Acta Neurochirurgica
https://doi.org/10.1007/s00701-022-05349-w

ORIGINAL ARTICLE - TUMOR - MENINGIOMA

Evaluating diploic vein blood flow using time-resolved whole-head computed tomography angiography and determining the positional relationship between typical craniotomy approaches and diploic veins in patients with meningioma

Kei Yamashiro[1,2] · Akira Wakako[1,2] · Tatsuo Omi[1,2] · Kazuhiro Murayama[3] · Daijiro Kojima[1] · Jun Muto[1] · Kazuhide Adachi[1] · Mitsuhiro Hasegawa[1] · Yuichi Hirose[1]

Received: 22 July 2022 / Accepted: 18 August 2022

Abstract

Background Diploic veins may act as collateral venous pathways in cases of meningioma with venous sinus invasion. Diploic vein blood flow should be preoperatively evaluated to consider preserving the veins. In this study, we evaluated the use of time-resolved whole-head computed tomography angiography (4D-CTA)—which is less patient-intensive than digital subtraction angiography (DSA)—for assessing diploic vein blood flow and the positional relationship between typical craniotomy approaches and diploic veins.

Methods We retrospectively examined 231 patients who underwent surgery for intracranial meningioma. We performed contrast-enhanced magnetic resonance imaging (MRI) to evaluate diploic vein pathways and compared the visualization rates of diploic vein blood flow assessed using 4D-CTA and DSA. Subsequently, we evaluated the rates of the diploic veins transected during craniotomy by comparing the pre- and postoperative contrast-enhanced MRI.

Results The diagnostic performance of 4D-CTA was assessed in 45 patients. Of the 320 diploic veins identified in these patients, blood flow in 70 (21.9%) diploic veins was identified by 4D-CTA and DSA, and both results were consistent. To assess the transection rates of the diploic veins, 150 patients were included. A trend towards a high transection rate of the diploic vein in the basal interhemispheric, frontotemporal, orbitozygomatic, combined transpetrosal, and convexity craniotomy approaches was observed.

Conclusions In patients with meningiomas, both 4D-CTA and DSA are useful in evaluating diploic vein blood flow. In meningiomas with venous sinus invasion, determining the extent of craniotomy after understanding the pathways and blood flow of diploic veins is recommended.

Keywords Digital subtraction angiography · Diploic vein blood flow · Meningioma · Time-resolved Whole-head computed tomography angiography

This article is part of the Topical Collection on *Tumor - Meningioma*

✉ Kei Yamashiro
keiyamashiro1577@gmail.com

1 Department of Neurosurgery, Fujita Health University, 1-98 Dengakugakubo, Kutsukake-Cho, Toyoake, Aichi 470-1192, Japan

2 Department of Neurosurgery, Fujita Health University Okazaki Medical Center, Okazaki, Aichi 444-0827, Japan

3 Department of Radiology, Fujita Health University, Toyoake, Aichi 470-1192, Japan

Abbreviations

4D-CTA	Time-resolved whole-head computed tomography angiography
DSA	Digital subtraction angiography
MRI	Magnetic resonance imaging
SSS	Superior sagittal sinus
PFO	Pterional part of the frontoorbital diploic vein pathway
OFO	Orbital part of the frontoorbital diploic vein pathway
PFP	Pteriorfrontoparietal
OP	Pteriorfrontoparietal
OC	Occipitocervical

ICA	Internal carotid artery
ICAG	Internal carotid artery angiography
ECAG	External carotid artery angiography
BIA	Basal interhemispheric approach
FTA	Frontotemporal approach
OZA	Orbitozygomatic approach
ATPA	Anterior transpetrosal approach
CTPA	Combined transpetrosal approach
LSOA	Lateral suboccipital approach

Introduction

The diploic veins are frequently connected to the venous sinuses, particularly with the superior sagittal sinus (SSS) [30, 34]. In healthy people, the diploic veins act as venous channels between the extra- and intra-cranial venous systems. It has been suggested that the diploic veins may be involved in the drainage of cerebrospinal fluid [2, 31]. They function as collateral pathways of intracranial venous perfusion in cases of venous sinus occlusion [5, 8, 11, 14, 15, 17, 23, 24, 28, 30, 34, 35], particularly in meningiomas with SSS invasion [34]. Moreover, it has been reported that sacrificing these diploic veins can cause intracranial venous infarction in patients with meningiomas [16, 23, 24, 34]. In cases of meningiomas with SSS invasion, preoperative assessment of diploic vein blood flow via digital subtraction angiography (DSA) is recommended [34].

While the utility of imaging techniques, such as magnetic resonance imaging (MRI), computed tomography (CT), and radiography in evaluating the pathways of the diploic vein, is widely known [1, 4, 7, 9, 19, 21, 23, 24, 27, 30, 32, 34], an optimal clinical examination technique to evaluate diploic vein blood flow is yet to be established. To date, only one study has evaluated diploic vein blood flow in detail using DSA [34]. However, compared to other imaging techniques, DSA burdens the patient, is time-consuming, and poses the risk of developing severe complications, including cerebral infarction. Hence, this necessitates a patient-friendly clinical examination technique.

Time-resolved whole-head CT angiography (4D-CTA) does not require hospitalization and is less time-consuming and minimally invasive than DSA [3, 6, 10, 18, 33]. Arteriovenous perfusion images of the head can be obtained by continuously capturing contrast-enhanced images from the arterial to the venous phase by 4D-CTA [3, 6, 10, 18, 33]. This modality has been reported to be useful in the evaluation of venous sinus occlusion and collateral venous pathways [18] and diploic vein blood flow [34]; however, there are no detailed studies to date. Furthermore, preserving high-flow diploic veins that function as collateral venous pathways should be considered in patients whose venous sinuses are obstructed by meningiomas [23, 24, 34]. Nevertheless, the positional relationship between a typical craniotomy and the diploic veins being transected and the optimal method for identifying and preserving diploic veins during craniotomy are yet to be clarified.

Herein, we investigated whether 4D-CTA could evaluate diploic vein blood flow in patients with meningioma and compared the diagnostic performance of DSA with that of 4D-CTA. Moreover, we retrospectively investigated the rates of the diploic veins being transected during typical craniotomy approaches, typically used in meningioma surgery, and discussed techniques for identifying and preserving diploic veins that function as collateral venous pathways during craniotomies.

Methods and materials

Study design and ethical considerations

The ethical review board of Fujita Health University approved this retrospective study (protocol number: HM19-472). Formal consent for study participation was not required considering the retrospective design of the present study; hence, we adopted an opt-out method. Informed written consent was obtained from the patients for all treatment procedures.

Study population

We identified patients who underwent craniotomies for intracranial meningioma at Fujita Health University from January 2015 to February 2020 using medical records.

To evaluate the diagnostic performance of 4D-CTA for diploic vein flow, we excluded patients without preoperative contrast-enhanced MRI and/or DSA and/or 4D-CTA (Fig. 1). Additionally, to accurately evaluate the transection rates of diploic veins during the typical craniotomy approaches, we excluded patients without pre- and/or postoperative contrast-enhanced MRI and those with recurrent meningioma or a history of craniotomy (Fig. 1).

Imaging modalities

We reviewed the patients' imaging studies to detect the pathways and blood flow of the diploic vein. All pre- and postoperative imaging studies were performed within 6 months prior to and after the craniotomy, respectively.

We performed contrast-enhanced MRI and DSA using the method employed in a previous study [34].

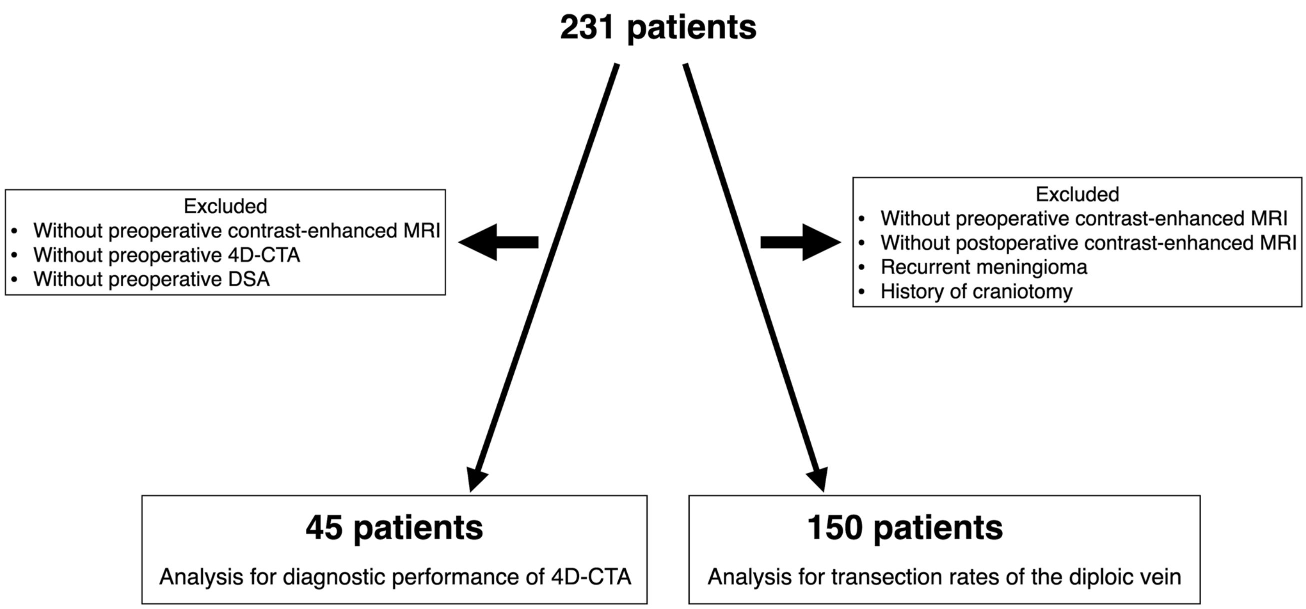

Fig. 1 Tree-diagram of the study population. MRI magnetic resonance imaging, 4D-CTA time-resolved whole-head computed tomography angiography, DSA digital subtraction angiography

4D-CTA

We acquired contrast-enhanced volume data for 4D-CTA using a 320-row area detector CT scanner (Aquilion ONE; Canon Medical Systems Corporation, Otawara, Japan) by volumetric dynamic scanning. These examinations were performed for the whole brain within a 16-cm area, without helical imaging with the following parameters: 320 × 0.5-mm collimation, 80 kVp, 70 mA in arterial phase, 30 mA in venous phase, a 1-s gantry rotation time, 512 × 512 matrix, and 240-mm field of view. We initially acquired dynamic 4D-CTA data in the arterial and venous phases every 1 s and 4 s, respectively. The contrast medium volume was calculated based on the patient's body weight. We injected 250 mgI/kg of iopamidol (Iopamiron 370; Bayer, Osaka, Japan) intravenously as a bolus at a fixed 10 s, followed by an intravenous bolus injection of 30 mL physiological saline solution at a rate similar to that of the contrast medium.

Evaluating imaging studies

Two board-certified neurosurgeons independently analyzed all the MRI and DSA results, while the second set of two board-certified neurosurgeons analyzed the 4D-CTA results.

Diploic vein pathways

We adopted the diploic vein pathways defined in previous studies [30, 34] and assessed them using preoperative contrast-enhanced MRI and classified them into five variations, including the pterional (PFO) and orbital (OFO) parts of the frontoorbital, pteriorfrontoparietal (PFP), occipitoparietal (OP), and occipitocervical (OC) pathways (Fig. 2).

While the OC diploic veins principally course in the midline, the PFO, OFO, PFP, and OP veins can course bilaterally [30, 34]. We evaluated all the diploic vein pathways bilaterally, except for the OC veins, which were evaluated without considering laterality. Only veins running in the diploic space were assessed as diploic veins and distinguished from the meningeal veins [1].

Diploic vein blood flow

Using preoperative DSA and 4D-CTA, we evaluated diploic vein blood flow and classified it into the following three types (as previously reported): early, late, and non-visualized [34]. Early type included the diploic veins where blood flow was concurrently visualized with venous sinuses on the internal carotid artery (ICA) angiography (ICAG) or 4D-CTA. The late type included the diploic veins where blood flow was visualized after the venous sinuses began to disappear on ICAG or 4D-CTA. The non-visualized type included the diploic veins where blood flow was not visualized on ICAG and 4D-CTA, while its presence was confirmed on contrast-enhanced MRI.

Transection rates of diploic veins

We investigated the transection rates of diploic veins for the basal interhemispheric (BIA), frontotemporal (FTA),

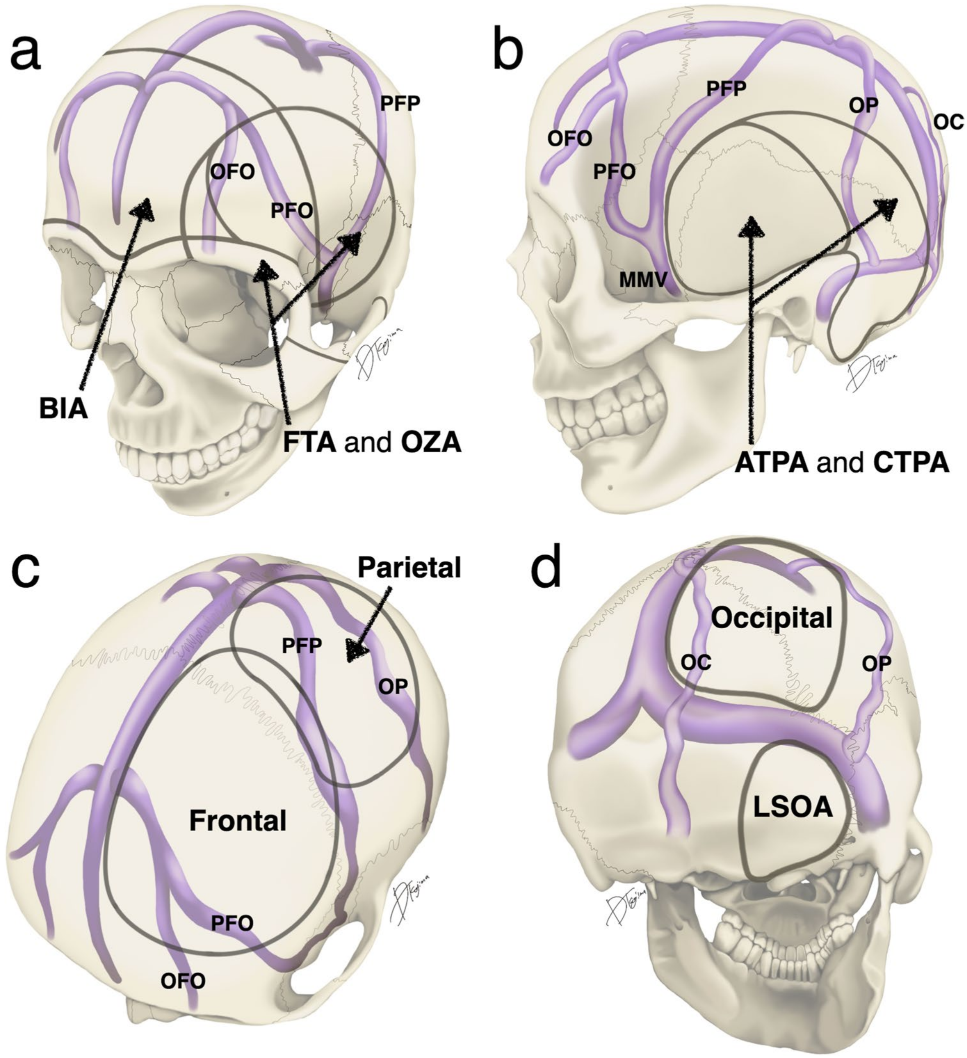

Fig. 2 Schematic representation of the diploic vein pathways and craniotomy range. OFO orbital part of the frontoorbital pathway; PFO pterional part of the frontoorbital pathway; PFP pteriorfrontoparietal pathway; OP occipitoparietal pathway; OC occipitocervical pathway; MMV middle meningeal vein; BIA basal interhemispheric approach; FTA frontotemporal approach; OZA orbitozygomatic approach; ATPA anterior transpetrosal approach; CTPA combined transpetrosal approach; frontal: frontal craniotomy; parietal: parietal craniotomy; occipital: occipital craniotomy; LSOA lateral suboccipital approach

orbitozygomatic (OZA), anterior transpetrosal (ATPA), combined transpetrosal (CTPA), and lateral suboccipital (LSOA) approaches and frontal, parietal, and occipital craniotomies; these are the typical craniotomy approaches for meningioma surgery (Fig. 2). In all cases, we determined the extent of the craniotomy based on the goal of total tumor removal. Among all the convexity craniotomies performed in patients with supratentorial meningioma, craniotomies centered on the frontal, parietal, and occipital lobe regions were defined as frontal, parietal, and occipital craniotomies, respectively. We excluded convexity craniotomy in the temporal lobe region because of inadequate cases to evaluate the transection rate (only two cases). Additionally, we excluded large, multi-regional convexity craniotomies, such as decompressive craniotomy, to clarify the positional relationship between the craniotomy region and the sacrificed diploic veins.

We evaluated the transection rates of the diploic veins by comparing the pre- and postoperative contrast-enhanced MRI findings. Considering the bilateral presentation of PFO, OFO, PFP, and OP diploic veins, we determined the transection rates of these diploic vein pathways using the number of diploic veins on the surgical side as the denominator for unilateral craniotomy and that on both sides as the denominator for bilateral craniotomy.

Results

Diploic vein blood flow visualized by 4D-CTA

During the study period, 231 patients with meningioma underwent craniotomy; 45 were included for the evaluation of the diagnostic performance of 4D-CTA for diploic vein blood flow (Fig. 1), while the remaining were excluded because preoperative contrast-enhanced MRI and/or DSA and/or 4D-CTA had not been performed.

The tumor attachment sites included the petroclival (11 cases), sphenoid ridge (eight cases), convexity (seven cases), cerebellopontine angle (four cases), parasagittal (three cases), tentorial (three cases), tuberculum sellae (two cases), olfactory groove (two cases), anterior clinoid process (one case), cavernous sinus (one case), falcotentorial (one case), falx (one case), and foramen magnum (one case).

Complications by 4D-CTA and DSA

Complications related to 4D-CTA did not occur in any of the 45 patients. However, DSA-related symptomatic cerebral infarction occurred in one patient (2.2%).

Characteristics of the diploic vein pathways and blood flow

We identified 320 diploic veins with the following pathways by contrast-enhanced MRI in the 45 patients: 71 PFO, 61 OFO, 81 PFP, 65 OP, and 42 OC.

We did not identify blood flow in 250 of the 320 diploic veins (78.1%) by ICAG and 4D-CTA and classified them as non-visualized type (Fig. 3a). In the remaining 70 diploic veins (21.9%), blood flow was identified in all on 4D-CTA. However, ICAG identified blood flow in only 65 diploic veins (20.3%) (Fig. 3a). Detailed data are presented in Table 1.

Of these 70 diploic veins, we classified 27 and 43 as early and late types, respectively, based on the ICAG and 4D-CTA findings (Fig. 3b). In the early type, we identified blood flow by both ICAG and 4D-CTA in 26 diploic veins (96.3%), while one diploic vein was not identified by ICAG (Fig. 3b). In the late type, we identified blood flow by both ICAG and 4D-CTA in 39 diploic veins (90.7%), while 4 diploic veins were not identified by ICAG (Fig. 3b). In the diploic veins visualized on both 4D-CTA and ICAG, the diagnosis of early and late types by 4D-CTA was concordant with that via ICAG. Diploic veins where blood flow was confirmed only by ICAG were not observed.

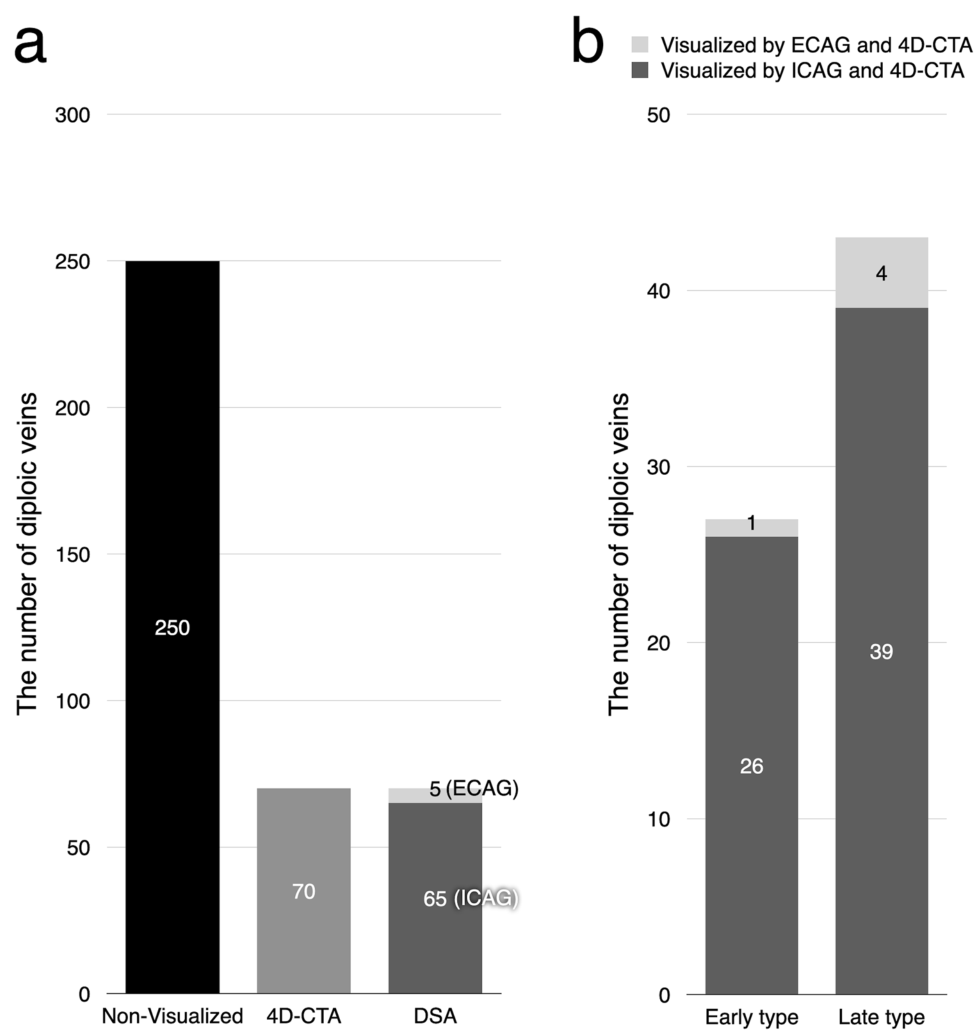

Fig. 3 The number of diploic veins identified by digital subtraction angiography and time-resolved whole-head computed tomography angiography (**a**), and the number of early-type and late-type diploic veins identified via these imaging techniques (**b**). 4D-CTA time-resolved whole-head computed tomography angiography, DSA digital subtraction angiography, ICAG internal carotid artery angiography, ECAG external carotid artery angiography

Table 1 Diploic vein routes identified by MRI, 4D-CTA, ICAG, and ECAG

Diploic vein route	The number of diploic veins identified by MRI	The number of diploic veins identified by 4D-CTA	The number of diploic veins identified by ICAG	The number of diploic veins identified by ECAG
PFO	71	12	12	0
OFO	61	2	2	0
PFP	81	39	34	5
OP	65	10	10	0
OC	42	7	7	0

MRI magnetic resonance imaging, *4D-CTA* time-resolved whole-head computed tomography angiography, *ICAG* internal carotid artery angiography, *ECAG* external carotid artery angiography, *PFO* pterional part of the frontoorbital diploic vein pathway, *OFO* orbital part of the frontoorbital diploic vein pathway, *PFP* pteriorfrontoparietal, *OP* pteriorfrontoparietal, *OC* occipitocervical

Characteristics of the five diploic veins in which blood flow was not identified by ICAG

Five diploic veins, all of which were PFP, were only visualized on 4D-CTA (Table 1). These veins, all of which were connected to the tumor attachment site, were observed in four out of eight and one of seven cases with sphenoid ridge and convexity meningiomas, respectively.

We could not identify the five diploic veins by ICAG. However, we identified them by external carotid artery angiography (ECAG) (Fig. 3; Table 1). Unlike the diploic veins found in ICAG, these veins were not involved in cerebral venous perfusion; however, they functioned as tumor drainers. Although these diploic veins were transected during craniotomy in all cases, no postoperative complications occurred.

Representative cases

Case 1: This case involved left-sided tentorial meningioma with sigmoid sinus invasion (Fig. 4a). We identified the late-type PFP diploic vein on preoperative ICAG. We did not identify the PFP diploic vein in the early venous phase. It was only visualized after the venous sinuses began to disappear in the late venous phase (Fig. 4b and c). This finding, confirmed by ICAG, was consistent with the 4D-CTA finding (Fig. 4d and e).

Case 2: This case involved left petroclival meningioma (Fig. 5a). We identified the early-type PFO and PFP diploic veins on preoperative ICAG. The PFO and PFP diploic veins were visualized concurrently with the venous sinuses in the early venous phase, consistent with the 4D-CTA findings (Fig. 5b–e).

Case 3: This case involved left-sided sphenoid ridge meningioma (Fig. 6a). The left PFP diploic vein was directly connected to the tumor attachment site (Fig. 6b). The early-type PFP diploic vein was identified on ECAG and not ICAG (Fig. 6c–e). This vein was not involved in normal cerebral perfusion and functioned as a tumor drainer. These findings identified on DSA were consistent with the 4D-CTA findings. However, it was difficult to distinguish if the PFP diploic vein functioned as a tumor drainer or was involved in cerebral venous perfusion, based on the 4D-CTA findings alone (Fig. 6f).

Transection rates of the diploic veins during the typical craniotomy approaches

We included 150 out of 231 patients in the analysis of transection rates of diploic veins during typical craniotomies (Fig. 1). The number of cases for each craniotomy approach was as follows: BIA, 10; ATPA, 15; CTPA, 5; OZA, 17; FTA, 20; LSOA, 18; and frontal, 29; parietal, 17; and occipital, 19 craniotomies.

In each typical craniotomy approach for meningioma surgery, 14/14 PFO (100%) and 16/16 OFO (100%) veins were occluded by the BIA; 17/17 PFO (100%), 3/9 OFO (33.3%), 20/20 PFP (100%), and 1/18 OP (5.6%) veins were occluded by the FTA; 11/11 PFO (100%), 11/13 OFO (84.6%), and 16/16 PFP (100%) veins were occluded by the OZA; 1/14 PFO (7.1%) and 2/11 PFP (18.2%) veins were occluded by the ATPA; 3/5 PFP (60%) and 4/4 OP (100%) veins were occluded by the CTPA; 1/16 OP (6.3%) and 3/18 OC (16.7%) veins were occluded by the LSOA; 25/35 PFO (71.4%), 21/28 OFO (75.0%), 17/41 PFP (41.5%), and 6/35 OP (17.1%) veins were occluded by frontal craniotomy; 13/17 PFP (76.5%), 7/17 OP (41.1%), and 4/17 OC (23.5%) veins were occluded by parietal craniotomy; and 2/20 PFP (10.0%), 6/20 OP (30.0%), and 13/19 OC (68.4%) veins were occluded by occipital craniotomy (Fig. 7).

Discussion

To the best of our knowledge, this is the first study to use 4D-CTA for identifying and evaluating diploic vein blood flow; this was consistent with DSA findings. However, unlike DSA, 4D-CTA did not cause complications and was safely performed. Thus, 4D-CTA is useful in evaluating diploic vein blood flow.

Although meningiomas may be vascularized by the pial blood supply, it is reasonable to assume that the diploic veins identified by ICAG and ECAG are involved in cerebral venous perfusion and in extracranial venous and tumor perfusion, respectively. In the present study, most of the diploic veins were identified by ICAG, indicating the involvement

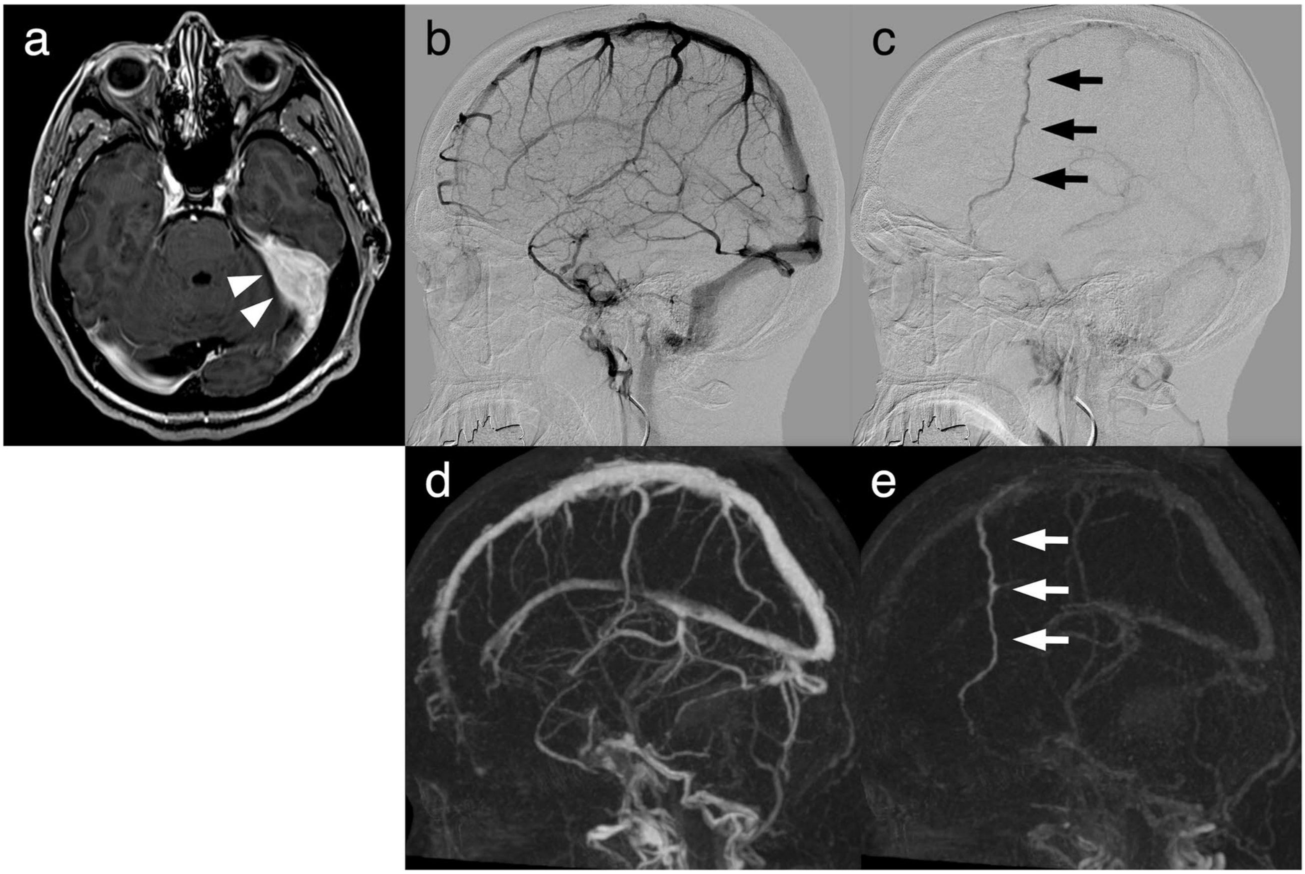

Fig. 4 Representative case of the late type diploic vein. Contrast-enhanced magnetic resonance imaging displays left-sided tentorial meningioma with sigmoid sinus invasion (**a**). On the preoperative internal carotid artery angiography, the late-type diploic vein is not visualized in the early venous phase (**b**); however, it is visualized after venous sinuses begin to disappear (**c**). These findings are consistent with those of time-resolved whole-head computed tomography angiography (**d**, **e**). To facilitate visualizing the venous pathway, the vein on the right side has been deleted (image editing) (**d**, **e**). White arrowhead (**a**): meningioma; black arrow (**c**): the late-type PFP diploic vein; white arrow (**e**): the late-type PFP diploic vein. PFP pteriorfrontoparietal

of diploic veins in cerebral venous perfusion. Conversely, there were a few cases wherein the diploic vein was involved in tumor perfusion. This study revealed that the diagnostic performance of 4D-CTA to evaluate diploic vein blood flow was similar to that of DSA. However, the external carotid artery was enhanced simultaneously, since 4D-CTA does not allow selective imaging of the ICA (Fig. 6f). Hence, in meningiomas with a direct connection between the diploic vein and tumor attachment site, distinguishing whether the diploic vein was functioning as a tumor drainer or involved in intracranial venous perfusion was not possible on 4D-CTA. Therefore, DSA might be more appropriate if the diploic vein courses just above the tumor.

All the diploic vein pathways that functioned as tumor drainers were PFP, and many were associated with sphenoid ridge meningioma. Anatomically, the PFP diploic veins are located above the tumor attachment site of the sphenoid ridge meningioma [30, 34]. These veins functioned as tumor drainers in 50% of the cases of sphenoid ridge meningiomas. Although the number of cases is limited, all five diploic veins functioning as tumor drainers in this study were safely transected. Conversely, it has been reported that the diploic vein functions as a collateral pathway of the superficial middle cerebral vein in sphenoid ridge meningioma and that complications occurred after the veins were sacrificed [16]. This indicates that similar to cases of meningioma with SSS invasion [34], the diploic venous blood flow in sphenoid ridge meningiomas needs to be carefully observed. Based on the results of this study, DSA would be more suitable than 4D-CTA for evaluating diploic vein blood flow in sphenoid ridge meningiomas.

Although the pathways of the diploic veins and the extent of craniotomy varied in each case, the transection rates of the diploic veins in each craniotomy were not unusual. In other words, the PFO and OFO veins, which usually course around the orbital rim [30, 34], were frequently cut in the BIA and OZA; the PFO and PFP veins, which typically join the sphenoparietal sinus or middle meningeal vein [30, 34],

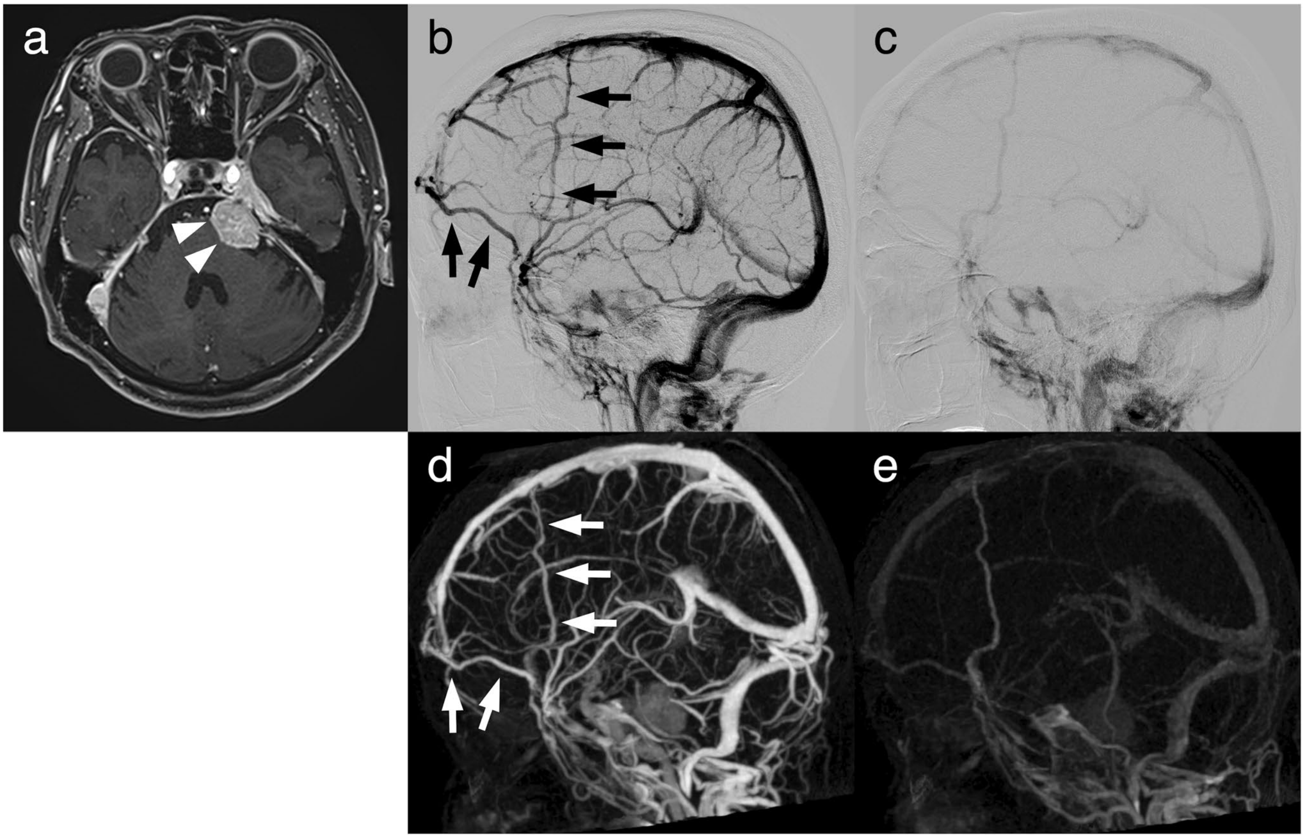

Fig. 5 Representative case of the early type diploic vein. Contrast-enhanced magnetic resonance imaging displaying left side petroclival meningioma (**a**). On the preoperative internal carotid artery angiography, the early-type diploic veins are concurrently visualized with venous sinuses (**b**) and simultaneously disappear with the venous sinuses (**c**). These findings are consistent with those of time-resolved whole-head computed tomography angiography (**d**, **e**). To facilitate visualizing the venous route, the vein on the right side has been deleted (image editing) (**d**, **e**). White arrowhead (**a**): meningioma; black arrow (**b**): the early-type PFO and PFP diploic vein; and white arrow (**d**): the early-type PFO and PFP diploic vein PFO pterional part of the frontoorbital, PFP pteriorfrontoparietal

were frequently cut in the OZA and FTA; and the OP veins that generally join the transverse-sigmoid junction [30, 34] were frequently cut in the CTPA (Fig. 7a and b). In addition, there was no contradiction between the extent of the convexity craniotomy and the transected diploic vein's pathway (Fig. 7c and d). In contrast, the ATPA and LSOA, which rarely include the diploic vein in the craniotomy range, displayed a low rate of diploic vein interruption (Fig. 7b and d). These findings were consistent with those of a previous cadaveric study that investigated the relationship between craniotomy around the pterion and obstructed diploic veins [5].

We have earlier reported on the risk of venous congestion due to sacrificing the diploic veins in the same patients as in the present study [34]. Diploic veins act as collateral venous pathways, especially in meningiomas with an SSS invasion (Fig. 8) [34]. Moreover, in these cases, postoperative venous complications occurred in two out of five cases (40%) in which the early-type diploic vein was sacrificed [34]. Convexity craniotomy is frequently used to resect meningiomas with SSS invasion (falx, parasagittal, and convexity); however, based on the results of the present study, an anterior–posterior long bilateral convexity craniotomy across the SSS sacrifices multiple diploic veins and may lead to the risk of postoperative venous congestion. Thus, a 2-stage strategy with limited craniotomy could be considered. First, the tumor is resected via a limited craniotomy only from anatomical areas corresponding to neurological findings, thereby preserving the diploic veins. Subsequently, clinicians monitor changes in diploic vein blood flow patterns elicited by tumor growth and/or development of collateral venous pathways, resecting the rest of the tumor at a later second stage when necessary. This strategy was adopted in one patient in the present study in whom no postoperative venous congestion was observed (Fig. 8). However, there are no studies on postoperative blood flow changes in the diploic veins to date; this indicates the need for future research. The recently reported minimally invasive keyhole or contralateral interhemispheric surgical approaches may be useful [22]. Furthermore, depending on the development of the venous

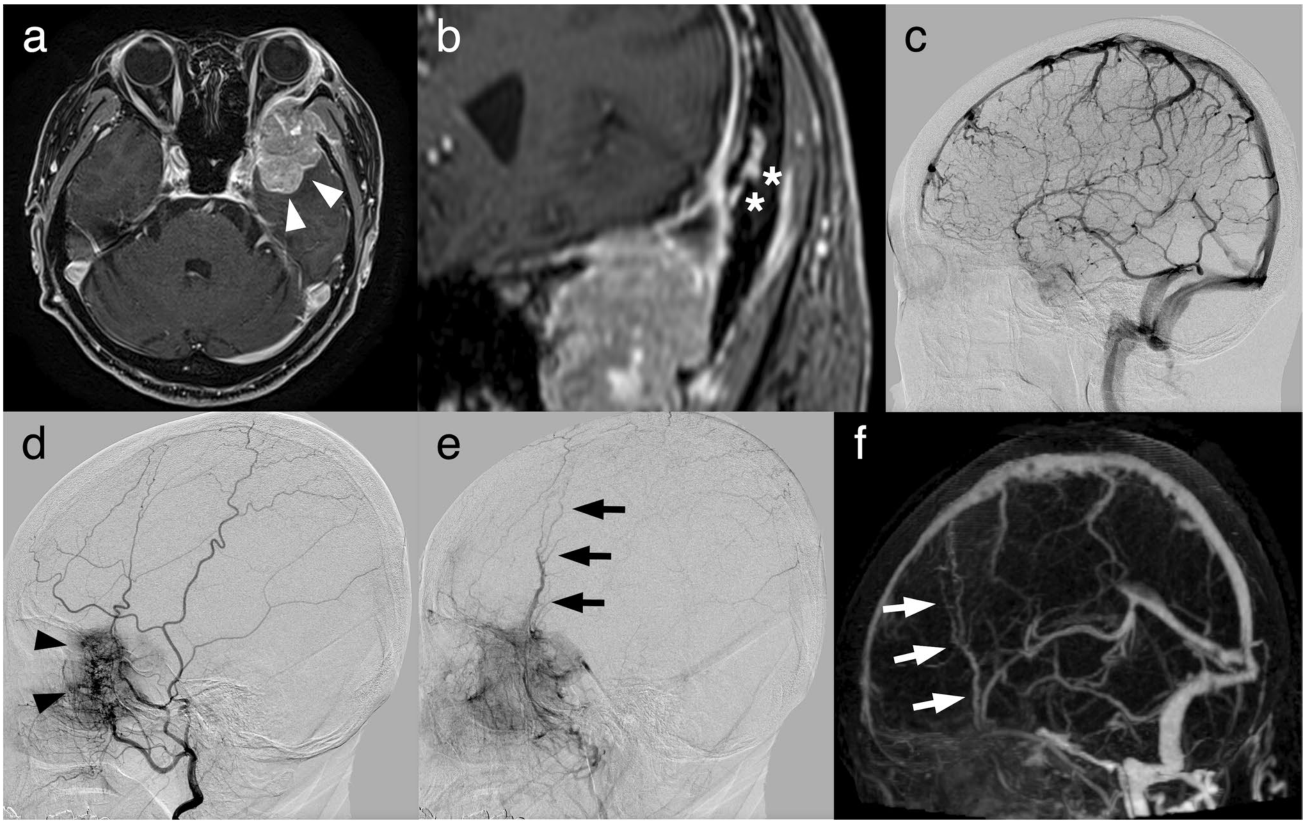

Fig. 6 Representative case of the diploic vein functioning as the tumor drainer. Contrast-enhanced magnetic resonance imaging displaying left-sided sphenoid ridge meningioma (**a**) and a direct connection between the diploic vein and tumor attachment (**b**). The diploic vein is not visualized on preoperative internal carotid artery angiography (**c**). In contrast, external carotid artery angiography displays a tumor stain (**d**) and early-type diploic vein functions as the tumor drainer (**e**). These findings are confirmed on the time-resolved whole-head computed tomography angiography (**f**). To facilitate visualizing the venous route, the vein on the right side has been deleted (image editing) (**f**). White arrowhead (**a**): meningioma; asterisk (**b**): direct connection between the diploic vein and tumor attachment; black arrowhead (**d**): tumor stain; black arrow (**e**): the PFP diploic vein functioning as the tumor drainer; and white arrow (**f**): the early type PFP diploic vein PFP: pteriorfrontoparietal

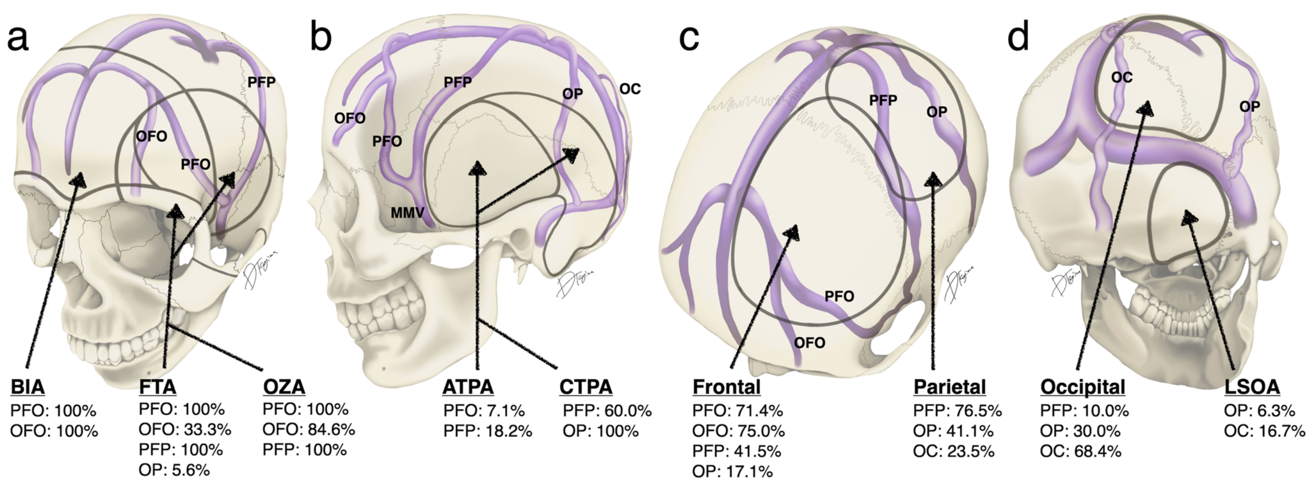

Fig. 7 Transection rates of the diploic vein pathway in each craniotomy approach. OFO orbital part of the frontoorbital pathway; PFO pterional part of the frontoorbital pathway; PFP pteriorfrontoparietal pathway; OP occipitoparietal pathway; OC occipitocervical pathway; MMV middle meningeal vein; BIA basal interhemispheric approach; FTA frontotemporal approach; OZA orbitozygomatic approach; ATPA anterior transpetrosal approach; CTPA combined transpetrosal approach; frontal: frontal craniotomy; parietal: parietal craniotomy; occipital: occipital craniotomy; LSOA lateral suboccipital approach

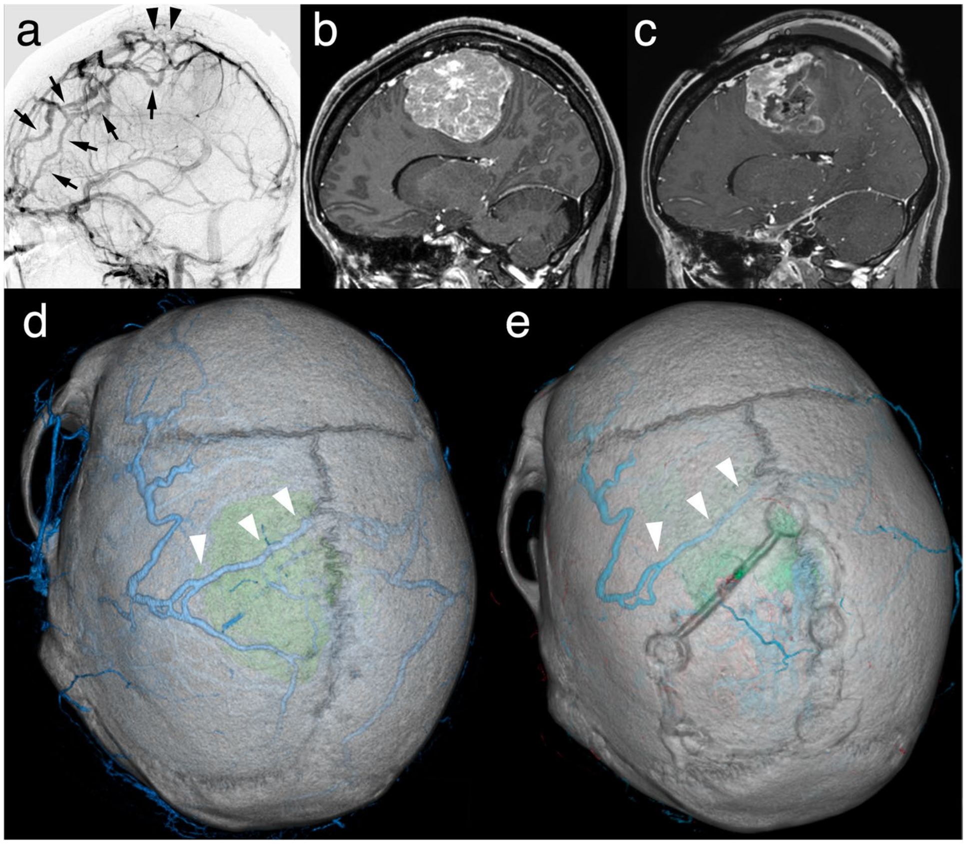

Fig. 8 Representative case of parasagittal meningioma with superior sagittal sinus invasion Preoperative internal carotid artery angiography displays an occluded superior sagittal sinus, and early-type diploic veins function as the collateral venous pathways of cerebral venous perfusion (**a**). Preoperative contrast-enhanced magnetic resonance imaging reveals motor cortex compression by the meningioma (**b**), and the posterior component of the tumor is removed via a limited craniotomy (**c**). A three-dimensional image based on preoperative computed tomography venography clearly depicts the positional relationship between the diploic veins and the tumor (**d**). Postoperative computed tomography venography displays a preserved early-type diploic vein coursing just above the tumor (**e**). Black arrowhead (**a**): occlusion of the superior sagittal sinus; black arrow (**a**): the early type diploic veins functioning as collateral venous pathways of cerebral venous perfusion; and white arrowhead (**d**, **e**): the preserved diploic vein coursing just above the tumor

sinus, venous congestion may occur in meningiomas with venous sinus invasion other than SSS, and in such cases, the diploic veins may function as collateral venous pathways [2, 12, 29]. No clear protocols are available to predict venous congestion after transecting the diploic vein; therefore, unnecessary transection of the diploic veins during craniotomy in these cases should preferably be avoided.

It is often difficult to confirm the diploic vein pathways from the bone surface during craniotomy [8, 20]. Therefore, researchers have established the usefulness of imaging techniques to evaluate the diploic vein pathway [1, 4, 7, 9, 19, 21, 23, 24, 27, 30, 32, 34]. The Plain X-ray of the skull can detect intraosseous collateral venous pathways and can be helpful in designing appropriate craniotomy [23, 24]. Topograms created based on DSA or MRI have also been reported to be useful in designing tailor-made approaches to avoid venous complications [25]. Furthermore, the use of a three-dimensional image created from contrast-enhanced CT facilitates the understanding of the positional relationship between the diploic vein and tumor, and in planning the optimal craniotomy range for early-type diploic vein preservation (Fig. 8). In combination with the intraoperative navigation system, determination of the diploic vein pathways during craniotomies and preserving the diploic veins more reliably has been made easier. 4D-CTA cannot entirely replace DSA and perform all functions, such as evaluating the feeding arteries; however, it is advantageous in understanding the positional relationship between tumor and important vessels, such as the diploic vein, venous sinus, and normal artery and vein. The choice between DSA and 4D-CTA must be made considering the invasiveness and the information required.

The preservation of the diploic veins limits the craniotomy range, which may reduce the volume of the tumor removed (Fig. 8). Total removal of the meningioma is generally recommended depending on the pathological findings.

However, information on the choice between preservation of collateral venous pathways such as diploic veins and radical tumor removal in meningiomas with venous sinus invasion is limited. It has been reported that in meningiomas with venous sinus invasion, tumor control can be achieved by tailored Simpson grade 4 surgery, with postoperative stereotactic radiosurgery [13], and that postoperative venous infarction can be prevented by venous reconstruction [26]. Furthermore, even if radical tumor resection is preferred, preserving a part of the diploic veins may reduce postoperative complications [34]. Since establishing an ideal treatment in these cases is challenging, a direct comparison between preservation of collateral venous pathways and radical tumor removal is necessary.

In conclusion, in this study, diploic vein blood flow was visualized on 4D-CTA. Moreover, 4D-CTA and DSA were equally useful for analyzing diploic vein blood flow in patients with meningioma. However, clinicians should consider DSA rather than 4D-CTA to distinguish whether the diploic veins function as tumor drainers or collateral venous pathways of cerebral venous perfusion, particularly if these veins have a direct connection to the tumor attachment site. Craniotomy approaches, such as the BIA, FTA, OZA, CTPA, and convexity craniotomy, have a high rate of diploic vein obstruction. In cases where the venous sinuses are obstructed by the meningiomas, determining the extent of the craniotomy after understanding the pathways and blood flow of the diploic veins is recommended.

Acknowledgements We would like to thank Editage for proofreading our work.

Author contribution Study conception and design: Kei Yamashiro. Data collection: Kei Yamashiro and Akira Wakako. Data Analysis; Kei Yamashiro, Tatsuo Omi, and Akira Wakako. Writing the article: Kei Yamashiro, Kazuhiro Murayama, and Daijiro Kojima. Revising the article: all authors.

Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee (institutional review board at Fujita health university, Protocol Number: HM19-472) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

Conflict of interest The authors declare no competing interests.

References

1. Alarfaj A, Sankar T, Bhargava R, Tyler J, Walji A, Fox R, Sagga A, Ishaque A, Aronyk K (2021) Magnetic resonance imaging analysis of human skull diploic venous anatomy. Surg Neurol Int 12:249. https://doi.org/10.25259/SNI_532_2020
2. Cheyuo C, Rosen CL, Rai A, Cifarelli CP, Qaiser R (2019) Venous manometry as an adjunct for diagnosis and multimodal management of intracranial hypertension due to meningioma compressing sigmoid sinus. Cureus 11:e4953. https://doi.org/10.7759/cureus.4953
3. Dundar TT, Aralasmak A, Kitis S, Yilmaz FT, Abdallah A (2019) Comparison of subtracted computed tomography from computed tomography perfusion and digital subtraction angiography in residue evaluation of treated intracranial aneurysms. World Neurosurg 132:e746–e751. https://doi.org/10.1016/j.wneu.2019.08.028
4. Eisova S, Rangel de Lazaro G, Pisova H, Pereira-Pedro S, Bruner E (2016) Parietal bone thickness and vascular diameters in adult modern humans: a survey on cranial remains. Anat Rec (Hoboken) 299:888–896. https://doi.org/10.1002/ar.23348
5. Garcia-Gonzalez U, Cavalcanti DD, Agrawal A, Gonzalez LF, Wallace RC, Spetzler RF, Preul MC (2009) The diploic venous system: surgical anatomy and neurosurgical implications. Neurosurg Focus 27:E2. https://doi.org/10.3171/2009.8.FOCUS09169
6. Harrigan MR, Magnano CR, Guterman LR, Hopkins LN (2005) Computed tomographic perfusion in the management of aneurysmal subarachnoid hemorrhage: new application of an existent technique. Neurosurgery 56:304–317. https://doi.org/10.1227/01.neu.0000148902.61943.df (discussion 304-317)
7. Hatipoglu HG, Ozcan HN, Hatipoglu US, Yuksel E (2008) Age, sex and body mass index in relation to calvarial diploe thickness and craniometric data on MRI. Forensic Sci Int 182:46–51. https://doi.org/10.1016/j.forsciint.2008.09.014
8. Hershkovitz I, Greenwald C, Rothschild BM, Latimer B, Dutour O, Jellema LM, Wish-Baratz S, Pap I, Leonetti G (1999) The elusive diploic veins: anthropological and anatomical perspective. Am J Phys Anthropol 108:345–358. https://doi.org/10.1002/(sici)1096-8644(199903)108:3%3c345::Aid-ajpa9%3e3.0.Co;2-s
9. Jivraj K, Bhargava R, Aronyk K, Quateen A, Walji A (2009) Diploic venous anatomy studied in-vivo by MRI. Clin Anat 22:296–301. https://doi.org/10.1002/ca.20767
10. Kortman HGJ, Smit EJ, Oei MTH, Manniesing R, Prokop M, Meijer FJA (2015) 4D-CTA in neurovascular disease: a review. Am J Neuroradiol 36:1026–1033. https://doi.org/10.3174/ajnr.A4162
11. Lachkar S, Dols MM, Ishak B, Iwanaga J, Tubbs RS (2019) The diploic veins: a comprehensive review with clinical applications. Cureus 11:e4422. https://doi.org/10.7759/cureus.4422
12. Mariniello G, Giamundo A, Donzelli R, Severino R, Russo C, Elefante A, Maiuri F (2013) Intracranial hypertension due to meningioma of the unique transverse sinus. Neuroradiol J 26:209–212. https://doi.org/10.1177/197140091302600211
13. Mathiesen T, Pettersson-Segerlind J, Kihlstrom L, Ulfarsson E (2014) Meningiomas engaging major venous sinuses. World Neurosurg 81:116–124. https://doi.org/10.1016/j.wneu.2013.01.095
14. Mizutani K, Akiyama T, Yoshida K, Toda M (2018) Skull base venous anatomy associated with endoscopic skull base neurosurgery: a literature review. World Neurosurg 120:405–414. https://doi.org/10.1016/j.wneu.2018.09.067
15. Mizutani K, Toda M, Kurasawa J, Akiyama T, Fujiwara H, Jinzaki M, Yoshida K (2017) Analysis of the venous channel within the clivus using multidetector computed tomography digital subtraction venography. Neuroradiology 59:213–219. https://doi.org/10.1007/s00234-017-1784-4
16. Murase M, Mizutani K, Kawata K, Fujiwara H, Jinzaki M, Toda M, Yoshida K (2020) Analysis of the superficial middle cerebral vein in sphenoid ridge meningioma using contrast-enhanced dynamic computed tomography angiography. Clin Neurol Neurosurg 191:105683. https://doi.org/10.1016/j.clineuro.2020.105683
17. Oka K, Go Y, Kimura H, Tomonaga M (1994) Obstruction of the superior sagittal sinus caused by parasagittal meningiomas: the role of collateral venous pathways. J Neurosurg 81:520–524. https://doi.org/10.3171/jns.1994.81.4.0520

18. Ono Y, Abe K, Suzuki K, Iimura H, Sakai S, Uchiyama S, Okada Y (2013) Usefulness of 4D-CTA in the detection of cerebral dural sinus occlusion or stenosis with collateral pathways. Neuroradiol J 26:428–438. https://doi.org/10.1177/197140091302600408
19. Patel N (2009) Venous anatomy and imaging of the first centimeter. Semin Ultrasound CT MR 30:513–524. https://doi.org/10.1053/j.sult.2009.08.003
20. Pisova H, Rangel de Lazaro G, Veleminsky P, Bruner E (2017) Craniovascular traits in anthropology and evolution: from bones to vessels. J Anthropol Sci 95:35–65. https://doi.org/10.4436/JASS.95003
21. Rangel de Lazaro G, de la Cuetara JM, Pisova H, Lorenzo C, Bruner E (2016) Diploic vessels and computed tomography: segmentation and comparison in modern humans and fossil hominids. Am J Phys Anthropol 159:313–324. https://doi.org/10.1002/ajpa.22878
22. Sakaeyama Y, Morisako H, Ohata H, Nakajo K, Valenzuela JC, Fernandez-Miranda JC, Goto T (2022) Endoscopic contralateral interhemispheric transfalcine keyhole approach for large falcine meningioma. World Neurosurg. https://doi.org/10.1016/j.wneu.2022.06.148
23. Sindou M, Auque J (2000) The intracranial venous system as a neurosurgeon's perspective. Adv Tech Stand Neurosurg 26:131–216. https://doi.org/10.1007/978-3-7091-6323-8_5
24. Sindou M, Auque J, Jouanneau E (2005) Neurosurgery and the intracranial venous system. Acta Neurochir Suppl 94:167–175. https://doi.org/10.1007/3-211-27911-3_27
25. Sindou M, Dumot C (2020) Planning of endocranial supratentorial basal cistern and skull base approaches depending on venous patterns using a topogram. World Neurosurg 134:365–371. https://doi.org/10.1016/j.wneu.2019.11.009
26. Sindou MP, Alvernia JE (2006) Results of attempted radical tumor removal and venous repair in 100 consecutive meningiomas involving the major dural sinuses. J Neurosurg 105:514–525. https://doi.org/10.3171/jns.2006.105.4.514
27. Skrzat J, Brzegowy P, Walocha J, Wojciechowski W (2004) Age dependent changes of the diploe in the human skull. Folia Morphol (Warsz) 63:67–70
28. Smith KR Jr (1968) Idiopathic bilateral sigmoid sinus occlusion in a child: case report. J Neurosurg 29:427–430. https://doi.org/10.3171/jns.1968.29.4.0427
29. Sumi K, Otani N, Mori F, Yamamuro S, Oshima H, Yoshino A (2021) Venous hypertension caused by a meningioma involving the sigmoid sinus: case report. BMC Neurol 21:119. https://doi.org/10.1186/s12883-021-02144-5
30. Tsutsumi S, Nakamura M, Tabuchi T, Yasumoto Y, Ito M (2013) Calvarial diploic venous channels: an anatomic study using high-resolution magnetic resonance imaging. Surg Radiol Anat 35:935–941. https://doi.org/10.1007/s00276-013-1123-3
31. Tsutsumi S, Ogino I, Miyajima M, Nakamura M, Yasumoto Y, Arai H, Ito M (2014) Cranial arachnoid protrusions and contiguous diploic veins in CSF drainage. AJNR Am J Neuroradiol 35:1735–1739. https://doi.org/10.3174/ajnr.A4007
32. Tsutsumi S, Ono H, Ishii H, Yasumoto Y (2019) Diploic veins of the cranial base: an anatomical study using magnetic resonance imaging. Surg Radiol Anat 41:1029–1036. https://doi.org/10.1007/s00276-019-02283-y
33. Wintermark M, Ko NU, Smith WS, Liu S, Higashida RT, Dillon WP (2006) Vasospasm after subarachnoid hemorrhage: utility of perfusion CT and CT angiography on diagnosis and management. AJNR Am J Neuroradiol 27:26–34
34. Yamashiro K, Muto J, Wakako A, Murayama K, Kojima D, Omi T, Adachi K, Hasegawa M, Hirose Y (2021) Diploic veins as collateral venous pathways in patients with dural venous sinus invasion by meningiomas. Acta Neurochir (Wien). https://doi.org/10.1007/s00701-021-04777-4
35. Yokota H, Noguchi H, Yokoyama K (2019) Epidermoid cyst with torcular herophili obstruction and unusual venous drainage. World Neurosurg 128:14–17. https://doi.org/10.1016/j.wneu.2019.04.223