Quantitative analysis of the surgical exposure and surgical freedom between transcranial and transorbital endoscopic anterior petrosectomies to the posterior fossa

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OBJECTIVE This study proposes a variation of the transorbital endoscopic approach (TOEA) that uses the lateral orbit as the primary surgical corridor, in a minimally invasive fashion, for the posterior fossa (PF) access. The versatility of this technique was quantitatively analyzed in comparison with the anterior transpetrosal approach (ATPA), which is commonly used for managing lesions in the PF.

METHODS Anatomical dissections were carried out in 5 latex-injected human cadaveric heads (10 sides). During dissection, the PF was first accessed by TOEAs through the anterior petrosectomy, both with and without lateral orbital rim osteotomies (herein referred as the lateral transorbital approach [LTOA] and the lateral orbital wall approach [LOWA], respectively). ATPAs were performed following the orbital approaches. The stereotactic measurements of the area of exposure, surgical freedom, and angles of attack to 5 anatomical targets were obtained for statistical comparison by the neuronavigator.

RESULTS The LTOA provided the smallest area of exposure ($1.51 \pm 0.5 \text{ cm}^2$, $p = 0.07$), while areas of exposure were similar between LOWA and ATPA ($1.99 \pm 0.7 \text{ cm}^2$ and $2.01 \pm 1.0 \text{ cm}^2$, respectively; $p = 0.99$). ATPA had the largest surgical freedom, whereas that of LTOA was the most restricted. Similarly, for all targets, the vertical and horizontal angles of attack achieved with ATPA were significantly broader than those achieved with LTOA. However, in LOWA, the removal of the lateral orbital rim allowed a broader range of movement in the horizontal plane, thus granting a similar horizontal angle for 3 of the 5 targets in comparison with ATPA.

CONCLUSIONS The TOEAs using the lateral orbital corridor for PF access are feasible techniques that may provide a comparable surgical exposure to the ATPA. Furthermore, the removal of the orbital rim showed an additional benefit in an enhancement of the surgical maneuverability in the PF.

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KEYWORDS anterior petrosectomy; transorbital endoscopic approach; craniotomy; posterior fossa; anatomy

OVER 2 decades ago, Kawase et al. pioneered the extended middle fossa approach, also known as the anterior transpetrosal approach (ATPA), allowing for adequate exposure of challenging areas of the skull base, including the petrous apex, anterior cerebello-pontine angle, and the upper clival region.¹⁹ Since its inception, this technique has been well studied and broadly reported in the literature.^{2,12,23,30} Moreover, its use has been widespread for managing a broad spectrum of skull base lesions, including not only tumors such as meningiomas,

cholesteatomas, and chondrosarcomas, but also vascular lesions such as aneurysms of the basilar artery and pontine cavernomas.^{13,19,30}

On the other hand, recent improvements in the field of skull base surgery have aimed to achieve an improved minimally invasive access to avoid brain retraction and injury to critical surrounding structures, as well as to hasten patients' postoperative recovery period. This has been made possible by the use of the direct surgical corridors offered by the nasal cavity and the orbits and by the avail-

ABBREVIATIONS ATPA = anterior transpetrosal approach; CN = cranial nerve; GSPN = greater superficial petrosal nerve; IAC = internal acoustic canal; ICA = internal carotid artery; LOR = lateral orbital rim; LOWA = lateral orbital wall approach; LSPN = lesser superficial petrosal nerve; LTOA = lateral transorbital approach; MMA = middle meningeal artery; PF = posterior fossa; REZ = root entry zone; TOEA = transorbital endoscopic approach.

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ability of innovative surgical instruments, particularly due to the improved illumination and panoramic visualization of the endoscope.

The transorbital endoscopic approach (TOEA) has caught the attention of many and is rapidly being incorporated into the skull base treatment armamentarium. Recently, an increasing number of studies have demonstrated the adequacy of TOEA for providing safe and satisfying access to critical skull base regions.²⁴ Notwithstanding, this approach has consistently been subject to modifications. Some investigators favor the preservation of the lateral orbital rim (LOR) throughout the procedure—herein referred to as the lateral transorbital approach (LTOA).⁷ However, others have proposed entirely removing the latter—herein referred to as the lateral orbital wall approach (LOWA)—with the aim of enhancing surgical maneuverability.^{4,22}

In this study, we propose a variant of TOEA, using the lateral orbit as our primary surgical corridor to complete an anterior petrosectomy and to thereby gain access to the posterior fossa (PF). In this study we sought to quantify the differences of the areas of exposure, surgical freedom, and angles of attack offered by the LTOA, LOWA, and ATPA.

Methods

Anatomical dissections were carried out in 5 red- and blue-colored latex-injected human cadaveric heads (10 sides) at the Anatomical Laboratory Toward Visuospatial Innovations in Otolaryngology and Neurosurgery (ALT-VISION) at The Ohio State University Wexner Medical Center.

Prior to dissection, specimens were submitted to thin-cut (0.5-mm slices), high-resolution CT scans, and the images were uploaded to an iNtellect Cranial Navigation System (Stryker Inc.) for the collection of stereotactic measurements and identification of anatomical structures.

Using a 3-point Mayfield Skull Clamp, specimens were positioned in slight extension and 30° contralateral head rotation, while during ATPAs, the heads were secured in contralateral 90° rotation and slight extension.

Surgical approaches were performed successively; LTOAs were performed first, followed by LOWAs, and then ATPAs. This particular sequence was employed so that increments in surgical exposure and surgical freedom could be accurately measured for each approach (Video 1).

VIDEO 1. Video demonstrating cadaveric dissection of LTOA, LOWA, and ATPA to Kawase's triangle (*blue area*). CN = cranial nerve; GSPN = greater superficial petrosal nerve; IAC = internal acoustic canal. Copyright Ohio State University. Published with permission. Click here to view.

All photographs were captured using an AIDA high-definition system (Karl Storz Endoscopy) and a high-resolution digital camera (Nikon).

Surgical Dissections

Lateral Transorbital Approach

LTOA dissections slightly modified the methodology reported in previous publications.^{7,28} A 2-cm linear incision was made at the lateral canthus and extended posteriorly along a natural skin crease (Fig. 1A).

Next, lateral canthotomy and cantholysis were per-

formed to completely expose the LOR from the frontozygomatic suture to the level of the zygomatic arch (Fig. 1B). The periorbita was then carefully dissected from the lateral orbital wall toward the orbital apex (Fig. 1C). Under endoscopic visualization, the lateral wall was then removed craniocaudally from the sphenoid ridge to the inferior orbital fissure and in a lateral direction away from the orbital apex until the temporalis muscle was identified (Fig. 1D). Throughout the entire procedure, great care was taken to limit globe retraction to less than a 10-mm distance from the lateral wall to prevent ischemic injury.^{6,7,25}

During the next step, the temporal dura was elevated from the cranial base to facilitate exposure and identification of the greater and lesser superficial petrosal nerves (GSPN and LSPN), middle meningeal artery (MMA), and cranial nerve (CN) V₁₋₃ (Fig. 1E). The MMA was sacrificed, and the GSPN and LSPN were both meticulously dissected and elevated away from their dural attachment (Fig. 1F).

Once exposed, Kawase's triangle was approached extradurally. Drilling of this area was carried out anteroposteriorly from the trigeminal ganglion to the internal acoustic canal (IAC); superoinferiorly from the superior petrosal sinus to the inferior petrosal sinus; and mediolaterally from the PF dura to the horizontal petrous portion of internal carotid artery (ICA) (Fig. 1G).

Wide exposure of the brainstem was completed after opening of the supra- and infratentorial dura and by cutting the tentorium cerebelli from its edge behind the dural entrance of CN IV laterally to superior petrosal sinus. At this point, structures of interest were appreciated and measurements were obtained (Fig. 1H).

Lateral Orbital Wall Approach

LOWAs were executed in agreement with the technique previously described by Altay et al.,⁴ which employs the removal of the LOR. The following steps were a continuation of the LTOA. Accordingly, we began by dissecting the temporalis muscle away from the LOR and the greater wing of sphenoid. The LOR and anterior portion of the lateral orbital wall were cut with an oscillating saw. The cut extended from the frontozygomatic suture superiorly to the level of the zygomatic arch inferiorly (Fig. 2A). After this, using a high-speed drill, the lateral orbital wall and rim were removed completely (Fig. 2B).

Next, exposure of the anterolateral temporal dura was achieved after removing a 2-cm portion of the adjacent greater wing of sphenoid (Fig. 2C). This allowed us to approach Kawase's triangle via the same method that was described for the LTOA. Measurements of interest were then obtained (Fig. 2D).

Anterior Transpetrosal Approach

ATPAs were carried out according to the standard technique.¹⁹ A linear skin incision perpendicular to the zygomatic arch was made from a point 1-cm anterior to the tragus upward to the level of the superior temporal line. The temporalis muscle was split and retracted away, exposing the temporal bone by two-thirds anterior and one-third posterior to the external acoustic canal.

Next, a square-shaped craniotomy was performed, and

FIG. 1. Demonstration of a right-sided LTOA. **A:** A linear incision was made along a natural skin crease of the lateral canthus. **B:** Lateral canthotomy and cantholysis were performed to expose the LOR. **C:** The periorbita was dissected from the lateral wall of orbit (LWO) posteriorly to the orbital apex. **D:** Exposure of temporal dura after removal of LWO. **E:** View of the middle cranial fossa (MCF) after exposure by lifting up temporal dura. **F:** View of Kawase's triangle after exposure (*dotted line*), following a cut of the MMA. **G:** Exposure of the PF after anterior petrosectomy. **H:** The surgical exposure of brainstem after tentorium cerebelli was cut. Can. = canthal; F. = foramen; FZ = frontozygomatic; IOF = inferior orbital fissure; Lat. = lateral; Lig. = ligament; M. = muscle; Pet. = petrosal; PO = periorbital; SCA = superior cerebellar artery; SOF = superior orbital fissure; Sup. = superior; Temp. = temporal; V. = vein. Copyright Ohio State University. Published with permission. Figure is available in color online only.

FIG. 2. Demonstration of a right-sided LOWA. **A:** The LOR was cut from frontozygomatic suture to the level of zygomatic arch (dotted line) after periorbital and temporalis muscle were dissected apart from it. **B:** Exposure of LWO and greater wing of sphenoid (GWS) after osteotomy of LOR. **C:** Exposure of the temporal dura and the orbital apex after removal of the LWO and the adjacent anterolateral segment of the GWS. **D:** Exposure of the brainstem showing neurovascular structures and measurement of the surgical exposure of infratentorial area (green line) and supra-infratentorial area (red line). Asterisk indicates variable point. Inf. = inferior. Copyright Ohio State University. Published with permission. Figure is available in color online only.

the inferior margin was then made flush with the floor of the middle fossa. The temporal dura was carefully dissected and elevated medially, thereby exposing the anatomical boundaries of Kawase's triangle.

Once exposed, using a self-retaining retractor, the temporal lobe was elevated, aiming to minimize measuring

biases that could potentially result from brain displacement (Fig. 3C). After that, measurements of interest were recorded.

Measurements

A neuronavigation system was used to collect the sur-

FIG. 3. Illustration of the trajectory of the LTOA (red area), LOWA (green area), and ATPA (blue area) and demonstration of the method used to collect the measurements of surgical freedom for LTOA (A), LOWA (B), and ATPA (C). Details are described in the *Methods* section. © The Ohio State University; used with permission. Base art in upper panel: © UpSurgeOn S.r.l.; modified and used with permission. Figure is available in color online only.

gical data of all 3 anatomical dissections. All the information from each procedure was computed into Excel spreadsheet software (Microsoft Office Excel 2013, Microsoft Corp.) and was used to calculate the areas of exposure, surgical freedom, angles of attack, and distance from the surgical portal to each target.

Area of Exposure

Two separate areas of exposure were calculated by

obtaining the sum of the areas formed by juxtaposed triangles.

For the first area of exposure, defined as the infratentorial area, 5 points forming a pentagon-shaped area were assigned to anatomical landmarks bordering the infratentorial region. The first 2 points were designated to fixed landmarks: the root entry zone (REZ) of CNs V and VII/VIII. The remaining 3 points were assigned to variable landmarks, including to the most anterosuperior, anteroin-

FIG. 4. Bar chart comparing the area of exposure of the infratentorial and supra-infratentorial areas between the LTOA, LOWA, and ATPA. Figure is available in color online only.

ferior, and posterosuperior accessible points of the brainstem (Fig. 2D).

In similar fashion, for the second area of exposure, 6 anatomical points were identified, yielding an area defined as the supra-infratentorial area. Here, the first 2 points were allotted to the dural entrance of CN IV and the REZ of CN VII/VIII, which served as the fixed landmarks. The other 4 points were assigned to the following variable landmarks: the most posterior accessible point of CN IV and the most anterosuperior, anteroinferior, and posterosuperior accessible points of the brainstem (Fig. 2D).

Surgical Freedom, Angles of Attack, and Distance to Target

Surgical freedom was defined as the maximal permissible working area at the proximal end of a 25-cm endoscopic dissector, placed along the 6 extreme-most positions in space forming an imaginary hexagonal area. The coordinates of each of the positions were obtained with the help of a navigation probe held to the proximal end of the dissector while the distal end was fixed over a particular target of interest.

The hexagonal area represented the maximal allowable working area of each approach. Thus, during LTOAs and LOWAs, techniques that approach targets anteriorly, the proximal end of the dissector was placed as far medially, inferomedially, inferolaterally, laterally, superolaterally, and superomedially as possible (Fig. 3A and B).

Similarly, in the ATPA, due to the lateral nature of the approach, the movements of the dissector about the specimen were different. Here, the dissector was moved as far anteriorly, anteroinferiorly, posteroinferiorly, posteriorly, posterosuperiorly, and anterosuperiorly as possible (Fig. 3C).

For the angles of attack, the targets of interest were the dural entrances of CNs IV, V, and VII/VIII and the REZs

TABLE 1. Area of exposure provided by the lateral orbital, lateral orbital wall, and anterior transpetrosal approaches

Area	Mean Area of Exposure (cm ²)		
	LTOA	LOWA	ATPA
Infratentorial	1.51 ± 0.5	1.99 ± 0.7	2.00 ± 1.0
Supra-infratentorial	2.61 ± 0.7	4.00 ± 1.2	4.14 ± 1.2

Data are presented as mean ± SD.

of CNs V and VII/VIII. The angles were calculated using the coordinates of the position of the proximal end of the dissector obtained by moving the latter as far as possible in the vertical and horizontal planes, while fixating its distal end on each target of interest.

Lastly, the distances from surgical entry to all the targets, provided by each approach, were measured.

Statistical Analysis

All data obtained during the measurements were exported to Stata Statistical Software (release 14, StataCorp). Comparisons of the area of exposure, surgical freedom, and angles of attack obtained for each approach were conducted using a one-way repeated-measure ANOVA with post hoc Holm-Šidák analysis. For all comparisons, *p* values < 0.05 were considered statistically significant.

Results

In the infratentorial region, the LTOA provided the smallest mean area of exposure (1.51 ± 0.5 cm²) compared with that created by the LOWA (1.99 ± 0.7 cm²) and ATPA (2.01 ± 1.0 cm²); however, the difference did not meet statistical significance (*p* = 0.07 and 0.61, respectively). Similarly, the differences were not significant when the areas of exposure of the supra-infratentorial area in the LTOA and LOWA were compared with that of the ATPA (*p* = 0.16 and 0.98, respectively).

Additionally, increments in the area of exposure for the infratentorial and supra-infratentorial areas (by 31.44% and 53.25%, respectively) were observed following lateral rim osteotomy (i.e., conversion of the LTOA to the LOWA; Fig. 4), although, again, the difference was not significant (*p* = 0.07 and 0.08, respectively). Data of the mean area of exposure for each approach are summarized in Table 1.

Regarding the surgical freedom, for all targets, the ATPA offered the greatest maneuverability by a significant amount. This was followed by those permitted by the LOWA and the LTOA. Of all the targets, the dural entrance of CN IV was associated with the greatest surgical freedom among approaches. In contrast, the REZ of CN VII was associated with the smallest area of surgical freedom (Fig. 5). Data of the surgical freedom for each approach are summarized in Table 2.

Furthermore, for all targets, the vertical angles of attack offered by the ATPA were significantly larger than those allowed by either transorbital approach. However, except for the dural entrances of CNs IV and V, the vertical angles of attack of the LTOA and the LOWA were almost equal.

Compared to the rest of the approaches, the horizontal

FIG. 5. Line graph showing the comparison of the surgical freedom for each target between the LTOA, LOWA, and ATPA. Figure is available in color online only.

attack angles permitted by the LTOA were significantly smaller for all of the targets. Conversely, except for the dural entrance and the REZ of CN V, the LOWA produced similar horizontal attack angles when compared to ATPA. The data of the angles of attack for each approach are summarized in Table 3. In addition, the LTOA required significantly longer distances for each the targets (Table 4).

Discussion

Historical records of the extension of middle fossa approach to the PF can be traced back to the late 19th century.²⁶ In the early 1960s, the approach was popularized by House to manage small intracanalicular lesions.^{15,26} In 1975, seeking to improve the working window into the CPA and IAC, Bochenek and Kukwa described the first anterior expansion of the approach,⁸ wherein the main modification involved drilling of the anterior petrous apex. However, this technique sacrificed the labyrinth, and hearing loss was an inevitable limitation of this procedure. Thereafter, Shiohara³¹ employed a combination of the techniques of Morrison and King²⁷ and Bochenek and Kukwa,⁸ emphasizing the advantages of his modified technique with comparable outcome for acoustic tumors. In 1985, Kawase et al.¹⁹ described the first extended middle fossa approach aimed at preserving audition (i.e., ATPA), made possible by limiting bone resection to the quadrangular area of the anterior petrous pyramid. Ever since then, the ATPA has been used extensively worldwide for managing lesions of the petrous apex, IAC, upper brainstem, petroclival junction, anterior cerebellopontine angle, and even vertebrobasilar aneurysms.^{13,16,18,30}

The ATPA is traditionally carried out by extradural dissection. The technique combines the advantages of complete tumor removal and minimal retraction injury to vital neurovascular structures, limited retraction of the temporal lobe, and preservation of hearing.^{21,32} Bone resection is limited to a quadrangular area that is devoid of nerve and vascular branches and is defined by the CN V₃ anteriorly, the ICA laterally, the petrous ridge medially, the arcuate eminence posteriorly, and inferior petrosal sinus inferiorly.¹²

TABLE 2. Surgical freedom for each surgical target provided by the LTOA, LOWA, and ATPA

Target	Mean Surgical Freedom (cm ²)		
	LTOA	LOWA	ATPA
IV dura	7.63 ± 2.7*†	34.59 ± 11.2	66.73 ± 9.4
V dura	5.54 ± 1.9*†	24.02 ± 7.75*	62.07 ± 9.2
V REZ	5.11 ± 1.8*†	17.07 ± 5.5*	34.75 ± 15.3
VII dura	4.50 ± 1.7*†	21.94 ± 7.2*	47.04 ± 14.1
VII REZ	3.25 ± 0.7*†	12.19 ± 4.5*	27.29 ± 3.7

Data are presented as mean ± SD.

* Significant when compared with the ATPA ($p < 0.05$).

† Significant when compared with the LOWA ($p < 0.05$).

Nevertheless, the ATPA may be subject to a number of complications since ICA and adjacent neuro-otological structures are potentially in harm's way from extensive bone drilling.^{23,33} Additionally, injuries to the GSPN and CSF leakage are among other difficulties that can be encountered.^{14,17} Thus, in an attempt to circumvent these shortcomings, the original ATPA technique has been modified, giving rise to an array of transcranial approaches including intradural anterior petrosectomy and posterior intradural petrous apicectomy.^{14,29,33}

Recently, increased focus has been placed on TOEAs to the skull base.^{3,10,11} In a previous publication, Moe et al.²⁴ described 4 endoscopic transorbital corridors based on disease location. Each of these is accessible via a small transconjunctival or transcutaneous incision made at the superior, medial, inferior, and lateral portals, based on a division of the orbit into 4 quadrants. Only minimal displacement of orbital contents is necessary, and the working pathway does not require brain retraction or crossing over major neurovascular structures.^{3,7} TOEAs are appealing options for accessing particular regions of the skull base and are also beneficial from excellent cosmetic and safety standpoints. Hence, they represent a group of procedures that can serve as alternatives or adjuncts to open and transnasal approaches. Moreover, their application will continue to grow as more advanced techniques and instrumentation become available.

This study sought to investigate the feasibility of the lateral orbital corridor as an alternative route to reach the petrous apex and the PF, as well as to explore the surgical nuances of the LTOAs for comparison with ATPAs.

Although not statistically significant, the mean area of exposure offered by the LTOA was found to be smaller compared to those of the ATPA and the LOWA. Similarly, relative to the rest of the approaches, the mean surgical freedom and angles of attack offered by the LTOA were significantly inferior. This was recognized to be a by-product not only of the narrowness of the lateral corridor (somewhat improved by meticulous < 10 mm of medial globe displacement) together with its proximity to the eyeball, but also of the significant length of the surgical pathway from the corridor's portal at the eyelid to the surgical targets in the PF.

Various studies have investigated the effects of LOR re-

TABLE 3. Angle of attack provided by the LTOA, LOWA, and ATPA

Target	Vertical Angle (°)			Horizontal Angle (°)		
	LTOA	LOWA	ATPA	LTOA	LOWA	ATPA
IV dura	10.1 ± 3.4*†	13.8 ± 3.9*	26.6 ± 6.0	5.5 ± 2.9*†	21.7 ± 9.9	24.2 ± 4.5
V dura	9.8 ± 2.9*†	15.9 ± 3.0*	26.3 ± 8.0	5.9 ± 2.5*†	17.5 ± 4.3*	26.8 ± 5.7
V REZ	9.6 ± 3.3*	12.0 ± 1.3*	17.9 ± 4.2	6.2 ± 2.5*†	14.3 ± 5.4*	21.4 ± 7.2
VII dura	7.5 ± 1.8*	8.5 ± 1.7*	24.1 ± 4.6	6.1 ± 1.2*†	15.0 ± 5.1	20.1 ± 5.4
VII REZ	6.9 ± 2.1*	10.1 ± 3.8*	17.0 ± 3.0	5.9 ± 2.8*†	11.5 ± 4.3	17.2 ± 3.3

Data are presented as mean ± SD.

* Statistically different ($p < 0.05$) in comparison with the ATPA.

† Statistically different ($p < 0.05$) in comparison with the LOWA.

removal for multiple purposes, ranging from orbital decompression to the complete resection of both intraorbital and intracranial pathologies.^{1,5,9,34} In addition, several authors agree on the advantages of LOR removal in TOEA.^{4,9,22} Altay et al.⁴ recently reported their experience with LOWA in addition to the removal a portion of the greater wing of sphenoid for lesions of the cavernous sinus. This technique provided a direct path with ample exposure of targets with improved visualization and enhanced maneuverability of instruments.

After orbital rim removal, 31.44% and 53.25% increases in the areas of exposures of the infratentorial and supra-infratentorial areas, respectively, were observed. This finding, however, was nonsignificant. Moreover, this procedure results in significantly wider horizontal attack angles, almost to the same level of ATPA. Despite this, LOR osteotomy may add to the morbidity of the procedure;^{7,20,25} therefore, further studies are necessary to clarify its clinical benefits.

Approaching the PF via the lateral orbital corridor offers several advantages, such as safety, minimal invasiveness, and optimal cosmetic results.^{4,7,9,20,34} However, the combination of a narrow surgical corridor and a complex endoscopic anatomy yields an approach with a steep learning curve, and thorough practice in the cadaver laboratory is paramount for optimal outcomes. Moreover, as opposed to the lateral microscopic view of the ATPA, the anteroposterior view of the LTOA and the LOWA makes manipulation of lesions of the clivus and petroclival junction particularly challenging, as the view may be potentially

blocked by CN V and the petrous apex. In addition, dissection of the GSPN from posterior to anterior from an anterior endoscopic perspective presents a degree of difficulty that may warrant the need for special surgical instruments.

Despite these disadvantages, the lateral orbital corridor provides direct, minimally invasive access to targets positioned posterior to the petrous apex, including the IAC and the posterolateral part of the brainstem. Therefore, TOEAs may be indicated for small lesions, such as intracanalicular schwannomas, as well as meningiomas and cholesterol granuloma of the petrous apex.

Finally, as this was a cadaveric study, several factors may preclude direct application of our results into clinical practice. These include the limited number of available specimens, postmortem changes in the consistency of brain and soft tissue, lack of intraoperative bleeding, and the use of specimens free from significant anatomical distortions or lesions of the skull base.

Conclusions

This study demonstrates the feasibility of using the lateral orbital corridor to approach the petrous apex and the PF. Although the maneuverability offered by the TOEAs is limited, they may provide an area of surgical exposure that is comparable to the ATPA. However, removal of the LOR may be possible to overcome these limitations. Further studies are necessary to define its precise clinical application.

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TABLE 4. Distance to each surgical target provided by the LTOA, LOWA, and ATPA

Target	Distance (mm)		
	LTOA	LOWA	ATPA
IV dura	87.7 ± 2.4*†	79.3 ± 3.2*	49.6 ± 1.5
V dura	88.0 ± 1.2*†	80.1 ± 1.4*	47.6 ± 0.8
V REZ	90.9 ± 1.6*†	83.8 ± 1.1*	49.7 ± 0.7
VII dura	90.8 ± 0.6*†	82.4 ± 0.6*	47.8 ± 0.9
VII REZ	93.5 ± 1.7*†	85.9 ± 1.2*	50.5 ± 1.2

Data are presented as mean ± SD.

* Statistically different ($p < 0.05$) in comparison with the ATPA.

† Statistically different ($p < 0.05$) in comparison with the LOWA.

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Disclosures

Dr. Carrau is a consultant for Medtronic. Dr. Prevedello is a consultant for Stryker, Medtronic, and Codman; has direct stock ownership in ELum; holds a patent with KLS-Martin; and receives honoraria from Leica Microsystems.

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Author Contributions

Conception and design: Noiphithak. Acquisition of data: Noiphithak, Yanez-Siller, Revuelta Barbero. Analysis and interpretation of data: Prevedello, Noiphithak, Yanez-Siller, Revuelta Barbero. Drafting the article: Prevedello, Yanez-Siller. Critically revising the article: Prevedello, Otto, Carrau. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Prevedello. Statistical analysis: Noiphithak, Yanez-Siller. Administrative/technical/material support: Prevedello, Otto, Carrau. Study supervision: Prevedello, Carrau.

Supplemental Information

Videos

Video 1. <https://vimeo.com/262820618>.

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