Usefulness of high-resolution 3D multifusion medical imaging for preoperative planning in patients with posterior fossa hemangioblastoma: technical note

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Successful resection of hemangioblastoma depends on preoperative assessment of the precise locations of feeding arteries and draining veins. Simultaneous 3D visualization of feeding arteries, draining veins, and surrounding structures is needed. The present study evaluated the usefulness of high-resolution 3D multifusion medical imaging (hr-3DMMI) for preoperative planning of hemangioblastoma. The hr-3DMMI combined MRI, MR angiography, thin-slice CT, and 3D rotated angiography. Surface rendering was mainly used for the creation of hr-3DMMI using multiple thresholds to create 3D models, and processing took approximately 3–5 hours. This hr-3DMMI technique was used in 5 patients for preoperative planning and the imaging findings were compared with the operative findings. Hr-3DMMI could simulate the whole 3D tumor as a unique sphere and show the precise penetration points of both feeding arteries and draining veins with the same spatial relationships as the original tumor. All feeding arteries and draining veins were found intraoperatively at the same position as estimated preoperatively, and were occluded as planned preoperatively. This hr-3DMMI technique could demonstrate the precise locations of feeding arteries and draining veins preoperatively and estimate the appropriate route for resection of the tumor. Hr-3DMMI is expected to be a very useful support tool for surgery of hemangioblastoma.

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because the existing image processing techniques are not accurate enough to visualize small anatomical structures, such as the feeding arteries and draining veins, running close to other structures. Our group previously demonstrated the use of high-resolution 3DMMI (hr-3DMMI), which addresses the limitations of present 3D medical imaging by adjusting the image processing techniques.11-13,24,25 Our hr-3DMMI technique can provide accurate information about the small anatomical structures. The present study evaluated the usefulness of preoperative planning with hr-3DMMI in patients with hemangioblastoma to estimate the precise locations of every feeding artery and draining vein in the actual operation field.

Methods

Patient Population

This study included 5 consecutive patients with hemangioblastoma who underwent preoperative planning with hr-3DMMI and then underwent surgery at the University of Tokyo Hospital from March 2011 through March 2013. None of the patients had von Hippel-Lindau disease. The characteristics of the patients are summarized in Table 1. All patients were treated by 2 neurosurgeons (N. Saito and H.N.). The internal review board of the University of Tokyo Hospital approved the study protocol, and written informed consent was obtained from all patients.

Image Acquisition

Magnetic resonance imaging was performed with a 3.0T system for the head (Signa 3.0T, GE Healthcare). Contrast-enhanced T1-weighted imaging, fast imaging employing steady-state acquisition (FIESTA), contrast-enhanced FIESTA, time-of-flight (TOF) MR angiography (MRA), contrast-enhanced TOF MRA, and time-resolved imaging of contrast kinetics (TRICKS) were acquired with an 8-channel head coil. The main imaging parameters for FIESTA and contrast-enhanced FIESTA were as follows: TR = 4.2 msec, TE = 1.6 msec, slice thickness = 0.8 mm, FOV = 20 cm, matrix size = 512 × 512, flip angle = 45°. The main imaging parameters for MRA and contrast-enhanced MRA were: TR = 26 msec, TE = 3 msec, slice thickness = 0.4 mm, FOV = 22 cm, matrix size = 512 × 512, flip angle = 20°. The primary imaging parameters for TRICKS were: TR = 3.6 msec, TE = 1.4 msec, slice thickness = 1 mm, FOV = 24 cm, matrix size = 512 × 512, flip angle = 20°.

Computed tomography was performed with a 64-section CT scanner (Aquilion, Toshiba Medical Systems) at the University of Tokyo Hospital. The slice thickness was 0.4 mm. A clinical C-arm angiography unit (Allura XperFD 20/10, Philips Medical Systems) was used for 3D rotated angiography (3DRA). The C-arm rotated through 240° at 55°/sec and obtained 120 images on a 17-inch FOV during contrast injection. The rotation was initially performed without contrast injection to obtain the bone image, after which the rotation was performed with contrast injection. Reconstruction of 3D volume data was performed with a matrix size of 512 × 512 × 512. All patients underwent MRI, CT, CT angiography (CTA), and 3DRA, but data from CTA were difficult to use for source image processing of 3D modeling in this study.

Image Processing

All data were provided as image stacks coded in DICOM format and were processed with Avizo 6.3 software (Visualization Science Group) on a personal computer (Precision T7500, Dell; CPU = Intel Xeon X5550, 2.67 GHz, 2.66 GHz; RAM = 8.00 GB; graphics card = NVIDIA Quadro FX5800) for 3D image reconstruction using a previously reported method.11-13 Briefly, the imaging data were fused automatically with the normalized mutual information method. The modality/sequence offering the highest contrast of the target tissue was selected for 3D modeling of the tissue. The 3D model was constructed with a hybrid method combining surface- and volume-rendering methods. In the surface-rendering method, a model employing multiple modalities and multiple thresholds for 1 tissue was used. For example, in artery 3D modeling, the 3D reconstruction was performed with TOF MRA for the thick arteries (main trunk and thick cortical arteries) and with original imaging data from contrast-enhanced TOF MRA for the thin arteries. Furthermore, arteries that could not be visualized on MRI were constructed in 3D by using original data from 3DRA. We usually increase the matrix size of 3DRA data to provide higher spatial resolution in 3D images.25 Reconstructed feeding arteries and draining veins were identified by referring to the shapes of the vessels and directions of the blood flow. The accuracy of hr-3DMMI was confirmed by overlaying the 2D source image with hr-3DMMI. A neurosurgeon (M.Y.) controlled the threshold level, opacity curve, and color map for the segmentation of anatomical structures.

Preoperative Planning With hr-3DMMI

First, the relationship between the feeding arteries and surrounding structures was analyzed using hr-3DMMI.
Then, the relationship between the draining veins and surrounding structures was analyzed, to estimate the route to reach the feeding arteries in the most direct way without damaging the tumor, draining veins, and surrounding normal structures. Simulation of this route usually involved rotation of the hr-3DMMI to investigate the feeding arteries and the draining veins from various directions. The individual anatomical structures were also made transparent on the hr-3DMMI to investigate the feeding arteries and the draining veins behind the tumor (Figs. 1–3).

**Evaluation of the Usefulness of hr-3DMMI**

The usefulness of hr-3DMMI in preoperatively identifying the exact locations of the feeding arteries and draining veins was assessed by comparison with the intraoperative findings of the number of feeding arteries and draining veins, and the points where the feeding arteries and the draining veins penetrated the tumor. Specifically, the points where the feeding arteries and the draining veins penetrated the tumor were classified as the upper pole, lower pole, right pole, left pole, ventral pole, and dorsal pole, considering the tumor as a sphere. In addition, the ventral and dorsal areas were classified as the right upper, right lower, left upper, and left lower (Fig. 4). Agreement between the prediction of hr-3DMMI and identification during surgery was judged as a correct prediction by hr-3DMMI. In addition, the results were compared with the findings of digital subtraction angiography (DSA). Intraoperative identification of the feeding arteries and draining veins was performed by the operating neurosurgeon (H.N.). Prediction by hr-3DMMI and DSA was performed by neurosurgeons (N. Shono, S.N., and S.T.) who were not involved in the surgery or preoperative image processing and planning, and consistency with intraoperative findings was judged by the first author (M.Y.) who developed the hr-3DMMI system.

The overall utility of hr-3DMMI was assessed qualitatively into the following categories: Class I, not useful; Class II, hr-3DMMI provided useful information obtainable by conventional medical imaging; Class III, hr-3DMMI provided useful information unobtainable by conventional medical imaging but with no effect on surgi-
Results
All patients showed mild neurological deficits. The most common symptoms were headache or dizziness (3 cases). Other symptoms were vomiting, nausea, ataxia, diplopia, hearing disturbance, sensory disturbance, and dysphagia in 1 case each (Table 1). hr-3DMMI visualized each anatomical structure (such as a feeding artery, draining vein, tumor, and other surrounding structures) in all cases. Preoperative planning based on hr-3DMMI was used to estimate the locations of the feeding arteries and the point at which the feeding artery penetrated the tumor in all cases. All 5 patients underwent surgery. All feeding arteries and draining veins were detected at the same position as estimated preoperatively, and were occluded in the same way as demonstrated preoperatively. Total resection of tumor was achieved in all patients. Preoperative symptoms disappeared in 3 patients and decreased in 2 patients after surgery. No new postoperative deficits were observed in any patient.

Prediction by hr-3DMMI and Verification of Results
All 3 observers reported the same results (Tables 2 and 3). Comparison of the predicted and intraoperatively identified feeding arteries and draining veins found agreement in all patients (100%). Therefore, the sensitivity of hr-3DMMI for feeding arteries and draining veins was 100%, specificity was 0%, positive predictive value was 100%, and negative predictive value was 0%. Positive predictive value indicates patients in whom predicted feeding arteries and draining veins agreed with intraoperative findings as a percentage of the total number of patients in whom feeding arteries and draining veins could be predicted by hr-3DMMI. Negative predictive value indicates those patients in whom predicted feeding arteries and draining veins did not agree with intraoperative findings as a percentage of the total number of patients in whom feeding arteries and draining veins could be predicted by hr-3DMMI.

Prediction by DSA and Verification of Results
DSA findings could predict some feeding arteries,
but not all locations of the feeding arteries in all patients (Table 2). Therefore, the sensitivity of DSA for the feeding arteries was 0%, specificity was 0%, positive predictive value was 0%, and negative predictive value was 0%. Comparison of the predicted and intraoperatively identified draining veins allowed Observer 1 (S.N.) to predict the precise locations of the draining veins in 1 (20%) of 5 patients, Observer 2 (N. Shono) in 2 (40%) of 5 patients, and Observer 3 (S.T.) in 2 (40%) of 5 patients. Therefore, the sensitivity of DSA for the draining veins was 100%, specificity was 0%, positive predictive value was 20%–40%, and negative predictive value was 0%.

**Qualitative Assessment of hr-3DMMI**

Hr-3DMMI was scored qualitatively as Class III in Case 1, and Class IV in Cases 2–5.

**Illustrative Cases**

**Case 2**

A tumor approximately 38 mm in diameter was recognized at the dorsal medulla (Fig. 1A). Cerebral angiography showed that the tumor was fed by arteries branching from the bilateral vertebral arteries, but the points where feeding arteries penetrated the tumor were difficult to identify (Fig. 1B and C). Hr-3DMMI showed the morphology of the feeding arteries in detail, and revealed the points where the feeding arteries penetrated the tumor. The detailed visualization of the feeding arteries demonstrated that the tumor was fed by 3 feeding arteries (Fig. 1D–H; Video 1).

VIDEO 1. Clip showing preoperative planning with hr-3DMMI in Case 2. Hr-3DMMI showed the morphology of the feeding arteries in detail, and revealed the points where the feeding branches penetrated the tumor. Copyright Hirofumi Nakatomi. Published with permission. Click here to view.

No other feeding arteries behind the tumor were recognized. Therefore, the midline suboccipital approach was considered to be the most appropriate approach in this case. During the operation, all feeding arteries and draining veins were occluded without damaging the draining veins and tumor, and the tumor was resected safely (Fig. 1I).

**FIG. 3.** Case 4. **A:** Contrast-enhanced axial and sagittal T1-weighted images showing the tumor at the upper part of the cerebellum. **B:** Conventional angiogram showing the tumor fed by the AICA. **C–H:** Images obtained using hr-3DMMI showing 1 feeding artery with 6 feeding branches. **I:** Postoperative contrast-enhanced axial T1-weighted image showing complete removal of the tumor.
Case 3

A tumor of about 44 mm in diameter was recognized at the cerebellum (Fig. 2A). Conventional cerebral angiography showed the tumor fed by the left posterior cerebral artery, left superior cerebellar artery, and right posterior cerebral artery (Fig. 2B and C). However, the morphology of the feeding arteries was difficult to show in detail, as in Case 2. Hr-3DMMI clearly visualized the feeding arteries in detail (Fig. 2D–G). Hr-3DMMI was also useful to simulate the method of occlusion of the feeding arteries without damaging the draining veins and tumor (Fig. 2H), and the occipital transtentorial approach was considered the most appropriate approach. Preoperative embolization of the feeding artery was performed because hr-3DMMI showed that the feeding branch located behind the tumor would be difficult to resect at the earlier stage of surgery (Fig. 2H). The other feeding arteries were resected as planned, and the tumor was resected completely and safely (Fig. 2I).

Case 4

A tumor approximately 47 mm in diameter was recognized at the right cerebellum and facing the cerebellopontine angle (Fig. 3A). Conventional angiography revealed that the anterior inferior cerebellar artery (AICA) was the feeding artery, but the exact locations where every feeding branch of the AICA penetrated the tumor in the actual operative field were difficult to estimate (Fig. 3B). Hr-3DMMI showed these locations precisely (Fig. 3C–H). The hr-3DMMI findings indicated that feeding branches 1–6 should be resected, but other branches of the AICA should be preserved to avoid infarction. In addition, hr-3DMMI showed that all feeding arteries could be resected without damaging the draining veins and tumor via the lateral suboccipital approach. During the operation, all feeding arteries and draining veins were found at the estimated positions, and all feeding arteries were occluded as planned preoperatively. The tumor was resected completely and safely (Fig. 3I).

Discussion

The present study showed that hr-3DMMI was useful for preoperatively estimating the precise locations of the feeding arteries and planning the approach for occlusion of these arteries without damaging the draining veins and tumor until the feeding arteries could be resected.

Preoperative Planning With hr-3DMMI

Our technique of hr-3DMMI visualized every feeding artery separately from the tumor and draining veins. This detailed visualization was useful to distinguish feeding branches from branches perfusing the normal tissue in the presence of 1 feeding artery with multiple feeding branches. Therefore, we could estimate the exact points of the feeding artery where the feeding branches should be resected without damaging the branches perfusing the normal brain tissue (Fig. 3). In addition, our hr-3DMMI technique could visualize both the feeding arteries and the surrounding structures (draining veins, tumor, brainstem, cerebellum, tentorium, etc.) simultaneously. As a result, we could estimate the precise relationship between the feed-

### TABLE 2. Results of preoperative prediction of the points where the feeding arteries penetrated the tumor and actual intraoperative findings

<table>
<thead>
<tr>
<th>Case</th>
<th>Intraop Findings</th>
<th>Observer 1 (S.N.)</th>
<th>Observer 2 (N. Shono)</th>
<th>Observer 3 (S.T.)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>DSA</td>
<td>Hr-3DMMI</td>
<td>DSA</td>
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<td>LP, LP, VLU</td>
<td>VRL, VRL, VLU, DRU, DRL</td>
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<tr>
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<td>UP, LP</td>
<td>DRL, DLU, DLL, DLL, VLL</td>
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<tr>
<td>3</td>
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<td>VP</td>
<td>DRU, DRU, DRU, VRU</td>
<td>DRU, DLU, VRL</td>
</tr>
<tr>
<td>4</td>
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<td>Rb, VP</td>
<td>DRU, DRU, VRU, VRU, VRU</td>
<td>DRU, DLU, VRL</td>
</tr>
<tr>
<td>5</td>
<td>DRL, DLU, DLL</td>
<td>Rb, VP</td>
<td>DRL, DLU, DLL</td>
<td>DRU, VRU</td>
</tr>
</tbody>
</table>

DLL = dorsal left lower; DLU = dorsal left upper; DP = dorsal pole; DRL = dorsal right lower; DRU = dorsal right upper; LP = lower pole; Llb = left pole; Rlb = right pole; UP = upper pole; VLL = ventral left lower; VLU = ventral left upper; VP = ventral pole; VRL = ventral right lower; VRU = ventral right upper.
ing arteries and the surrounding structures in all cases, which was important in preoperative planning. Moreover, our hr-3DMMI technique can provide transparent imaging of each structure, so we could assess the internal structures that cannot be seen in the early stage of surgery, such as a feeding artery located behind the tumor. In Case 3, the transparent image of the tumor showed that the feeding artery located behind the tumor would be difficult to resect (Fig. 2H), so embolization of that feeding artery was performed prior to resection of the tumor.

**Usefulness of hr-3DMMI**

The experience of our observers indicates that only hr-3DMMI could predict the precise locations of the feeding arteries. As mentioned above, our hr-3DMMI technique could visualize not only the feeding arteries but also the surrounding structures precisely. This complete anatomical visualization appeared to be very useful, especially in the case of a large tumor located near the brainstem, because hr-3DMMI could show the feeding artery located behind the tumor and could distinguish feeding arteries from arteries perfusing the normal tissue. Such information can help to avoid uncontrollable bleeding and brain infarction. Therefore, the qualitative assessment was scored as Class IV in Cases 2-4 with large tumor size or tumor located near the brainstem. Our findings suggest that hr-3DMMI is useful to avoid intraoperative complications, but this utility cannot be confirmed due to the lack of comparison between cases with and without hr-3DMMI. Experienced neurosurgeons may change their surgical strategy after using advanced virtual reality simulation, and the “déjà-vu” effect during the actual surgical procedure may be suggestive of the perspectives observed in the simulation, which can increase the surgeon’s confidence during an operation.20 The qualitative assessment indicated that the hr-3DMMI technique could increase the surgeon’s confidence during operation, which can be suggestive of the perspectives observed in the simulation, which can increase the surgeon’s confidence during an operation. The experience of our observers indicates that only hr-3DMMI could predict the precise locations of the feeding arteries.

**Technical Assessments of hr-3DMMI Processing**

The resolution of 3D medical imaging depends on the quality of the source images and the image processing techniques. Therefore, our hr-3DMMI technique mainly uses a surface-rendering method with several processing methods as follows: multiple source images were used for creating the 3D medical image; multiple thresholds were used to visualize the target tissue in a 3D medical image; and manual segmentation was used to distinguish the target tissue from surrounding noise.

The modality/sequence offering the highest contrast of the target tissue among the source images was selected to create the 3D image. However, the modality/sequence offering the highest contrast of any nontarget tissue, such as a main trunk vessel apart from the tumor, was not necessarily selected, because too much information from a nontarget tissue will interfere with the anatomical features of the target tissue. Specifically, visualization of feeding arteries with a diameter of 1 mm or less was based on 3DRA data. However, visualization of main trunk vessels apart from the tumor usually used MRA or 3D CTA data. Modeling of all vessels from 3DRA data would create too much information offered from surrounding vessels for observers to understand the precise relationship between the feeding arteries and surrounding vessels.

The surface-rendering model was usually created with 1 threshold. However, appropriate thresholds for creating 3D models with the surface-rendering method vary for small and large anatomical structures. Specifically, lower thresholds are needed for smaller vessels than for larger vessels. Therefore, we used multiple thresholds to create a high-resolution 3D model.

Manual segmentation was needed to distinguish small anatomical structures, such as feeding arteries, from surrounding noise in the present circumstances, although manual segmentation is time consuming and may introduce bias into 3DMMI.

**Comparison With Current 3D Medical Imaging**

Three-dimensional medical imaging includes 3D CTA, 3D MRA, 3DRA, and 3DMMI. The present study suggests that hr-3DMMI provides superior visualization of the feeding arteries and draining veins in hemangioblastomas.10,12,17 In fact, 3D CTA and 3D MRA are probably not as useful for preoperative planning in patients with hemangioblastoma because the poor spatial resolution cannot visualize every feeding artery precisely. The spatial resolution provided by 3DRA is superior to both 3D
CTA and 3D MRA for visualization of feeding arteries.\textsuperscript{3,21} Therefore, we used 3DRA to visualize feeding arteries in our hr-3DMMI technique. Recent technological advances can combine 2 separate sequences of images of bone and blood vessels into a single 3D image.\textsuperscript{10,17} This process can provide simultaneous visualization of vessels and osseous structures, but cannot visualize other surrounding structures, such as the cerebellum, brainstem, and cranial nerves, unlike our hr-3DMMI technique. Only one other study has assessed the application of current 3DMMI structures, such as the cerebellum, brainstem, and cranial seous structures, but cannot visualize other surrounding draining veins and tumor until the feeding arteries could be resected. This hr-3DMMI technique is expected to be a very useful support tool for surgery of hemangioblastoma. 

Limitations

Although we mainly used 3DRA for the visualization of feeding arteries and draining veins in this study, 3DRA did not necessarily visualize all feeding arteries. Angiography may not delineate all tumor-associated vessels clearly due to the catheter position during imaging, imaging timing, and small vessel sizes.\textsuperscript{18} Therefore, during the dissection of the tumor, the possibility should be considered that some feeding arteries were not visualized even by our hr-3DMMI technique. Another problem is the time required for creating hr-3DMMI. Although our hr-3DMMI technique is very useful, processing takes approximately 3–5 hours. Therefore, we are developing an automatic system for creating hr-3DMMI to reduce preparation time.

Conclusions

Our hr-3DMMI technique could preoperatively evaluate the precise relationship between the feeding arteries and surrounding structures, and estimate the appropriate route for resection of these arteries without damaging the draining veins and tumor until the feeding arteries could be resected. This hr-3DMMI technique is expected to be a very useful support tool for surgery of hemangioblastoma.

References


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

Author Contributions
Conception and design: Nakatomi, Yoshino. Acquisition of data: Yoshino. Analysis and interpretation of data: Yoshino. Drafting the article: Yoshino. Critically revising the article: Nakatomi, Yoshino. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Nakatomi. Administrative/technical/material support: Kin. Study supervision: N Saito.

Supplemental Information
Videos

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