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Topographic Anatomy of the Medial Labyrinthine Wall: Implications for the Transcanal Endoscopic Approach to the Internal Auditory Canal

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Hypothesis: To characterize transcanal endoscopic landmarks of the medial labyrinthine wall and correlate these with anatomical features of the fundus of the internal auditory canal (IAC).
Background: The transcanal transpromontorial approach (TTA) enables minimally invasive access to the IAC. The establishment of a landmark-based dissection technique for the approach is crucial to avoid injury to the facial nerve.
Methods: Twenty temporal bones were dissected endoscopically through the TTA. Furthermore, high-resolution computed tomography (CT) scans from ten adult normal temporal bones were analyzed and three-dimensionally reconstructed.
Results: A stepwise dissection technique for the TTA was demonstrated depending on a newly described landmark used in the identification of the facial nerve. The proposed landmark, which was named the intervestibulocochlear crest (IVCC), is an integrated part of the otic capsule. It can be differentiated after the excision of the lateral labyrinthine wall as a laterally based bony pyramid between the cochlea and the vestibule. Its medially directed apex blends with the central part of the falcifrom crest and points to the distal part of the meatal facial nerve. The IVCC is best detected on axial CT images at the level of the tympanic facial nerve. The union between the IVCC and the falciform crest appears radiologically as a short stem or mini-martini glass.
Conclusion: The proposed IVCC is a novel landmark with a consistent relationship to the IAC fundus and the facial nerve. It may be utilized in conjunction with the falciform crest to identify the facial nerve during minimally invasive transcanal surgeries.
Key Words: Bony labyrinth—Cerebellopontine angle—Facial nerve—Internal auditory canal—Lateral skull base—Transcanal transpromontorial approach—Vestibular schwannoma.
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The application of endoscopic techniques in skull base surgery has been extended from anterior endonasal routes to lateral transcanal skull base approaches. The main advantage brought by the endoscope as compared to the microscope is the magnified and angled exposure of small and difficult-to-access regions such as hidden areas of the middle ear and the fundus of the internal auditory canal (IAC). The transcanal transpromontorial approach (TTA) provides direct access to the IAC taking advantage of the external auditory canal as a natural surgical corridor (1). This represents a major advantage with respect to the traditional microscopic techniques, which encroach the IAC from posteriorly (translabyrinthine or retrosigmoid approach) or from superiorly (middle fossa approach). Moreover, these traditional approaches require wide external skin incisions, variable degrees of bone removal, neurovascular manipulations, and brain tissue retraction (2). The combination of the endoscope

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with microscopic techniques has also been described, particularly for the control of lesions extending to the fundus of the IAC during the retrosigmoid approach. This combined approach has been designed to avoid the extensive drilling of the posterior aspect of the petrous bone (3).

Recently, several studies have shown the feasibility and safety of the endoscopic transcanal transpromontorial approach (ETTA) in the resection of selected cases of vestibular schwannoma (VS) (4–17). Previous anatomical investigations have described the surgical steps of ETTA depending on anatomical landmarks of the middle ear, such as the anterior and posterior pillars of the round window, the cochleariform process, the geniculate ganglion, and the oval window (4–6). These landmarks indicate where the drilling of the inner ear can be started. However, deeper topographical landmarks, for example, on the medial labyrinthine wall, which is intimately related to the fundus of the IAC, are required to guide the operating surgeon beyond the middle ear.

The current study focuses on the endoscopic anatomy of the medial wall of the bony labyrinth from a transcanal endoscopic transpromontorial perspective. Its correlation with the anatomical structures at the fundus of the IAC is analyzed. Novel landmarks are investigated to facilitate the identification of the facial nerve. The aim is to provide an anatomical-based stepwise dissection for a safe approach to the fundus of the IAC.

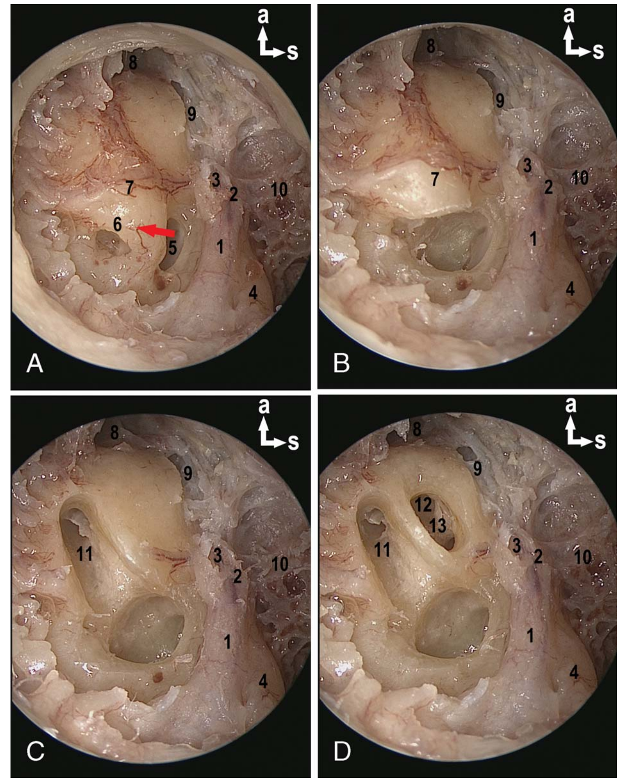

FIG. 1. Excision of the lateral labyrinthine wall. Endoscopic photographs taken with a 08 4mm Hopkins rod telescope (Left ear). The two arrows at the upper right corner of each panel refer to the anterior (a) and superior (s) directions of the dissected bone. Panel A and B: Exposure of the medial wall of the vestibular bony labyrinth. The red arrow in *A* refers to the direction of bone removal. *C* and *D*, Exposure of the cochlear turns and the modiolus. 1, facial nerve; 2, geniculate ganglion; 3, processus cochleariformis; 4, lateral semicircular canal; 5, oval window; 6, round window tegmen; 7, promontory; 8, Eustachian tube; 9, tensor tympani canal; 10, epitympanum; 11, basal cochlear turn; 12, middle cochlear turn; 13, modiolus.

MATERIALS AND METHODS

The experimental anatomical study was conducted after validation by our institutional review board (KEK-BE 2016-00887). The investigations included anatomical dissections, radiological analysis, and three-dimensional (3D) temporal bone reconstructions.

Anatomical Dissection

Twenty temporal bones (16 formalin-fixed, 4 thiel-fixed) were dissected under the guidance of 4mm diameter, 18 cm-long, 0° and 45° Hopkins rod telescopes coupled with a high-definition video camera and monitor (Karl Storz, Tuttlingen, Germany). Standard endoscopic ear instruments (Karl Storz, Tuttlingen, Germany) and high-speed drill (Bien-Air Surgery SA, Le Noirmont, Switzerland) were used throughout the dissections.

Endoscopic Transcanal Access to Bony Labyrinth

The preliminary dissection steps were performed as reported by Marchioni et al. (4). The steps included in this preparatory stage were circumferential removal of the tympanomeatal flap, wide canaloplasty, atticotomy, ossicular chain extraction, and excision of the tensor tympani muscle.

Excision of Lateral Labyrinthine Wall

The oval window was the site at which the dissection of the lateral wall of the bony labyrinth was initiated. Its opening was widened inferiorly towards the round window using a micro-curette (Fig. 1A and B). Drilling was carried out along the lateral surface of the cochlea to expose its basal, middle and apical turns and the modiolus, the conical central axis of the cochlea (Fig. 1C and D).

Radiological Analysis and Three-Dimensional Temporal Bone Reconstruction

High-resolution computed tomography scans (HRCTs) from 10 adult temporal bones free of gross pathology were acquired to analyze the radiological anatomy of the landmarks relevant to the TTA. Additionally, 3D reconstructed surface models of these bones were created using threshold-based segmentation (Amira, FEI, France). The surface models were used to achieve deep orientation of the anatomical aspects of the investigated approach and to illustrate its landmarks.

RESULTS

Anatomical Dissection

Endoscopic Landmarks on Medial Labyrinthine Wall

After the downward widening of the oval window opening toward the round window, three landmarks were

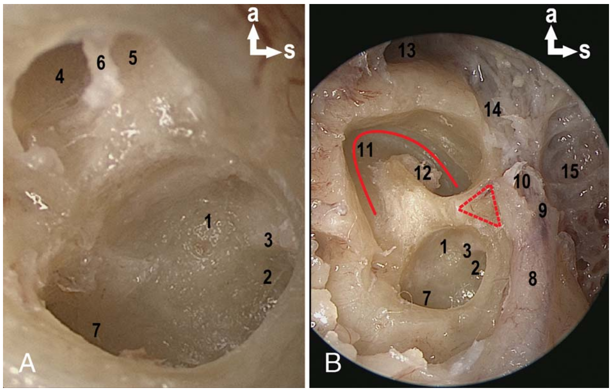

FIG. 2. Endoscopic landmarks on the medial labyrinthine wall. Endoscopic photographs taken with a 08 4mm Hopkins rod telescope (Left ear). The two arrows at the upper right corner of each panel refer to the anterior (a) and superior (s) directions of the dissected bone. Panel A: Vestibular landmarks and divisions of the basal turn of the cochlea. B, Cochlear landmarks (the deep aspect of the basal turn of the cochlea is marked by the red curved line, while the red dashed triangle refers to the intervestibulocochlear crest). 1, spherical recess; 2, elliptical recess; 3, vestibular crest; 4, scala tympani; 5, scala vestibuli; 6, basilar membrane; 7, posterior semicircular canal; 8, facial nerve; 9, geniculate ganglion; 10, processus cochleariformis; 11, basal cochlear turn; 12, lamina cribrosa; 13, Eustachian tube; 14, tensor tympani canal; 15, epitympanum.

identified on the medial wall of the vestibular bony labyrinth (Fig. 2A):

1. The first and lowest is the *spherical recess*, which is located in the saccular fossa. It is the site of termination of the inferior vestibular nerve fibers and it is located at the same level as the oval window.
2. The second and more cranial landmark is the *elliptical recess*, which is located in the utricular fossa and is where the superior vestibular nerve fibers end. The complete circumference of the elliptical recess is difficult to be visualized with a 0° Hopkins rod telescope because its upper portion is situated medial to the tympanic segment of the facial nerve.
3. In between the two recesses, the third landmark, the *vestibular crest*, was identified.

Then to expose the medial wall of the cochlear bony labyrinth, the bony septa in between the cochlear turns and the modiolus were removed leaving the lamina cribrosa in place. After this step, three other landmarks were recognized (Fig. 2B):

4. The lamina cribrosa, the thin bony plate separating the inner ear from the IAC.
5. The deep surface of the basal turn of the cochlea, which is the most medial part of the cochlea and the nearest to the fundus of the IAC.
6. The last landmark is a triangular-shaped superiorly based thick bone situated between the cochlea and the vestibule. This landmark is a part of the otic capsule that can be differentiated after the excision of the lateral labyrinthine wall. Due to its location, it was named "intervestibulocochlear crest" (IVCC).

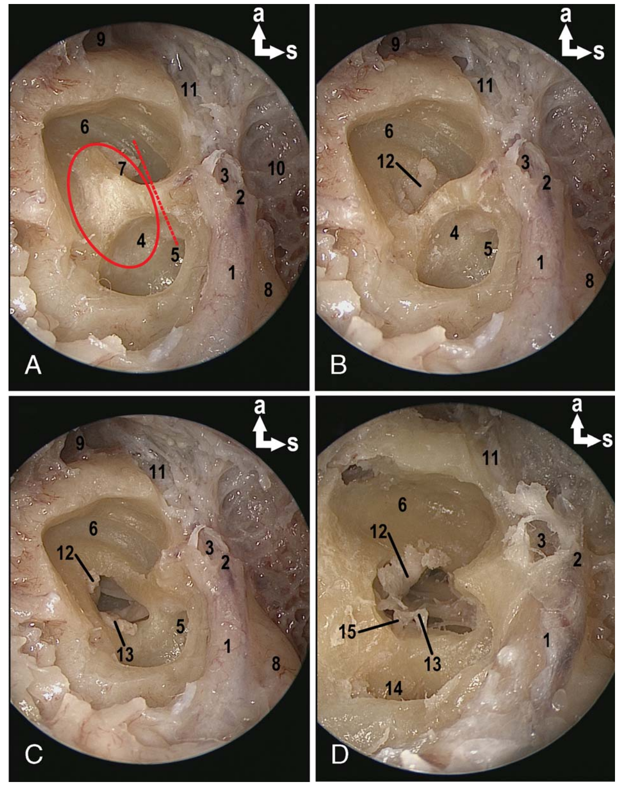

FIG. 3. Approaching the fundus of the internal auditory canal. Endoscopic photographs taken with a 0° 4mm Hopkins rod telescope (Left ear). The two arrows at the upper right corner of each panel refer to the anterior (a) and superior (s) directions of the dissected bone. Panel *A*: The dashed red line represents the horizontal level which is determined from the vestibular crest to the upper margin of the exposed lamina cribrosa. The medial labyrinthine wall is then excised in a circular fashion below the demarcated line. *B*, Exposure of the cochlear nerve. *C*, Exposure of the inferior vestibular nerve. *D*, The photograph shows the singular nerve branching out from the inferior vestibular nerve to enter its canal. 1, facial nerve; 2, geniculate ganglion; 3, processus cochleariformis; 4, spherical recess; 5, elliptical recess; 6, basal cochlear turn; 7, lamina cribrosa; 8, lateral semicircular canal; 9, Eustachian tube; 10, epitympanum; 11, tensor tympani canal; 12, cochlear nerve; 13, inferior vestibular nerve; 14, posterior semicircular canal; 15, singular nerve.

Anatomical Correlation Between Medial Labyrinthine Wall and IAC Fundus

The next step was to benefit from the detected landmarks on the medial labyrinthine wall in the formulation of a safe dissection technique to the IAC fundus. To reach this aim, the dissection should be based on a reliable anatomical correlation between the anatomical structures on the two side walls, the medial labyrinthine wall and the fundus.

The safest way to open the fundus of the IAC begins with the allocation of a horizontal line on the medial labyrinthine wall corresponding to the falciform crest at the fundus. The defined line passes from the vestibular crest posteriorly to the superior margin of the exposed lamina cribrosa anteriorly (Fig. 3A). It also divides the medial wall of the bony labyrinth into superior and inferior compartments, as the falciform crest does at the fundus of the IAC. Each labyrinthine compartment contains two important structures: the lamina cribrosa and the spherical recess inferiorly, the IVCC and the elliptical recess superiorly.

The determined horizontal line on the labyrinthine wall was used as a superior limit for the opening of the fundus of the IAC. Accordingly, a circular-shaped opening in the medial wall of the bony labyrinth below the mentioned line was performed (Fig. 3A). The first part removed was the lamina cribrosa, which was easily dissected by a microcurette to reveal the cochlear nerve (Fig. 3B). The opening was enlarged inferiorly and then posteriorly to reach the spherical recess and thus identify the inferior vestibular nerve (Fig. 3C). The opening was continued superiorly until reaching the vestibular crest. In some dissections, the singular nerve was observed branching out from the inferior vestibular nerve to pass through its bony canal to the ampulla of the posterior semicircular canal (Fig. 3D). From the above description, the medial wall of the bony labyrinth was opened circularly from anterior to posterior (clockwise on the right side and anticlockwise on the left side).

Facial Nerve Identification at IAC Fundus and Anatomical Relations of Intervestibulocochlear Crest

After removal of the lower part of the medial labyrinthine wall, the horizontal bony septum at the IAC fundus or the falciform crest was found to be intact in all specimens. The superior compartment of the fundus or the facial and superior vestibular nerves were recognized above the falciform crest. Moreover, the intermediate nerve was distinct from the facial nerve medial to the falciform crest (Fig. 4A and B).

For a better understanding of the IVCC anatomy and its relation to the facial nerve, the vestibulocochlear nerve was removed. Furthermore, the endoscopic corridor was widened inferiorly by hemi-circumferential drilling of the basal turn of the cochlea and the IAC (Fig. 4C). The IVCC was found to be a bony part of the otic capsule extending from the middle ear to the fundus of the IAC (Fig. 4D). It takes the shape of a triangular pyramid with an apex (directed medially to the IAC fundus), a triangular base (located laterally facing the middle ear), and three triangular walls (anterior, posterior, and superior). The walls are related to the cochlea anteriorly, the vestibule posteriorly, and the labyrinthine segment of the facial nerve superiorly. Additionally, the following findings were recorded at the fundus of the IAC in relation to the IVCC:

- The apex of the IVCC was fusing with the central part of the falciform crest. Concurrently, the apex was pointing to the distal part of the meatal segment of the facial nerve before it changes its direction and curves antero-superiorly to enter the labyrinthine canal (Fig. 4D).
- The labyrinthine segment of the facial nerve was still bony covered because it passes above the base of the IVCC, which is preserved in our dissection technique (Fig. 4D).
- On endoscopic examination of the IAC through the porus, the Bill's bar was found to be situated directly above the IVCC (Fig. 4E).

Radiological Analysis and Three-Dimensional Temporal Bone Reconstruction

Through a focused examination of the HRCTs data, it was concluded that the IVCC is an integrated bony part of the otic capsule that continues medially with the bony structures at the fundus of the IAC. The IVCC is best recognized in axial cuts at the level of the tympanic segment of the facial nerve (Fig. 5). It has the shape of a triangular bone between the cochlea and the vestibule. Medially, the IVCC blends with the central part of the falciform crest. The union between the IVCC and the falciform crest gives them combined the radiological shape of a short stem or mini-martini glass. The 3D surface models were a helpful tool in the anatomical orientation of the approach and confirmed the recorded dissection findings (Fig. 6).

DISCUSSION

Endoscopes were first used to perform otologic surgery in the 1990s with the promise of providing adequate exposure for hidden and difficult-to-access regions of the middle ear during cholesteatoma surgery (18). Endoscopy has certainly paved the way for a better understanding of the middle ear anatomy and pathology development. Currently, the indications of endoscopic middle ear surgery are gradually being increased in replacement of or addition to the traditional microscopic techniques (19–22). The expansion of the endoscopic application to lateral skull base surgery has been the natural consequence of the extensive experience gained from endoscopic middle ear surgery and advances in specialized instrumentation.

The TTA is a minimally invasive surgical route where the endoscope is used to tackle lesions located in the IAC and cerebellopontine angle (CPA). The approach was introduced by Presutti et al. in 2013 as an exclusive endoscopic technique through the ear canal for removal of an intracanalicular cochlear schwannoma (9). At present, the exclusive ETTA is indicated for lesions, mostly VS limited to the IAC (Koos Grade I), whereas the expanded TTA is suitable for lesions of the IAC involving the CPA (from Koos Grade II to selected cases of Koos Grade III) (10–17,23). The expanded TTA combines the advantages of the endoscope and the microscope, particularly the possibility to use both hands

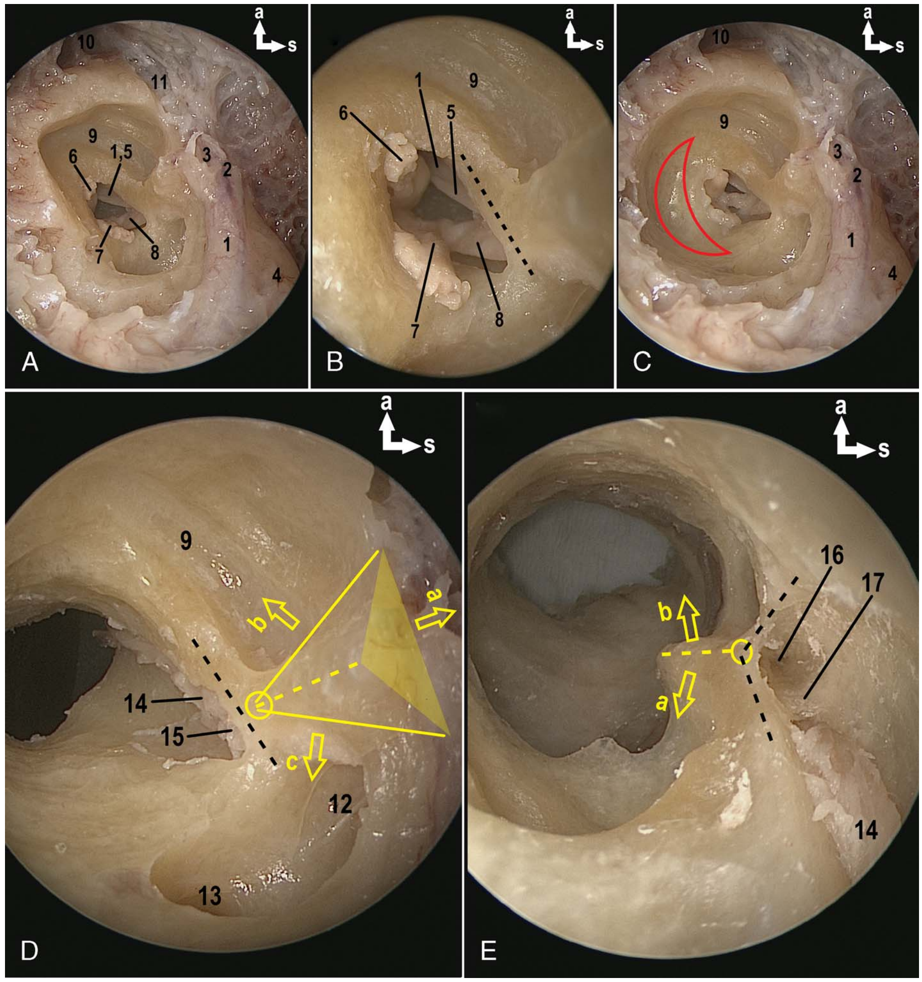

FIG. 4. Facial nerve identification and anatomical relations of the IVCC. Endoscopic photographs taken with a 0° 4mm Hopkins rod telescope (Left ear). The two arrows at the upper right corner of each panel refer to the anterior (a) and superior (s) directions of the dissected bone. Panel A and B: Both photographs are for the fundus, after it was opened, demonstrating the position of the facial and superior vestibular nerves above the falciform crest, which is marked by the dashed black line. *C*, Corridor widening, the red crescent indicates the bony area drilled. *D*, The photograph demonstrates the IVCC anatomy which is demarcated by the yellowish shapes. It is an integrated pyramidal-shaped bony part of the otic capsule with an apex, a triangular base, and three triangular walls (superior, anterior, and posterior). Its base (the yellowish triangle) is situated laterally facing the middle ear. Medially, the IVCC apex (the yellowish circle) fuses with the central part of the falciform crest (the dashed black line) and points to the distal part of the meatal segment of the facial nerve. The dashed yellowish line refers to the inferior border of the IVCC, while the three yellowish arrows point to the three IVCC walls: a, the superior related to the labyrinthine facial nerve; b, the anterior related to the cochlea; c, the posterior related to the vestibule. *E*, Endoscopic photograph taken through the porus acusticus shows the position of the Bill's bar above the IVCC. The small yellowish circle refers to the IVCC apex, the dashed yellowish line to the inferior border of the IVCC, and the dashed black line to the falciform crest. The two yellowish arrows a, b point to the anterior and posterior walls of the IVCC respectively. 1, facial nerve; 2, geniculate ganglion; 3, processus cochleariformis; 4, lateral semicircular canal; 5, intermediate nerve; 6, cochlear nerve; 7, inferior vestibular nerve; 8, superior vestibular nerve; 9, basal cochlear turn; 10, Eustachian tube; 11, tensor tympani canal; 12, elliptical recess; 13, posterior semicircular canal; 14, meatal segment of the facial nerve; 15, distal end of the meatal segment of the facial nerve; 16, superior vestibular nerve aperture; 17, Bill's bar. IVCC indicates intervestibulocochlear crest.

for dissection, which is advisable during the management of larger lesions in the CPA.

The current study demonstrates the endoscopic anatomy of the landmarks on the medial wall of the bony labyrinth through an exclusive ETTA. A stepwise technique is described for approaching the IAC fundus based on an anatomical correlation between the landmarks on the medial labyrinthine wall and the corresponding anatomical structures at the IAC fundus. The study proposes the IVCC as a feasible landmark for the identification of the facial nerve. The introduced landmark is a bony part of the otic capsule differentiated after the excision of the lateral labyrinthine wall between the cochlea and the vestibule.

In previously reported studies about the TTA, Komune and his colleagues have defined a triangular area on the medial wall of the middle ear between the cochleariform process and the two pillars (anterior and posterior) of the round window. The authors reported that drilling within the boundaries of this defined triangle leads to the

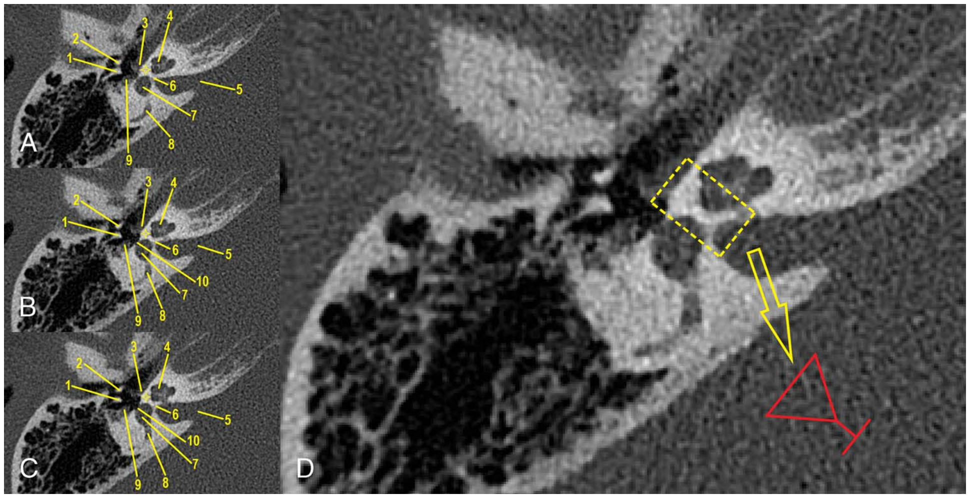

FIG. 5. Radiological anatomy of the IVCC. Panel *A, B*, and *C*: Consecutive axial cuts of a high-resolution computed tomography scan for a right temporal bone at the level of the tympanic segment of the facial nerve. The cuts show the radiological anatomy of the IVCC, which is marked by the yellow stars, and its relation to other temporal bone structures. *D*, A magnified view for the IVCC and the falciformcrest, which are surrounded by a dashed yellow rectangle. In axial cuts, the union between the IVCC and the falciform crest forms the shape of a short stem or mini-martini glass. 1, incus; 2, malleus; 3, tensor tympani; 4, cochlea; 5, porus acusticus; 6, falciform crest; 7, vestibule; 8, posterior semicircular canal; 9, facial nerve; 10, oval window. IVCC indicates intervestibulocochlear crest.

opening of the fundus of the IAC (6). In contrast, Marchioni et al. have concluded that drilling within the triangular area between the geniculate ganglion, the basal turn of the cochlea, and the spherical recess exposes the labyrinthine segment of the facial nerve (4). The previous anatomical studies on transcanal approaches to the IAC have focused on anatomical landmarks of the middle ear, such as the round window pillars, the geniculate ganglion,

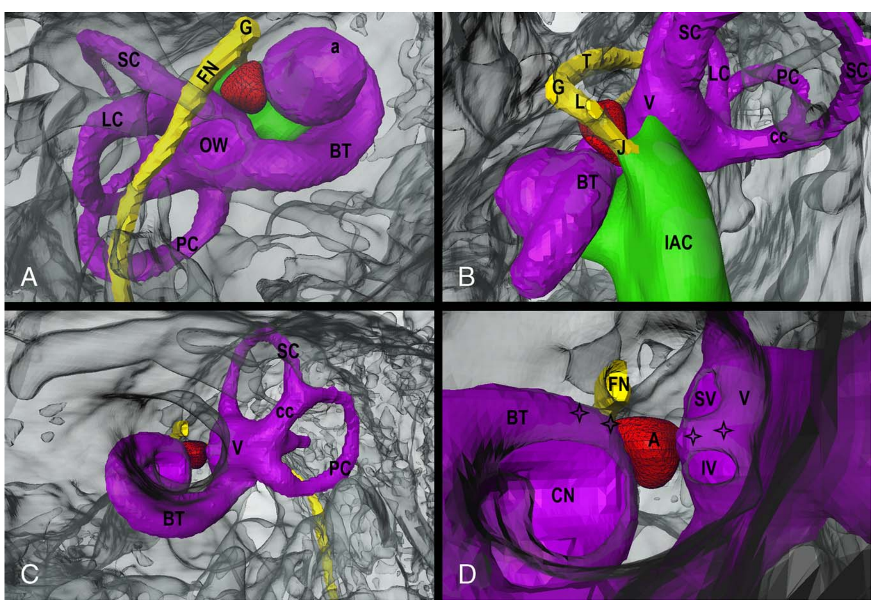

FIG. 6. Illustration of the IVCC anatomy. The photos are for a 3D reconstructed surface model of a right temporal bone. The intervestibulocochlear crest (IVCC) is presented by the segmented red structure. Panel A: The lateral aspect of the inner ear showing the anatomical position of the IVCC between the cochlea and the vestibule. B, Superior view for the temporal bone demonstrating the relationship between the superior surface of the IVCC and the labyrinthine segment of the facial nerve. C, Medial view of the temporal bone to show the relationship between the IVCC and the fundus. D, Close up view for the fundus through the porus acusticus confirming the fusion of the IVCC apex with the center of the falciform crest, which is referred to by the black stars. a, cochlear apex; A, IVCC apex; BT, basal cochlear turn; cc, crus communis; CN, cochlear nerve aperture; FN, facial nerve; G, geniculate ganglion; IAC, internal auditory canal; IV, inferior vestibular nerve aperture; IVCC, intervestibulocochlear crest; J, junction between the meatal and labyrinthine segments of the facial nerve; L, labyrinthine segment of the facial nerve; LC, lateral semicircular canal; OW, oval window; PC, posterior semicircular canal; SC, superior semicircular canal; T, tympanic segment of the facial nerve; SV, superior vestibular nerve aperture; V, vestibule.

the cochleariform process, and the oval window. These structures are guiding points where the drilling of the inner ear can be started. Middle ear landmarks are crucial for a safe approach such as the cochleariform process. The last structure is a guiding landmark for the cochlear apex and the geniculate ganglion and maintains the surgeon's anatomical orientation when proceeding deeper into the IAC. However, once the lateral wall of the bony labyrinth has been drilled out, the proximity to the labyrinthine and meatal portions of the facial nerve increases, within a limited area of exposure. Therefore, the operating surgeon needs to depend on reliable deeper landmarks for the actual opening of the IAC, without endangering the facial nerve. Our report is the first to describe a critical deep bony landmark during TTA and IAC dissection.

The stepwise landmark-based approach, proposed in this study, aims to depict the widest endoscopic corridor as passing deeper to the IAC and CPA. Unguided drilling of the inner ear may lead to a constricted area of exposure and a lack of orientation when opening the IAC, which could limit the surgeon's confidence in bone removal and endanger the facial nerve. As recently reported, considering the potential extension of the TTA, the maximal area of exposure at the middle ear and the CPA should be similar (8). Indeed, the surgeon is advised to dissect a cylindrical corridor, keeping the widest possible working area from lateral to medial.

Before opening the IAC fundus, the idea of localizing a horizontal line on the medial labyrinthine wall, corresponding to the falciform crest, has shown different advantages. The line is easily established between the vestibular crest and the upper margin of the exposed lamina cribrosa and used as a superior limit for the excision of the medial labyrinthine wall. This technique leads to the exposure of the inferior compartment of the fundus of the IAC that contains the cochlear and inferior vestibular nerves. After these steps, two landmarks would be available for the operating surgeon to safely approach the facial nerve. The first is the apex of the IVCC that blends with the falciformcrest and points to the distal end of the meatal segment of the facial nerve. The second is the falciform crest itself that superiorly separates and protects the facial nerve during the opening of the IAC fundus. The identification and preservation of the falciform crest, as proposed hereby, provide double benefits: it serves as a guiding landmark for dissection and it protects the facial nerve.

Our dissections were started with canaloplasty to acquire the highest possible surgical freedom for the instrumentation. This step enabled us to carry out the approach under the guidance of a 4 mm Hopkins rod telescope. However, it can be performed with a 3 mm Hopkins rod telescope that provides a smaller field of view, but extra room for surgical instruments. Moreover, we did not need to use an endoscope holder since it was an anatomical study with a bloodless field. In clinical cases, the utilization of an endoscope holder would ease the lesion resection and shorten the operative time as it allows double-handed dissection.

The major advantage of the TTA is the lateral-to-medial dissection of the middle and inner ear, directly exposing the IAC, which is considered a deep and difficult-to-reach region. In this surgery, bone drilling is very limited with no need for craniotomies or brain tissue manipulations. The main limitation of the TTA is a smaller surgical corridor compared with traditional microscopic techniques (8). The limited exposure restricts usage of the approach to selected lesions of specific size and extensions and may impair control of some intraoperative complications like hemorrhage. The landmarks described in the study have applications to clinical care but are reserved only for a few surgical centers with high volume endoscopic ear and tumor cases. That impairs popularity and gaining experience of such approaches. Since the TTA does not preserve the cochlear integrity, only patients with no serviceable hearing are appropriate candidates.

CONCLUSION

The proposed IVCC is a novel landmark with a consistent relationship to the IAC fundus and the facial nerve. It can be used with the falciform crest to identify the facial nerve during minimally invasive transcanal surgeries.

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