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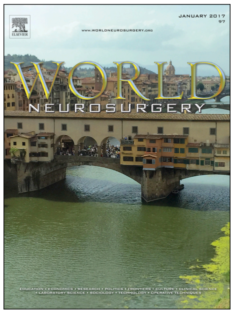


Novel multiportal approach to the internal auditory canal for hearing-preserving surgery: feasibility assessment in dissections

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Short title: Multiport approach to the IAC

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# Abstract

### Objective

State-of-the-art minimally invasive endoscopic transcanal surgery of the internal auditory canal (IAC) sacrifices the cochlea with complete hearing loss. With a combination of the transcanal infracochlear- and transmastoid retrolabyrinthine approaches, we aim to preserve hearing and enable minimally invasive surgical treatment of vestibular schwannoma. In this study, we investigate the anatomical indications and the feasibility of both approaches in dissections in human whole head specimens.

### Methods

We operated whole head anatomical specimens with a four-handed technique, using the retrolabyrinthine approach as the main surgical corridor and the infracochlear approach for endoscopic visualization. We tested four different powered surgical systems. We collected intraoperative data on the size of the access windows, the surgical freedom, and the exposed area of the IAC. Finally, we evaluated the outcome in postoperative computed tomography (CT) scans.

### Results

Six out of 14 sides were anatomically suitable and qualified for the surgery based on preoperative CT. In all attempted sides, the IAC could be reached and opened, leaving the ossicular chain and the labyrinth intact. 51% to 75% of the length and 22% to 40% of the circumference of the IAC could be exposed. All tested instruments were beneficial at different stages of the surgery. The four-handed technique enabled good maneuverability of the instruments.

### Conclusions

The combined multiportal approach to the IAC is feasible with a good surgical exposure and full anatomical preservation of hearing. State-of-the-art surgical instruments in specimens with suitable anatomy are sufficient to perform this approach.

## Introduction

Vestibular Schwannoma (VS) are benign tumors most frequently arising from the inferior vestibular nerve. They can cause deterioration of inner ear functions due to tumor growth and compression of the content of the internal auditory canal (IAC) [1], [2]. In progressive tumors, surgical treatment is usually advocated to prevent symptoms related to tumor growth over time [3], [4]. Traditional microscopic approaches include the middle cranial fossa approach, the retrosigmoid approach, or the translabyrinthine approach. These approaches are associated with operative morbidity following craniotomies, brain retraction, or the removal of the labyrinth, respectively [5], [6].

Minimally invasive endoscopic and endoscope-assisted transcanal approaches have become a valuable alternative [7]. However, the direct access through the promontory sacrifices the cochlea, limiting the indication for transcanal approaches [8] – [11]. Especially in young and well-hearing patients, minimally invasive surgical removal of small VS may be beneficial for long-term hearing prevention. More so, as recent follow-up studies have shown long-term hearing deterioration after stereotactic radiosurgery [12].

In a recent study, we examined the feasibility of two promising minimally invasive approaches to the IAC [13]. Firstly, the approach consists of an infracochlear route. Its concept is well known for many years and was re-popularized by Ghorayeb and Jahsdoerfer for the drainage of petrous apex cholesterol granulomas [14]. However, this microscopic approach required the lowering of the external auditory canal. Recent technical developments allowed the introduction of an exclusively endoscopic transcanal infracochlear approach [15]. The second approach, is also well described in literature and consists of an endoscope-assisted transmastoid retrolabyrinthine approach [16] – [18]. Although both concepts date back for more than 80 years, its combination and the versatile use of the endoscope, allows a thorough access to the IAC. Both approaches preserve the inner and middle ear and are free from craniotomies. However, anatomical structures including the labyrinth, the internal carotid artery (ICA), the jugular bulb (JB), and the facial nerve (FN) limit the surgical corridors. Therefore, we previously measured the maximal extensions of the surgical access windows in 3D surface models and found that the approaches could be feasible in approximately 80% of the measured cohort [13]. In the present study, we follow up on those results with dissections and measurements in human whole head specimens. The goal of this study is to assess the feasibility of this multiportal approach in human specimens and to identify and specify instruments needed to safely perform the herein described minimally invasive approach to the IAC.

# Materials and methods

## Surgical approaches and surgical setup (devices and instruments)

The corridor of the exclusively endoscopic transcanal infracochlear approach runs through the external auditory canal (EAC), passes the cochlear basal turn inferiorly, and turns around the cochlea to access the IAC from below [15], [19] (Figure 1A&B). This approach is anatomically limited by an access window between the cochlea superiorly, the ICA anteriorly, the JB inferiorly, and the FN posteriorly [13], [19] (Figure 1C).

The transmastoid retrolabyrinthine approach (also referred to as retrofacial or infralabyrinthine approach) requires both microscopes for the work in the mastoid and endoscopes for the work within the middle ear and the inferior petrous apex. Its corridor runs through the mastoid part of the temporal bone, passes the labyrinth inferiorly between the JB and the mastoid segment of the FN, and turns around the posterior semicircular canal (pSCC) to access the IAC from below [16], [17], [20], [21] (Figure 1A&B). This approach is anatomically limited by an access window between the pSCC superiorly, the mastoid segment of the FN anteriorly, the JB inferiorly, and the posterior cranial fossa dura (pCFD) posteriorly [13], [22] (Figure 1D).

The skeletonization and exposure of the IAC in this multiport approach is the key surgical step to enable precise dissection of the tumor and therefore successfully preserve hearing. The combination of the approaches allows the surgeon to work around the cochlea (in the infracochlear approach) and the pSCC (in the retrolabyrinthine approach). However, bent powered instruments are required to remove the bone covering the IAC. To allow sufficient space for the introduction of the endoscope and powered instruments a minimal diameter of 6mm for the retrolabyrinthine access window was set. Accordingly, we tested a variety of different devices and instruments that allow visualizing and working within bent corridors. For visualization, we used a surgical microscope (Leica, Germany) and 0° straight and 45° angled endoscopes (2.7 mm diameter and 140 mm long Hopkins® Telescopes, Karl Storz SE & Co. KG, Germany). For bone removal, we used standard otological burs (OsseoDuo control unit, Nano micromotor and PM2 handpiece, Bien-Air Surgery SA, Switzerland), 15° angled anterior skull base burs (Integrated Power Console (IPC™) control unit, and StraightShot™ M5 microdebrider handpiece, Medtronic, USA), a microdrill system (OsseoDuo control unit and OsseoStap handpiece, Bien-Air Surgery SA, Switzerland), and a Piezosurgery device (Piezosurgery® plus, Mectron s.p.a., Italy). For orientation and monitoring of the instrument location, we used a surgical navigation system (Brainlab Kolibri, Brainlab AG, Germany). Additionally, we used modified passive instruments such as a bent curette and bent suction tubes. The complete setup is shown in Figure 2.

## Specimen selection

We prepared 7 randomly selected human cadaver heads (14 sides) for screw navigation by placing 5 screws per side around the auricula and in the mastoid, followed by a preoperative high-resolution computed tomography (CT) scan (voxel size of 0.156 x 0.156 x 0.2 $mm^3$, SOMATOM Definition Edge, Siemens AG, Germany). Based on the CT scans, we determined the limiting access window extensions $RW - JB$ and $pSCC - JB$, respectively, as suggested by previous research [13], [22] (Figure 1B&C). 8 sides with less than 6 mm extension were excluded. The remaining 6 sides received complete image-guided surgery with both approaches, the transcanal infracochlear approach, and the transmastoid retrolabyrinthine approach. The proposed study was approved by our institutional review board (KEK-BE 2016-00887).

## Surgical technique

To optimally work within the restricted surgical area, we aim at a multiport approach in which the transcanal infracochlear approach is mainly used to introduce 0° and 45° endoscopes to visualize the surgical site and the transmastoid retrolabyrinthine approach is used to introduce powered instruments and suction to remove the bone around the IAC. This four-handed technique is shown in Figure 2C. The surgical steps were performed as follows (Figure 3):

A. Retroauricular c-shaped incision followed by incision of the musculoperiost with exposure of the planum mastoidale.

B. Mastoidectomy with identification of incus and lateral SCC, thinning of the posterior EAC wall, and skeletonization of the sigmoid sinus and the digastric ridge.

C. Drilling of the retrolabyrinthine access window with skeletonization of the pSCC, the mastoid portion of the FN, the JB, and the pCFD.

D. Incision of the EAC and raise of a tympanomeatal flap

E. Inferior canaloplasty followed by idenfification and skeletonization of the cochlear basal turn.

F. Drilling of the infracochlear access window with skeletonization of the ICA, the JB and the FN.

G. Connection of both access windows and the opening of the cavity for the multiport approach.

H. Progressive skeletonization of the IAC and posterior fossa dura with the four-handed technique.

I. Incision of IAC dura and exploration of its contents as well as cerebellopontine angle.

## Measurement procedure

We measured several parameters related to the surgical corridors and the exposure of the surgical site including the surgical access windows, the surgical freedom, and the exposed area of the IAC and the dura.

### Surgical access windows

We selected landmarks according to the structures that limit the surgical corridors and define the access windows in analogy with measurements taken from 3D surface models in our previous study [13]. For the transcanal infracochlear approach (Figure 1C):

- the center of the round window ($P_{RW}$)
- the most posterior point of the ICA at the axial level of the bony annulus ($P_{ICA}$)
- the JB dome, i.e., the most superior point of the JB ($P_{JB}$)
- the FN at the axial level centered between the JB and the labyrinth ($P_{FN}$)

with the surgical window extensions

- vertical extension (i.e., from superior to inferior limit) between $P_{RW} - P_{JB}$
- lateral extension (i.e., from posterior to anterior limit) between $P_{FN} - P_{ICA}$.

For the transmastoid retrolabyrinthine approach:

- the most inferior point of the pSCC ($P_{pSCC}$)
- the FN at $P_{FN}$
- the JB dome at $P_{JB}$
- the pCFD at the axial and sagittal level of $P_{FN}$ ($P_{pCFD}$).

with the surgical window extensions

- vertical extension between $P_{pSCC} - P_{JB}$
- lateral extension between $P_{pCFD} - P_{FN}$.

**Surgical freedom**

The surgical freedom (SF) is the maximum degree of movement for the handle of a surgical instrument [23]. It is represented as the effective area reachable with a cranial pointer (200 mm length) when the tip is placed on the target of interest and the handle moved to the extreme anterior, inferior, posterior, and superior limit of the surgical access (refer to [23] or [24] for a visualization). We selected the inferior border of the porus of the IAC as the target and assessed the SF for the retrolabyrinthine approach, as this is our primary work corridor regarding instrumentation.

**Area of exposure**

The area of exposure (AOE) is defined as the area reachable with the tip of a cranial pointer for a specific approach at a target region [23]. Here, we approximate the AOE of the IAC and the posterior fossa dura covering the cerebellopontine angle (CPA) with the area within a set of 12 points registered around the exposed area of the IAC and CPA dura, respectively. Additionally, we report the lateral and the vertical extension of the exposed area, measured at:

- the most medial exposed point ($P_{med}$)
- the most lateral exposed point ($P_{lat}$)

- the most superior exposed point on a vertical line from $P_{med}$ and $P_{lat}$ ($P_{sup}$)
- the most inferior exposed point on a vertical line from $P_{med}$ and $P_{lat}$ ($P_{inf}$).

with the extensions

- vertical extension between $P_{inf} - P_{sup}$
- lateral extension between $P_{med} - P_{lat}$.

All measurements were taken with the Brainlab navigation system. The surgeon pointed at each point once to register the coordinates. Figure 5 illustrates the assessment of the surgical access window and the AOE of the IAC in the specimens. The data were exported to MATLAB (The MathWorks Inc., Natick, MA) for further processing. 3D surface models used in the figures were prepared with a threshold-based segmentation software (Amira, FEI, Bordeaux, France).

**Exposed IAC length**

We measured the length of the IAC in all specimens in the preoperative and the postoperative CT scans. The length was taken from the posterior wall of the IAC and defined as the distance from the most lateral point of the posterior wall to the most medial point of the posterior wall, measured on an axial slice at the level of the lateral SCC (illustrated in Figure 4A&B). The exposed IAC length is calculated as the ratio between the remaining and the original IAC length.

**Exposed IAC circumference**

For this measurement, we approximate the IAC as a cone with a circular base. A circle is fit into the IAC on a sagittal slice at the level of the most medial point of the basal cochlear turn (Figure 4C). The access angle is defined as the angle between the two lines that connect the center of the circle with the most anterior and posterior parts of the open IAC, respectively (Figure 4D). The exposed IAC circumference is calculated as the ratio between the access angle and the full circle.

# Results

## Instrument selection

Both approaches could be successfully finished with the proposed selection of instruments. For the general access, i.e., the mastoidectomy and widening of the EAC, standard high-speed drills were used. For the delicate work within the middle and inner ear, the surgeon can benefit from the four-handed technique and the bent powered instruments to widely expose the IAC and CPA dura. The advantages and disadvantages of the used instruments are summarized in Table 1 (for photos of the instruments, see Figure 2).

## Intraoperative measurements

The access windows of the transcanal infracochlear approach extend between 11.3 ± 1.8 mm in lateral and 8.2 ± 1.3 mm in the vertical direction. The access windows of the transmastoid retrolabyrinthine approach extend between 11.5 ± 1.6 mm in lateral and 11.6 ± 2.8 mm in the vertical direction. The surgical freedom of the transmastoid retrolabyrinthine approach varies greatly between subjects and ranges within 981.1 ± 606.7 $mm^2$. The IAC can be exposed over an area of 38.6 ± 5.6 $mm^2$ with a lateral extension of 11.3 ± 2.1 mm and a vertical extension of 5.7 ± 0.6 mm. The dura can be exposed over an area of 231.0 ± 74.3 $mm^2$ with a lateral extension of 23.5 ± 4.9 mm and a vertical extension of 16.1 ± 4.3 mm. All measured data are summarized in Table 2.

## Postoperative analysis

The postoperative CT scans in Figure 6 show the area from which bone can be removed. In all included sides, the IAC could be accessed through the retrolabyrinthine approach. The porus could be reached more easily than the fundus: the remaining length was located at the fundus in all cases and ranged between 1.9 mm and 5.5 mm, i.e., 51% to 75% exposure of the full length. The full length of the IAC before the surgery was between 8.6 mm and 11.2 mm. The exposed circumference at the level of the medial end of the cochlea ranged between 22% to 40% of the circular cross-section of the IAC with access angles from 80° to 145°. All measured data are summarized in Table 3. From the images we can also conclude that no mechanical damage occurred at the cochlea, the pSCC, the FN, or any blood vessel. In contrast, the cochlea and the posterior semicircular canals could be fully skeletonized.

## Discussion

In the present study, we examined the feasibility of a minimally-invasive multiport approach to the IAC taking advantage of combining two hearing-preserving surgical approaches: the fully endoscopic transcanal infracochlear approach and the endoscope-assisted transmastoid retrolabyrinthine approach. In 6 dissections, we tested a variety of commercially available surgical devices and qualitatively assessed their suitability. After completion of the dissections, we measured the extensions of the surgical access windows, the surgical freedom, and the area of exposure of the IAC to provide comparable measures with regard to traditional approaches.

For the infracochlear approach, only one single case with near-total cochlea preservation [25] and few cadaver studies for vestibular schwannoma resection [15], [19] have been presented. The retrolabyrinthine approach has received more, but controversial, interest: reports of successful interventions with regards to hearing preservation [16], [18], [21] are put into question because subjects were selected based on favorable anatomy [26]. In line with this, we selected specimens based on their anatomy. Relying on earlier studies [21], we originally aimed to include all specimens with more than 3mm between RW and JB dome. However, the use of 2.7mm endoscopes along with powered instruments require in our opinion a larger access corridor. The access relies on thorough visualization of the field and precise bone removal, requiring a slightly larger corridor. With increasing experience, this cut-off may be lowered again according to the subjective judgment of the surgeon. With this newly gained insight, we increased this cut-off to at least 6mm, allowing us to include 6 of 14 sides. While this shows that the investigated approaches are not indicated in all cases, we strongly believe in the potential for those who are eligible. Especially, since it has been emphasized in a recent consensus statement, that the preservation of facial and cochlear function and thus maintaining patients' quality of life is crucial for surgical VS management [27]. The indications for this approach would be small (Koos grade I and II) up to selected Koos Grade III VS with limited extension to the cerebello-pontine angle. Treatment indications of course would not be changed by the approach itself and remain reserved for growing VS as depicted in serial MRI scans. In our opinion the approach would be particularly suitable for young patients with serviceable hearing as minimally-invasive strategy to remove the tumor and conserve cochlear function. As assessed by postoperative CT scan, the structural integrity of the hearing system was demonstrated. However, the preservation of hearing function in a clinical setting cannot be claimed from the present study on anatomical specimens.

In the following, the results from the included specimens are discussed. The dissections confirm earlier reports that a high JB or limited space between the sigmoid sinus and pSCC were the main bottlenecks and a possible cause for unsuccessful interventions [17], [22], [28], [29]. The access corridor of the infracochlear approach was limited by the vertical extension ranging at 8.2 ± 1.8 mm. For the retrolabyrinthine approach, the limiting lateral extension ranged at 11.5 ± 1.6 mm. Both lengths are slightly lower than what we found in the matching 3D models (8.8 ± 1.4 mm and 12.1 ± 1.5 mm). The measurements in the 3D models were taken directly on the selected structures. The measurements in the dissections are taken from points closest to the selected structures, which are still covered with a thin bone layer. This likely explains the discrepancy. Comparable literature defined the access windows between the labyrinth, the JB, the FN, and the pCFD and found smaller extensions in general. Vertical extensions were measured as $vestibule - JB$ (5.8 ± 2.1 mm) [22] or $pSCC - JBdome$ (4.6 ± 3.5 mm [30]). Lateral extensions were measured as $FN - pCFD$ (5.7 ± 1.5 mm) or $FN - SigmoidSinus$ (8.40 ± 2.74 mm) [28]. While this must be viewed with caution as we selected specimens with favorable anatomy, our earlier study showed sufficiently large access windows, i.e., 6mm and more, in approximately 60% of the measured cohort [13]. Additionally, the different types of specimens (dry temporal bones [22] vs. Thiel soft-fixed in this study) likely biases the measurement due to the shrinking of dry specimens.

During the dissections, we experienced good accessibility of large parts of the IAC. The exposure of the IAC ranged at 38.6 ± 5.6 $mm^2$ and more than 50% of the posterior wall of the IAC could be exposed in all specimens. Towards the fundus, the measurements intraoperatively showed limited access. This is because the fundus is located directly behind the cochlea, which needs to be preserved. However, this limitation could be overcome using angled endoscopes and dissectors, allowing the exploration of the full IAC fundus including the falciform crest and Bills bar. Similar findings are reported in various studies [17], [19], [20], [26], [31]. For example, an average exposure of 73% of the IAC was reported in 16 of 20 dissections of cadaveric temporal bones [30] and approximately 73% of the IAC could potentially be exposed via infracochlear approach when analyzed in CT scans [29]. The same authors state that this exposure can be predicted using preoperative CT. We experienced a similar outcome as possible candidates for the surgery could be accurately determined based on preoperative CT scans. We further found that the access of the fundus is better through the retrolabyrinthine approach as the angle of the approach with respect to the IAC is different between the two approaches. The retrolabyrinthine approach allowed for more exposure of the IAC and a focus on the posterior wall while the infracochlear approach allowed better exposure of the inferior wall of the IAC. Thus, in the experience from this dissection the infracochlear approach can mainly be used to visualize the surgical site and free valuable room for surgical freedom in the retrolabyrinthine corridor.

The postoperative CT scans show that a large amount of bone can be safely removed, and thus, a large access angle and a large range of motion can be achieved with the combination of both approaches. Large space can be freed with minimal risks, especially towards the CPA dura. This eases the work around the delicate structure in the middle and inner ear and opens the door for resecting of schwannomas extending to the CPA. For the drilling of the multiport cavity and the skeletonization of the dura, the navigation system, and the possibility to visualize the surgical site through the infracochlear approach were essential.

We were surprised by the effectiveness of the used instruments. All are off-the-shelf instruments for lateral or anterior skull base surgery. With a focus on the delicate work around the cochlea, the bent drills and Piezosurgery devices provided enough curvature to access the IAC within an acceptable time. A single surgery could be completed in approximately 2 hours. Problems mainly occurred because the tips of the instruments were too short, rather than of a wrong shape. The handpieces, i.e., the part held by the surgeon, were too wide and limited the range of motion. However, the dissection and removal of tumors from the IAC and CPA will require bent dissectors and micro-instruments, especially to access the IAC fundus as available by various manufacturers. Reaching locations closer to the fundus will eventually depend on advancements in endoscope technology and new angled instruments to expose and access the IAC from below. Our self-made passive instruments allowed to reach closer to the fundus. Other groups who report successful retrolabyrinthine surgeries used self-designed angled suction curettes [17] and other angled instruments [20] to resect tumors from the IAC.

## Conclusion

We believe that the investigated approaches can be used in certain cases with today's standard otological and lateral skull base instruments with one main indicator being the height of the JB that must be assessed preoperatively. To increase the number of potential users, further experience is required to, firstly, push the boundaries of the indication and, secondly, establish a clear set of requirements for powered surgical tools, which will allow treating more patients in return.

## Acknowledgments

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Furthermore, LA is a consultant für Stryker ENT.

# Tables

*Table 1: Experience gained from working with different instruments.*

| Name of instrument | Advantages | Disadvantages | Comments |
|---|---|---|---|
| Piezosurgery device | • Underwater technique<br>• Delicate bone removal with preservation of soft tissue (e.g. dura) | • Slow bone removal<br>• Possible sensorineural hearing loss when used on the cochlea [32], [ 33]<br>• Angulation insufficient for fundus | Ideal for bone removal transcanal and confection of infracochelar acces window and for bone removal from dura |
| Microdrill | • Protected shaft<br>• Small instrument tip<br>• Cutting and diamond drill bits available<br>• Low drill speed | • Slow bone removal<br>• Drill tip slips with increasing pressure<br>• Additional irrigation needed | Ideal for bone removal from cochlea or posterior SCC |
| Standard high-speed drill | • Fast bone removal | • Heating of tissue<br>• No protected shaft | Ideal for retrolabyrinthine access window |
| Angled anterior skull base burs | • Fast bone removal<br>• Included suction and irrigation | • Smallest drill bit available 3mm | Ideal curvature for IAC fundus and ideal for four-handed technique |

*Table 2: Results from intraoperative measurements including extensions of the surgical access windows, the surgical freedom, the extension of the exposed area, and the area of exposure.*

| | Individual specimens (L: left, R: right) | | | | | | **mean** | **sd** |
|---|---|---|---|---|---|---|---|---|
| | 1R | 1L | 2R | 3R | 3L | 4R | | |
| Lateral access window extension, infracochelar approach [mm] | 11.1 | 9.7 | 14.3 | 12.1 | 9.1 | 11.5 | **11.3** | **1.8** |
| Vertical access window extension, infracochelar approach [mm] | 7.1 | 7.3 | 6.8 | 8.5 | 9.9 | 9.6 | **8.2** | **1.3** |
| Lateral access window extension, retrolabyrinthine approach [mm] | 11.2 | 13.9 | 9.0 | 12.3 | 11.4 | 11.0 | **11.5** | **1.6** |
| Vertical access window extension, retrolabyrinthine approach [mm] | 11.6 | 10.1 | 9.4 | 17.0 | 10.6 | 11.2 | **11.6** | **2.8** |
| Surgical freedom, retrolabyrinthine approach [mm²] | 750.5 | 502.3 | 589.1 | 692.9 | 1254.1 | 2097.6 | **981.1** | **606.7** |
| Lateral extension exposed area, internal auditory canal [mm] | 13.8 | 13.1 | 10.3 | 12.6 | 8.9 | 9.2 | **11.3** | **2.1** |
| Vertical extension exposed area, internal auditory canal [mm] | 6.0 | 6.0 | 4.7 | 5.5 | 6.4 | 5.5 | **5.7** | **0.6** |
| Area of exposure, internal auditory canal [mm²] | 44.5 | 34.2 | 37.7 | 46.5 | 35.4 | 33.2 | **38.6** | **5.6** |
| Lateral extension exposed area, cerebellopontine angle dura [mm] | 24.4 | 28.9 | 24.3 | 19.8 | 27.5 | 15.8 | **23.5** | **4.9** |
| Vertical extension exposed area, cerebellopontine angle dura [mm] | 22.9 | 17.1 | 12.0 | 17.7 | 16.2 | 11.0 | **16.1** | **4.3** |
| Area of exposure, cerebellopontine angle dura [mm²] | 305.7 | 255.7 | 157.5 | 236.8 | 303.1 | 127.3 | **231.0** | **74.3** |

*Table 3: Results from measurements in preoperative and postoperative computed tomography images, evaluating the exposure of the internal auditory canal.*

| | Individual specimens (L: left, R: right) | | | | | | **mean** | **sd** |
|---|---|---|---|---|---|---|---|---|
| | 1R | 1L | 2R | 3R | 3L | 4R | | |
| Preoperative length [mm] | 8.6 | 11.2 | 10.3 | 9.9 | 9.1 | 8.7 | **9.6** | **1.0** |
| Postoperative length [mm] | 3 | 5.5 | 3.1 | 3.4 | 1.9 | 3.4 | **3.4** | **1.2** |
| Exposed length ratio [%] | 65 | 51 | 70 | 66 | 75 | 61 | **65** | **9** |
| Access angle [°] | 120 | 95 | 80 | 105 | 145 | 85 | **105** | **25** |
| Exposed circumference ratio [%] | 33 | 26 | 22 | 29 | 40 | 24 | **29** | **7** |

## Figures

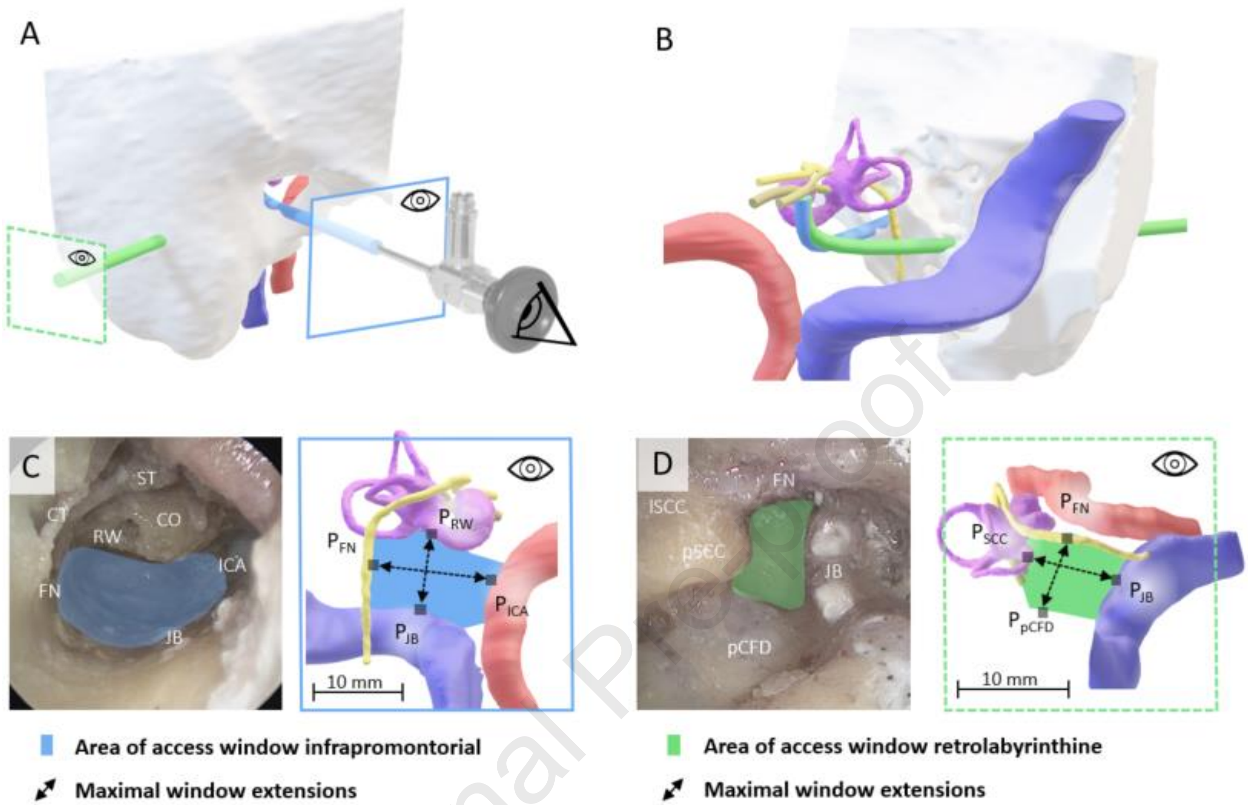


*Figure 1: Overview of the approach corridors (top) and the surgical access windows (bottom). Blue: transcanal infracochlear approach, green: transmastoid retrolabyrinthine approach. pCFD: posterior cranial fossa dura, CO: cochlea, CT: chorda tympani, FN: facial nerve, ICA: internal carotid artery, JB: jugular bulb, RW: round window, pSCC: posterior semicircular canal, ST: stapes.*

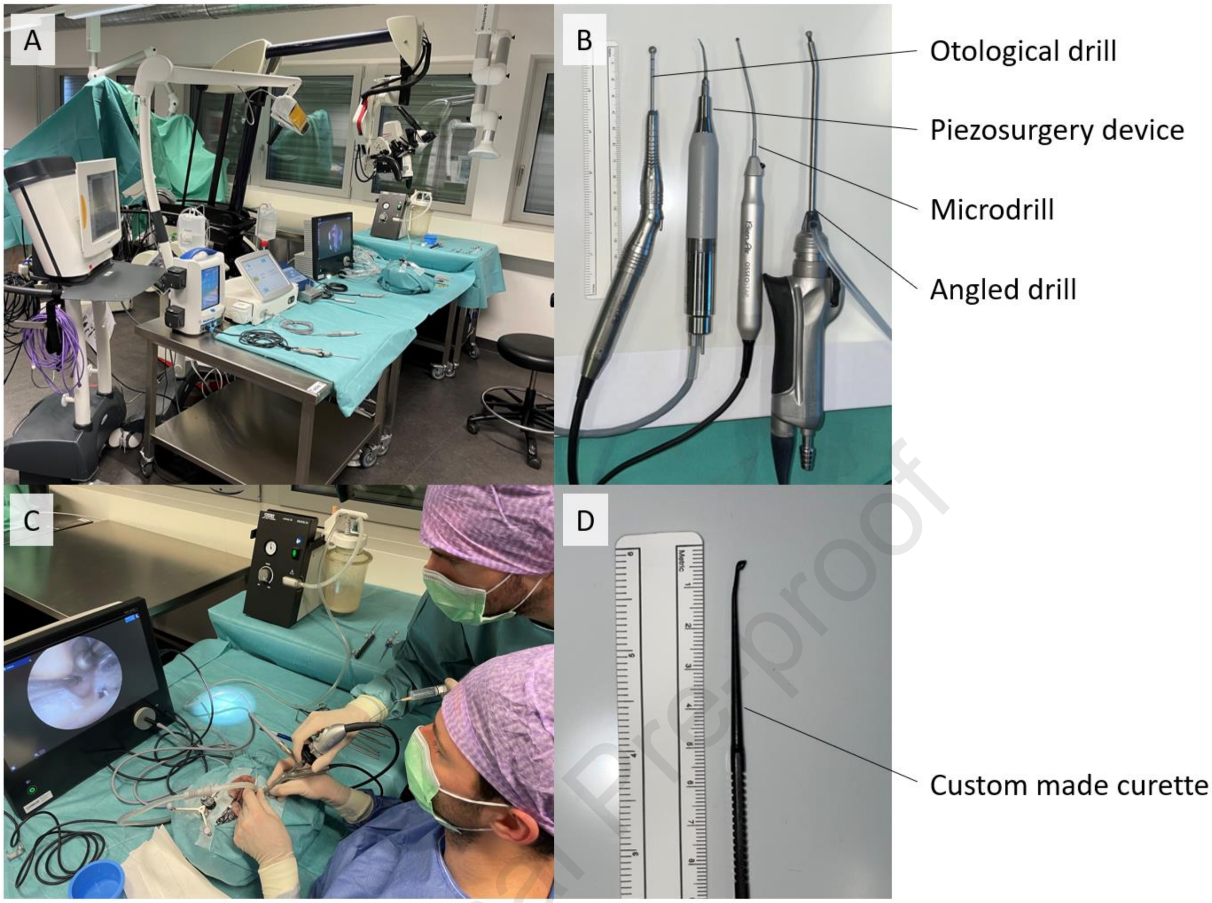


*Figure 2: Overview of the surgical setup and the used instruments. A: Surgical setup, B: State-of-the-art powered instruments, C: four-handed combined approach in which the infrapromontorial approach is used for the endoscope and the retrolabyrinthine approach is used to operate. D: custom-made bent curette.*

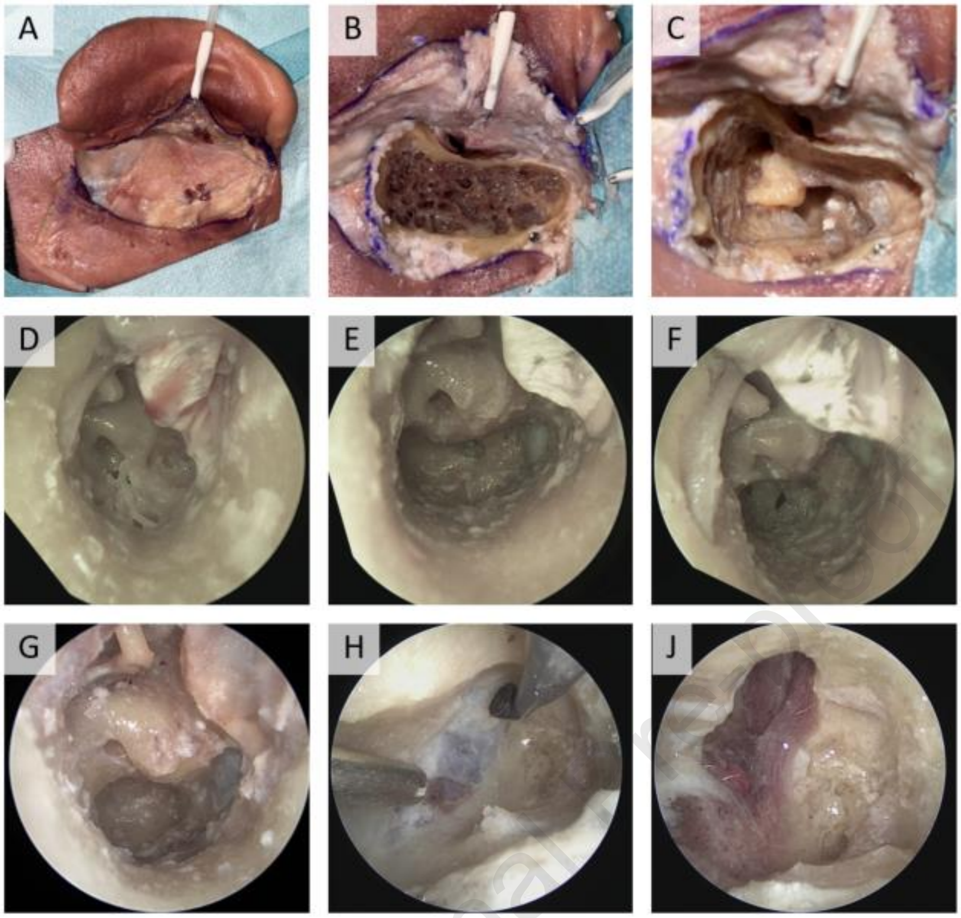


*Figure 3: Surgical steps of the approach retrolabyrinthine approach (A-C), the infracochlear approach (D-F), and the opening of the IAC with the multiport approach (G-J).*

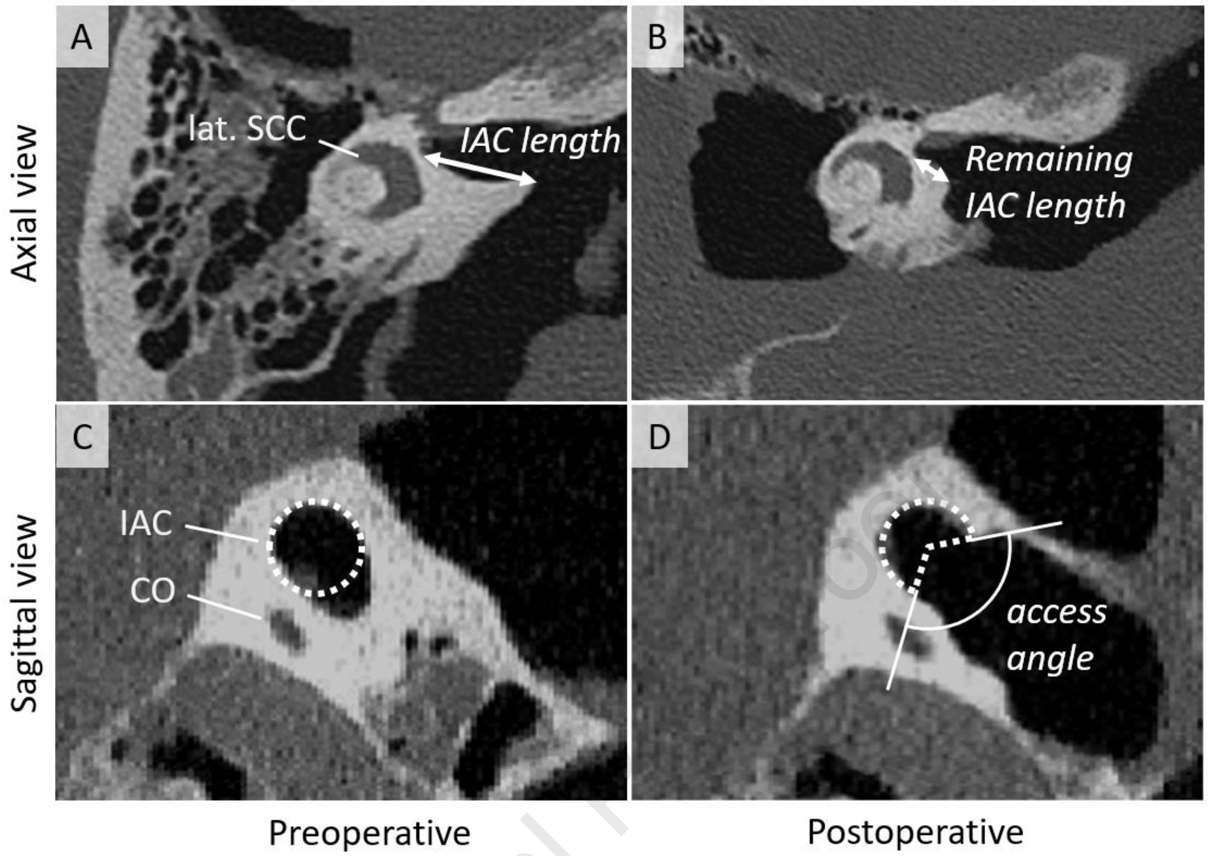


*Figure 4: Example of the exposed IAC length and the exposed IAC circumference.*

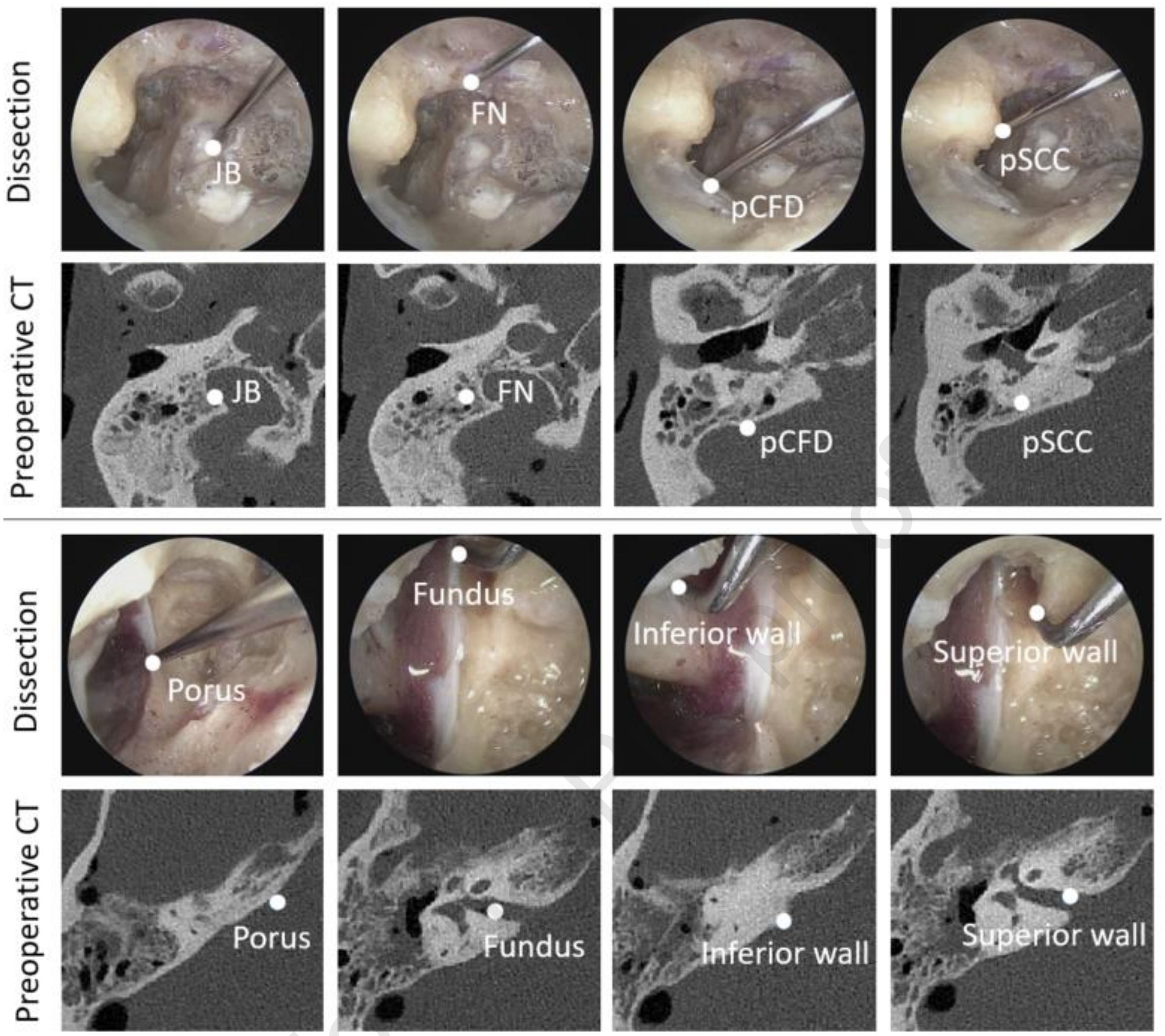


*Figure 5: Top: Surgical access window of the retrolabyrinthine approach. White points represent the extension of the access window at the jugular bulb dome (JB), the facial nerve (FN), the posterior cranial fossa dura (pCFD), and the posterior semicircular canal (pSCC). Bottom: Exposure of the internal auditory canal. White points represent the location of the most medial point (porus), the most lateral point (fundus), the most inferior point (inferior wall), and the most superior point (superior wall) that are exposed.*

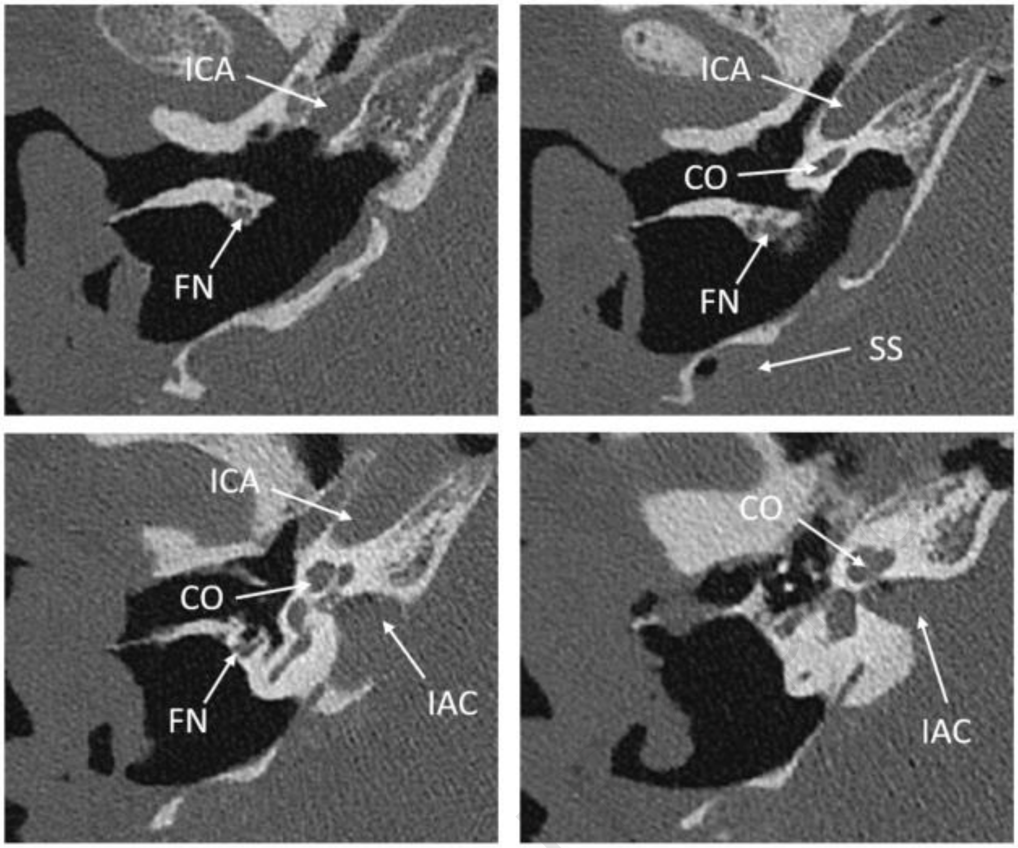


*Figure 6: Exposure of the internal auditory canal and surrounding structures in postoperative axial CT slices. The slices are arranged from inferior to superior level from top left to bottom right. CO: cochlea, FN: facial nerve, IAC: internal auditory canal, ICA: internal carotid artery, SS: sigmoid sinus.*

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ACRONYMS

AOE area of exposure.

CPA cerebellopontine angle.

EAC external auditory canal.

FN facial nerve.

IAC internal auditory canal.

ICA internal carotid artery.

JB jugular bulb.

pCFD posterior cranial fossa dura.

pSCC posterior semicircular canal.

SF surgical freedom.

VS vestibular schwannoma

*Table 1: Experience gained from working with different instruments.*

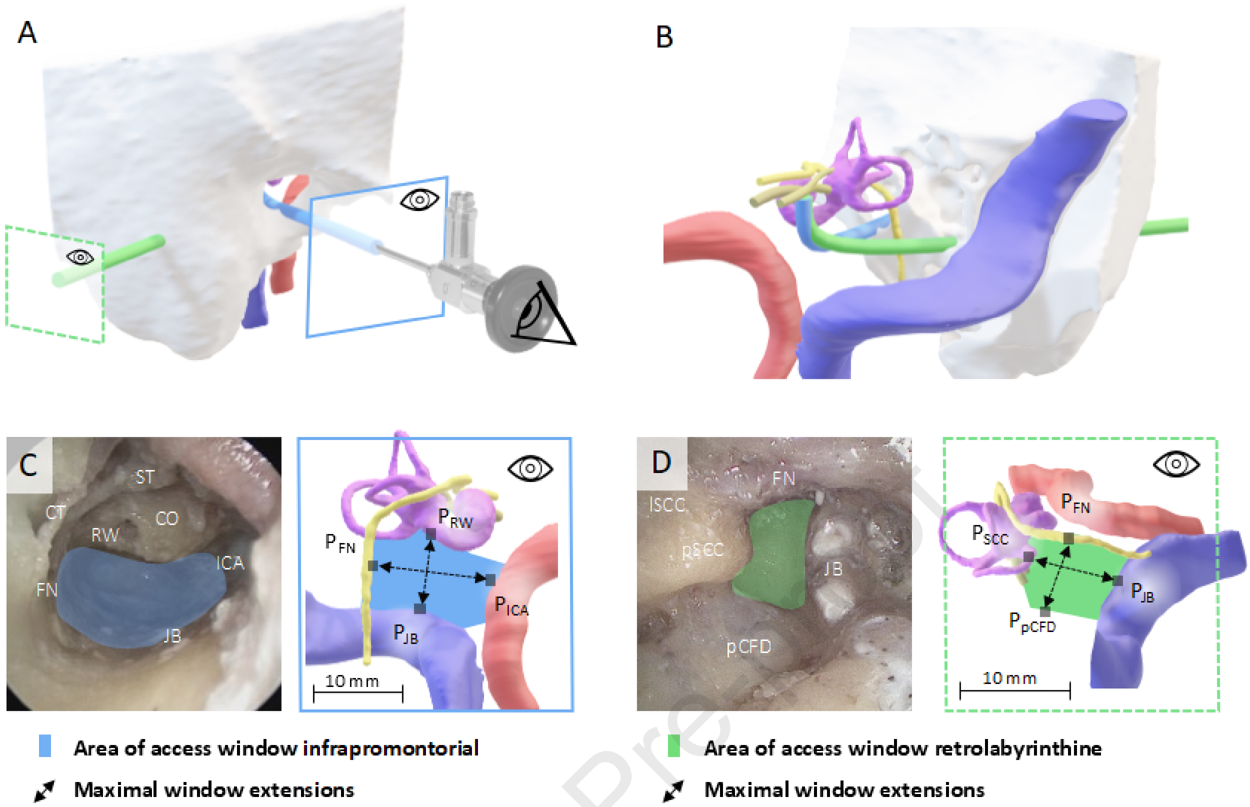
| Name of instrument | Advantages | Disadvantages | Comments |
|---|---|---|---|
| Piezosurgery device | • Underwater technique<br>• Delicate bone removal with preservation of soft tissue (e.g. dura) | • Slow bone removal<br>• Possible sensorineural hearing loss when used on the cochlea [32], [ 33]<br>• Angulation insufficient for fundus | Ideal for bone removal transcanal and confection of infracochelar acces window and for bone removal from dura |
| Microdrill | • Protected shaft<br>• Small instrument tip<br>• Cutting and diamond drill bits available<br>• Low drill speed | • Slow bone removal<br>• Drill tip slips with increasing pressure<br>• Additional irrigation needed | Ideal for bone removal from cochlea or posterior SCC |
| Standard high-speed drill | • Fast bone removal | • Heating of tissue<br>• No protected shaft | Ideal for retrolabyrinthine access window |
| Angled anterior skull base burs | • Fast bone removal<br>• Included suction and irrigation | • Smallest drill bit available 3mm | Ideal curvature for IAC fundus and ideal for four-handed technique |

*Table 2: Results from intraoperative measurements including extensions of the surgical access windows, the surgical freedom, the extension of the exposed area, and the area of exposure.*

| | Individual specimens (L: left, R: right) | | | | | | **mean** | **sd** |
|---|---|---|---|---|---|---|---|---|
| | 1R | 1L | 2R | 3R | 3L | 4R | | |
| Lateral access window extension, infracochelar approach [mm] | 11.1 | 9.7 | 14.3 | 12.1 | 9.1 | 11.5 | **11.3** | **1.8** |
| Vertical access window extension, infracochelar approach [mm] | 7.1 | 7.3 | 6.8 | 8.5 | 9.9 | 9.6 | **8.2** | **1.3** |
| Lateral access window extension, retrolabyrinthine approach [mm] | 11.2 | 13.9 | 9.0 | 12.3 | 11.4 | 11.0 | **11.5** | **1.6** |
| Vertical access window extension, retrolabyrinthine approach [mm] | 11.6 | 10.1 | 9.4 | 17.0 | 10.6 | 11.2 | **11.6** | **2.8** |
| Surgical freedom, retrolabyrinthine approach [$mm^2$] | 750.5 | 502.3 | 589.1 | 692.9 | 1254.1 | 2097.6 | **981.1** | **606.7** |
| Lateral extension exposed area, internal auditory canal [mm] | 13.8 | 13.1 | 10.3 | 12.6 | 8.9 | 9.2 | **11.3** | **2.1** |
| Vertical extension exposed area, internal auditory canal [mm] | 6.0 | 6.0 | 4.7 | 5.5 | 6.4 | 5.5 | **5.7** | **0.6** |
| Area of exposure, internal auditory canal [$mm^2$] | 44.5 | 34.2 | 37.7 | 46.5 | 35.4 | 33.2 | **38.6** | **5.6** |
| Lateral extension exposed area, cerebellopontine angle dura [mm] | 24.4 | 28.9 | 24.3 | 19.8 | 27.5 | 15.8 | **23.5** | **4.9** |
| Vertical extension exposed area, cerebellopontine angle dura [mm] | 22.9 | 17.1 | 12.0 | 17.7 | 16.2 | 11.0 | **16.1** | **4.3** |
| Area of exposure, cerebellopontine angle dura [$mm^2$] | 305.7 | 255.7 | 157.5 | 236.8 | 303.1 | 127.3 | **231.0** | **74.3** |

*Table 3: Results from measurements in preoperative and postoperative computed tomography images, evaluating the exposure of the internal auditory canal.*

| | Individual specimens (L: left, R: right) | | | | | | **mean** | **sd** |
|---|---|---|---|---|---|---|---|---|
| | 1R | 1L | 2R | 3R | 3L | 4R | | |
| Preoperative length [mm] | 8.6 | 11.2 | 10.3 | 9.9 | 9.1 | 8.7 | **9.6** | **1.0** |
| Postoperative length [mm] | 3 | 5.5 | 3.1 | 3.4 | 1.9 | 3.4 | **3.4** | **1.2** |
| Exposed length ratio [%] | 65 | 51 | 70 | 66 | 75 | 61 | **65** | **9** |
| Access angle [°] | 120 | 95 | 80 | 105 | 145 | 85 | **105** | **25** |
| Exposed circumference ratio [%] | 33 | 26 | 22 | 29 | 40 | 24 | **29** | **7** |


A
B
C
ST
CT
CO
RW
ICA
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JB
P FN
P RW
P ICA
P JB
10 mm
D
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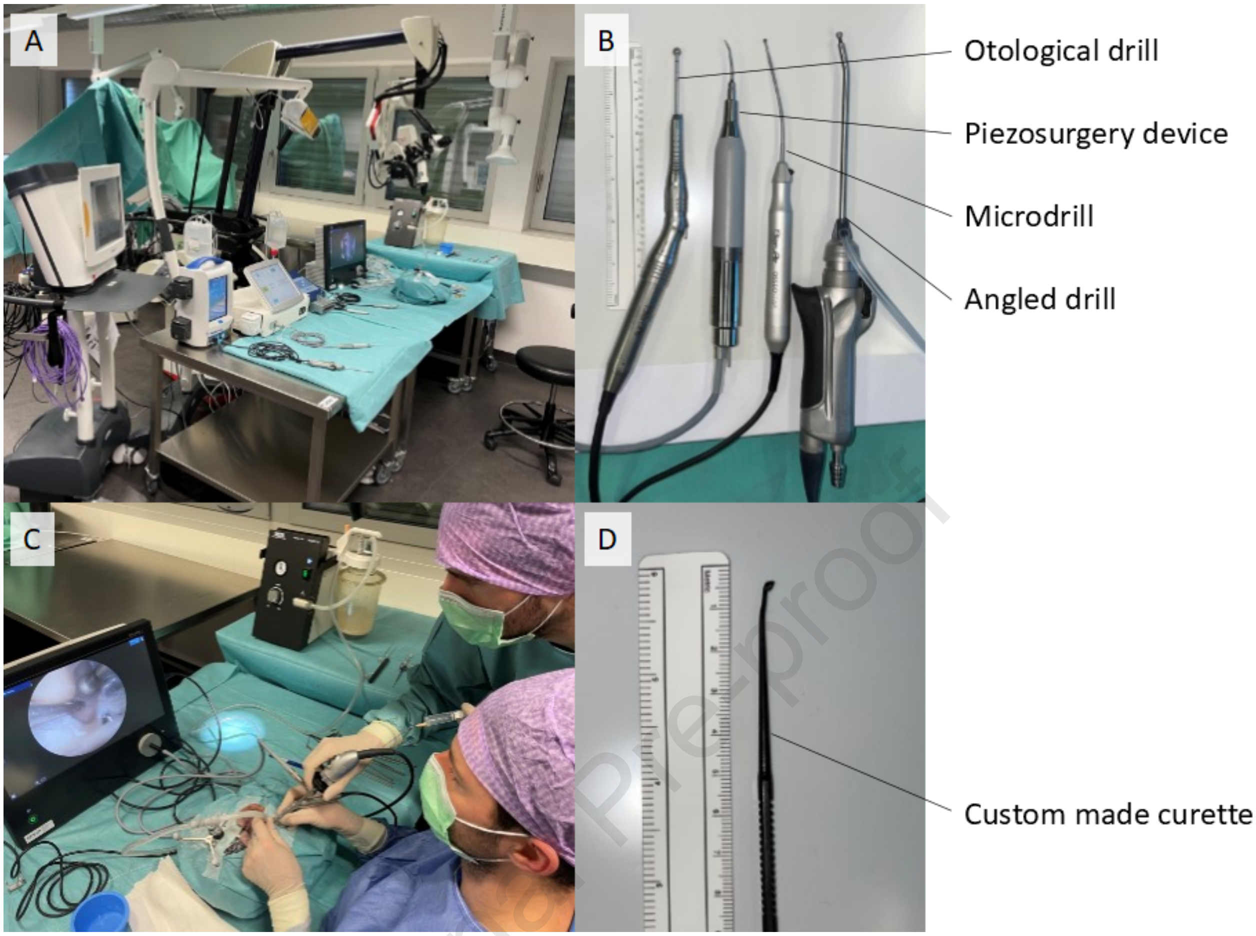
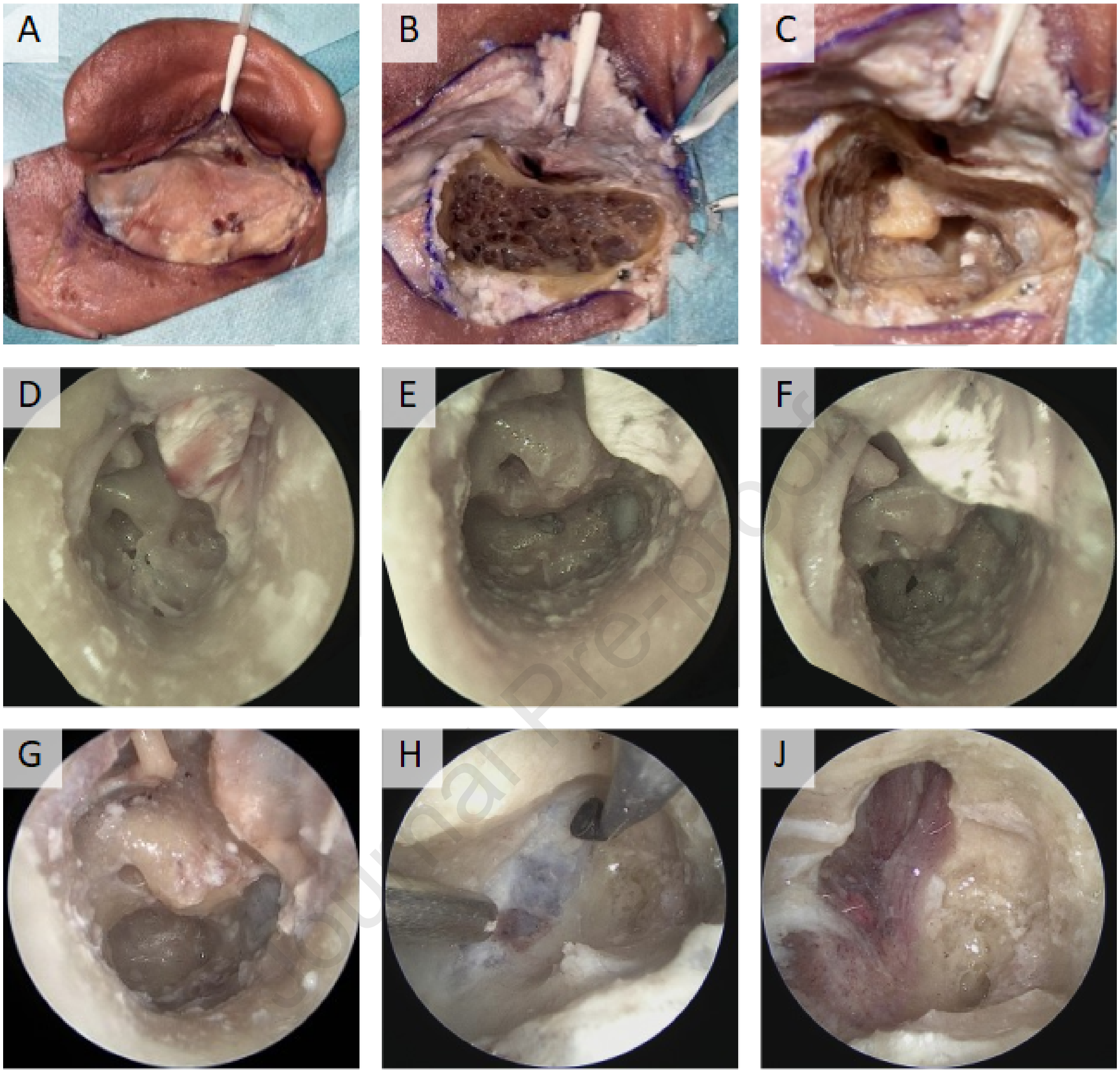
lSCC
pSCC
JB
pCFD
P FN
P SCC
P JB
P pCFD
10 mm
Area of access window infrapromontorial
Maximal window extensions
Area of access window retrolabyrinthine
Maximal window extensions


A
B
C
D
Otological drill
Piezosurgery device
Microdrill
Angled drill
Custom made curette



A
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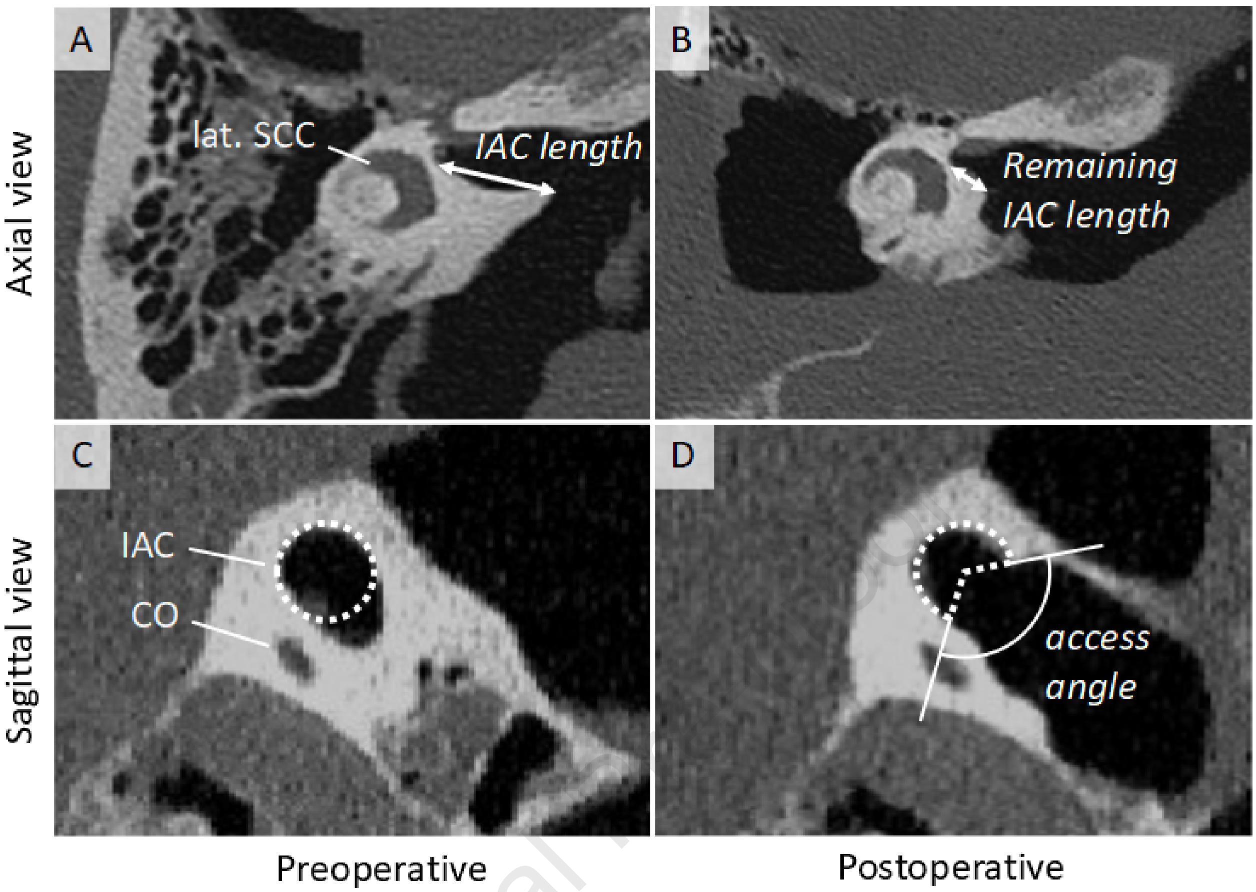
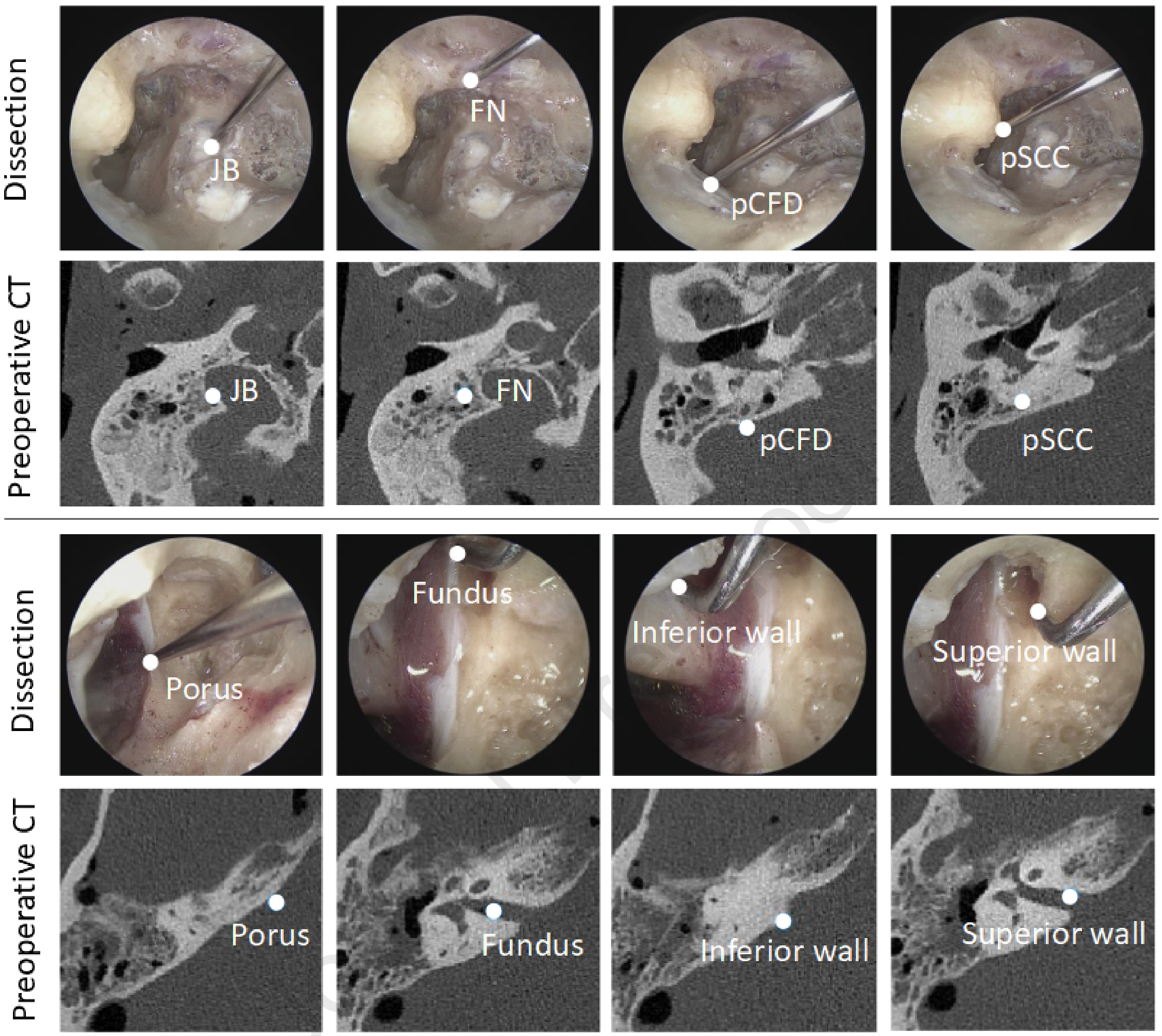
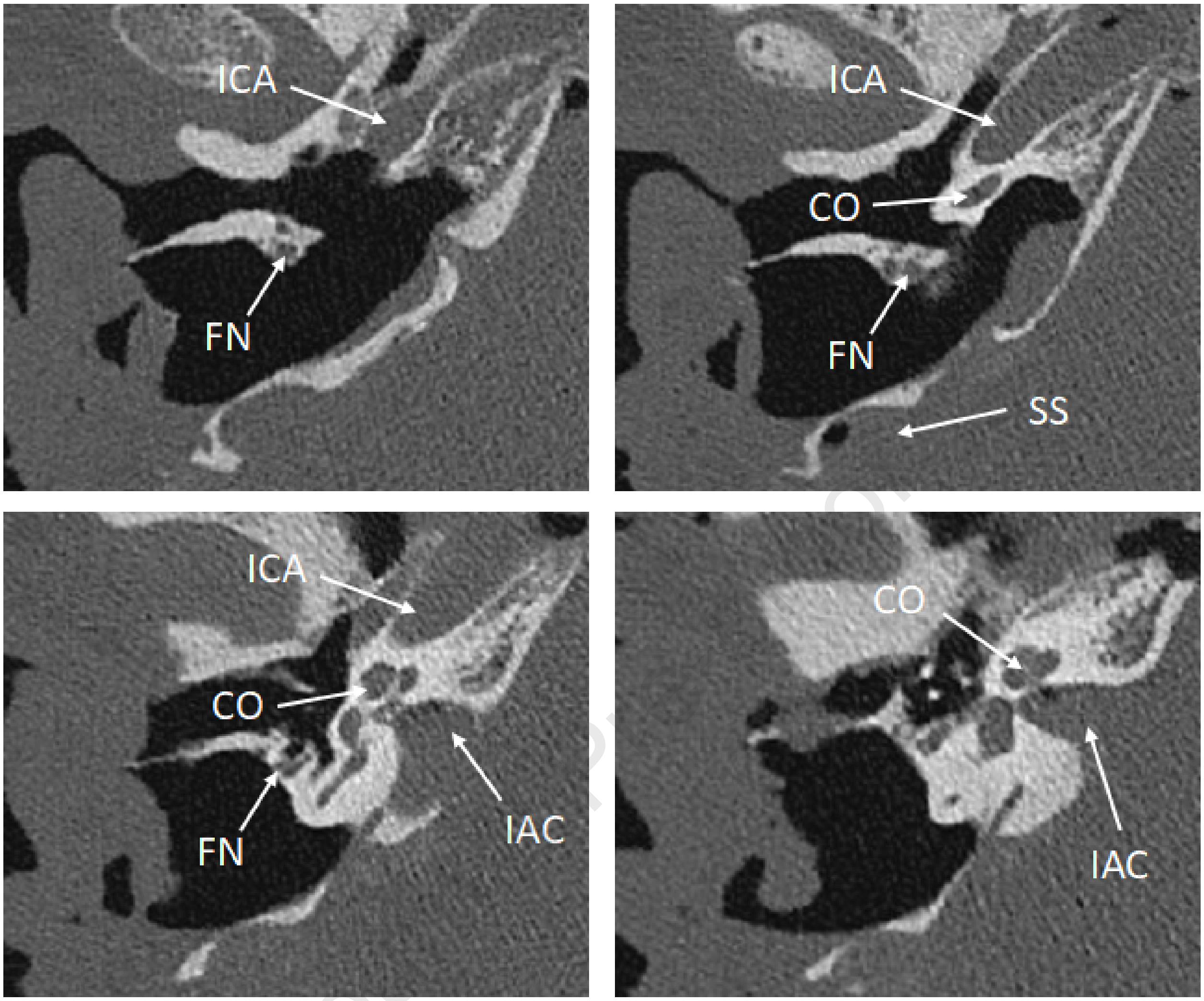

A
B
C
D
Axial view
Sagittal view
lat. SCC
IAC length
Remaining
IAC length
IAC
CO
access
angle
Preoperative
Postoperative


Dissection
JB
FN
pCFD
pSCC
Preoperative CT
JB
FN
pCFD
pSCC
Dissection
Porus
Fundus
Inferior wall
Superior wall
Preoperative CT
Porus
Fundus
Inferior wall
Superior wall


ICA
FN
ICA
CO
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SS
ICA
CO
FN
IAC
CO
IAC

ACRONYMS

AOE area of exposure.

CPA cerebellopontine angle.

EAC external auditory canal.

FN facial nerve.

IAC internal auditory canal.

ICA internal carotid artery.

JB jugular bulb.

pCFD posterior cranial fossa dura.

pSCC posterior semicircular canal.

SF surgical freedom.

VS vestibular schwannoma

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Furthermore, LA is a consultant für Stryker ENT.

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