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Transorbital and supraorbital uniportal multicorridor approach to the orbit, anterior, middle and posterior cranial fossa: Anatomic study

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ABSTRACT

Introduction: The transorbital route has been proposed for addressing orbital and paramedian skull base lesions. It can be complemented by further marginotomies, as per "extended-transorbital approach" and combined with others ventro-basal approaches featuring the concept of "multiportal surgery". Nevertheless, it cannot address some anatomical regions like the clinoid, carotid bifurcation and the Sylvian fissure. Therefore, we propose a combined transorbital and a supraorbital approach, attainable by a single infra-brow incision, and we called it "Uniportal multicorridor" approach.
Research question: The aim of our study is to verify its feasibility and deep anatomical targets through a cadaveric study.
Materials and methods: Anatomic dissections were performed at the Laboratory of ICLO Teaching and Research Center (Verona, Italy) on four formalin-fixed cadaveric heads injected with colored neoprene latex (8 sides). A stepwise dissection of the supraorbital and transorbital approaches (with an infra-brow skin incision) to the anterior tentorial incisura, clinoid area, lateral wall of the cavernous sinus, middle temporal fossa, posterior fossa, and Sylvian fissure is described.
Results: We analyzed the anatomic areas reached by the transorbital corridor dividing them as follow: lateral wall of the cavernous sinus, middle temporal fossa, posterior fossa, and Sylvian fissure; while the anatomic areas addressed by the supraorbital craniotomy were the clinoid area and the anterior tentorial incisura.
Conclusions: The described uniportal multi-corridor approach combines a transorbital corridor and a supraorbital craniotomy, providing a unique intra and extradural control over the anterior, middle, and posterior fossa, tentorial incisura and the Sylvian fissure, via an infra-brow skin incision.

1. Introduction

Since the dawn of neurosurgery, skull base has been considered a surgical and anatomic challenge. It has always required extensive and invasive approaches that often led to unsatisfactory functional, oncologic, and aesthetic outcomes especially in cases of multi-compartmental lesions, multiple or staged surgeries.

Lesions involving both ACF and MCF need extensive antero-lateral approaches warranting extensive brain retraction and neurovascular tissue manipulation for gaining the deepest-seated targets (Aftahy et al., 2020; Aguiar et al., 2009; Chokyu et al., 2011; Attia et al., 2012; Manzoor et al., 2021). A fortiori, the involvement of the orbit substantiated the deployment of further marginotomies or orbitotomies making the task even more tough (Parrilla et al.; VanKoevering et al., 2019; Abussuud et al., 2020).

Recently, thanks to the introduction of the endoscope, further routes have enriched the ventro-basal approaches wearpony (Cavallo et al., 2019). One of the major limitations of the median corridors, such as EEA, is their extension beyond the midline (Di Somma et al.a). In this scenario, the transorbital route has been proposed to address paramedian lesions located in the orbit, lateral wall of CS and MCF (Di

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Abbreviations

ACF	anterior cranial fossa
ACI	anterior incisural space
ACP	anterior clinoid
CS	cavernous sinous
CSF	Cerebrospinal fluid
CT	computer tomography
EEA	endoscopic endonasal approach
GSPN	the greater superior petrosal nerve
GSpW	greater sphenoid wing
HD	High definition
IAC	internal acoustic canal
IOF	inferior orbital fissure
LSpW	lesser sphenoid wing
MCA	middle cerebral artery
MCF	middle cranial fossa
MMA	middle meningeal artery
MOB	meningo-orbital band
OTPF	orbito-temporal-periosteal-fold
PCF	posterior cranial fossa
SF	Sylvian fissure
SOF	superior orbital fissure
V1	ophthalmic nerve
V2	maxillary nerve
V3	mandibular nerve

Somma et al.b; Locatelli et al.; Dallan et al., 2018; Jeon et al., 2018). Thereafter, the transorbital approach was completed by further margionotomies, such as the removal of the superior or lateral orbital rim to gain more cranio-caudal or lateromedial working angle, introducing the concept of "extended transorbital approach" (Matano et al., 2022; Lim et al., 2021). Nevertheless, this shrewdness still faces some anatomic and functional constrains, namely the access over the clinoidal, carotid bifurcation and the SF areas.

When perceiving this controversial scenario, we felt the urge to address those limitations pushing our draft further beyond the former boundaries pioneering the "Uniportal multicorridor" approach to the orbit, ACF, MCA and PCA, ACP region, ACI and SF. It is featured by an incision located in the infero-lateral aspect of the eyebrow (Lim et al., 2021), warranting the name of "orbital-superolateral", which allows execution of both a standard transorbital approach and a supraorbital craniotomy with or without removing the superior orbital rim. In the daily clinical practice, we entrust that the deployment of such infra-brow incision, placed 5 mm above the "standard eyelid incision", in either SOA and TOA may ensure enough working space for a "rescue" transorbital or supraorbital craniotomy if required during surgery.

The aim of our study was to verify the feasibility and deep anatomical targets of the Uni-portal Multi-corridor approach through a cadaveric study, proving that the combination of the transorbital corridor and the supraorbital craniotomy provides a satisfying intra and extradural control over the anterior, middle and even posterior cranial fossae.

2. Material and methods

Anatomic dissections were performed at the Laboratory of ICLO Teaching and Research Center (Verona, Italy). Four formalin-fixed cadaveric heads injected with colored neoprene latex (8 sides) were used. Before and after dissection, all specimens underwent a multi-slice helical computed tomography (CT) scan (SIEMENS Somaton GoTop software version VA30A-SP03) with 0.5 mm thick axial spiral sections and a 0° gantry angle. Both endoscopic transorbital and supraorbital approaches were performed using a rigid endoscope of 4 mm diameter and 18 cm length, with 0° and 30° lenses (Karl Storz, Tuttlingen, Germany). The endoscope was connected to a light source through a fiber optic cable (300 W Xenon; Karl Storz) and to an HD camera (Endovision Telecam SL; Karl Storz). Bone resection was performed with a high-speed drill (Midas Rex Legend Stylus, Medtronic). For documentation and confirmation of anatomical structures and defined landmarks, neuro-navigation was used (StealthStation Treon, Medtronic, Jacksonville, FL, USA). Intra-operative images were recorded and stored with the Karl Storz Aida system. Institutional review board approval was not required for this study. The authors state that every effort was made to follow all local and international ethical guidelines and laws that pertain to the use of human cadaveric donors in anatomical research (Iwanaga et al., 2022).

2.1. *Transorbital and supraorbital uniportal multicorridor approach*

The specimen is fixed in a three-point Mayfield head holder. The head was rotated of 10° contralaterally and positioned in a slightly extended position of around 15–20° to allow gravity to retract the frontal lobes away from the surgical field. In this setting, the surgeon works behind the patient, being able to perform both TOA and SOA as in a standard microsurgical operating room scenario. The dissection started with the aid of the surgical microscope. A 3 cm infra-brow incision is made immediately inferior to the eyebrow, laterally to the supraorbital groove (Fig. 1A) and extended directly on the bone by cutting the orbital portion of the orbicularis oculi muscle along its fibers and the periosteum.

Caudo-cranial subperiosteal dissection is performed approximately 2–3 cm superiorly to the supraorbital ridge and laterally up to the superior temporal line (Fig. 1B). The superior temporal line is exposed, and the temporalis fascia and muscle are visualized. The periosteal flap is reflected superiorly using stitches. Subperiosteal dissection of the temporalis muscle is carried out in an antero-posterior caudo-cranial fashion, peeling it off from the lateral aspect of the orbital rim and the temporal fossa (Fig. 1C). The MacCarty keyhole is exposed (Fig. 1D).

A cranio-caudal subperiosteal dissection is made in order to expose both the supraorbital rim and the frontozygomatic suture. The arcus marginalis is then visualized and detached from the orbital rim keeping the dissection plane strictly adherent to the bone in order to prevent periorbital disruption and fat prolapsing into the surgical field (Fig. 1F). The supraorbital groove and nerve are identified medially (Fig. 1G). The periorbita is elevated from the superolateral and lateral wall of the orbit up to the fronto-zygomatic suture, while taking care not to damage the supraorbital nerve medially.

Thereby, the transorbital corridor and the bony area for the supraorbital craniotomy are exposed (Fig. 1H).

2.2. *Transorbital approach*

The subperiosteal dissection proceeds in an antero-posterior direction detaching the periorbita from the lateral wall and lateral aspect of the roof of the orbit (Fig. 2A). Care should be taken to not violate the periorbita preventing orbital fat tissue to protrude into the surgical field hindering further deep surgical maneuvers. The endoscope is then brought into the surgical field to increase visualization. The zygomaticofacial and the zygomaticotemporal artery are identified (Fig. 2B), at the inferior and superior aspect respectively of the lateral orbital wall and cut (Fig. 2C). The inconstant Hyrtl foramen or the meningo-orbital foramen may be encountered superolaterally to the SOF (Fig. 2D). The IOF and SOF are then reached (Fig. 3A). The lateral wall of the orbit is drilled until the deep temporalis fascia is exposed. The three orientation landmarks are then identified forming a superiorly opened "V shape", namely SOF medially and the temporal fascia laterally, pointing toward

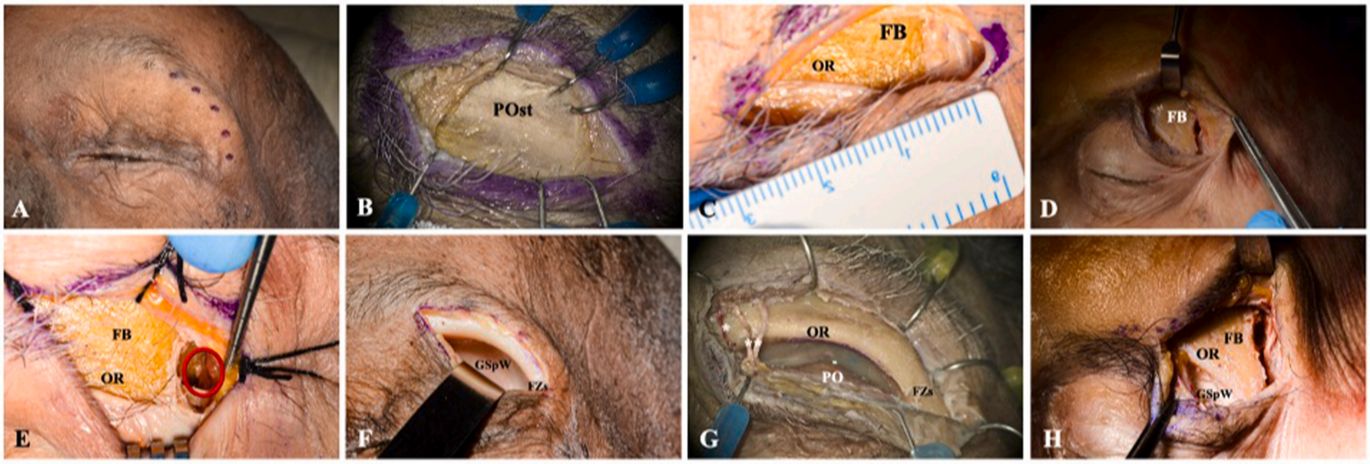

Fig. 1. Left side: A) A curvilinear skin incision is planned immediately inferior to the eyebrow from the supraorbital groove to the lateral canthus; B) The incision is made through the orbital portion of the orbicularis oculi muscle along its fibers until the periosteum is identified (POst); C) After caudo-cranial subperiosteal dissection, the orbital ridge (OR) and the frontal bone (FB) are exposed; D) The temporalis fascia and muscle are dissected in an antero-posterior caudo-cranial fashion from the lateral aspect of the orbital rim and the temporal fossa; E) the MacCarty keyhole is exposed (red circle); F) The orbital rim (OR) and the fronto-zygomatic suture (FZs) are exposed and the periorbita (PO) is peeled off the lateral and superior orbital wall exposing the greater sphenoid wing (GSpW); G) The supraorbital groove along with the supraorbital artery (*) and nerves (**) are identified medially; H) The transorbital corridor and the bony area for the supraorbital craniotomy are exposed.

(POst: periosteum; OR: orbital ridge; FB: frontal bone; FZs: frontozygomatic suture; GSpW: greater sphenoid wing; PO: periorbita). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

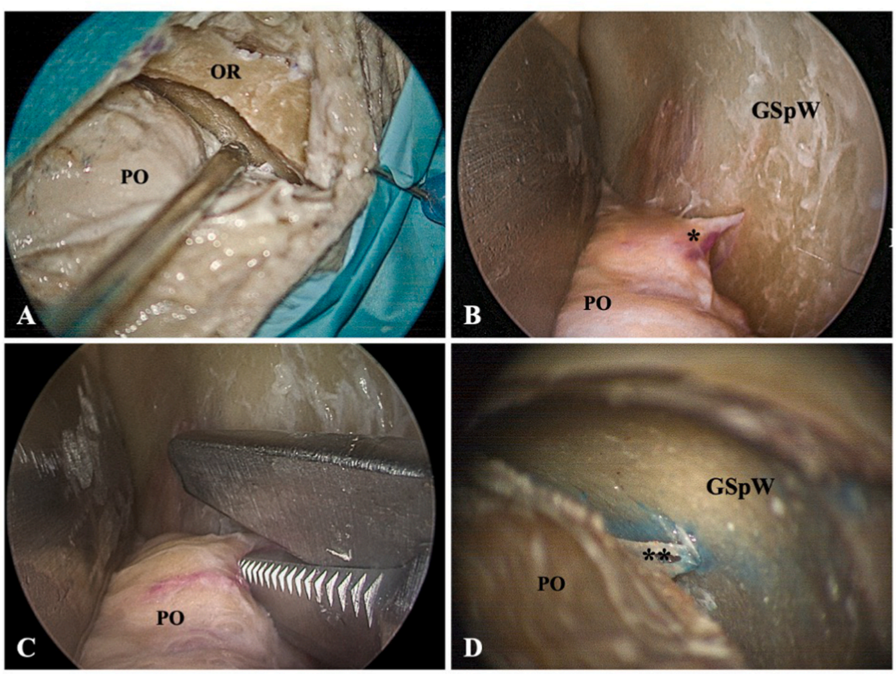

Fig. 2. Left transorbital approach: A) The periorbita is detached from the lateral wall and lateral aspect of the roof of the orbit; B) The zygomaticotemporal artery and nerve (*) are identified at the superior aspect of the lateral orbital wall; C) The zygomaticotemporal bundle is cut; D) The Hyrtl foramen (**) is visualized superolaterally to the superior orbital fissure.

(OR: orbital ridge; FZs: frontozygomatic suture; GSpW: greater sphenoid wing; PO: periorbita).

the IOF inferiorly; the *LSpW* represents the superior limit of the craniectomy (Fig. 3B). The drilling of the GSpW can be started, until the "sagittal crest" (Corrivetti et al., 2022) medially and the inner projection of the pterional and MacCarty keyoles laterally are visualized. The surgical maneuvers and handling of instrument in this phase may be easier by fitting a malleable spatula between the SOF and the sagittal crest. The drilling of the ventral portion of the greater sphenoid wing proceed until the dura mater of the temporal pole is identified (Fig. 3C). The sagittal crest is then disconnected from its intersection with the lesser sphenoid wing, peeled off from the periorbita, dura mater and the periosteum of the SOF and finally detached as previously described (Corrivetti et al., 2022).

The inferior and inferolateral portion of the GSpW should be drilled flush with the floor of the middle fossa in order to allow a straight

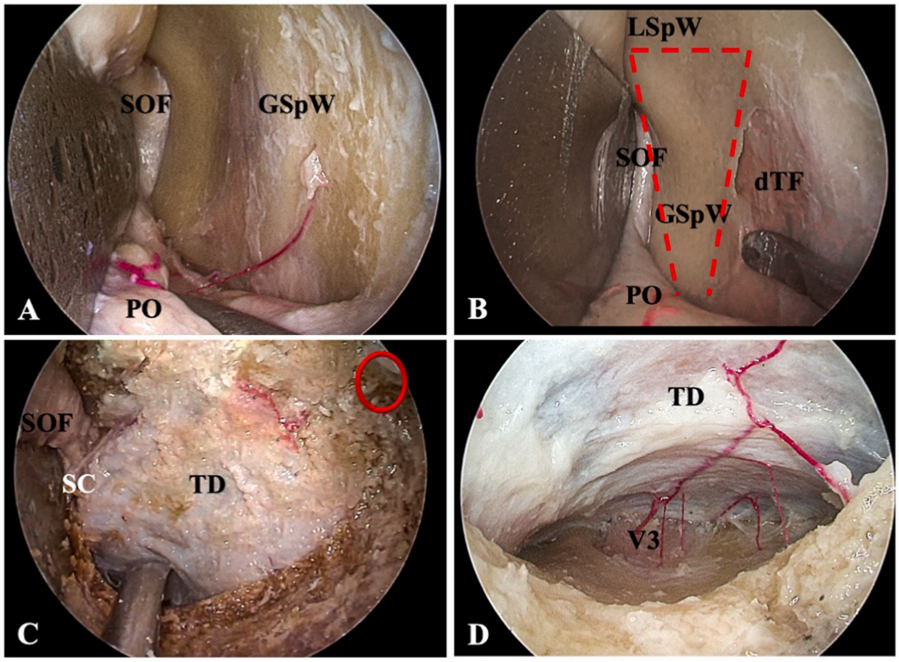

Fig. 3. Left side: A) The superior orbital fissures (SOF) is exposed; B) The lateral wall of the orbit is drilled until the deep temporalis fascia is exposed. The SOF medially, the deep temporal fascia (dTF) laterally, and the lesser sphenoid wing superiorly (LSpW), represents the limits of the "V shape" craniectomy; C) After the drilling of the greater sphenoid (GSpW), the dura mater of the temporal pole is exposed and the sagittal crest (SC) medially and the inner projection of the MacCarty keyhole (red circle) laterally can be identified; D) The inferior and inferolateral portion of the greater sphenoid wing should be drilled flush with the floor of the middle fossa in order to address the structure therein located.
(SOF: superior orbital fissure; suture; GSpW: greater sphenoid wing; PO: periorbita; LSpW: lesser sphenoid wing; dTF: deep temporal fascia; TD: temporal dura; SC: Sagittal crest; V3: mandibular nerve). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

corridor toward the deep-seated structures present therein (Fig. 3D).

2.3. Supraorbital craniotomy

After the delimitation of the craniotomy area a 5 mm burr hole is placed at the level of the MacCarty keyhole. A high-speed craniotome is used to make two cuts: the first cut is a straight line parallel to the orbital rim in a lateral-to-medial direction, ending medially to the lateral border of the frontal sinus; the second one connects the burr hole and the medial end of the former cut, extending 2 cm laterally and caudally into the GSpW, thus connecting the supraorbital craniotomy with the lateral aspect of transorbital craniectomy. A bone flap with a width of about 30–35 mm and a height of about 15–20 mm is created (Fig. 4A). The dura is then peeled off from the orbital roof. The inferior edge of the craniotomy and the orbital roof should be flattened with the high-speed drill for a better visualization of the deep-seated structures and instrument handling. The ACF is followed with an antero-posterior mediolateral elevation of the frontobasal dura, and the ACP is visualized. In vivo surgery, this maneuver allows the access and opening of the ipsilateral optic and opto-cartoid cisterns. An anterior clinoidectomy may be then performed as previously described (Andrade-Barazarte et al., 2017).

The double transorbital-supraorbital corridor is then exposed (Fig. 4B).

3. Results

We divided the anatomic areas exposed by the uniportal

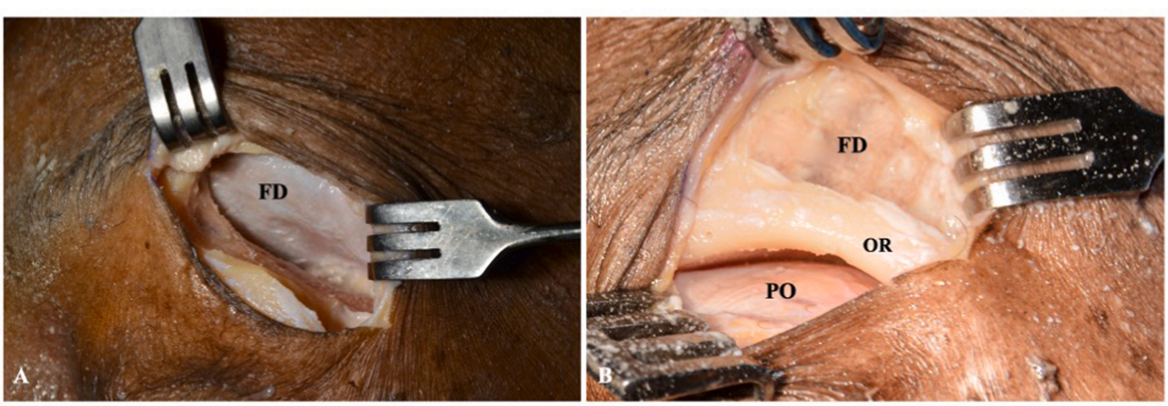

Fig. 4. Left side: A) Exposure of the frontal dura (FD) after latero-supraorbital craniotomy; B) The double transorbital and supraorbital corridors are exposed.
(FD: frontal dura; PO: periorbita; OR: orbital rim).

multicorridor strategy as follows.

3.1. Transorbital corridor

3.1.1. Lateral wall of the cavernous sinus

The OTPF, also known as MOB containing the meningo-orbital artery is identified, tethering the temporal basal dura to the periorbita (Fig. 5A). After the sharp dissection of its lateralmost portion, the lateral wall of the CS is exposed, and the peeling of the middle fossa can be performed in a medio-lateral antero-posterior fashion. Furthermore, the section of the MOB enables an evident release and lateral displacement of the temporal dura thus providing a natural "interdural" cleavage plane (Dallan et al.a). Following this virtually bloodless interdural plane, the nerves enclosed in the lateral wall of the cavernous sinus can be detected starting from V1 (Fig. 5B). The third and the fourth cranial nerves come then into view superomedially (Fig. 5C): posteriorly the oculomotor nerve is superior to the trochlear nerve but approximately at the level of the optic strut the latter crosses the third nerve passing laterally and superiorly for gaining the superior orbital fissure above the annular tendon (Jung et al., 2022). Visualization of the oculomotor and trochlear nerves may help to infer the anterior borders of the supratrochlear and infratrochlear triangles (Parkinson triangle). The first is bordered by the oculomotor nerve superomedially, the abducens nerve inferolaterally, and the tentorial edge at the site of the dural origin of the oculomotor and trochlear nerves medially. The second is defined by the trochlear nerve, ophthalmic nerve (V1) and the tentorial edge (Hendricks et al.) (Fig. 5D). Through the latter the abducens nerve may be followed (Fig. 5E).

Infero-laterally to V1, V2 is identified. The two neural structures are divided by a bone pillar known as maxillary strut (Fig. 5F).

3.1.2. Middle temporal fossa

The peeling of the middle fossa proceeds in a medio-lateral antero-posterior direction (Fig. 5F). The sharp dissection of the investing layer of the splitting dura covering V2 and V3 should be made in order to follow the proper plane preventing subsequent sensory and motor injury.

The anteromedial (Mullan triangle) and anterolateral triangles come then into view (Fig. 6A). The first is defined by V1, V2 and by a line from the superior orbital fissure to the foramen rotundum. The bone thereby present is known as maxillary strut and its drilling leads toward the lateral recess of the sphenoid sinus and pterygopalatine fossa. The anterolateral triangle is bordered by V2, V3, and the line from the foramen rotundum to the foramen ovale (Hendricks et al.), and it can be accessed to getting into the pterygopalatine and infratemporal fossa, as described by Watanabe et al. (2021).

The mid-subtemporal ridge comes into view in the lateral aspect of the surgical field, hindering the access to the foramen spinosum and the MMA (Fig. 6B). It should be drilled flush in order to allow a wider visualization of V3, foramen spinosum, MMA, and the eminentia arcuata. The MMA is divided giving access to the supero-lateral surface of the petrous bone, from the eminentia arcuata to the petrous apex, and the Gasserian ganglion. The anatomic limits of the posterolateral (Glasscock) and posteromedial (Kawase) triangles are visualized. The Glasscock's triangle is bounded by the lateral surface of the mandibular nerve distal to the point at which the greater superior petrosal nerve (GSPN) crosses below the lateral surface of the trigeminal nerve, and by the GSPN itself, postero-laterally. The Kawase triangle is featured by the GSPN laterally, the Gasserian ganglion and V3 anteriorly, the petrous ridge medially and a line connecting hiatus falopi to the dural ostium of Meckel's cave, posteriorly (Hendricks et al.) (Fig. 6C).

3.1.3. Posterior fossa

Once exposed, the Kawase's triangle is drilled with a 3 mm diamond burr in an anteroposterior direction from the trigeminal ganglion to the superificial inference of the internal acoustic canal, as described by Fisch; and in medio-lateral direction from the petrous ridge to GSPN overlying the horizontal petrous portion of internal carotid artery (Guo

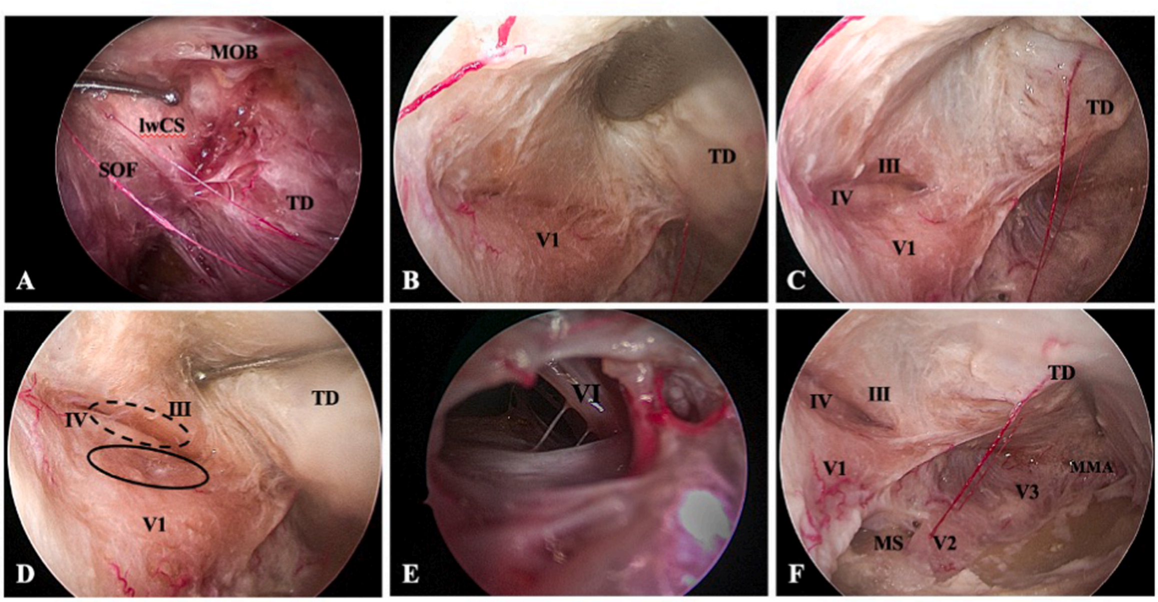

Fig. 5. Left transorbital approach to the cavernous sinus: A) The meningo-orbital band (MOB) tethers the temporal dura (TD) to the periorbita and the superior orbital fissure (SOF) hindering the access to the lateral wall of the cavernous sinus (lwCS); B) Exposure of the lateral wall of the cavernous sinus: the first structure that can be identified is V1; C) The third and the fourth cranial nerves come then into view supermoedially to V1; D) Visualization of the oculomotor and trochlear nerves may help to infer the anterior border of the supratrochlear (black dotted circle) and infratrochlear triangles (black circle). E) Through the infratrochlear triangle, the abducens nerve can be visualized; F) Infero-laterally to V1, the second division of the trigeminal nerve (V2) can be identified. The two neural structures are divided by a bone pillar known as maxillary strut (MS). Laterally, the mandibular nerve (V3) and the middle meningeal artery (MMA) can be seen.
(MOB: meningo-orbital band; TD: temporal dura; SOF: superior orbital fissure; lwCS: lateral wall of the cavernous sinus; V1: ophthalmic nerve; V2: maxillary nerve; V3: mandibular nerve; MS: maxillary strut; III: oculomotor nerve; IV: trochlear nerve; VI: abducens nerve; MMA: middle meningeal artery).

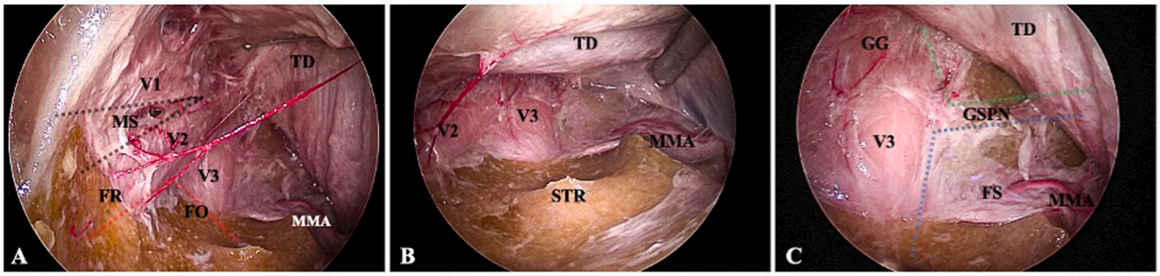

Fig. 6. Left transorbital approach to the middle fossa: A) The anteromedial (Mullan triangle) is defined by V1, V2 and by a line from the superior orbital fissure to the foramen rotundum (FR) (black dotted angle). The bone thereby present is known as maxillary strut (MS). The anterolateral triangle is bordered by V2, V3, and the line from the FR to the foramen ovale (FO) (red dotted angle); B) The mid-subtemporal ridge (STR) came into view in the lateral aspect of the surgical field, hindering the access to the foramen spinosum and the middle meningeal artery (MMA). C) The posterolateral (Glasscock) (blue dotted angle) and posteromedial (Kawase) (green dotted angle) triangles are visualized. The Glasscock's triangle is bounded by the lateral surface of the mandibular nerve, and the greater superior petrosal nerve (GSPN). The Kawase triangle is featured by the GSPN laterally, the Gasserian Ganglion (GG) and V3 anteriorly, and the petrous ridge medially.
(V1: ophthalmic nerve; V2: maxillary nerve; V3: mandibular nerve; FR: foramen rotundum; FO: foramen ovale; MS: maxillary strut; TD: temporal dura; STR: mid-subtemporal ridge; MMA: middle meningeal artery; GG: Gasserian Ganglion; GSPN: greater superior petrosal nerve; FS: foramen spinosum). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

et al., 2022) (Fig. 7A). A wide exposure of the roof of internal acustic canal, seventh and eight cranial nerves in both their cisternal and canalicular portions, and brainstem is achieved after the opening dura and the section of tentorium (Fig. 7B). We used the neuro-navigation to avoid any damage to the cochlea or the semicircular canals.

3.1.4. Sylvian fissure

The dorsal end of the LSpW can be drilled and the sphenoparietal sinus is identified lying behind it. The dura mater is opened in a H shape, as proposed by Almeida et at. (Almeida et al., 2017),running from inferior to superior over the frontal lobe and from superior to inferior over the temporal lobe; the two vertical incision are then connected by a horizonal cut over the Sylvian fissure. In this perspective, the spheno-parietal sinus is cut and ligated medially and laterally. The posterior orbital gyrus, the temporal pole and the superficial part of the sphenoidal segment of the SF are exposed. (Fig. 8A). Sharp dissection of the arachnoid membranes over the anterior aspect of the sylvian fissure allows its opening and visualization of the early branches of the MCA, the temporopolar and the anterior temporal arteries, which run over the anterior part of the temporal lobe guiding toward the main trunk and bifurcation of the MCA in the sylvian cistern (Fig. 8B). The orbitofrontal branch can be identified lying on the frontal aspect of the SF. The bifurcation of the MCA can be proximal or distal to the limen insulae. The main trunk of the MCA is located anteriorly to the anterior aspect of the uncus (Fig. 8C).

3.2. Supraorbital craniotomy

3.2.1. Anterior tentorial incisura

The dura is opened in a U-shaped fashion based on the orbital rim and secured with stitches. The frontal lobe and temporal lobe and the proximal end of the SF are exposed. The frontal lobes is mobilized away from the cranial base, in this context the former drilling of the orbital roof has been crucial. The optic nerves and chiasm along with the lamina terminalis are exposed (Fig. 9A). The proximal portion of the SF is opened, and the optico-carotid arachnoid membranes is sharply dissected. The anterior communicating artery complex is identified and the A1 is followed toward the carotid bifurcation and proximal segment of M1. The A2 segment is explored into the cistern of the lamina terminalis. Endoscopic exploration of the subchiasmatic area is possible, simulating clinical scenarios of tuberculum sellae meningiomas post-fixing the chiasm, suprasellar lesion elevating the chiasm, such as type I to IIIa craniopharyngiomas according to Kassam classification that prefix the chiasm and enlarge the infrachiasmatic space (Kassam et al.,

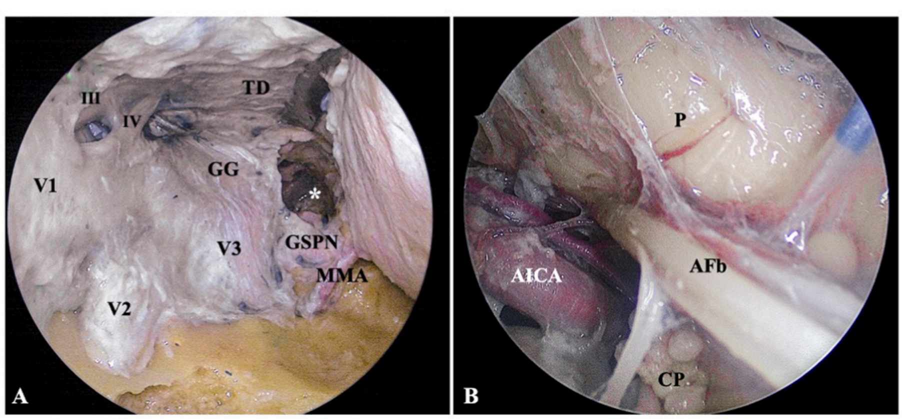

Fig. 7. Left transorbital approach to the posterior fossa: A) Wide overview of the lateral wall of the cavernous sinus and middle fossa. The Kawase triangle (*) is drilled exposing the posterior fossa dura. B) The cerebellopontine angle is exposed: the acoustic-facial boundle (AFb) is seen coursing laterally toward the internal acoustic canal. The facial nerve origin from the pons (P) can be inferred on the presence of the choroid plexus (CP) protruding from the Luschka foramen, also known as Bochdalek's flower basket. Anteriorly the anteroinferior cerebellar artery (AICA) follows its course around the brainstem.
(V1: ophthalmic nerve; V2: maxillary nerve; V3: mandibular nerve; TD: temporal dura; MMA: middle meningeal artery; GG: Gasserian Ganglion; GSPN: greater superior petrosal nerve; III: oculomotor nerve; IV: trochlear nerve; AFb: acoustic-facial boundle; P: pons; CP: choroid plexus; AICA: anteroinferior cerebellar artery).

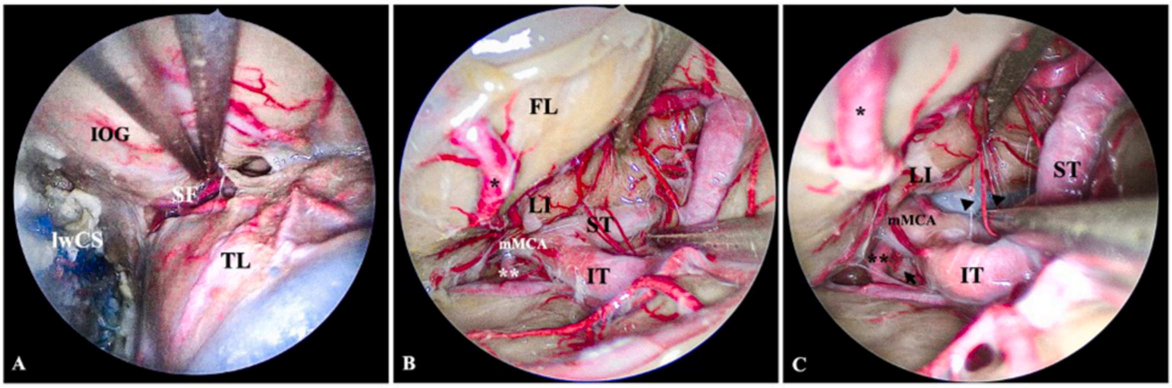

Fig. 8. Left transorbital approach to the Sylvian fissure: A) The inferior orbital gyrus (IOG) of the frontal lobe (FL) and the temporal lobe (TL) are exposed and the anterior aspect of sylvian fissure (SF) is opened via sharp dissection of its arachnoid membranes; B) The Sylvian fissure is opened until the main trunk of the middle cerebral artery (mMCA) is identified bifurcating into superior (ST) and inferior (IT) trunks distally to the Limen Insulae (LI). The lateral orbitofrontal artery (*) can be seen running over the frontal side of the Sylvian fissure while the early temporal branch (**) lies on its temporal aspect branching from the main trunk or bifurcation of MCA; C) inferiorly and dorsally to the main trunk of the mMCA the uncus (black arrow) can be seen (in the picture it is located behind the early temporal branch (**)). Beyond the LI the Sylvian or insular cistern can be identified covered by arachnoid membranes (black arrowhead).
(IOG: inferior orbital gyrus; FL: frontal lobe; TL: temporal lobe; lwCS: lateral wall of the cavernous sinus; SF: Sylvian fissure; mMCA: main trunk of the middle cerebral artery; ST: superior trunk of the MCA; IT: inferior trunk of the MCA; LI: limen insulae).

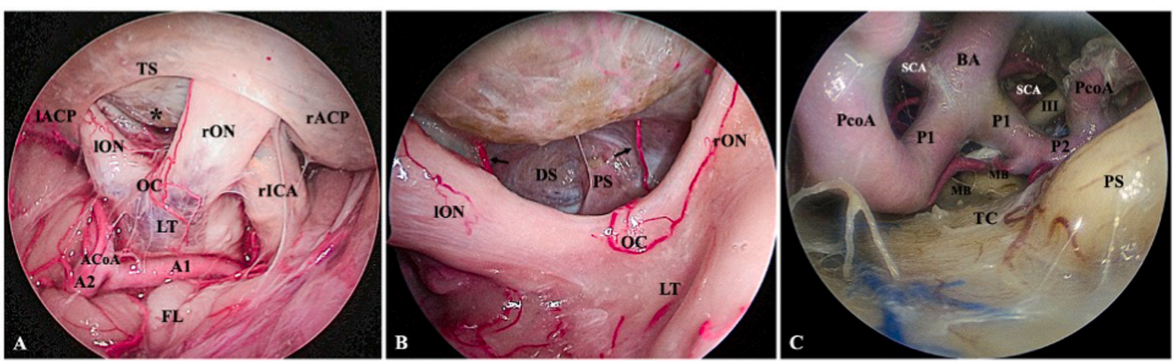

Fig. 9. A) Supraorbital approach to the anterior incisural space: The optic nerves (ON) and chiasm (OC) along with the lamina terminalis (LT) are exposed. Laterally to the optic nerves the supraclinoid segment of both internal carotid arteries (ICA) can be identified. The anterior communicating artery (AcoA) complex is detected, and the A1 segment of the anterior cerebral artery is followed toward the carotid bifurcation. The A2 segment is visualized into the cistern of the LT. The interoptic triangle is labelled by the *; B) Endoscopic exploration of the subchiasmatic area: the pituitary stalk (PS) piercing the diaphragm sellae (DS) is unveiled followed laterally by the superior hypophyseal arteries (black arrow); C) Endoscope exploration of the infrachiasmatic area and interpeduncular cistern: the basilar artery (BA) and its bifurcation, the right oculomotor nerve (III), the P1 segment of both posterior cerebral arteries, and the superior cerebellar artery (SCA) (Fig. 9C) can be identified. It should be noted the fetal conformation of the left posterior communicating artery (PcoA). The tuber cinereum (TC) and the mammillary bodies (MB) lie above the interpeduncular cistern.
(TS: tuberculum sellae; rACP: right anterior clinoid process; lACP: left clinoid process; rON: right optic nerve; lON: left optic nerve; rICA: right internal carotid artery; ICA: left internal carotid artery; OC: optic chiasm; LT: lamina terminalis; AcoA: anterior communicating artery; A1: A1 segment of the anterior cerebral artery; A2: A2 segment of the anterior cerebral artery inferior orbital gyrus; FL: frontal lobe; DS: diaphragm sellae; PS: pituitary stalk; BA: basilar artery; P1: P1 segment of the posterior cerebral artery; P2: P2 segment of the posterior cerebral artery; PcoA: posterior communicating artery; SCA: superior cerebellar artery; TC: tuber cinereum; MB: mammillary bodies; PS: pituitary stalk; III: oculomotor nerve).

2008) (Fig. 9B). Thither, the pituitary stalk, piercing the diaphragma sellae, and the interpeduncular cistern can be see hiding by the Liliequist membrane and accommodating the basilar bifurcation, the oculomotor nerves and the superior cerebellar artery (Fig. 9C).

3.2.2. Clinoid area

After ACP removal, the roof of the ipsilateral CS can be explored. The clinoidal triangle (Dolenc triangle) comes into view, bordered by the optic nerve, oculomotor nerve and the dural fold between them, as well as the oculomotor triangle, whose limits are featured by the anterior petroclinoid dural fold, posterior petroclinoid dural fold, and the interclinoid dural fold. In this way the cisternal segments of the third and fourth cranial nerves can be followed until their entrance into the CS. The supratrochlear triangle can also be identified among the third and fourth cranial nerve and the dural fold between them posteriorly (Fig. 10).

4. Discussion

In the last decades, the efforts of neurosurgical pioneers led to a paradigm shift in skull base surgery paved by a nuanced portrayal and exploitation of regional anatomy. This revolution witnessed the blooming of novel corridors featured by the direct access and visualization of the lesions, maximal exposure, the shortest distance between the surgeon and the target, minimal risk for brain retraction, and neurovascular manipulation and respect for the soft tissues, thus reducing post-operative cosmetic issues.

Among the ventro-basal routes, the endoscopic endonasal corridor, enriched by its extensions, claimed its sovereign over the pituitary region, ACF and MCF, as well as the anterior incisural space up to the third

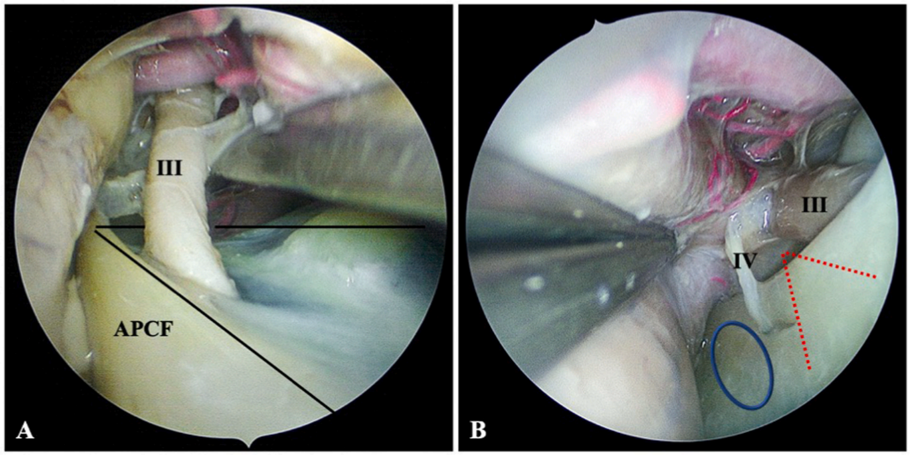

Fig. 10. Left supraorbital approach to the clinoid area: A) close up view of the oculomotor nerve (III) piercing the roof of the cavernous sinus inside the oculomotor triangle (black angle); B) the cisternal portion of the III and the trochlear nerve entering the posterolateral portion of the oculomotor triangle (Hakuba) can be used for inferring the supratrochlear (red dotted angle) and the superior portion of the infratrochlear triangle (blue circle).
(III: oculomotor nerve; IV: trochlear nerve; APCF: anterior petroclinoid fold). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

ventricle (Cavallo et al., 2019; Cavallo et al.; Cavallo et al., 2015; Fortes et al, Forbes et al.). Nevertheless, as purely midline corridor, it cannot cross the natural fence represented by critical neurovascular structures, as optic nerves, CS and carotid artery, and, in the PCF, by the acoustic-facial bundle and lower cranial nerves (Di Somma et al.a).

Therefore, the rose to the challenge for uncovering a ventral paramedian route to the parasellar area, MCF and PCF led to the introduction of novel ground-breaking corridors. Among those, recently the transorbital route held the attention of the stakeholders thanks to its direct and natural access to the lateral wall of the CS, MCF and with the further inclusion of the anterior petrosectomy, to the PCF and IAC (Dallan et al. a; Almeida et al., 2017; Alqahtani et al., 2015; Jeon et al., 2020; DI Somma et al. Dallan et al.b; De Rosa et al., 2019; Di Somma et al., 2018; Di Somma et al., 2020; Kong et al.; Kong et al., 2020; Lee et al., 2022; Topczewski et al., 2020; De Rosa et al., 2022).

It has been employed as either stand-alone approach or as a complementary corridor to the endoscopic endonasal route, laying the foundation of the multiportal surgical strategies (Alqahtani et al. DI Somma et al. Dallan et al.b; Ciporen et al. Di Somma et al.c). Ever since, several papers disclosing its anatomical targets and features, its variants also in regard of the skin incision, namely trans-eyelid or trans-eyebrow (Matano et al., 2022; Kong et al.; Zoia et al., 2018), and finally surgical series (Dallan et al., 2018; Jeon et al., 2018; Kong et al.; Corvino et al., 2022)have been published.

While its popularity increased, we begun to acknowledge some limitations and controversies regarding its anatomic constraints namely the ACF, ACP, carotid bifurcation, roof of CS and ACI. Therefore, we reconsidered the previous concept of multiportal surgery extrapolating it toward the novel concept of uni-portal multi-corridor approach. We exploited an infra-brow incision for complementing the trans-orbital corridor with a lateral-supraorbital craniotomy and vice-versa. We borrowed the previous experience of Di Somma et al., in 2018 that compared the bone removal and working areas of transorbital and supraorbital approaches in a multistage fashion via a trans-eyelid approach (Di Somma et al.d). In our experience, the trans-eyebrow soft tissue management and subperiosteal dissection of the temporalis muscle are straightforward as they have been already extensively described for both supraorbital craniotomy (Aldea et al., 2018; Cai et al.; El Shafei, 2011; Reisch et al.; Wilson et al., 2014; Mattogno et al.) and transorbital approach (Matano et al., 2022; Zoia et al., 2018; Luzzi et al.). A fortiori, the incision along the infero-lateral border of the eyebrow, that we called “orbital supero-lateral”, allows the slightest manipulation of soft tissues for addressing both corridors. In this vein, the deployment of this incision for standard transorbital approaches may allow for “rescue” supraorbital craniotomies if required without further incisions. Both approaches may be performed as per a standard SOA, with the surgeon operating behind the patient and without the need of repositioning the patient’ head during surgery. The head is slightly extended in order to allow the frontal lobe gravity retraction from the anterior fossa and the temporal lobe gravity retraction from the middle fossa.

Considering the recent proposal to extend the target of transorbital approach by removing the orbital rim (Lim et al., 2021), although it has been proved to be straightforward and helpful in broaden the indication for the transorbital approach (Matano et al., 2022; Lim et al., 2021), in our opinion it would not provide additional benefits when combined with the supraorbital craniotomy since the extensive bony work on the supraorbital rim would not further improve maneuverability, exposure and trajectories.

The supraorbital craniotomy is extended toward the GSpW, adjoining to the trans-orbital craniectomy, thus creating a wide double antero-lateral window through a small 2.5–3 cm skin incision. Such gate is divided transversally by the orbital roof, that behave like the sea-level with the sea-mountain: it divides the landmass from the drowned lands.

The landmass, lying superiorly to the sphenoid ridge, can be addressed by the supraorbital approach that gives access to the ACF floor and the clinoid space. Further posteriorly, the anterior incisural space can be visualized, accommodating the optic nerves and chiasm, the lamina terminalis, the anterior communicating artery, the internal carotid artery, the proximal portion of the sphenoid segment of the Sylvian fissure and M1, the pituitary stalk, the basilar bifurcation, the oculomotor nerves and the superior cerebellar artery (Spena et al., 2008; Rhoton)’. . The infrachiasmatic region and the interpeduncular cistern may be explored via the dissection of the Liliequist membrane (Volovici et al.; Froelich et al., 2008) up to the medial border of crural cistern (Ono et al., 1984) that can be visualized with the aid of an angled scope. It should be said that the subchiasmatic space, accessed via the inter-optics triangle that is a virtual fissure in vivo surgery, can be unveiled in cases tuberculum sellae meningiomas post-fixing the chiasm or suprasellar pathologies elevating it.

In this scenario, considering the anatomical exposure of the suprasellar extension of EEA, as described by Cavallo et al. (2019), the supraorbital corridor is not aimed at replacing the transsphenoidal corridor, but at complementing its lateral extension (Di Somma et al.a) exploiting at once their anatomic overlapping areas (Cavallo et al., 2007) as per surgical goals and lesions 'features. Moreover, the endoscopic endonasal approach and the supraorbital craniotomy are not mutually exclusive, and their combination has been already reported (van Lindert and Grotenhuis, 2009; Banu et al., 2016; Chabot et al., 2017).

Finally, thanks to an ipsilateral anterior clinoidectomy, as described by Andrade-Barazarte et al. (2017), the roof of the CS can be completely displayed, namely the anterior, oculomotor and supraorbital triangles, and the course of the oculomotor and trochlear nerves can be followed from their cisternal portion to their entrance in the cavernous sinus.

Regarding the drowning lands, located inferiorly to the sphenoid ridge, we propose the transorbital approach. Although, several anterolateral approaches have been described for unveiling the lateral wall of the CS and the MCF (Spena et al., 2015; Dolenc, 1994; Couldwell et al., 2014; Chen et al., 2020; Mastantuoni et al., 2022), they require a not negligible amount of brain retraction, and the target lies very deeply into the surgical field.

Contrarywise, the transorbital approach is featured by the major perks of the ventral approaches bestowing a direct and straightforward route to the MCF and lateral wall of the CS without brain retraction and manipulation of critical neurovascular structures. Furthermore, as reported by Dallan et al.the dissection of the MOB can further broaden the deep surgical corridor (Dallan et al.a).

Thus, combining the supraorbital and transorbital craniotomy, along with an anterior clinoidectomy, a 270° access over the superior and lateral wall of the cavernous sinus can be achieved exposing the clinoidal (Dolenc), oculomotor (Hakuba), supratrochlear (Fukushima), infratrochlear (Parkinson), anteromedial (Mullan), anterolateral, posterolateral (Glasscock) and posteromedial (Kawase) triangles (Hendricks et al.). Furthermore, as previously described, the transorbital approach can exploit the drilling of the petrous apex for getting the access to the PCF and the internal acoustic canal (Di Somma et al., 2018; Noiphithak et al., 2018; Lee et al., 2021; García-Pérez et al., 2022). The combination of the two corridors enables three trajectories: anterior route inferior to the sphenoid ridge, anterior route superior to the sphenoid ridge and anterolateral corridor as showed in Fig. 11. Finally, extending the dural incision into the trans-orbital window, or making a novel fronto-temporal "H shape" dural opeining (Almeida et al., 2017), the SF can be dissected and the bifurcation and M1 and M2 segment of the middle cerebral artery can be addressed.

In this scenario, the mini-invasiveness concept relies on the paradigm "more bone, less brain" where two small, tailored keyholes allow the exposure and direct visualization of key skull base neurovascular structures without brain retraction.

The main indications for the uniportal multicorridor approach are meningioma arising from the anterior clinoid, mostly type II and III, medial, middle and lateral third of the sphenoid wing (al-Mefty and Ayoubi, 1991), spheno-orbital meningiomas where anterior clinoidectomy and unroofing of the optic canal is warranted (Martínez-Pérez et al., 2021), sphenoidal and cavernous sinus meningiomas even with extension in posterior fossa. In the two latter cases, the supraorbital craniotomy may be considered as a rescue strategy per intraoperative needs and tumor extension and attachment.

These lesions are often multi-compartmental and the double transorbital and transcranial perspective, along with the close-up view provided by the endoscope, enables multiple viewpoints and trajectories toward the target and a thorough proximal and distal control over neurovascular structures engulfed inside the tumor.

Potential complications of the multicorridor approach encompasses complications of both transcranial and transorbital routes. Nevertheless, the possibility of exploiting customized corridors per lesions features enable minimizing the risks deriving from pushing each approach beyond its boundaries. We found among the major complications of the transorbital approach: vision loss, complete or partial superior orbital fissure syndrome, namely isolated or combined III, IV or VI cranial nerve palsy, diplopia, infections, palpebral edema, ptosis and pseudomeningocele (Locatelli et al.; Jeon et al., 2018; Feller et al., 2023).

Notably, regarding the soft tissues, post-operative ptosis, due to damage to the elevator palpebrae muscle, and post-operative lid swelling may occur. To avoid such complications, we move the incision slightly upward turning the trans-eyelid approach into infra-brow incision, exploiting a direct access to the periosteum through the orbital portion of the orbicularis oculi muscle. Such shrewdness allows a straightforward soft tissue management and subperiosteal dissection of the temporalis muscle, lowering the risk of soft tissue complications. Furthermore, the use of loupes or any other magnification system can be of great help.

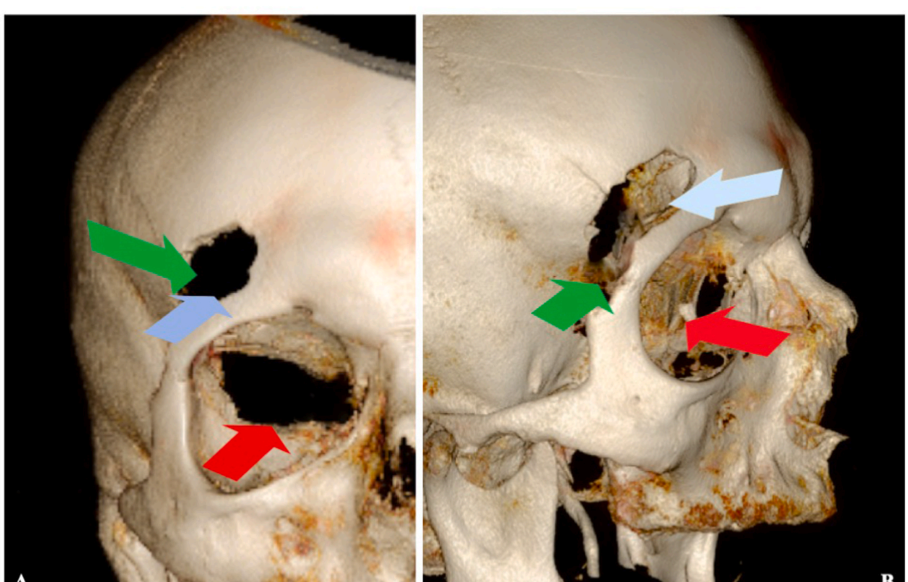

Fig. 11. Anterior (A) and lateral (B) views of the three trajectories attainable through the combined lateral-supraorbital and transorbital corridor: the anterior trajectory inferior to the sphenoid ridge (red arrow); the anterior trajectory superior to the sphenoid ridge (blu arrow) and the antero-lateral trajectory (green arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Chemosis can be present and significant and spontaneously resolves in few days.

Rarely, injuries of the extraocular muscles, mainly the lateral rectus muscle, occurring during the bony work, may lead to post-operative diplopia. A piece of silastic sheet could be placed to cover the periorbita protecting intra-orbital tissues.

The traction on the orbital structures and on the superior orbital fissure, leading to vision loss and damage to the oculomotor nerves, is minimized by laterally expanding the working chamber via the drilling of the greater sphenoid wing (Dallan et al., 2021).

Post-operative bleeding and orbital or intracranial hemorrhage can be prevented by a thorough hemostasis and a proper deployment of hemostatic agents (Schonauer et al., 2021).

All these aspects should be discussed extensively with the patients, and all the possible alternatives taken into considerations.

Moreover, the trans-eyebrow incision hides some pitfalls for both supraorbital keyhole and transorbital approach in the frontal, supraorbital and suprathroclear bundles injury risk. For avoiding damages of the frontal nerve, a subperiosteal dissection of the temporalis muscle should be performed. Supraorbital and suprathroclear bundles can be spared by keeping the incision lateral to the supraorbital notch and limiting the employment of monopolar and bi-polar coagulation (Dallan et al., 2021).

Reconstruction can be accomplished with the use of free fat tissue from the abdomen for filling both latero-orbital spaces and the space created after lesion removal. Dural closure can be performed either with fascia lata or with dural substitutes combined with dural sealants (Balakrishnan and Moe, 2011; Yoo et al., 2021; Di Somma et al., 2023; Han et al.).

Therefore, the modern skull base attitude may be pushed further forward by the introduction of a multicorridor strategy, respecting the soft tissues through a uniportal, small and aesthetic incision. Our investigation proved that the combination of the transorbital corridor and the supraorbital craniotomy enables a satisfying intra and extradural access over the anterior, middle and even posterior cranial fossae.

4.1. Limitation

We perceive that our study has some limitations: I) the solely cadaveric anatomic investigation, lacking cardinal feedbacks present in vivo surgery, namely tissues elasticity, CSF release of the subarachnoid spaces, brain gravity retraction and bleeding. A fortiori, the latter can pose serious issues when performing the peeling of the middle fossa and when dividing the middle temporal artery; II) the lack of a proper quantitative analysis.

Whist aware of the limits of our paper, we entrust that our contribution can be considered as an adjunct and complement to the pertinent literature further inspiring novel anatomic investigations and surgical series on this trail. Likewise, we already planned further studies for addressing these issues and for disclosing novel multi-corridors strategies.

5. Conclusion

The orbital supero-lateral uni-portal multi-corridor approach, via combining a transorbital corridor and an extended supraorbital craniotomy, provides a unique intra and extradural access over the anterior and middle skull base, including at the occurrence the posterior fossa, the anterior tentorial incisura and the Sylvian fissure, via a small trans-eyebrow incision. As one of the pillars of skull base surgery is the concept of drilling the bone for not touching the brain, we extended this paradigm to soft tissues preservation harnessing the conical visualization of the keyhole and applying it to the multiple corridors attainable via a small aesthetic door.

Credit author statement

Cesare Zoia: Conceptualization, Methodology, Writing - Review & Editing, Project administration, Resources, Investigation; Ciro Mastantuoni: Writing - Original Draft, Data Curation, Visualization, Project administration, Investigation, Formal analysis; Domenico Solari: Writing - Review & Editing, Data Curation, Visualization, Project administration, Supervision, Investigation; Matteo de Notaris: Writing - Review & Editing, Data Curation, Visualization, Project administration, Supervision, Investigation; Francesco Corrivetti: Visualization, Data Curation, Investigation; Giannantonio Spena: Visualization, Writing - Review & Editing, Supervision; Luigi Maria Cavallo: Visualization, Supervision, Writing - Review & Editing.

Declaration of competing interest

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