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ORIGINAL ARTICLE

Endoscopic Endonasal Accessibility and Maneuverability Around the Internal Carotid Artery from Distal Dural Ring to Foramen Lacerum: a Cadaveric Study

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Abstract

Background: **Expanded-endoscopic endonasal approaches (eEEA) to surgical targets around the internal carotid artery (ICA) remain inspiring and necessitate a special learning curve.**

Materials and methods: **Six formalin-fixed heads were dissected to study the 360° accessibility and maneuverability around ICAs from the distal dural ring to the foramen lacerum on each side ($n = 12$) via eEEA. The ICA course was divided into three segments: ICA in cavernous sinus, paraclival-ICA, and lacerum-ICA. Following total exposure of each ICA, the three-dimensional (3D = medial/lateral, superficial/deep, and above/below) anatomical targets ($n = 35$) around each ICA were evaluated. The data were collected and analyzed.**

Results: **Distinctively, we included 35 anatomical targets (pertinent to ICA in cavernous sinus, paraclival-ICA, and lacerum-ICA were 16, 10, and 9, respectively) in 360° around every ICA ($n = 12$) from the distal dural ring to foramen lacerum. Although reasonable visual validation was possible for all targets, microdissections were safely achievable for 19 (54.3%) targets through full or limited surgical freedom in 73.7 and 26.3%, respectively. In the remaining 45.7%, the accessibility to targets was abandoned due to hazardous manipulation. The most unreachable targets were around the lacerum-ICA (55.6%) with extremely restricted maneuverability (75%). However, favorable accessibility (60%) and full surgical freedom (100%) were around the paraclival-ICA.**

Conclusion: **This study delivers a distinctive view to appreciate the degree of complexity and invasiveness in relation to the degree of surgical freedom around ICA via eEEA. Illustrating these details for skull base surgeons can lead them to tailor their approach. It delivers prospective feedback for our operative theater.**

Keywords: Anatomy, Endoscopic endonasal approach, Internal auditory meatus, Sella

1. Introduction

Expanded-endoscopic endonasal approaches (eEEA) necessitate the gaining of novel knowledge and surgical skills based on intensive training on cadavers to abridge the learning curve before moving to the operating theater.[1–8] Endoscopic endonasal skeletonization of the internal carotid artery (ICA) requires extensive skull base drilling, which is full of dangers.[1,9–15]

The aim of the study was to study the 360° accessibility and maneuverability of surgical targets around the ICA from the distal dural ring (DDR) to the foramen lacerum (FL) via eEEA.

2. Materials and methods

Study design and intervention (Tables 1 and 2).

The idea, design, acquisition of data, and all cadaveric dissections were done by the corresponding author (A.N.).

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Table 1. The degree of complexity and invasiveness in relation to the degree of surgical freedom around ICA via eEEA.

Surgical target	Accessibility		
	Reasonable visual exposure	Safe microdissection	Maneuverability 'surgical freedom'
CS-ICA			
DDR	+	+	+
Carotid bifurcation	+	−	−
SC-ICA	+	+(#)	+(#)
CS (posterior compartment)	+(‡)(‼)(†)(ǂ)(●)	+(#)	+(#)(;)
CS (lateral compartment: III, IV, V1, VI)	+(‡)(‼)(†)(ǂ)(⁝)(●)	+	+(;)
ICA (anterior genu) (✓)	+(‡)(⁝)(●)	+	+
ICA (paraclinoidal-paraclival junction)	+(‡)(‼)(⁝)(●)	+	+
ACA (A1)	+	−	−
Mesial temporal lobe and optic tract (❖)	+	−	−
II (from chiasm to LOCR and orbital apex)	+	+(#)	+(#)
Ophthalmic artery	+	+(#)	+(#)
SHA	+	+	+
PcomA	+(*)(‡)(‼)(†)(ǂ)(●)	−	−
PCA (❖)	+(*)(‡)(‼)(†)(ǂ)(●)	−	−
SCA (❖)	+(*)(‡)(‼)(†)(ǂ)(●)	−	−
III-cisternal segment (❖)	+(*)(‡)(‼)(†)(ǂ)(●)	−	−
Paraclival-ICA			
ICA (paraclival/Gasserian segment)	+(‡)(‖)(ǂ)(●)	+	+
FR and V2 (✓)	+(⁂)	+	+
MS	+(⁂)	+	+
SOF	+(⁂)	+	+
Gasserian ganglion	+(‡)(⁂)(»)	+	+
VI (cisternal segment)	+(*)(‡)(‖)(¶)(§)(⁂)	+(#)	+(#)
VI (Dorello's canal segment)	+(*)(‡)(‖)(¶)(§)(⁂)	−	−
Midbrain (lateral surface)	+(*)(‡)(‖)(¶)(§)(⁂)	−	−
Pons (lateral surface)	+(*)(‡)(‖)(¶)(§)(⁂)	−	−
V (cisternal segment) and petrosal vein (❖)	+(*)(‡)(‖)(¶)(§)(!)(⁂)	−	−
Lacerum-ICA			
FL and lacerum-ICA (✓)	+(‡)(‖)(¶)(⁂)	+	+(;)
Petrous apex	+(*)(‡)(‖)(¶)(§)(⁂)	+(#)	+(;)
Petrosal process	+(‡)(¶)(§)(⁂)	+(#)	+(#)(;)
Gruber's ligament	+(‡)(¶)(§)(⁂)	−	−
IPS	+(‡)(¶)(§)(⁂)(●)	+	+
IAC, AICA and labryinthine artery (❖)	+(*)(‡)(‖)(¶)(§)(!)(⁂)	−	−
VII/VIII complex (cisternal segment) (❖)	+(*)(‡)(‖)(¶)(§)(!)(⁂)	−	−
VII/VIII complex (IAC segment) (❖)	+(*)(‡)(‖)(¶)(§)(!)(⁂)	−	−
VII/VIII complex Root exit/entry zone (REZ) (❖)	+(*)(‡)(‖)(¶)(§)(!)(⁂)	− (※)	− (※)

+, achievable; −, abandoned due to extreme risky manipulation; #, requires special curved instruments/distinct drill; ‡, needs ICA mobilization that requires tailored bone drilling/drilling around vidian canal/dissection at lateral edge of clivus; ‼, release of the parasellar ligaments/opening of proximal dural ring/special knife and scissors/scarifying the inferior hypophyseal artery/posterior clinoidal process removal; †, following pituitary transposition; ǂ, middle cranial fossa approach (suprapetrous) approach; ⁝, the sympathetic plexus around ICA at a great risk; ●, injectable hemostatic agent is as indispensable prerequisite during surgical exposure;(;), restricted maneuverability; ✓, most superficial surgical target; ❖, deepest surgical target, (*): angled endoscope (30°); ‖, removal of the lingual process; ⁂, the ipsilateral nasoseptal flap (NSF) at a great risk ' = a contralateral NSF should be prepared; ' », dissection in Meckel's cave; ¶, transpterygoid sublacerum approach to the petrous apex that necessitates sacrificing Vidian nerve, transect the pterygo-sphenoidal fissure tissue between the lacerum ICA and the Eustachian tube to facilitate lateral mobilization of the paraclival and lacerum ICA 'opening of foramen lacerum'/approach via the medial petrous triangle, (§): involves contralateral approach 'including contralateral transmaxillary (CTM); ' ! sacrificing the Eustachian tube; ※, 'lesion simulation' showed unsafe instrumental arrival/hazardous maneuverability/inability to reach the target.

II, optic nerve; III, oculomotor nerve; IV, trochlear nerve; V1, ophthalmic nerve; V, trigeminal nerve; VI, abducent nerve; VII/VIII, facial-vestibulocochlear nerve complex; ACA, anterior cerebral artery; AICA, anterior inferior cerebellar artery; CS, cavernous sinus; DDR, distal dural ring; FL, foramen lacerum; FR, foramen rotundum; IAC, internal auditory canal; ICA, internal carotid artery; IPS, inferior petrosal sinus; LOCR, lateral opticocarotid recess; MS, maxillary strut; PCA, posterior cerebral artery; PcomA, posterior communicating artery; REZ, root entry/exit zone; SCA, superior cerebellar artery; SC-ICA, supraclinoidal-ICA; SHA, superior hypophyseal artery; SOF, superior orbital fissure; V2, maxillary nerve.

Table 2 . Intervention.

Endoscopic skull base module	eEEA	Included/excluded
Sinonasal cavity, sphenoid sinus and sellar region.	Identification of the nasal landmarks	+
	Elevate the nasoseptal flap	+
	Transsphenoidal approach/identify the sphenoid sinus landmarks	+
	Identify the middle clinoid process/safe middle clinoidectomy	+
	Expose the pituitary dura (2 layers) and pituitary gland	+
Suprasellar region	Transtuberculum/transplanum approach	+
	Orbital apex decompression (for medial eye retraction in preparation for module #8)	+
	Carotid cave identification	+
	Suprasellar region (Intradural identification of the pertinent neurovascular structures)	+
Anterior skull base Medial orbital approach	Ethmoidectomy/medial orbital decompression/ligation of the anterior and posterior ethmoid arteries	+
	Frontal sinusotomy (Draf III)	−
	Anterior craniofacial resection	−
	Identification of the recti muscles and the optic nerve within the orbit	−
Transclival and transodontoid approaches	Superior transclival approaches-Extradural/interdural transcavernous pituitary transposition.	+
	Modified extradural pituitary transposition using the ‘look-up view’	
	Middle transclival approaches	+
	Inferior transclival and transodontoid approaches	−
Transpterygoid approach, Meckel's cave, petrous apex and Jugular foramen	Transpterygoid approaches	+
	Exposure of the pterygopalatine fossa	+
	Identify and preserve the vidian nerve	+
	Exposure of the foramen lacerum	+
	Suprapetrous middle cranial fossa approach (Identify V_2, V-R line, Maxillary strut, open the dura of the middle cranial fossa to the temporal tip and base, basal temporal veins)	+
	Expose V_3	−
	Meckel's cave (Joining of V_1, V_2 and V_3)	+
	Cavernous sinus compartments (superior, posterior, inferior and lateral) with identification of pertinent neurovascular structure in each compartment	+
	Sublacerum approach to the petrous apex	+
	Sublacerum approach to the Jugular foramen	−
Contralateral route	CTM to petrous apex	+
Skull base reconstruction using various vascularized flaps	Nasoseptal flap in association with ipsilateral transmaxillary approach	+
	Middle turbinate flap/Inferior turbinate flap	−
	Endoscopic pericranial flap	−
	Transpterygoid transposition of a temporoparietal fascia flap	−
Modified transpalpebral transorbital neuroendoscopic approaches	Transorbital approach to the anterior cranial fossa	−
	Transorbital approach to the middle cranial fossa and cavernous sinus	−
	Transorbital anterior petrosectomy (identification of the MMA, GSPN, arcuate eminence, PLL, petrous and paraclival-ICA, V_3)	− (*)
	Transorbital drilling of the internal auditory canal and identification of VII and VIII	−
	Transorbital ligation of the superior petrosal sinus and cutting the tentorium	−
	Transorbital approaches to the posterior cranial fossa, brainstem, supratentorial compartment and basal cisterns	−
	Transorbital skull base reconstruction using vascularized pedicle flap	−

+, included; −, excluded; *, another endoscopic corridor to study the ICA.
CTM, contralateral transmaxillary approach; eEEA, expanded-endoscopic endonasal approach; FL, foramen lacerum; GSPN, greater superficial petrosal nerve; ICA, internal carotid artery; MMA, middle meningeal artery; PLL, petrolingual ligament; V1, ophthalmic nerve; V2, maxillary nerve; V3, mandibular nerve; VII/VIII, facial-vestibulocochlear nerve complex; V-R, vidian-rotundum.

Six formalin-fixed heads were dissected to study the 360° accessibility and maneuverability around ICAs from DDR to FL on each side ($n = 12$) via eEEA. The ICA course was divided into three segments: ICA in cavernous sinus (CS-ICA), paraclival-ICA, and lacerum-ICA. The data were collected and analyzed.

2.1. Inclusion criteria

All anatomical targets ($n = 35$) in three-dimensional orientation (3D = medial/lateral, superficial/deep, and above/below) around the CS-ICA, paraclival-ICA, and lacerum-ICA were included.

2.2. Exclusion criteria

Cochlear/petrous/parapharyngeal/cervical ICAs, structures below FL, and midline neurovascular structures unrelated to ICA or approaching the ICA via an extranasal route (transorbital neuroendoscopy/transcranial microdissections) were excluded.

3. Technique

The endoscopic skull base anatomical dissections that included the most difficult approaches (coronal planes)[1,11,14,16,17] with significant depth, unique angle, challenging 3D-geometry, that involve careful skeletonization of the ICA, and innovative methods to discover CS compartments were accomplished based on the University of Pittsburg Medical Center (UPMC) Anatomical Dissection Guideline,[9–15,18] a thorough survey of the English literature,[19–25] and our modified techniques.[1,6,7]

3.1. Reasonable visual exposure

It is defined as the implementation of the indispensable eEEA, including tailored drilling, removing hindering projections (middle/posterior clinoidal processes) utilizing contralateral corridors, and/or scarifying obstructing structures (ex: pedicle of nasoseptal flap, vidian nerve, sympathetic around ICA, inferior hypophyseal artery, or Eustachian tube) to mobilize the ICA and to fully expose 360° surgical target with necessary angled-endoscopes (0°/30°).

3.2. Safe microdissection

It is defined as the art of driving key instruments (including curved tools, blunt/sharp micro-dissectors, retractable knife, and distinct scissors) to release ligaments/open tissue planes to reach/touch available surgical targets under proper endoscopic visual control without placing other neurovascular structures at risk. Extreme risky manipulation might occur while using curved instruments to reach deep targets (e.g. curved suctions to reach the IAC, as the jaw of the curve might injure superficial structures 'pons'). Risky movements/excess zoom-in/out were abandoned.

3.3. Full surgical freedom

It is defined as applying safe micro-dissection with two instruments and/or in 3D movement.

3.4. Restricted maneuverability

It is defined as safe micro-dissection with a single instrument and/or in 2D movement (in/out, up/down as in CS lateral compartment = the side-to-side movement between the ICA and cranial nerves is limited and associated with high risk).

3.5. Statistical analysis

The collected data were tabulated, and SPSS 26.0 was employed for statistical analysis along with Microsoft Excel 2016 and MedCalC program software, version 19.1.3 (MedCalc Software Ltd, Ostend, Belgium).

4. Results

Particularly, from the DDR to FL, we included 35 surgical targets at 360° around every single ICA ($n = 12$) (Tables 1 and 3). Despite reasonable visual validation being possible for all targets 100% ($n = 35$), the overall safe micro-dissections were achievable for 19 (54.3%) targets. In the remaining 45.7%, approachability to targets was avoided owing to dangerous navigation. Overall full surgical freedom and limited maneuverability were 73.7 and 26.3%, respectively (Figs. 1–4).

Surgical targets around ICA segments (Figs. 1–4 and Table 3).

(1) CS-ICA: reasonable visual exposure of 16 targets. Safe micro-dissection was achievable in 56.3% ($n = 9$), whereas risky movements were abandoned in 43.7% ($n = 7$). Full surgical freedom and restricted maneuverability were 77.7% ($n = 7$) and 22.3% ($n = 2$), respectively.
(2) Paraclival-ICA: reasonable visual exposure of 10 targets. Safe micro-dissection was achievable in 60% ($n = 6$), whereas risky movements were abandoned in 40% ($n = 4$). Full surgical freedom

Table 3. Results

* #	CS-ICA		Paraclival-ICA		Lacerum-ICA	
Achievable	56.3% ($n = 9$)		60% ($n = 6$)		44.4% ($n = 4$)	
	+	(;)	+	(;)	+	(;)
	77.7% ($n = 7$)	22.3% ($n = 2$)	100% ($n = 6$)	0% ($n = 0$)	25% ($n = 1$)	75% ($n = 3$)
Abandoned	43.7% ($n = 7$)		40% ($n = 4$)		55.6% ($n = 5$)	
Total ($n = 35$)	($n = 16$)		($n = 10$)		($n = 9$)	

*, ICA segments; #, surgical targets; +, full surgical freedom; (;), restricted maneuverability; *n*, number.
CS-ICA, ICA inside cavernous sinus; ICA, internal carotid artery.

and restricted maneuverability were 100% ($n = 6$) and 0% ($n = 0$), respectively.

(3) Lacerum-ICA: reasonable visual exposure of nine targets. Safe micro-dissection was achievable in 44.4 ($n = 4$), whereas risky movements were abandoned in 55.6% ($n = 5$). Full surgical freedom and restricted maneuverability were 25% ($n = 1$) and 75% ($n = 3$), respectively.

The most unreachable targets were around the lacerum-ICA with extremely restricted maneuverability. However, favorable accessibility and full surgical freedom were around the paraclival-ICA (Fig. 4).

5. Discussion

It should be emphasized that every visible target could not be made accessible. Besides, the skull base team had better to have sufficient learning curve and a full 360° understanding of the pertinent anatomical landmarks with extensive cadaver training before proceeding to complex approaches.[1–7,9–15,18–25] Surgeons have a duty to be aware of different skull base corridors (*trans*-cranial/eEEA/*trans*-orbital),[26–29] tailor the approach for each patient, and avoid bias to a particular instrument or surgical route.[27,28] eEEA cannot fit all patients.[1]

5.1. Approaches

eEEA to cavernous sinus and structures in the coronal plane (including *trans*-pterygoid approach) with skeletonization of ICA is well known.[9–15,18] Likewise, contralateral endoscopic corridors (including the contralateral *trans*-maxillary approach)[15] further improve visualization of the

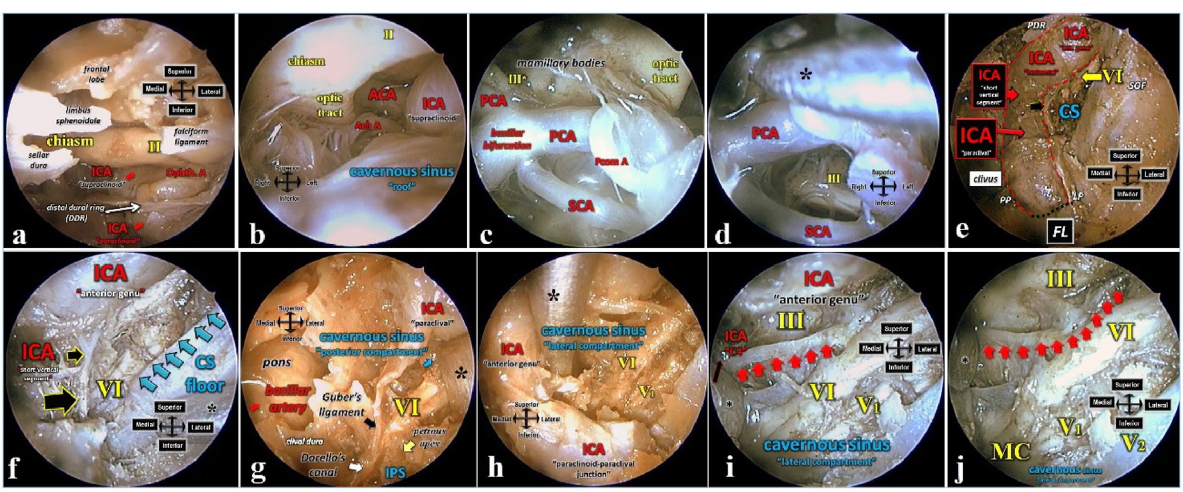

Fig. 1. Endoscopic video-captured view following cadaveric dissection: an illustration of complex skull base exposure and completing cavernous sinus approach and the left-sided sublacerum approach to the petrous apex. (a) The distal dural ring, and the limits btween the cavernous ICA and supraclinoidal ICA, ophthalmic artery under the optic nerve (II). (b) The cavernous sinus roof, supraclinoidal ICA, carotid bifurcation, anterior cerebral artery (ACA), anterior choroidal artery (Ach.A), perforators, optic nerve (II), chiasm, and optic tract. (c) Following upper clivectomy: the basilar bifurcation, both posterior cerebral arteries (PCA), superior cerebellr artery (SCA), posterior communicating artery (PcomA) interpeduncular cistern, and right oculomotor nerve (III). (d) Accessability with instruments (*) and left III between PCA and SCA. (e) The approach to foramen lacerum (FL), petrosal process (PP), lingual process (LP) (these two processes together with clivus shold be removed to mobilize the ICA), paraclival-ICA, caverous sinus, abducent nerve (VI), sympathetic around ICA (black arrow), superior orbital fissure (SOF), and proximal dural ring (PDR). (f) Access to the cavernous sinus and close view of the sympathetic around ICA (black arrow) and its relation to VI. (g) Access to posterior compartment of cavernous sinus with instruments (*), Gruber's ligament, Dorello's canal, petrous apex and inferior petrosal sinus (IPS). The course of VI can be appreciated. (h) Access to lateral compartment of cavernous sinus with instruments (*), VI and ophthalmic nerve (V1) are seen. (i) the lateral trunk (red arrows) from cavernous-ICA, III, VI and V1 followwing dissection of the lateral compartment of cavernous sinus. (j) Meckel's cave, V1 and V2 (maxillary nerve).

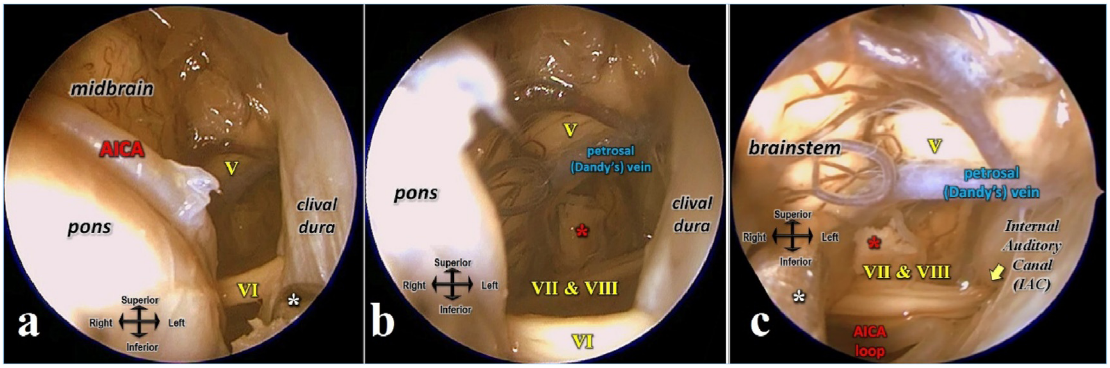

Fig. 2. 30° endoscopic video-captured view following cadaveric dissection. (a) Access to Dorello's canal with instruments (white *), VI, trigeminal nerve (V) and anterior inferior cerebellar artery (AICA). (b) Lesion simulation (red *) at the deepest point between V and facial-vestibulocochlear nerve complex (VII and VIII). (c) Restricted access to lesion simulation (red*) with instruments (white*) or internal auditory canal (IAC).

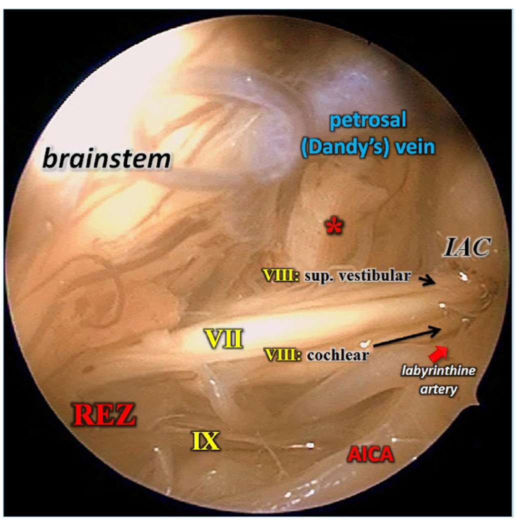

Fig. 3. 30° endoscopic video-captured view following cadaveric dissection. The beautiful arrangement of VII/VIII complex from the REZ: root entry/exit zone (REZ) and 9th cranial nerve (IX) to IAC with no access to lesion simulation (red*).

medial petrous triangle/petrous apex but are limited in their ability to achieve full surgical freedom.

Application of innovative and modified corridors[1,6,7] might expand the surgical freedom for particular targets around the lacerum-ICA, paraclival/Gasserian-ICA, or CS-ICA segments. Still, it requires an extra learning curve. *Trans*-orbital or *trans*-cranial approaches were outside the scope of this study.

5.2. Internal carotid artery classification

The ICA classification system from the skull base perspective aids expresses structures at risk during eEEA.[8] Nevertheless, it cannot give a solid conclusion regarding the degree of accessability or maneuverability.

The ICA segments include cochlear-ICA, petrous-ICA, paraclival/Gasserian-ICA, sellar-ICA, sphenoid-ICA, ring-ICA, and cisternal-ICA.[8] In our study based on surgical exposure via eEEA, we jointly defined the sellar-ICA, sphenoid-ICA, ring-ICA, and cisternal-ICA segments as CS-ICA segment. The paraclival/Gasserian-ICA segment had the same standard nomenclature in our study, whereas we used the lacerum-ICA to refer to the junction between paraclival/Gasserian-ICA and petrous-ICA. Our ICA segmentation was tailored based on the surgical nuances. Neither cochlear-ICA nor petrous-ICA was included in the index study.

5.3. Limitations and ideas to overcome them

The type of specimens (formalin-fixed heads), instruments, selected approaches, and surgeon's learning curve can affect the degree of accessibility and maneuverability in such challenging targets. To overcome these limitations, it is reasonable to have a well-prepared laboratory engaged with injected fresh cadavers and provided with navigation for teamwork experts having an advanced learning curve. This will push the boundaries for skull base surgery.

5.4. Conclusions

This study provides a unique prospect to understand the level complexity and invasiveness in relation to the degree of surgical freedom around ICA via eEEA. Clarifying this facts for skull base surgeons can lead them to choose/modify an

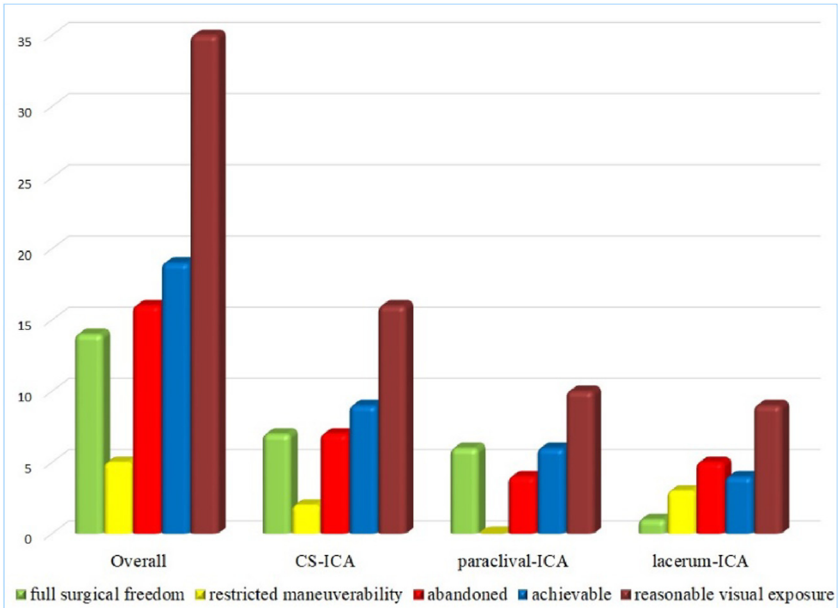

Fig. 4. Results of accessablility and manuverability to surgical targets.

appropriate approach. It delivers a prospective feedback for our operative theater.

Conflict of interest

There are no conflicts of interest.

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Authorship: the idea, design, acquisition/interpretation of data, all cadaveric dissections, drafting and critical revising were done by the corresponding author (A.N.).

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