Comprehensive Anatomic Assessment of Ipsilateral Pterional Versus Contralateral Subfrontal Approaches to the Internal Carotid Ophthalmic Segment: A Cadaveric Study and Three-Dimensional Simulation

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■ OBJECTIVE: **Medially pointing aneurysms of the ophthalmic segment of the internal carotid artery (oICA) represent a neurosurgical challenge. Conventional ipsilateral approaches require internal carotid artery and optic nerve (ON) mobilization as well as anterior clinoidectomy (AC), all associated with increased surgical risk. Contralateral approaches could provide a better exposure of the superomedial aspect of the oICA, ophthalmic artery, and superior hypophyseal artery, sparing AC and internal carotid artery or ON mobilization. However, the microsurgical anatomy of this approach has not been systematically studied. In the present work, we exhaustibly analyzed the anatomic and morphometric characteristics of contralateral approaches to the oICA and compared them with those from ipsilateral approaches.**

■ METHODS: **We assessed 36 ipsilateral and contralateral approaches to the oICAs in cadaveric specimens and live patients, using for the latter a three-dimensional virtual reality (VR) system.**

■ RESULTS: **Contralateral approaches spared sylvian fissure dissection and required only minimal frontal lobe retraction. The ipsilateral and contralateral oICA were found at a depth of 49.2 $\pm$ 1.8 mm (VR, 50.1 $\pm$ 2.92 mm) and 65.1 $\pm$ 1.5 mm (VR, 66.05 $\pm$ 3.364 mm) respectively. The exposure of the superomedial aspect of oICA was 7.25 $\pm$ 0.86 mm (VR: 6 $\pm$ 1 mm) contralaterally without ON mobilization and 2.44 $\pm$ 0.51 mm (VR, 2 $\pm$ 1 mm) ipsilaterally even after AC. Statistical analysis showed that, for nonprefixed chiasm, contralateral approaches achieved a significantly higher exposure of the ophthalmic artery, superior hypophyseal artery, and the superomedial aspect of the oICA with its perforating branches (all $P < 0.01$).**

■ CONCLUSIONS: **Contralateral approaches may enable successful exposure of the oICA and related vascular structures, reducing the need for AC or ON mobilization. Systematic clinical/surgical studies are needed to further determine the effectiveness and safety of the approach.**

INTRODUCTION

Aneurysms arising from the clinoid and ophthalmic segment of the internal carotid artery (oICA) classically have been summarized under the term paraclinoid aneurysms, because of their close anatomic relationship to the anterior clinoid process. Mainly because of limited access and difficulty in gaining proximal control, these aneurysms still present a challenge to surgeons and surgical approaches are associated with high morbidity.[1-8]

Key words
- Contralateral approach
- Internal carotid artery
- Ipsilateral approach
- Ophthalmic segment

Abbreviations and Acronyms
3D: Three-dimensional
CSF: Cerebrospinal fluid
CT: Computed tomography
ICA: Internal carotid artery
IQR: Interquartile range
OA: Ophthalmic artery
oICA: Ophthalmic segment of the internal carotid artery
ON: Optic nerve
SHA: Superior hypophyseal artery

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Traditionally, these aneurysms were approached via the ipsilateral side.[9,10] However, some neurosurgeons have advocated the use of contralateral approaches to paraclinoid aneurysms and the oICA. They argued that exposure of the oICA, especially its medial wall, where most ophthalmic and superior hypophyseal artery (SHA) aneurysms arise, is superior if approached from the contralateral side, although some technical aspects, especially related to proximal artery control, remain a concerning issue of these approaches (for extensive review see Ref.[11]).[3,7,12-16] Furthermore, the high incidence of multiple (bilateral) aneurysms associated with paraclinoid aneurysms encourages neurosurgeons to approach them bilaterally through a unilateral craniotomy.[12,13,15,17]

Yet, only a few small case series and case reports have been published assessing the contralateral approaches to paraclinoid aneurysms.[6,7,12-15,17-29] All investigators agree that the use of this approach can be highly effective and associated with good clinical and surgical results, if patients are correctly selected. However, there is a lack of systematic studies assessing the surgical anatomy and morphometry of contralateral approaches to the oICA and directly comparing ipsilateral versus contralateral approaches to the oICA. In the present work, we performed a comprehensive anatomic and morphometric characterization of pterional (ipsilateral) and contralateral subfrontal approaches to the oICA in a cadaveric investigation. Because moderate changes in vasculature morphology can occur during cadaveric conservation, we in addition assessed the anatomy during simulated approaches in a three-dimensional (3D) virtual workspace using magnetic resonance imaging and computed tomography (CT) data from real patients.[30]

METHODS

Cadaveric Specimens

All cadaveric dissections were performed in our experimental microsurgical research laboratory. Eight adult head cadaver specimens conserved in a formaldehyde solution of 40 g/L were used bilaterally (16 craniotomies).

All ethic and hygienic procedures strictly adhered to standards rules of the hygiene and public health department of our institution. Because it was a cadaveric study, specific review and approval by the corresponding ethics committee were not required.

Craniotomy and Surgical Preparation

Craniometric measurements on the sagittal, coronal, and axial planes were made for each head to rule out significant anthropometric differences between specimens and severe asymmetries between the right and left sides.

Each specimen was subjected to bilateral classic pterional craniotomies and microsurgical dissections directed to the oICA. Dissection was performed strictly adhering to a systematic stepwise agenda.[31]

Heads were mounted on a 19-cm × 19-cm quadrangular holder and fixed at 4 points with adjustable pins in a supine position. Head fixation resembled classic positioning for pterional approaches, with a downward inclination of the vertex of about 20° and about 45° rotation to bring the molar eminence to the most superior point of the operating field. The pterional craniotomy was extended anteriorly above the orbital roof up to the supraorbital foramen, as well as posteriorly up to 4 cm along the temporal squama. After the bone flap was elevated, the temporal squama and greater wing of the sphenoid bone were rongeured to the floor of the middle fossa, allowing greater retraction of the anterior temporal lobe. The rough bone of the posterolateral orbital roof was smoothened and the posterior ridge of the lesser wing of the sphenoid bone was flattened until the orbital-meningeal fold was reached.

After incision of the dura, dissection was continued intradurally toward the anterior parasellar region. Both approaches, by opening of the sylvian cistern, entering at the level of the opercular part of the inferior frontal gyrus (transsylvian route), as well as through a corridor above the orbital roof allowing frontal lobe retraction up to a maximum of 15 mm (subfrontal/supraorbital route), were prepared.

The following neurovascular structures were carefully exposed by microsurgical dissection (Figure 1):

- Ipsilateral olfactory nerve
- Ipsilateral and contralateral optic nerves
- Ipsilateral and contralateral oICA
- Ipsilateral and contralateral ophthalmic artery (OA)
- Ipsilateral and contralateral SHAs
- Perforating branches of the supraclinoid segment of the internal carotid arteries (ICAs)
- Ipsilateral and contralateral ophthalmic arteries

Once anterior parasellar region was exposed, the falciform fold was opened above both optic nerves (Figure 1).

Anatomic and Morphometric Measurements

Anatomic and morphometric parameters assessed in cadaveric specimen included the following measures:

- Distance from the MacCarty keyhole to the supraorbital foramen (i.e., supraorbital nerve)
- Optimal approach angle to the oICA: an imaginary line crossing the MacCarty keyhole point and the apex of the ipsilateral anterior clinoid process was established as 0° reference. From this line, we determined separately the angle at which the ipsilateral and contralateral oICA were maximally visualized and exposed.[32] Positive angles were considered anteriorly to the reference line and negative angles posteriorly to it.
- Depth to the ipsilateral olfactory nerve
- Ipsilateral olfactory nerve mobilization needed to approach the oICA
- Depth to the ipsilateral and contralateral optic nerve
- Depth to the superomedial aspect of the ipsilateral and contralateral oICA
- Optic nerve length between the anterior border of the optic chiasm and the entrance into the optic canal

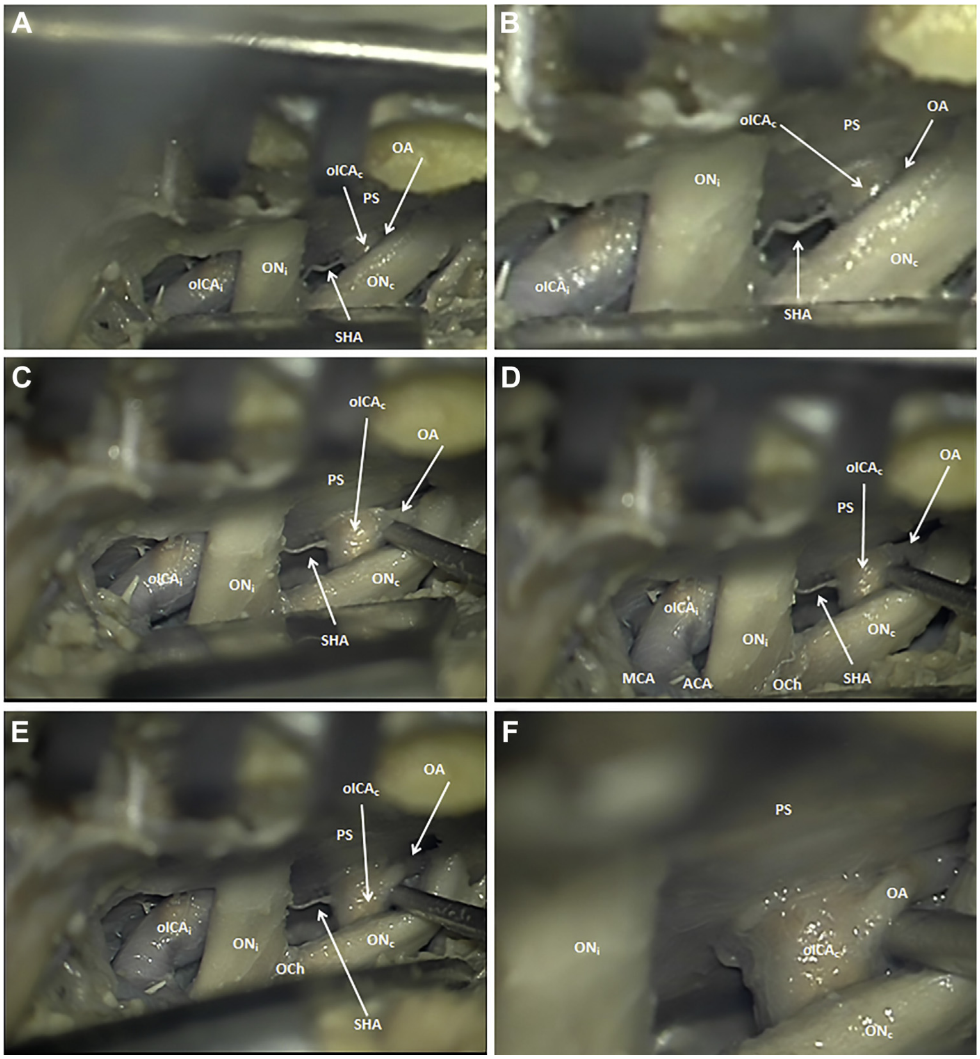

Figure 1. Exposure of the superomedial aspect of the contralateral internal carotid artery, as well as the superior hypophyseal and ophthalmic arteries. In this case, the ophthalmic artery can be visualized before the mobilization of the contralateral optic nerve (**A, B**). Only a light optic nerve mobilization is required to increase ophthalmic artery's exposure (**C**–**F**). ACA, anterior cerebral artery; OA, contralateral ophthalmic artery; Och, optic chiasm; $oICA_i$, ophthalmic segment of the ipsilateral internal carotid artery; $oICA_c$, ophthalmic segment of the contralateral internal carotid artery; ON_c, contralateral optic nerve; ON_i, ipsilateral optic nerve; MCA, middle cerebral artery; PS, planum sphenoidale; SHA, contralateral superior hypophyseal artery.

- Optic nerve mobilization needed to maximally expose the ipsilateral and contralateral oICA
- oICA mobilization needed to maximally expose the OA, SHA, and perforating branches arising from the oICA segment
- oICA length
- Visualization of the ipsilateral and contralateral OA origin
- Maximal ipsilateral and contralateral OA length exposed
- Visualization of the ipsilateral and contralateral SHA origin
- Maximal ipsilateral and contralateral SHA length exposed
- Number of perforating branches of the ipsilateral and contralateral oICA visualized.

Apart from these parameters, we recorded any obstacles encountered during ipsilateral and contralateral approaches and the percentage of cases in which the frontal sinus was opened.

The identification, exposure, and morphometric characterization of these parameters was performed at each of the following steps:

1) Before removal of any bony structure.

2) After ipsilateral intradural anterior clinoidectomy and opening of the falciform ligament.

3) After removing the contralateral half of the planum sphenoidale and tuberculum sellae.

4) Before and after mobilization of the contralateral optic nerve.

Virtual Surgical Approach by 3D Simulation

To perform 3D virtual surgical simulations, we randomly selected preoperative imaging data from 10 patients to perform 20 virtual 3D dissections and surgical simulations with the 3D image-processing tool Dextroscope (Volume Interactions Pte. Ltd., Singapore). The system allows 3D reconstruction and fusion of image sets. 3D image data sets were recorded by either a Vision Magnetom (Siemens, Munich, Germany) or an Aquilion CT scanner (Toshiba, Tokyo, Japan). For best reconstruction of anatomic features we used gadolinium-enhanced T1-weighted volume data sets fused to standard CTs to better visualize bony structures.

The Dextroscope software then allowed simulation of surgical approaches in 3D and manual tissue removal to expose underlying structures (for further details concerning image processing in the virtual workspace of the dextroscope, please compare Ref. [33]).

The procedure of anatomic dissection followed an identical stepwise manner as in a cadaveric specimen. Using the hand-held pen eraser tool, we first removed the skin and temporal muscle covering the pterion and performed a virtual craniotomy, adhering to the same anatomic landmarks as for cadaveric dissection. The standard pterional craniotomy was completed with the removal of the sphenoidal ridge up to the lateral border of the superior orbital fissure, and the roughness along the orbital part of the frontal bone was smoothed. Because brain retraction and deformation cannot be simulated in the Dextroscope, gentle frontal lobe retraction was virtually performed by erasing a 15-mm layer of brain parenchyma belonging to the orbitofrontal cortex. To simulate a transsylvian approach, we erased a brain layer of 5 mm superior and inferior to the sylvian fissure (Figure 2).

In each case, we erased selectively brain parenchyma, leaving the segmented vessels and optic apparatus intact. Using the Dextroscope, we exposed both ipsilateral and contralateral supraclinoid segments of the ICAs, ipsilateral and contralateral optic nerves, the optic chiasm, and ipsilateral and contralateral ophthalmic arteries (Figure 2). Because of the limited resolution, structures such as the olfactory nerves (difficult to segment on magnetic resonance imaging because of the close attachment to the brain), the SHAs, and the tiny perforating branches of the oICA (diameter in the range of the magnetic resonance voxel size) were not segmented.

Anatomic and morphometric measurements performed during simulation of surgical approaches corresponded to those performed during cadaveric dissection (Figure 2). Because mobilization of neural structures, specifically the optic nerve, was not replicable with the Dextroscope, the contralateral vascular elements were characterized without additional mobilization of the optic nerve only.

Statistical Analysis

For each parameter, we performed a Shapiro-Wilk goodness-of-fit test to determine the parametric or nonparametric distribution. For parameters following a normal distribution, we expressed the central tendency measure as the arithmetic mean and its dispersion as the standard deviation. For parameters following nonparametric distributions, the central tendency measure was expressed as the median of the sample and its dispersion as an interquartile range.

For comparing the means of 2 parameters following a normal distribution, we used either a Student t test or 1-way analysis of

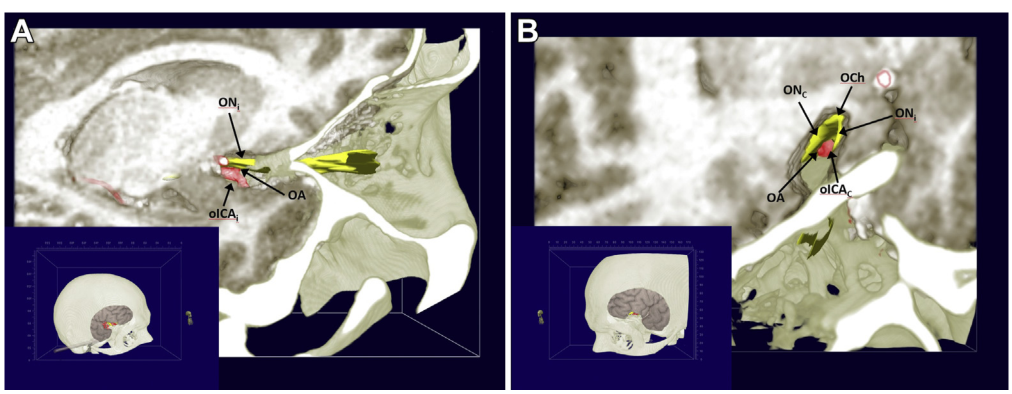

Figure 2. Approach to the ipsilateral and contralateral ophthalmic segment of the internal carotid artery (oICA) through a left pterional approach. A sylvian fissure opening was accomplished to better approach the ipsilateral oICA (**A**). To approach the contralateral oICA, the orbital gyri of the frontal lobe were partially removed and a supraorbital trajectory was adopted through the interoptic space (**B**). OA, ophthalmic artery; Och, optic chiasm; $oICA_i$, ophthalmic segment of the ipsilateral internal carotid artery; $oICA_c$, ophthalmic segment of the contralateral internal carotid artery; ON_i, ipsilateral optic nerve; ON_c, contralateral optic nerve.

variance. For comparison of the mean values of ≥2 normal distributed parameters, we used analysis of variance. The effect size for significant P values was expressed as partial eta square (η_p^2) values.

For variables following nonparametric distributions, we used the Mann-Whitney-Wilcoxon U test to assess significance between 2 samples. For >2 samples following nonparametric distributions, we used the Kruskal-Wallis test.

For frequency distributions we elaborated contingency tables (i.e., crosstabs), and the significance of the difference between the proportions was assessed with a Pearson χ^2 test. To set our α levels, post hoc Bonferroni corrections were performed. For statistical work, we used SPSS version 23 (IBM Corp., Armonk, New York, USA).

RESULTS

Assessment of Ipsilateral and Contralateral Approaches to the oICA and Related Neurovascular Structures in Cadaveric Specimens

Optimal Approach Angle to the Ipsilateral and Contralateral oICA. Maximum exposure of the ipsilateral oICA was obtained at an angle of −15.44° ± 4.11° posterior to the keyhole (Figure 3). After anterior clinoidectomy, this angle decreased to −28.56° ± 5.24° (the difference was statistically significant; $P < 0.001$). However, the optimal approach angle for contralateral approaches to the oICA was 17.56° ± 4.34°, anterior to the keyhole and independent of bone removal or optic nerve mobilization. The difference regarding optimal approach angle between ipsilateral and contralateral approaches was statistically significant ($P < 0.001$) (Figure 3).

Exposure of the oICA. The superomedial aspect of the ipsilateral oICA was reached at 49.25 ± 1.84 mm through the transsylvian route, whereas the medial wall of the contralateral oICA was reached at 65.18 ± 1.51 mm through a subfrontal/supraorbital trajectory.

The ipsilateral pterional approach exposed 2.063 ± 0.57 mm (median, 2 mm ± interquartile range [IQR], 0 mm) of the superomedial aspect of the ipsilateral oICA, with a trend to be increased by anterior clinoidectomy to 2.44 ± 0.51, although the difference did not reach significance ($P = 0.128$). Using a contralateral subfrontal/supraorbital approach, the exposure of the superomedial aspect of the oICA was 7.25 ± 0.86 mm (median, 7.5 mm ± IQR, 1.8 mm). This finding was significantly greater than the ipsilateral exposure before or after anterior clinoidectomy ($P < 0.001$).

Although anterior clinoidectomy did not influence the exposure of the oICA during contralateral approaches, removal of the contralateral half of the planum sphenoidale and tuberculum

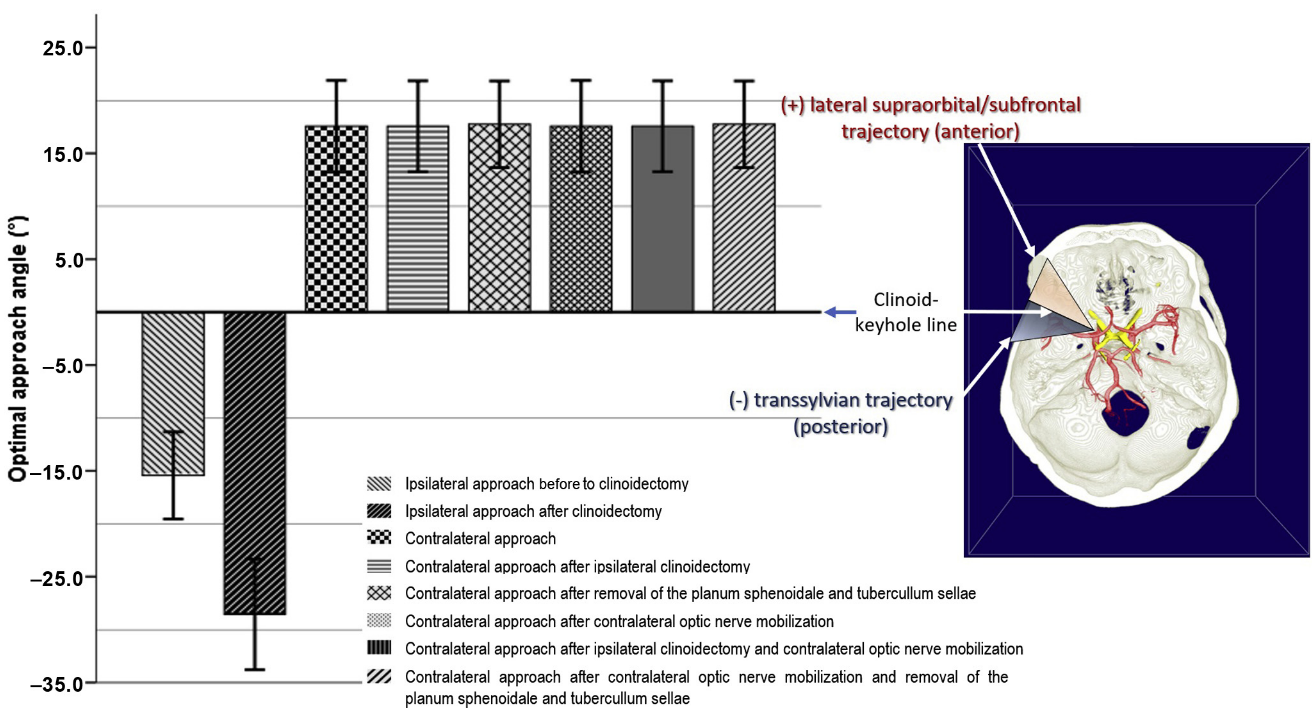

Figure 3. The optimal approach angle in relation to the clinoid-keyhole line measured in cadaveric specimens. Exposure of the ophthalmic segment of the internal carotid artery from the ipsilateral side was better accomplished through slightly posterior (negative) trajectories to the reference line, whereas contralateral approaches to the ophthalmic segment of the internal carotid artery benefited from anterior (positive) supraorbital trajectories. All values express mean ±2 standard deviation.

sellae further increased the exposure of the contralateral oICA to 8.31 ± 0.79 mm (P < 0.003; Figure 4A).

Mobilization of the contralateral optic nerve significantly increased the exposure of the contralateral oICA to 9,68 ± 1.19 mm (median, 10 mm ± IQR, 2.8 mm; P < 0.001). This effect was even greater than removal of the contralateral half of the planum sphenoidale and tuberculum sellae (P < 0.003). Combination of optic nerve mobilization and planum sphenoidale removal further significantly increased the exposure of the contralateral oICA to 10.75 mm ± 0.28 (P < 0.001).

Exposure of the OA. Pterional ipsilateral approaches exposed 0.31 ± 0.7 mm of the OA before anterior clinoidectomy with a maximal exposure of 2 mm in 2 specimens. Anterior clinoidectomy increased the average of exposure of the OA to 0.88 ± 1.36 mm with a maximal exposure of 3 mm in 3 specimens. Although this finding constitutes a tendency to greater OA exposure, the difference was not significant (P = 0.402). Contralateral approaches led to an OA exposure of 1.87 ± 1.25 mm. This exposure was significantly higher than that obtained on ipsilateral approaches before clinoidectomy (P < 0.001), and comparable to ipsilateral approaches after anterior clinoidectomy (P = 0.67). Ipsilateral anterior clinoidectomy did not influence OA exposure on contralateral approaches; removal of the planum sphenoidale and tuberculum sellae tended to increase the OA length exposed to 2.19 ± 1.22 mm (although statistically not significant; P = 0.423). Mobilization of the contralateral optic nerve did not significantly increase OA exposure and the combination of bone removal and optic nerve mobilization did not provide more OA exposure than did bone removal alone. However, a combination of planum sphenoidale and tuberculum sellae removal and/or mobilization of the contralateral optic nerve led to significantly larger OA exposure compared with ipsilateral approaches before and after anterior clinoidectomy (P <0.01; Figure 4B).

Given that aneurysms arise usually at sites of artery bifurcation or at the origin of collateral branches, we assessed the effectiveness of ipsilateral and contralateral approaches to expose the OA origin (Figure 4C). In classic ipsilateral pterional approaches before anterior clinoidectomy, the origin of the OA could not be visualized in any cadaveric dissections. Performing an ipsilateral anterior clinoidectomy significantly increased the likelihood of visualizing the origin of the OA to 31% (P < 0.01). A contralateral approach visualized the OA origin in 62.5% of cases. For contralateral approaches, either mobilization of the contralateral optic nerve or removal of the planum sphenoidale and tuberculum sellae increased the rate of visualized OA origins to 87.5%. Both maneuvers together raised the likelihood to 93.75%. The difference between ipsilateral and contralateral approaches was significant (P < 0.001).

Exposure of Perforating Arteries Arising from the oICA. The median number of perforating branches observed through ipsilateral pterional approaches was 2, which did not vary significantly after anterior clinoidectomy (P = 0.095). The contralateral supraorbital/subfrontal corridor enabled a significantly higher exposure of perforating branches (on average, 3; P < 0.005). Contralateral optic nerve mobilization on contralateral approaches further significantly increased the exposure of perforating branches (P < 0.005). This effect was not observed after bone removal of the contralateral half of the planum sphenoidale and tuberculum sellae (P = 0.128; Figure 4D).

Exposure of the SHA. Ipsilateral pterional approaches led to a poor exposure of the SHA (1 mm in only 3 specimens). Anterior clinoidectomy increased the exposure of this vessel only to 4 specimens (1 mm long in 2 cadavers and 2 mm in other 2 specimens, difference not significant; P = 0.96). When approached contralaterally, the median exposure of the SHA was increased to 2 mm ± IQR 3 mm (Figure 4E). Removal of the planum sphenoidale and tuberculum sellae did not increase the contralateral SHA exposure (median, 2 mm ± IQR, 2.5 mm). Contralateral optic nerve mobilization increased the median length of exposed SHA to 3 mm ± IQR 2 mm, although the trend did not yield significance compared with without optic nerve mobilization (P = 0.239). The combination of optic nerve mobilization and planum sphenoidale/tuberculum sellae removal for contralateral approaches did not significantly increase SHA exposure. The difference from ipsilateral exposure was significant (P < 0.001).

We also assessed the likelihood of visualizing the SHA origin arising from the C4 segment of the ICA (Figure 4F). Ipsilateral approaches before and after removal of the anterior clinoid process were unable to expose the SHA origin in any of the examined specimens. Via the contralateral subfrontal/supraorbital corridor, the SHA origin could be exposed in 62.5% (difference to ipsilateral was significant; P < 0.001). Removal of the planum sphenoidale and tuberculum sellae increased this value to 75%. Contralateral optic nerve mobilization increased the exposure of the SHA origin to 81.25%, a proportion that remained stable when both removal of the planum sphenoidale/tuberculum sellae and optic nerve mobilization were combined. Nevertheless, neither contralateral optic nerve mobilization nor removal of the sphenoidal plane/tuberculum sellae significantly increased exposure of SHA origin (all P values > 0.05; Figure 4F).

Assessment of Ipsilateral and Contralateral Approaches to the oICA and Parasellar Region Using 3D Simulation

Optimal Approach Angle to the Ipsilateral and Contralateral oICA. The optimal approach angle to the ipsilateral oICA before anterior clinoidectomy was −14.8 ± 2.42°, posterior to the clinoid-keyhole line (Figure 5). A slightly, but significantly, more posterior angle was optimal to expose the oICA after clinoidectomy (−24.5 ± 18.82°; P < 0.001). From the contralateral side, the optimal approach angle was 17.9 ± 4.42°, but anterior to the keyhole. This finding was again a significant difference from ipsilateral approaches (P < 0.001).

Exposure of the oICA. The ipsilateral oICA superomedial aspect was reached at 50.1 ± 2.92 mm on transsylvian trajectories, e the superomedial aspect of the contralateral oICA was reached at 66.05 ± 3.364 mm using the optimal approach angle through the subfrontal/supraorbital route. Visualization and exposure of the oICA significantly differed according to the approach selected (P < 0.001; Figure 6A). The median exposure of the oICA through an ipsilateral transsylvian approach was 2 mm ± IQR 1 mm, with a maximal exposure reached of 3 mm. Ipsilateral anterior clinoidectomy significantly increased the exposure to a median

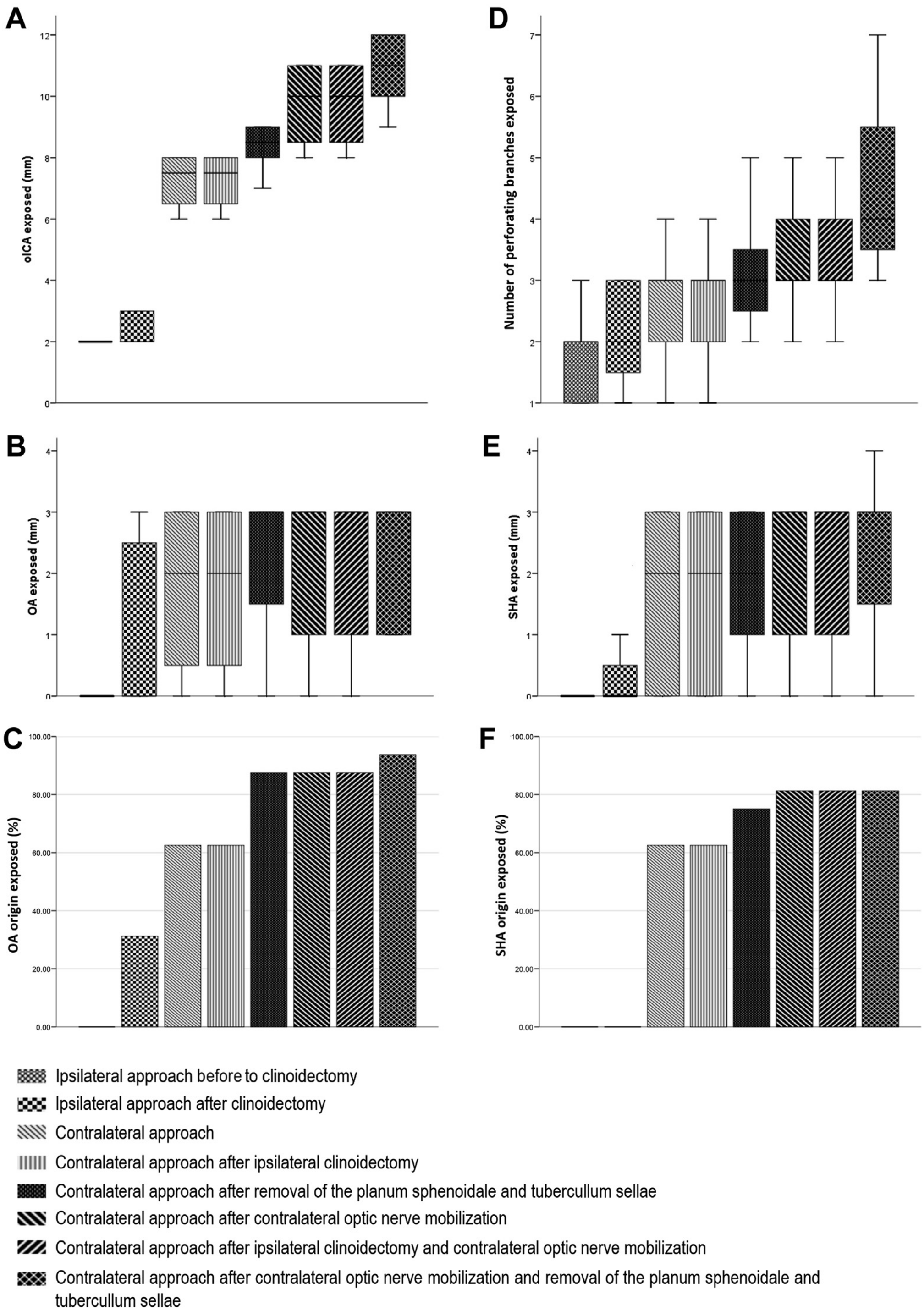

Figure 4. Exposure of the ophthalmic segment of the internal carotid artery (oICA), ophthalmic artery (OA), superior hypophyseal artery (SHA), and perforating arteries through ipsilateral and contralateral approaches assessed in cadaveric specimens. The use of contralateral approaches increased significantly the exposure of the oICA medial wall (**A**), the number of perforating branches visualized (**B**), the OA and SHA length (**C**, **D**), as well as the percentage of visualization of OA and SHA origin (**E, F**). Values from (**A**) to (**D**) express median ± interquartile range, whereas (**E**) and (**F**) express percentages.

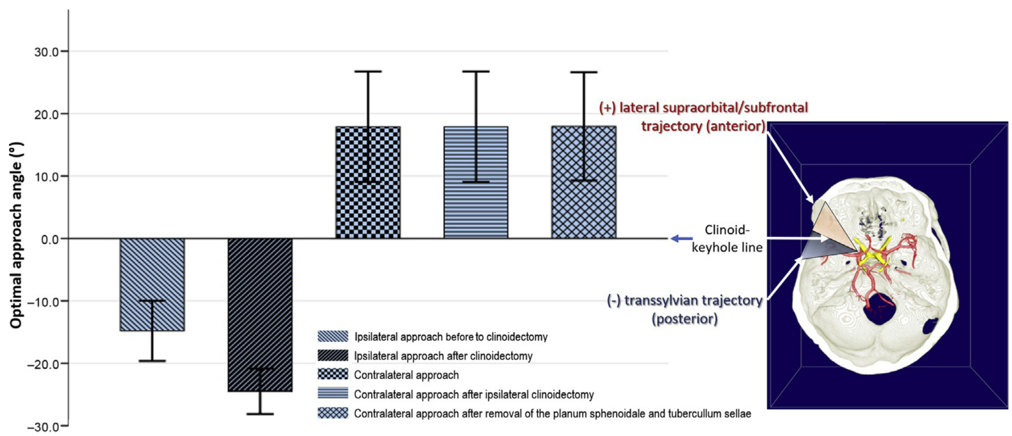

Figure 5. The optimal approach angle in relation to the clinoid-keyhole line measured in three-dimensional virtual dissections. Exposure of the ophthalmic segment of the internal carotid artery from the ipsilateral side was better accomplished through slightly posterior (negative) trajectories to the reference line, whereas contralateral approaches to the ophthalmic segment of the internal carotid artery benefited from anterior (positive) supraorbital trajectories. All values express the mean ±2 standard deviation.

value of 3 mm ± IQR 2 mm with a maximum of 4 mm ($P < 0.001$). The contralateral approach significantly increased the oICA visualization to a median of 6 mm ± IQR 1 mm compared with ipsilateral approaches even after anterior clinoidectomy ($P < 0.001$). Furthermore, the removal of the contralateral half of the planum sphenoidale and tuberculum sellae increased oICA exposure even more to a median of 9 mm ± IQR 1.75 mm, which was statistically significant compared with the contralateral approach before bone removal ($P < 0.001$).

Exposure of the OA. Again, we showed a general increase in OA exposure as a main effect of approach variants ($P < 0.001$; Figure 6B). In this case, the absolute lack of OS exposure through ipsilateral approaches before anterior clinoidectomy was overcome by removing the anterior clinoid process. This maneuver enabled visualization of a segment of the OA in 40% of cases, with a maximal length of 3 mm in 1 case. There was a significant increase in OA exposure on ipsilateral approaches after clinoidectomy ($P < 0.01$). The contralateral approaches to the oICA enhanced the exposure of a segment belonging to the OA to 50%, with a maximum of 3 mm in 2 cases. Drilling of the contralateral half of the planum sphenoidale and tuberculum sellae increased the proportion of cases in which the OA was exposed to 65%, with a maximum of 3 mm in 7 virtual cases. Despite this clear trend, separate Mann-Whitney-Wilcoxon tests comparing the contralateral approach alone against ipsilateral approaches after clinoidectomy or with the contralateral approach after removal of the contralateral half of the planum sphenoidale and tuberculum sellae failed to show statistical significance (both $P > 0.05$).

Because the observation of a segment belonging to the OA does not necessarily implicate the visualization of the OA origin, we assessed this variable separately. Contralateral approaches before bone removal increased significantly the likelihood of visualizing the OA origin compared with ipsilateral approaches ($P < 0.001$; Figure 6C) and removal of the planum sphenoidale and tuberculum sellae did not significantly contribute to our observations to a further increase of OA origin visualization ($P > 0.05$). Furthermore, in virtual cases in which OA origin was visualized, oICA exposure was significantly higher than in the cases in which OA origin was not seen. This pattern was observed not only for ipsilateral approaches after anterior clinoidectomy ($P < 0.01$) but also for contralateral approaches prior ($P < 0.01$) and after planum sphenoidale/tuberculum sellae removal ($P < 0.001$).

DISCUSSION

Targeting the oICA and its Branches

We determined the optimal route to the ophthalmic segment of the ICA for approaches directed from the ipsilateral and contralateral side. Findings in cadaveric and virtual surgical studies both consistently showed that the optimal approach to the oICA from the ipsilateral side is posterior of a reference line crossing the MacCarty keyhole and the apex of the ipsilateral anterior clinoid process via the sylvian cistern (transsylvian corridor), whereas the optimal approach from the contralateral side follows a lateral subfrontal/supraorbital route anterior to the reference line. These findings confirm earlier reports that advocated a contralateral supraorbital approach to the oICA.[16]

Ipsilateral approaches primarily expose the lateral wall of the artery, whereas the OA and SHA arise from the medial oICA (Figures 1, 2, and 7).[9,34-36] All variants of paraclinoid ICA aneurysms (except for extremely rare anterolateral variants of clinoid aneurysms and dorsal ophthalmic segment aneurysms) require exposure of the superior and medial aspect of the supraclinoid ICA.[31] To treat these variants, the ICA needs to be approached between its superior border and the optic nerve, which is best

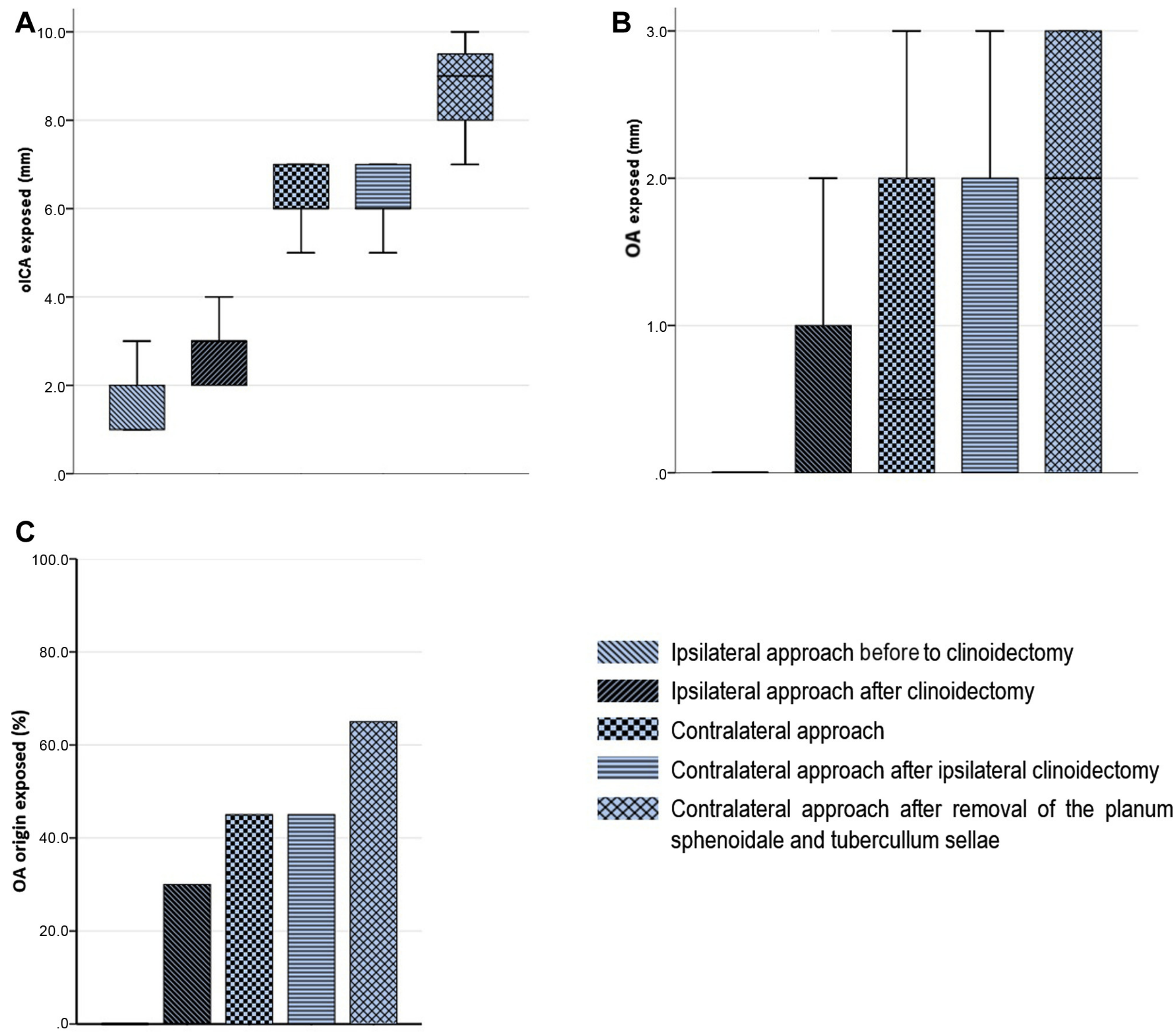

Figure 6. Exposure of the superomedial aspect of the ophthalmic segment of the internal carotid artery (oICA) and ophthalmic artery (OA) through ipsilateral and contralateral approaches assessed in three-dimensional virtual dissections in the Dextroscope. The use of contralateral approaches increased significantly the exposure of the ophthalmic segment of the internal carotid artery superomedial aspect (**A**), the OA (**B**) and the percentage of visualization of OA origin (**C**). Values from (**A**) and (**B**) express median ± interquartile range, whereas those in (**C**) express percentages.

achieved by a contralateral approach as shown by our dissections in both cadaver and virtual cases (Figures 1, 2, and 7). When this trajectory is adopted, the approach route passes above the previously smoothed orbit roof and below the orbital gyri of the frontal lobe and maximizes the visualization of the oICA and its branches through the space comprehended between both optic nerves converging into the chiasm.[37] Given that this approach profits from the window created by the interoptic space and because the anterior clinoid process on the side of the craniotomy is located laterally to this window, it is clear that anterior clinoidectomy does not influence contralateral approaches to the oICA, whereas removal of the contralateral half of the planum sphenoidale and tuberculum sellae does.

This approach exposes not only the superomedial aspect of the oICA but also its branches. In our data, the OA origin could be seen from the contralateral side in 62.5% of cases (93.8% if the contralateral optic nerve is mobilized and the planum sphenoidale and tuberculum sellae are removed). This finding

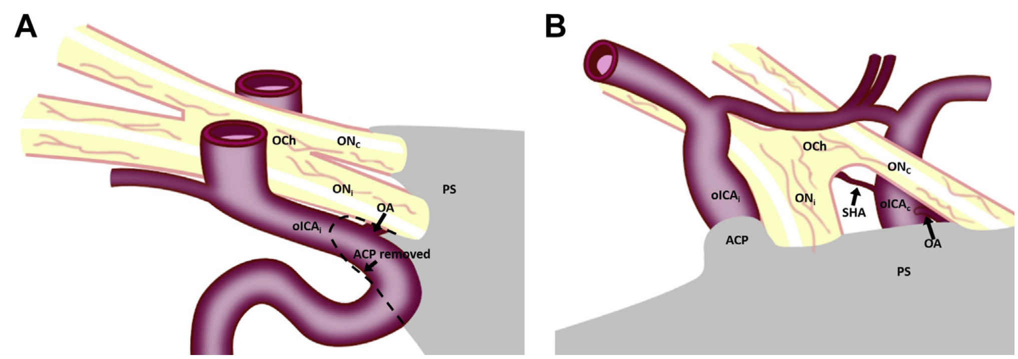

Figure 7. Schematic representation of ophthalmic segment of the internal carotid artery exposure through an ipsilateral (**A**) and contralateral (**B**) approach according to our anatomic and morphometric analysis in cadaveric specimens and three-dimensional virtual simulations. Ipsilateral approaches require anterior clinoidectomy for exposure of the ophthalmic artery (OA) origin (**A**). A further mobilization of the optic nerve would be needed to access the OA. In contralateral approaches, the medial aspect of the ophthalmic segment of the internal carotid artery as well as the origin of the OA and superior hypophyseal artery are exposed through the interoptic space (**B**). ACP, anterior clinoid process (*dashed line* corresponding to anterior clinoidectomy); Och, optic chiasm; $oICA_i$, ophthalmic segment of the ipsilateral internal carotid artery; $oICA_c$, ophthalmic segment of the contralateral internal carotid artery; ON_i, ipsilateral optic nerve; ON_c, contralateral optic nerve; PS, planum sphenoidale; SHA, contralateral superior hypophyseal artery.

corresponds to the report of Oshiro et al.,[25] who identified the origin of the OA through contralateral approaches in 62% of cadaveric specimens.

Contralateral approaches likewise provided greater exposure of the SHA (62.5% and 81.3% after removal of the planum sphenoidale and tuberculum sellae and contralateral optic nerve mobilization, respectively). Supporting these findings, several small clinical series have been reported that show the effectiveness of pterional contralateral approaches to treat aneurysms arising from the SHA, taking advantage of this key anatomic feature.[20]

Similar results were found when analyzing the exposure of perforating branches of the C4. In our cadaveric study, our median exposure of the oICA perforating branches through contralateral approaches was close to their total number.[9]

Anterior Clinoidectomy in Ipsilateral Approaches to the oICA

On ipsilateral approaches in our cadaveric study, anterior clinoidectomy tended to increase oICA superomedial aspect exposure, although this tendency did not reach statistical significance. Increase of oICA superomedial aspect exposure after clinoidectomy did reach statistical significance in virtual dissections. Likewise, anterior clinoidectomy improved OA visualization and optic nerve exposure and significantly reduced the need for optic nerve mobilization (see also **Supplementary Material**). These findings were in accordance with the literature, in which anterior clinoidectomy is attributed a key role in ipsilateral surgical exposure of paraclinoid aneurysms. It can be performed extradurally or intradurally, which allows simultaneous observation of the optic nerve and aneurysms and improves bleeding control in case of rupture.[38-42]

However, anterior clinoidectomy is associated with a relatively high risk of optic apparatus injury.[17,43,44] Mechanical and thermal injuries from the rotating drill include direct cranial neuropathies affecting the olfactory, optic, oculomotor, and trochlear nerves, as well as vascular injuries.[38] Drilling can cause temperature increases in the bone of up to 70°C around the drill tip, and heating nerve tissue to 45°C–47°C for only 1 or 2 minutes can produce permanent impairments and complete destruction of myelinated and unmyelinated fibers.[38,45,46] Already temperatures close to 58°C can lead to immediate axonal degeneration and cell death.[38,46] Furthermore, even in the hands of very experienced neurosurgeons, drilling or rongeur bites into the aneurysm dome have been reported during clinoidectomy.[38,47] The fact that some aneurysms erode into and through the anterior clinoid process may further enhance the risk of premature rupture. The ventilated cells of the sphenoid sinus can in some cases extend into the anterior clinoid process, increasing the risk of cerebrospinal fluid (CSF) fistula if anterior clinoidectomy is performed intradurally.[9] For the reasons mentioned, sparing anterior clinoidectomy constitutes a clear advantage of contralateral approaches to the oICA.

Risks of Removing the Contralateral Half of the Planum Sphenoidale and Tuberculum Sellae

Removal of the planum sphenoidale and tuberculum sellae surrounding the oICA resulted in a statistically significant improvement of oICA medial wall exposure in both cadaveric and virtual dissections. Some surgeons propose that the lateral part of the tuberculum sellae can be safely drilled and removed as much as needed to mobilize the optic nerve from suprasellar lesions.[48,49] However, the same risks mentioned earlier for anterior clinoidectomy, such as nerve or vascular mechanical or thermal injury, can be expected when power drills are used on the tuberculum sellae and planum sphenoidale next to the ICA or optic nerve. Further, it can penetrate the sphenoidal sinus and increase the risk of CSF fistula. For this reason, surgeons who advocate removal of the tuberculum sellae recommend careful analysis of the pneumatization of the sphenoid sinus preoperatively in bone window CT and, if it is opened intraoperatively, to reconstruct the dura with fat tissue and fibrin glue.[48,49] According to the extent of pneumatization, the sphenoid sinus can be classified in 3 types: conchal, presellar, and sellar.[50] In the conchal type, the area below the sella is a solid block of bone without any air cavities. In the presellar type, the air cavity does not penetrate beyond a vertical plane parallel to the anterior sellar wall. The sellar type of sphenoid sinus is the most common, and here, the air cavity extends into the body of the sphenoid below the sella and as far posteriorly as the clivus.[9,50] In adults, 76% of the sphenoid sinus are sellar types and 24% presellar types.[50] The conchal type is common only in children younger than 12 years, at which time pneumatization of the sphenoid begins. Accordingly, in our experience in cadaveric and virtual dissections, drilling of the tuberculum sellae frequently resulted in widely opened sphenoid sinus.

Most surgical series reporting clipping of oICA aneurysms using a contralateral approach have been successful without the need to remove bone from the tuberculum sellae or planum sphenoidale. However, in the series reported by Kakizawa et al.,[22] 3 of 11 patients with paraclinoid aneurysms approached contralaterally needed some extent of bone removal around the aneurysm neck corresponding to the tuberculum sellae. In these 3 patients, aneurysms were pointing relatively inferiorly. Similar experiences have been reported by other investigators, who have seen the need only for partial tuberculum sellae removal in contralateral approaches in cases of aneurysms arising very proximally from the carotid cave or pointing deep inferomedially.[7,17] In these cases of sphenoid sinus opening, interposition of abdominal fat and fibrin glue has been effective in sealing the defect and no cases of CSF fistula have been reported.[7,17]

Optic Nerve Mobilization on Contralateral Approaches to the oICA

For ipsilateral approaches to the OA and SHA origin, optic nerve mobilization was indispensable.[12,48,49,51-54] Accordingly, the surgical treatment of paraclinoid aneurysms is associated with a relatively higher risk of optic apparatus injuries.[17,43,44] As shown in our study, anterior clinoidectomy increased the mobility of the optic nerve and simultaneously reduced the need to mobilize it. Unexplained visual loss after technically successful clipping of intracranial aneurysms approached ipsilaterally constitutes a real concern because the prognosis for any recovery of vision in these cases is poor.[23,55-57] According to our morphometric measures in cadaveric specimens, a clear advantage of contralateral approaches was the fact that optic nerve mobilization was no prerequisite for sufficient exposure of the ICA superomedial aspect and its main branches. These findings support surgical experiences of contralateral oICA aneurysm clipping reported in the literature.[12,15,20,21,23] Consistent with these findings, small surgical series comparing clinical outcomes in patients operated on for oICA aneurysms from the ipsilateral or contralateral side have reported that all patients with permanent postoperative visual deficits were operated on via an ipsilateral approach.[6,12] In the series reported by Kakizawa et al.,[22] in contrast, no visual deficits occurred among the 11 patients operated on through a contralateral approach.

Although there is a lack of detailed knowledge about the exact duration and amount of mobilization that the optic nerve can tolerate, the literature suggests that light and gentle mobilization may be performed without any visual impairment.[48,49,52] Alterations on visual evoked potentials have been described during optic nerve mobilization, although these changes do not indicate permanent visual impairment in all cases.[51] Independently of the approach selected, optic nerve mobilization should be minimal and if absolutely required, the falciform dural fold should be opened to release the nerve before manipulation, a procedure that can be performed during ipsilateral and contralateral approaches.[12,25,37,48,51,52,58]

CONCLUSIONS

Our results provide anatomic and morphologic evidence supporting the thesis that contralateral approaches provide an effective route to the superomedial aspect of the oICA and its branches. If the trajectory is correctly planned and some anatomic conditions are given, a subfrontal/supraorbital contralateral approach provides better anatomic exposure of the oICA superomedial aspect and its perforating branches, the OA, and the SHA than do ipsilateral approaches, even after removal of the ipsilateral anterior clinoid process. In addition, the use of virtual 3D planning tools greatly facilitates anatomic evaluation when planning approaches to the oICA and related structures.

Despite these anatomic findings, technical aspects such as proximal artery control remain a concern in contralateral approaches and there is a lack of studies comparing clinical outcomes and complications between ipsilateral and contralateral approaches. For these reasons, systematic clinical/surgical studies are still needed to further determine the applicability, effectiveness, and safety of this approach in patients presenting medially pointing paraclinoid aneurysms.

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SUPPLEMENTARY MATERIAL

Additional morphometric data from cadaver specimens

Anthropometric Measurements. In order to rule out bias given by asymmetry between both right and left skull halves as well as other significant anthropomorphic differences between subjects, several measurements were performed in each cadaveric specimen. A survey of the measured values is depicted in **Supplementary Table 1**.

Craniotomy Extension and Rate of Frontal Sinus Opening. Pterional craniotomies were extended anteriorly up to the supraorbital foramen, which was 34.75 ± 1.39 mm anteriorly to the anterior margin of the MacCarty's keyhole. With this anterior extension of the craniotomy, the frontal sinus was opened in 25% of cases.

Position and Mobilization Required for the Olfactory Nerve. Measured via an ipsilateral trans-sylvian approach, the olfactory nerve was found at a depth of 44.38 ± 1.75 mm. Using a subfrontal/supraorbital corridor to the contralateral oICA, the ipsilateral olfactory nerve was found at a depth of 43.13 ± 2.13 mm (the difference was not significant, $P = 0.79$).

Approaches to the contralateral oICA required significantly more olfactory nerve mobilization than approaches to the ipsilateral oICA ($P < 0.001$). Whereas passive mobilization of the olfactory nerve of 5.50 ± 2.02 mm before anterior clinoidectomy and 3.17 ± 2.17 after anterior clinoidectomy was induced by dissecting the Sylvian cistern and elevating minimally the frontal operculum, the subfrontal/supraorbital corridor to the contralateral oICA required active mobilization and elevation of the olfactory nerve of 11.08 ± 0.9 mm. Bone removal along the planum sphenoidale and tuberculum sellae did not significantly reduce the need for olfactory nerve mobilization (10.58 ± 1.38 mm, $P > 0.05$).

Optic Nerve Exposure. The distance to the ipsilateral optic nerve was found to be 46.56 ± 1.67 mm using the optimal approach angle and trans-Sylvian corridor to the ipsilateral oICA and 46.56 ± 2.19 mm using the optimal subfrontal/supraorbital approach angle to the contralateral oICA. The mean distance to the contralateral optic nerve using the optimal contralateral supraorbital/subfrontal corridor was 62.75 ± 1.39 mm. Anterior clinoidectomy significantly increased ipsilateral optic nerve exposure from 11.25 ± 1 mm to 13.69 ± 1.25 mm ($P < 0.001$). The optic nerve length exposed through the contralateral approach was 12.94 ± 1.06 mm. The removal of the planum sphenoidale/tuberculum sellae significantly increased the length of the contralateral optic nerve exposed to 15.43 ± 0.96 mm ($P < 0.001$).

In order to expose the oICA, and specially its superomedial aspect, ipsilateral approaches required 2.375 ± 0.5 mm mobilization of the optic nerve before anterior clinoidectomy. After anterior clinoidectomy, optic nerve mobilization of 2.06 ± 0.57 mm was required. Even though the contralateral oICA could be successfully exposed without optic nerve mobilization, a maximal contralateral oICA exposure was achieved after optic nerve mobilization of 2.44 ± 0,51 mm.

Additional morphometrical data from 3D virtual simulations

Anthropometric Measurements of Selected Patients. Corresponding to the cadaver study, anthropometric skull measurements were assessed to rule significant interindividual differences or asymmetry between right and left skull halves (**Supplementary Table 2**).

Craniotomy Extension and Rate of Frontal Sinus Opening

In simulated cases, the mean distance from MacCarty's keyhole to the supraorbital foramen was 36.1 ± 2.4 mm. Extending the craniotomy anteriorly up to the lateral limit of the supraorbital foramen resulted in frontal sinus opening in 30% of cases.

Optic Nerve Exposure

On ipsilateral approaches to the oICA, the mean depth to the ipsilateral optic nerve through the optimal trans-Sylvian corridor was 45.9 ± 2.91 mm, with minimal variation when a subfrontal/supraorbital corridor was used (46.6 ± 3.27 mm). The measured depth to reach the contralateral optic nerve through the optimal subfrontal/supraorbital approach was 63.35 ± 3.360 mm.

The mean exposed length of the ipsilateral optic nerve was 11.05 ± 0.76 mm. Removal of the ipsilateral anterior clinoid process significantly increased this length to 13.05 ± 1.05 mm ($P < 0.001$). For contralateral approaches, the exposure of the contralateral optic nerve averaged 12.25 ± 1.16 mm. Bone removal from the contralateral half of the planum sphenoidale and tuberculum sellae significantly increased exposure of the optic nerve to 14.6 ± 1.19 mm ($P < 0.001$).

Supplementary Table 1. Anthropometric measurements ruled out the possibility of significant asymmetries between both halves of the skull in cadaver specimens

Anthropometric measure	Mean ± Standard Deviation		
Cephalic perimeter	53.63 ± 1.22		
Biauricular breadth	24.13 ± 1.36		
External biorbital breadth	11.25 ± 1.09		
	Rigth	**Left**	**t Tests**
Vertex-zygomatic length	15.75 ± 0.66	15.88 ± 0.6	ns
External obito-auricular length	6.88 ± 0.78	6.75 ± 0.66	ns
Internal orbito-auricular length	11.38 ± 0.78	11.25 ± 0.66	ns
External orbito-midline length	6.25 ± 0.43	6.38 ± 0.48	ns

ns, non-significant.

Supplementary Table 2. Anthropometric measurements ruled out the possibility of significant asymmetries between both halves of the skull in 3D virtual dissections

Anthropometric Measure	Mean ± Standard Deviation		
Cephalic perimeter	54.3 ± 0.78		
Biauricular breadth	24.6 ± 1.2		
External biorbital breadth	11.54 ± 1.18		
	Rigth	**Left**	**t Tests**
Vertex-zygomatic length	15.88 ± 0.66	15.84 ± 0.56	ns
External obito-auricular length	6.95 ± 0.51	6.82 ± 0.72	ns
Internal orbito-auricular length	11.45 ± 0.73	11.32 ± 0.68	ns
External orbito-midline length	6.33 ± 0.44	6.47 ± 0.39	ns

ns, non-significant.