Radiology* 2020;**297**:252–65
14 Casselman JW, Offeciers EF, De Foer B, Govaerts P, Kuhweide R, Somers T. CT and MR imaging of congential abnormalities of the inner ear and internal auditory canal. *Eur J Radiol* 2001;**40**:94–104
15 Joshi VM, Navlekar SK, Kishore GR, Reddy KJ, Kumar EC. CT and MR imaging of the inner ear and brain in children with congenital sensorineural hearing loss. *Radiographics* 2012;**32**:683–98
16 Feraco P, Piccinini S, Gagliardo C. Imaging of inner ear malformations: a primer for radiologists. *Radiol Med* 2021;**126**:1282–95
17 Metwally MI, Alayouty NA, Basha MAA. Ear malformations: what do radiologists need to know? *Clin Imaging* 2020;**66**:42–53
18 Hiremath SB, Biswas A, Mndebele G, Schramm D, Ertl-Wagner BB, Blaser SI *et al*. Cochlear implantation: systematic approach to preoperative radiologic evaluation. *Radiographics* 2023;**43**:e220102
19 Yadav N, Mishra A, Patel DK, Parihar S. Role of imaging in congenital inner ear anomalies in children with severe-profound sensory neural hearing loss. *Medical Research Archives* 2024;**12**
20 Yu FF, Feltrin FS, Bathla G, Raj K, Agarwal A, Lee WC *et al*. Imaging guide to inner ear malformations: an illustrative review. *Curr Probl Diagn Radiol* 2023;**52**:576–85
21 Vaidyanathan A, Van Der Lubbe M, Leijenaar RTH, Van Hoof M, Zerka F, Miraglio B *et al*. Deep learning for the fully automated segmentation of the inner ear on MRI. *Sci Rep* 2021;**11**:2885
22 Ahmadi SA, Frei J, Vivar G, Dieterich M, Kirsch V. IE-Vnet: deep learning-based segmentation of the inner ear's total fluid space. *Front Neurol* 2022;**13**:663200
23 Hussain R, Lalande A, Girum KB, Guigou C, Bozorg Grayeli A. Automatic segmentation of inner ear on CT-scan using auto-context convolutional neural network. *Sci Rep* 2021;**11**:4406
24 Li X, Zhu Z, Yin H, Wang Z, Zhuo L, Zhou Y. Labyrinth net: a robust segmentation method for inner ear labyrinth in CT images. *Comput Biol Med* 2022;**146**:105630
25 Wang J, Lv Y, Wang J, Ma F, Du Y, Fan X *et al*. Fully automated segmentation in temporal bone CT with neural network: a preliminary assessment study. *BMC Med Imaging* 2021;**21**:166
26 Ke J, Lv Y, Ma F, Du Y, Xiong S, Wang J *et al*. Deep learning-based approach for the automatic segmentation of adult and pediatric temporal bone computed tomography images. *Quant Imaging Med Surg* 2023;**13**:1577–91
27 Lim J, Abily A, Ben Salem D, Gaillandre L, Attye A, Ognard J. Training and validation of a deep learning U-net architecture general model for automated segmentation of inner ear from CT. *Eur Radiol Exp* 2024;**8**:104
28 Li X, Gong Z, Yin H, Zhang H, Wang Z, Zhuo L. A 3D deep supervised densely network for small organs of human temporal bone segmentation in CT images. *Neural Netw* 2020;**124**:75–85
29 Li W, Wijewickrema S, Margeta J, Kamraoui R, Hussain R, Gerard J-M. A systematic review of automated temporal bone segmentation methods. *Biomed Eng Adv* 2025;**10**:100195

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press

30 Stebani J, Blaimer M, Zabler S, Neun T, Pelt DM, Rak K. Towards fully automated inner ear analysis with deep-learning-based joint segmentation and landmark detection framework. *Sci Rep* 2023;**13**:19057
31 Sharma N, Aggarwal LM. Automated medical image segmentation techniques. *J Med Phys* 2010;**35**:3–14
32 Brotto D, Ariano M, Sozzi M, Cenedese R, Muraro E, Sorrentino F *et al*. Vestibular anomalies and dysfunctions in children with inner ear malformations: a narrative review. *Front Pediatr* 2023;**11**:1027045
33 Sekulic S, Lemajic-Komazec S, Sokolovac I, Topalidou A, Gouni O, Petkovic B *et al*. Inner ear malformations in congenital deafness are not associated with increased risk of breech presentation. *Fetal Pediatr Pathol*. 2021;**40**:674–84
34 Jackler RK, Luxford WM, House WF. Congenital malformations of the inner ear: a classification based on embryogenesis. *Laryngoscope* 1987;**97**:2–14
35 Sennaroğlu L, Bajin MD. Classification and current management of inner ear malformations. *Balkan Med J* 2017;**34**:397–411
36 Sennaroglu L. Cochlear implantation in inner ear malformations – a review article. *Cochlear Implants Int* 2010;**11**:4–41
37 Haber K, Konopka W, Amernik K, Mierzwiński J. Inner ear malformations – overview, current classifications, challenges in management. *Pol Otorhino Rev* 2020;**9**:1–11
38 Bhagat AC, Kumar J, Garg A, Prakash A, Meher R, Arya S. Imaging in congenital inner ear malformations – an algorithmic approach. *Indian J Radiol Imaging* 2020;**30**:139–48
39 O'Brien WT, Sr, D'arco F, Onofrj V, Koch BL. Nonsyndromic congenital causes of sensorineural hearing loss in children: AN illustrative review. *AJR Am J Roentgenol* 2021;**216**:1048–55
40 Bhattacharyya N, Gubbels SP, Schwartz SR, Edlow JA, El-Kashlan H, Fife T *et al*. Clinical practice guideline: benign paroxysmal positional vertigo (update). *Otolaryngol Head Neck Surg* 2017;**156**:S1–47
41 Nguyen-Huynh AT. Evidence-based practice: management of vertigo. *Otolaryngol Clin North Am* 2012;**45**:925–40
42 Swain SK. Revisiting pathophysiology of benign paroxysmal positional vertigo: a review. *Int J Otorhinolaryngol Head Neck Surg* 2023;**9**:355–60
43 Swain SK. Benign paroxysmal positional vertigo in pediatric age group: a review. *Int J Contemp Pediatr* 2022;**9**:863–8
44 Swain SK. Benign paroxysmal positional vertigo in patients with Ménière's disease. *Saudi J Otorhinolaryngol Head Neck Surg* 2022;**24**:51–5
45 Monsanto RDC, Sennaroglu L, Uchiyama M, Sancak IG, Paparella MM, Cureoglu S. Histopathology of inner ear malformations: potential pitfalls for cochlear implantation. *Otol Neurotol* 2019;**40**:e839–46
46 Farhood Z, Nguyen SA, Miller SC, Holcomb MA, Meyer TA, Rizk HG. Cochlear implantation in inner ear malformations: systematic review of speech perception outcomes and intraoperative findings. *Otolaryngol Head Neck Surg* 2017;**156**:783–93
47 Shah S, Walters R, Langlie J, Davies C, Finberg A, Tuset MP *et al*. Systematic review of cochlear implantation in patients with inner ear malformations. *PLoS One* 2022;**17**:e0275543
48 Si L, Ling X, Li Z, Li K, Shen B, Yang X. Clinical characteristics of patients with multi-canal benign paroxysmal positional vertigo. *Braz. J. Otorhinolaryngol*. 2022;**88**:89–100
49 Bhandari A, Sharma S, Zuma EMFC, Ramos BF, Martin-Sanz E. Editorial: Benign paroxysmal positional vertigo. *Front Neurol* 2024;**15**:1358860
50 Maia FZE, Ramos BF, Cal R, Brock CM, Mangabeira Albernaz PL, Strupp M. Management of lateral semicircular canal benign paroxysmal positional vertigo. *Front Neurol* 2020;**11**:1040
51 Tian J, Yin G, Zhang Q, Zhang S, Zeng X, Li Y. Triple semicircular canal occlusion with endolymphatic sac decompression for intractable Ménière's disease. *Front Neurol* 2024;**15**:1362603
52 Seiwerth I, Dlugaiczyk J, Schmäl F, Rahne T, Kösling S, Plontke SK. Superior semicircular canal dehiscence isolation by transmastoid two-point canal plugging with preservation of the vestibulo-ocular reflex. *HNO* 2025;**73**:414–20
53 Ward BK, Van De Berg R, Van Rompaey V, Bisdorff A, Hullar TE, Welgampola MS *et al*. Superior semicircular canal dehiscence syndrome: diagnostic criteria consensus document of the committee for the classification of vestibular disorders of the bárány society. *J. Vestib. Res*. 2021;**31**:131–41
54 Suzuki M, Ota Y, Takanami T, Yoshino R, Masuda H. Superior canal dehiscence syndrome: a review. *Auris Nasus Larynx* 2024;**51**:113–19
55 Zhang D, Fan Z, Han Y, Lv Y, Li Y, Wang H. Triple semicircular canal plugging: a novel modality for the treatment of intractable Ménière's disease. *Acta Otolaryngol* 2016;**136**:1230–5
56 Xie B, Wang M, Jiang Y, Xie W, Zhang S, Liu Y. Triple semicircular canal occlusion combined with endolymphatic sac decompression: an effective surgical strategy for vertigo control of intractable Ménière's disease. *Clin Otolaryngol* 2022;**47**:319–22
57 Leng S, Diehn FE, Lane JI, Koeller KK, Witte RJ, Carter RE *et al*. Temporal bone CT: Improved image quality and potential for decreased radiation dose using an ultra-high-resolution scan mode with an iterative reconstruction algorithm. *AJNR Am J Neuroradiol* 2015;**36**: 1599–603
58 Liu H, Durongbhan P, Davey CE, Stok KS. Image registration in longitudinal bone assessment using computed tomography. *Curr Osteoporos Rep* 2023;**21**:372–85
59 Hajnal JV, Saeed N, Soar EJ, Oatridge A, Young IR, Bydder GM. A registration and interpolation procedure for subvoxel matching of serially acquired MR images. *J Comput Assist Tomogr* 1995;**19**: 289–96
60 Cho YS, Song B, Cho BH, Chung W-H. The usefulness of inner ear magnetic resonance imaging in patient with Ménière's disease: a narrative review. *Precis Future Med* 2022;**6**:138–45
61 Ross T, Tanna R, Lilaonitkul W, Mehta N. Deep learning for automated image segmentation of the middle ear: a scoping review. *Otolaryngol Head Neck Surg* 2024;**170**:1544–54
62 Kim W, Kang Y, Lee S, Lee HJ, Nam Y. Deep learning-based inner ear subregion segmentation in 3D T2-weighted MRI using label-preserving data augmentation. *NMR Biomed* 2026;**39**:e70266
63 Zemmoura I, Burkhardt E, Herbet G. The inferior longitudinal fasciculus: anatomy, function and surgical considerations. *J. Neurosurg. Sci.* 2021;**65**:590–604
64 Yılmazer AB, Bircan HS, Erk H, Kış N, Göker AE, Hanci D *et al*. Semicircular canals are long in patients with benign paroxysmal positional vertigo. *J Laryngol Otol* 2024;**138**:265–9
65 Ping L, Yi-Fei Z, Shu-Zhi W, Yan-Yan Z, Xiao-Kai Y. Diagnosis and treatment of the short-arm type posterior semicircular canal BPPV. *Braz. J. Otorhinolaryngol* 2022;**88**:733–9

https://doi.org/10.1017/S0022215126105593 Published online by Cambridge University Press