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Optical Coherence Tomography Imaging of the Inner Ear: A Feasibility Study With Implications for Cochlear Implantation

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Cochlear implantation is now being performed in ears with residual hearing. Those implant recipients who keep residual hearing may benefit from improved pitch resolution through both electrical and acoustic hearing. Preservation of cochlear function after implantation is a challenging task for the surgeon. Current topics of hearing preservation research include electrode design and surgical technique. To maintain hearing, surgeons strive to create a cochleostomy and place the electrode in a minimally traumatic fashion. In this study, we examine a novel catheter-based real-time imaging modality with 10- to 15-μm resolution, optical coherence tomography (OCT), on the inner ear. We demonstrate the capability of OCT to allow visualization of inner ear structures through bone in live mice. We additionally used OCT to image the inner ear in a human temporal bone. Optical coherence tomography was able to delineate soft tissue structures within the cochlea and may be useful as an adjunct to cochlear implantation. Other potential otologic applications of OCT are discussed.

Key Words: cochlear implantation, electrical acoustic hearing, optical coherence tomography, round window membrane.

INTRODUCTION

The indications for cochlear implantation are expanding and include patients with significant residual hearing.[1] Because preoperative function may be present in the implanted ear, there has been an increased emphasis on its preservation during and after surgery.[2,3] Use of residual low-pitch acoustic hearing with electrical high-pitch hearing or so-called "electrical acoustic" hearing demonstrates advantages in acoustic speech processing and melody recognition.[4] Retention of more precise pitch resolution (frequency difference limens) may be how electroacoustic hearing improves word recognition and speech processing,[4] but an additive advantage is possibly conferred centrally.[5] Because preservation of residual hearing is of utmost importance to gain the benefits of electroacoustic hearing, it logically follows that cochlear trauma resulting from implantation should be kept to a minimum.

Cochlear implant trauma models have been studied in human temporal bones,[6-8] and a model of implant trauma has been developed in rats.[9] In a human cadaveric temporal bone implantation study, "severe basal trauma" (insertion of the electrode through the basilar membrane) was noted in 30% of temporal bones implanted, and inadvertent scala vestibuli placement occurred 20% of the time.[10] From these analyses, several methods of mitigating cochlear trauma during implantation have been proposed. Briggs et al[11] performed an anatomic study of the cochlear "hook" region and determined that cochleostomy placement anterior and inferior to the round window more consistently allowed electrode placement into the scala tympani than did anterior cochleostomy, and with less trauma. With the advent of softer, more flexible electrodes, the technique of round window placement of electrodes is currently being revisited.[9,10] Many implant surgeons will advocate a "soft" surgery technique that entails exposing the endosteum overlying the scala tympani, clearing bone dust from the field, and gently incising the endosteum near the end of the procedure; suctioning of perilymph is kept to a minimum.[12]

Despite attempts to lessen trauma during implant placement, some degree of damage is inevitable.

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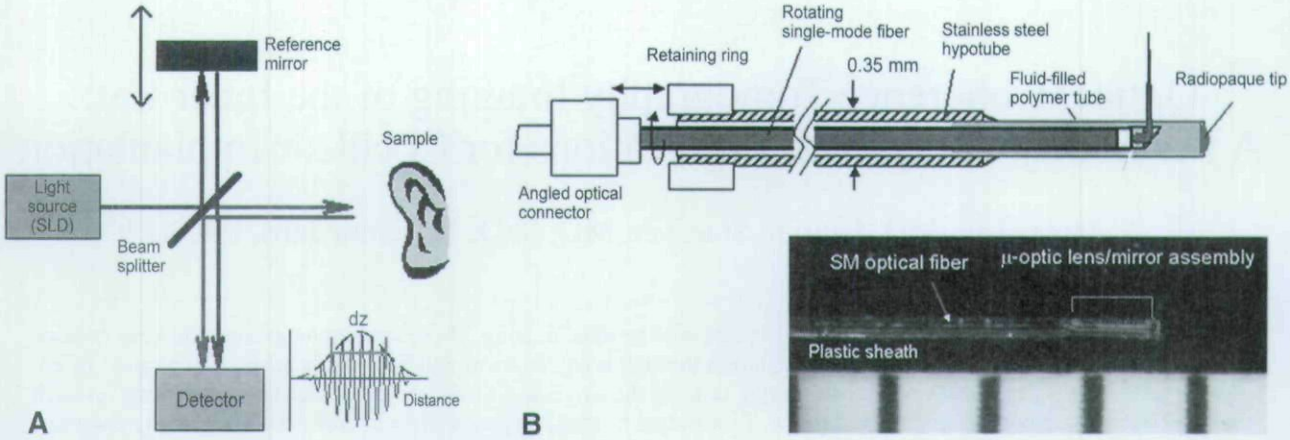

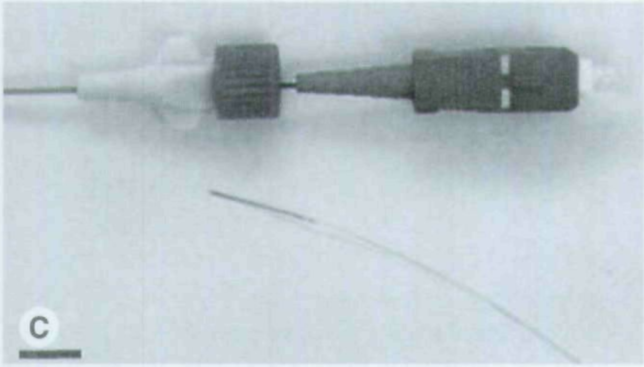

Fig 1. Schematic of optical coherence tomography (OCT) imaging. **A)** Basic interferometry principle of OCT. Low-coherence beam of infrared light is split between sampling arm and reference arm. Interference is detected when path lengths taken by two arms approximate each other. By moving accessible reference mirror, it is possible to indirectly measure distance to sample. Spatial resolution of this form of optical ranging (dz in inset) is determined by bandwidth of light source. SLD — superluminescent light–emitting diode. (Reprinted with permission.[16]) **B)** Detailed schematic of rotating (0.35 mm) OCT probe. Inset shows probe tip next to 1-mm scale. SM — single-mode. **C)** Photograph of rotating (0.35 mm) OCT probe. Scale bar — 1 cm.

Experimentally, otoprotective agents such as corticosteroids have been used in an attempt to decrease hearing loss by theoretically preserving cochlear hair cells and neurons after the stress of implantation.[2] The aforementioned rat model of implantation trauma is expected to allow investigation of the molecular biology behind postimplantation auditory cell loss; testing of otoprotective agents can also be achieved in this model.[9]

Researchers have examined fluoroscopy and electrode design as methods to facilitate less-traumatic implantation.[13] We propose that a new flexible catheter-based imaging modality, optical coherence tomography (OCT), may allow visualization of cochlear structures and guide placement of electrodes to decrease trauma. According to Huang et al,[14] it was first described by Fujimoto, and its mechanism is theoretically similar to B-mode ultrasonography, relying upon the backscattering of energy to produce a 2-dimensional image.[15] In contrast to ultrasonography, OCT uses near-infrared (1,310 nm) light rather than acoustic energy; Michelson interferometry is used to measure the distance traveled by the light backscattered from the sample (Fig 1A[16]). Infrared light is split into sample and reference arms with optical lengths that are unknown and known, respectively. The lights from the sample and reference arms are then processed and compared to each other. The sample light backscatter length (unknown) and the reference light backscatter length (known) generate an interference pattern from which reflective differences and intensities from the tissue sample may be extrapolated. Live images are generated from these interference patterns and intensities at a rate up to 15.6 frames per second. The present technology allows an axial resolution of approximately 10 μm and a lateral resolution of 15 to 20 μm.

In this study we demonstrated catheter-based OCT imaging of the cochlea in live mice and a fresh human cadaver. A catheter-based system lends itself to otologic applications, as it allows examination through tight channels such as the facial recess or a tympanotomy with little demand to create a line of sight.

MATERIALS AND METHODS

Optical Coherence Tomography Catheters. Two OCT catheters were constructed by LightLab Imaging, Inc (Westford, Massachusetts), and used in this study: one axial-imaging 0.35-mm-diameter catheter (Fig 1C) and one linear-imaging 0.80-mm-diameter catheter. Both catheters attach and function with the same OCT engine and computer system. Each catheter consists of a thin single-mode optical fiber in the center of the imaging probe extending to its tip. A low-coherence infrared light, generated by a superluminescent light–emitting diode, is guided through the optical fiber to its tip, where it is de-

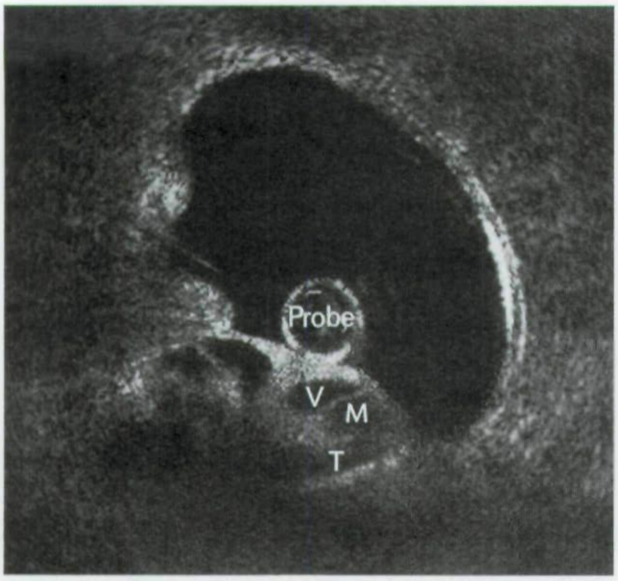

Fig 2. Image of mouse cochlea with 0.35-mm probe overlying promontory. Three scalar spaces — scala vestibuli (V), scala media (M), and scala tympani (T) — are visualized. Imaged at 3.1 Hz; no averaging.

flected laterally (Fig 1B). In the 0.35-mm catheter, the optical fiber rotates within the sheath around the axis of the probe at 3 to 30 Hz, generating a sideways scanning beam. A single 360° rotation can be recorded as a still 2-dimensional image, or the recording can be made continuously as a video.

The optical fiber in the 0.80-mm catheter oscillates along the longitudinal axis of the catheter within the sheath without rotating and provides linear 2-dimensional images covering a 5-mm path along the distal tip of the catheter. The image is very stable and thus allows real-time image averaging to improve the signal-to-noise ratio. The optical fiber can be rotated manually within the catheter to generate linear images on different sides of the probe. Both catheters provide a similar resolution of around 10 to 15 μm. In this study, images shown for this probe were the exponential average of 4 scans.

Surgery. All animal studies used 3-month-old CBA/6j mice and were approved by the University of Maryland guidelines for animal care and housing. Anesthesia for surgery was induced with an intraperitoneal injection of Avertin (0.5 mg/g). After induction of anesthesia, a dorsal postauricular approach allowed exposure of the facial nerve, the posterior semicircular canal, and the bulla. A diamond drill was used to open the bulla. This approach was performed bilaterally in each animal. Each mouse was then mounted in a stereotactic head frame with a snout holder. An OCT catheter was placed into both tympanic cavities for examination of the cochleas. Access to a fresh human cadaver was obtained through the State Anatomy Board of Maryland. The right tympanic cavity of the cadaver was approached through a tympanomeatal flap. The OCT catheter was used to examine the promontory, round window niche, and cochlea via a cochleostomy. The cochleostomy was extended to allow visualization of the spiral ligament, scala vestibuli, and scala tympani.

RESULTS

With the 0.35-mm catheter placed within the tympanic cavity over the cochlear promontory of a mouse, the cochlea, the scala vestibuli, and scala media are readily visible, as is the organ of Corti (Fig 2). The catheter is seen as the circle in the center of the image. Images from a mouse taken with the 0.80-mm, linear-imaging catheter show the 3 fluid-filled chambers, the basilar membrane, Reissner's membrane, and the tectorial membrane (Fig 3A). Adjustment of the linear-imaging catheter along the

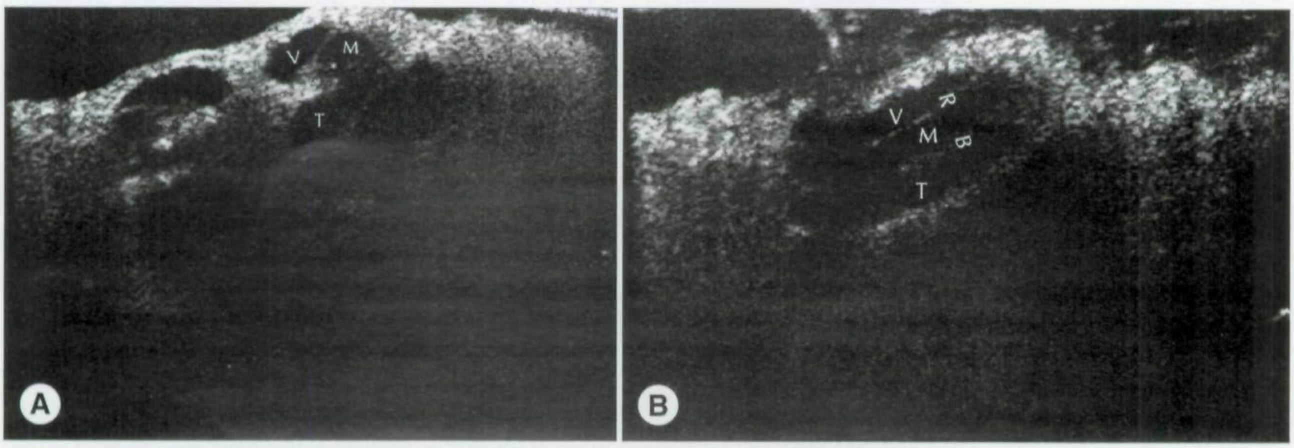

Fig 3. Images of mouse cochlea with 0.80-mm probe (not seen) overlying promontory. Imaged at 1.0 Hz; every 4 frames exponentially averaged. **A)** Three scalar spaces — scala vestibuli (V), scala media (M), and scala tympani (T) — are visualized. Tectorial membrane (asterisk) is also discernible. **B)** Three scalar spaces are seen longitudinally. Reissner's membrane (R) and basilar membrane (B) are also seen.

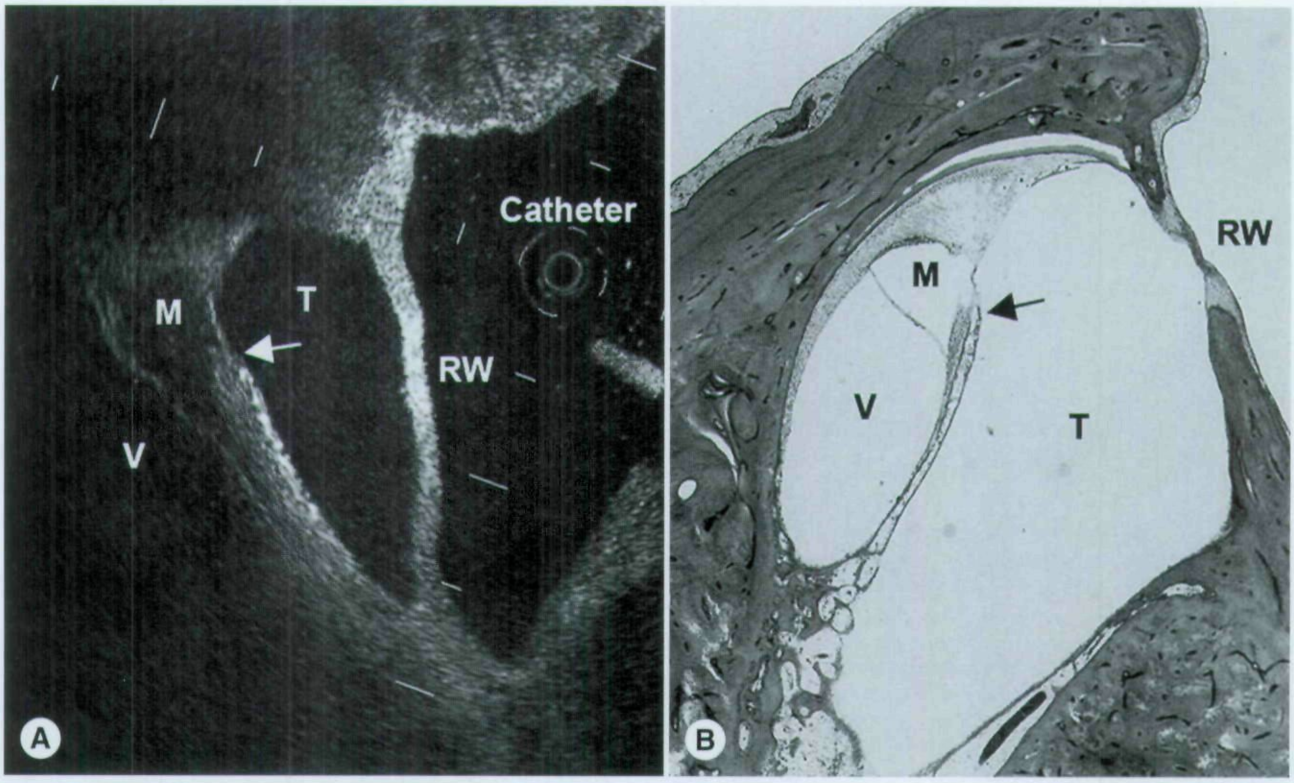

Fig 4. OCT imaging of inner ear through round window. **A)** OCT image from fresh human cadaver with 0.35-mm catheter (labeled) placed in round window niche. Imaging through round window membrane (RW) allows visualization of scala vestibuli (V), scala media (M), and scala tympani (T). Arrow denotes transition of osseous spiral lamina to basilar membrane. Imaged at 3.1 Hz; no averaging. **B)** Labeled histologic slide of same region is provided for comparison (slide was *not* created from imaged ear in our study; courtesy of Fred Linthicum, House Ear Institute).

promontory allows generation of a longitudinal image through the 3 scalar spaces (Fig 3B). For these mouse images, the flexible catheter was threaded through a 1.5- to 2.0-mm hole drilled in the bulla.

The 0.35-mm catheter was placed in the round window niche of a fresh human cadaver, demonstrating the osseous spiral lamina and Reissner's membrane by structural detail (Fig 4A). A histologic slide is provided for comparison and orientation (Fig 4B). Figure 5 demonstrates the OCT catheter within the scala tympani and vestibuli. Direct visualization of the scalar compartments in relation to the spiral ligament and structural details of the OCT images confirm the catheter's location.

DISCUSSION

Optical coherence tomography is a relatively novel catheter-based imaging technique capable of 10-μm resolution. The main limitation of OCT is its inability to penetrate beyond 1 to 2 mm of "turbid" tissue,[15] hence its initial studies on epithelial tissues. Non–catheter-transmitted OCT is used clinically for retinal imaging, which is performed through the relatively transparent humors of the eye.[17] Catheter-based OCT has been used to characterize endobronchial mucosal lesions,[18] esophageal lesions, human brain tissue,[16] and conduit quality for coronary artery bypass grafts[19] and has been examined for other potential cardiac applications.[20] A non-catheter OCT unit has been used to image the rat cochlea 2 to 4 hours after death.[21] The technology of OCT is improving, and devices that can achieve 1 to 2 μm of resolution,[22] as well as devices that use alternative light sources to improve image penetration, are currently being developed. Current OCT catheters are small and flexible enough to easily access the middle ear space and could potentially be used to image the inner ear in real time.

One of the first potential applications of OCT imaging may be cochlear implantation. Our studies (Figs 4 and 5) demonstrate that the cochlear fluid spaces can clearly be delineated in a human temporal bone. The inclusion criteria for cochlear implantation have broadened to allow patients with residual hearing to undergo implantation. Those patients with residual hearing display a benefit from use of both acoustic and electrical hearing.[4] "Soft" surgical technique, changes in electrode design,[4] and the exploration of otoprotective medications[9] have all been described to allow preservation of residual hearing.

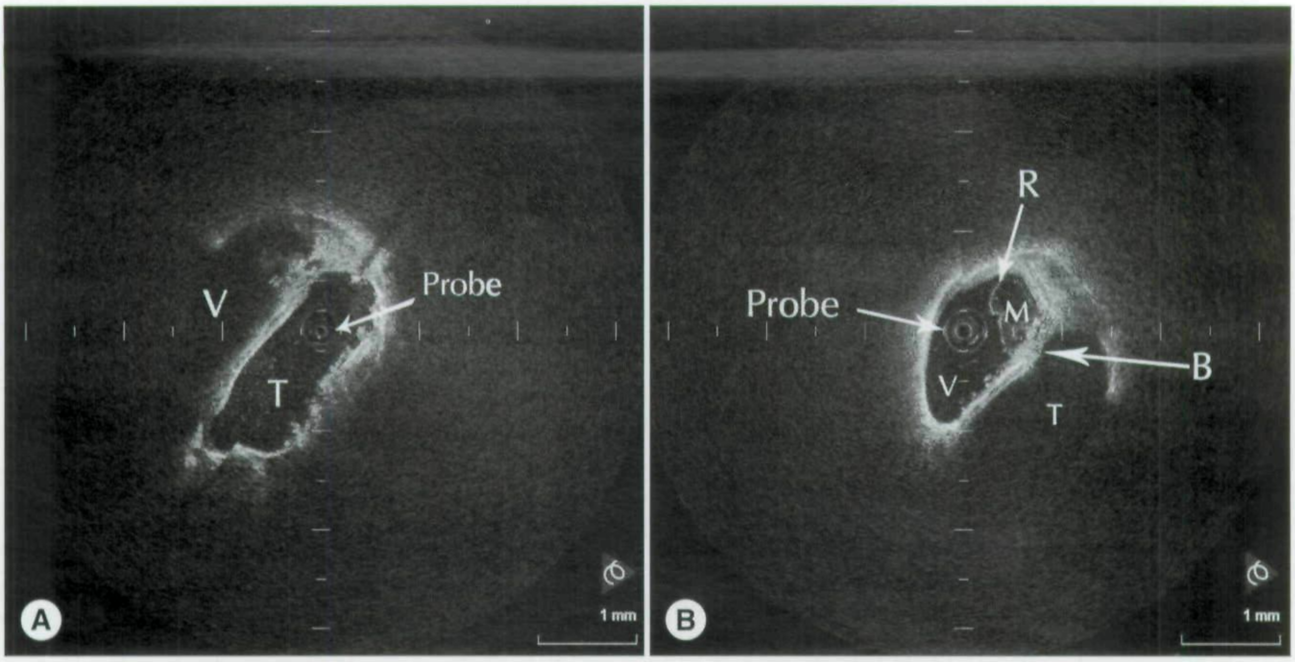

Fig 5. OCT images obtained with 0.35-mm probe. Imaged at 3.1 Hz; no averaging. **A)** Within scala tympani (T). Scala vestibuli (V) is visualized through osseous spiral lamina and basilar membrane. **B)** Within scala vestibuli (V). Scala tympani (T), scala media (M), Reissner's membrane (R), and basilar membrane (B) are visualized.

Electrode structure has been modified to lessen insertion trauma forces; changes in length and caliber, flexibility, and stylet insertion have been tested. As deeper electrode penetration theoretically increases the likelihood of damage to low-frequency cochlear regions, electrode depth has been examined after surgery,[3] and a shorter, "hybrid" electrode has been developed by Gantz et al[4] to stimulate the basal, high-frequency regions of the cochlea while curtailing electrode extension to the more apical, low-frequency regions. Cochlear Ltd (Lane Cove, Australia) has also developed an implant with an electrode insertion apparatus called the Advance-Off Stylet (AOS), which allows introduction of a curved implant to be inserted over a semirigid guide. This implant and technique may provide the advantages of perimodiolar placement, a more compliant electrode tip, and decreased contact with the cochlear lateral wall with lower insertion forces.[23] Med-El Corporation (Innsbruck, Austria) has been developing a more flexible electrode to achieve similar purposes.[24] Electrode placement external to the fluid-filled cochlear spaces has also been proposed, but to date no specifically configured electrodes have been created to test this technique in human subjects.[25]

We propose that catheter-based OCT can be used to help monitor and guide cochlear implant placement. This imaging can be helpful to implant surgeons in several ways. Placement of the cochleostomy may be improved by thinning bone over the promontory and checking the position of the cochleostomy via OCT before penetrating the endosteum. We have not performed an in-depth examination of combining a cochlear implant and an OCT catheter, but such a device may help decrease traumatic implantation by allowing imaging of the scala tympani boundaries during electrode insertion. The current system cannot resolve hair cells, but technological developments in existing prototypes may make examination of hair cells during cochlear implantation a possibility in the future. Finally, OCT offers a unique perspective in implant trauma models that could be complementary to the fluoroscopic imaging currently used.

The ability of OCT to image the basal cochlea noninvasively through the round window reveals other potential applications. Optical coherence tomography may serve as an adjunct to intratympanic injections by allowing the operator to screen for round window plugs or false membranes, found in approximately 10% and 20% of human temporal bones, respectively.[26] Endolymphatic hydrops may be correlated with patient symptoms by OCT imaging of the basal inner ear through a myringotomy or a tympanomeatal flap. Finally, as inner ear pharmocotherapy develops, OCT can potentially be used as a guide for intrascalar injections. In conclusion, catheter-based OCT has great potential for a variety of otologic procedures, as it allows unprecedented real-time viewing of microscopic structures of the middle and inner ear through a small, flexible catheter.

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