UNIVERSITAT DE
BARCELONA

Abordajes endoscópicos ventrales y multiportales al encéfalo

Aplicaciones neuroquirúrgicas mínimamente invasivas

Alberto Di Somma

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ABORDAJES ENDOSCÓPICOS VENTRALES Y MULTIPORTALES AL ENCÉFALO

APLICACIONES NEUROQUIRÚRGICAS MÍNIMAMENTE INVASIVAS

Tesis Doctoral presentada por:

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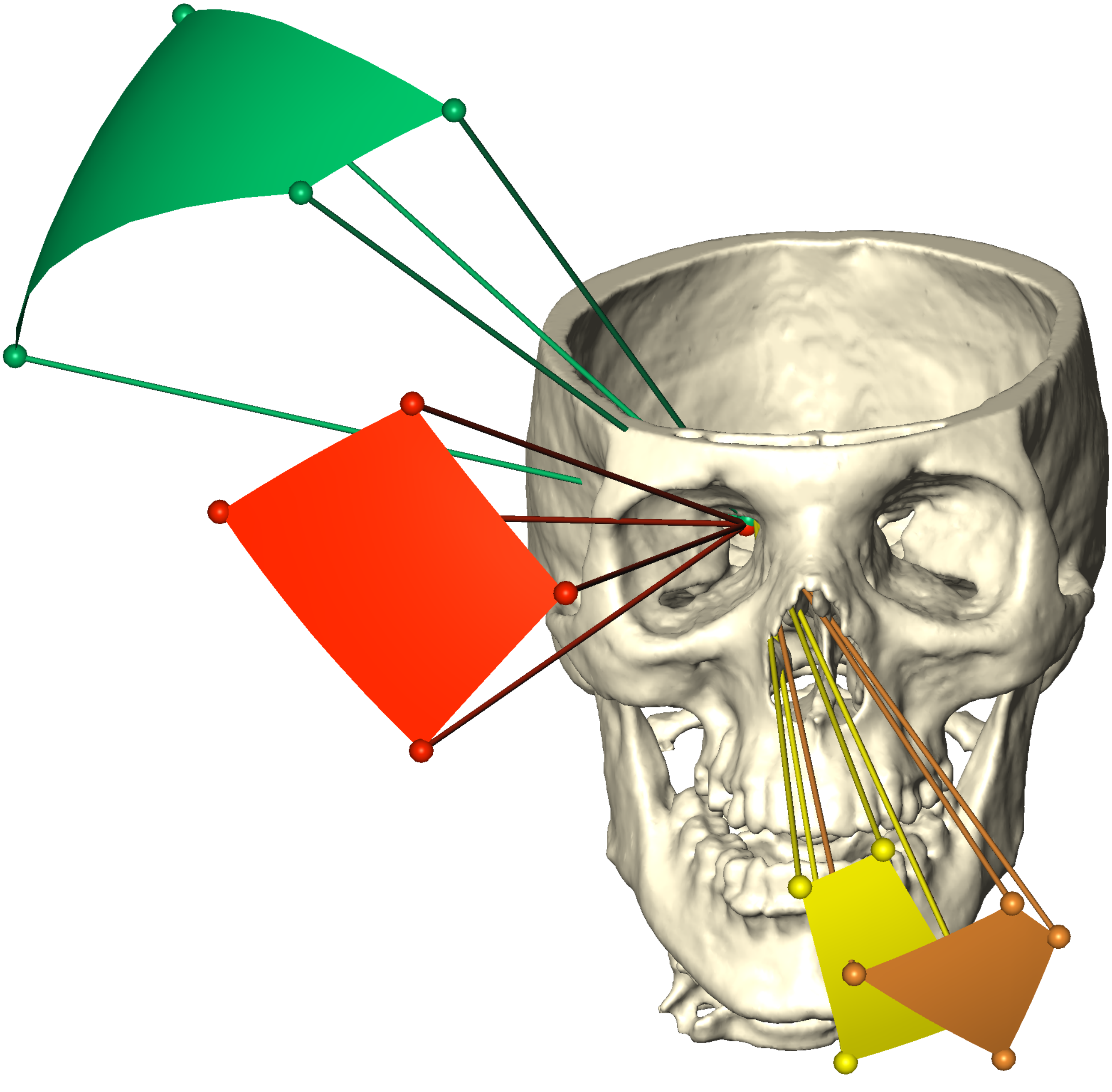

ÍNDICE

ACKNOWLEDGEMENTS

Allor si mosse/e io gli tenni dietro.
(Then he moved/and I moved on behind him.)

Dante Alighieri (1265-1321)
La Divina Commedia - Inferno: C. I, v. 136

This Ph.D. Thesis would not have been possible without the essential help I received along the way by many people.

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Finally, my large *Family* who has endured my constant absence and distance. Nevertheless, the joy of return, distinguished by the sharing of love, compensates for the fatigues produced abroad, always.

1. SUMMARY

Background

The **brain ventral surface** has been historically considered as a complex area to reach due to technical and operative difficulties when accessing it through 'classical' neurosurgical **transcranial approaches**. In recent years, '**ventral**' **approaches** through the nose (**endonasal**) and very recently through the orbit (**transorbital**) performed with the aid of the **endoscope**, have been proposed as relatively safe and effective pathways to unlock anatomic structures located at the level of the ventral surface of the brain, in a **minimally invasive** manner.

Hypothesis and Objective

The hypothesis of the present thesis is that the new **transorbital endoscopic approach**, through the upper eyelid, could allow the visualization and manipulation of some anatomic structures located mainly in the lateral part of the ventral surface of the brain. Further, the **combination** with the **endonasal path** could exceed the limits of a single approach thus providing better manipulation angles, working distances, and visualization of target areas.

Hence, the objective of this contribution would be to analyze, from a neuroanatomic fashion, the purely **transorbital endoscopic** approach and to combine it with the midline ventral route via the nose (**endonasal route**). Further, the aim is to **compare the ventral routes with the traditional transcraneal** ones when approaching specific anatomic targets located at the level of the ventral surface of the brain.

Material and Methods

Anatomic dissections will be performed on a total of **50 human cadaver heads**. The heads will be fixed and injected with colored silicone. Before and after the dissections, computed tomography (CT) scans will be performed. The dissections will initially be performed macroscopically, or microscopically if necessary, and subsequently with the endoscope as the sole visualization tool. A **virtual reality system** will also be used (*Dextroscope*) as well as tools for **morphometric calculation**, **three-dimensional reconstruction** (*Osirix*, *Amira*), and **statistical analysis** (*Microsoft Excel*).

Results

On one side, the purely endoscopic superior eyelid transorbital approach affords **good visualization and surgical manipulation** of structures in the anterior and middle cranial fossae. In particular, lateral orbital corridors to the superior and inferior orbital fissures permit the exposure of the most lateral portion of the middle or the anterior cranial fossa. Further, bone removal medially to the superior and inferior orbital fissures provides access to the optico-carotid region. Better surgical exposure appears more consistent with lateral approaches as compared with the medial corridor to the optico-carotid area.

On the other hand, the **combination** with the other ventral minimally invasive route provides a comprehensive management of specific anatomic targets. As a matter of fact, for example, used together, the endonasal and the transorbital paths allows a complete decompression of the optic nerve in its canal.

Conclusions

This work may further **extend the anatomic knowledge** related to those **ventral and endoscopic routes to the skull base**, from a strictly neurosurgical point of view. Further studies and, eventually, surgical case series are mandatory to confirm the effectiveness of these approaches, thereby refining the proper indications for each of them.

2. INTRODUCCIÓN

La **superficie ventral del encéfalo** ha sido considerada históricamente un área con una gran complejidad de abordar, debido a las dificultades técnicas que existen para acceder a ella mediante los abordajes neuroquirúrgicos 'clásicos' transcraneales. Efectivamente, los **abordajes transcraneales** proporcionan una exposición quirúrgica adecuada para el tratamiento de patologías localizadas en la superficie ventral del encéfalo, pero están asociados a un porcentaje de **complicaciones** funcionales, debido principalmente a la retracción cerebral necesaria para realizarlos [34,59,70,94,96,111].

En este contexto, en las últimas décadas se han desarollado **abordajes mínimamente invasivos** a la base del cráneo, dirigidos a la superficie ventral del cerebro y del tronco del encéfalo [19,29,57,73,90]. La introducción de la cirugía mínimamente invasiva ha alterado sustancialmente la práctica de la neurocirugía con el objetivo de **reducir la manipulación del cerebro** y, por lo tanto, la morbilidad.

El refinamiento de las técnicas microquirúrgicas, así como mejoras en la instrumentación, técnicas de imagen y sistemas de neuronavegación, han representado un fuerte impulso en este proceso evolutivo. En este sentido, la utilización reciente de las **técnicas endoscópicas** ha contribuido de manera significativa al desarrollo de nuevas estrategias quirúrgicas y al refinamiento de las ya existentes. Actualmente, muchas lesiones de la base craneal anterior, media y/o posterior pueden ser resecadas por vía endoscópica, principalmente a través de las fosas nasales (abordaje endoscópico endonasal transesfenoidal) [25,63,66,74,77,81,84].

En resumen, la modificación e integración de estas tecnologías ha permitido una considerable difusión de la vía endonasal [1,9,22,25,27,31,38,39,47,54,56,58,60,65,68,80,82,83,85,97-99,115]. De hecho, las principales indicaciones de la vía endoscópica endonasal corresponden a **lesiones de la base del cráneo de posición mediana**. El principio de 'no cruzar los nervios', es decir no abordar más allá del límite lateral de los pares craneales, ha sido considerado importante para optimizar las indicaciones y realizar una correcta cirugía endonasal. Abordajes endoscópicos endonasales se han propuesto y están siendo actualmente utilizados para reducir significativamente la morbilidad de los procedimientos quirúrgicos transcraneales y, en casos seleccionados, se han asociado con resultados quirúrgicos y clínicos comparables a estas técnicas tradicionales [78]. Sin embargo, a pesar de la reciente extensión y refinamiento de las técnicas endoscópicas endonasales, **las regiones más laterales de la base craneal** todavía se encuentran fuera de los límites de este abordaje.

Una **ruta complementaria a la endonasal**, pero igualmente **mínimamente invasiva**, podría ser necesaria para obtener un acceso completo a toda la superficie ventral del encéfalo.

Entre los enfoques transcraneales, en los últimos años y como trayectorias quirúrgicas laterales factibles para acceder a la base craneal anterior y media, se han introducido los abordajes supraorbitarios [101,114]. Incluso más recientemente, el **abordaje transorbitario** realizado a través del párpado superior y con la ayuda del endoscopio, se ha propuesto como un posible acceso **ventral mínimamente invasivo** a la superficie ventral del encéfalo (de hecho a su porción más lateral), complementando la ruta endonasal [4,41,44]. El abordaje endoscópico transorbitario no requiere la eliminación del reborde orbitario lateral y/o superior, evitando cualquier manipulación cerebral [4,10,12,32,35,42,61,67,87,90,93,98,104].

Efectivamente, las órbitas aparecen como una potencial puerta de entrada alternativa para el acceso endoscópico a la base del cráneo y a la superficie ventral del encéfalo. Por lo tanto, un nuevo conjunto de técnicas quirúrgicas transorbitarias para proporcionar acceso al espacio intracraneal ha sido recientemente resumida bajo el concepto de 'cirugía transorbitaria neuroendoscópica - *transorbital neuroendoscopic surgery (TONES)*' [93].

Las vías quirúrgicas a través de la nariz han sido descritas ampliamente en numerosos artículos anatómicos y clínicos [8,25,49-53,76,106,107], en contraste con la **vía endoscópica transorbitaria**, que **no ha sido suficientemente analizada y caracterizada desde el punto de vista neuroanatómico** [3,42,43,90,100].

En este contexto se desarrolla el presente proyecto de Tesis Doctoral cuyos **objetivos** son profundizar en la descripción de la anatomía expuesta en el abordaje endoscópico endonasal y establecer las bases del estudio anatómico del nuevo abordaje transorbitario endoscópico.

Además, se ha analizado una combinación entre las vías endonasal y transorbitaria con la finalidad de determinar si estas vías se pueden combinar en un sentido '*multiportal*' para mejorar aún más la capacidad de tener un acceso controlado a determinadas regiones anatómicas localizadas a nivel de la superficie ventral del encéfalo [29,36,41,113].

3. HIPÓTESIS Y OBJETIVOS

3.1 Hipótesis general

Las **hipótesis** de este trabajo son las siguientes:

- el empleo conjunto de técnicas anatómicas, de simulación y morfométricas permite caracterizar vías mínimamente invasivas mediante abordajes **endoscópicos endonasales extendidos** para accesos vasculares y ventriculares;
- el abordaje **endoscópico transorbitario**, a través del párpado superior, puede permitir la visualización y manipulación de ciertas estructuras anatómicas, ubicadas principalmente en la parte lateral de la superficie ventral del encefalo;
- la **combinación** de las vías endonasal y transorbitaria podría superar los límites de una sola ruta para proporcionar mayores ángulos de trabajo, menor distancia de trabajo y una visualización óptima del campo quirúrgico;
- la **comparación** de estos abordajes ventrales (endonasal y transorbitario) con los abordajes tradicionales trancraneales demostrará que los primeros podrían obtener resultados similares y, en algún caso específico, superiores a los segundos.

3.2 Objetivo general

El **objetivo general** de la Tesis Doctoral es el estudio detallado y la contribución en la búsqueda de abordajes quirúrgicos mínimamente invasivos para el manejo de estructuras neurovasculares localizadas en la superficie ventral del encéfalo.

3.3 Objetivos concretos

De esta consideración muy general se desprenden los **objetivos concretos**, que se enumeran a continuación:

- **Descripción** del abordaje **endoscópico endonasal** en accesos vasculares y ventriculares:
    - Exposición de las arterias cerebrales localizadas en la superficie ventral del encéfalo (artículo 1);
    - Revisión de la literatura para comprender la función del abordaje endoscópico endonasal en el tratamiento de los aneurismas cerebrales (artículo 2);
    - Exploración y clasificación del tercer ventrículo cerebral por vía endonasal (artículo 3);
- Nuevo **abordaje endoscópico transorbitario**:
    - Estudio anatómico desde una perspectiva exclusivamente neuroquirúrgica del abordaje endoscópico transorbitario (artículo 4);
    - Abordaje endoscópico transorbitario al seno cavernoso (artículo 5);
- **Combinación** de las vías endonasal y transorbitaria:
    - Abordaje combinado endonasal y transorbitario endoscópico al nervio óptico (artículo 6);
- **Comparación** de la vía endoscópica transorbitaria con los abordajes transcraneales:
    - Valoración de la libertad quirúrgica *('Surgical Freedom')* en procedimientos de descompresión del nervio óptico mediante los abordajes transcraneal pterional, transorbitario y endonasal (artículo 7);
    - Valoración de la vía transorbitaria a través del párpado superior para el acceso a la base craneal anterior y media comparada con el abordaje transcraneal supraorbitario (artículo 8).

Los artículos que han servido de base para la presente Tesis Doctoral, y que se incluyen en el último apartado de la misma, corresponden a:

Artículo 1. Extended endoscopic endonasal approaches for cerebral aneurysms: anatomical, virtual reality and morphometric study.

Di Somma A, de Notaris M, Stagno V, Serra L, Enseñat J, Alobid I, San Molina J, Berenguer

J, Cappabianca P, Prats-Galino A. *Biomed Res Int*. 2014:703792, **2014**.
IF:1.579, Q3-MEDICINE, RESEARCH & EXPERIMENTAL, rank 85/123.

Artículo 2. The ventral route to intracranial aneurysm: from the origin towards modern transsphenoidal surgery. An historical review and current perspective.
Di Somma A, de Notaris M, Enseñat J, Alobid I, Bernal-Sprekelsen M, Cavallo LM, Prats-Galino A, Cappabianca P. *Rhinology*. 52:195-207, **2014**.
IF:3.761, Q1-OTORHINOLARINGOLOGY Q1, rank 1/44.

Artículo 3. Extended Endoscopic Endonasal Approach to the Third Ventricle: Multimodal Anatomical Study with Surgical Implications.
Cavallo LM, **Di Somma A**, de Notaris M, Prats-Galino A, Aydin S, Catapano G, Solari D, de Divitiis O, Somma T, Cappabianca P. *World Neurosurg*. 84:267-78, **2015**.
IF: 2.685, Q1-SURGERY, rank 48/200.

Artículo 4. Endoscopic transorbital superior eyelid approach: anatomic study from a neurosurgical perspective.
Di Somma A, Andaluz N, Cavallo LM, de Notaris M, Dallan I, Solari D, Zimmer LA, Keller JT, Zuccarello M, Prats-Galino A, Cappabianca P. *J Neurosurg*. 15:1-14, **2017**.
(JCR 2016). IF: 4.059, Q1-SURGERY, rank 16/197.

Artículo 5. Endoscopic transorbital route to the cavernous sinus through the meningo-orbital band. A descriptive anatomic study.
Dallan I, **Di Somma A**, Prats-Galino A, Solari D, Alobid I, Turri-Zanoni M, Castelnuovo P, Catapano G, de Notaris M. *J Neurosurg*. 127:622–629, **2017**.
(JCR 2016). IF: 4.059, Q1-SURGERY, rank 16/197.

Artículo 6. Endoscopic endonasal medial-to-lateral and transorbital lateral-to-medial optic nerve decompression. An anatomic study with surgical implications.
Di Somma A, Cavallo LM, de Notaris M, Solari D, Topczewski T, Bernal-Sprekelsen M,

Enseñat J, Prats-Galino A, Cappabianca P. *J Neurosurg*. 127:199–208, **2017**.
(JCR 2016). IF: 4.059, Q1-SURGERY, rank 16/197.

Artículo 7. Surgical freedom evaluation during optic nerve decompression. Laboratory investigation.
Di Somma A, Andaluz N, Gogela S, Cavallo LM, Keller JT, Prats-Galino A, Cappabianca P. *World Neurosurg*. 101:227-235, **2017**.
(JCR 2016). IF: 2.592, Q2-SURGERY, rank 60/197.

Artículo 8. Supra-orbital versus endo-orbital routes to the lateral skull base: a quantitative and qualitative anatomic study.
Di Somma A, Andaluz N, Cavallo LM, Keller JT, Solari D, Zimmer LA, de Notaris M, Zuccarello M, Cappabianca P. Accepted for publication in *Operative Neurosurgery* (**2017**).

4. MATERIALES Y MÉTODOS

Este proyecto se basa principalmente en estudios de **disecciones anatómicas**, técnicas de imagen mediante tomografía computarizada con **reconstrucciones 3D** y **estudios cuantitativos**. Los trabajos de disección anatómica se realizaron en el Laboratorio de NeuroAnatomía Quirúrgica (*Laboratory of Surgical NeuroAnatomy* – LSNA) de la Universidad de Barcelona (***España***) y en el Laboratorio de Neuroanatomía (*Goodyear Lab*) de la Universidad de Cincinnati (Ohio, ***Estados Unidos***). Los estudios cuantitativos, el análisis de los datos y la preparación y redacción de los artículos se realizaron en estos mismos laboratorios y en la División de Neurocirugía de la Università degli Studi di Napoli 'Federico II' (***Italia***).

4.1 Revisión bibliográfica

La búsqueda de los artículos para la revisión de la literatura sobre **aneurismas cerebrales operados por la nariz** (Articulo 2) se realizó mediante la base de datos PubMed utilizando las siguientes palabras clave (individualmente o en asociación): '*transoral*', '*transcervical*', '*transclival*', '*transfacial*', '*transsfenoidal*', '*endonasal*', '*endoscopic*' y '*cerebral aneurysm*'.

Para el análisis de todos los abordajes ventrales se incluyeron la totalidad de los artículos clínicos referidos a los aneurismas operados a través de las vías '*transcervical-transclival*', '*transoral-transclival*', '*transfacial-transclival*' o '*transsphenoidal*': las referencias de los artículos fueron asimismo analizadas. La selección de los manuscritos fue realizada por dos autores que revisaron independientemente los artículos para su inclusión o exclusión. No se encontraron desacuerdos. Para el cálculo de la tasa global de complicaciones fueron considerados aquellos casos en los que los autores describieron al menos una de las siguientes complicaciones: *fístula* de líquido cefalorraquídeo (LCR), meningitis, lesión de al menos un nervio craneal, disfagia, masa retrofaríngea (por ejemplo, colección de LCR en el espacio retrofaríngeo), hidrocefalia, parada cardíaca, infección de la herida faríngea, hemorragia subaracnoidea, vasoespasmo, confusión postoperatoria leve, trombosis venosa profunda y muerte. De forma accesoria, para determinar el éxito o fracaso de la intervención quirúrgica, se han evaluado los siguientes criterios neurorradiológicos y clínicos: obliteración del saco aneurismático, posición apropiada del clip y permeabilidad de las arterias parentales.

4.2 Preparación de especímenes

Los procedimientos aplicados en la presente Tesis Doctoral han sido aprobados por la Comissió de Bioética de la Universitat de Barcelona (Institutional Review Board - IRB00003099) (ver apartado 'Aspectos éticos'). Las muestras, correspondientes a cabezas aisladas, fueron sometidas a una limpieza con solución fisiológica y se procedió al rasurado del pelo. Sucesivamente fueron canulados los vasos arteriales, principalmente las arterias carótidas internas, y venosos, principalmente las venas yugulares internas. En algún espécimen también fueron canuladas las arterias vertebrales. A continuación, las cabezas se perfundieron con suero fisiológico intravascular hasta la salida de todos los coágulos, para luego iniciar la perfusión con solución fijadora (solución *Cambridge*). Finalmente, se empleó látex rojo para el relleno de arterias y, en algún caso, látex azul para el de las venas (en algún caso fue utilizado: Dow Corning, Carrollton, Kentucky). Las cabezas fueron preservadas en frío (4°C).

4.3 Estudios neurorradiológicos y reconstrucción 3D

Antes de realizar las disecciones, todos los especímenes fueron sometidos a un estudio de tomografía computarizada multicanal y helicoidal (SOMATOM Sensation 64, Siemens, Forchheim, Alemania) con secciones espirales axiales de 0,6 mm de espesor y un ángulo de 0 grados (estudio para neuronavegación).

Para permitir el corregistro con el **sistema de neuronavegación**, se implantaron cinco tornillos en el cráneo como marcadores permanentes de referencia ósea. Se colocaron tres tornillos en la línea media: el primero se colocó 2 cm por encima del nasion (en el plano horizontal superior), el segundo se colocó 5 cm por encima del primero y el tercero se colocó 5 cm detrás del segundo; otros dos tornillos se colocaron 3,5 cm laterales al primer tornillo, en el borde superior de la órbita. Los datos de las imágenes se transfirieron a la estación de trabajo del neuronavegador y el registro de puntos se realizó utilizando los datos fiduciales implantados en el hueso. Se consideró aceptable una tolerancia de correlación de registro de 2 mm. Posteriormente, las disecciones anatómicas fueron realizadas en el laboratorio de disección.

4.3.1 Osirix

Se realizó un análisis preliminar de la exploración tomográfica computarizada previa a la disección mediante un software para navegar en imágenes DICOM multidimensionales (Osirix, visualizador DICOM Advanced Workstation Open-Source PACS) para evaluar de forma precisa la variabilidad anatómica de cada espécimen. Osirix fue utilizado asimismo para la cuantificación de diferentes parámetros (este procedimiento fue realizado de forma conjunta con Microsoft Excel).

4.3.2 Dextroscope

Antes de proceder a la disección de cadáveres, un **sistema de realidad virtual**, conocido como Dextroscope (Dextroscope; Volumen Interacciones Pte. Ltd., Singapur), se utilizó para llevar a cabo una simulación virtual de cada abordaje quirúrgico. Este equipo es un generador de imágenes holográfica que permite el análisis detallado de la anatomía de la base del cráneo a través de la integración y fusión de múltiples series de imágenes tomográficas incluyendo la tomografía computarizada, la resonancia magnética y la angiografía (mediante su corregistro manual). Con este sistema se ofrece la posibilidad de realizar la planificación quirúrgica y tomar decisiones sobre los diferentes abordajes, con el objetivo de evaluar el mejor de ellos. El cirujano puede definir y/o revisar la trayectoria o añadir una nueva ruta utilizando la visualización 3D interactiva. De hecho, el espacio de trabajo virtual que incorpora el Dexteroscope proporciona todas las herramientas necesarias para la planificación quirúrgica. Los conjuntos de datos radiológicos específicos para cada especimen fueron adquiridos y procesados como se describe a continuación.

Cada conjunto de imágenes de tomografía computarizada se almacenó en el Dexteroscope con la finalidad de crear una base de datos, a partir de ficheros en formato DICOM (*Digital Imaging and Communications in Medicine*). A partir de esta base de datos se generó un modelo tridimensional del sujeto. Con la ayuda de la herramienta de ajuste de color fue posible modificar las propiedades de color y de transparencia asignadas a diferentes estructuras para reconstruir claramente el hueso craneal, tejidos blandos y arterias cerebrales. Con la herramienta de cirugía virtual (*virtual surgery)*, como el trepano a elevada velocidad, se realizó, de forma virtual, el abordaje neuroquirúrgico seleccionado.

4.3.3 Sistemas de neuronavegación

En el laboratorio de disección, los especímenes fueron registrados con sistemas específicos de navegación. Estos sistemas fueron útiles para orientar cada abordaje quirúrgico y, lo que es más importante, para obtener datos morfométricos requeridos en los estudios cuantitativos (con el uso de Microsoft Excel).

4.3.4 Amira

Los modelos 3D fueron generados con *Amira Visage Imaging*, un **software específico para la visualización y la manipulación de los dados biomédicos** (Amira Visage Imaging Inc., San Diego, California, USA). Las estructuras óseas se segmentaron a partir de imágenes DICOM usando un procedimiento semiautomático. A los *labels* (etiquetas) resultantes de dicha segmentación se les aplicó una función de suavizado para refinar la representación de las superficies óseas.

Los diferentes volúmenes de interés se etiquetaron usando un editor 3D, a partir de los cuales se creó automáticamente un modelo triangular geométrico quirúrgico computarizado.

Las mediciones planares y esféricas, utilizadas principalmente en el análisis cuantitativo, se emplearon para comparar los diferentes abordajes.

4.4 Disecciones anatómicas

Las disecciones anatómicas se realizaron en el Laboratorio de Neuroanatomía Quirúrgica (**L**aboratory of **S**urgical **N**euro**A**natomy, **LSNA**) de la Universidad de Barcelona (España) y en el **Laboratorio 'Goodyear'** de la University of Cincinnati, Medical Center (Cincinnati, OH, USA).

Se utilizaron un total de **cincuenta cabezas de cadáver adultos**, sin patología intracerebral. Como se ha descrito previamente, los especímenes fueron inyectados con látex a través de las arterias carótidas internas, y en algún caso de las arterias vertebrales (en rojo), así como a través de las venas yugulares internas (en azul). Las disecciones comenzaron macroscópicamente, aplicándose seguidamente técnicas microquirúrgicas mediante el uso de un **microscopio quirúrgico** (Leica Microsystems, Viena, Austria y OPMI; Zeiss, Oberkochen, Alemania) y, en la mayor parte de los procedimientos, el endoscopio. Las disecciones endoscópicas se realizaron utilizando un **endoscopio** de 4 mm de diámetro, rígido, de 18 cm de longitud y ópticas de 0° y 30° (Stryker, Kalamazoo, Michigan, USA y Karl Storz GmbH y Co, Tuttlingen, Alemania), conectados a una fuente de luz a través de un canal de fibra óptica y una cámara de vídeo. El endoscopio también se hallaba conectado a un monitor de vídeo 21 pulgadas que soporta la alta resolución de la tecnología de tres CCD-HD. Las imágenes fueron capturadas usando un sistema de vídeo digital de alta definición. Un trepano de alta velocidad e instrumental de craneotomía fue utilizado para la eliminación de hueso.

4.4.1 Abordajes neuroquirúrgicos ventrales

4.4.1.1 Endoscópico endonasal

El **abordaje endoscópico endonasal** ha sido descrito detalladamente en la literatura [14,15,19,21,26,27,30,46]. De forma resumida, el endoscopio se introduce en la fosa nasal derecha, paralela al suelo nasal, y con el tabique nasal en la parte medial. El cornete inferior se identifica lateralmente y se sigue hasta la coana, que está limitada por el vómer medialmente y el suelo del seno esfenoidal superiormente. Una vez identificada la coana, el endoscopio se inclina hacia arriba, a lo largo del receso esfenoetmoidal, aproximadamente de 1 a 1,5 cm por encima del techo de la coana, y el seno esfenoidal puede ser abierto a través del ostium esfenoidal. La turbinectomía media unilateral junto con la extirpación bilateral de las celdillas etmoidales posteriores ofrece un campo quirúrgico más ámplio, principalmente cuando se trabaja con abordajes extendidos [17,24,46,74,75]. En este punto, el tabique nasal se separa de la pared anterior del seno esfenoidal con un disector o un microdrill de alta velocidad. A continuación, se reseca 1 a 2 cm del borde posterior del tabique nasal con pinzas de mordida posterior. Posteriormente, el cornete medio contralateral es fracturado. Todos los septos intraesfenoidales se remueven, para que se puedan visualizar todas las *referencias anatómicas* de la pared posterior del hueso esfenoides. El abordaje se puede ahora extender a toda la línea media, dependiendo del objetivo del abordaje.

4.4.1.2 Endoscópico transorbitario

Para el abordaje **endoscópico transorbitario** los especímenes se colocaron en decúbito supino, se fijaron al cabezal de Mayfield, girado 5 grados lateralmente hacia el lado contralateral. La incisión cutánea se realizó en el pliegue superior del párpado.

Después de abrir el músculo orbicular de los ojos de forma longitudinal a sus fibras, la disección se realizó en una dirección superolateral hasta el hueso cigomático y la sutura frontocigomática lateralmente. El periostio fue cortado y diseccionado hacia la órbita, hasta que se volvía continuo con la periórbita. Usando un disector de Penfield No. 1, se siguió el plano por debajo del periostio/periórbita dentro de la órbita. La disección prosiguió usando este plano hasta que se alcanzaron los bordes laterales de las fisuras orbitarias inferiores y superiores. En particular, la porción lateral de la fisura orbitaria superior representa el límite de la movilización del contenido orbitario medialmente. Se coloca entonces un retractor maleable para separar el contenido orbitario de la pared posterolateral de la órbita, creando espacio para la disección. El endoscopio fue entonces introducido en la porción superior del campo quirúrgico para monitorizar las etapas subsiguientes [42-44,90].

4.4.2 Abordajes transcraneales

Diferentes abordajes neuroquirúrgicos tradicionales se utilizaron para este proyecto de tesis. Principalmente los **abordajes transcraneales** 'clásicos' se utilizaron para la comparación con los abordajes endoscópicos ventrales.

4.4.2.1 Fronto-lateral – pterional

El abordaje pterional fue utilizado como vía anterolateral a la base craneal. Para la visualización del tercer ventrículo se utilizó la ruta translamina terminalis. La cavidad del tercer ventrículo fue explorada con el endoscopio de 0° y 30°.

4.4.2.2 Mínimamente invasivo supraciliar

Para este abordaje se utilizó una incisión de 3-cm a nivel de la ceja. Después de la craneotomía se emplearon dos *pasos* fundamentales para acceder a la base craneal: fresado del techo de la órbita y apertura de las cisternas de la base craneal (quiasmática, opto-carotídea, olfatoria).

4.4.2.3 Supraciliar extendido

El abordaje '*eyebrow*' fue extendido con la resección del ala menor y mayor del esfenoides. Este abordaje fue utilizado para la comparación con la vía ventral transorbitaria (Artículo 8).

4.4.2.4 Abordaje endoscópico frontal transcortical

El abordaje endoscópico frontal transcortical permite acceder al tercer ventrículo. Una vez se ha realizado una incisión recta a nivel de la sutura coronal, se realiza un trépano y se abre la duramadre. El endoscopio se inserta a través del lóbulo frontal para alcanzar el ventrículo lateral. Después de la identificación de los principales puntos de referencia en su interior (incluidos el plexo coroideo, el *fórnix* y las venas tálamo-estriado y septal), el endoscopio se movilizaba a través de los forámenes de Monro hacia el tercer ventrículo.

4.4.2.5 Transcalloso transcoroideo anterior

El abordaje transcalloso anterior se realiza a través de una vía frontal derecha. Tras la apertura dural, la superficie medial del lóbulo frontal se desprende de la *hoz del cerebro* para exponer el cuerpo calloso. Este último se secciona en la línea media para entrar al ventrículo lateral. Con la ayuda del microscopio, el tercer ventrículo se expone después de abrir la fisura coroidea. La introducción del endoscopio a través del foramen de Monro permite una amplia exploración del tercer ventrículo.

4.4.2.6 Abordaje supracerebeloso infratentorial a la fosa posterior

La vía supracerebelosa infratentorial ha sido utilizada para acceder a la porción posterior del tercer ventrículo. Ello permite visualizar el tercer ventrículo por una ruta postero-anterior. El endoscopio se inserta entonces para exponer el tercer ventrículo a través de su límite posterior.

4.5 Estudio cuantitativo

Tras el estudio de disección se procedió a la **cuantificación** real del abordaje realizado. En nuestro laboratorio, reunimos la información obtenida de la disección cadavérica guiada por imagen con la información obtenida de los sistemas de simulación quirúrgica virtual para analizar el desarrollo quirúrgico. El análisis de datos es un paso fundamental para descubrir los criterios críticos en entornos quirúrgicos complejos, mejorar el conocimiento general de cada abordaje y establecer la anatomía quirúrgica relevante. También se pueden comparar diferentes vías neuroquirúrgicas en términos de efectividad y maniobrabilidad para alcanzar el objetivo quirúrgico.

4.5.1 Área de trabajo ('*Working Area*')

La '*Working Area*' o **área de trabajo** es el área planar bidimensional más ámplia, definida por referencias anatómicas profundas específicas que pueden ser expuestas durante un abordaje quirúrgico estandarizado.

4.5.2 Libertad quirúrgica ('*Surgical Freedom*')

El concepto de '*Surgical Freedom*' o **libertad quirúrgica** se refiere al rango estimado de los movimientos posibles de los instrumentos del cirujano, representados por un segmento esférico parcial en el que los instrumentos quirúrgicos pueden ser insertados libremente mientras alcanzan un objetivo profundo.

4.5.3 Remoción de hueso

Para el cálculo de la **remoción de hueso alrededor del nervio óptico** se utilizó el software OsiriX (Fundación OsiriX) que permitió cuantificar la cantidad de hueso extraído del canal óptico a través de las diferentes vías quirúrgicas.

4.6 Análisis estadístico

El estudio estadístico específico de cada uno de los artículos se describe en detalle en el apartado de metodología de los mismos. Sin embargo, la metodología estadística que se ha desarollado en general se basa en la prueba **t de Student** (con dados no apareados) para la determinación de las diferencias entre las medias muestrales.

4.7 Aspectos éticos

A pesar de los importantes avances que se han producido en las últimas décadas en las técnicas aplicadas al estudio de la anatomía humana, debe asegurarse que su utilización en cadáveres o sus partes sean actos que garantizen el respeto propio de las actividades científico-técnicas.

El presente proyecto ha precisado del empleo de material cadavérico humano procedente del Servei de Donació de Cossos i Sala de Dissecció (SDCSD) de la Facultat de Medicina i Ciències de la Salut de la Universitat de Barcelona y ha seguido en todo momento los procedimientos aprobados por la Comissió de Bioética de la Universitat de Barcelona (*lnstitutional Review Board* n° 1R800003099).

Tal como se establece en dichos protocolos, una vez empleado el material cadavérico se procedió a su retorno al SDCSD para su eliminación según los cauces establecidos o, alternativamente, se incorporaron al pool de piezas anatómicas de la Facultad de Medicina para su uso en docencia. En ningún caso se hizo uso de datos personales que pudieran identificar al donante.

Finalmente expresar nuestro **agradecimiento** a los donantes de cuerpos y a sus familiares, quienes, a través de su altruismo, han contribuido a que este proyecto sea realizable.

5. RESULTADOS

5.1 Abordaje ventral endoscópico endonasal

5.1.1 Arterias cerebrales (Artículos 1 y 2)

5.1.1.1 Simulación de realidad virtual

Los resultados que se muestran en el presente estudio demuestran que con el abordaje *transtuberculum-transplanum* se obtiene un amplio ángulo de ataque para llegar a la unión de la arteria carótida interna con la arteria oftálmica y al complejo de la arteria comunicante anterior en comparación con las vías empleadas para alcanzar la arteria basilar mediante un abordaje *transclival* (37,75◦ y 32,22◦ frente a 31,4◦ y 27,47◦).

Por otra parte, la longitud del corredor *transtuberculum-transplanum* para llegar a la circulación anterior resultó ser más corto en comparación con la vía *transclival* (75,3 mm y 87,2 mm frente a 92,2 mm y 89,1 mm).

5.1.1.2 Exposición anatómica

El abordaje *transtuberculum-transplanum* permite visualizar los segmentos pre-comunicantes y postcomunicantes de las arterias cerebrales anteriores (A1 y A2), la arteria comunicante anterior (AcomA), la arteria fronto-polar (FPA), la arteria hipofisaria superior (SHA), la porción proximal de la arteria oftálmica (OphA), y la porción supraclinoidea de las arterias carótidas internas (ICA).

El abordaje al clivus superior permite visualizar la porción superior de la arteria basilar (BA), las arterias cerebrales posteriores (PCA), las comunicantes posteriores (PcomA), las arterias cerebelosas superiores (SCA), las arterias cerebelosas antero-inferiores (AICA), y, lateralmente, la porción paraclival de la carótida (ICA).

El abordaje al clivus inferior permite visualizar la totalidad de la arteria basilar (BA), las arterias cerebelosas anteroinferiores (AICA), las arterias vertebrales (VA), las arterias cerebelosas posteroinferiores (PICA), y la arteria espinal anterior (ASA).

Teniendo en cuenta estas consideraciones, el abordaje endonasal endoscópico *transtuberculum-transplanum* puede ser considerado como una alternativa en el tratamiento de aneurismas de la arteria comunicante anterior y/o carotideo-oftálmica, solos o en combinación con otro abordaje microquirúrgico y/o con procedimientos endovasculares.

Con respecto a los aneurismas de la circulación cerebral posterior, es necesario mencionar que a pesar de los ángulos de ataque y de la longitud del corredor quirúrgico endoscópico endonasal, la vía transclival podría ser una alternativa para los aneurismas de la arteria basilar y de VA-PICA sin posibilidad de tratamiento endovascular.

5.1.1.3 Aneurismas cerebrales intervenidos por vía transesfenoidal

En el análisis fueron incluidos un total de **48 casos de aneurismas intervenidos por la vía ventral** (**febrero 2013**). De ellos, 9 fueron intervenidos por la vía transesfenoidal. La tasa global de complicaciones para los abordajes 'tradicionales' ventrales (ej. *transcervical-transclival*, el *transoral-transclival* y la *transfacial-transclival*) fue del 74% (26/35), mientras que para las vías transesfenoidales (ej. *sublabial-transtuberculum-transplanum* endoscópica asistida, *transclival*, *transclival* endonasal endoscópica y endoscópica endonasal *transtuberculum-transplanum*) la tasa fue de un 44% (4/9). Se encontró que la tasa de éxito de la cirugía para los abordajes tradicionales ventrales fue del 87% (13/15), mientras que para una cirugía transesfenoidal extendida, fue del 78% (7/9).

5.1.2 Tercer ventrículo (Artículo 3)

El tercer ventrículo fue estudiado mediante diferentes abordajes transcraneales y endonasal. Para estandarizar la comparación entre ambos tipos de rutas la cavidad del tercer ventrículo se dividió en **cuatro áreas** a través de dos planos ideales, uno que pasa por el quiasma óptico y la comisura intertalámica (adhesio intertalámica) y otro que pasa a través del borde posterior del foramen interventricular de Monro y la comisura intertalámica. Estos planos resultan en la delimitación de dos áreas anteriores (**infundibular y foraminal**) y dos posteriores (**mesencefálica y tectal**) (Artículo 3).

El abordaje endoscópico endonasal permite una adecuada exploración y maniobrabilidad quirúrgica, especialmente en las áreas anteriores del tercer ventrículo. En las áreas infundibular y foraminal la maniobrabilidad quirúrgica parece ser mejor en comparación con la obtenida en la región mesencefálica. En particular, el tercer ventrículo puede ser explorado por la vía endonasal pasando por la *lámina terminalis* o por el *tuber cinereum*. Esta última trayectoria permite la visualización de los forámenes de Monro y el suelo del tercer ventrículo hasta el receso pineal y es la más ámpliamente utilizada en casos de tumoraciones como craneofaringiomas intra y supraselar extendidos al tercer ventrículo [5,26,37,69,89].

5.2 Abordaje ventral endoscópico transorbitario

5.2.1 Abordaje endoscópico transorbitario: clasificación (Artículo 4)

Para una mejor caracterización de la exposición de las estructuras neurovasculares intracraneales proporcionada por esta ventana puramente endoscópica, se definió una clasificación 'orientada neuroquirúrgicamente' de los corredores intracraneales que se pueden alcanzar a través de este abordaje. Éstos incluyen tres corredores discretos (*lateral corridors*) y uno combinado (*medial corridor*). Esta clasificación se basó principalmente en la posición de las fisuras orbitarias superior e inferior, ya que representan los primeros hitos clave anatómicos y quirúrgicos de esta ruta.

En consecuencia, **los corredores se definieron como sigue**: 1, corredor lateral a la fosa craneal media; 2, corredor lateral a la fosa craneal anterior; 3, corredor lateral combinado a la fosa craneal anterior y media, con remoción del ala menor del esfenoides; 4, corredor medial a la región óptico-carotidea.

5.2.1.1 Corredor lateral a la fosa craneal media

La craniectomía se realizó inicialmente a través del cuerpo del hueso malar para crear un espacio de trabajo adecuado. Posteriormente, la porción ventral y vertical del ala mayor del esfenoides fue fresada hasta que la duramadre fue expuesta. Esta área de la fosa craneal media fue delimitada: superior y medialmente, por la parte superior y lateral de la fisura orbitaria superior y la parte lateral del ala menor del esfenoides; lateralmente, por la superficie perióstica previamente expuesta del músculo temporal; infero-medialmente, por la fisura orbitaria inferior; e inferiormente, por el suelo de la fosa craneal media.

La disección extradural inferior (es decir, hacia el suelo de la fosa craneal media) era útil para descubrir el curso de la arteria meníngea media, hacia el foramen espinoso. Por otra parte, la disección medial extradural se llevó a cabo entre la periórbita y el polo temporal. En este caso, se completó una visualización extra/interdural de toda la pared lateral del seno cavernoso a través de la banda meningo-orbitaria (*meningoorbital band, MOB)*. Posteriormente, la duramadre se abrió, dejando al descubierto el polo temporal. Las arterias y estructuras venosas de esta región pueden ser visualizados en el centro del campo quirúrgico.

5.2.1.1.1 Exposición del seno cavernoso mediante abordaje transorbitario (Artículo 5)

El abordaje transorbitario endoscópico, con extracción parcial del ala mayor del esfenoides seguido de una **disección interdural ventral 'natural' del MOB**, permitió la exposición de toda la pared lateral del seno cavernoso hasta la porción plexiforme del trigémino.

Para obtener está exposición anatómica, la duramadre meníngea se despegó en dirección posterolateral, exponiendo así progresivamente los nervios de la pared lateral del seno cavernoso. La identificación de las ramas V1 (nervio oftálmico) y V2 (nervio maxilar) suele preceder a la identificación del tercer y cuarto nervios craneales. Este corredor interdural proporcionó una visualización fácil y directa de las dos primeras ramas del nervio trigémino. A medida que la disección prosiguió posteriormente, los nervios troclear y oculomotor aparecieron, justo superiores a la rama oftálmica del nervio trigémino.

Al finalizar la disección interdural se pudo obtener una visualización completa de la pared lateral del seno cavernoso, incluyendo la arteria carótida intracavernosa. En definitiva, el abordaje transorbitario puramente endoscópico a través de MOB proporciona una visión directa del seno cavernoso a través de una ruta simple y rápida.

5.2.1.2 Corredor lateral a la fosa craneal anterior

La craniectomía implicó el fresado del hueso fronto-basal lateral, correspondiente al techo orbitario. El ala mayor del esfenoides se puede dejar intacta. Los límites de este abordaje se delinearon de la siguiente manera: inferiormente, el ala menor del esfenoides; lateralmente, el pterion visto desde la perspectiva transorbitaria; medialmente, la fisura orbitaria superior; y el borde orbitario, superiormente.

Después de la craniectomía, la disección extradural permitió la exposición de la convexidad fronto-lateral. Tras la apertura dural, el lóbulo frontal lateral y basal apareció en la visión endoscópica. Esta parte del lóbulo frontal correspondía a los giros orbitarios, un grupo irregular de circunvoluciones de la superficie orbitaria. Estos giros pueden dividirse por el surco orbitario en forma de H en los grupos orbitarios anterior, medial, posterior y lateral; desde esta perspectiva, el surco orbitario puede ser bien apreciado. La fosa craneal anterior también se desbloqueaba en su parte más medial. En consecuencia, el hueso etmoides sobre esta región, correspondiente a la lámina cribosa, se retiró y se realizó una exploración extradural. Posteriormente, se abrió la duramadre para acceder a la parte más medial de lóbulo fronto-basal, que, en este caso, estaba representado por el giro recto.

La visualización del área fronto-medial con la ayuda de un endoscopio de 30 grados permitió la visualización del nervio olfatorio, justo por encima del nervio óptico, y la *hoz del cerebro* en la línea media.

5.2.1.3 Corredor lateral combinado a la fosa craneal anterior y media

Combinando el abordaje lateral a las fosas craneales anterior y media se puede acceder a la cisterna silviana; la resección se puede extender lateralmente hasta el pterion. De hecho, este procedimiento permitió una buena visualización del área pterional vista desde el interior de la órbita, es decir, desde una visualización totalmente diferente y opuesta a los procedimientos transcraneales estándar (ej., abordaje pterional). Después de la apertura dural, se visualizó la porción más anterior de la fisura silviana con su cisterna. La arteria cerebral media y sus ramas fueron expuestas usando este abordaje.

5.2.1.4 Corredor medial a la región opto-carotídea

El corredor medial a la región opto-carotídea se puede alcanzar removiendo la totalidad del ala menor del esfenoides y la apófisis clinoides anterior, que se fresó extraduralmente para visualizar dicha región. Esta región puede ser alcanzada extendiendo la eliminación ósea superior y medialmente a la fisura orbitaria superior y, por tanto, después de la movilización del contenido orbitario inferior y medialmente. El canal óptico se abrió en su parte superior y lateral y el nervio óptico se siguió en su segmento intracraneal donde se une al nervio óptico contralateral para formar el quiasma óptico. La exploración intracraneal de esta área permitió visualizar la región opto-carotídea desde una perspectiva ventral, incluyendo la bifurcación de la arteria carótida interna, la cisterna opto-carotídea y el III nervio craneal.

Con ayuda de un endoscopio de 30 ° y después de abrir la cisterna opto-carotídea, el tallo pituitario, rodeado por el diafragma selar, fue visualizado en el espacio subquiasmático.

Cabe mencionar que, si bien esta área se alcanzó en muestras anatómicas, su exposición quirúrgica puede ser difícil en el contexto clínico, a menos que exista una lesión que desplace las estructuras descritas.

5.3 Abordajes combinados: acceso multiportal

5.3.1 Descompresión del nervio óptico por las vías endonasal, transorbitaria y transcraneal (Artículos 6 y 7)

5.3.1.1 Análisis cuantitativo de los abordajes quirúrgicos

5.3.1.1.1 Abordaje endoscópico endonasal

Con el abordaje endoscópico endonasal el acceso al canal óptico se obtuvo en una dirección de proximal a distal. Después de la eliminación de la lámina papirácea se alcanzó la parte más ínfero-medial del canal óptico. La exposición de la porción intracanalicular del nervio óptico rodeado por la vaina óptica puede seguirse hasta el ápex orbitario. El anillo fibroso de Zinn representa el límite más proximal del abordaje. La visión endoscópica endonasal permitió mostrar las paredes mediales de ambas órbitas, así como las arterias etmoidales posteriores que se localizan lateralmente a la lámina cribosa.

El hueso se removió también de las protuberancias carotídeas y de la fisura orbitaria superior para resaltar las principales relaciones anatómicas entre las estructuras neurovasculares de esta región de la base del cráneo. Después de la descompresión ósea, se puede abrir la duramadre intracanalicular hasta el nivel del *tuberculum sellae*, permitiendo la exposición de la parte intracraneal del nervio óptico.

5.3.1.1.2 Abordaje endoscópico transorbitario

La vía endoscópica transorbitaria permitió alcanzar las superficies más laterales y superiores del canal óptico, que se encuentra medialmente a la fisura orbitaria superior. La vía quirúrgica a través del área opto-carotídea ha sido ya descrita previamente. El canal óptico se abrió en su superfície superior y lateral y el nervio óptico fue seguido en su segmento intracraneal, donde se fusiona con el contralateral, formando así el quiasma óptico. La región más superior de la fisura orbital superior, la arteria carótida interna y el nervio óptico quedan claramente expuestos.

Finalmente, una vista panorámica del nervio óptico después de **la retirada del canal óptico endonasal y transorbitario demuestra la descompresión del nervio óptico en 360°**, es decir, tras la descompresión endonasal y transorbitaria.

5.3.1.1.3 Abordaje transcraneal pterional

En primer lugar, la ruta pterional permitió obtener una visión general de la descompresión completa lograda combinando las rutas endonasal y transorbitaria (Artículo 6). Para el cálculo de la *libertad quirúrgica,* la ruta pterional fue realizada en otros especímenes que no tenían abordajes ventrales para poder obtener una visualización más correcta (Artículo 7).

5.3.1.2 Análisis morfométrico

El análisis morfométrico permitió comparar mediante un sistema de *realidad virtual* los dos abordajes ventrales (Artículo 6). La simulación computerizada se llevó a cabo con la ayuda del Dextroscopio. La longitud virtual del corredor quirúrgico y el ángulo de ataque al canal óptico fueron proporcionados por el sistema. En este estudio se determinó que las longitudes del corredor quirúrgico virtual para alcanzar el canal óptico eran 39,6 mm para la vía transorbital y 52,9 mm para la endonasal.

Por otro lado, los valores de realidad virtual del ángulo de ataque al canal óptico fueron 46,8° para el abordaje transorbital y 23,8° para el endonasal. De acuerdo con estos análisis basados en una simulación por ordenador, la vía transorbitaria proporciona una ruta más corta al nervio óptico con un ángulo quirúrgico más amplio en comparación con el endonasal.

5.3.1.3 Análisis cuantitativo de la remoción de hueso

El análisis cuantitativo de la remoción de hueso alrededor del canal del nervio óptico se realizó de forma independiente en los dos artículos (Artículo 6 y 7).

Considerando la circunferencia total del canal óptico (360°), la vía transorbitaria logró una eliminación media del 53,33%, en la porción más supero-lateral del canal óptico, mientras que el abordaje endonasal proporcionó una eliminación ósea media del 46,67%, en la parte más inferomedial. Se observó que la diferencia entre los dos abordajes era estadísticamente significativa (valor de p = 0,0029, es decir p <0,05) (Artículo 6).

El abordaje pterional con clinoidectomía anterior proporcionó la mayor descompresión circunferencial con una media de 245,2° (rango 211,0°-277,5°). Al considerar la circunferencia total del canal óptico (360°), la vía transcraneal permitió la descompresión de la circunferencia superolateral en un 68,1% del canal óptico (Artículo 7).

5.3.1.4 Estudio de la 'Surgical Freedom'

El estudio de la '*Surgical Freedom*' o libertad quirúrgica fue realizado en el Artículo 7. El **abordaje transcraneal proporcionó la mayor libertad quirúrgica**, seguido del abordaje transorbitario, y finalmente del corredor endonasal. La mayor maniobrabilidad de la ruta transcraneal fue estadísticamente significativa en comparación con todas las otras vías, mientras que la libertad quirúrgica de la vía transorbitaria fue significativamente mayor que la de la vía endonasal.

Un análisis posterior reveló que el ángulo de ataque al nervio óptico en el plano horizontal fue mayor para la vía pterional, seguido por el abordaje transorbitario y finalmente el endoscópico. Estas diferencias también alcanzaron significación estadística.

5.3.2 Valoración de la vía endoscópica transorbitaria comparada con la vía transcraneal supraorbitaria (Artículo 8)

En este último artículo se comparó la vía transorbitaria con una ruta transcraneal supraorbitaria. Se utilizaron 3 abordajes, en particular: *supraorbitario* (*supra-orbital approach*, SO), *transorbitario por párpado superior* (que en este trabajo se denominó *endo-orbital approach*, EO), y *supraorbitario extendido* (*extended supra-orbital approach*, ESO).

5.3.2.1 Remoción de hueso

El volumen de hueso removido se cuantificó para cada abordaje, excepto para el ESO, que fue calculado como la suma de SO y EO. No se observaron diferencias en la comparación de la eliminación ósea entre SO y EO. Como era de esperar, la ESO dió lugar a un mayor volumen de eliminación de hueso que SO o EO (p <0,01).

5.3.2.1 Cálculo del área de trabajo

Usando los triángulos originalmente descritos y más tarde reportados por Kurbanov et al. [86], definimos áreas de trabajo quirúrgico en cada abordaje.

Para la exposición de la región silviana, las áreas se establecieron con los siguientes puntos de referencia: apófisis clinoides anterior (ACP) ipsilateral, bifurcación de la arteria carótida interna ipsilateral, y la máxima exposición lateral en la fisura de Silvio (es decir, el punto más lateral de la arteria cerebral media observada). Las exposiciones por EO no fueron estadísticamente diferentes a ESO, pero superó las de SO. Así, la vía transorbitaria ventral (EO) proporcionó una perspectiva diferente de la MCA a la exploración transcraneal (ESO). Además, la exposición coplanar de la fisura de Silvio obtenida vía EO permitió la disección entre las ramas de MCA evitando la retracción del cerebro y con una buena vista de las arterias perforantes.

La extensión de la exposición temporal anterolateral a lo largo del ala mayor del esfenoides fue representada por un triángulo, con vértices en: ACP, bifurcación de la arteria carótida interna (ICA) y el punto más expuesto lateral (ala esfenoidal intacta). EO y ESO alcanzaron una exposición mayor que SO (p <0,01). Sin embargo, el área proporcionada por EO no alcanzó diferencias estadísticamente significativas respecto a ESO en la exposición de la región del temporal anterolateral.

Las **áreas de exposición paraselar** se calcularon fusionando tres puntos: punto vertical perpendicular a la bifurcación de la ICA (punto externo), bifurcación ipsilateral de la ICA, y punto más inferior expuesto a lo largo de la región paraselar (es decir, principalmente a lo largo de la pared lateral del seno cavernoso). Considerando la exposición paraselar, SO y ESO eran casi comparables mientras que **EO alcanzó una exposición estadísticamente mayor que cualquiera de los otros abordajes** (p <0,01).

6. Artículos en los que se basa la Tesis Doctoral

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Research Article

Extended Endoscopic Endonasal Approaches for Cerebral Aneurysms: Anatomical, Virtual Reality and Morphometric Study

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Introduction. The purpose of the present contribution is to perform a detailed anatomic and virtual reality three-dimensional stereoscopic study in order to test the effectiveness of the extended endoscopic endonasal approaches for selected anterior and posterior circulation aneurysms. *Methods*. The study was divided in two main steps: (1) simulation step, using a dedicated Virtual Reality System (Dextroscope, Volume Interactions); (2) dissection step, in which the feasibility to reach specific vascular territory via the nose was verified in the anatomical laboratory. *Results*. Good visualization and proximal and distal vascular control of the main midline anterior and posterior circulation territory were achieved during the simulation step as well as in the dissection step (anterior communicating complex, internal carotid, ophthalmic, superior hypophyseal, posterior cerebral and posterior communicating, basilar, superior cerebellar, anterior inferior cerebellar, vertebral, and posterior inferior cerebellar arteries). *Conclusion*. The present contribution is intended as strictly anatomic study in which we highlighted some specific anterior and posterior circulation aneurysms that can be reached via the nose. For clinical applications of these approaches, some relevant complications, mainly related to the endonasal route, such as proximal and distal vascular control, major arterial bleeding, postoperative cerebrospinal fluid leak, and olfactory disturbances must be considered.

1. Introduction

During the last decade, the management of intracranial aneurysms has moved from neurosurgical clipping to endovascular treatment as the preferred strategy. As a matter of fact, in many world renowned neurosurgical hospitals and centers, endovascular coiling has replaced neurosurgical clipping as the treatment of choice, when coiling is technically feasible [1]. Indeed, since the publication of the International Subarachnoid Aneurysm Trial, there has been a paradigm shakeup in the management of intracranial aneurysms, and more aneurysms are referred for endovascular coiling [2]. What is apparent in the pertinent literature and discussions is that a substantial amount of controversy still exists regarding the best therapeutic strategy in patients with ruptured aneurysms. As a matter of fact, in many centers worldwide endovascular techniques majorly replaced surgery for aneurysms; however, it is not possible to lay down definitive rules for the lack of consensus studies. On the other hand, single institutions experiences have been recently published [3–6]. In a recent single-center series, it was found that 87.5% of aneurysmal subarachnoid hemorrhage patients were treated with endovascular techniques, while 12.5% with craniotomy and clip ligation, thus demonstrating the amount of shifting toward the endovascular therapy [7].

Undoubtedly, the successful development and implementation of endovascular therapy have led to a less invasive approach to cerebrovascular disease and the room for surgery has been progressively confined.

On the other side, with the rapid development of the endoscopic endonasal technique, the interest in extended transsphenoidal approaches has been renewed for many pathological entities [8–10].

Recently, few specialized centers offered to treat selected patients through a less invasive approach, such as the extended endoscopic endonasal. This new approach carries a real clinical applicability and some papers have already been published in the pertinent literature. Since the pioneering innovative works presented by Kassam et al. [11, 12], a variety of vascular lesions, mainly posterior circulation aneurysm, have started to be approached through the transsphenoidal route [13–19]. In particular, the transtuberculum-transplanum route has been used in the recent years with the aim of clipping aneurysms arising from the superior hypophyseal, anterior communicating, ophthalmic, and paraclinoidal carotid arteries [12, 17–19]. In addition, concerning posterior cerebral circulation aneurysms, other authors published cases of vertebral, basilar, and vertebral-posterior inferior cerebellar arteries aneurysms treated through endoscopic endonasal or microscopic sublabial transclival approach [11, 13–16].

Moreover, recent anatomical studies and clinical reports have detailed the extended endoscopic endonasal transsphenoidal technique, demonstrating its utility for the management of selected midline intracranial aneurysms.

Applied to vascular surgery, the endoscopic endonasal approach offers some advantages due to the properties of the endoscope itself; the endoscopic endonasal approach offers the same benefits of the endoscopic-assisted microsurgical technique used to treat cerebral aneurysms resulting in a better exposure "around the aneurysm" in order to visualize blind corners, to preserve other vessels, and to be sure of full exclusion of the aneurysm from the main cerebral circulation. Moreover, it provides a wider, close-up view of the surgical field thus allowing a close and detailed visualization of the main neurovascular structures, that is, small perforator arteries without any brain retraction.

The purpose of the present anatomic study is to verify the usefulness of the extended endoscopic endonasal approaches to access selected anterior and posterior circulation aneurysms; in other words, the aim of the present feasibility study is to determine and select cerebral circulation aneurysms that could be managed through the extended endoscopic endonasal approaches.

The vascular exposure provided by the endonasal approaches has been firstly analyzed using a preoperative 3D model with the aid of advanced virtual reality system, based on conventional computed-tomography angiography of adult patients with intracranial aneurysms arising from different cerebral vascular regions. After that, six specimens were dissected in the anatomical laboratory with the aid of a neuronavigation system, in order to verify the vascular exposure gained using the same surgical approaches.

Specifically, three main routes were identified: the transtuberculum-transplanum, the superior transclival, and the inferior transclival pathways.

2. Materials and Methods

2.1. Computed-Tomography Images Acquisition. All specimens underwent a predissection computed-tomography scan with a multislice helical acquisition protocol (slice thickness: 0,6 mm; gantry angle 0°); heads were positioned in the scanner (Siemens SOMATOM Sensation 64) in order to obtain a projection perpendicular to the palate. The images achieved were subsequently stored into a PACS (Picture Archiving and Communication System).

To allow the coregistration with the neuronavigation system, five screws were implanted in the skull as permanent bone reference markers.

2.2. The Dextroscope and Data Acquisition, Visualization, and Measurement. Before proceeding with the cadaveric dissection, a Virtual Reality System, known as Dextroscope (Dextroscope; Volume Interactions Pte. Ltd., Singapore), was used to perform a virtual simulation of each surgical approach. Such tool is a holographic imager that permits detailed analysis of the skull base anatomy throughout integration and fusion of multiple tomographic images series derived from the multislice computed tomography.

It provides the opportunity to perform surgical planning and decision making for different neurosurgical approaches with the aim of evaluating the best one among them. The surgeon can define and/or revise the trajectory or add a new path using interactive 3D visualization. Indeed, the virtual workspace inside the Dextroscope provides all the necessary tools for surgical planning. The hardware and software have been previously described exhaustively [20, 21].

The patient-specific radiology data sets were acquired and processed as described as follows. Each computed-tomography image set was stored in order to create a database of Digital Imaging and Communications in Medicine (DICOM) files. This database was loaded into the Dextroscope in order to build up a tridimensional model of the patient. With the aid of color-adjustment tool, it was possible to adjust individual color and transparency to distinctly reconstruct the cranial bone, soft tissue, and cerebral arteries.

For this study, three extended endoscopic endonasal approaches were planned and simulated using the Dextroscope workstation: the transtuberculum-transplanum, the superior transclival, and the inferior transclival.

The following measurements were taken in order to standardize each procedure: (a) angle of attack for each approach, defined as the angle formed by two lines of which the first beginning at the lower margin of the nostril and running parallel to the hard palate and the second originating from the same lower margin of the nostril until the selected aneurysm (its midpoint); (b) size of the craniectomy; (c) length of the surgical corridor to reach the selected aneurysm (its midpoint).

In particular, for the transtuberculum-transplanum approach, the medial edges of the optic canal were considered as lateral limits of the craniectomy, while the origin of the posterior ethmoidal artery as the upper limit and the floor of the sella as the lower one.

For the upper clivus, the paraclival carotid protuberances were accounted as lateral limits of the craniectomy, whereas the floor of the sella as the upper limit and the middle third of the clivus, at the level of the dural entry of the sixth cranial nerve (which continues anteriorly with the Dorello's canal) [22], as the lower one.

Finally, for the inferior part of the clivus, the hypoglossal canals were considered as the lateral limit at this level, while the inferior third of the clivus as the lower limit and the middle third of the clivus as the upper one.

2.3. Anatomical Dissection. The endoscopic endonasal transsphenoidal dissections were performed at the Laboratory of Surgical NeuroAnatomy (LSNA) of the University of Barcelona (Spain). Endoscopic procedures were carried out using a high-definition camera attached to rigid endoscopes (Karl Storz GmbH and Co, Tuttlingen, Germany), 4 mm in diameter and 18 cm in length, with 0° and 45° lenses.

Six human heads were examined. The common carotid and vertebral arteries and the jugular veins were injected with red and blue colored latex, respectively.

Predissection computed-tomography data were transferred to the laboratory navigation planning workstation and point registration was performed using bone implanted screws. A registration correlation tolerance of 2 mm was considered acceptable.

Three endoscopic endonasal approaches were performed: the transtuberculum-transplanum, the superior transclival, and the inferior transclival, taking into account the same anatomical landmarks used during virtual reality three-dimensional simulation.

The anatomical dissections were carried out with the purpose of showing all the neurovascular structures implicated in the surgical paths. In a real operating room setting there is no need to plan and perform so extensive bone removal, but since this work is intended as an anatomical paper, it was considered necessary to broadly show all the landmarks of surgical interest that could be encountered.

The present contribution should be considered as a preliminary anatomical feasibility study of the endoscopic endonasal pathway for selected cerebral aneurysms. In such preliminary step we decided to not perform any comparison with the other traditional approaches currently used to treat cerebral aneurysms (pterional, orbitozygomatic, transpetrous, retrosigmoid, or far-lateral approach) in order to first demonstrate the feasibility of the endonasal route. Further investigations are required to clearly demonstrate this matter comparing different transcranial and endonasal approaches.

3. Results

3.1. Virtual Reality Three-Dimensional Stereoscopic Results. With the help of the Dextroscope *planning platform*, the surgical strategy for minimal invasive procedures was optimized thus allowing the simulation of the extended endoscopic endonasal approaches for different anterior and posterior circulation aneurysms.

The position of the head was properly adjusted depending on the extension of the approach, using Dextroscope *moving object* tool. Three main neurosurgical approaches were simulated: (1) the transtuberculum-transplanum, (2) the superior transclival, and (3) the inferior transclival. Once the approach was chosen, the surgical route was traced out, using the *surgical pathway* tool. Subsequently, with the *drill* and the *crop* tools, virtual bone removal was carried out.

As soon as the surgical route was created, a virtual clip was placed at neck of the aneurysm with the objective of achieving a virtual aneurysm clipping through an endoscopic endonasal route (Figure 1). Aneurysm clip and its specific applicator were scanned using a standard multislice CT, in order to insert them into the Dextroscope.

The angle of attack, the size of the craniectomy, and the length of the surgical corridor were calculated for each approach on 4 illustrative patients with intracranial aneurysms arising from different cerebral vascular regions (Table 1) (Figures 2 and 3).

The sizes of craniectomy for the anterior communicating artery complex and the basilar tip were 7,85 cm^2 and 3,52 cm^2 respectively, while for the carotid-ophthalmic and VA-PICA junctions were 7,86 cm^2 and 4,62 cm^2, respectively.

Angles of attack to the anterior communicating artery complex and basilar tip were 32,22 and 31,4 degrees, respectively, while to the carotid-ophthalmic and VA-PICA junctions were 37,75 and 27,47 degrees, respectively. The lengths of the surgical corridor to reach the anterior communicating artery complex and the basilar tip were 87,2 mm and 92,2 mm, respectively, while for the carotid-ophthalmic and VA-PICA junctions were 75,3 mm and 89,1 mm, respectively. Results are summarized in Table 2.

3.2. Anatomical Results

3.2.1. Transtuberculum-Transplanum Approach. The details of the transtuberculum-transplanum approach have been well cleared up elsewhere [23–25].

Table 1: List of 4 patients with different intracranial aneurysms selected for the virtual reality three-dimensional stereoscopic study.

Patient	Aneurysm location	Direction	Form	LL (mm)	AP (mm)
1	AcomA	Downward	Saccular	7.85	7.46
2	Carotid-ophthalmic junction	Anterior, medial, downward	Saccular	7.36	5.38
3	Basilar tip	Upward	Saccular	5.42	6.83
4	VA-PICA junction	Upward, anterior	Saccular	1.2	1.2

AcomA: anterior communicating artery; VA-PICA: vertebral artery-posterior inferior cerebellar artery; LL: laterolateral diameter of the aneurysm; AP: anteroposterior diameter of the aneurysm.

Table 2: List of the 4 approaches used to reach different intracranial aneurysms, and measurement taken in order to standardize each procedure.

Patient	Approach	Aneurysm	Craniectomy (cm^2)	AOA (°)	LSC (mm)
1	Transtuberculum-transplanum	AcomA	7.85	32.22	87.2
2	Transtuberculum-transplanum	Carotid-ophthalmic junction	7.86	37.75	75.3
3	Superior transclival	Basilar tip	3.52	31.4	92.2
4	Inferior transclival	VA-PICA junction	4.62	27.47	89.1

AcomA: anterior communicating artery; VA-PICA: vertebral artery-posterior inferior cerebellar artery; AOA: angle of attack; LSC: length of the surgical corridor.

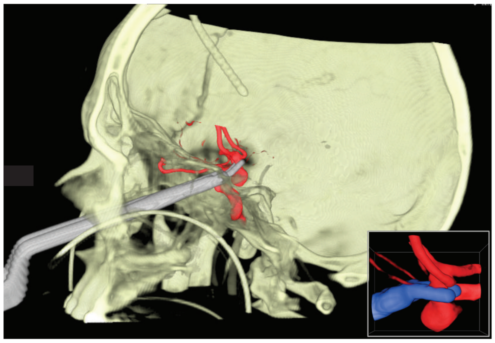


Figure 1: Clipping of an anterior communicating artery aneurysm via the nose in a stereoscopic virtual reality environment (patient number 1, view Table 1). Dextroscope screen shot.

The transtuberculum-transplanum approach permitted to show the precommunicating and postcommunicating segments of the anterior cerebral arteries (A1 and A2), the anterior communicating artery (AcomA), the frontopolar arteries (FPA), the superior hypophyseal arteries (sha), the proximal segment of the ophthalmic arteries (OphA), and the supraclinoid portion of the internal carotid arteries (ICA) (Figure 4).

The exposure of a large portion of the anterior cerebral circulation anatomy, provided by this approach, allows a safe proximal and distal vascular control, for example, in case of anterior communicating artery aneurysms. Therefore, according to the basic principles enunciated by Yaşargil [26], if a temporary clip is required, it should be applied first to the larger A1 segment and placed medial to the perforating arteries.

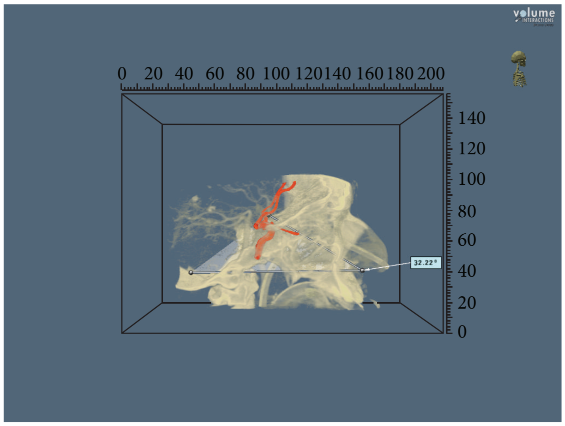


Figure 2: Angle of attack to an anterior communicating artery aneurysm approached via the transtuberculum-transplanum route (patient number 1, view Table 2). Dextroscope screen shot. For investigational use only.

3.2.2. *Superior Transclival Approach.*

The extended endoscopic endonasal transsphenoidal approach to the upper part of the clivus has been already described in the current literature [27].

The superior transclival approach permitted to expose the tip and the superior part of the trunk of the basilar artery (BA), the posterior cerebral arteries (PCA), the posterior communicating arteries (PcomA), the superior cerebellar arteries (SCA), the anterior inferior cerebellar arteries (AICA), and, laterally, the paraclival portion of the ICA (Figure 5).

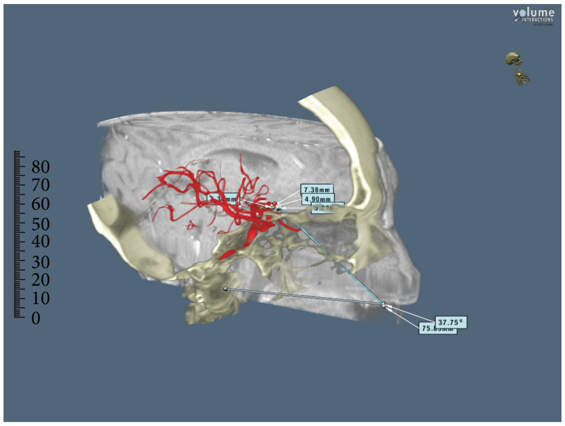


Figure 3: Angle of attack and length of the surgical corridor in a carotid-ophthalmic aneurysm approached via the transtuberculum-transplanum route (patient number 2, view Table 2). Dextroscope screen shot. For investigational use only.

From this ventral point of view, the exposure of the upper part of the posterior cerebral circulation enables a secure vascular control both proximal and distal, for example, in case of basilar tip aneurysms. Therefore, as illustrated by Yaşargil, if a temporary clip is required, it should be placed distal to the SCA although the SCA-PCA distance is often too short to accomplish this. Alternatively, If the bleeding is not well governed, temporal vascular control should be achieved by clipping the basilar trunk or one or both the PCA or the PcomA [26].

3.2.3. Inferior Transclival Approach. The extended endonasal approach to the lower part of the clivus has been also described in the pertinent literature [28, 29].

The transclival approach permitted to show the trunk of the basilar artery (BA), the anterior inferior cerebellar arteries (AICA), the vertebral arteries (VA), the posterior inferior cerebellar arteries (PICA), and the anterior spinal artery (ASA) (Figure 6).

The exposure of the lower part of the posterior cerebral circulation enables a direct proximal and distal vascular control, for example, in case of midline aneurysms arising from the VA-PICA junction [16]. Therefore, if a temporary clip is required in those cases, it should be placed on the basilar trunk proximally and on both vertebral artery and lateral medullary or anterior medullary segments of the posterior inferior cerebellar artery distally.

4. Discussion

The management of cerebral aneurysms has undergone significant evolution in the recent years. Nowadays, it can be considered as the result of a close cooperation between different specialists, giving their own contribution to the final result, specifically devoted to single patients.

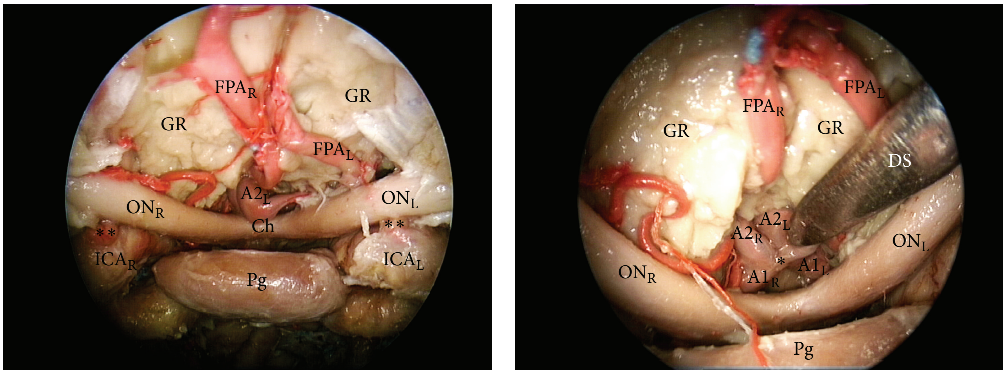
During the last decades, the endovascular technique has rapidly evolved, and actually, endovascular therapy has largely replaced microsurgery as the first line treatment modality for the majority of cerebral aneurysms [2]. On the other side, regarding the surgical approach to cerebral aneurysms, it has to be said that vascular neurosurgery improved dramatically when the operating microscope was introduced in the 1960s and the pterional approach was described by Yaşargil in the 1980s [26, 30].

In spite of these great advances made both in surgical and endovascular techniques, the complexity of some vascular lesions makes their treatment still a challenge for vascular teams, as such pathologies are associated with a high incidence of complications, which is particularly true for posterior circulation aneurysms. For such reasons, starting from the late sixties, "the ventral route," namely, the transcervical-transclival, transoral-transclival, transfacial-transclival, and, finally, extended endoscopic endonasal approaches, has been advocated as a valid alternative to reach a variety of anterior and posterior circulation aneurysms. Indeed, the ventral pathway was considered a reasonable option allowing direct access to the surgical field obviating brain retraction and, in selected cases, obtaining an early and safe proximal and distal vascular control [31].

Concerning the transsphenoidal route, Kassam et al. published the first case of cerebral aneurysm clipping via the nose [11]. Afterwards, other reports appeared in the literature stating that some specific midline anterior and posterior circulation aneurysms, not amenable to endovascular treatment, could be managed via the anterior route, in particular throughout the extended endoscopic endonasal pathway [11–19].

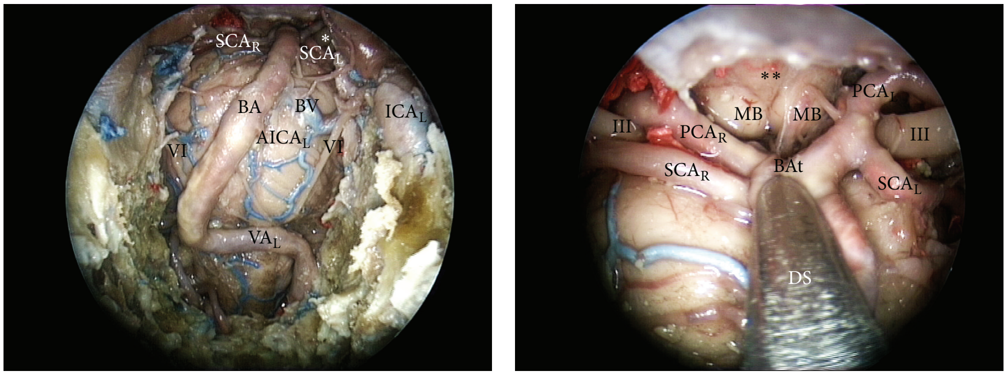
Nevertheless, the endoscopic endonasal surgery applied to vascular lesions brings also some disadvantages that should be taken into consideration. The exposure provided by the approach is limited to certain anatomical skull base regions, and proximal and distal vascular control may be hard in case of difficulties, but it is possible when performing the transtuberculum-transplanum, the superior transclival, or the inferior transclival approach depending on the aneurysm location on the vessel (see results paragraph). On the other hand, it should be highlighted that, in some cases, also transcranial approaches do not ensure a safe and valid proximal and distal vascular control, but it happened not so often.

Furthermore, the inability to perform a bypass graft and the significant endoscopic skills required can be considered as other important drawbacks, making the ventral corridor indicated only in very selected cases. Moreover, in the endonasal approach the surgical corridor may be narrow, with less leaving room for the surgeon to comfortably dissect and definitively clip the aneurysm. Another major issue from the extended endoscopic endonasal route still remains achieving effective cranial base repair. The widespread use of extended approaches for the removal of different skull base lesions has led to the reemergence of the postoperative CSF leak as a major complication for this kind of surgery. However, neurosurgical familiarity and experience



(a) (b)

Figure 4: (a) Endoscopic endonasal transtuberculum-transplanum approach to the anterior brain circulation; (b) close-up view of the suprasellar area (30 degree endoscope). FPA: frontopolar artery; A1: precommunicating tract of anterior cerebral artery; A2: post communicating tract of anterior cerebral artery; ICA: internal carotid artery; ON: optic nerve; Ch: chiasm; Pg: pituitary gland; Pg: pituitary gland; GR: gyri recta; DS: dissector; L: left; R: right; ∗: anterior communicating artery; ∗∗: ophthalmic artery.



(a) (b)

Figure 5: (a) endoscopic endonasal approach to the superior part of the clivus; (b) close up view of the superior third of the retroclival area. III: third cranial nerve; SCA: superior cerebellar artery; BA: basilar artery; BV: basilar vein; AICA: anterior inferior cerebellar artery; PCA: posterior cerebral artery; MB: mammilary body; BAt: tip of the basilar artery; ICA: internal carotid artery; DS: dissector; L: left; R: right; ∗: third cranial nerve; ∗∗: floor of the third ventricle.

in transsphenoidal surgery and otorhinolaryngologist expertise in the use of autologous mucosal flaps have contributed to the reduction in the incidence of postoperative CSF leaks, also after extended endoscopic endonasal approaches [10, 32].

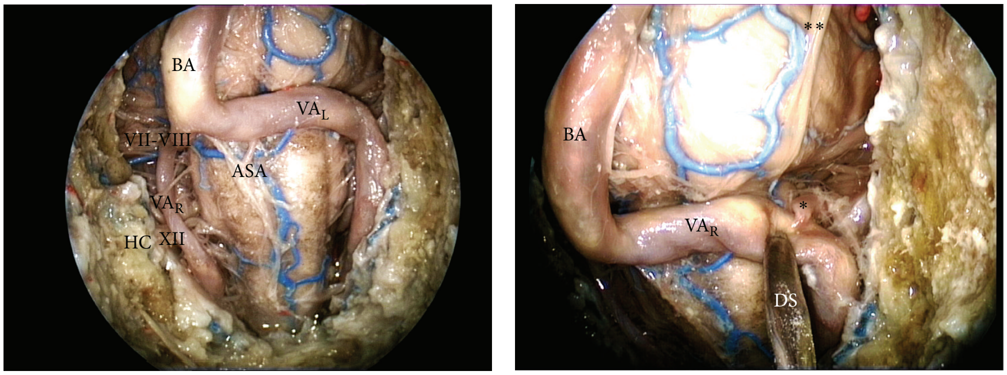
In the present anatomical study we measured the exposition of selected anterior and posterior brain circulation aneurysms provided by three different endoscopic endonasal routes, that is, the transtuberculum-transplanum, the superior transclival, and the inferior transclival pathways.

Furthermore, we analyzed the utility of a Virtual Reality System, as the Dextroscope, to perform a virtual simulation of each surgical approach. Using the Dextroscope we gave detailed measurements for each surgical approach used in this study, calculating the angle of attack, the size of the craniectomy, and the length of the surgical corridor.

The results shown in the present study demonstrate that an extended endoscopic endonasal approach to the suprasellar area, such as the transtuberculum-transplanum route, provided a wider angle of attack to reach the carotid ophthalmic junction and the anterior communicating artery complex compared to the approaches used to reach the clivus for posterior circulation aneurysms (37,75° and 32,22° versus 31,4° and 27,47°).

Moreover, the length of the transtuberculum-transplanum corridor to get to carotid ophthalmic and anterior communicating artery aneurysms was found to be shorter compared to the other posterior circulation aneurysms cases analyzed (75,3 mm and 87,2 mm versus 92,2 mm and 89,1 mm).

Regarding carotid-ophthalmic aneurysms, it should be said that if on one hand endovascular treatment is safe and



(a) (b)

Figure 6: (a) Endoscopic endonasal approach to the inferior part of the clivus; (b) close-up view of the vertebral artery-posterior inferior cerebellar artery complex. BA: basilar artery; VA: vertebral artery; ASA: anterior spinal artery; VI: abducent nerve; VII-VIII: acoustic-facial nerve bundle; HC: hypoglossal canal; XII: hypoglossal nerve; DS: dissector; L: left; R: right; ∗: posterior inferior cerebellar artery; ∗∗: abducent nerve.

efficacious, even if associated with risks of retinal artery occlusion or delayed optic ischemia [33, 34], on the other hand the microsurgical management of these lesions can be challenging due to their proximal location and their close relationships with the cavernous sinus, carotid siphon, and optic nerve, which often cover the neck of the aneurysm, thus making clipping particularly hazardous [35–37].

Regarding vascular lesion of the anterior communicating artery complex, it should be stressed that this region has got a peculiar anatomy, including anatomic variations, multiple perforators, and a deep location which make access to aneurysms arising from those arteries considerably difficult, with respect to both microsurgical and endovascular treatments [38].

Taking into account these considerations, the endoscopic endonasal transtuberculum-transplanum approach can be evaluated as an effective and available alternative in order to treat carotid-ophthalmic and anterior communicating artery aneurysms, alone or in combination with the other different microneurosurgical and endovascular procedures.

With regard to posterior cerebral circulation aneurysms, it should be said that despite the fact that angles of attack and length of the surgical corridor obtained with endoscopic endonasal approaches to clivus were less favorable compared to the suprasellar approach for anterior circulation aneurysms, in experienced hands the endoscopic endonasal superior and inferior transclival pathways could be alternative for selective and more accessible basilar tip and VA-PICA complex aneurysms, not amenable to endovascular treatment [13–16]. It must be remarked that the endovascular approach has to be considered as the first line of treatment, whereas the endonasal route could be an alternative, a second or even a third line strategy, for small posterior cerebral circulation aneurysms, with ventral orientation and midline position.

Indeed, endoscopic endonasal approaches to the clivus allow direct exposure of the posterior cerebral circulation system via minimal craniectomies compared to the other anterior circulation aneurysms cases shown in this study (3,52 cm^2 and 4,62 cm^2 versus 7,85 cm^2 and 7,86 cm^2), thus avoiding more extensive skull base approaches which could require complex and larger craniotomies, demanding a certain neurovascular manipulation to gain an adequate intradural exposure, even though the lesion has small dimensions and is located in the midline.

In the present study we determined that the most feasible anterior circulation aneurysms that could be managed through the extended endoscopic endonasal approaches are selected anterior cerebral, communicating, ophthalmic, and superior hypophyseal arteries aneurysms. Concerning posterior circulation, the basilar, proximal superior cerebellar, anterior inferior cerebellar, posterior inferior cerebellar, and vertebrobasilar junction artery segments can be exposed as well. This paper is intended as strictly anatomic study in which we highlighted some specific anterior and posterior circulation aneurysms that can be reached via the nose.

For clinical applications of these approaches, some relevant complications, mainly related to the endonasal route, such as bleeding control, postoperative cerebrospinal fluid leak, and olfactory disorders must be considered. In the future, the endonasal routes could be taken into account as a routinely valid alternative for selected anterior and posterior circulation aneurysms, not amenable to endovascular and/or microneurosurgical treatment.

5. Conclusions

Advances in endoscopic skull base surgery have increased our ability to access to complex cranial base and, more recently, vascular lesions. However, there is no doubt that aneurysm surgery is greatly advanced with the advent of endovascular techniques and the reserved space for open surgery has been and will be progressively limited.

Anyway, in specialized centers, where extended transsphenoidal approaches are routinely performed, selected cases may be treated with such techniques alone or in combination with other different procedures.

Conflict of Interests

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this paper that might lead to a conflict of interests for any of the authors.

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The ventral route to intracranial aneurysm: from the origin towards modern transsphenoidal surgery. An historical review and current perspective*

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Abstract

Objective: A review of the main studies that have explored the use of the ventral pathway for treatment of intracranial aneurysms, including the recent reported extended transsphenoidal approaches.

Methods: A comprehensive literature review was performed using the PudMed database. We recovered 48 cases of cerebral aneurysms, approached via the transcervical-transclival, transoral-transclival, transfacial-transclival ventral pathways and the extended transsphenoidal route. The overall rates of complications and surgical success were evaluated and compared for both traditional ventral and transsphenoidal approaches.

Results: For traditional routes, the overall complications and surgical success rates were 74% (26/35) and 87% (13/15), respectively. For extended transsphenoidal approaches were 44% (4/9) and 78% (7/9), respectively.

Conclusion: Our paper is a reconnaissance of what has been done via "the anterior route" and a notification of the existence of this "surgical window". Present and future of cerebral aneurysm treatment is represented by the endovascular technique. A few selected cases in specialized centers, where transsphenoidal approaches with the aid of the endoscope are routinely performed, may be treated with such techniques alone or in combination with other different procedures. Further studies in large numbers of patients will be required to validate the full benefit of this approach.

Key words: cerebral aneurysms, endoscopic endonasal approaches, minimally invasive surgery, skull base surgery

Introduction

The ventral route for intracranial aneurysms was first employed in late sixties to clip a basilar artery aneurysm via a transoral-transclival approach (1) and it was not a coincidence that such a "peculiar" pathway for vascular surgery was successfully applied for a posterior circulation aneurysm, namely a proximal basilar artery aneurysm. The posterior circulation has historically been viewed as an area that presents a significant access challenge, because of the operative technical difficulties and the potential surgical morbidity. First of all, it has to be reminded that in the period between 1930 and 1960, surgical treatment of posterior circulation aneurysms was only possible by indirect trapping or parent vessel ligation and neurosurgeons were attempting direct surgical clipping of vertebrobasilar aneurysms via a transcranial route only in early sixties: Drake from Canada published his initial experience with four ruptured basilar bifurcation aneurysms in 1961 (2) and Jamieson from Australia reported 19 surgical cases in 1964 (3). He commented that "it is clear that the basilar bifurcation is no place for the faint of heart".

More recently, many authors (4-6) stressed the concept that surgical access to vascular lesions behind the lower third of the clivus could be difficult by any route. However, it is possible to reach such complex anatomical areas from both the cerebellopontine angles and the transtentorial-suboccipital routes, but those aneurysms could be obscured from a vital neurovascular structure, i.e. the ventral exit of the glossopharyngeal, vagus, accessory, hypoglossal cranial nerves and from the vertebral artery (VA), posterior cerebral artery (P1 segment) and tonsillomedullary, lateralmedullary, and anteriormedullary segments of the posterior inferior cerebellar artery (PICA) (7).

For such reason, several authors, over the past 50 years, began to plan alternative routes to get access to aneurysms arising from the midline posterior circulation. As a matter of fact, the ventral pathway was considered a reasonable alternative, because it permits direct access to the surgical field with exposure and dissection of the aneurysm from the surrounding neurovascular tissue, obviating brain retraction and obtaining an early and safe proximal and distal vascular control (1,8-13).

More recently, with the advent of transsphenoidal surgery and, in particular, with the rapid development of the endoscopic endonasal technique, the interest in extended transsphenoidal approaches has been renewed for many pathological entities (14,15). Particularly, the wider and panoramic view offered by the endoscope increased the versatility of the transsphenoidal approach and allowed it to be expanded to different parts of the skull base (16). Indeed, a variety of vascular lesions, mainly posterior circulation aneurysm, have started to be approached through the transsphenoidal route, pioneered by the innovative works presented by Kassam et al. in 2006 and 2007 (17,18).

The purpose of the present contribution is to review the ventral approaches to intracranial aneurysms and to discuss its surgical results and complications over the years.

Materials and methods

A comprehensive literature review of manuscripts was performed as shown below.

Literature analysis

The search was conducted in the PubMed database using the following keywords (individually or in association): "transoral", "transcervical", "transclival", "transfacial", "transsphenoidal", "endonasal", "endoscopic" and "cerebral aneurysm". The date of the latest search was February 2013.

Selection criteria

All clinical manuscripts that approached aneurysms via the transcervical-transclival, transoral-transclival, transfacial-transclival or transsphenoidal routes were analyzed as well as their references.

Data collection

Manuscript selection was performed by two authors that independently reviewed the articles for inclusion or exclusion. No disagreements were found.

Data analysis

To calculate the overall complication rate, cases in which the authors described at least one complication, namely CSF leak, meningitis, cranial nerve injury, dysphagia, retropharyngeal mass (for example CSF collection in the retropharyngeal space), hydrocephalus, slip-out of the clip, cardiac arrest, pharyngeal wound infection, subarachnoid hemorrhage, vasospasm, mild postoperative confusion, deep venous thrombosis and death, were used. To determine the success or insuccess of the surgical performance, by means of postoperative computerized tomography (CT) or magnetic resonance (MR) or angiography, the following neuroradiological and clinical criteria have been evaluated including obliteration of the aneurysm sac, proper position of the clip and patency of the parent arteries.

Overall complication and surgical success rates were calculated for papers providing all required data.

Historical background of the ventral approaches: complications, surgical results and reconstruction techniques

Pioneering work: the transoral approach

In 1966, Sano et al. (1) reported the first successful case of transoral-transclival coating and wrapping of an aneurysm of the proximal basilar artery, located at the lower third of the clivus, i.e. the so-called "no man's land". The authors stressed the advantages of this route in permitting dissection of the aneurysm under direct vision control without any retraction of the brain or the cranial nerves. Their patient did not report cerebrospinal fluid (CSF) leak and/or meningitis and recovered well. This pioneering report encouraged other authors to use the ventral approach in selected patients (Table 1 and 2, Figure 1).

First transcervical-transclival approaches

As previously described (8), the transcervical-transclival approach is used to access lesions arising or extending into the craniovertebral junction, the lower part of the clivus up to C1. A transverse cervical incision, from the midline to the mastoid tip is performed. After dissected the underlying tissues, the clival bone can be visualized and partially removed. A midline dural incision is then made to reach the surgical target (basilar artery

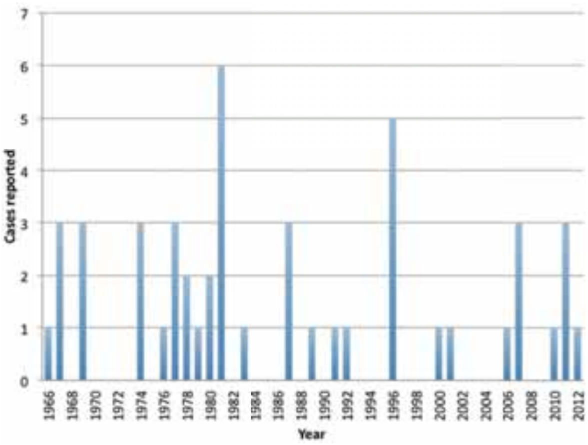


Figure 1. Graph showing 48 cases of cerebral aneurysms reported in the PudMed database and treated via the ventral route, from 1966 to 2012 (blue bars).

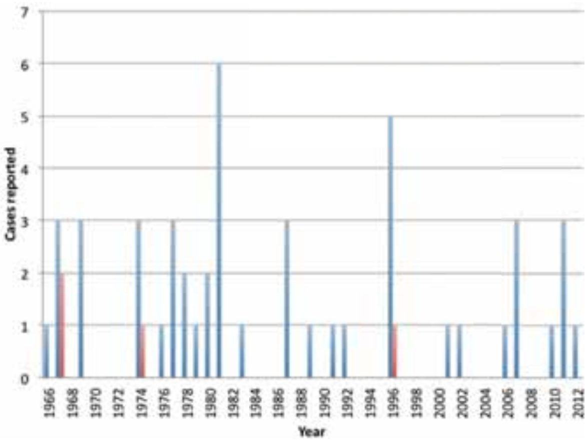


Figure 2. Graph showing the cases of aneurysms approached via the ventral route (blue bars) and cranial nerve lesion (red bars) as complication after surgery. In 1967 and 1974, the cases of cranial nerve injury were associated with transcervical-transclival approach, while the case reported in 1996 was related to trasfacial-transclival approach.

or vertebral artery aneurysm).

Between 1967 and 1976, many authors reported cases of posterior brain circulation aneurysms treated via the transcervical-transclival route (8). In his "Microsurgery applied to Neurosurgery" monograph, Yaşargil (11) described two unsuccessful ligations of posterior circulation aneurysms attacked via the transcervical-transclival route resulting in death of both patients. The most common postoperative complications were cranial nerve injury (hypoglossal nerve, XII; Figure 2), CSF leak and pharyngeal stenosis. In particular, Wissinger et al. (10) and Chou et al. (13) reported two cases of transection of the hypoglossal nerve and subsequent palsy. In those years, the skull base reconstruction technique was limited to free flaps from the pharyngeal mucosa and CSF leaks were present in the majority of cases.

Revival of the transoral-transclival approach

In the following years, the transcervical route to get access to the clival region was gradually abandoned and many authors began to manage aneurysms of the posterior circulation via the transoral-transclival route.

As described (19), the transoral-transclival approach allowed to reach the surgical target after a midline hard and soft palatal split and mobilizing each hemi-maxillae laterally (following or not a standard Le Fort I maxillotomy).

Surgical results and outcomes were in most of cases acceptable (12, 20-28). Nevertheless, Drake et al. (29), Hashi et al. (30), Saito et al. (9), Matricali et al. (31), and Hayakawa et al. (32-34) reported 5 casualties related to surgery but the most common complications were CSF leak (Figure 3) and meningitis. However, the most dangerous event was the possibility that the clip could move away from the neck of the aneurysm. Indeed, in two cases, Saito et al. (9) and Litvak et al. (25), showed that the head of the clip was larger than the bone window in the clivus and, for this reason, the clip slipped out from the aneurysm neck, causing death of the patient in one case. Concerning the reconstruction technique, in 1979, Yamaura et al. (23) published a notable work describing the

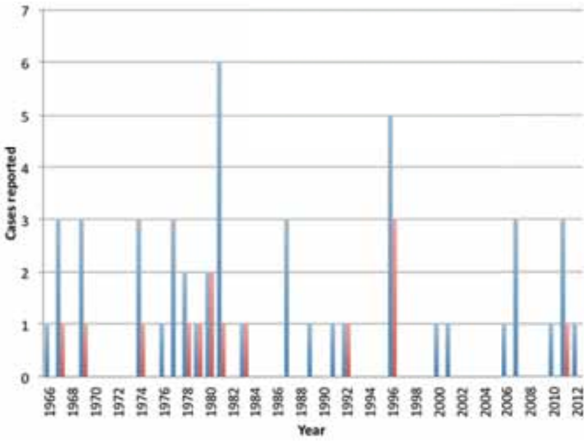


Figure 3. Graph showing the cases of aneurysms approached via the ventral route (blue bars) and cerebrospinal fluid (CSF) leak (red bars) as complication after surgery. Between 1966 and 1996, the cases of ce-rebrospinal fluid leak were related to transcervical-transclival, transoral-transclival and transfacial-transclival approaches, while the case reported in 2011 was associated with the endoscopic endonasal transclival approach.

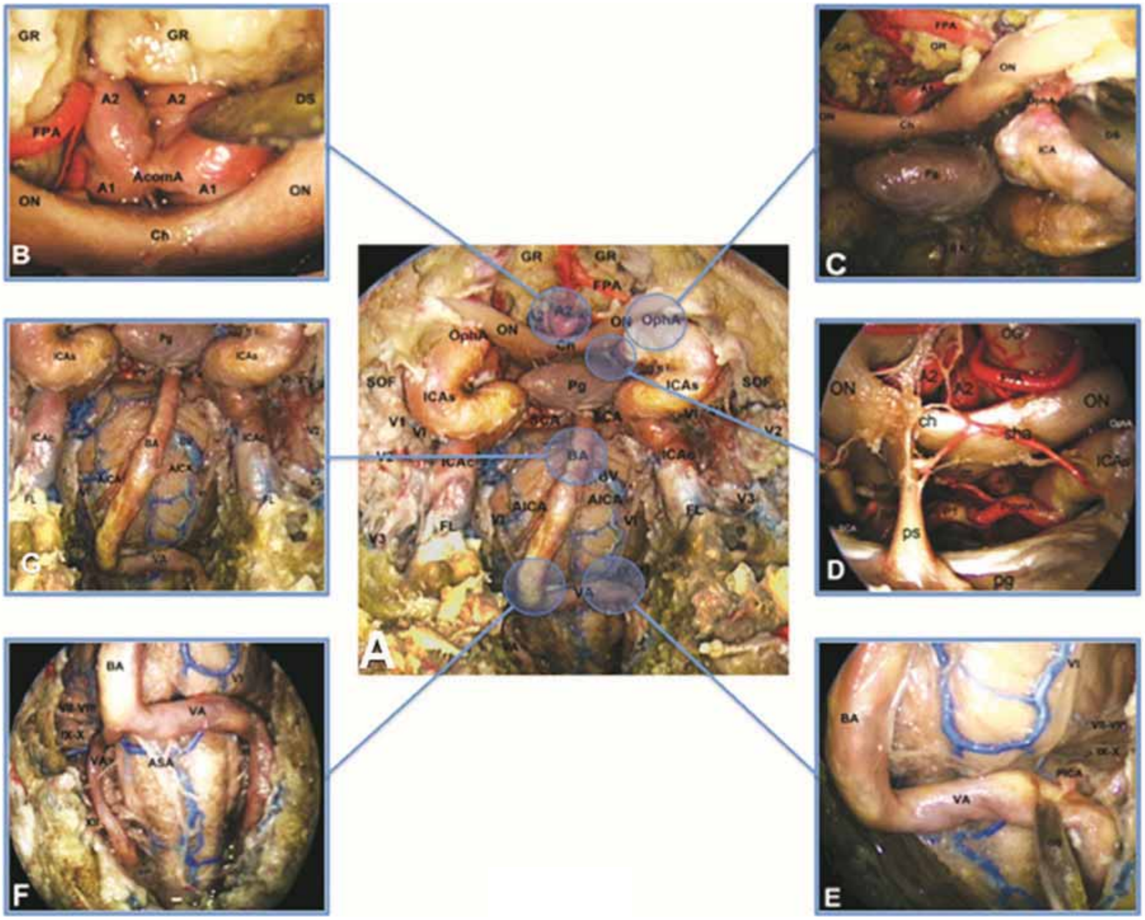
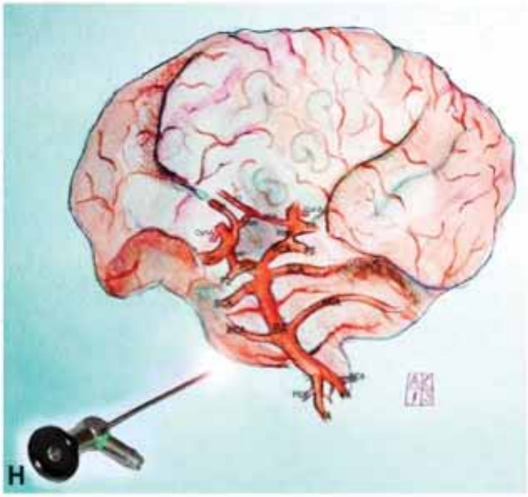


Figure 4. Anatomical picture: Dissection at the Laboratory of Surgical NeuroAnatomy of Barcelona, Spain. Vascular areas already reached via extended endoscopic endonasal approaches. Panoramic image (A) showing the main anterior and posterior circulation vessels exposed via extended endoscopic endonasal route. Close-up view of the suprasellar area with (B) the anterior communicating artery complex, (C) the ophthalmic artery and (D) the superior hypophyseal artery; detailed images (E) of the posterior inferior cerebellar artery arising from the vertebral artery, (F) the origin of the basilar artery and (G) the basilar trunk; schematic drawing (H) showing the entire cerebral circulation as seen through the ventral endoscopic view. Ch = optic chiasm; ON = optic nerve; Pg = pituitary gland; GR = gyrus rectus; FPA = frontopolar artery; A1 = pre-communicating tract of the anterior cerebral artery; A2 = post-communicating tract of the anterior cerebral artery; AcomA (Acom) = anterior communicating artery; OphA = ophthalmic artery; ICA = internal carotid artery; ICAs = sellar segment of the internal carotid artery; ICAc = clival segment of the internal carotid artery; FL = foramen lacerum; SOF = superior orbital fissure; VI = abducent nerve; GG = gasserian ganglion; V1 = ophtalmic branch of the trigeminal nerve; V2 = maxillary branch of the trigeminal nerve; V3 = mandibular branch of the trigeminal nerve; VII-VIII = acoustic-facial nerve bundle; IX = glossopharyngeal nerve; X = vagus nerve; XII, hypoglossal nerve; sha = superior hypophyseal artery; PcomA (Pcom), posterior communicating artery; PCA = posterior cerebral artery; P2 = post-communicating tract of the posterior cerebral artery; SCA = superior cerebellar artery; BA = basilar artery; BV = basilar venous plexus; ASA = anterior spinal artery; VA = vertebral artery; AICA = anteriorinferior cerebellar artery; PICA = posteriorinferior cerebellar artery; DS = dissector.



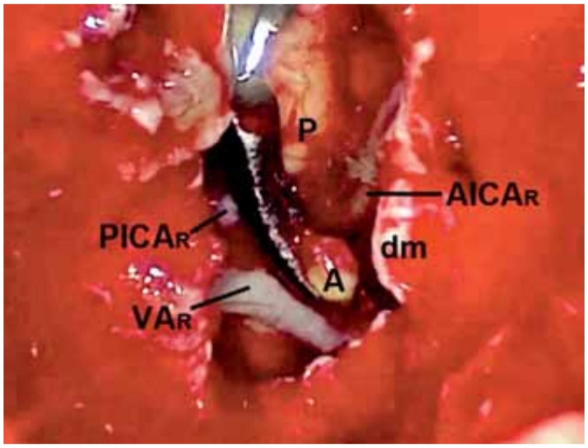


Figure 5. Endoscopic endonasal inferior transclival view of a vertebral artery-posterior inferior cerebellar artery aneurysm clipping. A = aneurysm; AICAr = right anterior inferior cerebellar artery; dm = dura mater; P = perforator arteries; PICAr = right posterior inferior cerebellar artery; VAr = right vertebral artery.

Figure 6. Graph showing the complications rate and the success rate of traditional ventral (blue bars) and extended transsphenoidal approaches (red bars), performed in order to treat cerebral aneurysms.

first report of employment of a vascularized flap for transclival-transoral approach; indeed, after the clipping of a basilar artery aneurysm, the authors repaired the postoperative CSF fistula using a rotation flap of the nasal septum mucosa, which was exploited to cover the skull base defect.

In the next years, Archer et al. (35), de Los Reyes et al. (36), and Crockard et al. (37,38) described a modification of the transoral-transclival route involving a Le Fort I osteotomy (maxillotomy) rather than splitting the soft and hard palates, offering a much improved view of the clivus. The authors achieved a reduced rate of CSF fistula thanks to the improved exposure provided by the Le Fort I osteotomy. Another notable case report was described by Crockard et al. (19). In their paper, the authors showed the occlusion of an aneurysm with a curved variangle McFadden clip enforced using a rotating pistol-grip aneurysm clip applier that was especially developed for transoral vascular surgery.

Transfacial-transclival approach

In 1996, Ogilvy et al. (39) described five patients with mid-posterior circulation aneurysms treated through a transfacial-transclival approach.

A lateral rhinotomy incision is usually made from the glabella around the lateral alar margin. After osteotomy of nasal bones and disarticulation of the septal cartilage from the ethmoid, the nose can be reflected laterally. Further dissection of the retropharyngeal mucosa permitted to perform the bone removal on the clivus. Afterwards, the dura can be opened to reach the midline target (39).

For reconstruction, the authors used a multilayer closure including free fat grafts, septal bone, cartilage, fascia lata, fibrin glue, and an overlying split-thickness skin graft, as well as perioperative drainage with lumbar drains and ventriculostomies. Despite these measures, three of their patients developed transient CSF leaks after nasal packs removal.

In the years following, due to frequent complications, mainly meningitis for recurrent CSF leak, the transcervical, transoral and transfacial approaches for the treatment of cerebral aneurysms were gradually discarded.

Minimally invasive approaches: transsphenoidal approaches and extended endoscopic endonasal surgery

The evolution of the transsphenoidal technique over the last decade, resulting largely from better instrumentation, surgical navigation and, perhaps most importantly, endoscopy, has lead to the extension of the approach beyond treating pituitary adenomas to the management of different skull base lesions. Indeed, during the early nineties, the endoscopic endonasal approach has been progressively accepted by neurosurgeons, and in many centers throughout the world, this route has been used following the same indications of conventional microsurgical technique. Currently, a variety of anatomical and clinical studies have demonstrated the possibility to reach different areas of the skull base (40-43).

These apporaches permitted to reach the midline target passing through the sphenoid sinus, by means of a microscope or an endoscope.

For vascular surgery, extended endoscopic endonasal approaches provide excellent exposure of important anterior and posterior circulation arteries. For this reason, up to now, a total

Table 1. Clinical and operative characteristics in 39 reported patients with intracranial aneurysms treated via the "traditional" ventral routes (transcervical-transclival, transoral-transclival, transfacial-transclival), literature review.

Authors & Year	Aneurysm location & size (mm)	Clinical presentation	Approach	Post-operative imaging	Complications	Outcome
Sano et al., 1966	BA (NA)	NA	Transoral-transclival	NA	None	Full recovery
Fox et al., 1967	VA (15)	Headache, hyperactive OTR, ataxia	Transcervical-transclival	Aneurysm obliterated	CSF leak, dysphagia, retropharyngeal mass (CSF collection), hydrocephalus	Cranial Nerve Lesion
Wissinger et al., 1967	VA-BA (NA)	SAH	Transcervical-transclival	NA	None	Full recovery
	BA (NA)	SAH	Transcervical-transclival	Aneurysm obliterated	Hypoglossal nerve injury	Cranial Nerve Lesion
Drake et al., 1969	VA (NA)	NA	Transoral-transclival	NA	Clip extrusion	Full recovery
Yasargil, 1969	VA-BA (NA)	NA	Transcervical-transclival	NA	Hemiparesis, CSF leak? (1 pz had CSF leak)	Death
	BA (NA)	NA	Transcervical-transclival	NA	Hydrocephalus, tetraplegia, CSF leak?	Death
Chou et al., 1974	BA (10)	HH grade II, headache, transitory loss of vision, coma	Transcervical-transclival	NA	Hypoglossal nerve injury, cardiac arrest	Cranial Nerve Lesion
	BA (9)	HH grade II, headache, loss of consciousness	Transcervical-transclival	NA	Vasospasm, retropharyngeal mass	Full recovery
	BA (7)	HH grade II, seizure, pulmonary edema	Transcervical-transclival	NA	Vasospasm, CSF leak	Full recovery
Hashi et al., 1976	VA (2)	Bronchial asthma, dysphagia, dysphonia	Transoral-transclival	NA	Meningitis	Death
Takeuchi et al., 1977	VA (NA)	NA	Transoral-transclival	NA	Meningitis, hydrocephalus	Full recovery
Laine et al., 1977	AICA (NA)	NA	Transoral-transclival	NA	NA	NA
	PICA (NA)	NA	Transoral-transclival	NA	NA	NA
Drake et al., 1978	VA (NA)	NA	Transoral-transclival	NA	Meningitis, CSF leak	Death
Haselden et al., 1978	BA (NA)	NA	Transoral-transclival	NA	NA	Full recovery
Yamaura et al., 1979	BA (NA)	NA	Transoral-transclival	NA	CSF leak	Full recovery
Saito et al., 1980	VA-BA (NA)	SAH, loss of consciousness, dysdiadochokinesis	Transoral-transclival	Aneurysm obliterated	CSF leak	Full recovery
	VA-BA (NA)	SAH, lethargic, acute respiratory failure	Transoral-transclival	Aneurysm obliterated	CSF leak, meningitis, slip-out of the clip	Death
Hayakawa et al., 1981	BA-AICA (NA)	NA	Transoral-transclival	NA	None	Death
	BA-AICA (NA)	NA	Transoral-transclival	NA	Meningitis, hydrocephalus	Full recovery

Table 1. continued.

Authors & Year	Aneurysm location & size (mm)	Clinical presentation	Approach	Post-operative imaging	Complications	Outcome
Hayakawa et al., 1981	BA-AICA (NA)	NA	Transoral-transclival	NA	Hydrocephalus	Full recovery
Matricali et al., 1981	BA (NA)	SAH, headache	Transoral-transclival	Incomplete closure of the aneurysm	CSF leak	Death
	BA (NA)	SAH, headache	Transoral-transclival	NA	None	Full recovery
Litvak et al., 1981	BA (NA)	Syncope, seizure, come	Transoral-transclival	Slip-out of the clip	Slip-out of the clip	Full recovery
Hitchcock et al., 1983	VA (NA)	Collapse, loss of consciousness	Transoral-transclival	Aneurysm obliterated	CSF leak, meningitis	Full recovery
Archer et al., 1987	BA (NA)	SAH, coma	Transoral-transclival + Le Fort I	NA	None	Full recovery
	BA (NA)	HH grade I, headache, neck stiffness	Transoral-transclival + Le Fort I	NA	Pharyngeal wound infection	Full recovery
	BA (NA)	HH grade I, SAH	Transoral-transclival + Le Fort I	NA	None	Full recovery
Yamashita et al., 1989	VA-PICA (5)	SAH	Transoral-transclival	NA	Hemiparesis, meningitis	Full recovery
Crockard et al., 1991	BA-AICA (NA)	SAH, trochlear and abducent nerves palsies	Transoral-transclival + Le Fort I	Aneurysm obliterated	None	Full recovery
de Los Reyes et al., 1992	BA (NA)	Headache	Transoral-transclival + Le Fort I	Aneurysm obliterated	CSF leak	Full recovery
Ogilvy et al., 1996	BA (NA)	HH grade I, SAH	Transfacial-transclival	Aneurysm obliterated	None	Full recovery
	AICA (NA)	HH grade III, SAH	Transfacial-transclival	Aneurysm obliterated	SAH, CSF leak	Death
	PICA (NA)	HH grade II, bilateral abducent nerve palsy	Transfacial-transclival	Aneurysm obliterated	CSF leak (other 2 pz had CSF leak)	Full recovery
	VA-BA (NA)	HH grade III, abducent nerve palsy	Transfacial-transclival	Aneurysm obliterated	Delayed trochlear nerve palsy	Cranial Nerve Lesion
	BA (NA) + fusiform dilatation	HH grade II, abducent nerve palsy	Transfacial-transclival	Aneurysm obliterated	None, CSF leak	Full recovery
Stacey et al., 2000	BA-AICA (NA)	NA	Transoral-transclival	NA	NA	NA
Imamura et al., 2001	VA-PICA (3)	HH grade II, SAH, headache	Transoral-transclival	Aneurysm obliterated	None	Full recovery

HH Hunt and Hess grade, NA not available, SAH subarachnoid hemorrhage, CSF cerebrospinal fluid, OTR osteotendinous reflexes, BA basilar artery, VA vertebral artery, AICA anteriorinferior cerebellar artery, PICA posteriorinferior cerebellar artery, pz patient, * computerized tomography (CT) and/or magnetic resonance imaging (MRI) and/or arteriography of 9 aneurysms were clipped via the nose.

In particular, as shown in Figure 4 (an anatomical and schematic picture demonstrating different vascular areas reached via extended endoscopic endonasal approaches until now; Laboratory of Surgical NeuroAnatomy of Barcelona), the transtuberculum/transplanum approach allows the exposure of the pre-communicating and post-communicating segments of the anterior cerebral arteries (A1 and A2), the anterior communicating artery (AcomA), the frontopolar arteries (FPA), the superior hypophyseal arteries (sha), the proximal segment of the ophthalmic arteries (OphA) and the supraclinoid portion of the internal carotid arteries (ICA); the sellar/parasellar approach provides an optimal visualization of the cavernous portion of the ICA and superior hypophyseal arteries (sha). The transclival approach allows the exposure of the basilar artery (BA), the posterior cerebral arteries (PCA), the posterior communicating arteries (PcomA), the superior cerebellar arteries (SCA), the anterior inferior cerebellar arteries (AICA), the vertebral arteries (VA), the posterior inferior cerebellar arteries (PICA) and the anterior spinal artery (ASA) (Figures 4 and 5).

The first case of aneurysm clipping via the nose was published in 2006 by Kassam et al. (17). It was a case of a large vertebral artery aneurysm that, after the endovascular trapping, was completely clipped by the endoscopic endonasal transclival approach. The dura was reconstructed with an intradural inlay Duragen graft (Integra Life Sciences, Boston, MA, USA), followed by an extradural onlay allograft plus fibrin glue and a Foley catheter balloon, inserted to provide support to the grafts and to prevent graft migration. Intranasal silastic splints were sutured in place bilaterally, and a lumbar drain was placed. The patient was discharged with an improvement of preoperative symptoms including weakness, incoordination and sensory changes.

One year later, the same group reported a case of a 56-year-old woman found to have two unruptured aneurysms: an anterior communicating artery (AComA) aneurysm and a superior hypophyseal artery (sha) aneurysm (18). The aneurysm was clipped by an endoscopic endonasal transtuberculum/transplanum approach and, except from a mild postoperative confusion, the patient was free of any infection and/or CSF leak.

In 2007, Kitano et al. (44) reported a case of a small incidental unruptured AComA aneurysm, which was clipped via a microscopic endoscopic-assisted sublabial-transtuberculum/transplanum approach, after a subtotal removal of a macroadenoma. An autologous fascia graft was placed subdurally on the anterior cranial base to cover the dural opening and the fascial graft was sutured to the dural edges. Moreover, ceramic cement was applied to reconstruct the bony defect, reinforce the dural closure, and inhibit CSF leakage. Interestingly, Kitano et al. performed an anatomical dissection of two cadaveric heads to confirm the usefulness of the extended endoscopic endonasal approach to expose the AcomA complex and its lesions. In the same year, Eloy et al. (45) used a Weck clip (Weck Closure Systems Research, Triangle Park, NC, USA), which provided a low profile for closure, to obliterate an aneurysm of the mid-basilar trunk via a microscopic sublabial-transclival approach. For persistent fusiform dilation in the region of the aneurysm, endovascular stenting was also performed and, at the 3-month follow-up examination, the patient had made a full recovery. Moreover, Acerbi et al. (46) demonstrated the use of nitinol U-Clips to reconstruct the cranial base dura in a series of 11 patients that included 1 case with a mid-basilar trunk aneurysm. One year later, Enseñat et al. (42) managed a ruptured vertebral-posterior inferior cerebellar artery complex (VA-PICA) aneurysm, successfully treated via an endoscopic endonasal extended approach to the clival region. It was the first report of a pure endoscopically treated VA-PICA aneurysm. The aneurysm was accurately reached and successfully clipped from the parent artery. For reconstruction of the skull base defect a copolymer of l-lactic acid and glycolic acid (LactoSorb) as a bone substitute was used and, as a dural substitute, fascia lata. In detail, an inlay fascia lata graft was placed intradurally, and another large piece of the same material exceeding the size of the osseous defect was placed over it; then, a fragment of LactoSorb was wedged into the extradural space. Finally, it was placed as a Hadad-Bassagaisteguy Flap (HBF) (47), fixed with an oxidized cellulose polymer and fibrin glue. A postoperative arteriogram showed proper placement of the clip, obliteration of the aneurysm, and the patency of the VA and the PICA. Seven days after surgery, the patient had a CSF rhinorrhea and underwent endoscopic endonasal repair of a CSF leak. The patient was discharged 1 month after reoperation without any neurological deficit.

In the same year, Froelich et al. (40) and Germanwala et al. (48) performed an endoscopic endonasal transtuberculum/transplanum surgery for aneurysms of the anterior circulation. A multilayer reconstruction technique was used in all cases and the postoperative course was uneventful.

The last report appeared in the literature in 2012 by Drazin et al. (49). The authors used an expanded endoscopic endonasal-transclival approach to successfully clip a basilar trunk aneurysm and feeding arteriovenous malformation (AVM) vessel. In this case, a small straight Yaşargil mini aneurysm clip (Aesculap AG, Tuttlingen, Germany) was applied across the aneurysm using an endonasal clip applier (Sephernia Neurosurgical micro-instruments, Karl Storz, Tuttlingen, Germany) and the dural defect was repaired using a multilayer technique, with placement of the nasoseptal flap. The patient was discharged from the hospital without any neurological deficits.

Results

Forty-eight cases, mostly case reports, were included and carefully analyzed. Data about these papers are summarized in Table

1 and Table 2. Only abstracts and/or full text manuscripts in English were analyzed, with the aim of calculating complication and surgical success rates for both "traditional" ventral (transcervical-transclival, transoral-transclival, transfacial-transclival) and extended transsphenoidal (microscopic endoscopic-assisted sublabial-transtuberculum/transplanum, microscopic sublabial-transclival, extended endoscopic endonasal) approaches. As shown in Figure 6, the overall complication rate for traditional ventral approaches, namely the transcervical-transclival, the transoral-transclival and the transfacial-transclival was 74% (26/35), whereas for extended transsphenoidal approaches, i.e. the microscopic endoscopic-assisted sublabial-transtuberculum/transplanum, the microscopic sublabial-transclival, the endoscopic endonasal transclival and the endoscopic endonasal transtuberculum/transplanum, the rate was found to be 44% (4/9).

The overall surgical success rate for traditional ventral approaches was found to be 87% (13/15), while for an extended transsphenoidal surgery, it was 78% (7/9).

Discussion

The management of both ruptured and unruptured cerebral aneurysms has undergone significant evolution in the modern era. Nowadays, it can be considered as the result of a close cooperation between different specialists, i.e. the ENT surgeon, the neuroradiologist, the neurologist and the neurosurgeon (50). In such a combined neurovascular team, each member plays a well-defined role, offering his contribution to the final result, specifically tailored to a single patient. During the last decades, the endovascular technique has rapidly evolved thanks to the Food and Drug Administration approval of Guglielmi detachable coils in 1995, which since then allowed successful treatment of a great deal of cerebral aneurysms in many centers all over the world. In the latter half of the 1990s, as experience of endovascular techniques spread, such treatment began to displace open surgery and the International Subarachnoid Aneurysm Trial (ISAT) was set up to compare the efficacy of the two treatments (51,52). The endovascular technique has changed the way we practice neurosurgery. Endovascular therapy has largely replaced microsurgery as the first line treatment modality for the majority of cerebral aneurysms. Recently, reconstructive endovascular treatment, including stent, stent-assisted coiling or flow diverters, has been applied to complex posterior circulation aneurysms and high viscosity liquid embolization agents have been used effectively, particularly in the treatment of distal posterior circulation aneurysms (53,54).

The history of intracranial surgery for aneurysms is not a long one. The first direct operation on an intracranial aneurysm was performed by Dott, who wrapped a ruptured aneurysm in 1933 (55) and the first obliterative clipping of an aneurysm was performed by Dandy in 1938 (56). The results of surgery improved dramatically when the operating microscope was introduced in the 1960s and its propagation in the 1970s, 1980s and 1990s greatly influenced the results of aneurysm surgery. The pterional approach first described by Yaşargil in those years, allowed an excellent exposure of the circle of Willis and the management of aneurysm affecting this anatomical region (11,57). Since then, important intraoperative adjuncts such as micro-Doppler ultrasonography (MDU), intraoperative angiography (IOA), and near-infrared indocyanine green (ICG) video angiography have been emerging as very useful tools in vascular surgery. However, during the endovascular era, the challenge for contemporary vascular neurosurgeons is to understand the different but complementary role each treatment modality currently has to offer, and to maintain the proficiency and technical skills to deal with an emergence of complex and in many cases, recurrence of previously coiled aneurysms.

Despite these great advances made both in surgical and endovascular techniques, the complexity of some vascular lesions makes their treatment still a challenge for vascular teams, as they are associated with a high incidence of complications, which is particularly true for posterior circulating aneurysms. Indeed, reviewing the literature, it is apparent that posterior circulation aneurysms present as significant endovascular challenge to the neurointerventionalist as it does to the neurosurgeon. Historically, such vascular lesions present a difficult challenge because they are located in an exquisitely eloquent and sometimes difficult-to-reach area in the posterior cranial fossa.

For such reasons starting from the late 1960's, the ventral route has been advocated as a valid alternative to reach those lesions. The ventral pathway was considered a reasonable option because it permits direct access to the surgical field obviating brain retraction and obtaining an early and safe proximal and distal vascular control. Since then, more than thirty authors report the use of transcervical-transclival, transoral-transclival, transfacial-transclival and, finally, extended transsphenoidal approaches to occlude posterior circulating aneurysms. As demonstrated by the publication of more than 45 cases in the last 50 years, the ventral pathway is an attractive and valid alternative to established neurosurgical procedures currently in use for the treatment of intracranial aneurysms.

Nowadays, the oribitozygomatic, transpetrous, retrosigmoid, or far-lateral approaches have been well recognized as preferred pathways to treat complex posterior circulation aneurysms that cannot be treated by endovascular therapy. On the other hand, tranditional ventral approaches including transcervical-transclival, transoral-transclival, and transfacial-transclival routes have been gradually discharged and, actually, they can be considered seldom.

Table 2. Clinical and operative characteristics in 9 reported patients with intracranial aneurysms treated via extended transsphenoidal approaches (microscopic endoscopic-assisted sublabial-transtuberculum/transplanum, microscopic sublabial-transclival, extended endoscopic endonasal), literature review.

Authors & Year	Aneurysm location & size (mm)	Clinical presentation	Approach	Post-operative imaging	Complications	Outcome
Kassam et al., 2006	VA (11)	Left leg weakness and sensory changes	Endoscopic endonasal-transclival	Aneurysm obliterated	None	Full recovery
Kassam et al., 2007	Sha (5)	Incidental	Endoscopic endonasal transtuberculum/ transplanum	Aneurysm obliterated	Mild postoperative confusion	Full recovery
Kitano et al., 2007	AComA (NA)	Incidental	Microscopic endoscopic-assisted sublabial-transtuberculum/ transplanum	Aneurysm obliterated	None	Full recovery
Eloy et al., 2007	BA (2.5)	HH grade III	Microscopic sublabial-transclival	Persistent fusiform dilation of BA	Vasospasm, hydrocephalus	Full recovery
Acerbi et al., 2010	BA (NA) + fusiform dilatation	SAH	Microscopic sublabial-transclival	Aneurysm obliterated, reduced fusiform dilation	Vasospasm, DVT right leg, hydrocephalus	Full recovery
Ensenat et al., 2011	VA-PICA (1.2)	Headache and decreased level of consciousness	Endoscopic endonasal-transclival	Aneurysm obliterated	CSF leak, hydrocephalus	Full recovery
Froelich et al., 2011	AComA (7)	Incidental	Endoscopic endonasal transtuberculum/ transplanum	Aneurysm obliterated	None	Full recovery
Germanwala et al., 2011	Ophtalmic (5), Paraclinoid (10)	HH grade II	Endoscopic endonasal transtuberculum/ transplanum	Aneurysm obliterated	None	Full recovery
Drazin et al., 2012	BA (4), cerebellar AVM	HH grade II	Endoscopic endonasal-transclival	Partial aneurysm occlusion (1st surgery)	None	Full recovery

HH Hunt and Hess grade, NA not available, SAH subarachnoid hemorrhage, CSF cerebrospinal fluid, DVT deep venous thrombosis, AComA anterior communicating artery, Sha superior hypophyseal artery, BA basilar artery, VA vertebral artery, PICA posteriorinferior cerebellar artery, AVM arteriovenous malformation, * computerized tomography (CT) and/or magnetic resonance imaging (MRI) and/or arteriography.

However, in recent years, thanks to Kassam et al. (17), some reports have been published stating that specific midline anterior and posterior circulating aneurysms not amenable to endovascular treatment could be managed via the anterior route, in particular throughout the extended endoscopic endonasal route. The evolution of the transsphenoidal technique, which was initially reserved to sellar lesions, has lead in the last decades to a progressive possibility to access the different areas of the skull base. Indeed, such a route allows midline access and visibility to the suprasellar, retrosellar, parasellar and clival space while obviating brain retraction, and makes it possible to treat transsphenoidally a variety of midline skull base lesions. Particularly, among transsphenoidal surgeries, the endoscopic endonasal pathway allows the treatment of wide range of the midline skull base region pathologies, with the advantage of a wider vision of the surgical field, less traumatism of the brain structures, lower cases of cranial nerves lesions, greater facility in the treatment of possible recurrences and reduced complications.

Applied to vascular surgery, the extended endoscopic endonasal approach offers some advantages due to the properties of the endoscope itself; it provides a wider, close-up view of the surgical field thus allowing, for selected midline vascular lesions, the achievement of a safe proximal and distal vascular control in the majority of cases, a comfortably bimanual dissection and a close and detailed visualization of the main neurovascular structures, i.e. small perforator arteries without any brain retraction (58-60).

The endonasal route provides different advantages compared to previous approaches used. In general, it is less traumatic, as compared with the transoral pathway, and the bacterial flora of the nose is less virulent and represented than that of the oral cavity, thus reducing the risk of infection of the CSF. Moreover, the availability of broad-spectrum antibiotics with adequate CSF penetration, such as third-generation cephalosporin, allows patients to recover without complications despite clinical evidence of meningitis (39, 61). Very relevant is that the time to reach the lesion is mainly focussed on the extradural space, i.e. nose or sphenoid cavity, while during classical neurosurgical approaches the main part of the procedure is aimed to reach the deep vascular territory by shifting vital neurovascular structures. Bleeding control can be seen as one of the major issues during intracranial aneurysm surgery. This is particularly challenging for endonasal approaches in which blood can obscure the main anatomical landmarks of the surgical field and dirties the endoscope lens, causing greater difficulty with visualization. Another important point during this kind of surgery is the impossibility to perform vascular by-passes and the difficulties that may be encountered for the application of proximal and distal temporary clips coupled with the room for a permanent clip. On the other hand, the development of new techniques in skull base surgery also allowed maintaining, in most cases, the same basic principles of the microsurgical technique for vascular surgery. Indeed, the endoscopic endonasal technique in selected cases can allow the achievement of a safe proximal and distal vascular control, a comfortably bimanual dissection, and a close and detailed visualization of the main neurovascular structures (especially small perforator arteries). For such reason, we consider that the same principles of microsurgical vascular repair must be strictly followed during transsphenoidal surgery.

Regarding surgical success and overall complications, as shown in the present paper, the overall surgical success seems to be comparable between “traditional” ventral approaches and extended transsphenoidal routes (87% vs. 78%). On the other hand, the overall complication rate using transsphenoidal approaches, such as the microscopic endoscopic-assisted sublabial-transtuberculum/transplanum, the microscopic sublabial-transclival, the endoscopic endonasal transclival and the endoscopic endonasal transtuberculum/transplanum, has been dramatically reduced compared to previous approaches used (44% vs. 74%).
However, the transsphenoidal surgery and, as a specific reference, endoscopic endonasal surgery, brings some disadvantages that should be taken in consideration. The exposure provided by the approach is limited to certain anatomical skull base regions, proximal and distal vascular control may be hard in case of difficulties. Furthermore, the inability to perform a bypass graft, risk of CSF leak and the significant endoscopic skills required are other drawbacks, which could make the ventral corridor indicated only in very selected cases. Moreover, in the endonasal approach the surgical corridor is narrow, with less leaving room for the surgeon to comfortably dissect and definitively clip the aneurysm.

Finally, regarding the issue of transsphenoidal surgery applied to cerebrovascular diseases, it should be stressed that, at present, this kind of approach is still in its infancy - only 9 cases in the current literature - so we have to wait further developments, in terms of surgical technique as well as tools and reconstruction materials, to reach proper conclusions. Moreover, these are the reasons why it is not possible at present to make a comparison with the relevant open and endovascular pathways.
Another major issue emerging in recent years refers to skull base reconstruction, which continues to be a major challenge and an obstacle for the use and acceptance of the expanded endonasal approaches (62,63). A significant progress in reconstruction of dural defects has been made thanks to the description of the Hadad–Bassagasteguy flap (HBF) in 2006 (47). The HBF is a witness reconstructive technique for extensive defects of the anterior, middle, clival, and parasellar skull base and its use has resulted in a sharp decrease in the incidence of postoperative CSF leaks after endoscopic endonasal approaches.

Conclusion

Increasing technological developments have led to the application of the endoscope to cranial base and, more recently, cerebrovascular surgery. However, no doubt, aneurysm surgery is greatly advanced with the endovascular techniques and room for surgery has been and will be progressively reduced. We stress that the present and future of cerebral aneurysm treatment is the endovascular technique. With this in mind, our paper wants to be a reconnaissance of what has been done via “the anterior route” and a notification of the existence of this “surgical window”, which should be sparingly used. Just a few selected cases in specialized centers, where transsphenoidal approaches are routinely performed, may be treated with such techniques alone or in combination with the other procedures.

Authorship contribution

ADS: Design, acquisition of data, analysis and interpretation of data, drafting of the manuscript, final approval of draft. MdN: Design, acquisition of data, analysis and interpretation of data, drafting and revision of the manuscript, final approval of draft JE: Analysis and interpretation of data, revision of the manuscript, final approval of draft. IA: Analysis and interpretation of data, revision of the manuscript, final approval of draft. MB-S: Analysis and interpretation of data, revision of the manuscript, final approval of draft. LMC: Analysis and interpretation of data, revision of the manuscript, final approval of draft. AP-G: Design, Analysis and interpretation of data, revision of the manuscript, final approval of draft. PC: Analysis and interpretation of data, revision of the manuscript, final approval of draft.

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Conflicts of Interest

The authors have no personal financial or institutional interest in the devices described in this article.

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ORIGINAL ARTICLE

Extended Endoscopic Endonasal Approach to the Third Ventricle: Multimodal Anatomical Study with Surgical Implications

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■ INTRODUCTION: **A certain interest for the extended endoscopic endonasal approach for the management of sellar-suprasellar lesions extending inside the third ventricle has been growing in recent years. The aim of this anatomical study was to evaluate the possibilities in terms of exposure and access to the different areas of the third ventricle, with the endoscopic endonasal technique, as compared with the microscopic or endoscopic view provided via different transcranial approaches. The advantages and limitations of both surgical pathways were analyzed.**

■ MATERIALS AND METHODS: **Ten human cadaver heads were dissected. In order to standardize the comparison between the endonasal and the transcranial routes, the third ventricle cavity has been divided into four areas by means of two ideal planes, one passing through the optic chiasm and the interthalamic commissure and one passing through the posterior edge of the foramen of Monro and the interthalamic commissure. Accordingly, two anterior (infundibular and foraminal) and two posterior (mesencephalic and tectal) areas have been defined.**

■ RESULTS: **The endoscopic endonasal approach allows for exploration and surgical maneuverability, especially in the anterior areas of the third ventricle. In the infundibular and foraminal areas the surgical maneuverability seems to be better as compared with that obtained inside the mesencephalic region, while via the endonasal route the tectal area could not be reached. In particular, the infundibular area can be explored either passing through the lamina terminalis or via the tuber cinereum; this latter trajectory enables visualization of the foramina of Monro and the floor of the third ventricle up to the pineal recess.**

■ CONCLUSION: **This anatomical study shows that the lamina terminalis and, above all, the tuber cinereum represent two safe entry points defining possible surgical corridors to be considered for the extended endoscopic endonasal approach to the third ventricle.**

INTRODUCTION

The third ventricle is a unilocular cavity positioned on the midline at the center of the head. It is among the most challenging areas to access because of its deep location and its intimate relationships with perforating arteries and white matter tracts. Surgical strategies to enter this region critically depend on multiple surgical anatomic considerations, accounting for the need to minimize the risk of injuring cortical, subcortical, and vascular structures (48).

In fact, surgical manipulation of the walls of the third ventricle may cause hypothalamic damage, which can determine consciousness disturbances, temperature dysfunctions, and/or hypophyseal axes defects; visual loss due to damage of the optic chiasm and tracts; and memory loss due to injury to the columns of the fornix. However, the ability to access and remove lesions without harming the surrounding critical neurovascular structures must be considered the key point of surgery for intraventricular tumors.

Several surgical pathways to the different portions of the third ventricle, including the translamina terminalis, frontal transcortical transforaminal, anterior transcallosal, and infratentorial

Key words
- Craniopharyngiomas
- Endoscopic transsphenoidal surgery
- Extended endoscopic endonasal approach
- Lamina terminalis
- Neuroendoscopy
- Third ventricle
- Third ventricle anatomy

Abbreviations and Acronyms
CSF: Cerebrospinal fluid
ICA: Internal carotid artery

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supracerebellar approaches, have been described (15, 22, 27, 32, 37, 44-46).

Most of these surgical approaches enable the entrance to the third ventricle cavity via its natural communication, foramina, and/or passing through avascular regions of the third ventricle walls (i.e., the suprapineal recess, lamina terminalis, and tuber cinereum).

The latter is a gray matter layer of the third ventricle floor, and it is commonly opened during endoscopic third ventriculostomy for the treatment of hydrocephalus as it represents a safe entry point within its floor.

However, it should be remembered that the exact location of the lesion within the cavity of the third ventricle should drive the choice of the surgical approach; because this cavity is surrounded by a great number of neurovascular structures, there is no unique route allowing access to the entire ventricular cavity.

The transsphenoidal approach, with both microsurgical and endoscope-assisted techniques, has shown the possibility to access the third ventricle cavity, especially in the presence of lesions such as craniopharyngiomas that, developing in the supra and/or retrosellar area, may enter the cavity of the third ventricle via the tuber cinereum.

More recently, the use of the pure endoscopic transsphenoidal technique has expanded the horizons of this route, allowing surgical exploration of the third ventricle cavity as reported by different authors (4, 5, 11, 12, 14, 33).

Relying on recent clinical experiences using the endoscopic endonasal approach for craniopharyngiomas involving the third ventricle (7, 18, 19, 21, 23, 24, 26, 28, 29, 31, 34, 49), we developed an anatomical study to evaluate the accessibility of the different areas inside the third ventricular cavity. We aimed to evaluate advantages and limitations in terms of visualization of the third ventricle as compared with the microscopic or endoscopic view provided via different transcranial approaches (translamina-terminalis, frontal transcortical, anterior transcallosal, and supracerebellar-infratentorial).

MATERIALS AND METHODS

The anatomical dissections were performed at the Laboratory of Surgical NeuroAnatomy (LSNA) of the University of Barcelona (Spain) and at the Institute of Forensic Medicine of the Department of Justice of Republic of Istanbul (Turkey). Ten fresh-frozen human heads were examined. The common carotid and vertebral arteries were injected with red-colored latex. Continuous irrigation of the third ventricle cavity was done during the anatomical dissection in order to prevent the collapse of the ventricular walls.

Microanatomical dissections were performed at optical magnification ranging from 3x to 40x (OPMI; Zeiss, Oberkochen, Germany). Endoscopic procedures were carried out using a high-definition camera attached to rigid endoscopes (Karl Storz GmbH and Co, Tuttlingen, Germany), 4 mm in diameter and 18 cm in length, with 0- and 30-degree lenses. The endoscope was connected to a light source via a fiber-optic cable and to a high-definition (HD)-camera fitted with three charge-couple device (CCD) sensors. The video camera was connected to a 21-inch monitor that supports the high resolution of HD-three-CCD technology.

In order to standardize the comparison between the endonasal and the transcranial routes, we divided the third ventricle into four areas, as related to the foramen of Monro, optic chiasm, and interthalamic commissure. These structures are particularly relevant during the intradural part of any surgical procedure and, above all, they are involved during the endoscopic exploration of the third ventricle.

Two ideal planes, one passing through the optic chiasm and the interthalamic commissure and one passing through the posterior edge of the foramen of Monro and the interthalamic commissure, divide the third ventricle into four areas: the anterior-inferior (*infundibular*), anterior-superior (*foraminal*), posterior-inferior (*mesencephalic*), and posterior-superior (*tectal*) areas.

The endoscopic anatomy of each region is described from both the transcranial and endonasal perspectives, and the different spatial relationships identified from the two opposite routes are analyzed (**Figure 1**).

Extended Endoscopic Endonasal Transsphenoidal Approach to the Planum Sphenoidale

This approach has been used, as already detailed in previous publications, according to the basic principles of endoscopic endonasal surgery (1, 2, 8, 12, 35). Access to the suprasellar structure is provided by drilling out the tuberculum sellae, namely the suprasellar notch (16), which corresponds to the angle formed by the planum sphenoidale and the sellar floor as seen via the endoscopic endonasal view. The removal is extended to the level of both medial opto-carotid recesses (16). Thereafter, the superior (or anterior) intercavernous sinus is identified and

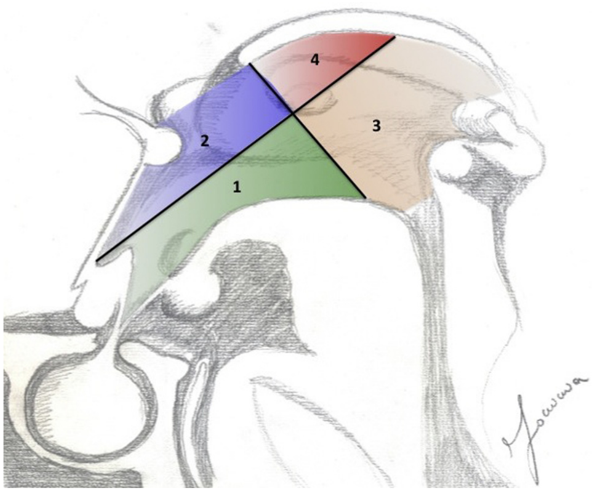

Figure 1. Artistic drawing showing a sagittal view of the third ventricle. The third ventricle has been divided into four areas by means of two ideal lines passing between the optic chiasm and the interthalamic commissure and between the posterior edge of the foramen of Monro and the interthalamic commissure, respectively. *1*: anterior-inferior (infundibular) area; *2*: anterior-superior (foraminal) area; *3*: posterior-inferior (mesencephalic) area; *4*: posterior-superior (tectal) area.

isolated, the dura over the planum is opened, and the sella and suprasellar neurovascular structures are exposed.

At this stage of the dissection, two surgical corridors (i.e., suprachiasmatic and subchiasmatic) can be identified to access the third ventricle (Figure 2). The subchiasmatic route allows the entrance into the third ventricle cavity via its floor, at the level of the tuber cinereum. On the other hand, the suprachiasmatic pathway permits access to the third ventricle via the lamina terminalis, just above the optic chiasm.

Transcranial Approaches

An endoscopic exploration of the third ventricle cavity was performed using a different transcranial approach (i.e., translamina terminalis, frontal transcortical, anterior transcallosal, and supracerebellar infratentorial) in order to show the same anatomical areas from different perspectives.

Translamina Terminalis Approach (Microscopic and Endoscopic-Assisted). The translamina terminalis approach, realized through a fronto-temporal craniotomy, allows a wide exposure of the anterior area of the third ventricle. The dural incision is made in the usual semicircular fashion, and the dural flap is reflected toward the orbit and sphenoid ridge. After sylvian fissure opening, the suprasellar area, along with all its neurovascular contents, comes into view, thus permitting the visualization of the lamina terminalis. The lamina terminalis is widely opened, and the third ventricle cavity is explored with either a 0- or 30-degree endoscope.

Endoscopic Transcortical Frontal Approach. The endoscopic transcortical frontal approach enables surgeons to access the third ventricle cavity via a single burr-hole. Once a 3-cm straight scalp incision has been made, a precoronal burr-hole is placed. After dura opening, the endoscope is inserted through the frontal lobe to reach the lateral ventricle. After identification of the main landmarks inside it (i.e., choroid plexus, fornix, thalamo-striate, and septal veins), the endoscope could be moved via the foramen of Monro into the third ventricle cavity.

Anterior Transcallosal Transchoroidal Approach (Microscopic and Endoscopic Assisted). The anterior transcallosal approach has been performed via a right frontal bone flap extending across the sagittal sinus and located two thirds in front and one third behind the coronal suture. Upon dural opening, the medial surface of the frontal lobe is detached from the falx to expose corpus callosum. This latter has been divided at the midline to enter the lateral ventricle. With the aid of the microscope, the third ventricle cavity is exposed after opening the choroidal fissure. The introduction of the endoscope through the foramen of Monro permits a wide exploration of the third ventricle chamber.

Endoscopic Supracerebellar Infratentorial Approach. The skin incision extends from 2 cm above the inion to the level of the foramen magnum. Sharp dissection of the muscles is run from the superior nuchal line down to the external occipital protuberance on both sides. The burr-hole is placed about 1–2 cm above the inion in the midline, and the craniotomy is performed. A Y-shaped dura incision is made, and microsurgical dissection above the cerebellum is performed, thereby permitting the access into the third ventricle via the suprapineal recess. The endoscope is then inserted to allow exposition of the third ventricle cavity via its posterior aspect.

RESULTS

Area 1: Infundibular Area

Endoscopic Endonasal View. After the dura mater is opened over the tuberculum sellae and the planum sphenoidale, the chiasmatic and the lamina terminalis cisterns with relative contents are accessible. In the chiasmatic cistern, the anterior margin of the optic chiasm and the medial portion of the optic nerves are clearly visible. Once the arachnoid of the lamina terminalis cistern is opened, both the A1 segments of the anterior cerebral arteries, anterior communicating artery, recurrent arteries of Heubner, and A2 segments and gyri recti of the frontal lobes are visible. At this stage of the dissection the infundibular area of the third ventricle

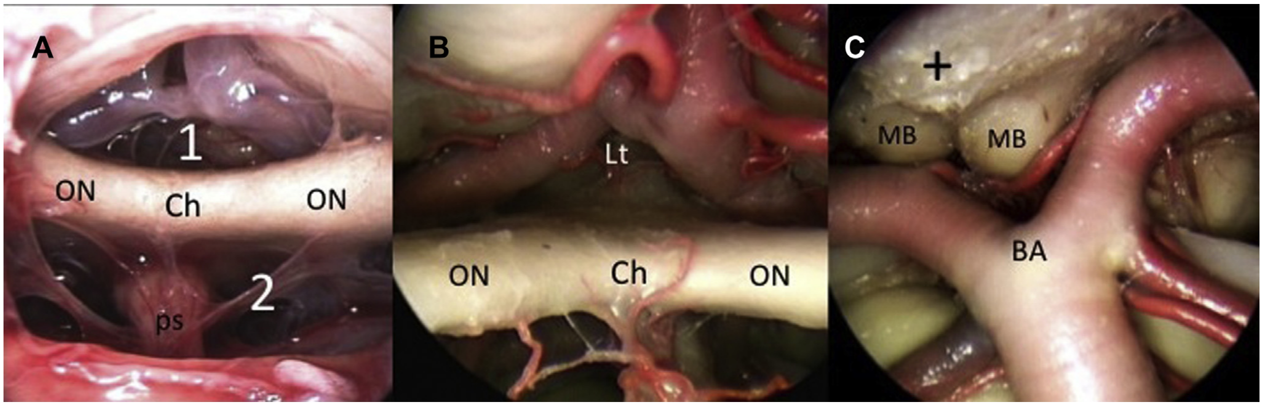

Figure 2. (**A**) Endoscopic endonasal view of the suprasellar area showing two surgical corridors that can be used to get inside the third ventricle. *1*: suprachiasmatic route; *2*: subchiasmatic route. (**B**) Close-up view of the suprachiasmatic pathway and (**C**) subchiasmatic pathway. ON, optic nerve; Ch, optic chiasm; ps, pituitary stalk; Lt, lamina terminalis; MB, mammillary body; BA, basilar artery; +, tuber cinereum.

can be reached through two corridors: suprachiasmatic and subchiasmatic.

Once the lamina terminalis has been opened, the infundibular area of the third ventricle is accessed via a suprachiasmatic route (Figure 3). The endoscopic inspection with a 0-degree endoscope allows one to visualize the thalami and the interthalamic commissure (the use of angled endoscopes permits a better view, especially of the foraminal area). The possibility of introducing the endoscope via this corridor is influenced by the position of the anterior cerebral-anterior communicating artery complex that could restrict the access to the lamina terminalis. Moreover, the surgical maneuverability through the lamina terminalis is highly affected by the position and orientation of the optic chiasm that, in many cases, need to be gently stretched downward during the endoscopic exploration of the third ventricle chamber.

On the other hand, the third ventricle cavity can be opened via a subchiasmatic pathway. When the endoscope is advanced below the optic chiasm, the superior surface of the pituitary gland and the dorsum sellae are well visualized. On the lateral aspects of the field, it is possible to recognize the internal carotid artery, its bifurcation, and the proximal A1 segment—the tract inferior to the optic chiasm. In this case the third ventricle is accessed through the tuber cinereum, which is localized on the floor of the third ventricle between the pituitary stalk and the mammillary bodies; accordingly, the endoscope is advanced in an inferior-superior trajectory inside the ventricular cavity, obtaining a wide panoramic view, not only over the infundibular area. The thalami and interthalamic commissure, foramen of Monro anteriorly, and bulging of mammillary bodies posteriorly can be seen. If the pituitary stalk is transected or the pituitary gland together with its stalk is transposed anteriorly (30), a wide view of the outer surface of the third ventricle floor can be obtained. The tuber cinereum, which appears to be surrounded by many perforators coming from the anterior and posterior cerebral circulation, can be entered in this part also with a surgical instrument. Angled endoscopes allow a further anterior exposure up to the column of the fornix and the chiasmatic prominence (Figure 4).

Transcranial View. After the lamina terminalis and its cistern are opened through a fronto-temporal approach, the anterior part of the third ventricle, above all the infundibulum, is exposed (Figure 5).

Using this approach, the foramen of Monro should be considered as a "blind zone" for the surgeon, unless an angled scope is used; definitely, this corridor does not grant any maneuverability. However, if the endoscope is inserted through the lamina terminalis, the infundibular area can be explored from the optic chiasm recess up to the interthalamic commissure posteriorly; the lateral wall of the inferior part of the third ventricle can be identified as well (Figure 6).

On the other hand, using an endoscopic transcortical frontal route, passing through the foramen of Monro, the infundibulum of the third ventricle, as well as its floor, from the mammillary bodies to the optic chiasm recess, can be unlocked (Figure 7).

With an anterior transcallosal approach, after the introduction of a 30-degree endoscope angled anteriorly, it is possible to visualize the infundibular area of the third ventricle (Figure 8C).

Area 2: Foraminal Area

Endoscopic Endonasal View. As for the infundibular area, the foraminal area can also be better exposed via a subchiasmatic route through the tuber cinereum. Advancing the endoscope inside the ventricular chamber, a panoramic view of the foraminal area is obtained. Angled endoscopes increase the view of the foraminal area.

The endoscopic endonasal exploration of the foraminal area permits to show the inner surface of the foramen of Monro (i.e., the portion that faces the third ventricle). As seen from this perspective, the body of the fornix is located on the middle of the field and continues upwards and laterally with its columns; on the other hand, the inferior-lateral surface of each foramen of Monro, as seen from below, is formed by the ipsilateral thalamus. The choroid plexus extends within each foramen of Monro, surrounding the body of the fornix like a collar before entering the lateral ventricle through the choroidal fissure. The anterior commissure is visualized anteriorly to the foramen of Monro.

Regarding surgical accessibility, it is noteworthy that the foramen of Monro can be reached only by passing through the tuber cinereum and using angled instruments (Figure 9). Moreover,

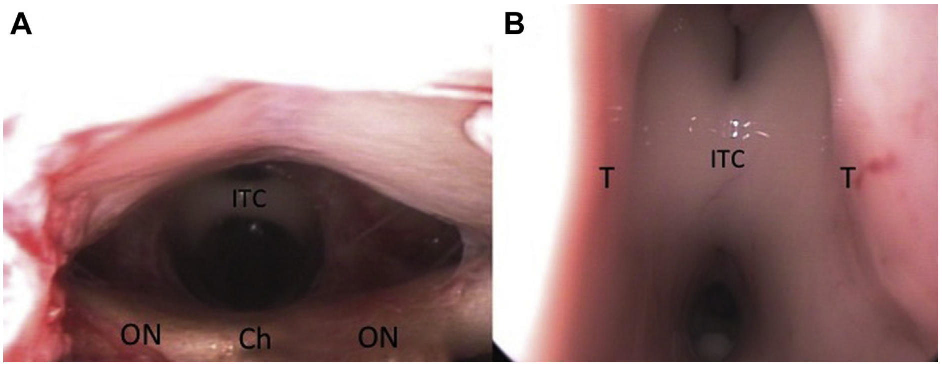

Figure 3. Endoscopic endonasal trans-lamina terminalis view (**A**) of the infundibular region of the third ventricle. (**B**) The endoscope is advanced inside the third ventricle cavity via the lamina terminalis. ITC, interthalamic commissure; ON, optic nerve; Ch, optic chiasm.

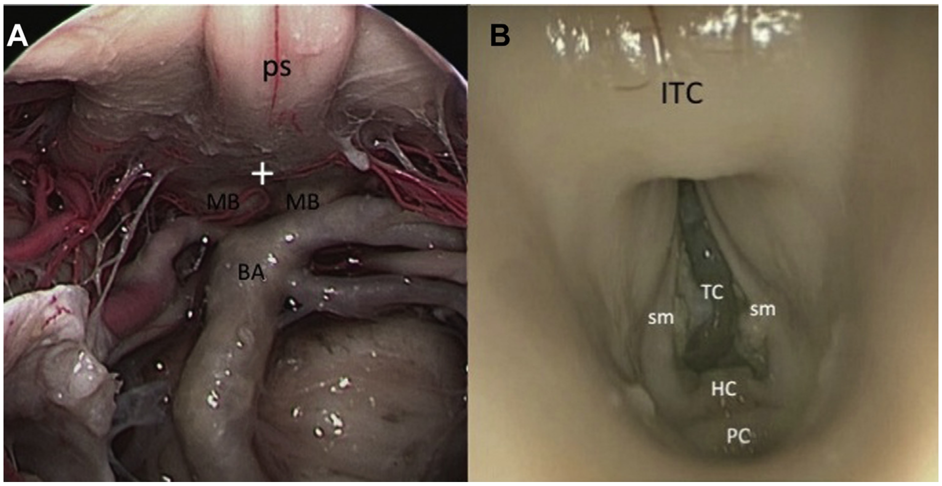

Figure 4. (**A**) Endoscopic endonasal transtuber cinereum approach to the infundibular region of the third ventricle; the pituitary gland with its stalk has been transposed anteriorly. (**B**) The endoscope is advanced inside the third ventricle cavity via the tuber cinereum. ps, pituitary stalk; BA, basilar artery; MB, mammillary bodies; +, tuber cinereum; HC, habenular commissure; sm, strie medullaris; PC, posterior commissure; TC, tela choroidea.

from this perspective the optic chiasm recess could be completely hidden.

Transcranial View. The common route to access the foraminal area is the endoscopic frontal transcortical approach, even if each foramen of Monro is visualized on its superior surface, which appears in the lateral ventricle, and not on the inferior surface, which appears inside the third ventricle. The anterior transcallosal approach, as well, provides a microscopic visualization of the foramen of Monro as seen from the lateral ventricle perspective (Figure 8B).

The supracerebellar-infratentorial approach provides limited access to the foramen of Monro, with a minimal surgical accessibility (Figure 10C).

Area 3: Mesencephalic Area

Endoscopic Endonasal View. The endoscopic exposure of posterior portions of the third ventricle on cadaver is more complex due to the natural collapse of the ventricular walls that determine a reduction of the space between the two thalami. Passing under the interthalamic commissure, the posterior portion of the third ventricle can be reached, so it is possible to visualize the pineal gland and suprapineal recesses, posterior commissure, habenular commissure, habenular trigona, and beginning of the cerebral aqueduct. The pineal gland and the internal cerebral veins lateral to the pineal gland can be seen as well (Figure 11). This area can be better visualized passing through the tuber cinereum than via the lamina

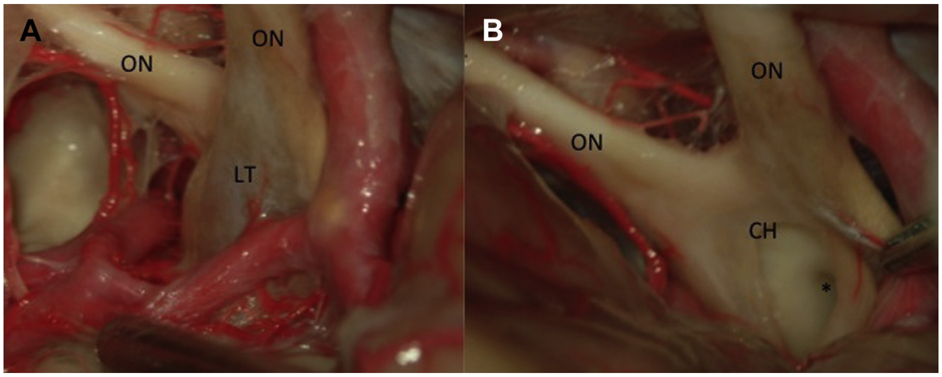

Figure 5. Microsurgical transcranial view (**A**) of the lamina terminalis. After the lamina terminalis has been opened (**B**), the infundibular area of the third ventricle came into view. Lt, lamina terminalis; ON, optic nerve; Ch, optic chiasm; *, infundibular region of the third ventricle.

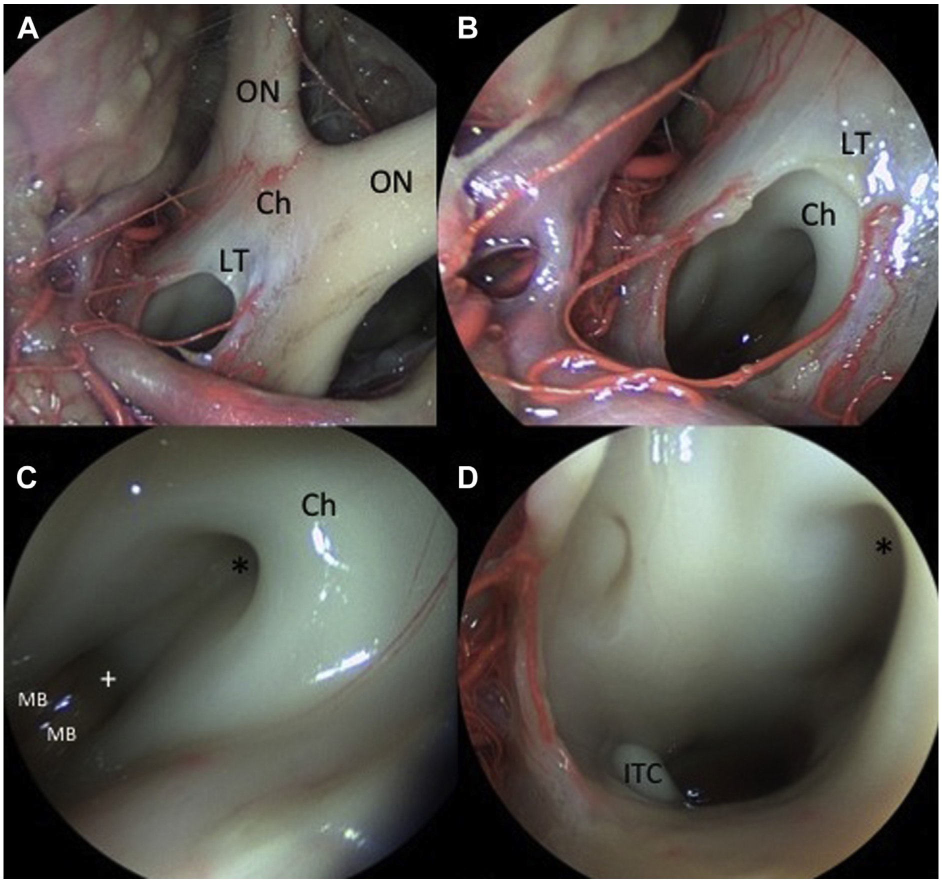

Figure 6. Endoscope-assisted translamina terminalis view (**A**–**D**) of the third ventricle cavity. Lt, lamina terminalis; ON, optic nerve; Ch, optic chiasm; *, infundibular recess; ITC, interthalamic commissure; MB, mammillary body; +, tuber cinereum.

terminalis; the surgical maneuverability can be limited, and the use of angle lenses does not seem to add any advantage.

Transcranial View. The anterior transcallosal approach provides the visualization of the posterior part of the floor of the third ventricle. If a 30-degree angled endoscope is inserted behind the interthalamic commissure pointing posteriorly, the posterior commissure, habenular commissure with striae medullaris, and tela choroidea can be seen, as well as the superior aspect of the cerebral aqueduct (Figure 12B).

The supracerebellar infratentorial approach allows the visualization of the posterior part of the third ventricle except of its floor (Figure 10A, B). On the other hand, with a neuroendoscopic frontal transcortical access, performed via a more anterior burrhole and with the aid of angled endoscopes, when entering the foramen of Monro and passing above the interthalamic commissure, it is possible to expose the posterior area of the floor of the third ventricle from the aqueduct to the suprapineal recess (Figure 13).

Area 4: Tectal Area

Endoscopic Endonasal View. The tectal area is not accessible through an endoscopic endonasal approach via a suprachiasmatic or subchiasmatic route.

Transcranial View. The posterior-superior part of the third ventricle (i.e., tectal area) can be exposed via the supracerebellar infratentorial approach. Once inside the third ventricle, the interthalamic commissure, column of the fornix, anterior commissure, protuberance formed by the optic chiasm, upper optic recess, and lamina terminalis are identified (Figure 14). On the other hand, using an anterior transcallosal approach the anterior portion of the tectal area must be passed through, namely via a transchoroidal pathway, to access the third ventricle cavity (see Figure 12A).

DISCUSSION

The third ventricle is considered a true surgical challenge because of the extreme complexity of anatomical structures and their relationships at the level of this deep-seated brain region.

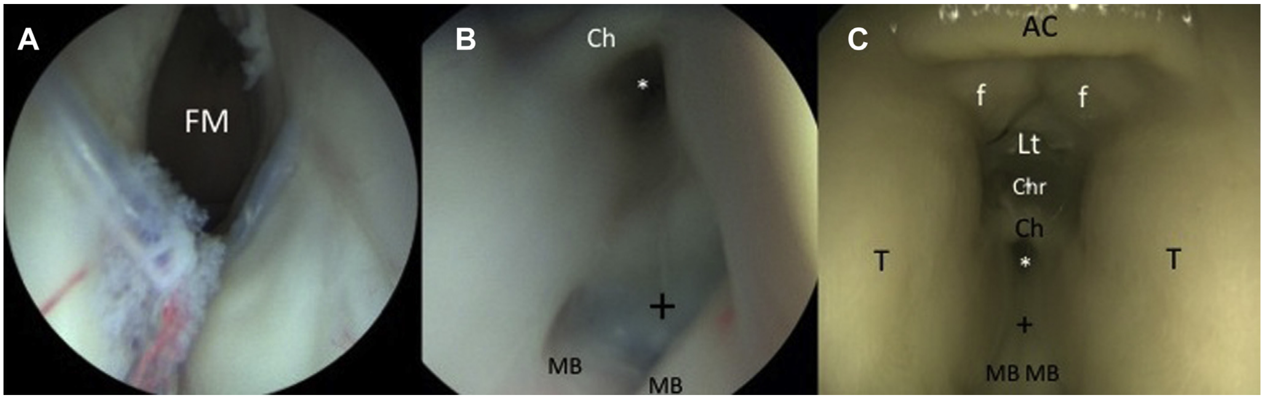

Figure 7. (**A**, **B**) Endoscopic transcortical frontal view of the third ventricle cavity. (**C**) Endoscopic view of the third ventricle infundibular area in a formalin-fixed cadaveric head, as seen passing the endoscope through the foramen of Monro. FM, foramen of Monro; MB, mammillary body; +, tuber cinereum; *, infundibular recess; Lt, lamina terminalis; Chr, optic chiasm recess; Ch, optic chiasm; f, column of fornix; T, thalamus; AC, anterior commissure.

Surgery on the third ventricle dates back to 1930, and Cushing and Dandy pioneered contributions. Dandy defined the basic concepts of the interhemispheric approach for a third ventricular tumor (10, 13).

The technological progress and refinement of microsurgical techniques have improved considerably over the years the outcomes of neurosurgical procedures for the management of lesions involving or arising from this region.

Indeed, different surgical corridors have been defined in order to access the third ventricle area with the aim of achieving effective tumor control, while respecting the surrounding critical structures, above all avoiding injuries to this complex anatomical environment.

The translamina terminalis (36, 37, 42), transcortical frontal (22, 40), anterior transcallosal (27, 43, 45, 46), and infratentorial-supracerebellar (3) are the most common microsurgical routes used to expose and remove lesions involving or arising from the third ventricle.

However, transcranial approaches may carry risks mainly related to brain retraction and manipulation of the vital structures along the surgical route (9, 41).

Although different surgical approaches can provide access to the third ventricle cavity, we adopted the routes that allowed us to explore with the aid of the endoscope the entire ventricular cavity. Our aim was not to compare effectiveness of any surgical approach but rather to compare the endoscopic view of the third

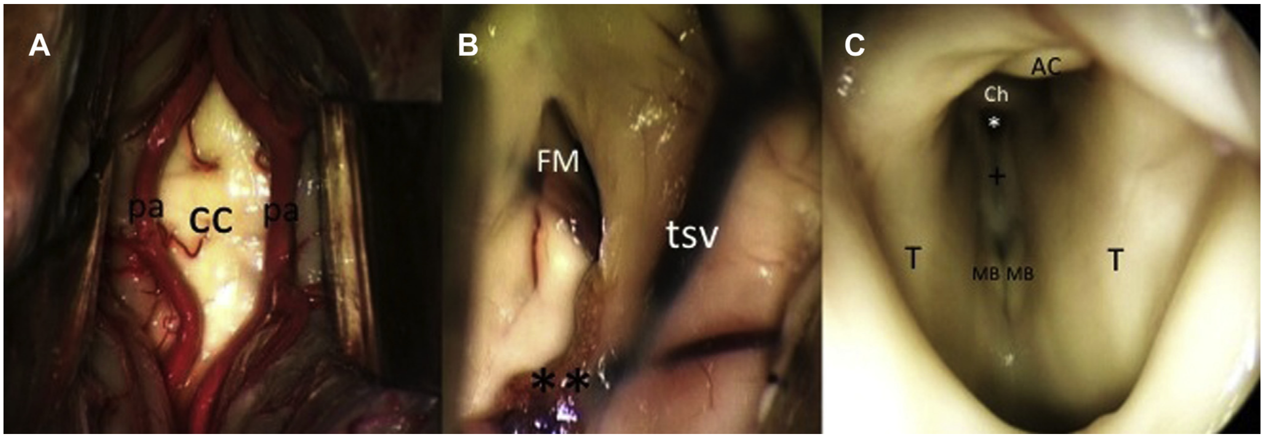

Figure 8. (**A**) Anterior transcallosal approach. (**B**) The foramen of Monro is clearly visualized. (**C**) The 30-degree endoscope is angled anteriorly up to visualize the anterior commissure. pa, pericallosal artery; CC, corpum callosum; FM, foramen of Monro; tsv, thalamostriate vein; MB, mammillary body; +, tuber cinereum; **, choroid plexus; *, infundibular recess; T, thalamus; AC, anterior commissure.

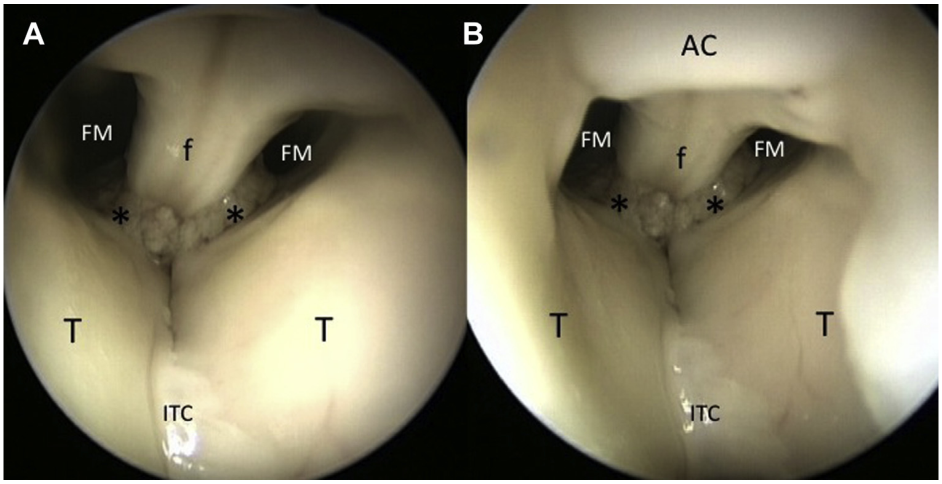

Figure 9. (**A**) Endoscopic endonasal view of the third ventricle foraminal area. (**B**) The endoscope is angled upward to visualize the anterior commissure. FM, foramen of Monro; MB, mammillary body; +, tuber cinereum; *, choroid plexus; ITC, interthalamic commissure; f, body of fornix; T, thalamus; AC, anterior commissure.

ventricle achieved from different, and somehow opposite, points of view.

During the past two decades, the endoscope has significantly contributed to the reduction of the invasiveness and morbidity of third ventricle surgery, mainly through the transforaminal approach, thus allowing the management of various diseases (9, 17, 20, 25, 38, 47).

At the same time, use of the endoscope has been gaining favor in transsphenoidal surgery and the so-called "pure" endoscopic endonasal approach, with the endoscope as the only visualization tool of the surgical field, is now adopted in many neurosurgical centers (4, 6, 21, 23, 28, 29, 31, 34).

The introduction of the endoscope in pituitary surgery has provided advantages for patients and surgeons, widening the possibilities of this approach from the sellar region (i.e., the infradiaphragmatic area) to different skull base regions surrounding the sellar area, via the so-called "extended" transsphenoidal approach.

Anatomical studies and surgical series of patients treated with these approaches have recently demonstrated the possibility of

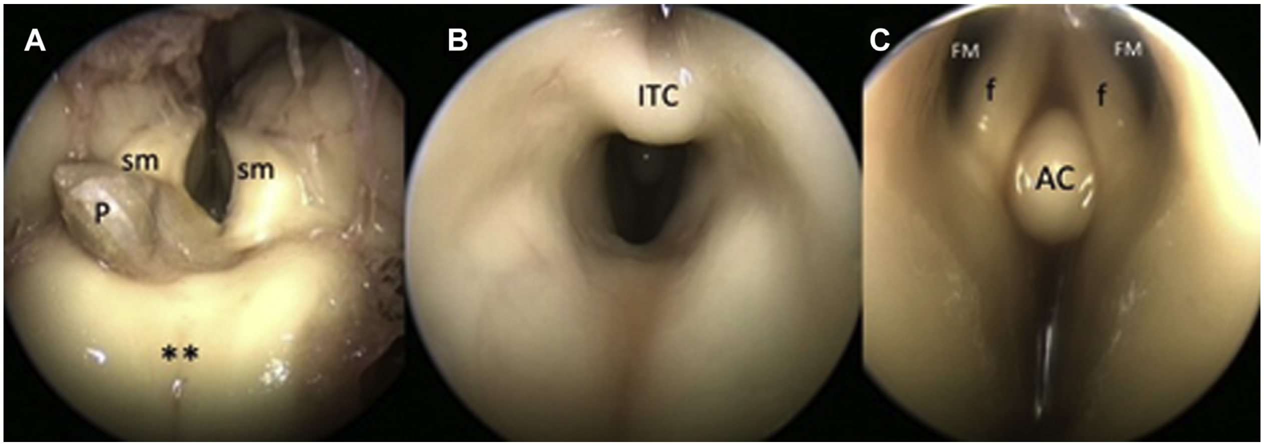

Figure 10. (**A**, **B**) Endoscopic supracerebellar infratentorial view of the third ventricle cavity. (**C**) The endoscope is advanced forward, behind the interthalamic commissure, in order to show the foraminal area of the third ventricle. p pineal gland; sm, striae medullaris; **, quadrigeminal lamina; ITC, interthalamic commissure; fm, foramen of Monro; f, columns of fornix; AC, anterior commissure.

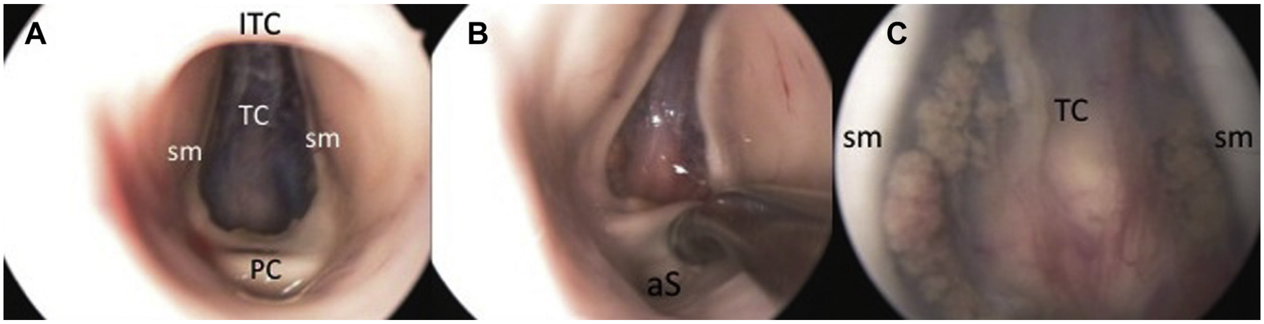

Figure 11. (**A**) Endoscopic endonasal exposure of posterior portions of the third ventricle. (**B**, **C**) The endoscope is advanced forward, behind the interthalamic commissure, in order to show the third ventricle mesencephalic area. sm, striae medullaris; ITC, interthalamic commissure; TC, tela choroidea; PC, posterior commissure; aS, aqueduct of Sylvius.

exploring the third ventricle cavity with the aid of the endoscope, especially in the case of certain craniopharyngiomas; nevertheless, none defined the real advantages and limitations of the use of this instrument inside the ventricle cavity (4, 5, 7, 21, 23, 28, 31, 34).

If on one side, upon normal anatomical conditions, entering the third ventricle through the sphenoid sinus leads requires manipulation of the pituitary-hypothalamic axis, it must be considered that, in a pathological contest, especially in the presence of craniopharyngiomas, the anatomy of the area can be subverted, thus creating conditions that make it easier to enter the third ventricle via this route.

Accordingly, the different growth patterns of tumors inside the third ventricle cavity may influence the surgical accessibility to its various areas.

Such objectives are the prerequisite for the present anatomical study, in which we carried out an analysis of different areas of the third ventricle cavity, exposed by means of the endoscopic endonasal approach, as compared with the microsocopic and endoscopic views of the same areas achieved through transcranial corridors.

Although the endoscopic endonasal approach offers the possibility to enter the third ventricle and eventually manage several lesions involving this area, cogent surgical considerations must be drawn. Differently from endoscopic transsphenoidal pituitary surgery, in which the subarachnoid space is usually not disrupted, the extended endoscopic endonasal approach, especially for craniopharyngiomas, requires opening the arachnoid layers in the suprasellar area and anterior wall of the third ventricle. A direct

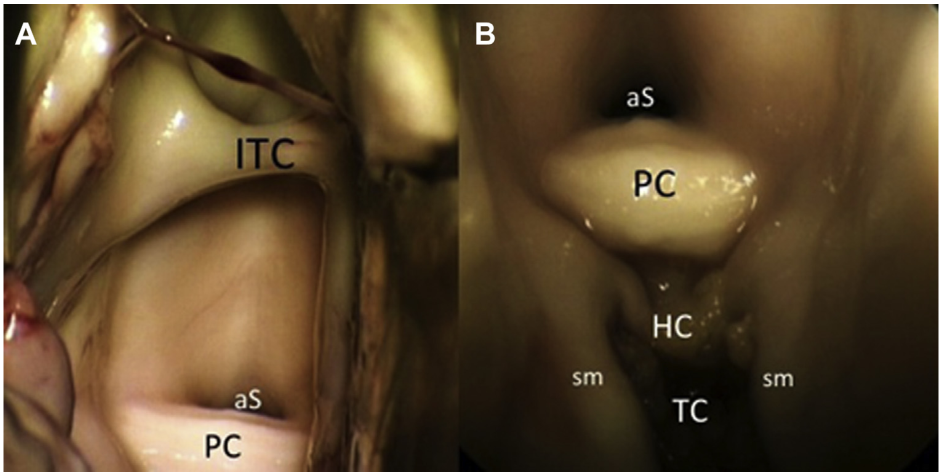

Figure 12. (**A**) Transcallosal microsurgical view of posterior portions of the third ventricle. (**B**) The endoscope is advanced and angled posteriorly in order to show the third ventricle mesencephalic area. ITC, interthalamic commissure; aS, aqueduct of Sylvius; PC, posterior commissure; sm, striae medullaris; HC, habenular commissure; TC, tela choroidea.

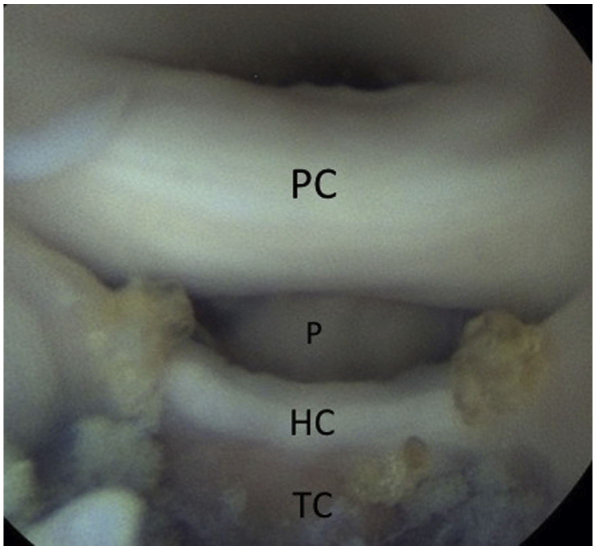

Figure 13. Neuroendoscopic frontal transcortical view of the third ventricle mesencephalic area. PC, posterior commissure; P, pineal gland; HC, habenular commissure; TC, tela chorioidea.

communication between the ventricular system and the sphenoid sinus is therefore created: An accurate multilayer reconstruction of the osteo-dural defect is mandatory in order to reduce the risk of postoperative cerebrospinal fluid (CSF) leak. An adequate barrier against CSF pulsation must be accomplished: We believe that aside from a peer multilayer osteodural reconstruction, the use of a vascularized naso-septal flap supported by a Foley balloon and positioning of lumbar drainage are useful.

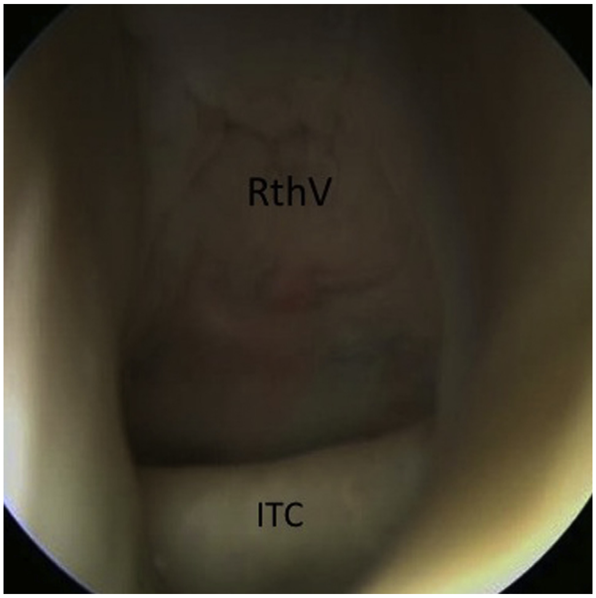

Figure 14. Endoscopic-assisted supracerebellar infratentorial view of the third ventricle tectal area. RthV, roof of the third ventricle (tectal area); ITC, interthalamic commissure.

According to our results, the endoscopic endonasal approach allows a clear and effective exposure of different areas of the third ventricle, especially the infundibular and the foraminal. The infundibular area can be explored passing through the lamina terminalis and, more frequently, through the tuber cinereum. This latter trajectory enables one to reach the foramen of Monro and the floor of the third ventricle up to the pineal recess. In the infundibular and foraminal areas the surgical maneuverability seems to be better as compared with that obtained inside the mesencephalic area. However, such maneuverability is closely related to the variability of the samples used for anatomical dissections (**Table 1**).

The results in terms of visualization and accessibility are consistent with the clinical experience with the management of infra- and retrochiasmatic craniopharyngiomas entering the third ventricle, thus creating a natural corridor to this region. Again, the growth of a lesion within the third ventricle cavity may modify its morphology and dimensions so that access could be easier than in an anatomical specimen.

One should consider when entering the ventricle that location of the neurovascular structures can affect entrance and exposure of the cavity: the position of the anterior communicating artery complex above the lamina terminalis can prevent the access inside the third ventricular cavity, regardless the surgical pathway. However, while during a transcranial approach it is possible to retract posteriorly the anterior communicating artery complex to expose the lamina terminalis, this maneuver is not feasible during an endonasal approach.

Furthermore, it must be highlighted that when approaching the third ventricle via an endonasal pathway, it is crucial to prevent damage to the blood supply of the optic chiasm coming from the branches of superior hypophyseal arteries. The superior hypophyseal arteries come from the supraclinoid internal carotid artery and occupy the lateral aspect of the endoscopic surgical field. They usually do not interfere with the surgical route to the third ventricle, especially when there is a midline tumor growing in the subchiasmatic area. On the other side, the degree of pneumatization of the sphenoid sinus, angle of the tuberculum sellae as seen via an endoscopic endonasal route (i.e., the suprasellar notch) (16), and position of the sella inside the sphenoid sinus can widen the subchiasmatic corridor, thus making favorable the access to the third ventricle via the tuber cinereum.

The endonasal access inside the third ventricle, via either tuber cinereum or lamina terminalis, may be encouraged in case of an optic chiasm that is prefixed or tilted vertically due to the presence of a retrochiasmatic tumor development.

Finally, the interthalamic commissure, which may be not present (almost 25% of cases) and is subject to considerable variations from the morphological point of view, can influence the exploration of the ventricular cavity. In fact, when this structure is thick, the exposition of the mesencephalic portion of the third ventricle using the endonasal corridor through the tuber cinereum could be troublesome (39).

Table 1. Suggested Approach to Each Area of the Third Ventricle Chamber

	Area 1: Infundibular	Area 2: Foraminal	Area 3: Mesencephalic	Area 4: Tectal
Extended endoscopic endonasal transsphenoidal approach to the planum sphenoidale	Best/suitable	Suitable	Suitable	Unsuitable
Translamina terminalis approach (microscopic and endoscopic assisted)	Best/suitable	Unsuitable	Suitable	Unsuitable
Endoscopic transcortical frontal approach	Suitable	Best/suitable	Suitable	Unsuitable
Anterior transcallosal transchoroidal approach (microscopic sand endoscopic assisted)	Suitable	Best/suitable	Suitable	Unsuitable
Endoscopic supracerebellar infratentorial approach	Unsuitable	Unsuitable	Best	Best

CONCLUSION

This anatomical study supports recent surgical experiences that afforded the possibility of entering the third ventricle by means of the endoscopic endonasal technique.

The comparison of approaches showed that the anterior parts of the third ventricle (i.e., the infundibular and foraminal areas) are better explored through the endoscopic endonasal route.

The lamina terminalis and, above all, the tuber cinereum represent two safe entry points defining possible surgical corridors to be considered for the extended endoscopic endonasal approach to the third ventricle. In particular, it must be considered that the tuber cinereum may usually be involved with a tumor, thus representing a natural corridor of access during endoscopic endonasal surgery.

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LABORATORY INVESTIGATION

Endoscopic transorbital superior eyelid approach: anatomical study from a neurosurgical perspective

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OBJECTIVE Recent studies have proposed the superior eyelid endoscopic transorbital approach as a new minimally invasive route to access orbital lesions, mostly in otolaryngology and maxillofacial surgeries. The authors undertook this anatomical study in order to contribute a neurosurgical perspective, exploring the anterior and middle cranial fossa areas through this purely endoscopic transorbital trajectory.

METHODS Anatomical dissections were performed in 10 human cadaveric heads (20 sides) using 0° and 30° endoscopes. A step-by-step description of the superior eyelid transorbital endoscopic route and surgically oriented classification are provided.

RESULTS The authors' cadaveric prosection of this approach defined 3 modular routes that could be combined. Two corridors using bone removal lateral to the superior and inferior orbital fissures exposed the middle and anterior cranial fossa (lateral orbital corridors to the anterior and middle cranial base) to unveil the temporal pole region, lateral wall of the cavernous sinus, middle cranial fossa floor, and frontobasal area (i.e., orbital and recti gyri of the frontal lobe). Combined, these 2 corridors exposed the lateral aspect of the lesser sphenoid wing with the Sylvian region (combined lateral orbital corridor to the anterior and middle cranial fossa, with lesser sphenoid wing removal). The medial corridor, with extension of bone removal medially to the superior and inferior orbital fissure, afforded exposure of the opticocarotid area (medial orbital corridor to the opticocarotid area).

CONCLUSIONS Along with its minimally invasive nature, the superior eyelid transorbital approach allows good visualization and manipulation of anatomical structures mainly located in the anterior and middle cranial fossae (i.e., lateral to the superior and inferior orbital fissures). The visualization and management of the opticocarotid region medial to the superior orbital fissure are more complex. Further studies are needed to prove clinical applications of this relatively novel surgical pathway.

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KEY WORDS endoscopic keyhole; transorbital; eyelid approach; anatomy; surgical technique

The evolution of minimally invasive skull base approaches has accelerated dramatically as a result of refinement of microsurgical techniques and improvements in instrumentation, imaging, and surgical image guidance systems. Endoscopic endonasal techniques have served recently as a foundation and platform for the development of new strategies and the refinement of existing ones.[39] For example, some midline ventral lesions of the anterior cranial fossa are now managed via the endoscopic endonasal route. In contrast, gold-standard open transcranial procedures, which generally achieve adequate surgical exposure for anterior and middle fossa patholo-

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ABBREVIATIONS TONES = transorbital neuroendoscopic surgery.

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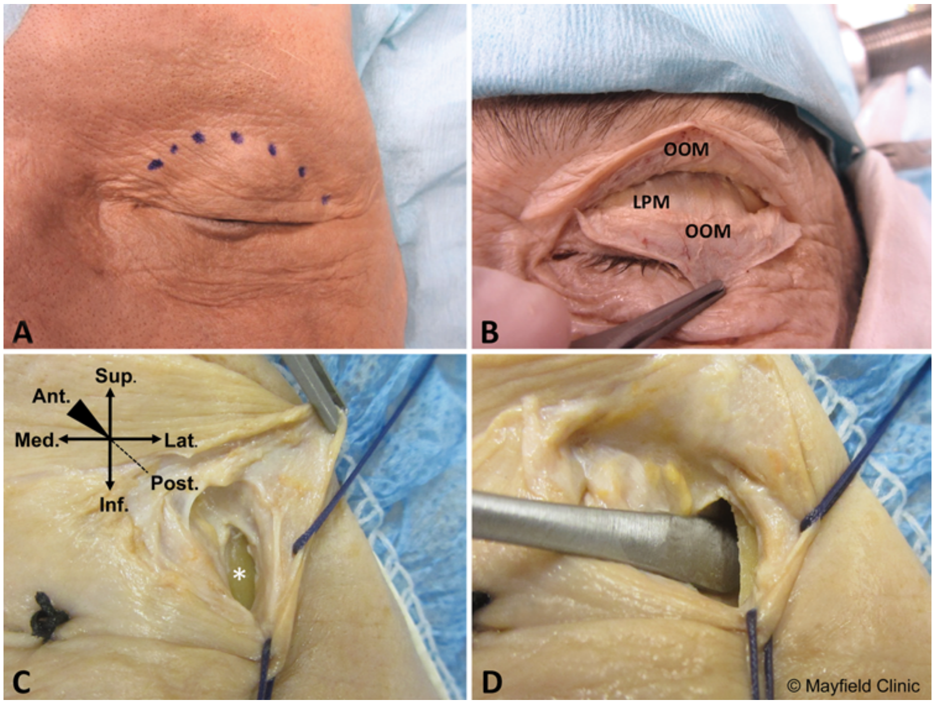

FIG. 1. Stepwise dissection of the superior eyelid endoscopic transorbital approach (left side). The head is slightly rotated to the contralateral side. After positioning, tarsorrhaphy is performed, and a skin incision is made in the crease of the superior eyelid (**A**, *dotted line*). The orbicularis oculi muscle (OOM) is separated in line with its fibers (**B**) to reach the frontal process of the zygoma, laterally (**C**). The periosteum covering the zygoma is cut and dissected sharply toward the orbit where it becomes continuous with the periorbita (**D**). The *asterisk* (*) indicates the frontal process of the zygoma. Ant. = anterior; Inf. = inferior; Lat. = lateral; LPM = levator palpebrae muscle aponeurosis; Med. = medial; Post = posterior; Sup. = superior. Printed with permission from Mayfield Clinic.

gies, can be associated with cosmetic and functional complications caused by the brain retraction needed to expose the skull base surface.[7,11,20,26,36,38,46,47]

Compared with open techniques, endoscopic and endoscope-assisted approaches can significantly reduce morbidity and achieve comparable outcomes in selected patients.[4,22,25,31] In this context of endoscopic access, a potential alternative gateway to the skull base is the orbit. Indeed, a new group of surgical techniques that access the orbit and intracranial space has been recently referred to as transorbital neuroendoscopic surgery (TONES).[35] One TONES corridor, the superior eyelid route, has proven to be clinically feasible as a route to selected anterior and middle skull base pathologies.[6,32,35,39,40] However, the applicability and potential neurosurgical role of each transorbital corridor are not yet defined.

To this end, we provide a step-by-step cadaveric prosection using the superior eyelid endoscopic transorbital route and qualitatively assess its feasibility for selected skull base pathologies. We propose a surgically oriented classification based on extradural and intradural structures that can be exposed through these avenues. Specifically, our classification applies the most recent clinical applications of this minimally invasive pathway.

Methods

Ten adult cadaveric specimens (20 sides), without known intracerebral abnormality, were embalmed and injected with colored silicon rubber (Dow Corning) via the internal carotid arteries, vertebral arteries, and internal jugular veins. Before and after dissection, CT scans of the heads were performed, using 0.65-mm cuts.

Anatomical Dissections

Anatomical dissections were performed at the University of Cincinnati Goodyear Microsurgery Laboratory and Laboratory of Surgical Neuroanatomy of the University of Barcelona (Spain). Dissections started macroscopically and then continued endoscopically. Endoscopic dissections were performed using a rigid 4-mm-diameter endoscope, 14 cm in length, with 0° and 30° rod lenses (Stryker) that were connected to a light source through a fiber optic canal and a video camera, which was connected to a video monitor; images were captured using a high-definition digital video system (Stryker). Specimens were positioned supine, pinned, and fixed in a Mayfield head holder, rotated 5° laterally to the contralateral side (Fig. 1). A skin incision was placed in the superior eyelid crease, above the tarsal plate. A high-speed drill was used for bone removal.

After the orbicularis oculi muscle was opened in line with its fibers, dissection was performed in a superolateral direction up to the zygoma and frontozygomatic suture laterally. The periosteum was cut and dissected sharply

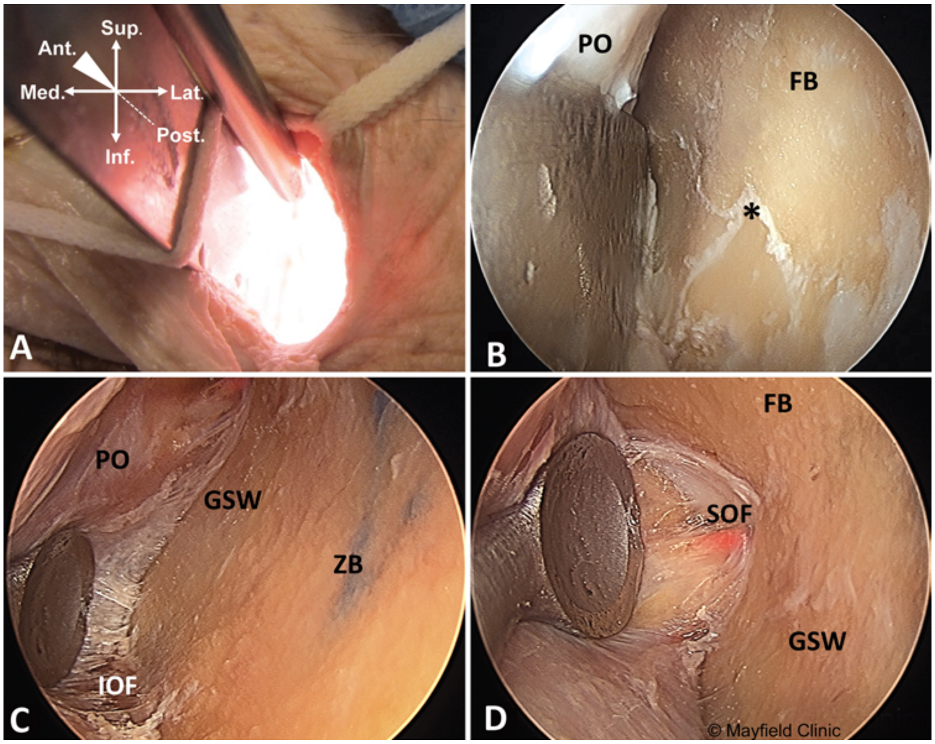

FIG. 2. Endoscopic transorbital access via the superior eyelid (left side). With the endoscope introduced in the upper portion of the orbit (**A**), subperiorbital dissection is performed following the frontozygomatic and frontosphenoidal sutures (**B**) until reaching the lateral end of the inferior (**C**) and superior orbital fissures (**D**). The *asterisk* (*) indicates the frontozygomatic and frontosphenoidal sutures. FB = frontal bone; GSW = greater sphenoid wing; IOF = inferior orbital fissure; PO = periorbita; SOF = superior orbital fissure; ZB = zygomatic bone. Printed with permission from Mayfield Clinic.

toward the orbit, where it becomes continuous with the periorbita. Using a No. 1 Penfield dissector, the surgeon followed the periosteum/periorbita plane within the orbit. Dissection proceeded along this plane until the lateral aspects of the inferior and superior orbital fissures were reached; this represented the limit to medial orbital content mobilization. Of note, near the superior orbital fissure, the cranio-orbital foramen (i.e., Hirtl's foramen) can be found; it usually accommodates the recurrent meningeal artery or the meningolacrimal branch (this vessel can pass even through the superior orbital fissure).[2,21] Placement of a malleable retractor separated the orbital contents medially from the posterolateral wall of the orbit, creating room for further dissection. The endoscope was then introduced in the upper portion of the surgical field to monitor the subsequent steps (Fig. 2).

In characterizing the exposure of intracranial neurovascular structures afforded by this purely endoscopic window, we defined a surgically oriented classification of the intracranial corridors that can be reached via this path—3 discrete corridors and 1 combined one (Fig. 3). This classification was based primarily on the position of the superior and inferior orbital fissures because they represent the early key anatomical and surgical landmarks of this route. Accordingly, the corridors were defined as follows: 1) lateral corridor to the middle cranial fossa; 2) lateral corridor to the anterior cranial fossa; 3) combined lateral corridor to the anterior and middle cranial fossa, with lesser sphenoid wing removal; and 4) medial corridor to the opticocarotid region.

Medial mobilization of the orbital contents, usually obtained during this kind of surgery, consisted of performing the lateral approaches to the anterior and middle cranial fossae (2 simple and 1 combined). Moreover, the removal of the most medial part of the lesser sphenoid wing, obtained after inferomedial mobilization of the orbital contents, provided additional surgical exposure with further exposition up to the opticocarotid region (Fig. 4).[19]

Quantitative Statistical Analysis and 3D Reconstruction

Following a complete transorbital approach, the area of exposure obtained for each region was calculated using the Brainlab cranial navigation system. For each of the 4 areas, 4 points were defined to represent the limits of bone removal.

For the middle fossa region, points included p1, maximal medial and lower extension toward the middle cranial base; p2, maximal lateral and lower extension toward the middle cranial base; p3, the superolateral edge of the superior orbital fissure; and p4, maximal lateral extension along the lesser sphenoid wing. For the anterior cranial fossa region, points included p1, maximal medial and higher extension toward the anterior cranial base; p2, maximal lateral and higher extension toward the anterior

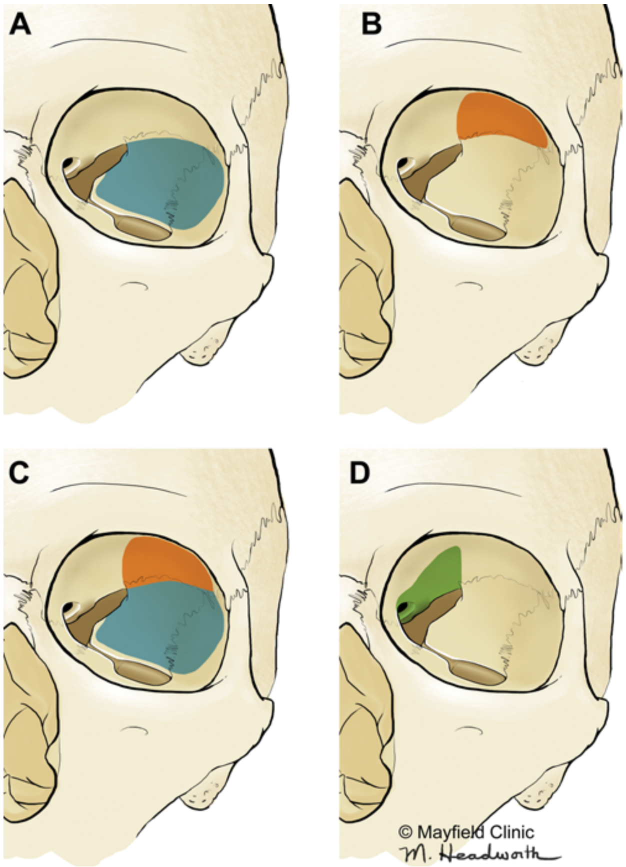

FIG. 3. Drawings (coronal view) of the left orbit showing 3 lateral corridors—2 simple (**A and B**) and 1 combined (**C**)—and 1 medial corridor (**D**). Lateral approaches allow visualization of the anterior and middle cranial fossae; the medial corridor allows visualization of the opticocarotid region. Printed with permission from Mayfield Clinic.

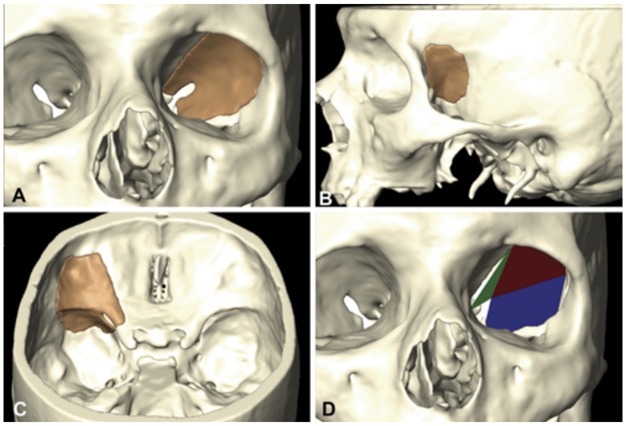

FIG. 4. A–C: 3D CT reconstructions showing bone removal via the endoscopic superior eyelid transorbital approach in coronal (A), sagittal (B), and axial (C) perspectives. **D:** 3D CT reconstruction showing the lateral and medial transorbital corridors. *Blue* indicates the middle fossa approach, *red* the anterior cranial fossa approach, and *green* the opticocarotid region. Figure prepared by the Laboratory of Surgical Neuroanatomy, University of Barcelona.

cranial base; p3, corresponding to the superolateral edge of the superior orbital fissure; and p4, maximal lateral extension along the lesser sphenoid wing. The combined areas were calculated as the sum of anterior and middle fossa area exposures. The opticocarotid area was defined by merging these 3 points: p1, the midportion of the optic canal; p2, superolateral edge of the superior orbital fissure; and p3, maximal medial and higher extension toward the anterior cranial base.

Cartesian coordinates of each point, obtained from the Brainlab workstation, yielded 3 vectors that were used to delineate 2 juxtaposed triangles. Areas of exposure were then calculated as the sum of the area of these 2 triangles; the opticocarotid area was represented by only 1 triangle.

A virtual 3D model of each area of exposure (Figs. 4 and 5) was created using Amira Visage Imaging software for visualization and manipulation of biomedical data. After bony structures were segmented from DICOM images using a semiautomatic threshold-based process, a smoothing feature was applied to further improve the rendering of the bony surfaces. The 3D reconstruction of the brain was obtained from a sample MRI study (Fig. 5).

All data were uploaded into Microsoft Excel, and an unpaired Student t-test was used to calculate statistical differences among the 4 modular approaches. A p value < 0.01 was considered significant.

Results

In this step-by-step cadaveric prosection using the superior eyelid endoscopic transorbital route, our surgically oriented classifications defined 4 corridors based on the exposures of extradural and intradural structures (Table 1, Fig. 6). Our schematic classification defined the corresponding anatomical structures exposed, thus establishing possible surgical indications for each of these surgical modules and their eventual possible combinations. Consequently, 2 straightforward lateral corridors accessed the middle and anterior cranial fossae, respectively; a combined lateral corridor accessed both fossae by removal of the lesser sphenoid wing; and a medial corridor reached the opticocarotid region. Potential surgical indications for the superior eyelid endoscopic transorbital approach are summarized in Table 2.

Lateral Orbital Corridor to the Middle Cranial Fossa

The craniectomy, which was initially performed through the body of the zygoma to access the temporal fossa, was necessary to create adequate working room. The zygomatic body was drilled endo-orbitally without the necessity of removing the zygomatic arch, thus avoiding any cosmetic defect. Subsequently, the ventral and vertical portion of the greater sphenoid wing was drilled until the dura mater was exposed. This approach to the middle cranial fossa was bounded superomedially by the upper and lateral portion of the superior orbital fissure and the lateral part of the lesser sphenoid wing; laterally by the previously exposed periosteal surface of the temporalis muscle; inferomedially by the inferior orbital fissure; and inferiorly by the floor of the middle fossa.

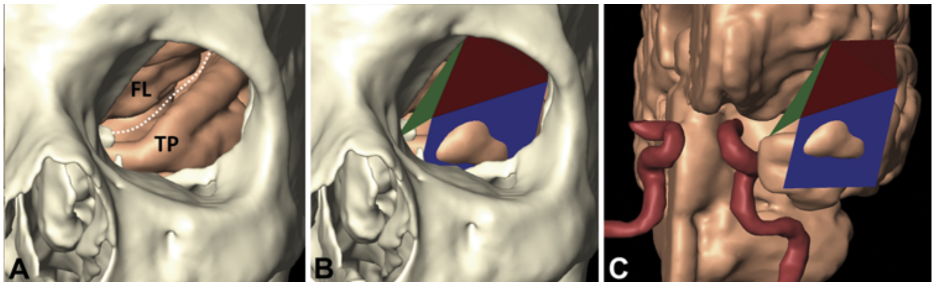

FIG. 5. 3D reconstructions obtained by merging the postdissection CT scan with a sample MR-based 3D reconstruction of the brain (made at the Laboratory of Surgical Neuroanatomy, University of Barcelona). **A:** Exposure of the temporal and frontal lobes seen via the transorbital route. The *white dotted line* indicates the Sylvian cistern. **B and C:** Lateral and medial areas with (B) and without (C) 3D reconstruction of bone removal. FL = frontal lobe; TP = temporal pole. Figure prepared by the Laboratory of Surgical Neuroanatomy, University of Barcelona.

Once the dura was exposed, an extradural dissection was performed in both lateral and inferior directions (Fig. 7). The inferior extradural dissection (i.e., toward the middle cranial fossa floor) was helpful in discovering the course of the middle meningeal artery as it emerged from the foramen spinosum. Moreover, medial extradural dissection was performed between the periorbita and the temporal pole. In this case, a complete extra/interdural visualization of the entire lateral wall of the cavernous sinus was achieved via the meningo-orbital band (Fig. 8).[14] Subsequently, the dura mater was opened, exposing the temporal pole. The arterial and venous structures in this region can be closely seen at the center of the surgical field (Fig. 9).

Lateral Orbital Corridor to the Anterior Cranial Fossa

The craniectomy involved drilling the lateral basal frontal bone, corresponding to the orbital roof. The greater wing of the sphenoid can be left intact, whereas removal of the zygoma body must be adequate to gain appropriate space for dissection. The boundaries of this approach were delineated as follows: inferiorly, the lesser sphenoid wing; laterally, the pterion point as seen from the transorbital perspective; medially, the superior orbital fissure (i.e., its lateral aspect; medially and superiorly, the limit depended on the surgical target because it can potentially extend up to the posterior ethmoidal artery medially); and the orbital rim, superiorly.

After the craniectomy, extradural dissection allowed for exposure of the frontolateral convexity. Upon dural opening, the lateral and basal frontal lobe came into view. This portion of the frontal lobe corresponded to the orbital gyri, an irregular group of convolutions of the orbital surface. The orbital gyri were divided by the roughly H-shaped orbital sulcus into the anterior, medial, posterior, and lateral orbital groups; from this perspective, the orbital sulcus can be well appreciated (Fig. 10). The anterior cranial fossa was also unlocked in its most medial portion. Accordingly, the frontal bone over this region, corresponding to the cribriform plate, was removed and an extradural exploration performed. Subsequently, the dura was opened to access the most medial portion of the basal frontal lobe, which in this case was represented by the gyrus rectus. Visualization of the frontomedial area with the aid of a 30° endoscope allowed visualization of the olfactory nerve, just above the optic nerve, and the falx cerebri at the midline (Fig. 11).

Combined Lateral Orbital Corridor to the Anterior and Middle Cranial Fossae, With Lesser Sphenoid Wing Removal

The most lateral aspect of the lesser sphenoid wings lay in between the anterior and middle cranial fossae. Accordingly, the bone removal was extended so that this portion of the lesser sphenoid wing was totally removed extradurally, with the possibility for the resection to extend later-

TABLE 1. Extradural and intradural structures that can be exposed through different lateral and medial orbital corridors

	Structures	
Corridor	Extradural	Intradural
Lateral corridor to MCF	Temporalis muscle, pterion region, temporal pole dura, recurrent meningeal artery, MMA, lateral wall of cavernous sinus, middle cranial fossa floor	Temporal pole, MCF floor
Lateral corridor to ACF	Frontolateral basal dura, frontomedial basal dura	Orbital gyri, gyri recti, olfactory nerve, falx cerebri
Combined lateral corridor to ACF & MCF	Lesser sphenoid wing, pterion region	Sylvian fissure, MCA & its branches
Medial corridor to OCR	Posterior ethmoidal artery, anterior clinoid process, optic nerve	Optic nerve, optic chiasm, ICA, oculomotor nerve, pituitary stalk

ACF = anterior cranial fossa; ICA = internal carotid artery; MCA = middle cerebral artery; MCF = middle cranial fossa; MMA = middle meningeal artery; OCR = opticocarotid region.

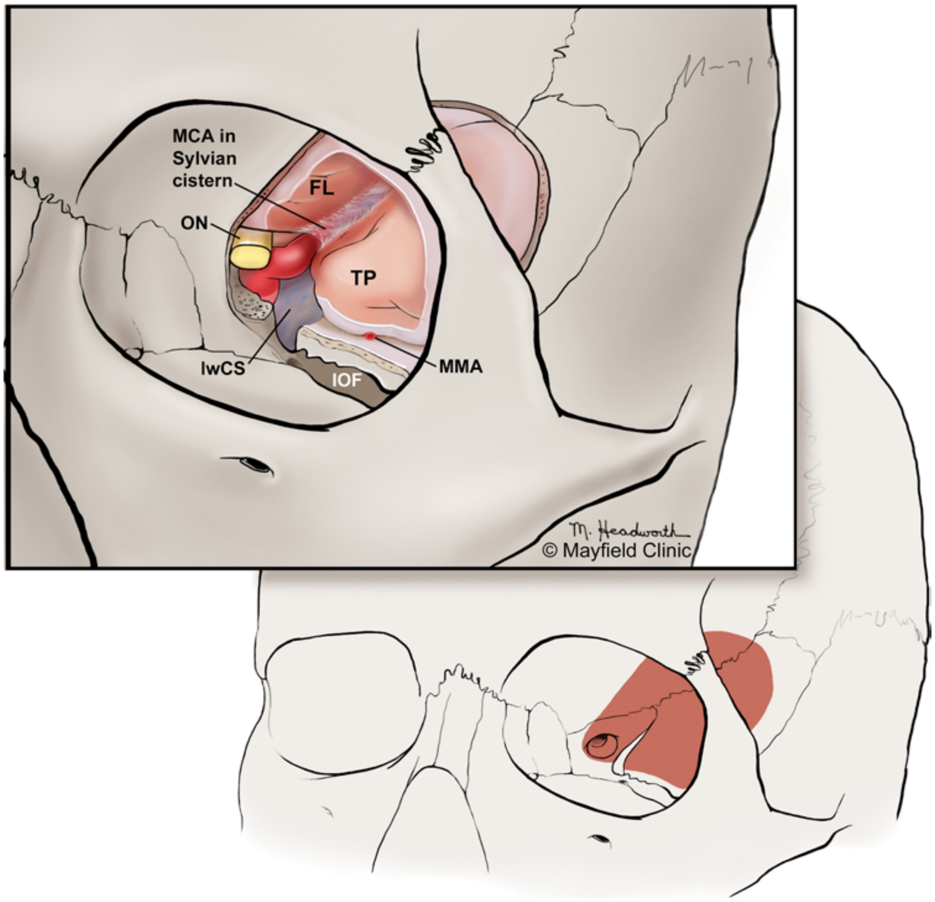

FIG. 6. Artistic illustration depicting the main neurovascular structures seen via the transorbital window. lwCS = lateral wall of the cavernous sinus; MCA = middle cerebral artery; MMA = middle meningeal artery; ON = optic nerve. Printed with permission from Mayfield Clinic.

ally up to the pterion. In fact, this procedure allowed good visualization of the pterional area as seen from inside the orbit: a visualization totally different and opposite from standard transcranial procedures (e.g., pterional route). After dural opening, the most anterior portion of the sylvian fissure, with its cistern, was visualized. The middle cerebral artery and its branches were exposed using sharp dissection (Fig. 12).

TABLE 2. Potential indications for the transorbital approach, based on each area

	Indication			
Approach	Primary Brain Tumors	Primary Bone Diseases	Vascular Diseases	Other
Middle cranial base	Selected spheno-orbital meningiomas, lesions at lateral wall of cavernous sinus, biopsy for temporal pole gliomas	Osteoma, Paget, Crouzon, fibrous dysplasia	AVMs or other vascular anomalies at temporal pole, vascular anomalies at lateral wall of cavernous sinus (cavernous hemangioma)	Amygdalohippocampectomy, other functional neurosurgical procedures
Anterior cranial base	Selected spheno-orbital meningioma, biopsy for fronto-basal gliomas	Osteoma, Paget, Crouzon, fibrous dysplasia	AVMs or other vascular anomalies at lateral frontobasal lobe	Functional neurosurgical procedures
Combined anterior & middle fossa	Selected spheno-orbital meningiomas	Osteoma, Paget, Crouzon, fibrous dysplasia	MCA aneurysms	Complex CSF leaks, meningoencephalocele
Opticocarotid region	Optic nerve sheath meningiomas, optic nerve biopsy	Osteoma, Paget, Crouzon, fibrous dysplasia		Foreign body or fracture at lateral side of optic canal

AVM = arteriovenous malformation; DBS = deep brain stimulation.

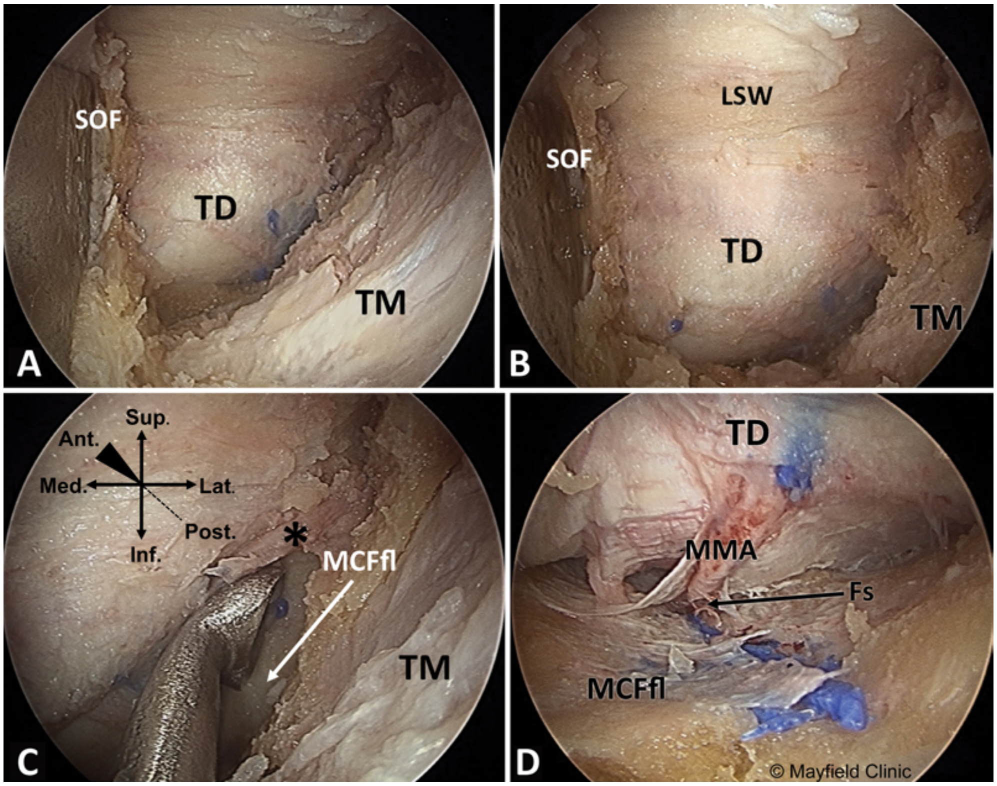

FIG. 7. Lateral orbital corridor to the middle cranial fossa. Body of the zygoma and greater sphenoid wing drilled up to the lateral end of the superior orbital fissure. The temporalis fossa, containing the temporalis muscle covered by its fascia, is first unlocked to gain room (**A**). The dura mater of the middle cranial fossa (MCF) is exposed (**B**). Dissection can proceed laterally and inferiorly in an extradural fashion; thus the most lateral part of the MCF can be exposed near the pterion point. With use of this pathway in an inferior direction, the entire MCF floor (MCFfl) can be evaluated (**C**) while the middle meningeal artery (MMA) can be followed, entering into the foramen spinosum (Fs) (**D**). The *asterisk* (*) indicates the recurrent meningeal artery. LSW = lesser sphenoid wing; TD = temporal pole dura; TM = temporal muscle, covered by its fascia. Printed with permission from Mayfield Clinic.

Medial Orbital Corridor to the Opticocarotid Area

The dissection described above was continued in a medial direction up to the most medial portion of the lesser sphenoid wing. The opticocarotid region can be reached by extending the bone removal superiorly and medially to the superior orbital fissure—that is, after mobilization of the orbital contents inferomedially. This area was limited by the superior orbital fissure laterally, the posterior ethmoidal artery medially, the floor of the optic canal and the optic strut inferiorly, and the frontosphenoidal suture superiorly. The posterior ethmoidal artery should be cut to facilitate mobilization of the orbital contents and thus better expose this region. With the optic canal opened in its superior and lateral part, the optic nerve was followed in its intracranial segment where it joined the contralateral optic nerve to form the optic chiasm. Intracranial exploration of this area allowed visualization of the opticocarotid region from a ventral perspective, including the internal carotid artery bifurcation, opticocarotid cistern, and the third cranial nerve.

With the aid of a 30° endoscope and after opening of the opticocarotid cistern, the pituitary stalk, surrounded by the diaphragma sellae, was appreciated in the subchiasmatic space (Fig. 13). Of note, although this area was reached in anatomical specimens, its surgical exposure may be difficult in the clinical setting, unless there is a specific space-occupying lesion.

Quantitative Analysis

In quantifying the extent of bone removal for each area, we found the middle and anterior fossa approaches achieved a greater amount of bone removal than the opticocarotid region approach (Table 3, Figs. 4 and 5). When compared with the middle fossa and opticocarotid region approaches, the anterior cranial base approach yielded greater bone removal. Obviously, the combined approach achieved the greatest bone removal. Statistical significance, calculated with an unpaired Student t-test, was defined as $p < 0.01$. However, the t-value was quite low, and the difference in bone removal between anterior cranial base and middle fossa approaches was small (Table 3, Fig. 14).

Discussion

As the new group of transorbital neuroendoscopic surgery procedures (TONES) emerged, the superior eyelid route represented a clinically feasible corridor to selected anterior and middle skull base pathologies. With the

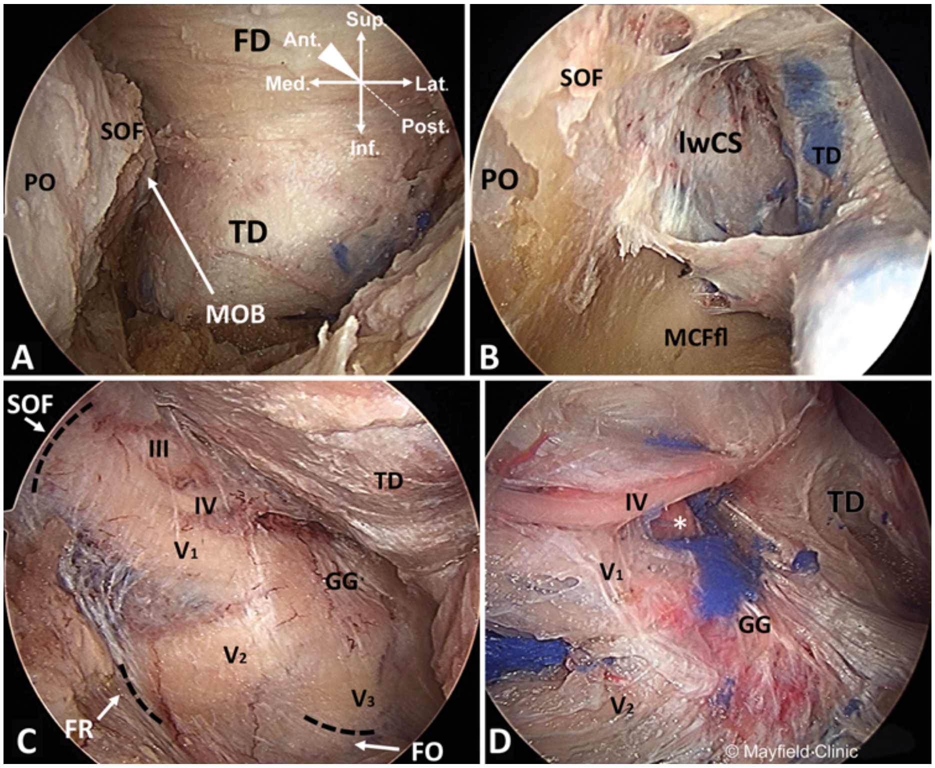

FIG. 8. Extradural medial exposure of the periorbita–temporal pole interface (**A**). Dissection between the periorbita and temporal pole, inferior to the superior orbital fissure (i.e., at the level of the meningo-orbital band) (**B**). Lateral wall of the cavernous sinus (**C**) and intracavernous carotid artery (*) (**D**) exposed. FO = foramen ovale; FR = foramen rotundum; GG = gasserian ganglion; MCFfl = middle cranial fossa floor; MOB = meningo-orbital band; III = CN III (oculomotor nerve); IV = CN IV (trochlear nerve); V1 = ophthalmic branch of CN V (trigeminal nerve); V2 = maxillary branch of CN V; V3 = mandibular branch of CN V. Printed with permission from Mayfield Clinic.

applicability and potential neurosurgical role of various transorbital corridors yet to be established, our cadaveric prosection defined, in a stepwise fashion, 3 modular routes and qualitatively assessed their feasibility for selected skull base pathologies. As a result, our proposed classifications are surgically oriented based on the extradural and intradural structures exposed through this avenue and based on the most recent clinical applications of this minimally invasive pathway. The superior eyelid endoscopic transorbital approach can yield good visualization of the

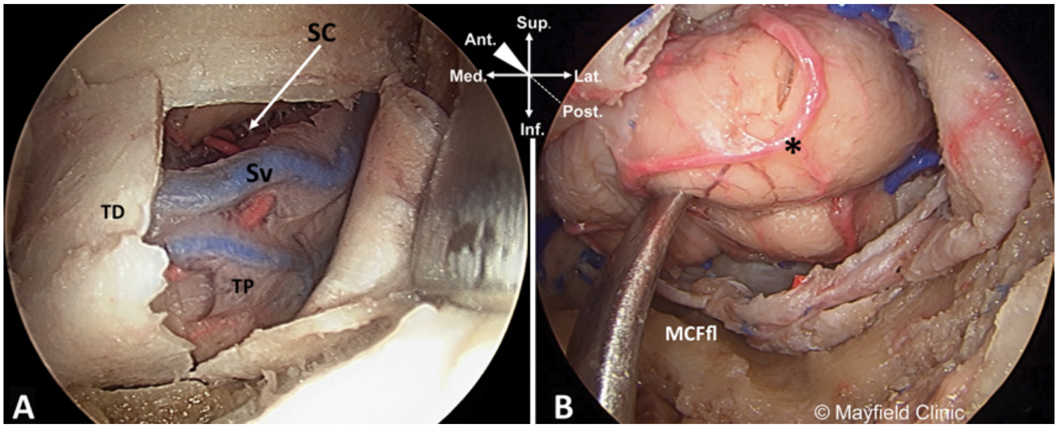

FIG. 9. Intradural exploration of the middle cranial fossa. After dura opening, temporal pole came into view. The *asterisk* (*) indicates the temporal cortical branches of the middle cerebral artery. SC = Sylvian cistern; Sv = Sylvian vein; TP = temporal pole, covering by the arachnoid. Printed with permission from Mayfield Clinic.

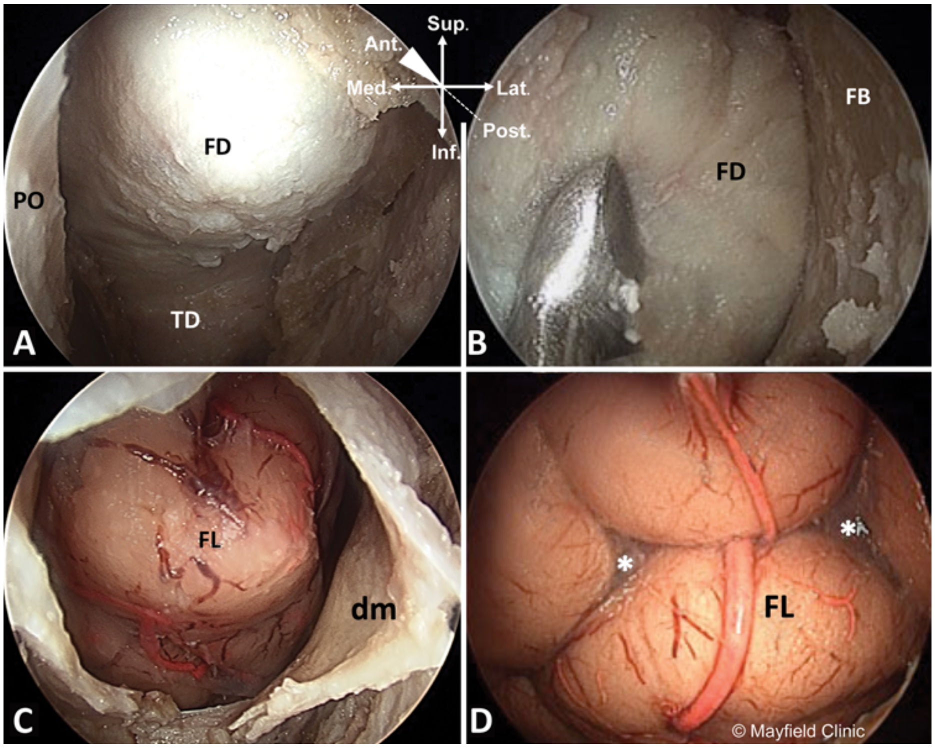

FIG. 10. Lateral orbital corridor to the anterior cranial fossa. With removal of the basal frontal bone medial to the superior orbital fissure and superior to the lesser sphenoid wing, the dura covering the frontal lobe (FL) came into view (**A**). Dissection can proceed laterally in extradural fashion (**B**). Opening of the dura mater (dm) then allows intradural exploration of the basal frontal lobe (**C**); the H-shaped orbital sulcus can be appreciated (**D**). The *asterisks* (*) indicate cortical arterial branches of the frontal lobe. Printed with permission from Mayfield Clinic.

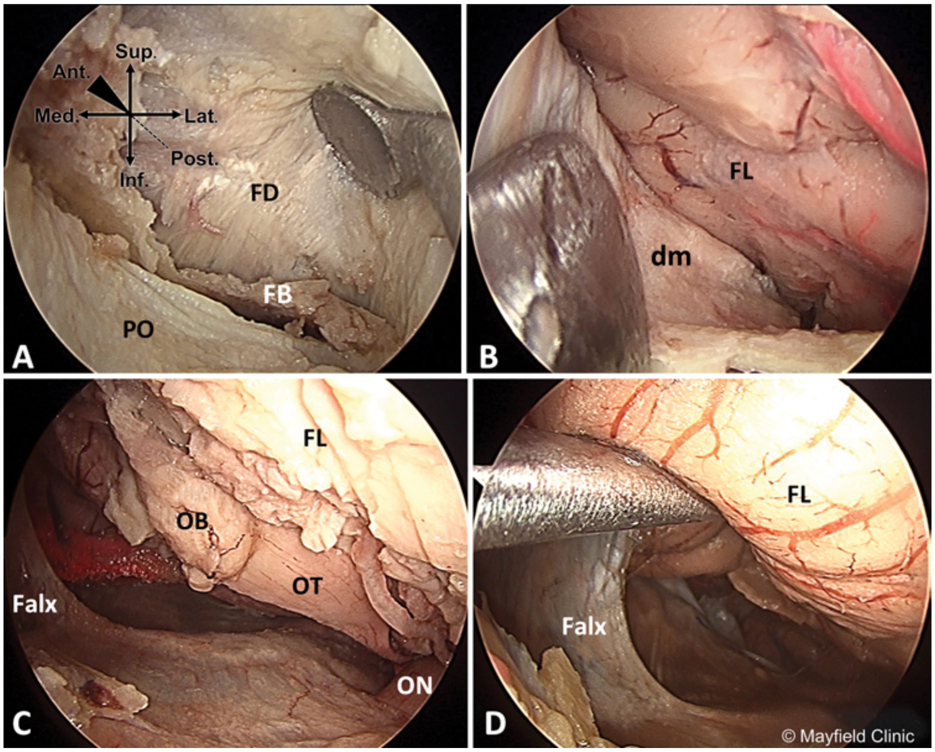

FIG. 11. Views obtained with a 30° endoscope, showing further exposure of the anterior cranial fossa via the lateral orbital corridor. Even with the 30° endoscope, the area can be explored extradurally (**A**) and intradurally (**B–D**). Falx = falx cerebri; OB = olfactory bulb; OT = olfactory tract. Printed with permission from Mayfield Clinic.

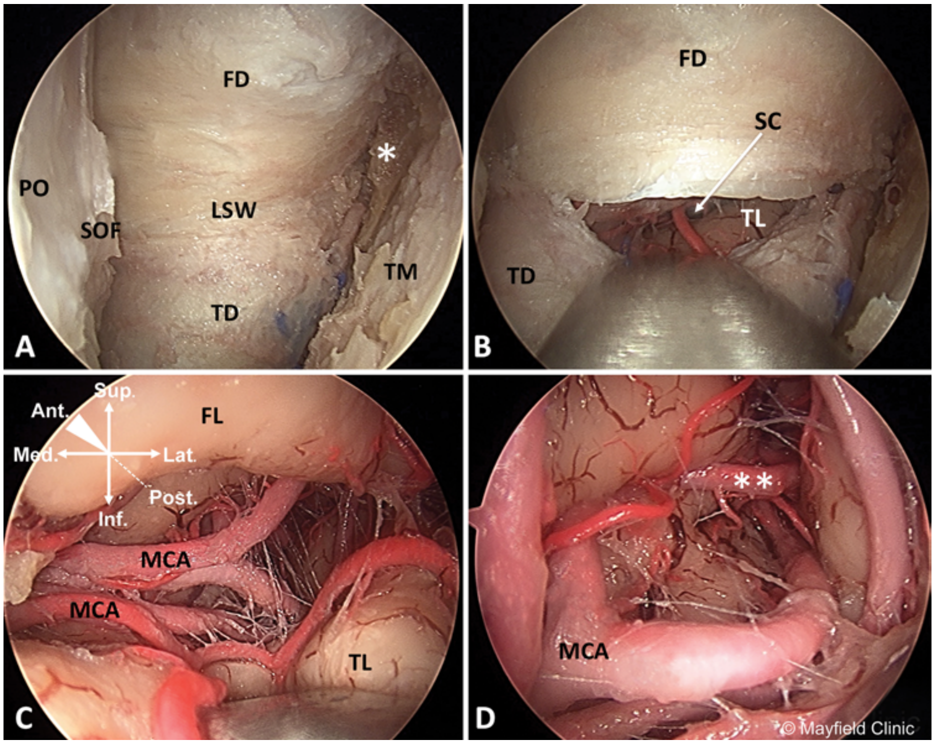

FIG. 12. Combined lateral approach to the anterior and middle cranial fossa. Close-up view showing lesser sphenoid wing (LSW) dividing the anterior and middle cranial fossae (**A**). The dura is cut between the anterior and middle cranial fossae at the level of the LSW to reach the intracranial space (**B**). The main course of the middle cerebral artery (MCA) can be appreciated (**C and D**). The *asterisk* (*) indicates the pterion seen through the transorbital perspective; the *double asterisks* (**) indicate insular branches of the MCA. TD = temporal dura; TL = temporal lobe. Printed with permission from Mayfield Clinic.

basal anterior fossa and anteromedial middle fossa. Using the endoscopic microsurgical technique, surgical manipulation of structures in the anterior and middle cranial fossae is feasible. Lateral orbital corridors to the superior and inferior orbital fissures exposed the entire rostral middle fossa and the anterior cranial fossa laterally to the convexity. Additional bone removal medial to the superior and inferior orbital fissures defined a medial transorbital corridor to the opticocarotid region.

Evolution of the Transorbital Path

The transorbital pathway has been used intermittently in neurosurgery for at least 60 years. In 1948, the American physician Walter J. Freeman II popularized the transorbital leucotomy[24] based on a technique developed by the Italian psychiatrist Amarro Fiamberti.[23] This “minimal invasive” transorbital procedure soon became ubiquitous across the landscape of psychiatric care in the United States and many parts of Europe. Subsequently, the social and ethical implications of widespread overuse of transorbital lobotomies drove this procedure to near extinction.[40] Several other approaches were reported based on the ventral transorbital route, including intraventricular procedures,[34,47–49] decompression for orbital and Graves’ disease,[1,3,33] and experimental and diagnostic vascular applications.[12,17,27,28,37] Thereafter, targets such as the cavernous sinus,[6,16,41] pituitary stalk,[42] and optic nerve[29,45] were considered reachable via this minimally invasive avenue for various diagnostic, experimental, and/or therapeutic purposes.

During the past 2 decades, improvements in endoscope optics quality, materials, instrumentation, and surgical navigation systems have advanced the development of modern skull base surgery. The collaboration of otolaryngologists and neurosurgeons for the treatment of pathologies that were beyond the reach of each other’s specialties invited a new subspecialty called endoneurosurgery, with its route based mainly on the endonasal corridor.[8]

Despite these impressive developments, nasal anatomy and geometrical relations to the skull base often limit working angles and visualization of certain structures, particularly for lesions that cross neurovascular structures or are situated in far-lateral areas.[44] In such cases, decreased visualization can lead either to complications or to incomplete surgery. In contrast, traditional external skull base approaches offer wide exposure and control of lesions, but sometimes at the expense of increased brain exposure and retraction, thus leading to postoperative functional and cosmetic sequelae.[7,11,20,26,36,38,46,47]

In this context, craniofacial anatomy studies suggested that the orbits, if crossed safely, can provide access to those areas of the anterior and middle skull base that are not safely accessed endonasally. That is, the obstacle represented by the carotid arteries and cranial nerves in the

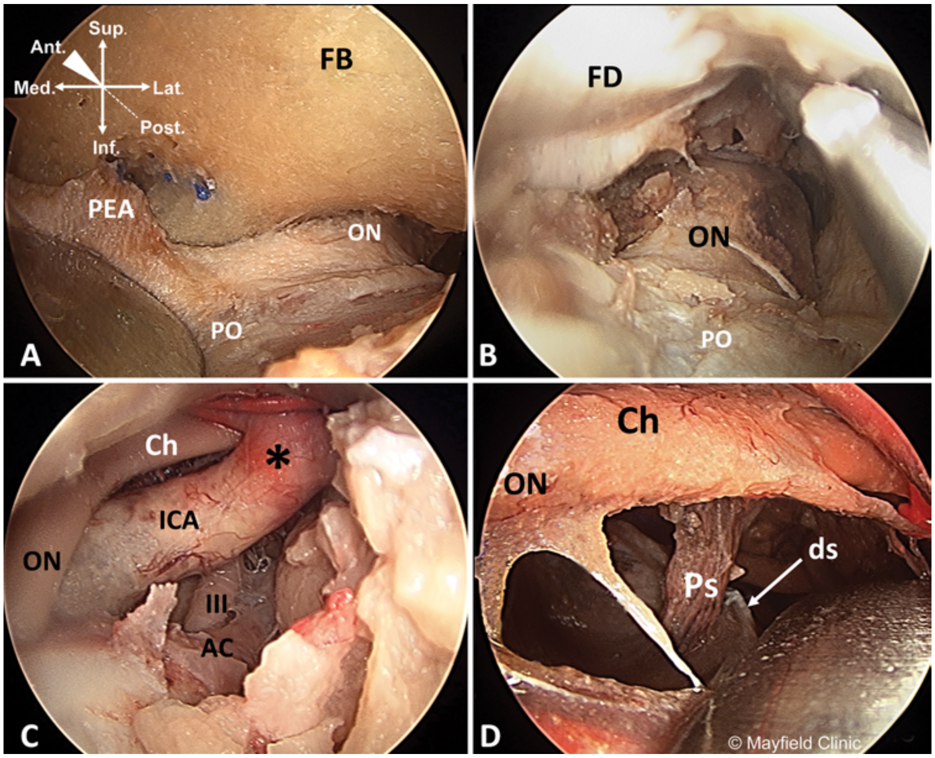

FIG. 13. Medial orbital corridor to the opticocarotid area (left orbit) (**A**). The optic nerve can be followed from its intracanalicular portion (**B**) up to the intracranial segment, where it lies close to the internal carotid artery (ICA) (**C**). With aid of a 30° lens, the subchiasmatic region can be explored through this window. The *asterisk* (*) indicates the ICA bifurcation. AC = anterior clinoid process; Ch = chiasm; ds = diaphragma sellae; PEA = posterior ethmoidal artery; Ps = pituitary stalk. Printed with permission from Mayfield Clinic.

lateral extension of endonasal approaches can be overcome by accessing the areas lateral to those anatomical hurdles. Consequently, the addition of transorbital approaches presented a complementary resource to endonasal approaches for the treatment of lesions that involve the neurovascular structures, a concept recently introduced as "multiportal endoneurosurgery."[5,8,10,18,43]

Transorbital Neuroendoscopic Surgery

Access to the anterior skull base through the orbit with endoscopic assistance is not a new concept. The concept presented as "transorbital neuroendoscopic surgery (TONES)"[6,32,35,39] described a group of endoscopic surgical pathways, a system of orbitotomies that could be indicated for various pathologies that affect the anterior and middle fossae. Truly transorbital, these procedures do not require removal of the orbital rim or frontal bone convexity. Their novel, attractive routes offer minimal morbidity, no visible scars, small craniotomy size, minimal brain retraction, and in some cases, coplanar path-to-target dissection. As a result, collateral damage to adjacent neurological and vascular structures is held to a minimum, patient recovery is rapid, and intensive care unit stays can be reduced or avoided.[6,32,35,39,49]

One TONES corridor is the superior eyelid route, proven in clinical settings as a possible way to select mainly laterally placed anterior and middle skull base targets.[30] Its superior eyelid skin incision offers the advantage of being hidden when the patient's eyes are open, provides dissection in natural anatomical planes, and affords preservation of the temporalis muscle, thus facilitating an acceptable cosmetic outcome, as described in initial surgical experiences and anatomical reports.[2,9,13,15] With no dedicated

TABLE 3. Quantitative analysis of bone removal obtained with the endoscopic superior eyelid approach

Analysis for Bone Removal	Area (mm^2)*	t Value†	DF	p Value
MCF	490.24 ± 76.94	—	—	—
ACF	620.47 ± 73.46	—	—	—
Combined lateral approach	1110.71 ± 131.89	—	—	—
OCR	115.41 ± 52.43	—	—	—
MCF vs ACF	—	3.87	18	<0.01
MCF vs combined lateral	—	12.85	18	<0.01
MCF vs OCR	—	12.73	18	<0.01
ACF vs combined lateral	—	6.61	18	<0.01
ACF vs OCR	—	17.70	18	<0.01
Combined lateral vs OCR	—	16.87	18	<0.01

DF = degrees of freedom.
* Mean ± SD.
† Student t-test.

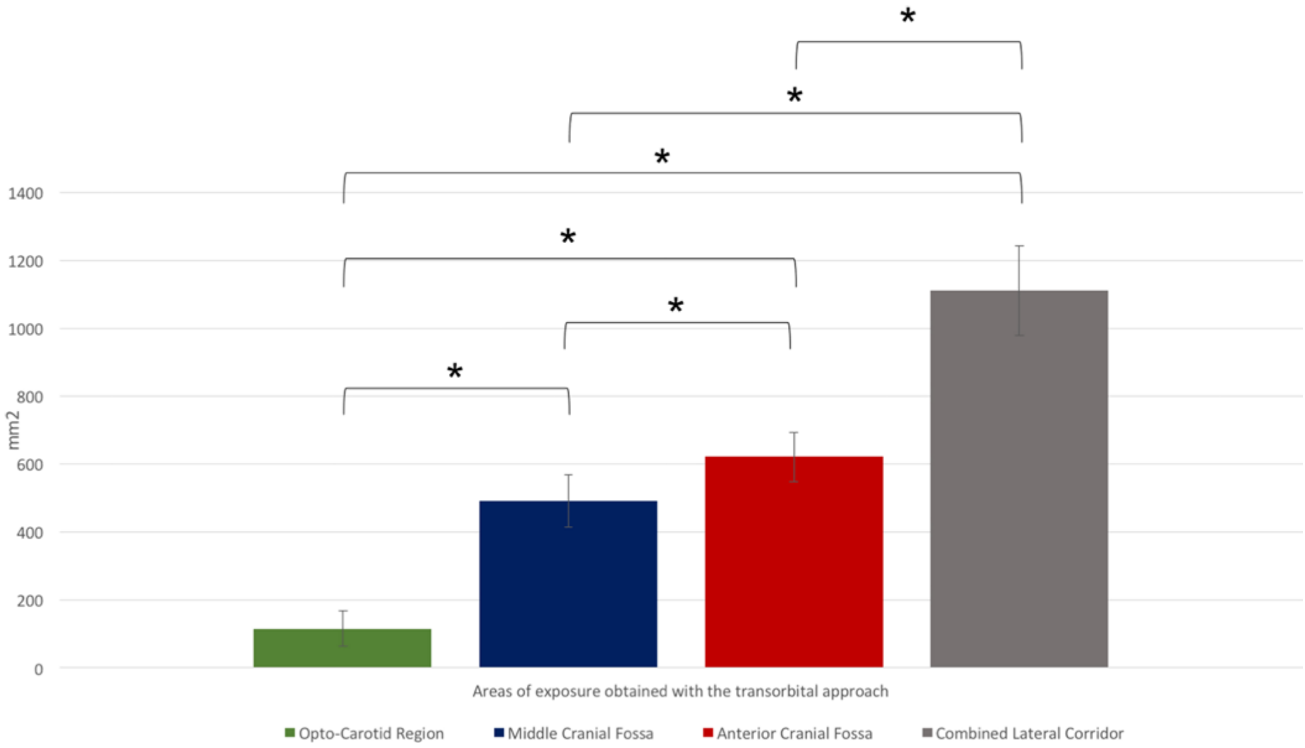

FIG. 14. Areas of exposure obtained with the endoscopic superior eyelid transorbital approach. Corridors represented included the lateral orbital corridor to the middle cranial base (*blue*); the lateral orbital corridor to the anterior cranial base (*red*); the combined lateral orbital corridor to the anterior and middle cranial fossae (*gray*); and the medial orbital corridor to the opticocarotid area (*green*). Compared with opticocarotid region approach, the middle and anterior fossa approaches achieved greater bone removal. Compared with middle fossa and opticocarotid region approaches, the anterior cranial base approach had greater bone removal, and the combined approach had the greatest bone removal of all. $^*p < 0.01$ (unpaired t-Student test).

study that addressed a schematic classification of the intracranial structures approached via this novel route, we undertook the anatomical analysis presented in this paper in order to determine the applicability of the various transorbital routes to the neurosurgical pathologies of the anterior and middle cranial fossae.

Using anatomical landmarks in relation to the orbital contents, we built a modular approach that was defined by discrete corridors and further separated these into lateral (i.e., lateral to the superior and inferior orbital fissures) and medial (i.e., extension medial to the superior and inferior orbital fissures) corridors. Based on our observations, we defined 3 lateral corridors (2 simple and 1 combined) and 1 medial corridor. The lateral corridors permitted exposure of the most lateral portion of the middle or anterior cranial fossa whereas the medial corridor, which included further bone removal medially to the superior and inferior orbital fissures, extended to reach the opticocarotid area. We concluded that the first 3 approaches (i.e., the 2 discrete lateral approaches and their combination) achieved better surgical exposures than the medial one, related to the opticocarotid region. Nonetheless, maneuverability was closely related to globe compliance and variability of the specimens for anatomical dissections.

Future applications of this minimally invasive, purely endoscopic route may include resection of tumors that extend in the parasellar region or other tumors (e.g., spheno-orbital meningiomas and selected anterior and middle skull base meningiomas). With increased experience and improved instrumentation and repair techniques, the treatment of selected skull base pathologies could be possible though these approaches.[7,17,37]

The purely endoscopic, superior eyelid, transorbital approach to the anterior and middle cranial base represents an additional avenue in the evolving discipline of minimally invasive skull base surgery or a possible alternative and/or adjunct to transcranial approaches for pathologies of the rostral anterior and middle fossae.[48,49] Combining transnasal and transorbital ports, surgeons can optimize visualization, choose the trajectory and working distance, and maximize the working space between their hands and instruments.[13]

In selected clinical situations, this technique has been reported as safe, offers better access and visualization than open or transnasal approaches, and retains the benefits of minimally disruptive surgery. Further comparative anatomical analyses, mandatory to understand pros and cons of a new technique, are ongoing to help understand the specifics of each route.

Limitations

In this study, one limitation was our use of cadaveric specimens, which, though useful models to investigate surgical approaches, cannot fully replicate the clinical environment. Tissue characteristics, bleeding, and the tolerable amount of globe retraction must be taken into consideration. Continuous intraoperative globe tonometry might be useful to determine the maximal safe degree and duration of globe retraction. The current literature reports no orbital complications despite operative times of up to 4 hours[35] and concerns about the risk of cerebrospinal fluid leak. However, Dallan et al. suggested that the orbit contents may act as a natural seal, minimizing the risk of a postoperative CSF leak.[13] Finally, other concerns include the cosmetic effect associated with the loss of orbital bone, and the risk of postoperative enophthalmos and diplopia. Although initial clinical experience appears encouraging,[35] surgical series are necessary to assess the burden of those potential complications.

This anatomical study on the feasibility of the superior eyelid endoscopic transorbital route is promising, with its contribution to understanding the anatomy and the capabilities of this relatively novel approach, but limited in clinical utility. Limits of its clinical utility should be considered as a separate issue; these deserve additional studies that are currently underway.

Conclusions

The purely endoscopic superior eyelid transorbital approach affords good visualization and allows surgical manipulation of structures in the anterior and middle cranial fossae. In particular, we demonstrated that lateral orbital corridors to the superior and inferior orbital fissures permitted exposure of the most lateral portion of the middle or the anterior cranial fossa. Further bone removal medially to the superior and inferior orbital fissures provides access to the opticocarotid region. Better surgical exposure appeared more consistent with lateral approaches as compared with the middle corridor to the opticocarotid region. Surgical series are needed to establish the clinical value of these approaches to better determine their place in the armamentarium of modern skull base surgery.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Andaluz, Di Somma, Cavallo, Cappabianca. Acquisition of data: Andaluz, Di Somma, Cavallo, de Notaris, Solari, Zimmer, Keller, Prats-Galino, Cappabianca. Analysis and interpretation of data: Andaluz, Di Somma, Cavallo, de Notaris, Dallan, Solari, Zimmer, Zuccarello, Cappabianca. Drafting the article: Andaluz, Di Somma, Cavallo, de Notaris, Dallan, Solari, Zimmer, Zuccarello. Critically revising the article: Andaluz, Di Somma, Cavallo, de Notaris, Dallan, Solari, Zimmer, Keller, Prats-Galino, Cappabianca. Reviewed submitted version of manuscript: all authors.

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LABORATORY INVESTIGATION

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Endoscopic transorbital route to the cavernous sinus through the meningo-orbital band: a descriptive anatomical study

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OBJECTIVE Exposure of the cavernous sinus is technically challenging. The most common surgical approaches use well-known variations of the standard frontotemporal craniotomy. In this paper the authors describe a novel ventral route that enters the lateral wall of the cavernous sinus through an interdural corridor that includes the removal of the greater sphenoid wing via a purely endoscopic transorbital pathway.

METHODS Five human cadaveric heads (10 sides) were dissected at the Laboratory of Surgical NeuroAnatomy of the University of Barcelona. To expose the lateral wall of the cavernous sinus, a superior eyelid endoscopic transorbital approach was performed and the anterior portion of the greater sphenoid wing was removed. The meningo-orbital band was exposed as the key starting point for revealing the cavernous sinus and its contents in a minimally invasive interdural fashion.

RESULTS This endoscopic transorbital approach, with partial removal of the greater sphenoid wing followed by a "natural" ventral interdural dissection of the meningo-orbital band, allowed exposure of the entire lateral wall of the cavernous sinus up to the plexiform portion of the trigeminal root and the petrous bone posteriorly and the foramen spinosum, with the middle meningeal artery, laterally.

CONCLUSIONS The purely endoscopic transorbital approach through the meningo-orbital band provides a direct view of the cavernous sinus through a simple and rapid means of access. Indeed, this interdural pathway lies in the same sagittal plane as the lateral wall of the cavernous sinus. Advantages include a favorable angle of attack, minimal brain retraction, and the possibility for dissection through the interdural space without entering the neurovascular compartment of the cavernous sinus. Surgical series are needed to demonstrate any clinical advantages and disadvantages of this novel route.

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KEY WORDS cavernous sinus; endoscopic transorbital; superior eyelid transorbital; meningo-orbital band; anatomy

Lesions in the cavernous sinus were long considered inoperable because of the risk of bleeding from the venous plexus or injury to important neurovascular structures such as the internal carotid artery and the cranial and sympathetic nerves. Even in experienced hands, surgery in this region is associated with significant morbidity.[1,9,37]

Pioneering surgeons such as Parkinson,[38–41] Dolenc,[15–18] and Hakuba[25–28,35,36] have paved the way for a greater multidimensional understanding of the anatomy of the cavernous sinus, with the result that this previously inaccessible region is no longer a "no-man's land." Using Dolenc's technique, tumors in this location can be resected safely without entering the cavernous sinus neurovascular

ABBREVIATIONS MOB = meningo-orbital band; SOF = superior orbital fissure.
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compartment,[17] and over the past 2 decades several studies have described numerous approaches with acceptable morbidity and mortality.[2,3,20,22,26,27,30,42,43] Nevertheless, controversy relating to the optimal route for different kinds of cavernous sinus lesions persists, and the cavernous sinus remains one of the most challenging and unfamiliar sites for many neurosurgeons and skull base surgeons. As a consequence, new routes are still needed to unlock this deep region more safely.

Over the years, transnasal corridors have been extensively described in both anatomical and clinical studies.[4,5,8,13,14,21] However, lesions arising in or extending to the lateral wall of the cavernous sinus remain out of range for such approaches. On the other hand, data from the literature shows that trans- and supra-orbital approaches have allowed management of the anterior and middle skull base with a superolateral trajectory.[7,32,33] The idea of using the lateral orbital wall as a corridor for entry to deeper brain areas is not new, and in recent years the superior eyelid transorbital approach, with endoscopic assistance, has been proposed as a way to access, in a minimally invasive fashion, the anterior and middle cranial fossa.[6,31]

From a technical viewpoint, this kind of transorbital route does not require the removal of the orbital rim or frontal bone and offers easy access to the anterior portion of the greater sphenoid wing covering the temporal pole. From this perspective, the endoscopic transorbital route provides straight, ventral access to the most superficial dural band tethering the frontotemporal basal dura to the periorbita—the so-called meningo-orbital band (MOB).[24,29] The MOB is a sagittally oriented structure between the temporobasal dura and the lateral aspect of the periorbita. It is typically exposed transcranially via a frontotemporal craniotomy along the lateral border of the superior orbital fissure (SOF) when the temporal basal dura is fully retracted. From an anatomical viewpoint the MOB has been described as leading directly to the interdural space of the cavernous sinus.[22,23]

Taking such data into account, we hypothesized that if the meningo-orbital band is sharply dissected via an endoscopic superior eyelid transorbital approach, it might allow us to expose the lateral wall of the cavernous sinus in a minimally invasive interdural fashion with very limited brain retraction or cranial nerve manipulation and with a favorable attack angle. Accordingly, in the present study, we describe just such a surgical route to the cavernous sinus that involves the removal of the greater sphenoid wing via an endoscopic transorbital pathway.

Methods

Anatomical dissections were performed at the Laboratory of Surgical Neuroanatomy in the Human Anatomy and Embryology Unit of the University of Barcelona Faculty of Medicine. The ethics committee of the University of Barcelona approved this study.

Surgical photographs were obtained in selected cases in which patients were treated by means of the transorbital endoscopic approach in 2 Italian tertiary care referral institutions (University of Pisa and University of Varese). The superior eyelid transorbital approach was performed using a rigid endoscope 4 mm in diameter and 18 cm in length and with 0° and 30° optic lenses (Karl Storz). The endoscope was connected to a light source through a fiberoptic cable and to a high-definition (HD) camera (Endovision Telecam SL, Karl Storz). The microanatomical part of the dissections was performed at optical magnification ranging from 3 to 40 (OPM, Zeiss).

Anatomical dissections were performed in 5 cadaver heads (10 sides). The common carotid arteries were isolated, cannulated, and injected with red latex. Veins were perfused in selected specimens using blue latex.

In accordance with previously published papers,[10,12] the incision was made through the skin and the orbicularis muscle and a skin-muscle flap was raised, mostly superolaterally, until the bony orbital rim was identified. The periosteum was then cut and a subperiosteal/subperiorbital plane was found (Fig. 1). Dissection proceeded using this plane until the superior and inferior orbital fissures were reached, to adequately expose the anterior portion of the greater wing of the sphenoid.

A malleable retractor was used to protect the periorbita, displacing the orbital content inferomedially and creating room for further dissection. Next, a 0° and/or 30° endoscope (Karl Storz) was introduced to monitor the subsequent steps. The SOF was then protected, and drilling of the greater sphenoid wing allowed us to clearly identify the MOB (Fig. 2).

Results

Transorbital Interdural Pathway—Anatomical Observations

In all specimens, once the orbital rim was skeletonized, a careful subperiosteal/periorbital dissection was performed until the SOF was identified (Video 1).

VIDEO 1. Video clip showing anatomical demonstration of the endoscopic superior eyelid transorbital approach to the lateral wall of the cavernous sinus. ACF = anterior cranial fossa; dMCF = dura propria of the middle cranial fossa; GG = gasserian ganglion; III = third cranial nerve; IOF = inferior orbital fissure; IV = fourth cranial nerve; MCF = middle cranial fossa; MMA = middle meningeal artery; OC = optic canal; OR = orbital rim; RMA = recurrent meningeal artery; SOF = superior orbital fissure; TM = temporalis muscle; lwCS, lateral wall of the cavernous sinus; V1 = ophthalmic branch of the trigeminal nerve; V2 = maxillary branch of the trigeminal nerve; V3 = mandibular branch of the trigeminal nerve. Copyright Alberto Di Somma. Published with permission. Click here to view.

Several bridging vessels were seen and cut during dissection.[6] Not infrequently, small, generally nameless, foramina were identified lateral to the SOF. The closest and largest of these is known as the cranio-orbital foramen or Hirtl's foramen.[19] The recurrent meningeal artery or meningolacrimal branch may pass through this foramen, which is present in 50%–60% of cases.

The greater wing of the sphenoid was then removed until the dura mater covering the temporal pole came into view. In some cases, the bone covering the basal frontal lobe was also removed to obtain better exposure of the SOF.

Accordingly, the MOB leading to the lateral wall of the cavernous sinus could be seen in the center of the surgical field (Fig. 2). Anatomically, the lateral wall of the cavernous sinus is composed of 2 dural layers; the outer layer

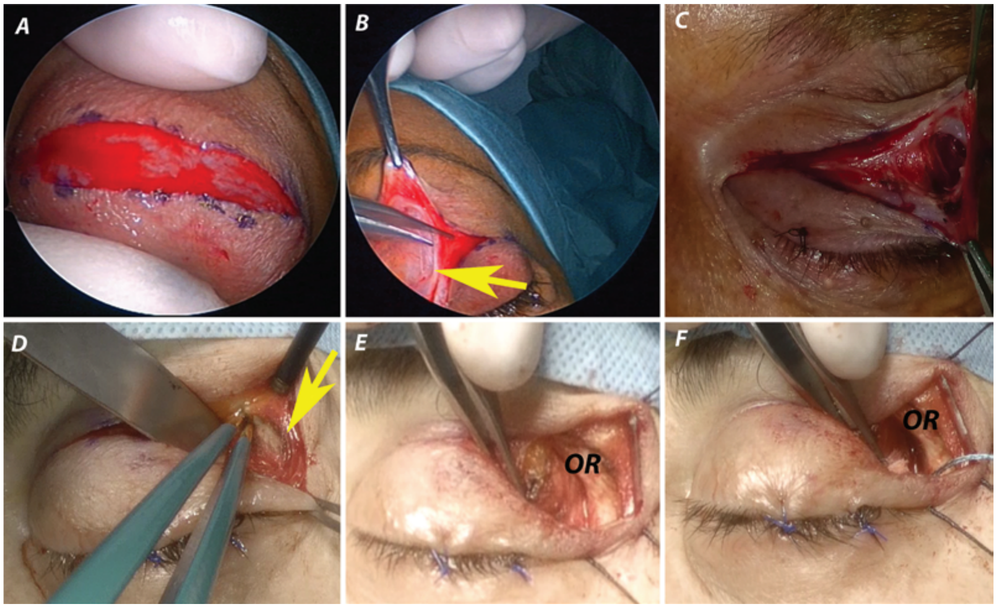

FIG. 1. Intraoperative photographs showing the superior eyelid transorbital approach, left orbit. The incision is made through the skin (**A**) and the orbicularis muscle (**B and C**); the skin-muscle flap is raised mostly superolaterally. A malleable retractor is used to mobilize the orbital content inferomedially (**D**). The periosteum is cut and a subperiosteal/subperiorbital plane is followed (**E and F**). The *yellow arrows* indicate the orbicularis oculi muscle. OR = orbital rim. Figure is available in color online only.

(meningeal dura or dura propria), and the inner one (true cavernous membrane). This last layer is made up of the epineurium of cranial nerves and surrounding connective tissue, and a cleavage plane between the inner and outer dural layers can be easily identified.[45]

Strictly speaking, the MOB is not a true anatomical structure. It is described as the most superficial dural-periosteal band that tethers the frontotemporal basal dura to the periorbita. Anatomically speaking, along the lateral margin of the SOF the periosteal layer of the dura mater is contiguous with the periosteal layer of the periorbita.[23] So, in fact, the MOB can be identified as a periosteal fold/bridge stretching between the periorbita and the temporal lobe dura. As highlighted by Froelich et al.,[23] the width of this fold varies according to the shape of the lateral end of the narrow part of the SOF.

Running through the MOB are several nameless dural vessels and sometimes also the recurrent meningeal artery. There is usually a space between the dura propria and the epineurium of the cranial nerves where the nerves exit the intradural space. This space is more evident in the case of the mandibular nerve and trigeminal ganglion but it can be identified in other areas as well.

At the level of the lateral wall of the cavernous sinus, the true cavernous membrane continues intraorbitally as the epineurium of the cranial nerves. So, removing the greater wing of the sphenoid close to the lateral aspect of the SOF, allows the periorbita–periosteal dura transition (corresponding to the MOB) to float off the underlying dura propria and true cavernous membrane. Therefore a sharp and gentle dissection of this bridge, and in particular of the meningo-orbital band, "naturally" reveals the lateral wall of the cavernous sinus via an interdural pathway (Fig. 3).

Surgically speaking, this space is very important because it offers access to the inner layer of the lateral wall without the need to enter the venous compartment of the sinus itself, and, even more importantly, it provides access without manipulation of the cavernous sinus' cranial nerves. This virtually bloodless surgical plane has been reported in the clinical setting by Fukuda et al.[24]

Additionally, MOB release permits the gentle and partial displacement (extradurally) of the medial part of the temporal lobe.

In the subsequent steps of the dissection, the meningeal dura was peeled off in a posterolateral direction, thus progressively exposing the nerves enclosed in the true cavernous membrane. The identification of V1 and V2 usually preceded identification of the third and fourth cranial nerves. This interdural corridor provided an easy and straight visualization of the first 2 branches of the trigeminal nerve (Fig. 4). As the dissection proceeded posteriorly, the trochlear and oculomotor nerves came into view, just superior to the ophthalmic branch of the trigeminal nerve (Fig. 5).

At the end of the interdural dissection, a complete visualization of the lateral wall of the cavernous sinus could be obtained, including oculomotor and trochlear nerves, the first 2 branches of the trigeminal nerve up to the gasserian ganglion and the distal/plexiform portion of the trigeminal root posteriorly and the mandibular branch of the trigeminal nerve and the middle meningeal artery laterally (Fig. 6).

Discussion

The traditional belief that lesions arising in or extending to the cavernous sinus are inoperable has been abandoned over the years. Innovative surgical techniques have

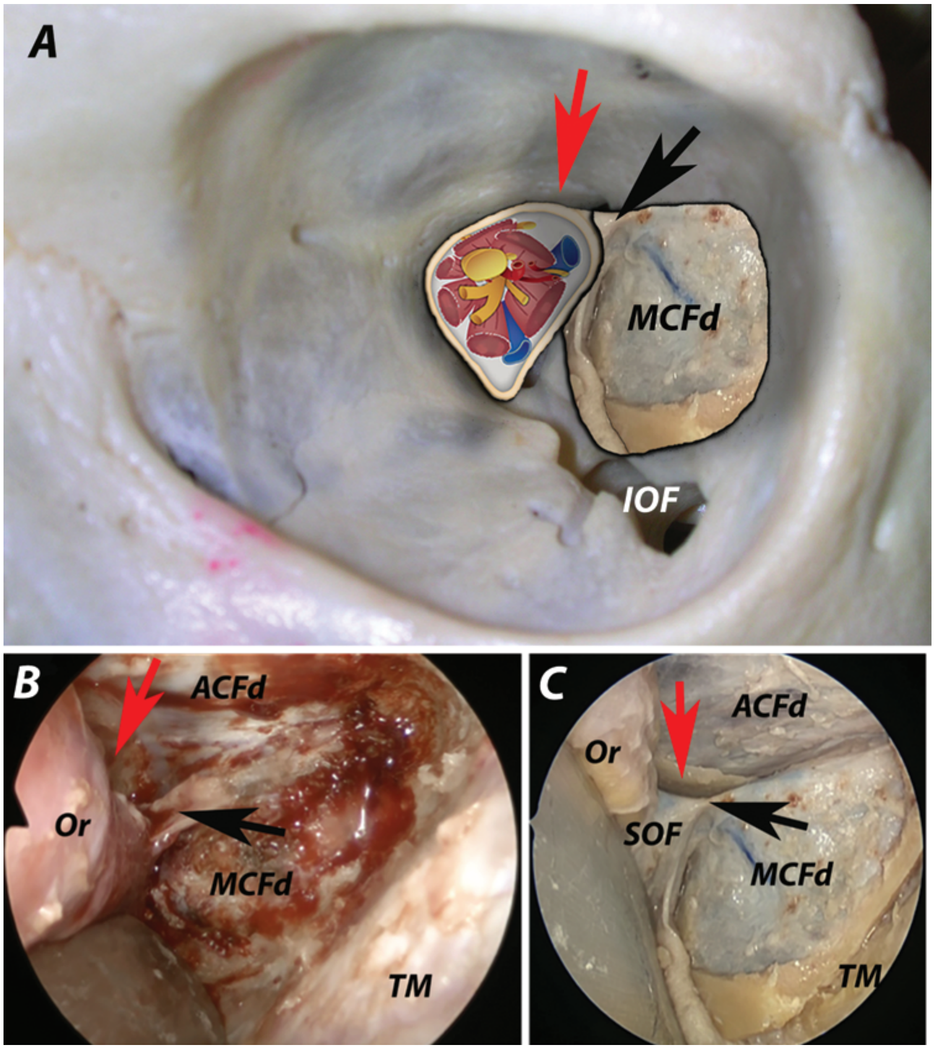

FIG. 2. Photograph of orbit in cadaveric specimen with superimposed artistic drawing showing the position of the left meningo-orbital band in a coronal section and photograph from anatomical endoscopic approach (**A**). Surgical (**B**) and anatomical (**C**) visualization of the MOB. The *black arrows* indicate the MOB; the *red arrows* indicate the orbit and its contents. ACFd = anterior cranial fossa dura; IOF = inferior orbital fissure; MCFd = middle cranial fossa dura; Or = orbit; SOF = superior orbital fissure; TM = temporalis muscle. Figure is available in color online only.

been developed to treat lesions located in this area, often by means of the endoscopic endonasal routes.[1,4,9,20–22,34]

Numerous approaches have been proposed, and most of them are based on the philosophy of more extensive bone removal while minimizing cerebral retraction. For example, Yaşargil and colleagues[46,47] popularized the transsylvian approach to lesions in the sellar and parasellar regions. They used frontotemporal craniotomy with frontoorbital and sphenoidal osteotomy—the so-called "pterional" craniotomy—to take advantage of the cisternal route, while Dolenc[15–18] pioneered the intra- and extradural approach to the cavernous sinus, which combined a pterional approach with a subtemporal pathway. More recently, Frank and Pasquini[21,22] proposed a ventral pathway, namely the endoscopic endonasal route, to the cavernous sinus. Their work related primarily to the management of soft lesions (mostly pituitary adenomas).

Each of the proposed approaches has had a significant role in the improvement of surgical treatment of cavernous sinus lesions. Most of these approaches require extensive bone drilling, wide intra- and/or extradural exposure, manipulation of critical neurovascular structures and detachment of temporal muscle to varying degrees. Some of the procedures are also technically demanding and may require a significant expenditure of time and energy.

Considering all these factors, we committed our efforts to evaluating a less-invasive approach to the cavernous sinus, accessing it in a minimally invasive interdural fashion, through what we call an endoscopic superior eyelid transorbital approach.

Cavernous sinus anatomy has been described controversially in a large number of publications. Anatomically speaking,[29] 2 dural layers, medial to the trigeminal foramina and in the lateral cavernous sinus wall, can be

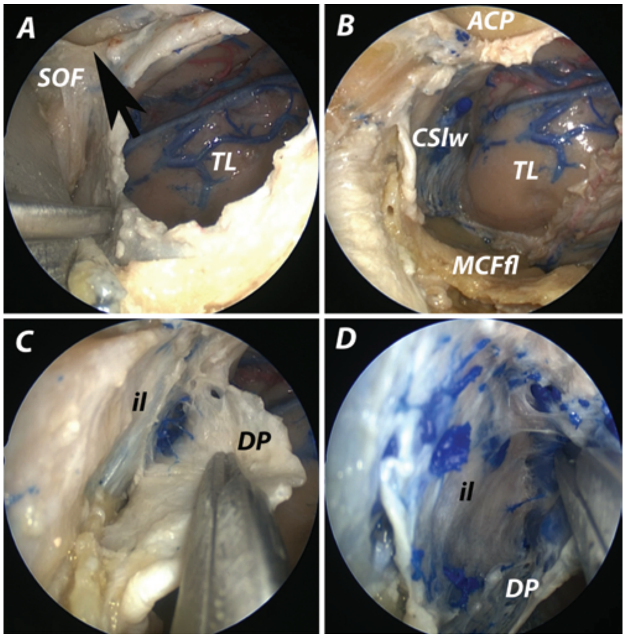

FIG. 3. Endoscopic transorbital exposition of the lateral wall of the cavernous sinus, left orbit. Stepwise dissection (**A–D**). The *black arrow* indicates the MOB. ACP = anterior clinoid process; CSlw = cavernous sinus lateral wall; DP = deep layer; il = inner layer; MCFfl = middle cranial fossa floor; SOF = superior orbital fissure; TL = temporal lobe. Figure is available in color online only.

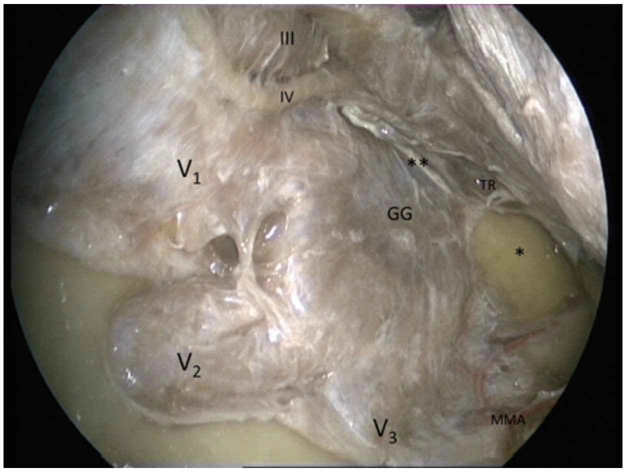

FIG. 4. Complete interdural exposition of the lateral wall of the cavernous sinus via an endoscopic transorbital approach, left orbit. The *single asterisk* indicates the petrous part of the temporal bone; the *double asterisk* indicates the dural layer of the Meckel cave. III = oculomotor nerve; IV = trochlear nerve; GG = gasserian ganglion; MMA = middle meningeal artery (entering the foramen spinosum); TR = trigeminal root; V1 = ophthalmic nerve; V2 = maxillary branch of the trigeminal nerve; V3 = mandibular branch of the trigeminal nerve. Figure is available in color online only.

identified. These layers have been demonstrated histologically.

From a surgical standpoint, these layers are of paramount importance because it is possible to separate them, creating the so-called "interdural incision zone." According to Fukuda et al.,[24] the MOB should be considered as a fused periosteal-dural layer that tethers the temporal dura to the periorbita at the level of the lateral aspect of the SOF; its dissection may lead to the interdural space in the lateral wall of the cavernous sinus.

Nonetheless, looking at the specific results of our study and based on our data, we would like to emphasize that an endoscopic superior eyelid approach presents several advantages, which are related to its intrinsic anatomical aspects. Principally, it can be performed very quickly—in our cadaver laboratory it took approximately 30 minutes—and needs only a small eyelid incision, which is virtually hidden when the patient's eyes are open. Even more importantly, this "anterior" approach reduces to a minimum extradural temporal lobe retraction and cranial nerve manipulation, thus avoiding wide exposure of the cerebrum and the associated complications typically related to these maneuvers. Importantly, the temporalis muscle insertion is left intact, virtually eliminating the risk of atrophy. Last but not least, the interdural ventral "transorbital" corridor, performed on a clear and natural sagittal plane through the MOB, allowed us to expose the entire lateral wall of the cavernous sinus without entering its neurovascular compartment and with a favorable angle of attack. The other available approaches (pterional, frontotemporal and supraorbital), require an interdural dissection performed with a more perpendicular, and thus less favorable, angle of attack. In our view, this could make the dissection, in such a delicate plane, more difficult and consequently risky. In fact, the favorable working direction offered by our anterior transorbital approach allows for quite easy dissection of this interdural plane, completely exposing the lateral wall of the cavernous sinus. By working accurately in this plane, it is possible to inspect the cavernous sinus lateral wall without opening the venous spaces or manipulating any cranial nerves. This route requires minimally invasive drilling of the greater sphenoid wing and offers an immediate exposure of the temporal pole and the lateral wall of the cavernous sinus with a favorable angle of attack (working direction).

The disadvantages of this approach include the unfamiliar perspective of the anatomy of this region as seen from a ventral viewpoint. In consequence, practice in the cadaver laboratory is mandatory to develop familiarity with the approach. We must also stress that in a clinical setting excessive globe retraction or the use of improper equipment for retraction could potentially cause injury to the periorbita or globe. However, despite such potential risks, the clinical application of this procedure in more than 1500 orbital decompressions (made through this approach for Graves' orbitopathy) has demonstrated the feasibility and safety of such a route when properly selected and applied.[44] Furthermore, ongoing experience in the management of selected spheno-orbital meningiomas seems to confirm the applicability of such an approach in the clinical scenario[10] (Video 2).

VIDEO 2. Video clip showing surgical application of the endoscopic superior eyelid transorbital approach for a spheno-orbital meningioma. ACFd = anterior cranial fossa dura; CSlw = cavernous sinus lateral wall; GWS = greater wing of the sphenoid; LWS = lesser wing of the sphenoid; MCF = middle cranial fossa; MCFd = middle

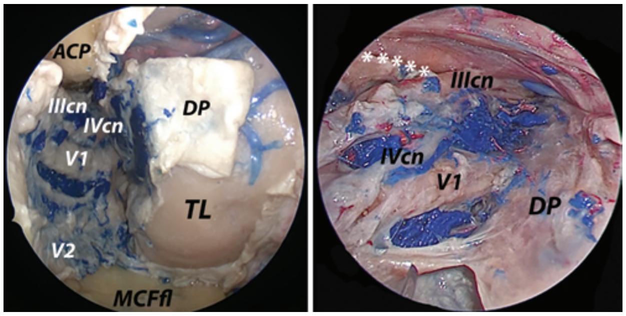

FIG. 5. Close-up views of the lateral wall of the cavernous sinus, accessed via the left orbit. The lateral wall of the cavernous sinus has been disclosed between the temporal lobe and the orbit. The *asterisks* indicates the inner layer. ACP = anterior clinoid process; DP = dura propria; IIIcn = oculomotor nerve; IVcn = trochlear nerve; V1 = ophthalmic branch of the trigeminal nerve; V2 = maxillary branch of the trigeminal nerve. Figure is available in color online only.

cranial fossa dura; MOB = meningo-orbital band; PO = periorbita; RMA = recurrent meningeal artery; SOF = superior orbital fissure; TL = temporal lobe; TM = temporalis muscle. Copyright Alberto Di Somma. Published with permission. Click here to view.

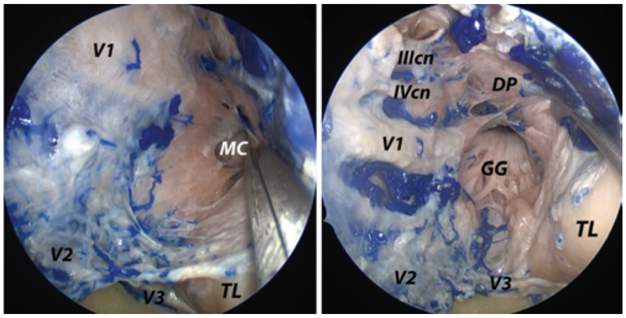

FIG. 6. Close up view of the Meckel cave (MC) and gasserian ganglion (GG), accessed via the left orbit. DP = dura propria; IIIcn = oculomotor nerve (third cranial nerve); IVcn = trochlear nerve (fourth cranial nerve); TL = temporal lobe; V1 = ophthalmic branch of the trigeminal nerve; V2 = maxillary branch of the trigeminal nerve; V3 = mandibular branch of the trigeminal nerve. Figure is available in color online only.

In such cases, we have partially exposed the lateral wall of the cavernous sinus (at least the anterior part) without the need to retract the temporal lobe. But the practicability of working in this area depends, at least in part, on the space occupied by the tumor. Accordingly, it is important to stress that in a preclinical scenario there is absolutely no need to retract the temporal lobe to expose the lateral wall of the cavernous sinus.

To demonstrate that the approach can be done purely extradurally, we have included an anatomical video highlighting this key technical aspect (see Video 1).

The primary aim of the study, however, is to demonstrate that, by using a transorbital approach, surgeons can enter the interdural space and expose parasellar regions without injuring the neurovascular compartments of the cavernous sinus, other cranial nerves, or the temporal lobes. Selected lesions—i.e., trigeminal schwannomas and meningiomas lateral to the cavernous sinus and covered with the inner layer of the lateral wall of the cavernous sinus—may be the best candidates for this approach. In this context, we should remember that stereotactic radiosurgery is a valid, although palliative, treatment alternative for cavernous sinus pathologies. Nevertheless, we believe that cavernous sinus surgery should still be considered as an important and viable field today.

Finally, regarding the issue of the transorbital route for intracranial pathology, it should be stressed that at present this kind of approach is still in its infancy, so we have to await further developments, in terms of both surgical technique and surgical tools, to reach proper conclusions.[10–12] Above all, the present work has been designed to provide useful anatomical details with regard to the transorbital approach. A peer understanding of the anatomy represents the backbone of any surgical procedure; we aimed to detail the main features of the MOB as the key landmark in identification of the cavernous sinus.

In this study we have described an interesting surgical approach to this area. Based on our data, we think that this route may be applicable in the treatment of a variety of lesions, especially tumors, in or around the cavernous sinus. However, at the time of this writing, no clinical case of pure cavernous sinus meningioma had been treated via this approach.

In conclusion, we believe that the transorbital pathway, through a minimally invasive superior eyelid approach and via an interdural corridor, could provide, at least from an anatomical viewpoint, a valid route to access and manage the lateral wall of the cavernous sinus.

Conclusions

Advances in endoscopic skull base surgery have increased our ability to access complex cranial base regions. The endoscopic transorbital approach provides a simple, rapid and direct view of the cavernous sinus lateral wall. Advantages of this novel interdural pathway include minimal "extradural" brain retraction, no interruption of the temporalis muscle and no entering inside the cavernous sinus neurovascular compartment. This route may be useful for getting inside the lateral wall of the cavernous sinus in a minimally invasive interdural manner. However, it has to be emphasized that surgical series are needed to prove any clinical advantage or disadvantage of this novel route.

Acknowledgments

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Di Somma, Dallan, Turri-Zanoni, de Notaris. Acquisition of data: Di Somma, Dallan, Turri-Zanoni. Analysis and interpretation of data: Di Somma, Dallan, Turri-Zanoni, Fiacchini. Drafting the article: Di Somma, Dallan, Turri-Zanoni, Fiacchini, de Notaris. Critically revising the article: Dallan, Prats-Galino, Solari, de Notaris. Reviewed submitted version of manuscript: Dallan, Prats-Galino, Solari, Alobid, Castelnuovo, Catapano, de Notaris. Statistical analysis: de Notaris. Study supervision: Dallan, Prats-Galino, Castelnuovo, Catapano, de Notaris.

Supplemental Information

Videos

Video 1. https://vimeo.com/181195690.
Video 2. https://vimeo.com/181195874.

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JNS

LABORATORY INVESTIGATION

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Endoscopic endonasal medial-to-lateral and transorbital lateral-to-medial optic nerve decompression: an anatomical study with surgical implications

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OBJECTIVE Different surgical routes have been used over the years to achieve adequate decompression of the optic nerve in its canal including, more recently, endoscopic approaches performed either through the endonasal corridor or the transorbital one. The present study aimed to detail and quantify the amount of bone removal around the optic canal, achievable via medial-to-lateral endonasal and lateral-to-medial transorbital endoscopic trajectories.

METHODS Five human cadaveric heads (10 sides) were dissected at the Laboratory of Surgical Neuroanatomy of the University of Barcelona (Spain). The laboratory rehearsals were run as follows: 1) preliminary preoperative CT scans of each specimen, 2) anatomical endoscopic endonasal and transorbital dissections and Dextroscope-based morphometric analysis, and 3) quantitative analysis of optic canal bone removal for both endonasal and transorbital endoscopic approaches.

RESULTS The endoscopic endonasal route permitted exposure and removal of the most inferomedial portion of the optic canal (an average of 168°), whereas the transorbital pathway allowed good control of its superolateral part (an average of 192°). Considering the total circumference of the optic canal (360°), the transorbital route enabled removal of a mean of 53.3% of bone, mainly the superolateral portion. The endonasal approach provided bone removal of a mean of 46.7% of the inferomedial aspect. This result was found to be statistically significant ($p < 0.05$). The morphometric analysis performed with the aid of the Dextroscope (a virtual reality environment) showed that the simulation of the transorbital trajectory may provide a shorter surgical corridor with a wider angle of approach (39.6 mm; 46.8°) compared with the simulation of the endonasal pathway (52.9 mm; 23.8°).

CONCLUSIONS Used together, these 2 endoscopic surgical paths (endonasal and transorbital) may allow a 360° decompression of the optic nerve. To the best of the authors' knowledge, this is the first anatomical study on transorbital optic nerve decompression to show its feasibility. Further studies and, eventually, surgical case series are mandatory to confirm the effectiveness of these approaches, thereby refining the proper indications for each of them.

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KEY WORDS optic nerve decompression; endoscopic transorbital; superior eyelid transorbital; endoscopic endonasal, anatomy

The optic nerve can be considered an extension of the brain, as it runs protected by the 3 meningeal sheaths in its extracranial portion. According to the literature, 4 anatomical segments of the optic nerve can be identified:[4,41] intraocular, intraorbital, intracanalicular, and intracranial. Generally, the intracanalicular segment, approximately 10 mm in length, is the most vulnerable to compression and shear forces such that surgical optic nerve decompression identifies this segment as the one to target to obtain relief.[4] Different surgical approaches have

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been used over the years including, more recently, endoscopic approaches either performed through the endonasal corridor or the transorbital pathway.[1,2,4,10,14,16,25–28,50]

The endoscopic endonasal route is currently gaining favor as a viable surgical technique to achieve optic nerve decompression, because it provides a minimally invasive, adequate exposure of the optic canal.[1,4,27,32] Furthermore, the corridor itself provides excellent visualization of the medial aspect of the orbital apex while avoiding brain retraction and olfactory bulb injuries as can happen in transcranial approaches. However, despite the recent extension and refinements of endoscopic endonasal techniques, the superior and lateral aspects of the optic canal still stand outside the limits of this approach. However, the endonasal route may be considered advantageous for the removal of the most inferomedial portion of the optic canal, whereas a transcranial corridor should be adopted when unroofing of the optic canal is planned. A complementary route to the endonasal one may be necessary to achieve the decompression of the superolateral segment of the optic canal.

Among the transcranial approaches, the trans- and supraorbital approaches have been introduced as feasible lateral surgical trajectories for accessing the optic canal and the anterior and middle skull base.[5,6,12,16,33,40,45,47] More recently, the superior eyelid transorbital approach, with the aid of the endoscope, has been proposed as a possible minimally invasive ventral access to selected areas of the anterior and middle cranial fossae,[31] allowing exposure of the optic nerve from above and laterally.[31] Furthermore, this latter route does not require the removal of the orbital rim or the frontal bone convexity, also avoiding brain manipulation.

The aim of this study was to detail and quantify the extent of bone removal of the optic canal at the intracanalicular portion of the optic nerve from a medial-to-lateral endonasal and from a lateral-to-medial transorbital eyelid endoscopic approach.

To our knowledge, this is the first contribution to provide a quantitative assessment of the bone removal of the optic canal, when combining endonasal and transorbital endoscopic approaches.

Methods

Anatomical Dissections

Anatomical dissections were performed at the Laboratory of Surgical Neuroanatomy of the Human Anatomy and Embryology Unit, University of Barcelona (Barcelona, Spain) on 5 cadaveric heads (10 sides), in which the arterial system had been injected with red latex. This study was approved by the institutional review board of the University of Barcelona.

Before and after the dissections, all specimens underwent a multislice helical CT scan (Siemens SOMATOM Sensation 64) with 0.6-mm-thick axial spiral sections and a 0° gantry angle.

Five screws were previously implanted in each specimen's skull as permanent bone reference markers to allow coregistration with the neuronavigation system (Medtronic, Inc. Surgical Technologies). Imaging data were transferred to the laboratory navigation-planning workstation, and point registration was performed. A registration correlation tolerance of 2 mm was considered acceptable.

Endoscopic endonasal and transorbital approaches were performed using a rigid endoscope 4 mm in diameter, 18 cm in length, with a 0° and a 30° lens (Karl Storz). The endoscope was connected to a light source (300 W Xenon, Karl Storz) through a fiberoptic cable and to a high-definition camera (Endovision Telecam SL; Karl Storz). The microsurgical dissections, that is, initial steps of the transorbital approach, were run at magnifications ranging from ×3 to ×40 (OPMI; Zeiss).

Prior to the dissection, surgical corridor length and angle of approach to the optic nerve of both endonasal and transorbital routes were simulated in a virtual reality system, that is, the Dextroscope (Volume Interactions Pte. Ltd.), as published previously[3,22] in 2 specimens. The required virtual values, that is, length of the surgical corridor to reach the optic canal and angle of attack, were provided by the system once the parameters were set, and with the aid of the Dextroscope measurement tool. In the Dextroscope simulation, we overlapped the CT scan with the arteriography image showing the ophthalmic artery entering the optic canal. This permitted us to draw the course of the optic canal and therefore perform the morphometric analysis in the correct manner.

Thereafter, cadaveric dissections were performed as follows.

Endoscopic Endonasal Approach

Through a binostril approach, we performed a middle turbinectomy in 1 nostril with complete ethmoidectomy, wide sphenoidotomy, and removal of the posterior portion of the nasal septum. The uncinate process was removed, and a middle meatal antrostomy provided access to the inferior and medial orbital walls. The lamina papyracea was then removed. The optic canal was opened in a proximal-to-distal direction, up to the lateral edge of the tuberculum sellae, either by a dissector and gentle drilling with the diamond bur. Finally, the intracanalicular portion of the optic nerve was uncovered (Fig. 1). The optic sheath was then opened by using a sickle blade, not extending over the annulus of Zinn, which is considered the most proximal anatomical landmark.

Transorbital Approach

A superior eyelid approach was performed as follows. A skin incision was made through an eyelid wrinkle, and the orbicularis muscle was cut so that the skin-muscle flap was raised superolaterally until the bony orbital rim and the frontozygomatic suture were identified as described previously.[15,31] The periosteum was cut, and dissection proceeded in the subperiosteal and then the subperiorbital plane until the superior and inferior orbital fissures were reached. A malleable retractor was used to protect and displace the orbit content inferomedially, and, from this point, the procedure was run under endoscopic guidance, alternating between 0° and 30° lenses. Because the optic canal is located medial to the superior orbital fissure, we gained access to it by pushing the orbit and its content inferiorly (Fig. 2). Craniectomy for decompression of the op-

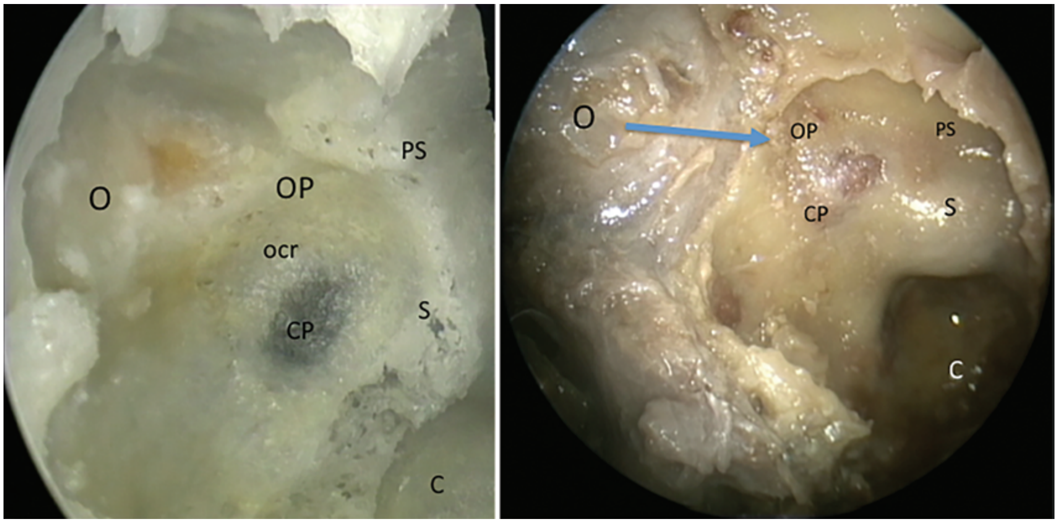

FIG. 1. Endoscopic endonasal view of the right orbit and optic prominence. The *blue arrow* indicates the direction of optic canal decompression via a proximal-to-distal technique. C = clivus; CP = carotid protuberance; O = orbit; ocr = opto-carotid recess; OP = optic protuberance; PS = planum sphenoidale; S = sella. Figure is available in color online only.

tic canal was achieved by means of adequate bone removal from the greater and subsequently the lesser wing of the sphenoid, forming the lateral portion of the optic canal. Finally, anterior clinoid process removal was accomplished.

Pterional Approach

A conventional pterional approach was used to observe the decompression achieved via both routes from a transcranial perspective.

Quantitative, Statistical Analysis and 3D Reconstruction

OsiriX software (OsiriX Foundation) was used to measure and quantify the amount of bone removed from the optic canal through both the endonasal and transorbital pathways, comparing it with data retrieved from the postoperative CT scan. A nonpaired Student t-test was used to compare the optic canal bone removal achieved in the 2 approaches. A p value < 0.05 was considered significant.

Results

Qualitative Assessment of Surgical Approaches

Endoscopic Endonasal Approach

Access to the optic canal was gained from a proximal-to-distal direction. After removal of the lamina papyracea, the most inferomedial part of the optic canal was reached. The exposure of the intracanalicular portion of the optic nerve surrounded by the optic sheath can be followed to the orbital apex. At this level, the optic nerve is held by the fibrous annulus of Zinn, which represented the most proximal limit of the approach. The endoscopic endonasal view showed the medial walls of both orbits as well as

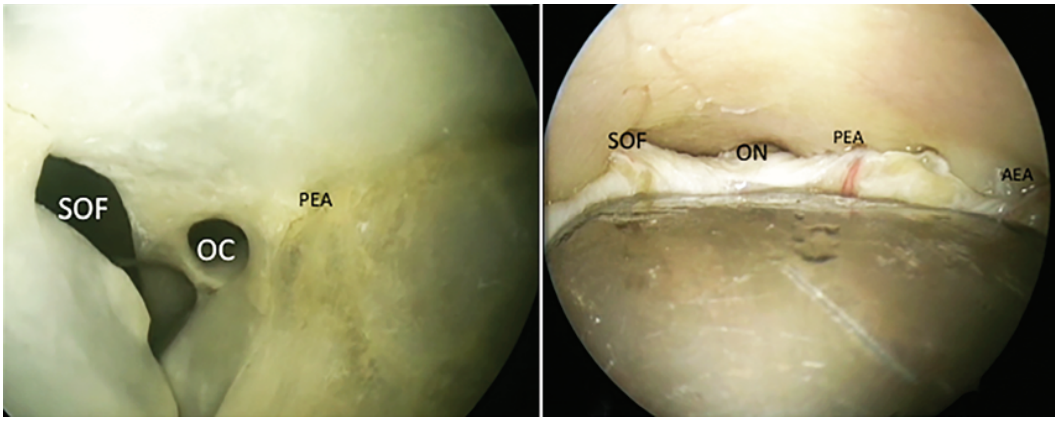

FIG. 2. Right orbit. View with a 30° scope from lateral to medial. Dry skull base (**left**) and cadaver (**right**) endoscopic transorbital view. The main anatomical landmarks that are considered to reach the optic canal are shown. AEA = anterior ethmoidal artery; OC = optic canal; ON = optic nerve; PEA = posterior ethmoidal artery; SOF = superior orbital fissure. Figure is available in color online only.

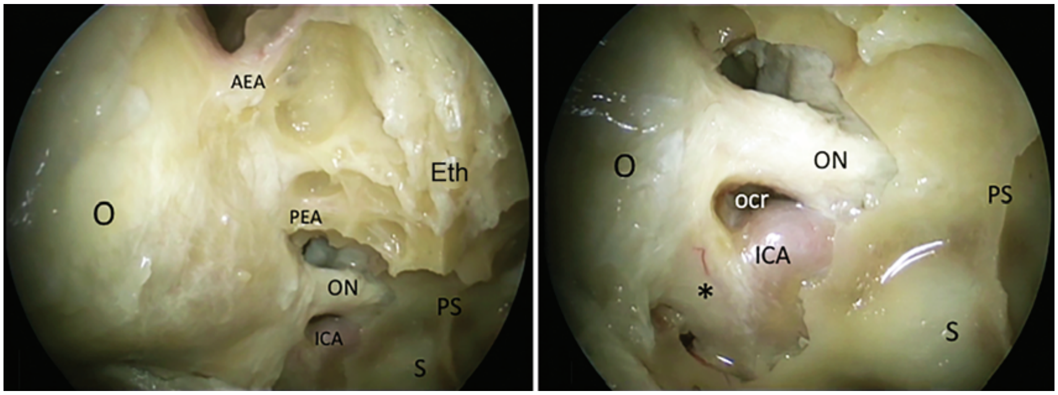

FIG. 3. Left: Endoscopic endonasal right optic nerve decompression. Vision through a 30° endoscope. **Right:** Close-up view of the optic nerve and surrounding structures. Eth = ethmoid plate; ICA = internal carotid artery; *asterisk* indicates proximal dural ring. Figure is available in color online only.

the posterior ethmoidal arteries that are located laterally to the cribriform plate (Fig. 3 left). Bone was also removed from the carotid protuberances and superior orbital fissure to highlight the key anatomical relationships between the main neurovascular structures of this region of the skull base. We note that in clinical scenarios, such extended bone removal may not be required; tailored bone opening is suggested according to the disease-specific management.

A close-up exploration of the opticocarotid region highlighted the proximal dural ring of the internal carotid artery and its relationships (Fig. 3 right). This dural ring, which surrounds the internal carotid artery, courses obliquely over the artery and afterward it blends smoothly into the periorbita. After bony decompression, the intracanalicular dura can be opened up to the level of the tuberculum sellae. This allows exposure of the intracranial part of the optic nerve, as well as the ophthalmic artery branching off of the supraclinoid tract of the internal carotid artery and then running, in most cases, in an inferomedial direction. Hence, the course of the ophthalmic artery, which typically lies inferomedial to the optic nerve, can be better appreciated using a 30° endoscope.

Endoscopic Transorbital Approach

The transorbital eyelid endoscopic route permits access to the most lateral and superior aspects of the optic canal, which lay medially to the superior orbital fissure. The orbital lateral wall is drilled to gain adequate access to the corridor. Lateral and posterior aspects of the sphenoid bone greater wing and the inner surface of the frontal process of the zygoma are removed to create enough room to work, and to mobilize superior orbital fissure contents to expose the optic nerve and to reduce the retraction over the eye. Following the lesser sphenoid wing, and pushing inferomedially the orbit with its content, the optic canal was exposed.

From this perspective, the optic canal is located in a deeper plane and it is surrounded by the superior orbital fissure, laterally, and the posterior ethmoidal artery running in its foramen, medially. Thus the optic canal has been opened in its superior and lateral surface and the optic nerve follows in its intracranial segment, where it merges with the contralateral to form the optic chiasm. The most superior aspects of the superior orbital fissure, the internal carotid artery and the optic nerve, were clearly exposed (Fig. 4). Finally, a panoramic view of the optic nerve after both endonasal and transorbital optic canal removal demonstrates the 360° optic nerve decompression.

Transcranial Exploration

The pterional route allowed an overview of the full decompression achieved by combining the endonasal and transorbital routes. Microscopic and endoscopic views have been provided, showing the intracanalicular optic nerve up to its intracranial portion and optic chiasm.

Morphometric Analysis

To obtain a virtual analysis of the 2 pathways, a computer-based simulation was obtained with the aid of the Dextroscope. Virtual length of the surgical corridor and angle of approach to the optic canal were provided by the system. Accordingly, we found that virtual lengths of the surgical corridor to reach the optic canal were 39.6 mm for the transorbital route and 52.9 mm for the endonasal one (Fig. 5).

On the other hand, virtual reality values of the angle of approach to the optic canal were 46.8° for the transorbital approach and 23.8° for the endonasal route. According to this virtual analysis based on a computer simulation, the transorbital route provides a shorter way to the optic nerve with a wider surgical angle compared with the endonasal one (Table 1).

Quantitative Analysis of Bone Removal

The quantitative analysis of optic canal removal showed that the endoscopic endonasal approach allowed the removal of the most inferomedial aspect of the canal (Fig. 6). In particular, with this route, the bone removal can be extended by an average of 168.0° (range 141.2°–188.2°) in an inferomedial fashion. On the other hand, the transorbital endoscopic route permits removal of the superolateral aspect of the canal, by an average of 192.0° (range 171.8°–218.8°).

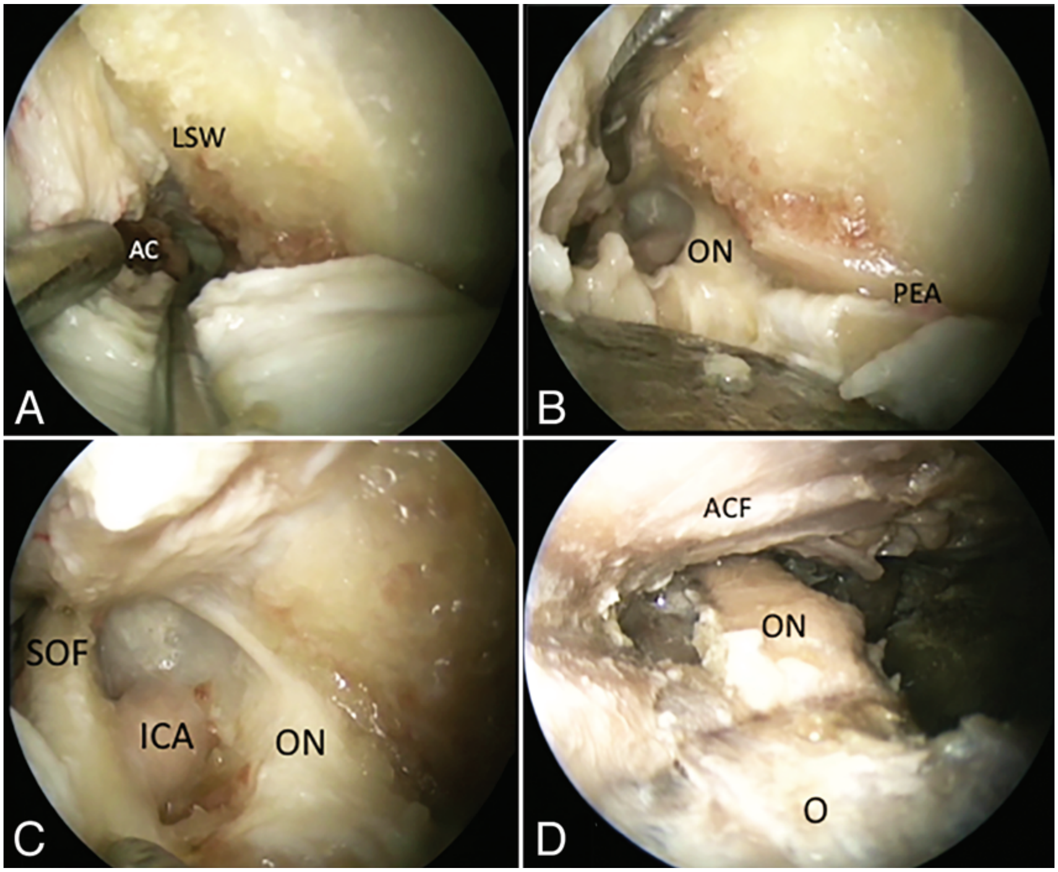

FIG. 4. Endoscopic (30° lens) transorbital stepwise dissection to the right optic canal. Removal of the anterior clinoid process (**A**) is followed by visualization of the optic nerve running in its canal (**B**). Close-up view of the main neurovascular structure surrounding the optic nerve (**C**). Endoscopic transorbital optic nerve decompression performed via both endonasal and transorbital pathway (**D**). AC = anterior clinoid; ACF = anterior cranial fossa; LSW = lesser sphenoid wing. Figure is available in color online only.

Considering the total circumference of the optic canal (360°), the transorbital route achieved a mean of 53.3% removal in the most superolateral portion of the optic canal, whereas the endonasal approach provided a mean of 46.7% bone removal in the most inferomedial part. The difference between the 2 approaches was found to be statistically significant for the transorbital approach ($p = 0.0029$, i.e., $p < 0.05$; Table 2).

Discussion

Several pathologies, both extracranial (orbital) and intracranial, can cause optic neuropathy. The visual tract may also be affected by head trauma, specifically to the frontoorbital region. Compression of the optic nerve leading to visual deficits may occur either because of a fracture of the bony canal or as the result of intraneural contusion and hemorrhage, secondary vasospasm and venous occlusion, edema and compartment syndrome, and/or necrosis.[23] Among ophthalmological diseases, Graves orbitopathy may be considered the leading cause.[7,9,29]

Bone diseases (e.g., Paget,[19] Crouzon,[49] and fibrous dysplasia) can be considered as other conditions determining compressive optic nerve neuropathy, as well as benign idiopathic intracranial hypertension.[42] Under these conditions, surgical optic nerve decompression may be indicated[17] and, eventually, may also represent a valid alternative for those patients harboring pseudotumor cerebri.[20,35,36,42,46]

Lesions of the suprasellar and parasellar regions, particularly meningiomas (including tuberculum sellae, clinoidal, and sphenoorbital meningiomas), may often cause loss of vision due to compression of the intracranial and/or intracanalicular segments of the optic nerve.[34] In cases of meningiomas, however, it should not be underestimated that the hyperostosis involving the optic canal may cause an irreversible nerve compression.[37,44] Finally, nerve compression can result from rare optic nerve sheath meningiomas, which, albeit slowly progressive, feature an unremitting loss of vision.[43]

In the past decades, several transcranial approaches (that is, the pterional, supraorbital, or orbitozygomatic routes) have been successfully used to achieve an effective decompression of the optic nerve. All techniques aim to split the falciform ligament, extradurally, to an anterior clinoidectomy and optic canal unroofing. In an attempt to reduce morbidity and mortality, minimally invasive

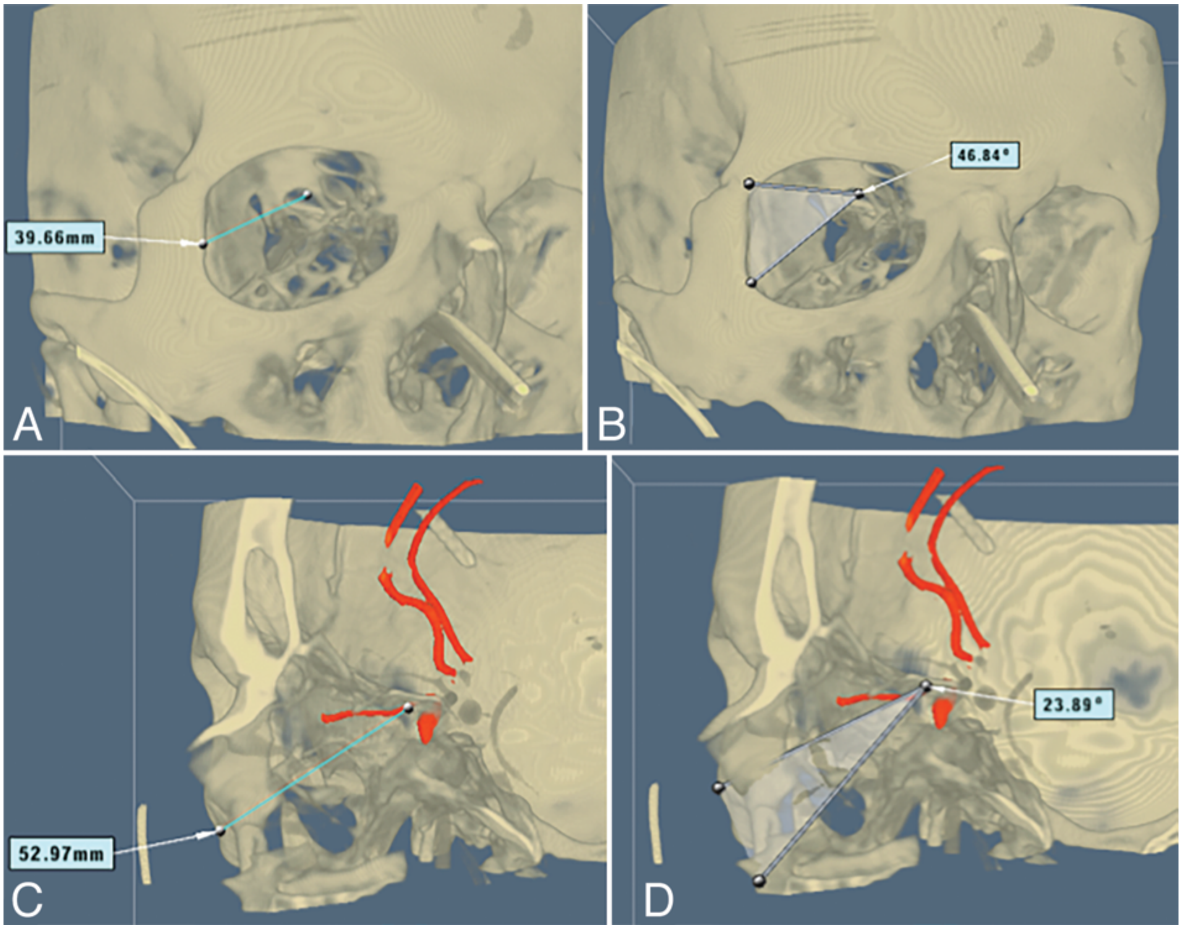

FIG. 5. Morphometric analysis of the endoscopic transorbital and endonasal routes to the optic nerve obtained with the aid of the Dextroscope. Virtual surgical length (**A**) and virtual angle of attack to the optic canal (**B**) via the transorbital route; virtual surgical length (**C**) and virtual angle of attack to the optic canal (**D**) via the endonasal route. Figure is available in color online only.

routes, such as the endoscopic endonasal and the transorbital, to access the optic canal area have been suggested more recently.[1,33]

The transnasal endoscopic route, initially reserved for the management of paranasal sinuses diseases, was deemed an alternative corridor to approach different areas of the midline skull base and, therefore, to treat selected lesions involving those areas.

According to the literature, open approaches allow a wide decompression of the optic nerve. There are, however, inner limitations related to the approach itself—during the conventional transcranial route, it remains difficult to access the inferomedial aspect of the ipsilateral optic canal.

This concept is of utmost importance, especially when dealing with tuberculum sellae meningiomas that can occupy the optic canal at its inferomedial aspect. From a surgical standpoint, the involvement of an optic canal compartment influences the choice of surgical approach between endoscopic and open surgical treatment. Successful surgical outcomes and likelihood of recurrence mostly depend on the possibility of accessing and removing the tumor component within the canal. In these cases, a detailed preoperative study focused on the entity and degree of optic canal invasion is critical for the selection of the optimal approach. According to a recent study,[38] a 1-mm spoiled gradient coronal MRI scan with contrast can be considered useful to determine optic canal invasion in anterior skull base meningiomas.

Abhinav et al.[1] defined the feasibility of the endoscopic endonasal technique with an anatomical study of the optic canal decompression from both endonasal and transcranial perspectives. A 270° decompression of the optic canal was performed endonasally and then confirmed with a transcranial exposure of the optic nerves and 3D CT reconstructed imaging. However, even in a well-pneumatized sphenoid sinus, a 270° decompression including the

TABLE 1. Computer-based morphometric data of endonasal and transorbital approaches to the optic canal

Route	Virtual Surgical Length (mm)	Virtual Angle of Approach (°)
Endonasal	52.97	23.89
Transorbital	39.66	46.84

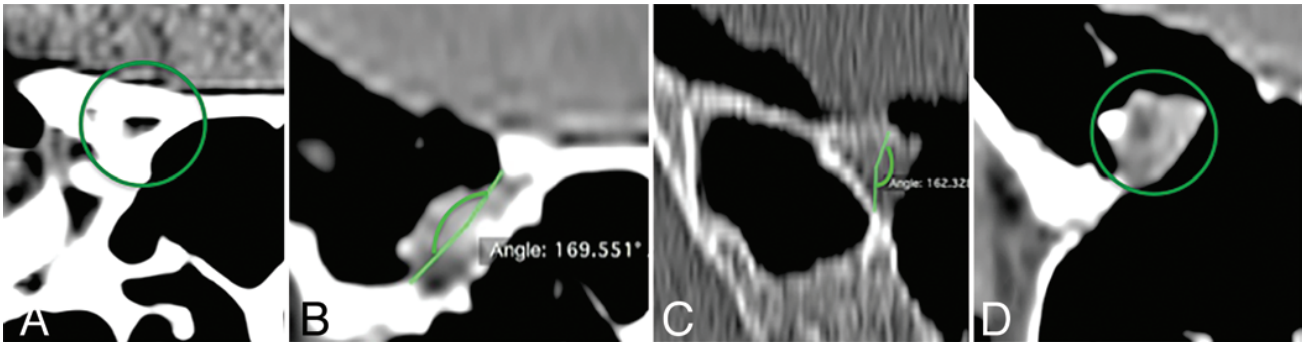

FIG. 6. Quantitative assessment of progressive removal of the bony optic canal. **A:** Predissection CT scan. **B:** Post-transorbital approach. **C:** Postendonasal approach. **D:** Total decompression of the optic nerve. Figure is available in color online only.

superior optic roof is not easily achievable via the endonasal route.[1,18]

It cannot be underestimated that the degree of sphenoid sinus pneumatization can influence the amount of bone removal from the optic nerve canal. A wide variability in terms of exposure of the medial wall of the optic canal inside the sphenoid sinus has been recently reported; this may limit the surface area of nerve available for endoscopic endonasal decompression.[24] However, even in a sphenoid sinus that is not well pneumatized, that is, a conchal type, the optic canal may be localized and decompressed in its medial aspect.

Furthermore, the degree of pneumatization is an important consideration in the clinical setting. The extensive drilling required to decompress the optic canal in a sphenoid sinus that is not well pneumatized could cause thermal damage to the optic nerve.

In the clinical scenario, the feasibility of optic canal exploration with the transnasal approach in patients with tuberculum and planum sphenoidale meningiomas has been already described.[21,28,30,48]

Koutourousiou et al. reported a large series of 75 suprasellar meningiomas treated via the endoscopic endonasal route. They found that 26.7% of the lesions involved the medial aspect of the optic canal; nevertheless, this feature did not change the partial or total tumor removal rates.[32] Furthermore, they achieved a 270° decompression of the intracanalicular optic nerve by means of the endoscopic endonasal approach after removing the medial wall, floor, and roof of the canal.

On the other hand, the most superolateral aspect of the optic canal seems to be more difficult, if not impossible, to access from an endonasal approach. Data from the literature show that trans- and supraorbital approaches have recently become an option for accessing the anterior and middle skull base via a lateral trajectory.[5,6,12,16,33,39,40,47] Thirty years ago, Call[8] was the first to describe optic nerve decompression through a transorbital approach in a case series of 8 patients. Afterward, the widespread acceptance of endoscopic skull base surgery for the management of different skull base pathologies pushed the development of new strategies and the refinement of existing ones, that is, the transorbital route. In these terms, this lateral-to-medial trajectory, with the aid of the endoscope, may be a valuable route to address the superolateral corner of the optic canal as well as other anterior and middle cranial fossa targets.[11] Thus, the transorbital neuroendoscopic surgery, including different transorbital endoscopic corridors that do not require removal of the orbital rim or the frontal bone,[33] has been recommended for a variety of pathologies.

In a recent publication, Dallan et al.[16] proposed the superior eyelid approach to access the lateral and superolateral walls of the orbit and, through this window, selected anterior and middle cranial fossa lesions, such as the sphenoorbital meningiomas. Hence, the superior eyelid transorbital approach, with the aid of the endoscope, may also be proposed as a means to access the optic canal in a minimally invasive fashion. In certain ways, it can be considered the equivalent of the frontoorbitozygomatic ap-

TABLE 2. Quantitative analysis of optic nerve decompression via endonasal and transorbital approaches

	Approach (°)		Statistical Data
Specimen	Endonasal	Transorbital	
1			
Rt side	155.5	204.5	
Lt side	188.2	171.8	
2			
Rt side	180.2	179.8	
Lt side	165.5	194.5	
3			
Rt side	141.2	218.8	
Lt side	148.4	211.6	
4			
Rt side	177.1	182.9	
Lt side	165.2	194.8	
5			
Rt side	179.5	180.5	
Lt side	179.5	180.5	
Mean	168.0 (46.67%)	192.0 (53.33%)	$p < 0.05$; t value 3.4420; df 18
SD	15.5	15.5	

df = degrees of freedom; t = Student's t-test value.

TABLE 3. Potential indications for optic nerve decompression via endonasal, transorbital, or combined endonasal-transorbital approach

Indication	Endonasal	Transorbital	Combined
Primary brain tumors	Tuberculum sellae meningioma	Sphenoorbital meningioma	Optic nerve sheath meningioma
Primary bone diseases	Osteoma, Paget, Crouzon, fibrous dysplasia	Osteoma, Paget, Crouzon, fibrous dysplasia	Osteoma, Paget, Crouzon, fibrous dysplasia
CSF pathology	Benign idiopathic hypertension	Benign idiopathic hypertension	Benign idiopathic hypertension
Traumatic disease	Foreign body or fractures at the medial side of the optic canal	Foreign body or fractures at the lateral side of the optic canal	

proach, but with several benefits (e.g., no skin incisions, no brain retraction, shorter surgical time, faster recovery, and potentially decreased trauma to the orbital structures).

In this study, the morphometric analysis performed in a virtual realty setting demonstrated that the simulation of the transorbital path might grant a shorter surgical corridor with a wider virtual angle of approach (39.6 mm; 46.8°) compared with the simulation of the endonasal route (52.9 mm; 23.8°). The pterional transcranial exploration, performed after both routes, allowed demonstration from above that the optic nerve was totally freed from its bony canal.

Therefore, the endonasal pathway permits access to the most inferomedial part of the optic canal (by an average of 168°), whereas the transorbital route allows access to the superolateral aspects of the canal (by an average of 192°). Both surgical routes can be considered complementary to obtain a 360° decompression of its intracanalicular portion.

The specific circumstances and clinical scenarios in which one technique should be preferred over the other have not been clearly defined in the pertinent literature. Our experience over the years with the endoscopic endonasal approach has given us the opportunity to treat some pathologies via the medial-to-lateral corridor (endonasal) and also to define indications and limits for this route. The relatively novel transorbital corridor has been described and used in selected pathologies with specific intracanalicular extension, but a clear definition of the indications and pitfalls of this route has not yet been presented. This purely anatomical contribution has the primary aim of demonstrating that the endoscopic transorbital pathway may solve the problem of reaching the most lateral and superior portion of the optic canal, thus providing a complementary route to the well-known endonasal approach. Using such a transorbital corridor, we aimed to overcome the limits of endonasal surgery, thus providing an alternative route in cases of lesions that involve the orbit and compress the optic canal lateral to medial.

From a potential clinical standpoint, a complete decompression of the optic nerve through both the endonasal and the transorbital routes could be planned mainly in 2 circumstances: 1) when the lesion surrounds the optic canal, as often happens in primary bone pathologies, that is, Paget, fibroosseous dysplasia, and/or other ossifying diseases or in cases of optic nerve sheath meningiomas; and 2) after failure of first surgery using 1 of the 2 routes, e.g., if the patient does not show clinical improvements after an endoscopic endonasal (or transorbital) decompression of the optic nerve.

Although this is a purely anatomical study, we tried to provide a guideline that can be useful for understanding when it is potentially advisable to use one approach versus the other. Furthermore, we list some pathologies that may be treated via the endonasal, transorbital, or both pathways in Table 3.

Study Limitations

Cadaveric specimens are useful models to investigate surgical approaches, but they do not fully render the clinical environment. In particular, some considerations have to be made concerning the endoscopic transorbital approach. The amount of orbit content retraction that can be tolerated in a true clinical setting may be inferior, although the retractor has been well tolerated and has not shown any important complications.[15] Intraoperative globe tonometry might be useful to determine the maximal safe degree of globe retraction. Alternatively, intermittent relief from retraction during surgery might be useful to protect the globe when a longer or higher tension is needed intraoperatively.

Conclusions

Exploration and decompression of the optic canal can be accomplished via both endonasal and transorbital endoscopic routes. These 2 approaches can be considered complementary, because they can provide a complete 360° opening of the intracanalicular portion of the optic nerve. Further studies and surgical case series are mandatory to confirm the effectiveness of these approaches, thus refining the proper indications for each of them.[13,15]

To our knowledge, this is the first study to provide a quantitative assessment of bone removal from the optic canal, with the combination of medial-to-lateral endonasal and lateral-to-medial transorbital endoscopic paths.

Acknowledgments

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ORIGINAL ARTICLE

Surgical Freedom Evaluation During Optic Nerve Decompression: Laboratory Investigation

Alberto Di Somma[1], Norberto Andaluz[2], Steven L. Gogela[2], Luigi Maria Cavallo[1], Jeffrey T. Keller[2], Alberto Prats-Galino[3], Paolo Cappabianca[1]

BACKGROUND AND OBJECTIVE: **Various surgical routes have been used to decompress the intracanalicular optic nerve. Historically, a transcranial corridor was used, but more recently, ventral approaches (endonasal and/or transorbital) have been proposed, individually or in combination. The present study aims to detail and quantify the amount of bony optic canal removal that may be achieved via transcranial, transorbital, and endonasal pathways. In addition, the surgical freedom of each approach was analyzed.**

METHODS: **In 10 cadaveric specimens (20 canals), optic canals were decompressed via pterional, endoscopic endonasal, and endoscopic superior eyelid transorbital corridors. The surgical freedom and circumferential optic canal decompression afforded by each approach was quantitatively analyzed. Statistical comparison was carried using a nonpaired Student *t* test.**

RESULTS: **An open pterional transcranial approach allowed the greatest area of surgical freedom (transcranial, 109.4 ± 33.6 cm^2; transorbital, 37.2 ± 4.9 cm^2; endonasal homolateral, 10.9 ± 5.2 cm^2; and endonasal contralateral, 11.1 ± 5.6 cm^2) with widest optic canal decompression compared with the other 2 ventral routes (transcranial, 245.2; transorbital, 177.9; endonasal, 144.6). These differences reached, in many cases, statistical significance for the transcranial approach.**

CONCLUSIONS: **This anatomic contribution provides a comprehensive evaluation of surgical access to the optic canal via 3 distinct, but complementary, approaches: transcranial, transorbital, and endonasal. Our results show that, as expected, a transcranial approach achieved the widest degree of circumferential optic canal decompression and the greatest surgical freedom for manipulation of surgical instruments. Further surgical experience is necessary to determine the proper surgical indication for the transorbital approach to this disease.**

INTRODUCTION

Over the past few decades, several approaches have been proposed for decompression of the optic canal.[1-18] Historically, transcranial routes (i.e., pterional, supraorbital, and orbitozygomatic) were preferred for optic nerve decompression. In an effort to reduce morbidity, focus has shifted toward minimally invasive approaches, with endonasal and transorbital corridors gaining increasing support in the current literature.[7,19-22] Recent anatomic contributions have eloquently quantified the extent of bony optic canal decompression that can be obtained via ventral[19] and transcranial approaches, both individually and in combination. The extent to which a surgeon may maneuver operating instruments using these approaches has not yet been analyzed. This concept is commonly described in the literature as surgical freedom (i.e., the maximum range of surgical instruments within the operative field).[23] Given the limited operative field and the abundance of critical neurovascular structures in the region, a detailed analysis of the exposure afforded by each of these routes is lacking to refine the indications and support the choice of approach according to the disease causing optic nerve compression.

Key words
- Endoscopic endonasal
- Endoscopic transorbital
- Optic nerve
- Quantitative analysis
- Surgical freedom
- Transcranial optic nerve decompression

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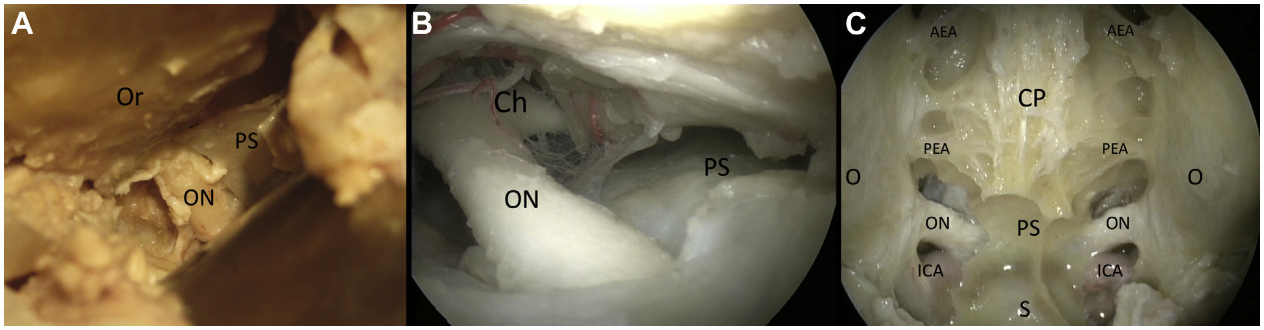

Figure 1. Anatomic cadaveric pictures showing optic nerve decompressed via pterional (**A**), endoscopic transorbital (**B**), and endoscopic endonasal (**C**) paths. The relationships with the surrounding structures are highlighted. AEA, anterior ethmoidal artery; Ch, optic chiasm; CP, cribriform plate; ICA, internal carotid artery; O, orbit; ON, optic nerve; Or, orbital roof; PEA, posterior ethmoidal artery; PS, planum sphenoidale; S, sella.

A quantitative understanding of surgical freedom combined with recent anatomic data could provide significant insight when determining the best approach for optic canal decompression for various diseases. This is the basis for the present laboratory investigation, in which we carried out a quantitative comparison of surgical freedom when approaching the optic canal via 3 different routes: transcranial, transorbital, and endonasal. In addition, we sought to provide a volumetric analysis of the bony removal afforded by each approach and a qualitative assessment of the effectiveness of each route, both alone and in combination. To our knowledge, this is the first contribution to the literature providing a comprehensive evaluation of surgical access to the optic canal via these 3 distinct but complementary paths.

METHODS

Ten adult cadaveric specimens, without known intracerebral abnormality, were dissected. Anatomic dissections were performed at the Laboratory of Neuroanatomy (Goodyear Laboratory) of the University of Cincinnati (Ohio, USA) and at the Laboratory of Surgical Neuroanatomy of the University of Barcelona (Spain). Cadavers were registered with the Brainlab Curve (Brainlab, Feldkirchen, Germany) for the acquisition of landmark points used in the calculation of operative exposure. A registration correlation tolerance of 2 mm was considered acceptable.

Dissections began macroscopically and then proceeded microscopically using a Leica operating microscope (Leica Microsystems Inc., Buffalo Grove, Illinois, USA). Endoscopy was performed using a rigid 4-mm-diameter endoscope, 14 cm long, with 0° and 30° rod lenses (Stryker, Kalamazoo, Michigan, USA). These pieces of equipment were connected to a light source through a fiber-optic cable and a video camera. Images were captured using a high-definition digital video system (Stryker). A high-speed drill and craniotome were used for bony removal. In 5 specimens, both transcranial and endonasal approaches were performed, whereas in the remaining 5 cadaveric heads both the transorbital and endonasal routes were evaluated.

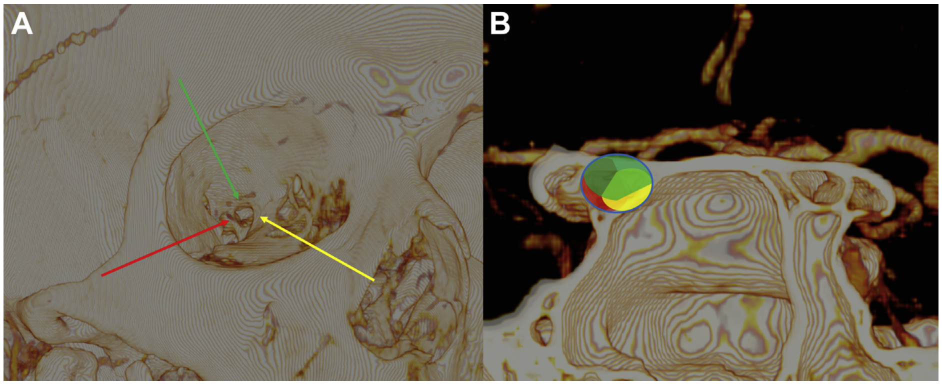

Figure 2. Three-dimensional representation obtained with Osirix MD software (OsiriX [Osirix Foundation]) of the optic nerve decompression via different surgical routes (**A**). The degree of optic canal removal is shown in coronal section (**B**). Transcranial pterional (*green*); transorbital (*red*); endonasal (*yellow*).

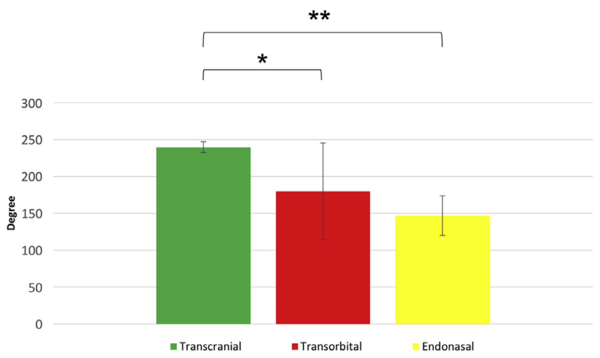

Figure 3. Degree of optic canal removal obtained via the different surgical approaches (transcranial in *green*; transorbital in *red*; endonasal in *yellow*). The difference between transcranial and endonasal optic canal removal was found to be strongly statistically significant ($**P < 0.01$). On the other hand, the transcranial optic nerve decompression achieved a higher and statistically significant degree of bone removal compared with the transorbital approach ($*P < 0.05$).

Transcranial Approach

Cadaveric heads were positioned supine, fixed in a Mayfield Modified Skull Clamp (Integra, Plainsboro, New Jersey), rotated 5°—10° to the contralateral side, and extended 10°—15°. A curved incision was made immediately behind the hairline, extending from the zygoma to the midline. The temporalis muscle was then dissected subperiosteally and retracted in a single myocutaneous flap until the pterion was exposed. A standard pterional craniotomy and extradural anterior clinoidectomy were performed following our previously published technique[24] using a Budde Halo Retractor System (Integra) for exposure. Decompression proceeded with an operating microscope (Leica Microsystems) via a combination of a high-speed 3-mm drill and microdissectors. Bony decompression included the complete unroofing of the superolateral optic canal and optic strut, stopping before violation of the sphenoid sinus. A C-shaped incision was then made in the dura and optic nerve decompression completed by sharply dividing the falciform ligament and optic nerve sheath. Thin-cut computed tomography scans were then repeated to confirm circumferential decompression. In 4 specimens, the transcranial approach preceded the endonasal procedure, with computed tomography imaging between stages to ensure accuracy of measurements.

Endoscopic Transorbital Approach

Specimens were positioned supine, pinned, and fixed with a Mayfield head holder, rotated 5° laterally to the contralateral side. The skin incision was placed in the superior eyelid in a supratarsal skin crease, as previously described.[25] The orbicularis oculis muscle was divided parallel to its fibers and the frontal process of the zygoma was exposed laterally. The periosteum covering the zygoma was cut and dissected sharply toward the orbit, where it continued with the periorbita. This layer was followed to the orbital septum and then into the orbit using a number 1 Penfield dissector. Dissection proceeded in this plane until the inferior and superior orbital fissures were reached. At this point, a 0° endoscope was introduced into the upper portion of the surgical window to monitor the subsequent steps. A malleable retractor was placed to deflect the orbital contents inferomedially and to create space for further dissection, because the optic canal is medial to the superior orbital fissure. Bony decompression of the optic canal was achieved by removing portions of the greater and lesser wings of the sphenoid, which form the lateral portion of the optic canal. In some specimens, anterior clinoidectomy was required for adequate optic decompression from this approach.

Endoscopic Endonasal Approach

Through a binostril approach, a middle turbinectomy, posterior ethmoidectomy, wide sphenoidotomy, and posterior nasal septectomy were performed. Removal of the uncinate process and medial antrostomy allowed for access to the inferior and medial orbital walls. The medial orbital wall, namely the thin lamina papyracea, was removed to expose the proximal optic nerve as it exits the annulus of Zinn and enters the canal. The medial optic canal was unroofed in a proximal to distal fashion to the lateral edge of the tuberculum sellae via a blunt dissector and gentle drilling, uncovering the intracanalicular portion of the optic nerve. The optic sheath was then opened using a sickle blade, taking care to avoid injury to the annulus of Zinn. The sheath was opened superiorly to avoid injuring the ophthalmic artery, which courses inferior to the nerve.

Data Acquisition and Statistical Analysis

Osirix MD software (OsiriX [Osirix Foundation, Geneva, Switzerland]) was used to quantitatively analyze the degree of bony optic canal decompression. Then, the surgical freedom was calculated as described by de Notaris and Prats-Galino[23] and Dallan et al.[26] using the midpoint of the intracanalicular optic nerve as the base for the stereotactic pointer.

Table 1. Quantitative Analysis of Optic Nerve Decompression Via Pterional Transcranial, Endoscopic Superior Eyelid Transorbital, and Endoscopic Endonasal Approaches

				P Value		
	TC	**TO**	**E**	**TC versus TO**	**TO versus E**	**TC versus E**
Angle of decompression, degrees (%)	245.20 ± 18.8 (68.11)	177.90 ± 65.61 (49.93)	144.61 ± 26.87 (40.22)	0.0311	0.0891	<0.01

P value, nonpaired Student *t* test; percentages refer to the total volume of the optic canal (100%).
TC, pterional transcranial; TO, endoscopic superior eyelid transorbital; E, endoscopic endonasal.

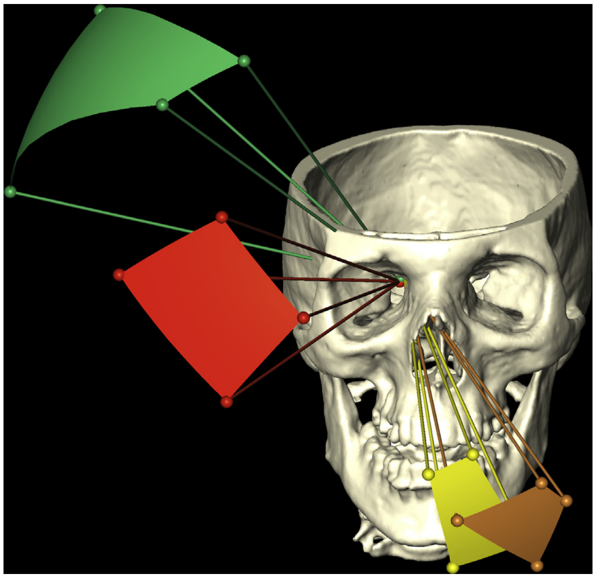

Figure 4. Three-dimensional representation in a ventral perspective of the surgical freedom areas calculated after different approach to the optic nerve. Transcranial pterional (*green*), transorbital (*red*), endonasal homolateral (*yellow*), and endonasal contralateral (*orange*). The three-dimensional reconstruction has been obtained in an example specimen using Amira Visage Imaging.

For each approach, points for calculating surgical freedom were acquired as follows: p_1, the point of maximal cranial extension in the direction of the nasion; p_2, the point of maximal caudal extension in the cephalad direction to the vertex; p_3, the point of maximal lateral extension toward the external acoustic meatus; and p_4, the point of maximal medial extension toward the nasal septum. Cartesian coordinates of each point were then obtained from the Brainlab working station, which yielded 3 vectors that were used to delineate 2 juxtaposed triangles. Surgical freedom was then calculated as the sum of the area of these 2 triangles. The horizontal angle of attack was retrieved by merging p_1 and p_2 with the optic nerve point, whereas the vertical angle of attack was measured by connecting p_3 and p_4 with this target.

The virtual three-dimensional model of the surgical freedom related to each routes was created using Amira Visage Imaging (Amira Visage Imaging Inc., San Diego, California, USA). Bony structures were segmented and surgical freedom areas were then represented using advanced instruments for measurement and quantification provided by the Amira workstation.

All data were uploaded into Microsoft Excel, and the nonpaired Student t test function was used to calculate statistical differences among approaches.

RESULTS

Anatomic Observations

A pterional craniotomy combined with extradural clinoidectomy allowed for extensive decompression of the superolateral optic canal. After drilling down the lesser sphenoid wing, the lateral limit of the superior orbital fissure was identified for anatomic orientation to the optic canal. Along with unroofing of the superior canal, the anterior clinoid process and optic strut were removed in an extradural fashion. Next, the falciform ligament was incised, thus achieving a wide superolateral decompression of the intracanalicular optic nerve with relative ease and safety (**Figure 1A**).

Alternatively, the transorbital pathway permitted access to the most lateral aspect of the optic canal from a ventrolateral vantage point. The optic canal was exposed by following the lesser sphenoid wing and retracting the orbital contents inferomedially. From this window, borders of the optic canal could be appreciated, namely the superior orbital fissure laterally and the posterior ethmoidal artery running in its foramen medially. The optic canal was then decompressed laterally and the optic nerve could be followed intracranially to the optic chiasm (**Figure 1B**).

The endonasal approach provided access to the inferomedial optic canal that protrudes into the sphenoid sinus. Decompression of this border of the optic canal proceeded after removal of the lamina papyracea, as described earlier. The exposure of the intracanalicular portion of the optic nerve, surrounded by the optic sheath, was followed to the orbital apex, where the nerve passes through the annulus of Zinn at the proximal limit of the canal. After bony decompression, the intracanalicular dura was opened to the level of the tuberculum sellae, exposing the intracranial part of the optic nerve, as well as the ophthalmic artery as it branches off the supraclinoidal internal carotid artery and courses most commonly in the inferomedial canal (**Figure 1C**).

Decompression Analysis

Quantitative analysis of the degree of optic canal decompression obtained through each of the 3 operative routes showed significant

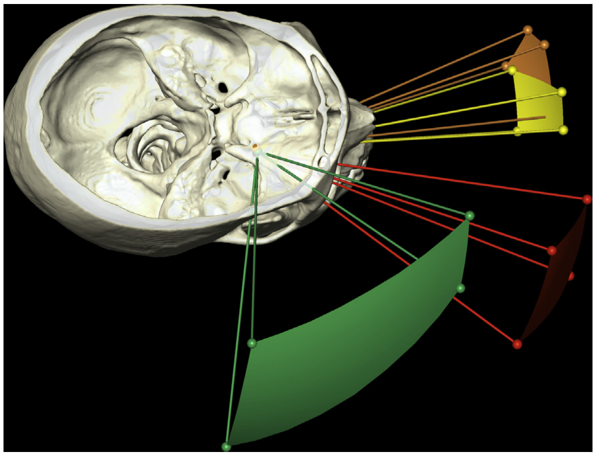

Figure 5. Representation of the surgical freedom with a three-dimensional reconstruction oriented in the axial plane and showing the different surgical freedom areas to the optic nerve. Transcranial pterional (*green*), transorbital (*red*), endonasal homolateral (*yellow*), and endonasal contralateral (*orange*). The three-dimensional reconstruction has been obtained in an example specimen using Amira Visage Imaging.

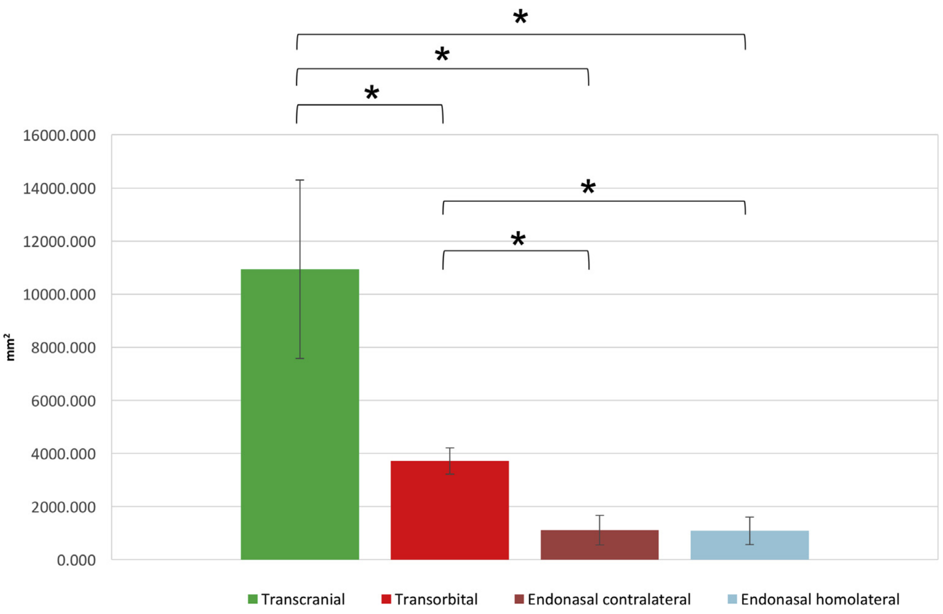

Figure 6. Surgical freedom evaluation during transcranial pterional (green), transorbital (red) and endonasal homolateral (pink) and contralateral (blue) approaches to the optic canal. The increased maneuverability of the transcranial route was statistically significant compared with all other routes ($*P < 0.01$). Further, the surgical freedom obtained with the transorbital approach was significantly greater than endonasal approaches ($*P < 0.01$).

differences between 3 corridors (Figure 2A). The pterional approach with anterior clinoidectomy provided the largest circumferential decompression with a mean of 245.2° (range, 211.0°–277.5°). Conversely, the transorbital endoscopic pathway afforded an average of 177.9° of circumferential decompression (range, 171.8°–273.5°), whereas the endoscopic endonasal route averaged 144.6° (range 109.8°–180.2°) circumferential decompression (Figure 2B).

When considering the total circumference of the optic canal (360°), the transcranial pathway allowed for decompression of the superolateral 68.1% circumference of the optic canal; the transorbital route provided removal of the most lateral 49.9% of the optic canal; and the endonasal approach afforded a 40.2% decompression of the most inferomedial aspect of the canal. Only the difference between the transcranial and endonasal approaches was found to be statistically significant ($P < 0.01$) (Figure 3, Table 1).

Surgical Freedom and Angle of Attack

An open pterional transcranial approach allowed the greatest area of surgical freedom (transcranial, 109.4 ± 33.6 cm^2; transorbital, 37.2 ± 4.9 cm^2; endonasal homolateral, 10.9 ± 5.2 cm^2; and endonasal contralateral, 11.1 ± 5.6 cm^2), respectively (Figures 4 and 5). The increased maneuverability of the transcranial route was statistically significant compared with all other routes, whereas the surgical freedom of the transorbital approach was significantly greater than that of the endonasal route (Figure 6, Table 2).

Further analysis showed that the angle of attack to the optic nerve in the horizontal plane was greatest for the transcranial route (73.632 ± 8.57°), followed by the transorbital approach (27.40 ± 3.38°), and the endonasal ipsilateral (14.12 ± 2.62°) and contralateral (13.54 ± 3.38°) corridors, respectively. These differences also reached statistical significance (Figure 7).

The angle of approach to the optic nerve attained in the vertical plane was greater for the transcranial versus the transorbital approach, although this did not reach statistical significance (Figure 8). However, both the ipsilateral and contralateral endonasal pathways provided a statistically significantly lower vertical angle of attack to the optic nerve than did both transcranial and transorbital routes (Table 3).

DISCUSSION

The results of this study show that the transcranial approach affords the greatest surgical freedom and degree of optic canal decompression compared with the alternative minimally invasive corridors to this region.

Several diseases, both extracranial and intracranial, may cause compressive optic neuropathy.[27-29] Anterior skull base meningiomas (ie, suprasellar and parasellar region, optic nerve sheath, or olfactory groove) represent the most common oncologic source of compression of the optic nerve in its canal. Tumors typically result in visual loss secondary to intracranial and/or intracanalicular compression of the optic nerve.[30,31] An

Table 2. Surgical Freedom Analysis During Pterional Transcranial, Endoscopic Superior Eyelid Transorbital, and Endoscopic Endonasal Contralateral and Homolateral Approaches for Optic Nerve Decompression

					P Value					
	TC	**TO**	**EC**	**EH**	**TC versus TO**	**TO versus EC**	**TO versus EO**	**TC versus EC**	**TC versus EO**	**EC versus EO**
Surgical freedom	10939.09 ± 3361.46	3717.91 ± 493.30	1114.52 ± 555.72	1091.03 ± 518.29	<0.01	<0.01	<0.01	<0.01	<0.01	0.931

P value, nonpaired Student *t* test.
TC, pterional transcranial; TO, endoscopic superior eyelid transorbital; EC, endoscopic endonasal contralateral; EH, endoscopic endonasal homolateral.

additional strangling effect may occur at the level of the optic canal as it transitions from its bony, rigid optic canal into the suprasellar region, where the optic nerve(s) and chiasm, denuded of any circumferential fixating structures, may be displaced and angulated at the level of the optic foramen.

Historically, transcranial approaches have been the preferred method for optic canal decompression. More recently, reports in the literature have gravitated toward endonasal and minimally invasive microscopic approaches in an effort to reduce morbidity and decrease hospitalization. Optic nerve decompression has also been reported using those techniques.[7]

In the present study, we performed a quantitative analysis of 3 different pathways that may be used to reach the optic canal: transcranial, transorbital, and endonasal. A pterional craniotomy allowed for wide decompression of the optic nerve However, with this route, it was difficult to access the inferomedial aspect of the ipsilateral optic canal. Recent literature has identified the transorbital and supraorbital corridors as viable options for access to the anterior and middle skull base.[1-11] Call et al.[32] were the first to describe optic nerve decompression through a transorbital approach in a series of 8 patients. Since that time, the increase of endoscopic skull base surgery for the management of a wide range of diseases has propelled both the development of new techniques and the refinement of established procedures (e.g., the transorbital approach). Accordingly, this ventromedial trajectory, with the aid of the endoscope, may be a valuable option for accessing the superolateral optic canal in addition to other anterior and middle cranial fossa disease in select situations. At this juncture, transorbital neuroendoscopic surgery has been advocated for a variety of indications, with or without removal of the orbital rim and/or frontal bone.[16] In a recent publication, Dallan et al.[10] adopted the superior eyelid approach to access the lateral and superolateral walls of the orbit in addition to anterior and middle cranial fossa lesions, for tumors such as spheno-orbital meningiomas. Combined with endoscopic visualization, this approach could be extrapolated to minimally invasive optic canal decompression. Although this approach addresses a similar region of the canal to the orbitopterional or fronto-orbitozygomatic approaches, it requires a minimal skin incision and shorter surgical time, necessitates zero brain retraction, potentially decreases idiopathic trauma to orbital structures, and allows for faster recovery.

The other ventral pathway that we analyzed in our study was the transnasal endoscopic route. Initially reserved for the management of paranasal sinus disease, this route has become widely accepted as a minimally invasive approach for a variety of locations of the skull base. This route includes endoscopic endonasal decompression of the orbit and optic nerve, which has become a valid treatment for thyroid-related orbitopathy and select cases of traumatic optic neuropathy.[1,3]

From a surgical standpoint, the location of optic canal compression should dictate the choice of surgical approach between endoscopic and open surgical approaches, especially in the case of tumor resection. Thus, comprehensive preoperative assessment of the location and degree of optic canal invasion is critical for selecting the optimal approach. Compression of the optic nerve in the superior part of its canal may mandate a

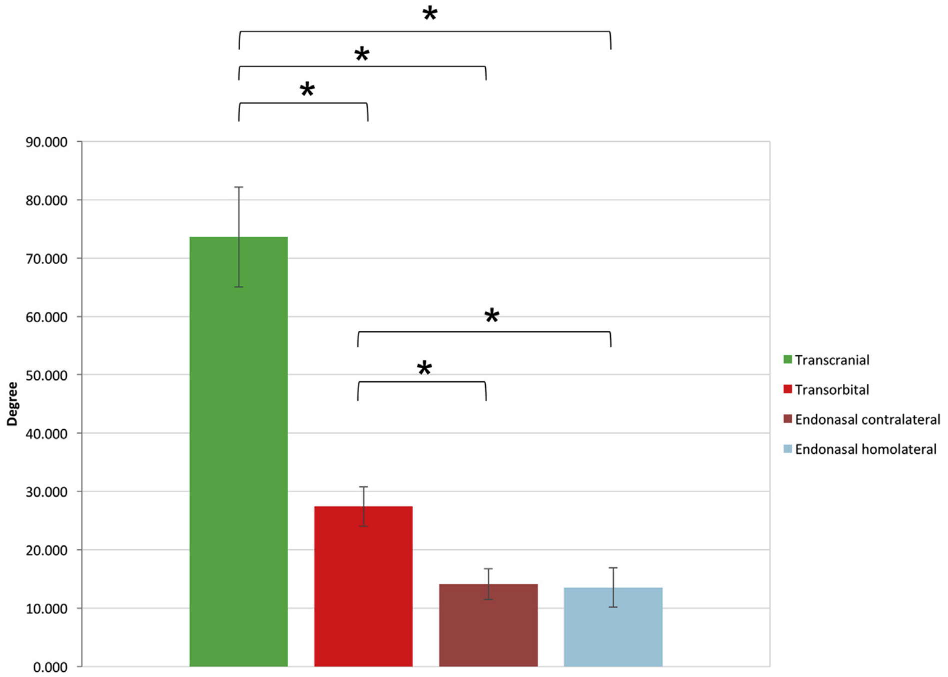

Figure 7. Horizontal angle of attack to the optic canal via the different routes used in the study. This angle of attack to the optic nerve in the horizontal plane was greatest for the transcranial route (*green*) when compared with all the other approaches (*$P < 0.01$). The transorbital horizontal angle of attack (*red*) was found to be greater compared with the one obtained with the endonasal contralateral (*pink*) and homolateral (*blue*) pathways (*$P < 0.01$).

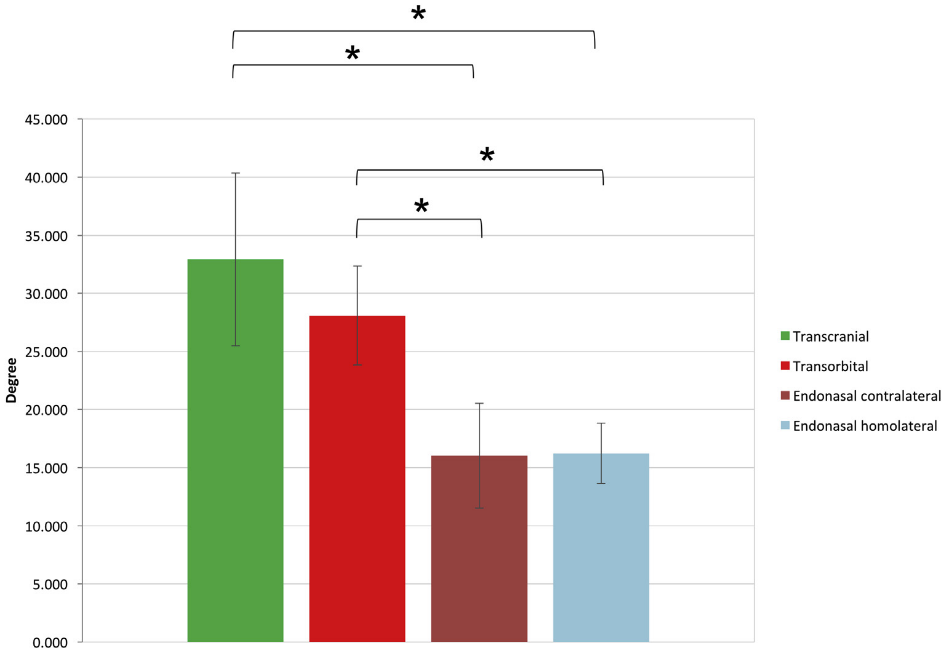

Figure 8. Vertical angle of attack to the optic canal. This angle of attack was greater for the transcranial (*green*) versus the transorbital (*red*) approach but this difference did not reach statistical significance. On the contrary, both transcranial and transorbital paths reserved greater vertical angles of attack if compared with the endonasal contralateral (*pink*) and homolateral (*blue*) routes (*$P < 0.01$).

Table 3. Angle of Attack During Pterional Transcranial, Endoscopic Superior Eyelid Transorbital, and Endoscopic Endonasal Contralateral and Homolateral Approaches for Optic Nerve Decompression

					P Value					
	TC	TO	EC	EH	TC versus TO	TO versus EC	TO versus EO	TC versus EC	TC versus EO	EC versus EO
Horizontal angle (°)	73.632 ± 8.57	27.40 ± 3.38	14.12 ± 2.62	13.54 ± 3.38	<0.01	<0.01	<0.01	<0.01	<0.01	0.7097
Vertical angle (°)	32.91 ± 7.42	28.08 ± 4.25	16.02 ± 4.50	16.22 ± 2.59	0.1324	<0.01	<0.01	<0.01	<0.01	0.9125

P value, nonpaired Student *t* test.
TC, pterional transcranial; TO, endoscopic superior eyelid transorbital; EC, endoscopic Endonasal Contralateral; EH, endoscopic endonasal homolateral.

transcranial approach, whereas a more inferomedial disease may suggest using a ventral route such as the endonasal route. The specific indications for the transorbital pathway have not yet been clarified in proper surgical series, and further surgical experience of this approach and associated repair techniques is wanting.

We show that a transcranial approach allows for the greatest surgical freedom and degree of optic canal decompression compared with other plausible minimally invasive corridors to this region. These approaches, which should be considered complementary, offer the skull base surgeon an array of options for treating disease in this area. A thorough, thoughtful evaluation of the disease causing optic nerve compression is mandatory to decide the best strategy and application of this full complement of approaches to the optic canal.

Limitations

Cadaveric specimens are useful models to investigate surgical approaches, but they do not fully replicate the clinical environment. Particularly concerning the endoscopic transorbital approach, the amount of orbital content retraction that may be tolerated in the operative versus laboratory setting must be considered. Orbital retraction has been well tolerated without any significant reported complications. Intraoperative globe tonometry might be a useful adjunct to determine the maximal safe degree of globe retraction. Alternatively, intermittent relief from retraction (dynamic retraction) could be useful to protect the globe from undue pressure.

In addition, it is important to stress that our quantitative measurements must be interpreted as rough values and cannot be analyzed with strict statistical methods. These data represent the arithmetic mean of each parameter, and therefore can be used primarily for surgical orientation and instruction and not as absolute reference values for all clinical scenarios, because individual anatomy can be widely variable. Further experience and thorough scrutiny of intraoperative observations must be undertaken to better determine the usefulness of the transorbital approach to this location. Surgeon experience and preference should be weighed in the context when selecting the most appropriate surgical approach.

CONCLUSIONS

This study provides a comprehensive quantitative analysis of surgical access to the optic canal via 3 distinct but complementary pathways: transcranial, transorbital, and endonasal. Our results show that a transcranial approach achieved the widest degree of circumferential optic canal decompression and the greatest area of surgical freedom of instruments. Further surgical experience is needed to determine the proper indications for each procedure. However, the present contribution is merely a quantitative anatomic study of optic canal decompression via different neurosurgical routes. Our hope is to contribute to the understanding of the anatomy and the capabilities of various surgical approaches to the optic nerve, including a relatively novel avenue in the superior eyelid transorbital endoscopic approach. The limits of clinical applications should be considered as a separate issue that deserves additional study, which is ongoing.

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Supraorbital vs Endo-Orbital Routes to the Lateral Skull Base: A Quantitative and Qualitative Anatomic Study

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BACKGROUND: Various extensions of the supraorbital approach reach the lateral and parasellar middle cranial fossa regions by removing the orbital rim and greater/lesser sphenoid wings. Recent proposals of a purely endoscopic ventral transorbital pathway to these regions heighten the need to compare these surgical windows.

OBJECTIVE: To detail the lateral and parasellar middle cranial fossa regions and quantify exposures by 2 surgical windows (transcranial and transorbital) through anatomic study.

METHODS: In 5 cadaveric specimens (10 sides), dissections consisted of 3 stages: stage 1 began with the supraorbital approach via the eyebrow; stage 2, endo-orbital approach via the superior eyelid, continued with removal of lesser and greater sphenoid wings; and stage 3, extended supraorbital, re-evaluated the gains of stage 2 from the perspective of stage 1. Operative working areas were quantified in Sylvian, anterolateral temporal, and parasellar regions; bone removal volumes were measured at each stage (nonpaired Student *t*-test).

RESULTS: Visualization into the anterolateral temporal and Sylvian areas, though varied in perspective, were comparable with either eyelid or transcranial routes. Compared with transcranial views through a supraorbital window, the eyelid approach significantly increased exposure in the parasellar region with wider angle of attack ($P < .01$) and achieved comparable bone removal volumes.

CONCLUSION: Stage 2's unique anatomic view of the lateral and parasellar middle cranial fossa regions paves the way for possible surgical application to select pathologies typically treated via transcranial approaches. Disadvantages may be the surgeon's unfamiliarity with the anatomy of this purely endoscopic, ventral route and difficulties of dural and orbital repair.

KEY WORDS: Endoscope-assisted craniotomy, Keyhole craniotomy, Supraorbital craniotomy, Tansorbital craniotomy, Endo-orbital approach, Superior eyelid approach

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Of numerous operative pathways described to access the parasellar region and lateral aspect of the middle cranial fossa, the strategies devised to widen exposure were often at the expense of large amounts of bone removal or significant brain retraction. Both effects were associated with increased postoperative complications.[1-7] Keyhole approaches proposed alternatives to reduce surgical morbidity, decrease hospital stay, and improve cosmetic outcome. One often-used keyhole approach is the supraorbital (SO) craniotomy.[8,9] Although it affords exposure of the anterior fossa and suprasellar region,[10-14] the SO pathway is limited in certain regions, especially the lateral and parasellar areas of the middle cranial fossa. Strategies proposed to overcome this limitation were endoscope-assisted visualization[15] and/or total or partial removal of adjacent bone, including the greater and lesser sphenoid wings, orbital roof, and

ABBREVIATIONS: ACP, anterior clinoid process; **CN,** cranial nerve; **EO,** endo-orbital; **ESO,** extended supraorbital revaluation; **ICA,** internal carotid artery; **MCA,** middle cerebral artery; **SO,** supraorbital; **V1,** ophthalmic branch of the trigeminal nerve; **V2,** maxillary branch of the trigeminal nerve; **V3,** mandibular branch of the trigeminal nerve lateral wall of the orbit.[16] Efficacy of these maneuvers is yet undetermined.

One novel minimally invasive route that accesses the middle and anterior skull base from a ventral perspective is the endoscopic transorbital eyelid approach.[17-19] Purely endo-orbital (EO), this surgical window exposes the lateral middle cranial fossa by extradural removal of the greater and lesser sphenoid wings but foregoes removal of the orbital rim or frontal calvarium. While variations of this route continue to evolve, with qualitative findings, our cadaveric study provides quantitative comparisons of several supra/transorbital minimally invasive approaches. Specifically, our 3-staged dissections included: (1) SO approach: begins performed via the eyebrow; (2) EO approach: continues with the EO approach performed via the upper eyelid and with removal of the lesser and greater sphenoid wings; and (3) extended supraorbital approach (ESO): finishes by revaluation of the target areas via the transcranial route. Thus, stage 3 evaluates the structures uncovered after bone drilling in stage 2, and quantifies the gains afforded by stage 2 using the perspective of stage 1. Our qualitative descriptions dimension the effectiveness of each in exposing neurovascular structures.

METHODS

With a waiver by the University of Cincinnati Institutional Review Board, 5 embalmed adult cadaveric specimens (10 sides), without known intracerebral pathology, were injected with colored silicon rubber (Dow Corning, Carrollton, Kentucky) via the internal carotid arteries (ICAs), vertebral arteries, and internal jugular veins. Five implanted screws served as permanent bone reference markers for coregistration with the neuronavigation system. Before and after each dissection (described later), heads underwent computed tomography scans at 0.65-mm slices. Cadavers were registered with the BrainLab Curve (Feldkirchen, Germany) frameless stereotactic system, with landmark points used to calculate operative exposure (registration correlation tolerance 2 mm acceptable).

Dissections started macroscopically and proceeded microsurgically (Leica operating microscope, Leica Microsystems, Vienna, Austria). The microscope was used for the SO eyebrow approach in stages 1 and 3 while the endoscope for the greater part of the EO procedure (except initial steps). Furthermore, an endoscope-assisted technique was used during transcranial procedures (stages 1 and 3). In endoscopic dissections, a rigid 4-mm diameter endoscope (14 cm length, 0° and 30° rod lenses; Stryker, Kalamazoo, Michigan) was connected to a light source through a fiber optic canal. By a video camera connected to a video monitor, images were captured using a high-definition digital video system (Stryker). A high-speed drill (Midas Rex, Fort Worth, Texas [Medtronic Inc, Dublin, Ireland]) was used for bone removal. Each specimen underwent 3 successive dissections. In stages 1 to 3 (Figure 1), respectively, we began with the eyebrow approach, continued with the eyelid approach with removal of the lesser and greater sphenoid wing, and finished with an extended eyebrow approach.

Stage 1, SO Approach

Specimens positioned supine were fixed with a Mayfield headholder (Integra Neurosciences, Plainboro, New Jersey), rotated 10° laterally to the contralateral side with 10° to 15° of extension.

A 3-cm eyebrow incision was made immediately lateral to the SO notch. The skin flap was retracted; temporalis muscle was mobilized laterally; and periosteum was dissected and elevated.

A single frontobasal burr hole was created posterior to the temporal line and a SO craniotomy was completed. After the inner edge of bone under the orbital rim was drilled, dura was opened in a C-shaped manner and Budde halo retraction system (Integra Neurosciences) placed. After chiasmatic and opticocarotid cisterns were opened, the Sylvian, anterolateral temporal, and parasellar regions were evaluated (Figure 2).

Stage 2, EO Approach

Specimens positioned supine were fixed with a Mayfield headholder with the head rotated 5° laterally to the contralateral side.

A skin incision was made in the superior eyelid. The orbicularis oculis muscle was divided parallel to its fibers; the frontal process of the zygoma was reached laterally. Periosteum covering the zygoma was cut, dissected sharply toward the orbit, and followed. The surgeon followed the orbital septum plane within the orbit, using a no. 1 Penfield dissector. Dissection proceeded until reaching the inferior and superior orbital fissures to ensure adequate exposure of the greater wing of the sphenoid and superolateral aspect of the superior orbital wall. A malleable retractor retracted the orbital contents medially, creating room for further dissection.

A 0° endoscope was introduced into the upper surgical window to monitor dissections. The craniectomy, performed initially through the body of zygoma to unlock the temporalis fossa, yielded adequate working space, and continued through the ventral and vertical portions of the greater sphenoid wing. Subsequent extradural removal of the lesser sphenoid was dictated by the exposure required: potentially, it extended from the anterior clinoid process (ACP) medially to the pterion laterally to obtain the most anterolateral temporal visualization. The craniectomy was also extended superiorly to partially remove the frontobasal bone using 0° and 30° endoscopes (Figure 3).

Extra/interdural dissection proceeded to unlock the parasellar region (Figure 4). The endoscopic EO route provides straight, ventral access to the most superficial dural band tethering the frontotemporal basal dura to the periorbita—the so-called meningo-orbital band. A sharp and gentle dissection of this bridge "naturally" reveals the lateral wall of the cavernous sinus via an interdural pathway. Next, an X-shape durotomy exposed the fronto-basal lobe and temporal tip. Between them, the anterolateral margin of the Sylvian fissure was visualized. It served as the entry point for exposure of the most lateral portion of the middle cerebral artery (MCA), which was followed to the insula laterally and ICA medially (Figure 5).

Stage 3, ESO Revaluation

Specimens were repositioned supine on the Mayfield headholder, rotated 10° laterally to the contralateral side with 10° to 15° extension (like stage 1). We re-evaluated specific regions (Sylvian, anterolateral temporal, parasellar) after removal of greater and lesser sphenoid wings (stage 2).

Quantifying the Sylvian, Anterolateral Temporal, and Parasellar Exposures

Fixed points common to stages 1 to 3, identified using stereotactic navigation, included the ipsilateral and contralateral ACPs, ipsilateral ICA bifurcation, and skin-to-ipsilateral ICA bifurcation points. After each stage, we identified and quantified 3 operative working areas: (1) Sylvian area defined by the most lateral point visually attainable on

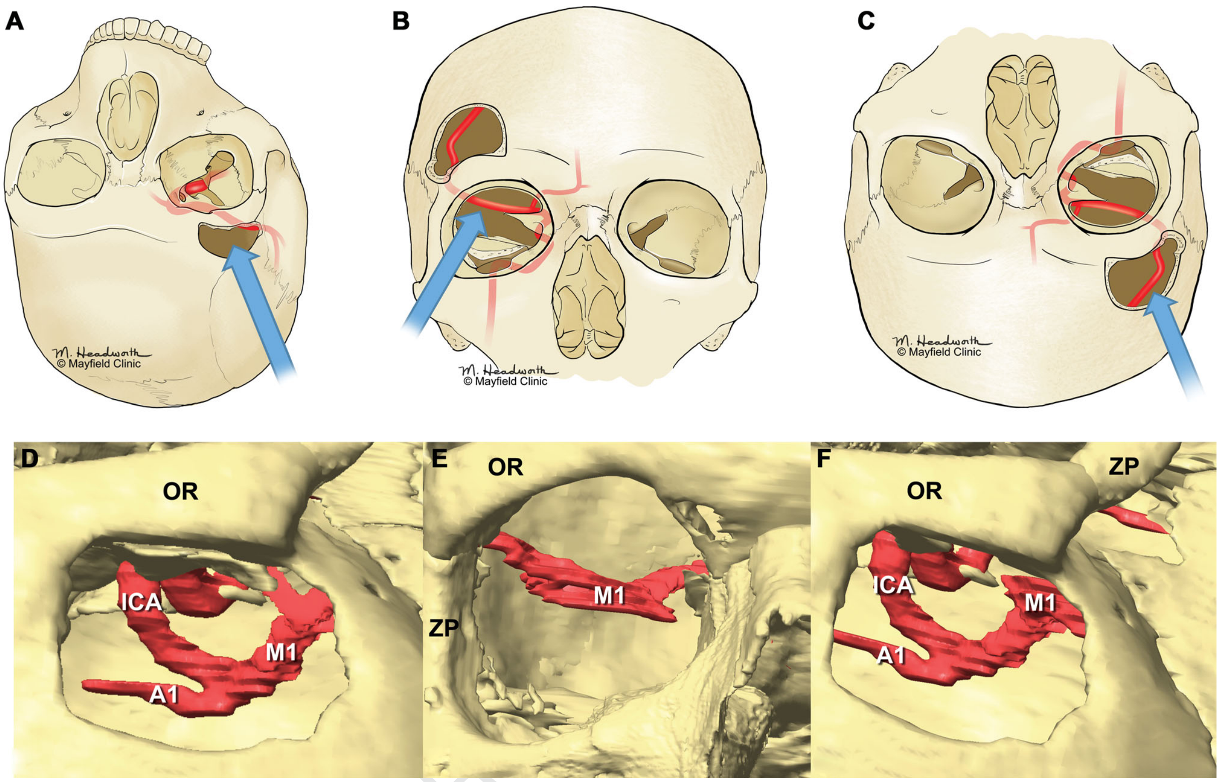

FIGURE 1. *Drawing and 3-dimensional reconstruction showing 3 successive, staged dissections performed.* **A**, *Stage 1: SO.* **B**, *Stage 2: EO, with removal of the greater and lesser sphenoid wings.* **C**, *Stage 3: SO revaluation.* **D-F**, *Three-dimensional reconstruction of the staged procedures, respectively. Printed with permission from Mayfield Clinic.*

the ipsilateral MCA; (2) anterolateral temporal exposure defined by lateral and inferior extension along the sphenosquamosal suture; and (3) parasellar exposure defined by most inferior point visible on the lateral wall of the cavernous sinus. Surgical angle of approach to the parasellar area referred to the skin-to-ICA bifurcation point.

Statistical Analysis

Distances and angles were calculated using Brainlab 3.0 software. Linear measurements for extent of exposure and triangle areas were compared. Bone removal was calculated by region-of-interest function (Osirix MD software, Osirix Foundation, Geneva, Switzerland). Nonpaired Student *t*-test determined statistical differences by stage.

RESULTS

Our cadaveric study characterized the supra/transorbital minimally invasive approaches by quantifying bone removal volumes and defining surgical working areas for parasellar and lateral middle fossa regions after each of 3-staged dissections (detailed in Methods).

Bone Removal

In quantifying volume by approach, we found no differences between stages 1-eyebrow and 2-eyelid approaches. Stage 3, the extended eyebrow, represented the sum of stages 1 and 2, and as expected, resulted in the greatest volume of bone removal ($P <$ .01, Table). In volumetric analysis, stages 1 and 2 were similar (Figure 2).

Surgical Working Area

Using the triangles originally described[20] and later reported by Kurbanov et al,[16] we defined surgical working areas at each stage (Figure 6).

For Sylvian region exposure, areas were based on reference points of the ipsilateral ACP, ipsilateral ICA bifurcation, and most lateral exposure in the Sylvian fissure (ie, most lateral point of the MCA observed). Exposures by stage 2-eyelid approach were statistically equal to stage 3-extended eyebrow but exceeded that of stage 1-eyebrow approach (Table). Of note, although not statistically significant increases in exposure, the ventral transorbital route (stage 2) provided a different perspective of

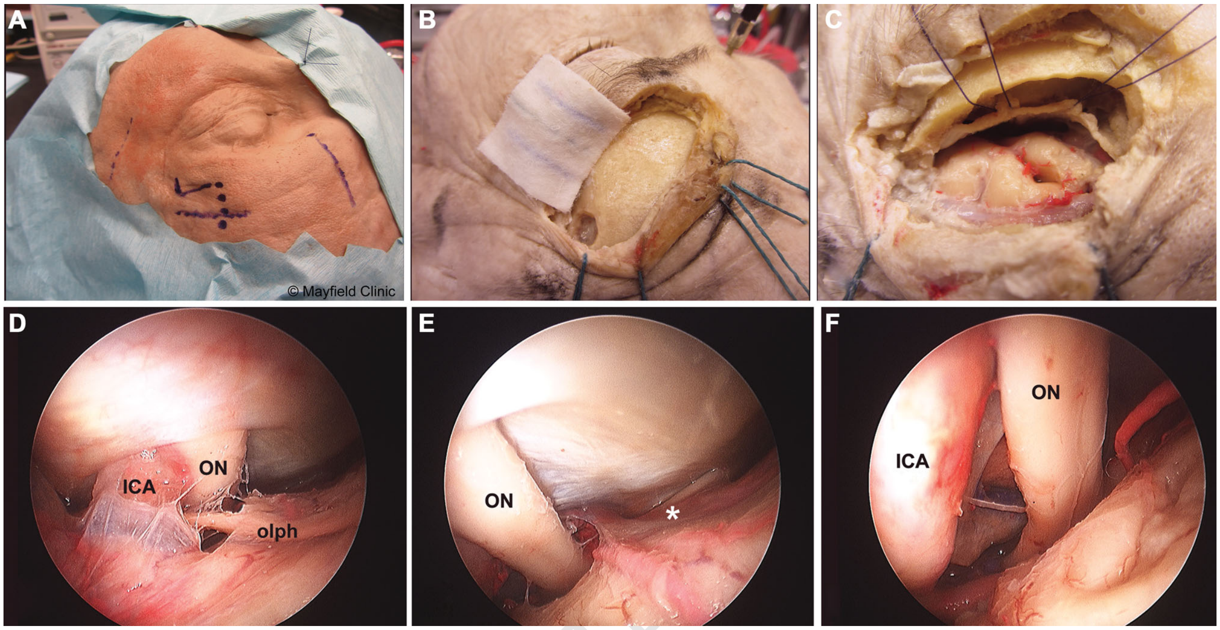

FIGURE 2. *Keyhole endoscope-assisted transcranial SO craniotomy (stage 1-eyebrow), left side.* **A**, *Skin landmarks. After eyebrow incision, a single frontobasal burr hole is created posterior to the temporal line. SO craniotomy is completed* **B**, *and opened* **C**. *Under endoscopic views* **D**, *opening the chiasmatic* **E**, *and opticocarotid* **F**, *cisterns shows the optic nerve and internal carotid artery (ICA). olph = olfactory nerve, ∗ = chiasmatic cistern, ON = optic nerve. Printed with permission from Mayfield Clinic.*

the MCA than transcranial exploration (stage 3). Furthermore, coplanar exposure of the Sylvian fissure obtained via stage 3 permitted comfortable dissection between the MCA branches, obviating brain retraction and affording clear view of the perforators. Exposure of the MCA in the Sylvian cistern was obtained using distal-to-proximal dissection in stage 2 (ie, retrograde), whereas the transcranial route (stage 3) favored a proximal-to-distal dissection (ie, antegrade; Figure 7).

Extent of anterolateral temporal exposure along the greater sphenoid wing was represented by a triangle from the ipsilateral ACP, ipsilateral ICA bifurcation, and lateral-most exposed point; stage 1-eyebrow approach, this was the intact sphenoid wing. In quantifying surgical exposure by triangle area, as expected, stages 2-eyelid and 3-extended eyebrow approaches achieved greater exposure than the stage 1 ($P < .01$). However, area provided by stage 2 statistically equaled stage 3 for the Sylvian exposure (Table).

Areas of parasellar exposure were calculated by merging 3 points: vertical point perpendicular to ICA bifurcation (skin-to-ipsilateral ICA bifurcation), point at ipsilateral ICA bifurcation, and inferior-most point exposed along the parasellar region (ie, mainly along the lateral wall of the cavernous sinus). Considering parasellar exposure, stages 1 and 3 were nearly comparable, whereas stage 2 exposure was statistically larger than either one ($P < .01$). Considering attack angles, stages 1 and 3 were statistically equal, whereas stage 2 differed by giving a wider angle to the parasellar compartment of the middle cranial fossa (Table).

Via the path of the stage 2-eyelid approach, the mesial temporal dura was peeled in a posterolateral direction, without cranial nerve (CN) manipulation, thus exposing V1 entering the upper part of the superior orbital fissure, V2 entering the foramen rotundum, and, as dissection proceeded posteriorly, CNs IV and III, just superior to V1. At dissection's end, complete visualization of the lateral wall of the cavernous sinus was seen up to the mandibular branch of V3 and the gasserian ganglion (Figure 8).

DISCUSSION

Our stepwise cadaveric study of the minimally invasive supra- and transorbital approaches demonstrated that extradural removal of the greater and lesser wings of the sphenoid bone through a stage 2-eyelid (ventral endoscopic transorbital) route greatly increased exposure of anatomic structures in the parasellar region. Compared with SO approaches, stage 2 gave a distinctive anatomic view and significantly wider angle of attack to the parasellar region. Compared with transcranial visualization, this dissection rendered an opposite view of the

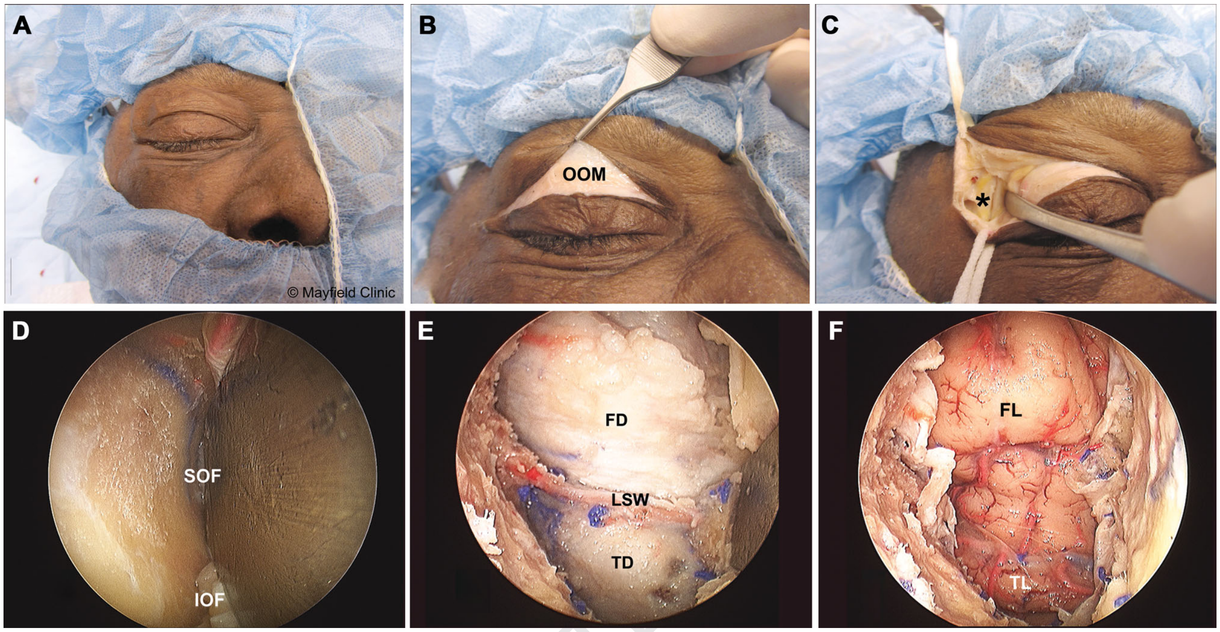

FIGURE 3. *Stepwise endoscopic transorbital dissection in stage 2-eyelid approach, right side. Head slightly rotated on contralateral side.* **A**, *Incision in eyelid.* **B**, *Orbicularis oculis muscle is separated parallel to its fiber.* **C**, *After reaching the frontal process of the zygoma (∗), laterally, the periosteum covering the zygoma was cut and dissected sharply toward the orbit, where it continued with the periorbita.* **D**, *With introduction of the endoscope, subperiorbital dissection proceeds until reaching the lateral end of the superior and inferior orbital fissures. Dura covering the frontal and temporal lobes is reached* **E**, *and opened* **F**. *FD = frontal dura; FL = frontal lobe; IOF = inferior orbital fissure; LSW = lesser sphenoid wing; OOM = orbicularis oculis muscle; SOF = superior orbital fissure; TL = temporal lobe; TD = temporal dura. Printed with permission from Mayfield Clinic.*

middle cranial fossa (ie, from medial to lateral), most notably exposing the MCA coursing antegrade within the Sylvian fissure.

Evolution of Transorbital Approaches

The idea of the lateral orbital wall as a corridor to expose deep brain structures in the supra- and parasellar regions is not new. The concept also pertains to its various modifications based on keyhole concepts to increase Sylvian, anterolateral temporal and parasellar surgical exposures.[16,20-24]

Building on those benefits, stage 2 (endoscope-assisted superior eyelid transorbital) gave minimally invasive access to the anterior and middle cranial fossae. Using a small incision that is virtually hidden in the eyelid crease, this approach allows extradural removal of the greater and lesser sphenoid wings to directly expose the parasellar region, proximal Sylvian fissure, and anterior temporal lobe. Importantly, its minimal temporal pole retraction and absence of CN manipulation thus potentially avoids extensive exposures and associated morbidity. Additionally, the temporalis muscle insertion remains intact, thus eliminating the risk of atrophy.

Bone Removal

In volumetric analysis, bone removal was comparable for stage 2-eyelid approach and the standard keyhole craniotomy of stage 1-eyebrow approach. Although their operative windows differed, our findings dispel any speculations of a theoretical larger amount of bone removal for stage 2. With the removal of the greater and lesser sphenoid wings, this afforded comparable exposures to that of the transcranial window. Notably, stage 2 achieved similar exposure with less bone removal than the stage 3-expanded eyebrow approach, and larger exposure of the lateral wall of the cavernous sinus and anterolateral temporal lobe with comparable bone removal to the stage-1 eyebrow approach.

Sylvian Fissure Dissection

Our anatomic study of the MCA within the Sylvian fissure deserves further discussion related to 2 previously described methods.[25] The eyelid approach opens the Sylvian fissure in a retrograde direction (ie, distal to proximal), starting by identifying anterolateral and ventral entry points to the Sylvian fissure. This was the only technical way to expose the MCA running in the Sylvian fissure since the approach comes from the ventral skull base instead from above, like in the transcranial pathways.

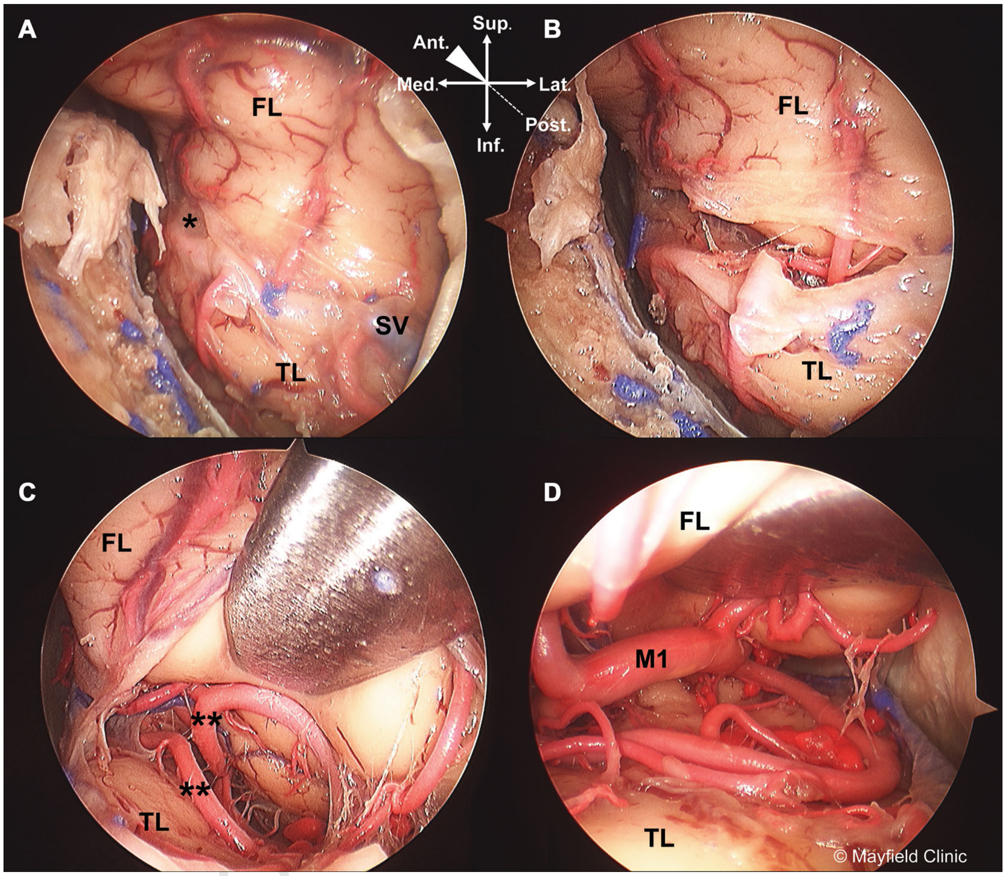

FIGURE 4. *Detail of the Sylvian region exposure via the eyelid approach (endoscopic transorbital), right side. Once dura is cut* **A***, entry point to the Sylvian fissure is identified laterally* **B***.* **C***, dissection proceeds sharply to visualize the MCA coursing through the entry point (∗) to the Sylvian fissure* **D***. FL = frontal lobe; TL = temporal lobe; M1 = pre-bifurcation tract of the MCA; ∗∗ = M2: postbifurcation branches of the MCA; Sv = Sylvian vein. Printed with permission from Mayfield Clinic.*

Reported advantages include wider Sylvian fissure dissection and decreased brain retraction. Disadvantages include difficult early proximal vascular control and complex venous anatomy limiting dissection. In transcranial procedures, the Sylvian fissure was opened from proximal to distal. It is equally feasible to open the Sylvian fissure proximal to distal or distal to proximal depending on the pathology or the surgeon's preference. As such, the carotid and chiasmatic cisterns are opened initially, allowing for removal of cerebrospinal fluid to achieve brain relaxation and early vascular control. Main disadvantages relate to subfrontal retraction and subsequent injury.

The extra/interdural ventral transorbital corridor, performed on an obvious, natural sagittal plane, allowed unveiling the entire lateral wall of the cavernous sinus, without penetration. Such wide exposure of the parasellar was not attainable using the transcranial corridor, either before the eyebrow approach or after the extended eyebrow approach (with removal of greater and lesser sphenoid wings). Our quantitative analysis strongly validates statistically that areas exposed via the eyelid approach exceeded that obtained with either transcranial approach.

The eyelid approach has potential application for tumors and vascular pathologies of the medial temporal fossa (ie, trigeminal schwannomas, meningiomas, cavernomas). A main disadvantage can be a surgeon's unfamiliarity with regional anatomy from a ventral perspective, and thus the need for extensive practice in cadavers. Although recent clinical applications have demonstrated the feasibility and safety of this route,[26] we stress that in the clinical setting, excessive globe retraction or improper instruments for retraction could cause injury to orbital contents.

Preceding this report, the transorbital neuroendoscopic surgery, including different corridors without orbital rim removal, was advocated for select pathologies.[27,28] Our evaluation of

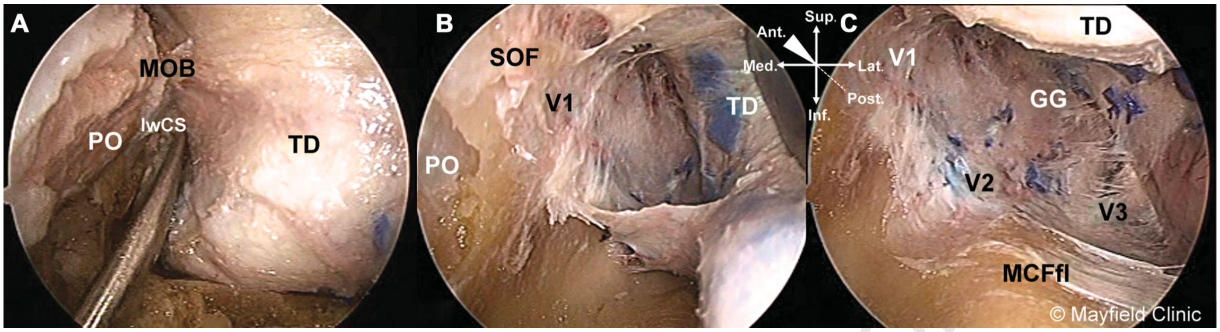

FIGURE 5. *Endoscopic EO route.* **A**, *Left orbit, extradural medial dissection between the periorbita and temporal pole, inferiorly to the superior orbital fissure aimed to expose the parasellar area. Lateral wall of the cavernous sinus can be progressively exposed proximally* **B** *and distally* **C**. *Trigeminal nerve showing V1 (ophthalmic), V2 (maxillary), and V3 (mandibular) branches. GG = gasserian ganglion; MCFfl = middle cranial fossa floor; PO = periorbita; SOF = superior orbital fissure; TD = temporal dura; PO = periorbit; MOB = meningo-orbital band. Printed with permission from Mayfield Clinic.*

TABLE. Quantitative Analysis Comparing Bone Removal and Operative Exposure Areas for Each Surgical Approach.

	Stage 1-SO	Stage 2-EO	Stage 3-ESO	*P*-value		
Analysis	Measurement ± Standard Deviation (SD)			**EO-SO**	**EO-ESO**	**SO-ESO**
Size of craniectomy (cm^3 ± SD)	6.097 ± 0.899	6.841 ± 1.349	12.911 ± 1.284	NS	$P < .01$	$P < .01$
Sylvian area (mm^2 ± SD)	25.162 ± 10.651	159.690 ± 48.453	146.890 ± 27.247	$P < .01$	NS	$P < .01$
Anterolateral area (mm^2 ± SD)	102.417 ± 41.485	231.086 ± 99.232	230.096 ± 100.074	$P < .01$	NS	$P < .01$
Parasellar area (mm^2 ± SD)	232.350 ± 148.021	845.085 ± 181.065	378.984 ± 188.748	**$P < .01$**	**$P < .01$**	NS
Parasellar angle of attack (degrees ± SD)	7.131 ± 6.703	16.536 ± 3.081	6.932 ± 2.767	**$P < .01$**	**$P < .01$**	NS

NS, not statistically significant.
Key results highlighted in bold. Stage 1 SO, keyhole endoscope-assisted transcranial SO craniotomy; stage 2 EO, superior eyelid ventral endoscopic transorbital approach with removal of the lesser and greater sphenoid wings; and stage 3 ESO, endoscope-assisted transcranial SO with removal of the lesser and greater sphenoid wings.

3 dissection stages offers a modular strategy, similar to that previously defined for combined or multistage approaches to extensive cranial base lesions. As such, these routes can be tailored to lesions of the middle fossa, Sylvian fissure, and parasellar regions—areas typically approached via a pterional craniotomy.

Utility of the frontotemporal approaches popularized by Yasargil and colleagues[29,30] remains unquestionable. However, in select cases, keyhole approaches afford adequate or increased exposure while avoiding complications associated with large craniotomies.[16] Pterional, SO, transorbital, and their modifications should not be considered mutually exclusive, but rather represent a menu of options for each patient's pathology. Further anatomic analyses using those surgical corridors are ongoing toward better understanding of each specific role. Clinical studies and surgical case series will help refine the indications for each approach.

Limitations

Cadaveric models cannot fully replicate the clinical environment, specifically related to tissue characteristics, bleeding, and pathological anatomy. Clinically, the anatomy reached by the approaches could depend on the extent of retraction achieved or the amount of cerebrospinal fluid drained. Thus, this significant bias should be considered when interpreting our findings. In our study of anatomic exposures, staged dissections began with the eyebrow approach, proceeded to the eyelid approach, and ended with the extended eyebrow approach. Taking into account our previously published results concerning the sphenoid wings removal via the eyebrow approach,[16] this study removed the sphenoid wings via the orbit and evaluated the possibilities of this new approach.

Despite recent reports of clinical tolerance, concerns about endoscopic transorbital approaches relate to the burden of orbital content retraction. In this preliminary anatomic study, we did not evaluate the possibility or possible benefits of removing the orbital rim. However, some recent papers have confirmed the effectiveness of the EO route that does not require removal of the orbital rim,[31,32] finding it to be feasible, effective, and safe for parasellar lesions (eg, spheno-orbital meningiomas[32-34]). Others have reported good results with a technique that included the removal of such bone bar.[35]

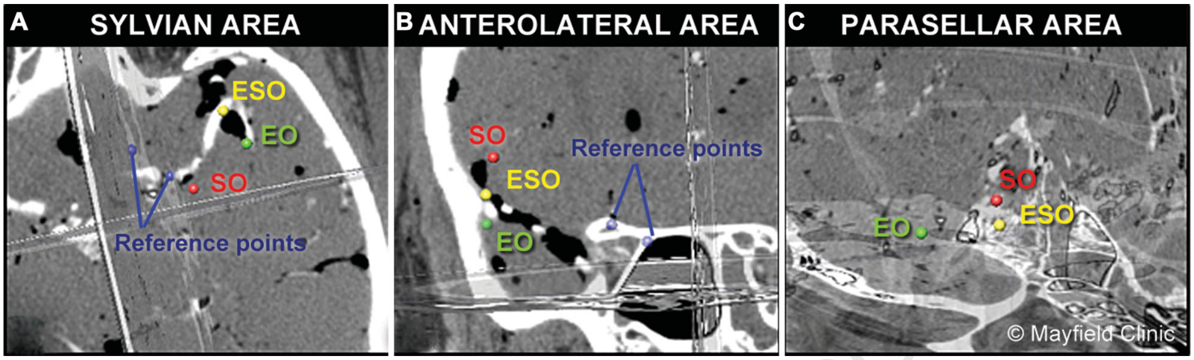

FIGURE 6. *Analysis of the lateral and parasellar compartment areas of the middle cranial fossa as reached with our staged procedures and obtained with Brainlab 3.0 software (Brainlab Curve).* **A**, *Sylvian areas;* **B**, *temporal areas; and* **C**, *parasellar areas. Blue = reference points; red = stage 1-SO approach; green = stage 2-EO approach; yellow = stage 3-extended SO revaluation. The parasellar exposition provided by the stage 2 was larger than the one provided by the transcranial ones (see Figure 6C, distance between green point and red/yellow point). Printed with permission from Mayfield Clinic.*

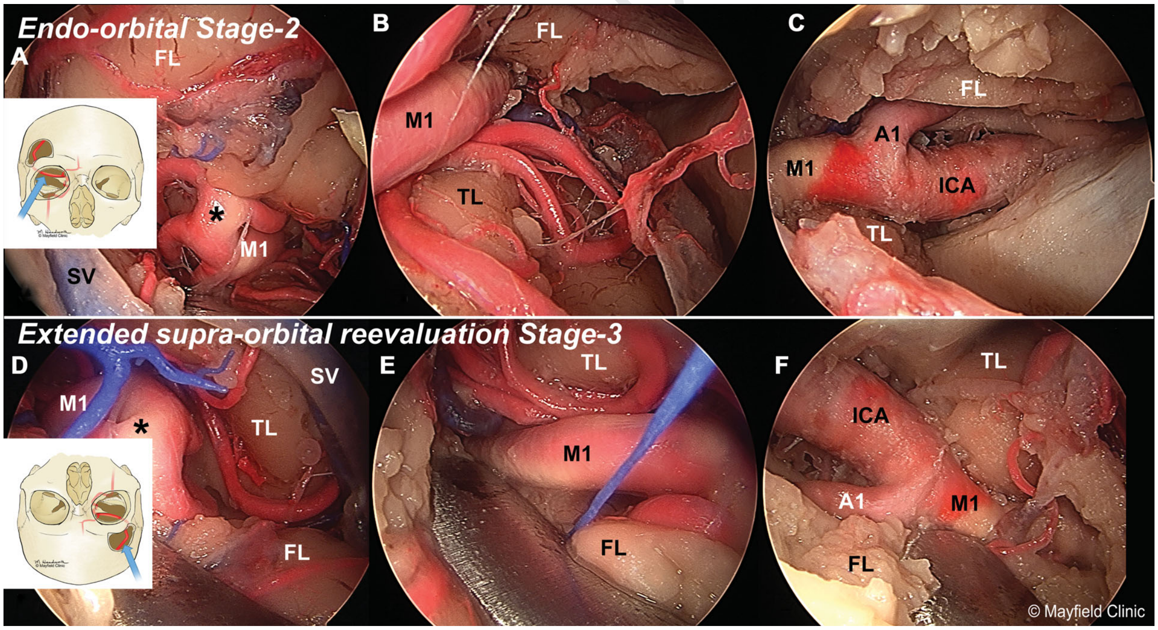

FIGURE 7. *Anatomic views of the Sylvian fissure and MCA. Comparing the ventral endoscopic EO corridor (stage 2, upper line figures) and transcranial window after greater and lesser sphenoid wings removal (stage 3, lower line figures).* **A**, *Sylvian fissure was opened between the frontal and the temporal lobes, just above the Sylvian vein and MCA bifurcation was identified.* **B**, *Next, the MCA was followed backward in the Sylvian fissure and* **C**, *reaching up to the ipsilateral internal carotid artery terminus.* **D**, *Same dissection performed via the transcranial pathway (stage 3); bifurcation of the MCA identified.* **E**, *Artery followed medially and* **F**, *up to access ICA bifurcation. SV = Sylvian vein. Printed with permission from Mayfield Clinic.*

Currently, no laboratory evidences confirm the possible advantages of this additional bone removal in terms of surgical freedom and working area data. Therefore, quantitative anatomic studies that aim to compare the advantages and limitations of such bone removal are still needed. Intraoperative globe tonometry might be useful to determine maximal safe globe retraction, or intermittent relief from retraction could help protect the globe when greater tension is necessary. Given concerns for ocular

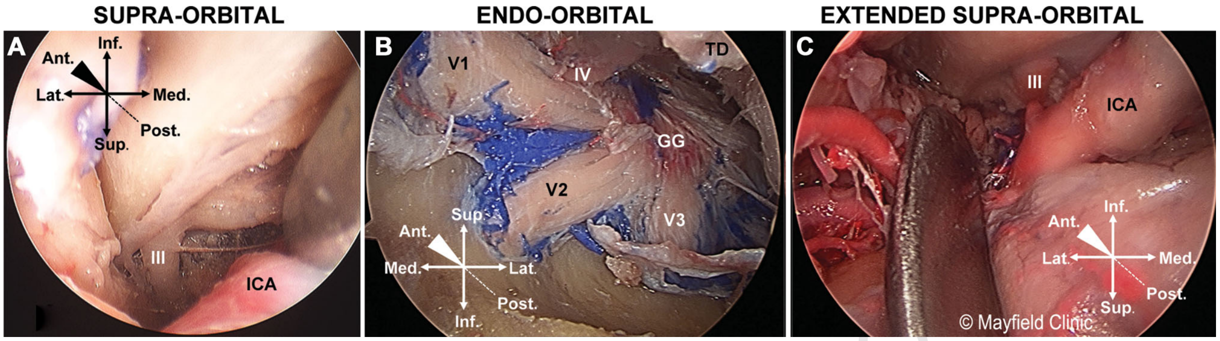

FIGURE 8. *Comparative anatomic views of the parasellar area reached by the 3 stages.* **A**, *Parasellar area evaluated with the stage 1-SO route.* **B**, *Next, the entire lateral wall of the cavernous sinus unlocked via stage 2-the superior eyelid transorbital avenue, passing via the orbital-temporal pole corridor (ie, via meningo-orbital band).* **C**, *Stage 3-extended SO eyebrow re-evaluates the parasellar area via the transcranial perspective. ICA = internal carotid artery; V1-V3 = V1 (ophthalmic), V2 (maxillary), V3 (mandibular) branches; III and IV = cranial nerves III and IV; TD = temporal dura; GG = Gasserian ganglion. Printed with permission from Mayfield Clinic.*

complications, further studies are warranted, such as retraction and issues about effective dural closure and avoidance/management of cerebrospinal fluid leakage.

CONCLUSION

Our cadaveric study characterized the supra- and transorbital minimally invasive approaches by quantifying bone removal volumes and establishing surgical working areas in the parasellar and lateral middle fossa regions. In our staged dissections, the eyelid approach with EO removal of the greater and lesser sphenoid wings significantly increased exposure of the parasellar region, and provided another view with wider attack angle than the transcranial SO window. Stage 2-eyelid's alternative route to the lateral and parasellar middle cranial fossa regions may have potential for select vascular and neoplastic pathologies. A disadvantage may be the surgeon's unfamiliarity with the anatomy in this purely endoscopic ventral route, risk of ocular injury, and cerebrospinal fluid leakage. This purely anatomic study serves as a foundation to build upon, and will further the clinical applications. We stress that performing this novel eyelid route requires collaboration between specialists, specifically, neurosurgeons, ENTs, and eye specialists. Our initial collaborations and clinical results are encouraging.

Disclosure

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

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7. DISCUSIÓN

7.1 Justificación de la Tesis Doctoral y concepto de neurocirugía mínimamente invasiva

'*The world is in perpetual motion, and we must invent the things of tomorrow. One must go before others, be determined and exacting, and let your intelligence direct your life. Act with audacity*' [92]. Con este énfasis *Madame Clicquot* en la primera mitad del 1800 revolucionó la industria del vino de su marido y dió a luz al primer prototipo de champán que aún lleva su nombre, *Veuve Clicquot*.

Los mismos **ideales innovadores** han inspirado este proyecto de investigación. De hecho, en esos principios se basa el desarrollo de los abordajes **mínimamente invasivos** para el tratamiento neuroquirúgico de los tumores cerebrales que involucran la base del cráneo y la superficie ventral del cerebro, utilizando como puerta de entrada agujeros naturales (concepto de *natural hole surgery*), es decir, en este caso, las cavidades nasales (en la línea media) y las órbitas (por la porción más lateral de la base craneal). En este proyecto, y con la perspectiva de una cirugía mínimamente invasiva, el instrumento principal de visualización ha sido el endoscopio; este proyecto tiene una orientación claramente anatómica, pero con implicaciones prácticas en la vertiente clínica, con el fin de mejorar el resultado de la cirugía aplicada a los pacientes afectos de tumores y/o otras patologías cerebrales y mantener una **buena calidad de vida**.

De hecho, en la actualidad, el tratamiento de los pacientes neuroquirúrgicos requiere no sólo la consecución de un resultado quirúrgico adecuado al tipo específico de patología, sino también el respeto de la calidad de vida y la integridad estética de la persona afectada. En un período como el actual, en el que el desarrollo tecnológico y científico es explosivo, no podemos darnos el lujo de tratar enfermedades importantes, tales como tumores cerebrales, de forma radical, sin pensar en el **resultado estético y funcional**, y también las consecuencias que un abordaje neuroquirúgico puede ocasionar. El trabajo del cirujano, de hecho, no debe estar exclusivamente dirigido a la eliminación de una lesión cerebral como lo era hace treinta años, sin duda de una manera excelente, pero con las herramientas y el conocimiento disponibles en aquel tiempo. Hoy en día, por un lado, el **soporte tecnológico**, tal como el uso de neuronavegación, nos ayuda a movernos a través del cerebro, alcanzar el objetivo y reducir al mínimo el daño al tejido cerebral sano. El **estudio de la neuroanatomía** con el uso de tecnologías dedicadas, tales como el endoscopio, nos permite realizar la mayor parte de la técnica quirúrgica con el fin de obtener el mejor resultado global para cada paciente individual en un entorno de cirugía mínimamente invasiva.

En esta Tesis Doctoral se desarrollaron dos abordajes neuroquirugicos mínimamente invasivos ventrales y endoscópicos: endoscópico endonasal (a través de la nariz) y endoscópico transorbitario (a través la órbita).

7.1.1 Evolución de la cirugía endonasal

Hace más de cien años, Henry Schloffer utiliza por primera vez la vía endonasal en cirugía de la hipófisis. Siguientes generaciones de neurocirujanos, que incluyen figuras clave como Harvey Cushing, Norman Dott, Gerard Guiot, y Jules Hardy, conservarán y generalizarán la técnica, analizando sus ventajas e inconvenientes [117].

Después de algunas décadas, el desarrollo de la tecnología endoscópica mejoró las limitaciones inherentes al abordaje endonasal microquirúrgico. De hecho, desde sus inicios, uno de los principales problemas en la cirugía endonasal ha sido la adecuada visualización de las estructuras anatómicas. A medida que este tipo de cirugía ha evolucionado, los avances técnicos han mejorado la visión del cirujano del campo quirúrgico. Así, las primeras aplicaciones del endoscopio en la cirugía endonasal fueron descritas por el Dr. Apuzzo et al., en 1977, que utilizó inicialmente está técnica para patologías sinonasales y de la región selar[7]. Hoy en día las indicaciones se han ampliado a lesiones que se extienden a la base del cráneo ventral y de la línea media, y por tanto, mucho más allá de su limitación original a la glándula pituitaria.

En la actualidad, la literatura científica recoge numerosos artículos y series de casos que demuestran la eficacia y ventajas de la vía endonasal endoscópica para toda la línea media de la base del cráneo. El grupo de Nápoles empezó este tipo de cirugía en el 1997 con el Prof. Cappabianca, siendo hoy en día uno de los grupos más importantes en el mundo en este campo [8,13,16,18,28].

De hecho, el abordaje endoscópico endonasal supone importantes ventajas, incluyendo una menor e incluso nula retracción del cerebro y la mejora de la visualización del campo quirúrgico. Y lo que es más importante: la vía endonasal endoscópica proporciona una ruta directa a lesiones de la línea media de la base del cráneo que desplazan estructuras neurovasculares críticas, lo cual permite minimizar cualquier manipulación de estas estructuras, disminuyendo así su potencial daño.

7.1.2 Evolución de la cirugía transorbitaria

La vía transorbitaria se ha utilizado de forma discontínua en neurocirugía durante al menos 60 años. En 1948, el médico estadounidense Walter J. Freeman II popularizó la leucotomía transorbitaria [64] basada en una técnica desarrollada por el psiquiatra italiano Amarro Fiamberti [62]. Este procedimiento 'mínimamente invasivo' pronto se hizo omnipresente por la gran atención que despertó en el campo psiquiátrico en los Estados Unidos y en muchas partes de Europa. Posteriormente, las implicaciones sociales y éticas del uso excesivo y generalizado de lobotomías transorbitarias condujeron a la práctica extinción de este procedimiento [102]. Algunos otros abordajes se idearon sobre la base de la vía transorbitaria ventral, incluidos los procedimientos intraventriculares [91,112,116,118], descompresión para la patología orbitaria y de Graves [2,6,88], y aplicaciones vasculares experimentales y de diagnóstico [40,48,71,72,95]. A partir de entonces, ciertos objetivos, tales como el seno cavernoso

[12,45,103], tallo hipofisario [105], y nervio óptico [79,110] se consideraron accesibles a través de esta vía mínimamente invasiva para diversos fines diagnósticos, experimentales y/o terapéuticos.

Durante las últimas dos décadas, las mejoras en la calidad óptica del endoscopio, nuevos materiales, instrumentación y sistemas de navegación quirúrgicos han impulsado un gran avance en el desarrollo de la cirugía moderna de la base del cráneo. La colaboración entre otorrinolaringólogos y neurocirujanos para el tratamiento de patologías que estaban fuera del alcance de sus respectivas especialidades fomentó una nueva subespecialidad llamada *endoneurocirugía*, con su ruta basada principalmente en el corredor endonasal.

A pesar de estos impresionantes desarrollos, la anatomía nasal y las relaciones geométricas con la base del cráneo a menudo limitan los ángulos de trabajo y la visualización de ciertas estructuras, particularmente en las lesiones que atraviesan estructuras neurovasculares o se encuentran en áreas laterales más alejadas [109]. En tales casos, la disminución de la visualización puede conducir a complicaciones o cirugía incompleta. Por el contario, los abordajes tradicionales de la base del cráneo ofrecen una amplia exposición y control de las lesiones, pero a veces a expensas del aumento de la exposición y retracción del parénquima, dando lugar a secuelas funcionales y cosméticas postoperatorias [20,34,59,70,94,96,111].

En este contexto, los estudios de anatomía craneofacial sugirieron que las órbitas, si se cruzan con seguridad, pueden proporcionar acceso a aquellas áreas de la base craneal anterior y media que no se acceden con seguridad por vía endonasal. Es decir, el obstáculo representado por las arterias carótidas y los nervios craneales en la extensión lateral de las vías endonasales se puede superar accediendo a las áreas laterales a esos obstáculos anatómicos. En consecuencia, la adición de abordajes transorbitarios representa un recurso complementario a las vías endonasales para el tratamiento de lesiones que comprometen las estructuras neurovasculares, un concepto recientemente introducido como 'endoneurocirugía multiportal' [11,23,33,55,108].

7.2 'Abordajes combinados' y análisis de los resultados

Las lesiones de la base del cráneo pueden ser manejadas a través de diferentes enfoques. La creciente experiencia adquirida por ciertos equipos de cirugía de base de cráneo ha permitido el tratamiento de muchos casos más complejos utilizando diferentes abordajes quirúrgicos cada uno con sus propias ventajas y limitaciones. Los abordajes tradicionales a la base del cráneo son actualmente menos utilizados que en el pasado, aunque siguen siendo una opción importante en ciertos casos seleccionados y siempre deben ser tenidos en cuenta.

Los abordajes transnasales endoscópicos permiten el tratamiento de diversas patologías localizadas no sólo en la base ventral del cráneo, sino también las que se extienden lateralmente y al interior de ciertas áreas de la órbita, como las regiones inferomediales. A pesar de estos importantes desarrollos, existen limitaciones a los procedimientos transnasales endoscópicos, principalmente relacionados con aquellos casos con una mayor extensión lateral de las lesiones. En estos casos, la trayectoria endonasal parece ser inadecuada para el control óptimo de las lesiones, siendo obligatoria una ruta alternativa o complementaria. Un abordaje que tiene su 'inicio' en la parte lateral de la cara (la órbita) podría superar los límites de la vía endonasal mediana y responder bien a las necesidades de determinados casos complejos. Además, los dos abordajes ventrales pueden ser combinados en un sistema 'multiportal' a fin de mejorar aún más la capacidad de manejar lesiones complejas de la base del cráneo [29,41,113,119].

En esta Tesis Doctoral, el **objetivo general se ha alcanzado** ya que ambas vías se han utilizado para llegar a las principales estructuras neurovasculares situadas a nivel de la base del cráneo y la superficie ventral del cerebro. En particular, esta contribución **resaltó el concepto anatómico relacionado con la bien establecida vía endoscópica endonasal** y, al mismo tiempo, proporcionó **elementos nuevos y neuroquirúrgicos para el abordaje endoscópico transorbitario** a través del párpado superior. A continuación, **se analizaron conjuntamente estos abordajes ventrales** por la nariz y la órbita con el fin de evaluar las ventajas y limitaciones del objetivo anatómico específico de la superficie ventral del cerebro.

Finalmente, se ha propuesto y evaluado una **comparación con rutas transcraneales** seleccionadas. En conclusión, este trabajo puede **ampliar aún más el conocimiento anatómico** endoscópico relacionado con la vía endonasal y sobre todo con la vía transorbitaria desde el punto de vista neuroquirúrgico. **Se necesitan estudios adicionales** y, eventualmente, series de casos quirúrgicos que empleen las vías endonasales y seguramente obligatorias para las transorbitarias para confirmar la efectividad de estos abordajes, refinando así las indicaciones adecuadas para cada uno de ellos.

7.3 Limitación del estudio

Los **especímenes cadavéricos** son modelos útiles para investigar abordajes quirúrgicos, pero **no representan completamente el ambiente clínico**. En particular, hay que hacer algunas consideraciones sobre el abordaje transorbitario endoscópico. La cantidad de retracción del contenido orbitario que puede tolerarse en un entorno clínico verdadero puede ser inferior, aunque el retractor ha sido bien tolerado y no ha mostrado complicaciones importantes. La tonometría intraoperatoria del globo ocular podría ser útil para determinar el grado máximo seguro de retracción aplicable. Alternativamente, el alivio intermitente de la retracción durante la cirugía puede ser útil para proteger el globo ocular cuando se necesita aplicar una tensión más prolongada o más alta intraoperatoriamente. Estos conceptos necesitan proyectos quirúrgicos futuros.

7.4 Perspectivas futuras

El desarrollo **futuro de la neurocirugía** va a verse impulsado principalmente por el desarrollo concurrente en ciencia y tecnología. La **tecnología** tiene una ubicación clara en la cirugía moderna y, hoy en día, es imprescindible su utilización (microscopio, endoscopio, neuronavegador, etc.). Actualmente se está asistiendo a una gran expansión tecnológica con la introducción de la robótica, biosensores, dispositivos derivados de nanotecnología, computación cuántica y electrónica molecular. El minimalismo progresivo es evidente a través de estos desarrollos, lo que conduce en última instancia a un cambio de paradigma a medida que se aproxima la nanoescala.

En todos estos procesos, la **investigación anatómica**, como ciencia básica, va a constituir un pilar fundamental en el desarrollo y aplicación de las nuevas tecnologías. Por lo tanto, la formación del neurocirujano de hoy y de mañana debe tener en cuenta la neuroanatomía, realizada a través de proyectos específicos de investigación y el desarrollo tecnológico actualmente imparable.

8. CONCLUSIONS

1. Regarding the **general aim** of this thesis, it is worth concluding that this work may significantly move forward the surgical anatomic research related to minimal invasive neurosurgical approaches to the skull base.

2. Some specific anterior and posterior circulation **aneurysms** that can be reached **via the endonasal route** has been highlighted and a literature review has been properly performed. With regard to this specific point, this work has to be intended as a notification of the existence of this endoscopic endonasal route even to cerebral aneurysms, but clear clinical indications have not been stated yet.

3. The **third ventricle** has been studied and classified from the **endonasal perspective**. Accordingly, lamina terminalis and, above all, the tuber cinereum has been found to represent two safe entry points defining possible surgical corridors to be considered for the extended endoscopic endonasal approach to the third ventricle.

4. On the other hand, along with its minimal invasive nature, the **superior eyelid transorbital approach** allows good visualization and manipulation of anatomic structures mainly located in the lateral portion of the skull base (i.e. anterior and middle cranial fossae lateral to the superior and inferior orbital fissures). A **classification** of this relatively novel, ventral and minimally invasive endoscopic avenue has been provided from a **neurosurgical perspective**.

5. In particular, this purely endoscopic transorbital approach, if performed **via the meningo-orbital band**, provides a direct view of the **cavernous sinus**. The transorbital ventral endoscopic route when compared to the supraorbital transcranial one has be proved to permit a unique anatomic view of the lateral and parasellar middle cranial fossa regions, thus paving the way for possible surgical application to select pathologies typically treated via transcranial approaches.

6. Concerning the **combination** of **endonasal** and **transorbital** routes related to a specific anatomic target, that is the optic nerve, it has to be stressed that used together, these 2 endoscopic surgical paths (endonasal and transorbital) may allow a 360° decompression of the optic nerve. However, when **compared** with the fronto-lateral **transcranial** window, it has been proved that the latter achieves the widest degree of circumferential optic canal decompression and the greatest **surgical freedom** for manipulation of surgical instruments.

7. As a general conclusion, it has to be stressed that **surgical series are needed** to establish the clinical value of the minimal invasive approaches herewith studied in order to better determine their place in the armamentarium of modern skull base surgery.

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