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ORIGINAL ARTICLE

Optical coherence tomography as an orientation guide in cochlear implant surgery?

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Abstract

Conclusion: With optical coherence tomography (OCT) it is basically possible to reveal parts of the cochlear morphology without opening its enveloping membranes. Thus, it may serve as a helpful guide for the surgeon to localize the scala tympani precisely before opening the fluid-filled inner ear to insert the electrode array. *Objective:* To improve anatomical orientation in cochlear implant surgery before definitively opening the fluid-filled inner ear. The question was whether a new imaging technique, OCT, might provide information about the site of the underlying inner ear structures (scala tympani, scala vestibuli) and could, consequently, guide the surgeon towards the scala tympani. *Materials and methods:* In a preliminary study, OCT was carried out on human temporal bone preparations, in which a cochleostomy ('fenestration') was performed leaving the endosteum and the fluid-filled inner ear intact. OCT was applied via a prototype of a specially equipped operating microscope. The mode of OCT used in this context was spectral-domain (SD)-OCT. *Results:* On scans, which can be read analogous to B-mode sonography, OCT provides information about structures on the inner surface of the partly exposed but still intact membranous cochlear lining – such as scala tympani or scala vestibuli.

Keywords: *Optical coherence tomography (OCT), inner ear topography, orientation guide to the scala tympani, cochlear implant insertion, residual hearing*

Introduction

Surgical techniques for cochlear implantation are widely standardized and accepted as safe. In the past, however, it was not imperative for these standards to be particularly high, since in the early years of cochlear implantation the electrode arrays were inserted into completely deaf ears, in which the cochlea more or less simply served as a sheath for the electrodes, i.e. the exact position of the electrode array was less critical, as the auditory nerve could be stimulated regardless of the fluid chamber into which the electrode was actually inserted. The requirement was, of course, to insert the array into the scala tympani, which every surgeon claimed to have done anyway. However, there was no real proof for this assumption. In recent studies, Aschendorff et al. could demonstrate by rotational tomography that in many cases the electrode finally was in the 'wrong' scala, without the surgeon having noticed this malposition [1]. As long as only really deaf ears were operated on, this was no disaster. However, in recent years the indication for cochlear implantation has been extended, and surgery has even been carried out on patients who still had significant residual hearing [2–6]. The idea of a bimodal electric and acoustic stimulation of the same ear has been gaining increased importance. In such cases it is essential to preserve the hearing function by (1) performing 'soft surgery technique' [7] and (2) strictly fulfilling the demand of inserting the electrode array into the 'correct' scala: the scala tympani. The question of specific landmarks became important again.

It is by no means easy or safe to predict the subjacent cochlear topography if only a small area of soft tissue encasing the fluid-filled inner ear is

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exposed. It would be helpful to know the exact projection of the basilar membrane on the exposed endosteum, which could then be opened precisely above the scala tympani.

In this paper the question is raised as to whether an additional imaging technique, optical coherence tomography (OCT), could be a tool to help visualize the site of the scalae through the intact soft tissue layer and, consequently, function as guide for the surgeon. OCT is an imaging technique that provides optical cross-sections of tissue structures, which can be read analogous to B-scan sonography [8]. Advantages of OCT over ultrasound are its higher resolution at about 10 µm or better (ultrasound: 100–200 µm) [9], the possibility of working in a non-contact mode and an easy integration of optical devices. The use of this technique in otolaryngology has been described elsewhere [10,11].

Materials and methods

Equipment for OCT

OCT is an interferometric method (Figure 1). To generate an OCT A-scan, light is split into probe and reference light. After reflection at the probe, the probe light is combined with the reference light by a beam splitter and registered by a detector, passed through a beam splitter and sent to the sample and a reference mirror. Reflections from the reference mirror and the sample are combined by a beam splitter and registered by a detector. Interference of low coherence light only occurs when the optical path length of reference and probe light are matched. This means that the position of the reference mirror determines the depth in the sample at which the magnitude of reflection is registered within the coherence length of the light source. Consequently, the difference Δz between the optical path of the reference and the probe light determines the depth in the sample at which the magnitude of reflection is registered.

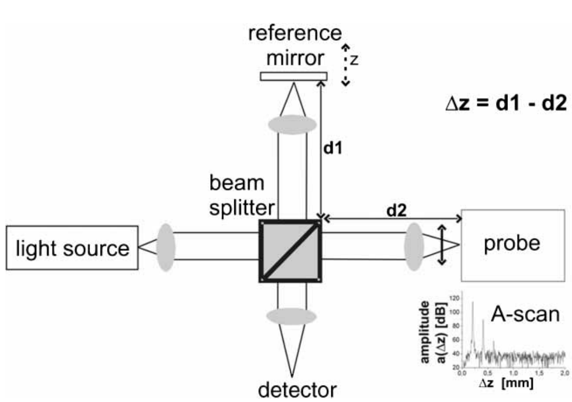

Figure 1. Schema of optical coherence tomography (OCT) (explanations are given in the text).

Scanning the sample beam along a transverse axis can be used to create a B-scan image where the measured amplitude is converted into a logarithmic gray scale.

Two different systems can be used for experiments: time-domain (TD)-OCT with a central wavelength of 1310 nm (Sirius, 4Optigs AG, Lübeck, Germany) and spectral-domain (SD)-OCT with a central wavelength of 930 nm (Thorlabs Inc., USA) [12–15].

To begin with, OCT systems were designed with a moving reference mirror. The system measures reflections, one after the other, from different depths in the tissue. The disadvantage of this TD-OCT was the complex set-up and limited scanning speed due to the moving mirror. By coupling a spectrometer to the interferometer a whole A-scan can be sampled at one time with increased signal to noise ratio. Up to 5000 A-scans per second can be acquired by SD-OCT.

The optical imaging technique can be applied in contact as well as in a non-contact mode. At the Institute for Biomedical Optics in Lübeck, a variety of applicators have recently been developed. For use in otolaryngology, besides the use of a small handpiece (Figure 2a) (the OCT measurement resolution: about 6 µm), two applicators are suitable: either a rod-lens endoscope modified for OCT (Figure 2b) with a measurement resolution of about 15 µm (TD-OCT endoscope, 0°, 3 mm diameter, length 300 mm; Richard Wolf GmbH, Knittlingen, Germany) or a specially adapted operating microscope (Figure 2c) with a measurement resolution of about 24 µm (Hi Res 1000, Möller Wedel GmbH, Wedel, Germany), which admits OCT scanning on any object in the centre of the field of vision on which the microscope is focused. Devices for all three options: handpiece, endoscope, and microscope are prototypes, not yet commercially available. As for the problem addressed, the operating microscope originally developed for OCT-guided brain tumor surgery [15] fulfils the requirements best, we consequently focused on that method. However, similar findings can also be obtained with the other applicators.

Preparation of temporal bones

The question addressed in this paper was whether or not the OCT could visualize intracochlear structures when applied from the outside of the intact membranous labyrinth. For this purpose special preparations were performed on three fresh or formalin-fixed human temporal bones from body donors from the Anatomical Institute of Rostock University.

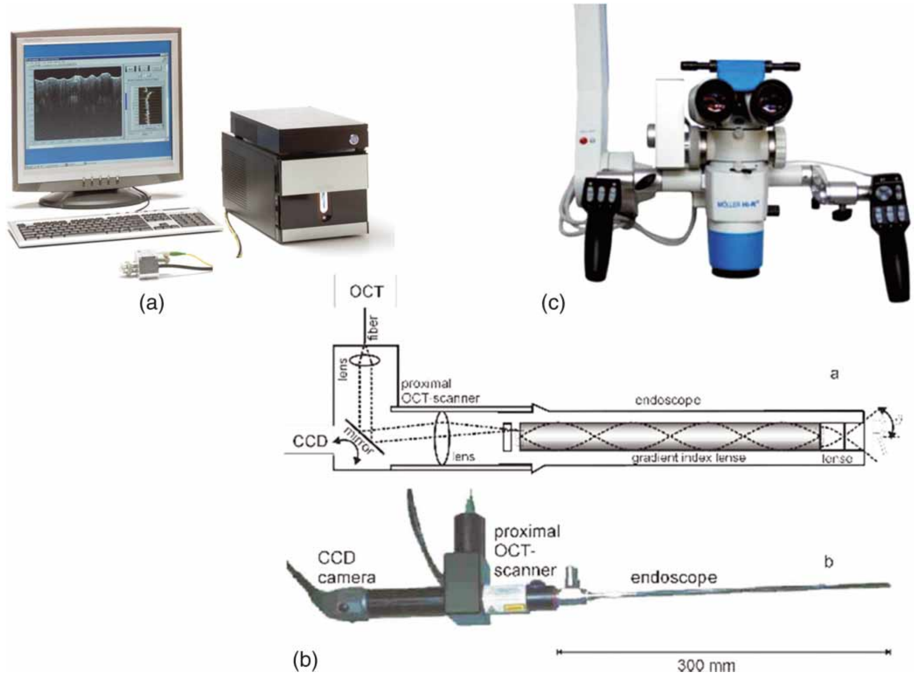

Figure 2. Different applicators for OCT. (a) A small handpiece (e.g. for applications in dermatology). (b) A modified rod lens endoscope (TD-OCT endoscope, 0°, 3 mm diameter, length 300 mm, Richard Wolf GmbH, Knittlingen, Germany). (c) A special OCT-adapted microscope, developed for OCT-guided tumor surgery of the brain (Hi Res 1000, Möller Wedel GmbH, Wedel, Germany).

To answer the basic question of feasibility, the first experiments were performed on temporal bone preparations, in which the outer and middle ear was removed in order to have the easiest possible access to the cochlea.

The medial wall of the tympanon was exposed by removing the outer ear canal with the tympanic membrane and the ossicular chain except the stapes, as described by our group in previous papers [16,17], for better accessibility in two temporal bone specimens (P1: formalin-fixed and P2: fresh – taken from the body 24 h after death, kept deep-frozen till 3 h prior to the preparation).

In both specimens the bone of the promontory was gradually removed by grinding with a 2 mm diamond bur, exposing the endosteum covering the lateral aspect of the basal cochlear turn in an area of approximately 1.5×1.5 mm (Figure 3). The membrane was left intact. For direct correlation between the cochlear anatomy and the structures shown on the OCT scan in one temporal bone specimen (P1) additional preparations were carried out. A vertical section at right angles divided the whole piece of bone with the basal cochlear turn anterior to the 'cochleostomy' (or, better, 'fenestration' [7]). This was achieved by a diamond thread saw. From this intersecting plane a cross-section of the basal cochlear turn became visible, and OCT images taken in the area of the fenestration could be compared and related to cochlear anatomy. In the third temporal bone (P3), preparations were performed as in real cochlear implant surgery, with a rather large posterior tympanotomy through which a fenestration of the cochlea was made at the typical cochleostomy site (inferior and anterior to the round window). In each experiment, the scanning axis for OCT via the operating microscope was perpendicular to the axis of the cochlear turn and, thus, transverse to the lateral aspect of the basilar

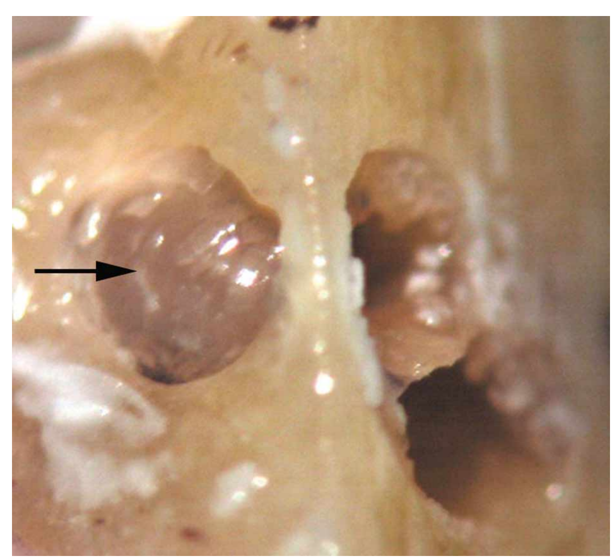

Figure 3. Temporal bone preparation (formalin-fixed temporal bone specimen, P1) with the cochlear endosteum exposed to the extent of approximately 1.5×1.5 mm (arrow). Slightly anterior to this 'fenestration' a cross-section through the temporal bone reveals the cochlear anatomy.

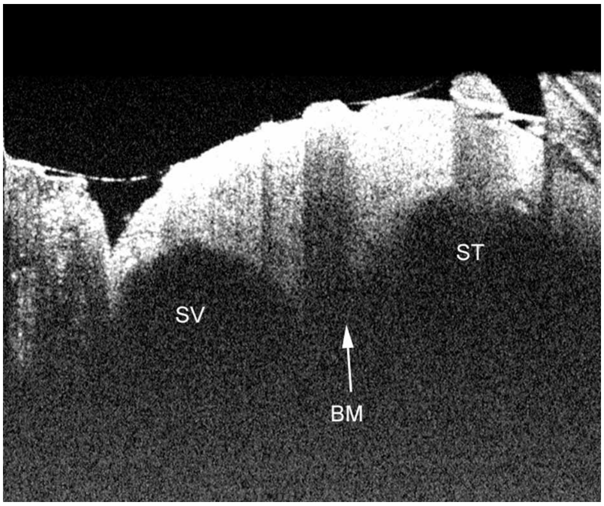

Figure 4. OCT scan representing a vertical cross-section through the lateral part of the cochlea in the formalin-fixed temporal bone (P1). The membranous sheath of the cochlea can be seen between two portions of bone bordering the 'fenestration' (left and right). The lateral borders of the scalae (SV = scala vestibuli, ST = scala tympani) can be detected with the 'ridge' of the basilar membrane (BM) in between (arrow).

membrane. The images obtained during OCT recordings were stored digitally.

Results

The bone window (fenestration) can be demonstrated easily in each of the specimens on the OCT images. A typical SD-OCT B-scan is shown in Figure 4 (P1). Between the 'echoes' of the two sections of bone – left and right side of the image – the membranous labyrinth (mainly spiral ligament) is visible in the form of a very dense structure convex to the outside. The medial aspect of this structure has a characteristic pattern: the borderline towards the inside has two concavities. The structure between these concavities has the shape of a ridge (arrow), the top of which cannot be seen as the signals vanish in the depth. This 'ridge' represents the complex of the basilar membrane and the structures enclosing the scala media. The two concavities represent the lateral aspects of the scala tympani (ST) and scala vestibuli (SV). On some scans even the continuation of the membrane underneath the bone at the very edge of the fenestration can be displayed. Figure 5 shows the comparison of the SD-OCT B-scan and the aspect of the cochlear cross-section laid open on the perpendicular intersecting plane, thereby demonstrating the usefulness of this new imaging technique.

Even more cochlear structures can be seen on the fresh temporal bone preparation (P2) (Figure 6). While the enveloping membranes seem less compact than those of the formalin-fixed specimen, even such delicate structures as the boundaries of the scala media (RM = Reissner′s membrane) are revealed. Unfortunately, however, it was not possible to provide a comparison of the OCT scan and the anatomical situs in this case, because in this fresh temporal bone specimen the scala media collapsed,

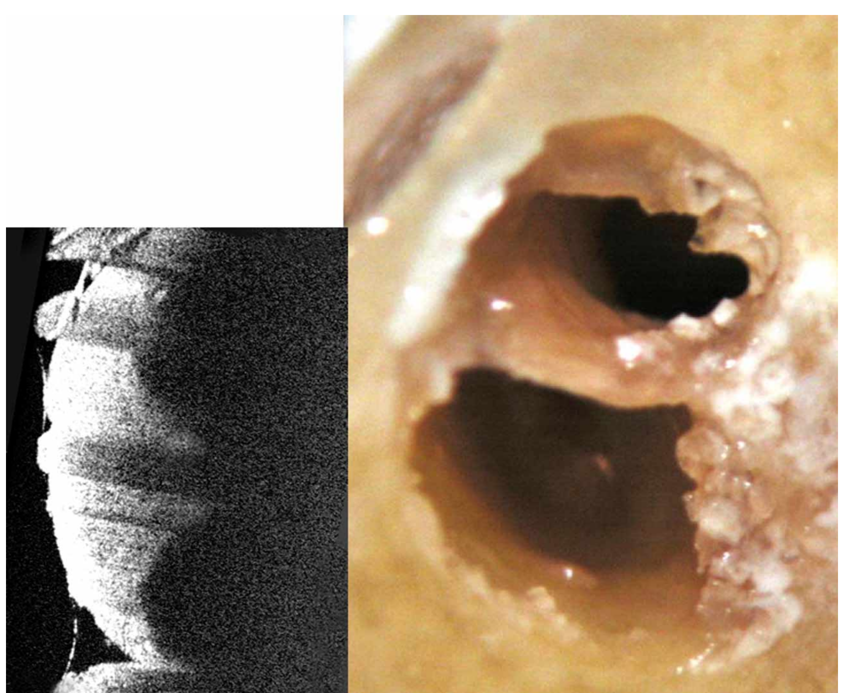

Figure 5. Comparison of the OCT 'echoes' and the underlying anatomical structures (cross-section of the basal cochlear turn (P1)).

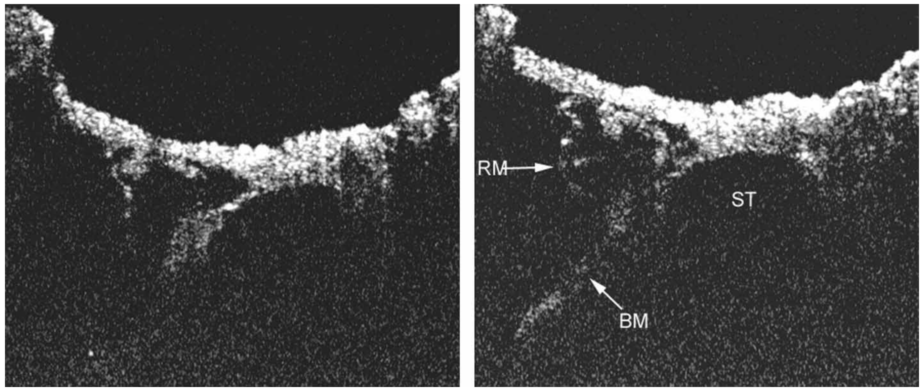

Figure 6. OCT scan of the lateral part of the exposed cochlea in a fresh temporal bone (P2). Besides the projections of the scalae some fine structures within the cochlear can be identified: the triangular cross-section of the scala media with the Reissner's membrane. SV, scala vestibule; ST, scala tympani; RM, Reissner's membrane; BM, basilar membrane.

when the bone was dissected. So far, we have not been able to preserve Reissner's membrane while cutting fresh cadaver cochleae with a saw.

In the third fresh temporal bone (P3) the access was comparable to real cochlear implant surgery. The intact endosteum was watched and scanned through the posterior tympanotomy. Figure 7 shows that basically it is possible to visualize the lateral view of the cochlea even in this more difficult condition with regard to the narrower access. However, further developments of the prototype seem necessary to improve the quality of the scans.

Intracochlear structures could be visualized in each of the preparations examined. The number of temporal bones was limited to three, as the problem addressed was the very basic question of whether the new technique may help to visualize structures beyond the membranous surface for better orientation or not. The results reveal that the answer to this question is definitely yes.

Discussion

Most surgeons expose the basal turn of the cochlea by drilling a cochleostomy hole through the bone of the promontory. There are clear surgical instructions for that approach: Drilling should be started from a level inferior/anterior to the round window moving the drill slightly upwards, thus exposing the scala tympani from below. If possible, the membrane ('endosteum') covering the basal turn should be left intact until it is exposed in sufficient size to allow the insertion of the electrode array. Particularly when surgery is performed for electric-acoustic stimulation (EAS) in ears with a significant residual hearing of the low frequencies, those membranes should be

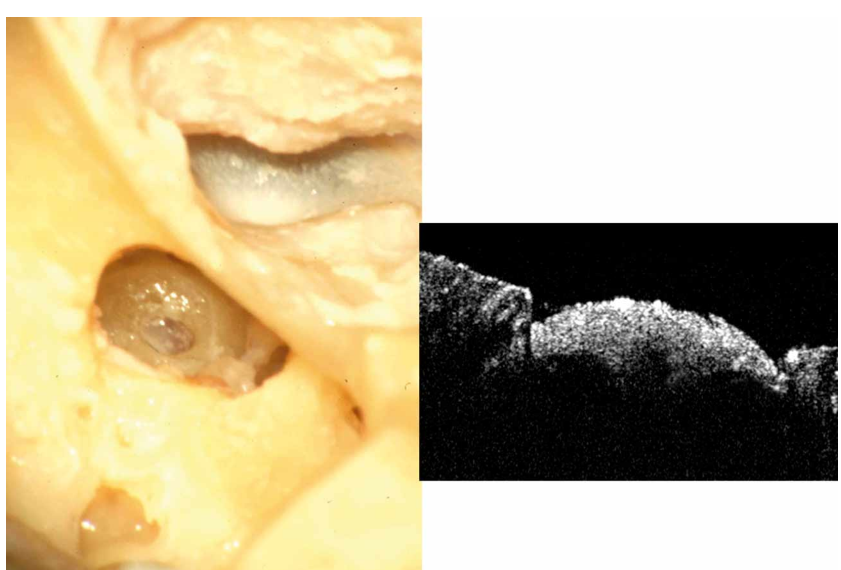

Figure 7. Aspect of the exposed cochlear endosteum through the posterior tympanotomy and the corresponding OCT scan (P3).

Figure 8. Exposed endosteum during 'live' cochlear implant surgery. A surgical instrument points at the intact membrane.

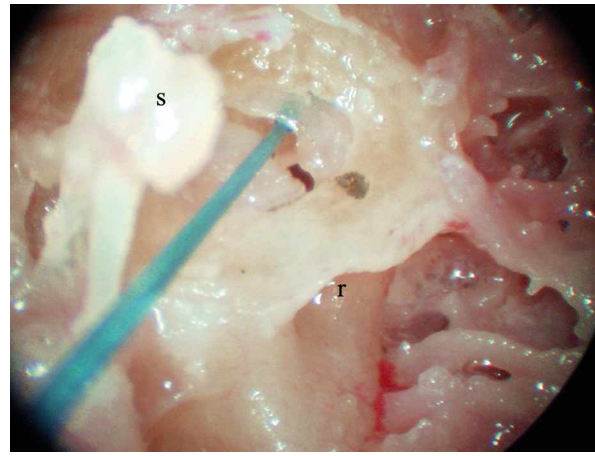

Figure 10. Temporal bone preparation demonstrating the anatomy of the basal cochlear turn with regard to the position of the basilar membrane. Both scalae are opened; a probe is introduced into the scala vestibule. s, stapes; r, round window.

opened in a controlled and careful manner using special instruments [18]. Figure 8 shows an intraoperative view of the still-intact 'endosteum' in 'live' cochlear implant surgery. However, at that very point the surgeon has no actual information about the anatomical site of the scalae or the lateral projection of the basilar membrane.

Figure 9 demonstrates an intraoperative situation in which both scalae were involuntarily opened, exposing the basilar membrane and at least damaging it locally. It has to be considered that in the lateral aspect of the basal cochlear turn the scala vestibuli can be exposed much more easily owing to its more superficial position. There is a specific angle between the plane of the basilar membrane and the promontorial bone, which can even vary individually. In a previous temporal bone study we exposed the basal cochlear turn just to recall this situation (Figure 10).

Figure 9. During cochlear implant surgery, both scalae were accidentally opened – exposing the basilar membrane in between.

We consider it of great advantage for the surgeon to know the anatomical site of the scalae/projection of the basilar membrane for the 'correct' insertion prior to opening the membranous cochlear walls. In this situation the new imaging technique, OCT, might be a helpful instrument.

In other concepts for cochlear implantation this additional support may be even more important. For cases with residual hearing, Lehnhardt et al. developed the idea of an endosteal electrode [19]. In such cases a very flat electrode array should be inserted into the crevice between the bony cochlear capsule and the spiral ligament without opening the fluid-filled inner ear. This might potentially reduce the inner ear trauma and preserve the hearing function better. In preliminary feasibility studies we could demonstrate that it is indeed possible to introduce an electrode array this way [16,17]. However, in such cases it is essential to know which part of the exposed soft tissue membrane is sufficiently thick (spiral ligament) to offer enough resistance to the electrode and prevent it from penetrating into the lumen, or which is too thin. Lehnhardt et al. did some experiments which were based on laser-Doppler-sonography [19]. At least in guinea pigs they could localize the stria vascularis as an indicator for the 'thick part' of the lateral membranous cochlear boundaries. With our new technique it should be much easier to localize specific structures.

The images presented in this preliminary report show that OCT may offer further information about cochlear structures without definitively opening the fluid-filled inner ear. However, the quality of the scans varies with the width of the exposure. In the third experiment, using the same access as in live surgery, the method reaches its limits. The prototype of the operating microscope equipped with OCT will be improved in the near future by adding a reference laser, the beam of which will be a precise indicator for the area being scanned. Moreover, the optical strength of OCT will be increased.

The method for this particular indication is still at an experimental stage. The most promising option is the use of OCT via the specially equipped operating microscope, which is already in an advanced stage of development. The advantage of the method – when compared with sonography – is that it can be applied in a non-contact mode and can be performed easily during surgery without having to leave the operating microscope.

We do think that intraoperative OCT might contribute significantly to the safety of cochlear implant surgery in terms of 'hitting' the 'right' scala. However, this is just a very preliminary report showing the basic feasibility. The development of the OCT-equipped operating microscope has to be enhanced further to allow its use in the temporal bone laboratory on a larger series of temporal bones – and later in the operating theatre during cochlear implant surgery.

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