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Usefulness of the Multimodal Fusion Image for Visualization of Deep Sylvian Veins

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Abstract

The preoperative assessment of cerebral veins is important to avoid unexpected cerebral venous infarction in the neurosurgical setting. However, information is particularly limited regarding deep Sylvian veins, which occasionally disturb surgical procedures for cerebral anterior circulation aneurysms. The predictability of detecting deep Sylvian veins and their tributaries using a modern multimodal fusion image was aimed to be evaluated. Moreover, 51 patients who underwent microsurgery for unruptured cerebral aneurysms with Sylvian fissure dissection were retrospectively reviewed. The visualization of the four components of the deep Sylvian veins in conventional computed tomography (CT) venography and multimodal fusion images was evaluated. To compare the detection accuracy among these radiological images, the sensitivity and specificity for the detection of each of the four venous structures were calculated in comparison with those of intraoperative inspections. The kappa coefficients were also measured and the inter-rater agreement for each venous structure in each radiological image was examined. In all veins, the multimodal fusion image exhibited a high detection rate without statistical difference from intraoperative inspections (P = 1.0). However, CT venography exhibited a low detection rate with a significant difference from intraoperative inspections in the common vertical trunk (P = 0.006) and attached vein (P = 0.008). The kappa coefficients of the fusion image ranged from 0.73 to 0.91 and were superior to those of CT venography for all venous structures. This is the first report to indicate the usefulness of a multimodal fusion image in evaluating deep Sylvian veins, especially for the detection of nontypical, relatively small veins with large individual variability.

Keywords: cerebral aneurysm, common vertical trunk, computed tomography venography, multimodal fusion image, deep Sylvian veins

Introduction

Sylvian veins, especially middle cerebral veins, form a pathway comprising two distinct but connected superficial and deep veins.[1)] Neurosurgeons are familiar with the superficial Sylvian veins (SSVs) because of their relatively large size and presence in almost all cases. Many reports of the morphological patterns of the SSVs for dissection of the Sylvian fissure were observed.[2)] Conversely, deep Sylvian veins, which receive tributaries from the insula and neighboring gyri and run in the lower part of the lateral sulcus, have been under-recognized because they are difficult to radiologically visualize due to their small size and individual variability. These veins occasionally limit the development of the operative field, attach to an aneurysm, and interfere with the microscope's line of view. Neurosurgeons may be able to sacrifice the small veins encountered during surgery without harming the patient. However, serious complications occasionally result from seemingly minor injuries to these interconnected veins; the sacrifice of deep

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Sylvian veins may also induce neurological deficits.[3-7] Therefore, venous structures at risk should be considered to construct a better and safer surgical plan to prevent postoperative neurological deficits.[8]

Both three-dimensional computed tomography angiography (3D-CTA) and computed tomography (CT) venography provide useful information on the Sylvian veins for preoperative simulation.[9,10] However, these imaging modalities are often unable to distinguish between adjacent small arteries and veins observed during microscopic procedures. With the recent development of radiological imaging technologies, depicting local anatomy with high accuracy has become possible. In clinical neurosurgery, the usefulness of radiological fusion images with multiple modalities for preoperative simulation has been reported.[11-13] However, no reports exist on the use of fusion images of deep Sylvan veins for preoperative evaluation. Therefore, this study aimed to evaluate the usefulness of multimodal fusion images in detecting deep Sylvan veins. First, the predictability of the deep Sylvian veins was evaluated using a multimodal fusion image or conventional CT venography by comparing intraoperative findings. Second, the difference in the fusion image readings for each vein between examiners was confirmed.

Material and Methods

All experiments were conducted following the guidelines of the Declaration of Helsinki. All research protocols were approved by the institutional review board of the institution of this study (approval number: 2834). The need for informed consent was waived.

Patient selection

Consecutive patients who underwent surgical procedures for unruptured cerebral anterior circulation aneurysms with Sylvian fissure dissection were retrospectively analyzed at the institution of the current study between November 2017 and October 2020. Patients without any preoperatively created fusion image or those who underwent reoperation via the ipsilateral Sylvian fissure were excluded.

Radiological imaging condition

Multimodal fusion images were reconstructed using plain CT images, CTA, CT venography, and three-dimensional rotational angiography (3DRA). Plain CT images, CTA, and CT venography were performed using a dual-source CT scanner (SOMATOM Definition Flash, Siemens Healthineers, Forchheim, Germany). The parameters for CT acquisition were field of view (210 mm), detector collimation (128 × 0.6 mm), gantry rotation speed (0.33 s/rotation, 80-140 kV, and 123-246 mAs). The image reconstruction parameters were a section thickness of 0.5 mm and overlapping steps of 0.5 mm. In all cases, a nonionic contrast medium (50 mL of 370 mg/mL solution) was injected with a pump into an antecubital vein at a rate of 4.0 mL/s. A bolus tracking method was routinely used to achieve optimal synchronization of contrast medium flow and scanning. First, the CTA was helically scanned, and the CT venography was scanned using the same method 10 s later. The axial source images were transferred to a workstation.

All cerebral angiography procedures were performed in an angiographic suite equipped with a flat-panel biplane system (Siemens Artis Q biplane, Siemens Healthcare, Forchheim, Germany). Angiography was performed via 5-F transfemoral sheath access, and a 5-F diagnostic catheter was placed in the internal carotid artery. A noniodinated contrast medium (370 mg/mL solution) was injected intraarterially. Conventional digital subtraction angiography was performed, followed in sequence by 3DRA of the ipsilateral carotid artery to the aneurysm to be treated (5 s acquisition; 3 mL/s contrast injection with 2 s before injection).

Creation of multimodal fusion image

Digital imaging and communications in medicine images of plain CT, CTA, CT venography, and 3DRA were imported into the SYNAPSE VINCENT medical imaging system (FUJIFILM Medical Solutions Co., Ltd., Tokyo, Japan).[14-16] Reconstructed images were obtained using the volume-rendering technique by three experienced radiologic technicians who were blinded to the intraoperative inspections (Fig. 1A). Arterial images were obtained using 3DRA. Venous images were produced in two parts: deep Sylvian veins were produced based on 3DRA and SSVs were produced based on CT venography. Brain and bone parenchyma were identified based on the plain CT images. All images were fused to create simulated images for aneurysm clipping surgery. Using bone and depicted blood vessels as indicators, CT and 3DRA were aligned in three dimensions.

Axial, sagittal, and coronal cross-sections were created for the original CT venography image and the fusion image created, and these images were subsequently used for image evaluation (Fig. 1B, C).

Image analysis

Four of the three microvenous structures presented in the deep Sylvian fissure, i.e., the deep middle cerebral vein (DMCV), common vertical trunk (CVT), and frontobasal bridging vein (FBBV), were targeted for the current study, along with the attached vein to the aneurysm (Fig. 2). In detail, veins draining from the common stem of the insular veins to the basal vein were defined as DMCVs, and those draining to the sphenoparietal sinus (SPS) or SSV as the CVT.[1] The FBBV was defined as the vein across the proximal Sylvian fissure draining from the basal surface of the frontal lobe to the SPS. An attached vein was defined as a vein in contact with the dome of the aneurysm (Fig.

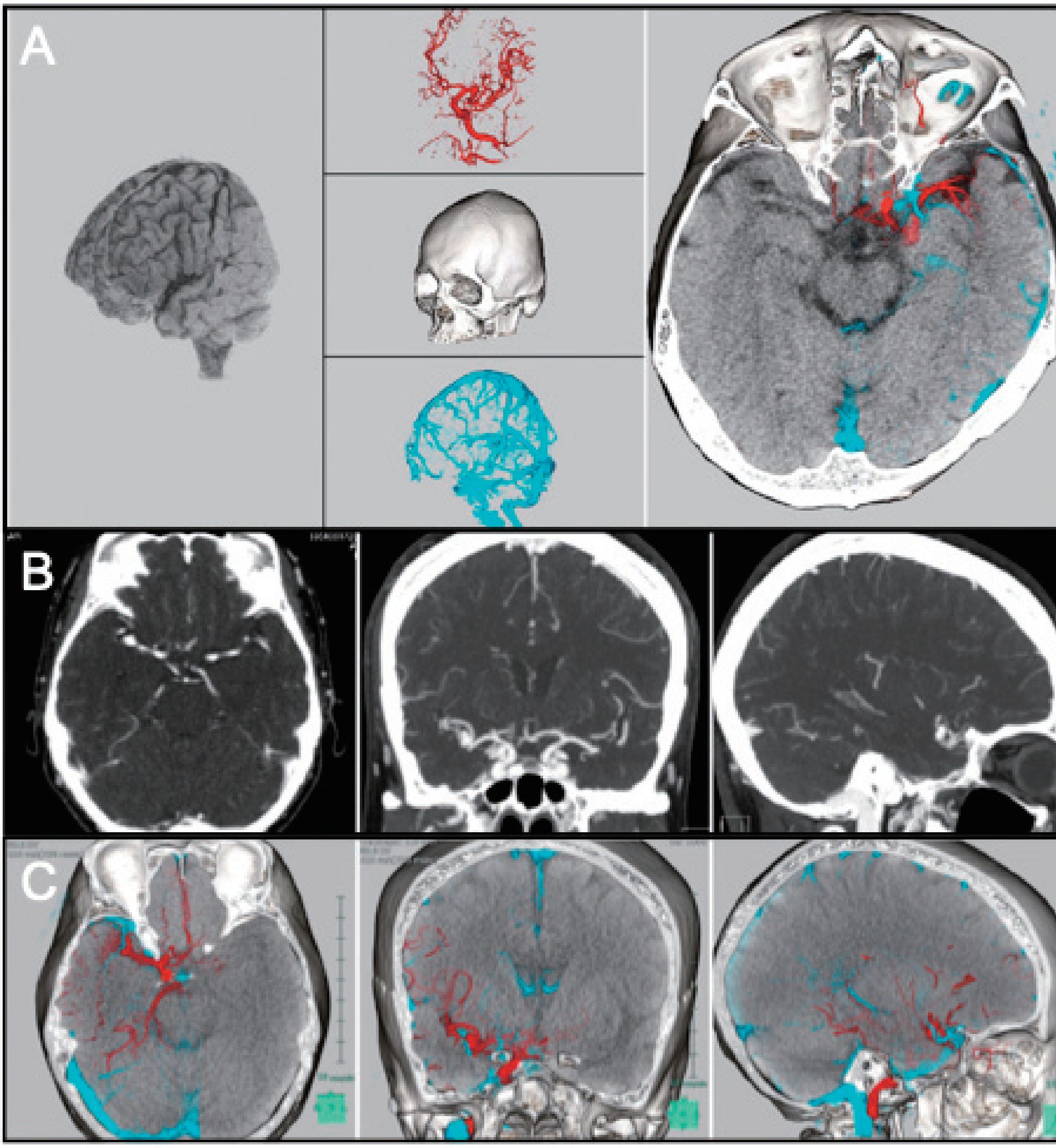

Fig. 1 Technical steps for multimodal image fusion (A) and image analysis of deep Sylvian veins (B and C). A: Three-dimensional brain and skull bone depicted by plain CT imaging, and high-resolution arterial and venous images depicted using three-dimensional rotational angiography and CT angiography with venography were used for the reconstruction of the fusion image on a computer workstation (A). B and C: Each construct of the four veins was carefully assessed in the three directions of each image concerning the interrelationship among the brain, blood vessels, and bones using computed tomography venography (B) and multimodal fusion imaging (C).

3).

Each vein construct was carefully assessed for its presence separately in the three directions of each image based on their anatomical locations. To minimize observer bias, the order of evaluation was multimodal fusion imaging, followed by CT venography. The order of cases in the reviews was also randomized to be different for the two images, and the interval between the reviews of the two images was planned to be at least 12 weeks. These assessments were performed by two neurosurgeons independent of surgery: a senior instructor and a younger one with 20 and 10 years of experience, respectively, and any differences in the review results were finalized through discussion.

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After reviewing these images, the presence or absence of four deep Sylvian veins within the opened surgical field was evaluated on the intraoperative videos of all patients based on their anatomical locations by the two neurosurgeons independent of surgery. However, confirming whether all the deep Sylvian veins were actually present was impossible because the extent of the Sylvian fissure dissection varied from case to case depending on the location, size, and direction of the cerebral aneurysm. Therefore, in each of the included patients, the deep Sylvian vein whose presence or absence could be confirmed on the surgical video was selected for investigation.

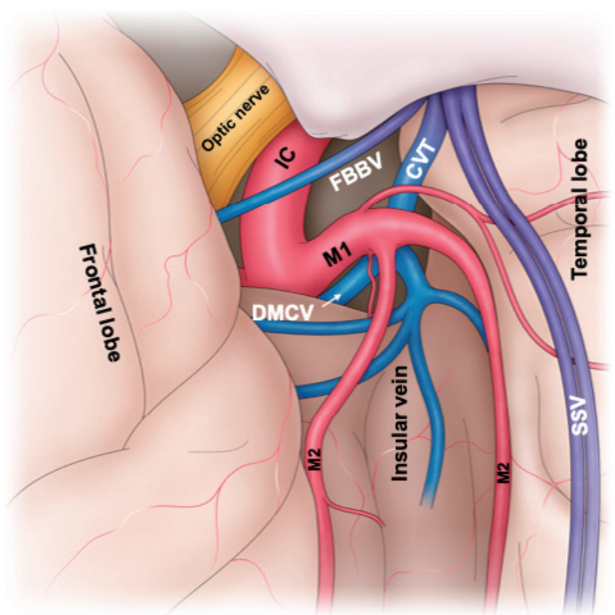

Fig. 2 Illustration of deep Sylvian veins encountered during dissection of the right Sylvian fissure. *DMCV* deep middle cerebral vein, *FBBV* frontobasal bridging vein, *IC* internal carotid artery, *M1* horizontal part of the middle cerebral artery, *M2* insular part of the middle cerebral artery, *SSV* superficial Sylvian vein

Two analyses were conducted to evaluate the usefulness of multimodal fusion images compared with that of CT venography in detecting deep Sylvan veins. First, the detection rates with sensitivity and specificity of the veins on each image were assessed by comparing intraoperative findings to evaluate the predictability of the deep Sylvian vein. Moreover, the detection of the veins in each image was statistically calculated to determine whether it was equal or not to the evaluation in the surgical video to compare the diagnostic performance of the deep Sylvian veins in the two images. Second, to identify interexaminer differences in image reading for detecting deep Sylvian veins, the inter-rater agreement in each image was calculated for each vein.

Statistical analysis

All statistical analyses were performed using IBM SPSS 26 (IBM Corp., Armonk, NY, USA). The detection powers of the veins were assessed by sensitivity and specificity. The McNemar test was adopted to compare the diagnostic performance of these veins in the two images. The inter-rater agreement in each image of each vein was confirmed using Cohen's kappa statistic. An overall significance level of $P < 0.05$ was adopted.

Results

Fifty-one patients were finally included in this study, which consisted of 15 men and 36 women, ranging from 24 to 86 years old (mean age, 69 years), with 54 aneurysms (Fig. 4). Of the 54 aneurysms, 34 (62.9%) were located in the middle cerebral artery, eight (14.8%) in the internal carotid artery-posterior communicating artery bifurcation, five (9.2%) in the anterior communicating artery (Acom A), five (9.2%) in the internal carotid artery, and two (3.7%) in the internal carotid artery-anterior choroidal artery bifur-

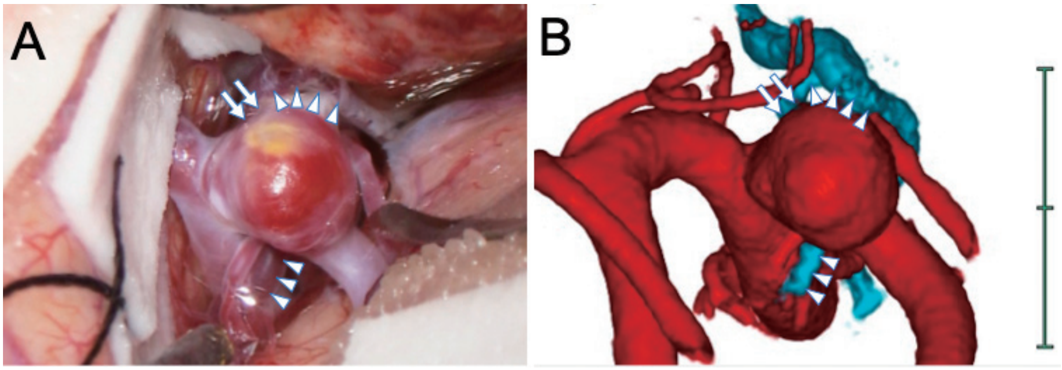

Fig. 3 Representative intraoperative microscopic (A) and preoperative fusion images (B) indicate the attached vein. A, B: CVT (*arrowheads*) was attached to the aneurysmal dome (*arrow*). In craniotomy for cerebral aneurysms, deep Sylvian veins, such as the DMCV and CVT, can anatomically form attached veins.

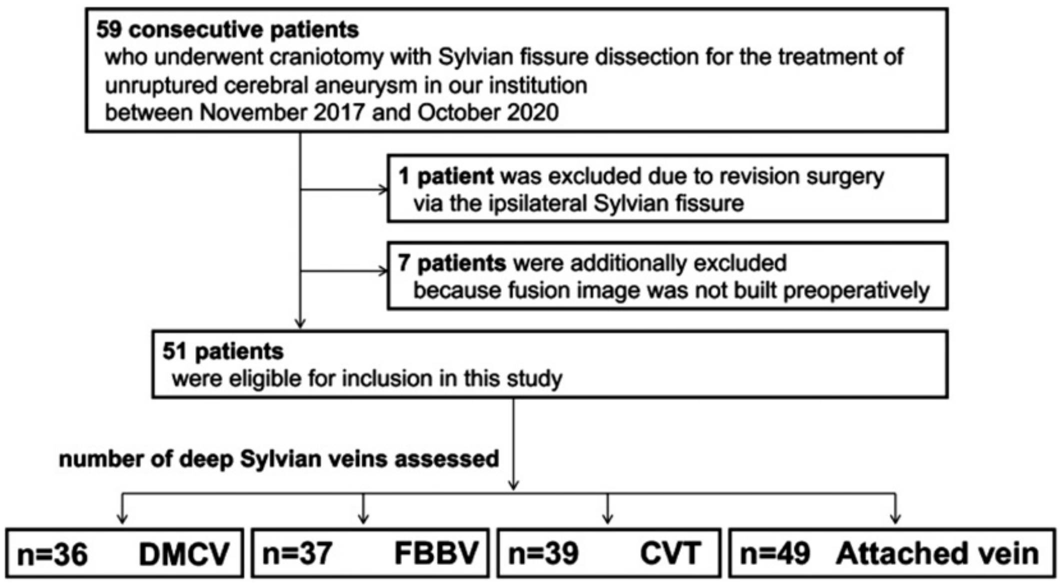

Fig. 4 Flowchart of patient selection. *CVT* common vertical trunk, *DMCV* deep middle cerebral vein, *FBBV* frontobasal bridging vein

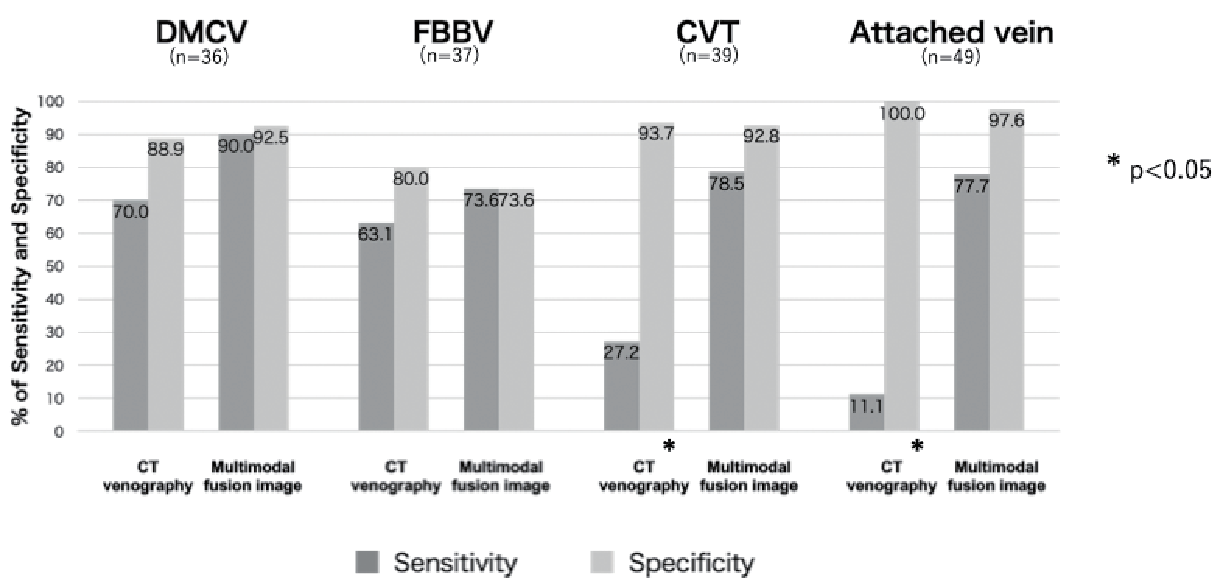

Fig. 5 Comparison of the diagnostic performance of CT venography and multimodal fusion imaging in predicting four venous structures compared with that of intraoperative videos. Significant differences were observed between CT venography and intraoperative findings in the common vertical trunk and attached vein. Moreover, significant differences were observed between CT venography and intraoperative findings in CVT and attached vein ($P < 0.05$). *CVT* common vertical trunk, *DMCV* deep middle cerebral vein, *FBBV* frontobasal bridging vein

cation. Among these cases, the evaluable cases for each venous structure were selected for investigation. The number of cases in which the presence or absence of venous constructs was confirmed by the intraoperative video was 36, 37, 39, and 49 for the DMCV, FBBV, CVT, and attached veins, respectively. Attached veins were found in nine of the 49 cases evaluated, including six and three CVTs and DMCVs, respectively.

Both CT venography and the fusion image showed high specificity for the detection of all four deep Sylvian veins. However, differences were observed between the two images in terms of their sensitivity (Fig. 5). In the assessment of the predictability of the deep Sylvian veins on each image compared to the intraoperative findings, the sensitivity and specificity of CVT identification by CT venography were 27.2% and 93.7%, respectively, and those of attached vein identifications were 11.1% and 97.6%, respectively. Significant differences were observed between CT venography and intraoperative findings in CVT (P = 0.006) and the attached vein (P = 0.008). Moreover, no significant difference was observed between the fusion image and intraoperative findings for all veins, indicating the marked inferiority of CT venography to the fusion image in detecting CVT and attached veins preoperatively.

In the evaluation of the inter-rater difference in the fusion image reading to identify the four deep Sylvian veins, DMCV, CVT, FBBV, and attached vein, high degrees of the inter-rater agreement were confirmed using Cohen's kappa coefficient, with κ values of 0.85, 0.82, 0.73, and 0.91, respectively. Moreover, inter-rater agreement in CT venography was lower, with κ values of 0.66, −0.034, 0.52, and −0.032, respectively.

Discussion

This is the first report indicating that the fusion image is useful in identifying deep Sylvian veins for preoperative surgical simulation. The results of this study showed that the fusion images were superior to CT venography for the detection of the CVT and attached vein with a significant difference. Moreover, the fusion image showed high agreement concerning all four deep Sylvian veins between the two evaluators with different years of experience.

Multimodal fusion imaging for the evaluation of Sylvian veins

Multimodal fusion imaging is a new technology that was initially described in neuroradiology.[17] Since the 2010s, it has been introduced to neurosurgical simulations of tumors, spinal vascular malformations, and cerebral vascular lesions.[12,13] In these reports, assessing the positional relationship between neighboring structures and focused lesions was useful.

Preoperative simulation has also been attempted for Sylvian veins. Kaminogo et al. reported that simulated images based on 3D-CTA data could be used to visualize the Sylvian veins,[9] but the venous delineation was relatively low and did not reveal enough information. Moreover, Hashimoto et al. reported that fusion images using cone-beam CTA are useful for the evaluation of SSVs.[14] The fusion image identifies the optimal dissecting plane to obtain a wide surgical corridor without sacrificing the SSVs and may be useful as a preoperative simulation for Sylvian fissure dissection. Moreover, deep Sylvian veins cannot be found by conventional imaging in many cases and have not received much attention. Therefore, this study is significant in that it is the first to bring deep Sylvian veins into preoperative simulations. Recently, cerebral vein depictions using 3D digital subtraction venography were proposed as an efficient technique.[18] The current method used 3DRA images that depicted arteries and veins in a single phase, but the use of such imaging methods that separate arteries and veins and achieve higher resolution as basic fusion images may further enhance the visualization of cerebral veins in the future.

Impact of depicting deep Sylvian veins on microsurgery for cerebral aneurysms

The CVT is a common stem of insular veins joining the frontobasal and uncal veins or sometimes with an FBBV tributary,[19] which then drains with the SSV[1] into the sphenoparietal or cavernous sinus. The presence of this venous structure reflects a mixture of superficial and deep connections,[20] and its development varies markedly from case to case. In cases of cerebral aneurysms, these deep Sylvian veins and their branches can constitute the attached vein. Various running patterns for the different outflow points and anastomoses were observed, and a CVT can pose an obstacle to accessing the aneurysms. Akasu et al. reported that the CVT presence increased the rate of ischemic complications in short M1 aneurysms.[21] In addition, the presence of a CVT required additional intraoperative manipulation, such as aneurysm dissection, vein cutting, and denuding techniques, in five of 12 (41%) cases in the current study (data not shown). Thus, the presence of not only an attached vein but also a well-developed CVT affects the difficulty of surgery.

One of the advantages of introducing multimodal fusion images to Sylvian fissure dissection is that it allows the depiction of nontypical, relatively small blood vessels adjacent to other large vessels or aneurysms, such as a CVT and an attached vein. The fusion image can depict very fine structures of ≤1 mm.[15] In the fusion image used in this study, the veins, arteries, and brain are extracted separately, sharpened, and then fused so that the anatomical structure is clearer than in the original image. Therefore, it is excellent for depicting fine vascular structures and understanding their positional relationship with the surrounding structures. It may also be useful in depicting an arteriovenous shunt or vascular tumor and its relationship with the surrounding tissue. However, predicting their adherence is difficult even if the adjacent blood vessels are found in advance using the fusion image.

In addition, the sensitivity of deep vein detection in fusion images is rather low at ~70%. The first is the limitation of deep vein delineation: it is still difficult to completely separate fine arteries and veins, although delineation is based on 3DRA. Second is the issue of video review. The retrospective video review may miss some of the details because some of the cases included a small extension of the subarachnoid space. Future improvements in the spatial resolution of radiological images and the introduction of prospective studies will increase sensitivity.

Surgical strategy with reference to preoperative images

The most important considerations in craniotomy for a cerebral aneurysm are the shape of the aneurysm, length of the M1 portion, and branching vessels and perforating branches associated with the aneurysm; deep veins are not a high priority. However, that preliminary confirmation is not without value and is sometimes useful in some cases. Preoperative anatomical findings of deep Sylvian veins using multimodal fusion imaging enhance the visual understanding of the difficulty of intraoperative manipulation around an aneurysm. Bridging veins, such as CVT or FBBVs, potentially restrict brain retraction for the widening of the surgical field. Saito et al. reported that ~5.3% of cases in which FBBV was sacrificed presented with venous perfusion defects.[22] Therefore, previous studies have reported venous preserving techniques in cases in which the bridging vein obstructed the surgical corridor.[23,24]

If the developed deep Sylvian veins could be identified preoperatively and the need for these additional procedures considered, it would be very significant, especially when planning key-hole craniotomy or applying a minimally invasive method because, in such a case, a larger craniotomy may be an option from the perspective of medical safety.

Multimodal fusion imaging as a simulation and educational tool

The current study found considerable agreement between the two neurosurgeons in locating all deep Sylvian veins using multimodal fusion imaging. Moreover, the diagnostic concordance rate with CT venography was relatively low, especially for CVT and attached veins that have significant individual variability in their running. This may be because a multimodal fusion image is superior in depicting small vessels. Moreover, as the brain parenchyma and each corresponding structure are depicted in different colors, easily recognizing the interpositional relationship between them, thus resulting in no difference between the examiners' opinions.

Moreover, the two neurosurgeons had different years of experience. Therefore, this study may indicate that reading multimodal fusion images can overcome the differences in clinical experience and correctly identify deep Sylvian veins. Previous reports have indicated that three-dimensionally printed models[25] and multimodal image-based virtual reality[26] are useful tools for not only preoperative planning and simulation but also for education. Multimodal fusion imaging can be a preoperative education tool that bridges the experience gap between younger trainees and senior surgeons.

In recent years, treatment strategies for cerebral aneurysms have changed dramatically with the development of endovascular treatment, such as neck bridging stents, and the opportunities for neurosurgeons to perform microsurgical cerebral aneurysm surgery have decreased.[27] Furthermore, some conditions that are difficult to treat without microsurgery still exist, such as large aneurysms or cerebral aneurysms that require revascularization; however, the surgical risk of these conditions is relatively high. Therefore, supportive tools to ensure safe surgery and educational tools to supplement surgical experience, such as intraoperative neuromonitoring[28] and surgical simulation using virtual reality technology are greatly needed.[29] Based on the findings of this study, multimodal fusion imaging may also help experienced neurosurgeons make informed decisions regarding the choice of treatment (clipping or coiling) or surgical approach.

Limitations

The present study has several limitations. First, it was a retrospective study of a small case series from a single institution. Second, differences in the size of the microsurgical field were observed depending on the case, and, resultantly, not all fissures were opened in many cases. Therefore, many deep Sylvian veins had to be omitted from the analysis because their presence could not be confirmed on video. These veins were omitted from the evaluation. Third, although efforts to minimize observer bias as described above were made, observer bias may still have existed. Fourth, the fusion images were manually merged on the workstation, so slight deviations may exist.

Despite these limitations, this was the first study to show that multimodal fusion images are significantly more effective in reading deep Sylvian veins, which are very fine and patient-specific.

Conclusions

Multimodal fusion imaging was significantly better at identifying smaller and more variable deep Sylvian veins compared with conventional CT venography, with fewer differences in diagnostic performance among examiners. The preoperative assessment of the deep Sylvian veins using multimodal fusion images may additionally provide useful cerebral venous information for microsurgical planning and contribute to the provision of safe surgery.

Conflicts of Interest Disclosure

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

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