Neurosurgical Review (2022) 45:2087–2093
https://doi.org/10.1007/s10143-021-01707-x

ORIGINAL ARTICLE

Hakuba's triangle: a cadaveric study detailing its anatomy and neurovascular contents with vascular and skull base implications

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Received: 29 June 2021 / Revised: 20 October 2021 / Accepted: 24 November 2021 / Published online: 7 January 2022

Abstract
Hakuba's triangle is a superior cavernous sinus triangle that allows for wide and relatively safe exposure of vascular and neoplastic lesions. This study provides cadaveric measurements of the borders of Hakuba's triangle and describes its neurovascular contents in order to enrich the available literature. The anatomical borders of the Hakuba's triangle (lateral, medial, and posterior borders) were defined based on Hakuba's description and identified. Then the triangle was dissected to reveal its morphology and relationship with adjacent neurovascular structures in Embalmed Caucasian cadaveric specimens. The oculomotor nerve occupied roughly one-third of the area of the triangle and the nerve was more or less parallel to its medial border. The mean lengths of the lateral border, posterior border, and medial border were 17 mm ± 0.5 mm, 12.2 mm ± 0.4 mm, and 10.6 mm ± 0.4 mm, respectively. The mean area of Hakuba's triangle was 63.9 $mm^2 \pm 4.4\ mm^2$. In this study, we provided cadaveric measurements of the borders of Hakuba's triangle along with descriptions of its neurovascular contents.

Keywords Cavernous sinus · Cavernous internal carotid · Oculomotor nerve · Cadaver · Skull base

Introduction

The skull base is a complex intracranial area that houses many important nerves and vessels. As these structures are typically located in small, tightly-packed regions, a number of triangular corridors have been described to assist with surgical approaches. In particular, ten triangles surrounding the cavernous sinus have been described in the literature with borders consisting of various dural folds, nerves, and arteries [6]. Four triangles are considered to be cavernous sinus triangles because of their close proximity to the cavernous sinus: (1) oculomotor, (2) clinoidal, (3) supratrochlear, and (4) infratrochlear. The oculomotor triangle, also known as Hakuba's triangle (Figs. 1 and 2) or the medial triangle, was originally defined by the Japanese neurosurgeon Akira Hakuba as a route to accessing lesions involving the entire cavernous sinus via a combined orbitozygomatic infratemporal

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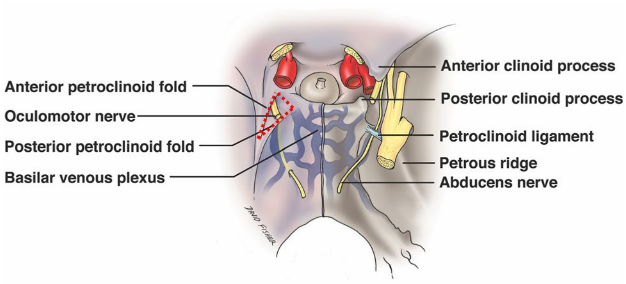


Fig. 1 Schematic view of the left Hakuba's triangle

extradural and intradural approach [8]. The immediate and most important contents of the triangle are the oculomotor nerve and the internal carotid artery (ICA).

The borders of Hakuba's triangle for efficient surgical exposure have most recently been reported as the petroclinoid and interclinoid dural folds in the superior wall of the cavernous sinus (Figs. 1 and 2) [4, 14]. However, other studies have defined the borders of Hakuba's triangle differently. For example, Day et al. described the borders as the subclinoidal carotid segment, posterior clinoid process, and porus oculomotorius [3]. This might have resulted in misunderstanding of the triangle or miscommunication among neurosurgeons. The aim of this study is to provide clear and specific anatomical details of Hakuba's triangle including measurements, contents, and relationships to adjacent structures in order to help standardize the nomenclature, along with anatomical photographic illustrations, and aid the skull base surgeon who operates in this region.

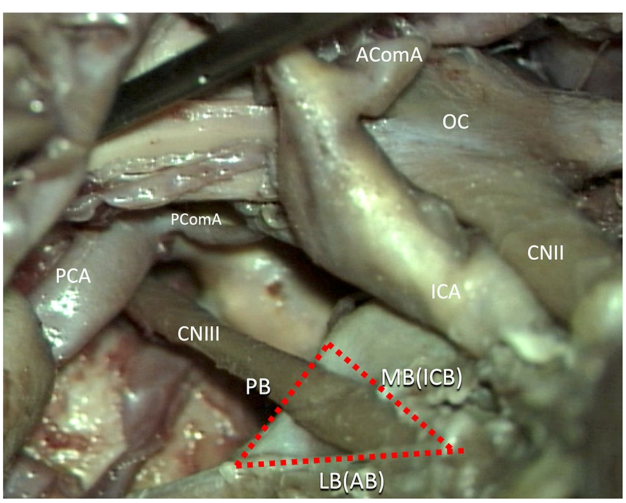


Fig. 2 Right-sided surgical approach in a cadaveric specimen illustrating Hakuba's triangle. LB(AB), lateral (anterior) border; MB(ICB), medial (interclinoid) border; PB, posterior border

Materials and methods

The anatomical quality assurance (AQUA) checklist was used for this study [13]. Five adult Caucasian formalin-fixed cadaveric heads (ten sides from three male and two female specimens) were used. The cerebral tissues were dissected out in all specimens to expose the cranial nerve roots and the dura mater of the skull base. Specifically, after removal of the calvaria using an oscilatting bone saw, the dura mater was incised and removed with dissecting scissors. Next, the frontal lobes were lifted up, and the cranial nerves and blood vessels sequentially cut from anterior to posterior, as close to the brain as possible, along with adjacent vessels, e.g., internal carotid artery. Once the brainstem was observed, the tentorium cerebelli was incised at its attachment onto the petrous parts of the temporal bones. A scalpel was then introduced anterior to the brainstem and into the foramen magnum where the upper spinal cord was transected. The brain was then lifted out of the cranium. Using an OPMI Lumera 300 surgical microscope, Hakuba's triangle was then identified and the borders defined as previously reported by Drazin et al. (Figs. 1 and 2) [4]. The lateral or anterior border was defined along the anterior petroclinoid dural fold from the anterior clinoid process to the petrous part of the temporal bone. The posterior border was defined along the posterior petroclinoid dural fold from the posterior clinoid process to the petrous part of the temporal bone, where the anterior petroclinoid fold joins the posterior petroclinoid fold. The medial or interclinoid border was defined along the interclinoid dural fold between the anterior and posterior clinoid processes (Fig. 3).

A digital caliper with 0.1-mm precision was used to measure each border. The length and width of the oculomotor nerve within the triangle were also measured. Using *length x width* as the formula for calculating the surface area of the oculomotor nerve and Heron's formula ($\sqrt{s(s-a)(s-b)(s-c)}$, where $s=(a+b+c)/2$ and *a, b, and c* denote the three borders of the triangle) for calculating the surface area of the triangle, the proportion of the triangle occupied by the oculomotor nerve was estimated. Additionally, the posterior entrance into the triangle for the trochlear nerve, the presence of ICA branches within the triangle, and the location of the abducens nerves relative to the ICA were all recorded.

Results

Borders of the triangle

On all sides, the lateral border of the triangle was steep compared to the medial border which was less inclined.

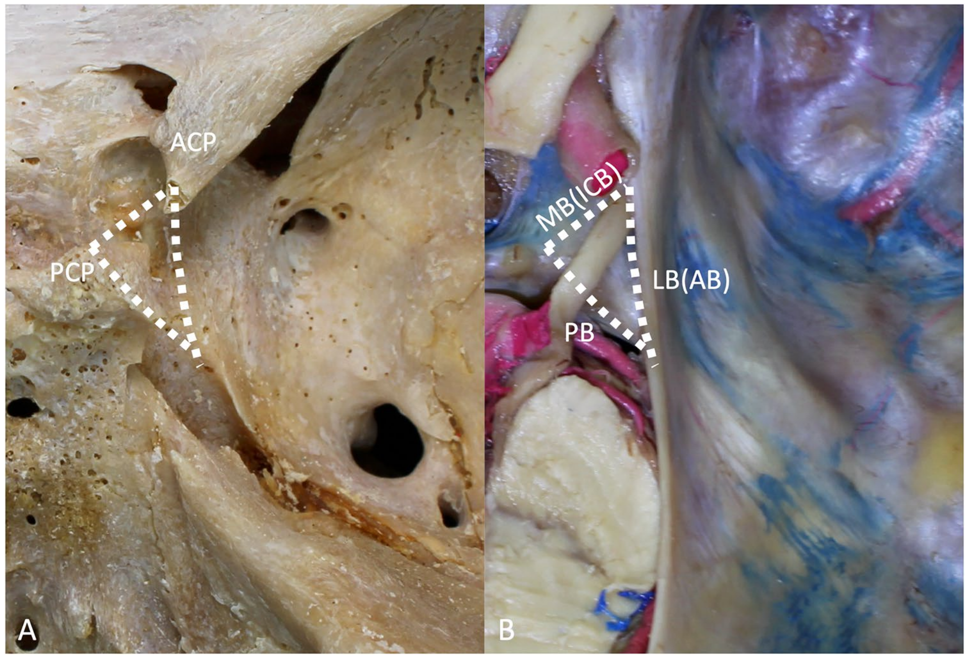


Fig. 3 Superior view of the Hakuba's triangle with its borders in a dry skull (**A**) and cadaveric specimen (**B**). LB(AB), lateral (anterior) border; MB(ICB), medial (interclinoid) border; PB, posterior border

The medial border was continuous with the diaphragma sella on all sides. The posterior border was the entrance of the oculomotor nerve to the triangle on all sides (Fig. 4). Between the three borders of the triangle, the floor of the triangle was observed, and this overlaid the cavernous part of the internal carotid artery.

Triangle and the cranial nerves

On all sides, the oculomotor nerve occupied roughly one-third of the area of the triangle, and the nerve was more or less parallel to its medial border where it hugged the clival clinoid junction. For all but three sides, the trochlear nerve was noted to enter the triangle at the junction of the lateral and posterior borders (posterior apex of the triangle) (Fig. 5).

Vascular structures within the triangle

On three cadaveric sides, the dural floor of Hakuba's triangle was more or less translucent where the underlying vascular structures were appreciated (Fig. 6). In general, the area deep to the triangle was relatively devoid of cavernous sinus, especially under the pathway of the oculomotor nerve through the triangle (Fig. 7). Within Hakuba's triangle and inferior to the oculomotor nerve, the posterior

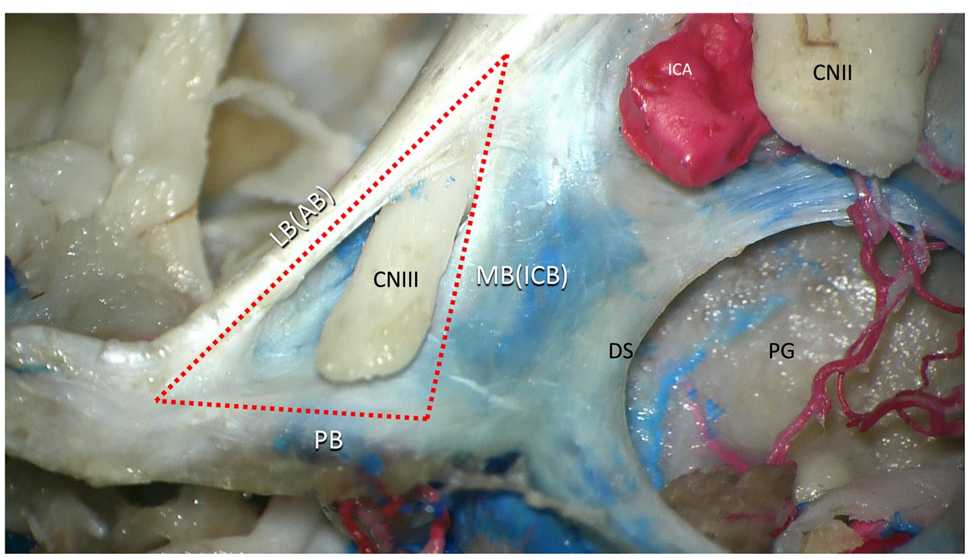


Fig. 4 Superior cadaveric view of the a left-sided Hakuba's triangle with the oculomotor nerve (CNIII). Also, note the optic nerve (CNII), diaphragma sella (DS), internal carotid artery (ICA), and pituitary gland (PG). LB(AB), lateral (anterior) border; MB(ICB), medial (interclinoid) border; PB, posterior border

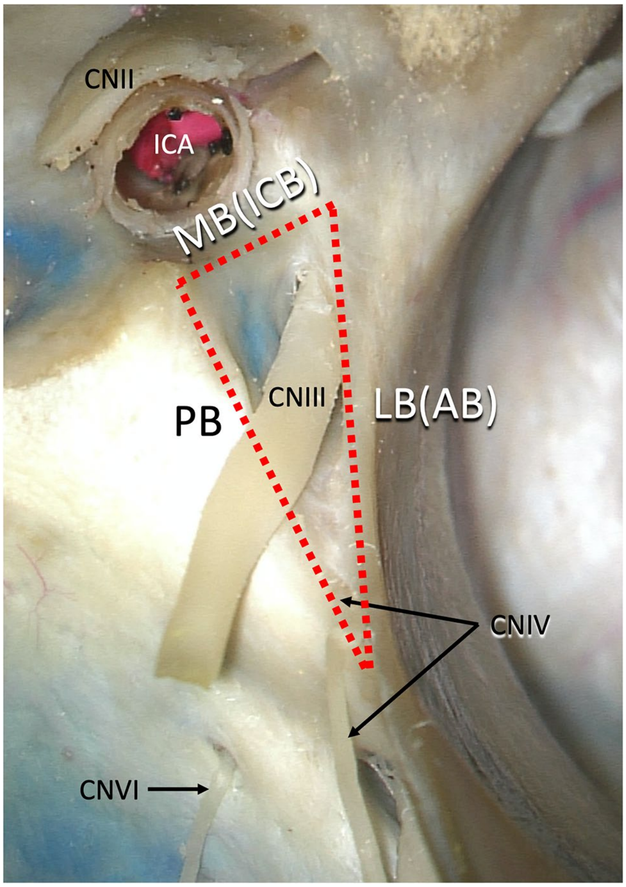


Fig. 5 Right-sided Hakuba's triangle noting the entrance of the trochlear nerve (CNIV) into its posterior aspect. Also, note the relationship of the abducens nerve (CNVI). LB(AB), lateral (anterior) border; MB(ICB), medial (interclinoid) border; PB, posterior border

genu of the ICA cavernous segment was identified in all specimens, and the meningohypophysial trunk was the only branch contained within the triangle (Fig. 8). This vessel was always found deep to the floor of the triangle with many of its branches, e.g., dorsal meningeal artery also seen.

Measurements

The lengths of the lateral border (along the anterior petroclinoid fold) ranged from 16 to 17.5 mm, with a mean of 17 mm ± 0.5 mm. The lengths of the posterior border (along the posterior petroclinoid fold) ranged from 11.5 to 13.0 mm, with a mean of 12.2 mm ± 0.4 mm. The lengths of the medial border (along the interclinoid fold) ranged from 10 to 11.1 mm, with a mean of 10.6 mm ± 0.4 mm. The area of Hakuba's triangle ranged from 59.2 to 72.1 mm^2, with a mean of 63.9 mm^2 ± 4.4 mm^2.

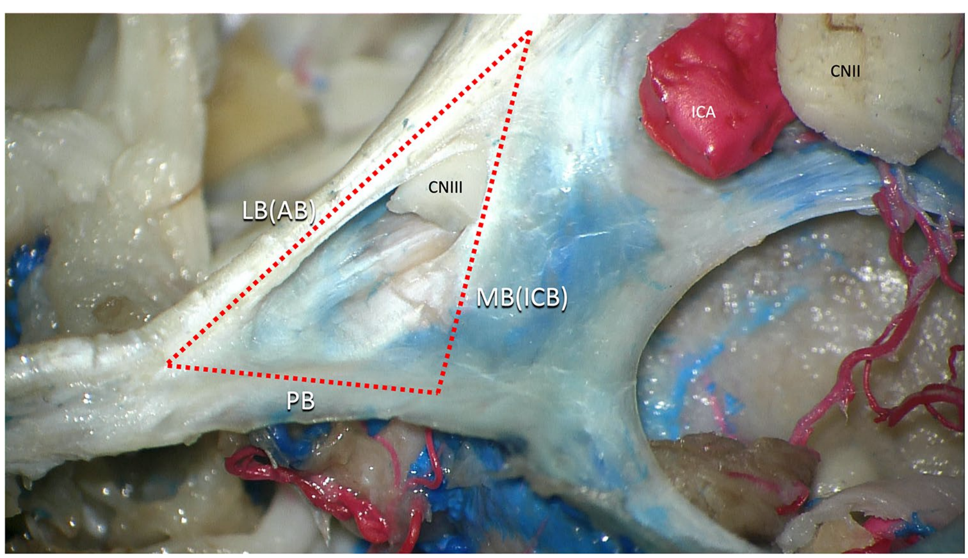
For the eight sides with available oculomotor nerve, the length of the nerve from the anterior to the posterior border, i.e., the length of nerve within the borders of the triangle, ranged from 8 to 10 mm with a mean of 9.3 mm ± 0.6 mm. The nerve width ranged from 2 to 3 mm with a mean of 2.1 mm ± 0.3 mm. The oculomotor nerve surface area ranged from 18 to 24 mm^2 with a mean of 19.5 mm^2 ± 1.9 mm^2. From these values, the percentage of the triangle occupied by the oculomotor nerve was calculated to have a mean of 31% ± 2.7%, with a range from 27.7 to 36.2%.

Discussion

Akira Hakuba

Akira Hakuba was born in Nara, Japan on May 5, 1934. He was a renowned neurosurgeon who studied at and spent most

Fig. 6 Figure 3 with additional segment of oculomotor nerve (CNIII) removed to note that in this specimen, the floor of the triangle is more or less transparent and, for example, the cavernous segment of the intenral carotid artery (ICA) can be viewed through the triangle. LB(AB), lateral (anterior) border; MB(ICB), medial (interclinoid) border; PB, posterior border



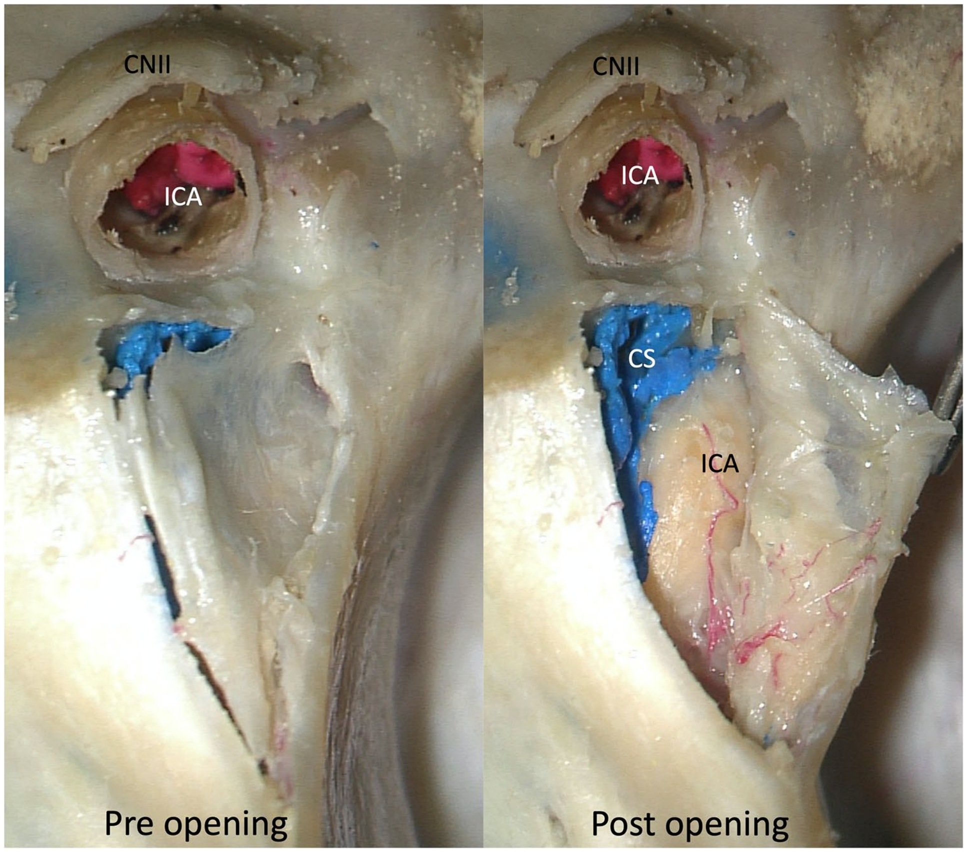


Fig. 7 Right-sided Hakuba's triangle pre and post opening to illustrating the uderlying cavernous sinus (CS) and cavernous segment of the intenral carotid artery (ICA)

of his professional career in Osaka City University Hospital in Osaka. He received a portion of his training under Professor Leonard Malis at Mount Sinai Medical Center in New York. His most significant contributions came in the fields of skull base and spine surgery, where he published extensively on various operative techniques including infratemporal [8], transpetrosal-transtentorial [9], and transcavernous approaches [7]. In fact, Dr. Hakuba is one of the earliest surgeons credited with establishing the skull base as its own separate discipline within neurosurgery. In addition to his

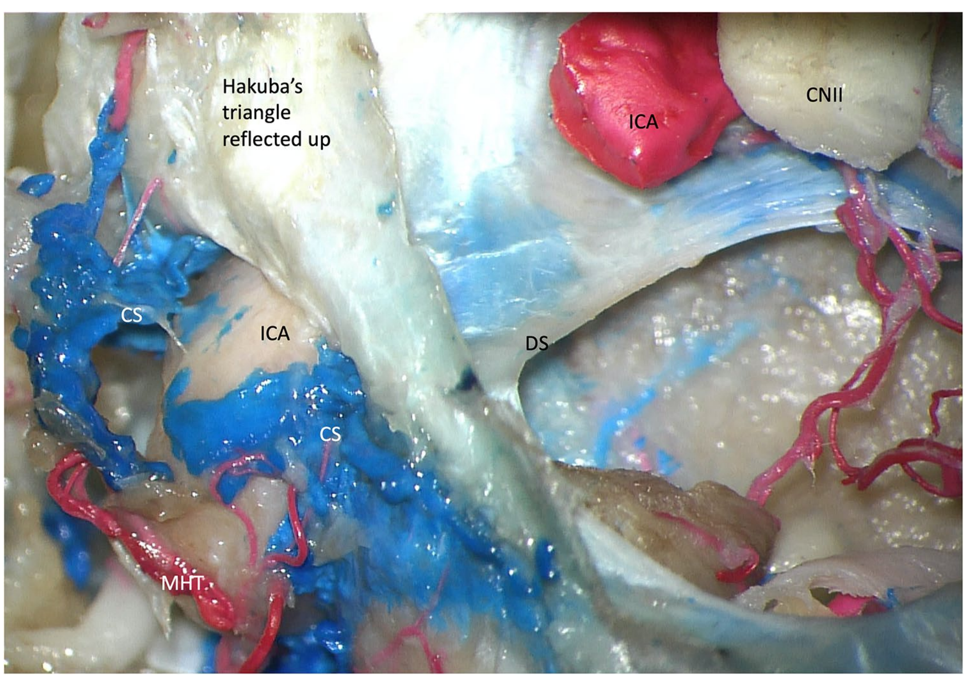


Fig. 8 Figure 5 after anterior reflection of the dura making up Hakuba's triangle and noting the cavernous sinus (CS), cavernous segment of the internal cartoid artery (ICA), and branches of the meningohypophysial trunk (MHT). Also, note the optic nerve (CNII) and diaprhagma sella (DS)

numerous publications, Dr. Hakuba helped further the field of neurosurgery by inspiring and training medical students and residents with a special focus on patient care [12]. He passed away on November 20, 2004.

Historical definitions of Hakuba's triangle

Hakuba first defined this medial triangle by the connection of three points in the superior wall of the cavernous sinus: the anterior margin of the petrous segment of the ICA, the dural entrance of the oculomotor nerve, and the anterolateral margin of the posterior clinoid process [8]. Other definitions can also be found in the literature. *The Fukushima Manual of Skull Base Dissection* describes Hakuba's triangle as formed by the siphon angle, the lateral wall of the intradural ICA, the posterior clinoid process, and the porus oculomotorius [5]. Watanabe et al. defined slightly different borders: the anterior and posterior clinoid processes, the fold of dura running from the posterior clinoid process to the petrous apex, and the fold of dura between the anterior clinoid process and the petrous apex [14]. Watanabe et al.'s borders expose the same contents but are more easily visualized intraoperatively during transcranial approaches and provide a well-defined window of dura mater to resect. Our measurements are in close agreement with Watanabe's values of 10.4 mm ± 4.2 mm for the medial border, 16.1 mm ± 4.0 mm for the lateral border, and 12.2 mm ± 5.1 mm for the posterior border.

Contents of Hakuba's triangle and contained pathology

Accessing the skull base through Hakuba's triangle allows for exposure of the superior cavernous sinus and for visualization and manipulation of the cavernous ICA segment medially and the horizontal ICA segment and oculomotor nerve laterally [4, 8, 14]. All of the contents of Hakuba's triangle found in our specimens corroborated prior reports. In regard to pathology, vascular lesions such as aneurysms, carotid-cavernous fistulas, and arteriovenous malformations can be exposed and accessed through Hakuba's triangle [2, 4, 7, 11]. We noted that the oculomotor nerve traversed in close proximity superior to the ICA, so a cavernous segment aneurysm could compress this nerve against the dura and cause oculomotor nerve palsy (somatic), which has previously been reported [11]. Cavernous sinus tumors such as cavernous extensions of pituitary adenomas or craniopharyngiomas, or meningiomas and teratomas, can also be exposed through Hakuba's triangle [1, 9].

Surgical applications

As a method of approaching and exposing the cavernous sinus to treat a related pathology, Hakuba considered his triangle a relatively safe corridor because the ICA is the only important anatomical structure located within [8]. In addition, our finding that the oculomotor nerve takes up less than 1/3 of the triangle's 63.9 mm^2 surface area shows that lesions of the intracavernous space can be safely accessed microsurgically without injuring the oculomotor nerve. Ample space is available for the resection of tumors or clipping of aneurysms [2, 3, 11]. Additionally, this triangle provides access to the proximal siphon and horizontal segment of the cavernous ICA, which can be advantageous in procedures requiring proximal control that typically employ cervical proximal carotid control or anterior clinoidectomy [2]. Most C4 segment aneurysms, tumors of the cavernous sinus, and carotid-cavernous fistulas can be approached through Hakuba's triangle [5]. When a distal vasculature pathology such as an ICA terminal segment aneurysm is treated, proximal control via ICA segments C2-C4 is potentially favored over proximal control through the cervical ICA as it avoids multiple surgical sites. Intracavernous oculomotor and abducens nerve pathologies such as schwannomas can also be approached through Hakuba's triangle.

Other cavernous sinus triangles, including the anteromedial and superolateral triangles, can be used to maximize the surgical window for exposing a large intracavernous pathology [8], and the appropriate triangle should be chosen depending on where the lesion is located. For instance, inferior or posterior compartment lesions are not as suitable for exposure via Hakuba's triangle because they would not be directly in the field of view. Another potential limitation of using Hakuba's triangle is the presence of cavernous venous plexuses, which increase the risk of intraoperative bleeding and may obstruct the surgical view upon manipulation; however, that caveat is not unique to any one triangle [1].

Conclusion

The skull base is considered the most complex anatomical area of the human body, and many neurosurgeons make use of triangles to optimize exposures. Hakuba's triangle allows for a wide and relatively safe exposure of the superior cavernous sinus to aid in treating vascular and neoplastic lesions. In this study, we provided cadaveric measurements of the borders of Hakuba's triangle along with descriptions of its neurovascular contents.

Acknowledgements The authors sincerely thank those who donated their bodies to science so that anatomical research could be performed.

Results from such research can potentially increase mankind's overall knowledge that can then improve patient care. Therefore, these donors and their families deserve our highest gratitude [10].

Author contribution Conceptualization: JI, ASD, RST. Data acquisition: MM, CW, JFB, JI, RST. Data analysis or interpretation: MM, CW, GW, JW. Drafting of the manuscript: MM, CW, JW. Critical revision of the manuscript: JI, ASD, RST. Approval of the final version of the manuscript: all authors.

Data availability Not applicable.

Code availability Not applicable.

Declarations

Ethics approval The protocol of the study did not require approval by the ethical committees or informed consent. The study followed the Declaration of Helsinki (64th WMA General Assembly, Fortaleza, Brazil, October 2013).

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

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