Three-dimensional visualization of neurovascular relationships in the posterior fossa: technique and clinical application

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Object. The goal of this study was to describe the authors’ technique for three-dimensional (3D) visualization of neurovascular relationships in the posterior fossa at the surface of the brainstem. This technique is based on the processing of high-resolution magnetic resonance (MR) imaging data. The principles and technical details involved in the accurate simultaneous visualization of vessels and cranial nerves as tiny structures are presented using explicit and implicit segmentation as well as volume rendering.

Methods. In this approach 3D MR constructive interference in steady state imaging data served as the source for image processing, which was performed using the Linux-based software tools SegMed for segmentation and Qvis for volume rendering. A sequence of filtering operations (including noise reduction and closing) and other software tools such as volume growing are used for a semiautomatic coarse segmentation. The subsequent 3D visualization in which implicit segmentation is used for the differentiation of cranial nerves, vessels, and brainstem is achieved by allocating opacity and color values and adjusting the related transfer functions. This method was applied to the presurgical evaluation in a consecutive series of 55 patients with neurovascular compression syndromes and the results were correlated to surgical findings. The potential for its use, further developments, and remaining problems are discussed.

Conclusions. This method provides an excellent intraoperative real-time virtual view of difficult anatomical relationships.

KEY WORDS • neurovascular compression • cranial nerve • brainstem • segmentation • direct volume rendering

The relationships of the cranial nerves and the vessels at the surface of the brainstem constitute a very complex 3D structure. Hyperactive cranial nerve dysfunction syndromes resulting from neurovascular compression, such as trigeminal neuralgia, hemifacial spasm, and glossopharyngeal neuralgia as well as the association of hypertension with neurovascular compression are some entities that need a comprehensive 3D analysis and spatial understanding of these relationships. Exact information about these relationships can be helpful for both diagnosis and preoperative surgical planning. Until now, imaging of the neurovascular structures in the posterior fossa and, especially, of the relationship between cranial nerves and vessels has depended on 2D representations (slice images) of tomographic volumes. As an exclusive source of information the 2D slice images require extensive experience on the part of the observer to achieve a correct assessment, which may be incomprehensible to other observers. In many cases, this modality does not give a satisfactory overview of the underlying complex anatomy in the posterior fossa.

Since the introduction of MR imaging, neurovascular relationships have been examined using several modalities including T1- and T2-weighted sequences, MR angiography, combinations of different imaging sequences within a protocol, and different orientations. Improvements in MR technology and progress in developing new MR imaging protocols like CISS resulting in strongly T2-weighted images provide sufficiently high resolution below 1 mm, even between consecutive slices. The imaging data demonstrate improved contrast between neighboring structures, allowing us to differentiate cranial nerves and vessels within the CSF at the surface of the brainstem. Although MR CISS, fast turbo spin echo, and time-of-flight MR angiography produce 3D imaging data, it is important to point out the principal difference between 3D imaging data and 3D visualization. A number of studies apply 3D MR sequences and their authors claim to have achieved 3D illustrations or visualizations. Nonetheless, this is misleading in terms of computer graphics, because 3D visualization comprises all methods of volume rendering, which allow us to extract and show 3D representations of 3D imaging data (for example, MR imaging volumes). The resulting illustrations should provide 3D objects that are close to reality based on the underlying imaging data. Attempts at 3D visualization have been made in two studies, but neither of them presented any details about the applied principles and methods of image

Abbreviations used in this paper: AICA = anterior inferior cerebellar artery; CISS = constructive interference in steady state; CSF = cerebrospinal fluid; MR = magnetic resonance; MVD = microvascular decompression; PC = personal computer; PICA = posterior inferior cerebellar artery; REZ = root exit zone; REZ = root entry zone; 2D = two-dimensional; 3D = three-dimensional.
processing, which are key issues for reliability, reproducibility, and accuracy. Until now, such procedures have not been performed routinely for the evaluation of neurovascular relationships in the posterior fossa. Knowledge of the principles and methods applied for generating 3D images, and the abilities and limitations involved, are important for the interpretation of such results, which are introduced in this study and are gaining importance.

**Clinical Material and Methods**

**Patients, Clinical Data, and Surgery**

A comparative analysis of the anatomical relationships of the cranial nerves and the vessels at the surface of the brainstem was performed using MR imaging and 3D visualization. A consecutive series of 55 patients (30 women and 25 men) was introduced to this study. Thirty-one patients suffered from trigeminal neuralgia, eight from hemifacial spasm, and one from glossopharyngeal neuralgia. In addition, we examined 15 patients who had arterial hypertension for neurovascular compression at the ventrolateral medulla. Of 55 patients examined, 41 underwent MVD of the affected nerve (Table 1). The imaging data obtained in 12 patients were processed postoperatively as a retrospective analysis (Group A), and in 43 patients (29 of whom underwent MVD) image processing was performed prospectively before the operation (Group B). Group A served as a training group for the evaluation and improvement of the image processing software. The resulting 3D visualizations were correlated with surgical findings in 41 patients. The local intraoperative findings served as a reference for the comparison between the 3D visualization results and the actual anatomy.

The MVD was performed in the standard way with retromastoid craniotomy and exploration of the REZ of the affected nerve in the posterior fossa by the first (R.N.) and the senior author (R.F.). Decompression was achieved by placing Teflon felt pieces between the offending vessel and the cranial nerve. Documentation of the surgical findings was accomplished by obtaining photomicrographs and video sequences. Intraoperative electrophysiological monitoring of acoustic evoked potentials and facial nerve monitoring as well as stimulation and lateral spread in hemifacial spasm were applied routinely.

**Imaging Procedures**

To scan neural tissue, cranial nerves, and vessels in the posterior fossa simultaneously, we developed a specific protocol of MR imaging in a head coil on a Siemens Sonata 1.5-tesla MR unit (Medical Solutions, Erlangen, Germany), taking care to depict neurovascular relationships with sufficiently high resolution (Table 2). An MR fluid-attenuated inversion-recovery sequence producing water-suppressed $T_2$-weighted image and a routine $T_2$ sequence were used to detect or exclude pathological conditions such as infarction, inflammation, or tumors. Then, the MR CISS sequence provided images with high signal intensity for CSF and low intensities for nerves and vessels. Using this approach, the cranial nerves and the vessels that are within the space of the CSF surrounding the brainstem can be clearly and easily differentiated. Nevertheless, within the MR CISS data the cranial nerves, the vessels, the brainstem, and the surrounding tissues are in the same range of low-intensity values, which prohibits a conventional approach of direct volume rendering because it is impossible to separate the target structures by simple assignment of color and opacity values. On the other hand, a detailed, explicit segmentation of the nerve and vessel structures would be very time consuming and prone to errors because of their very small size.

**TABLE 1**

Clinical data for 55 patients in whom MR images were obtained to diagnose neurovascular compression*

<table>
<thead>
<tr>
<th>Entity</th>
<th>No. of Patients</th>
<th>M/F Ratio</th>
<th>Group</th>
<th>Group</th>
<th>No. of Ops</th>
</tr>
</thead>
<tbody>
<tr>
<td>trigeminal neuralgia</td>
<td>31</td>
<td>10:21</td>
<td>12</td>
<td>19</td>
<td>31</td>
</tr>
<tr>
<td>hemifacial spasm</td>
<td>8</td>
<td>5:3</td>
<td>0</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>glossopharyngeal neuralgia</td>
<td>1</td>
<td>1:0</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>essential hypertension</td>
<td>15</td>
<td>9:6</td>
<td>0</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>total</td>
<td>55</td>
<td>25:30</td>
<td>12</td>
<td>43</td>
<td>41</td>
</tr>
</tbody>
</table>

* See Patients, Clinical Data, and Surgery for a description of the groups.

**TABLE 2**

Protocol of MR parameters and values for applied MR sequences*

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CISS</th>
<th>$T_2$-Weighted</th>
<th>FLAIR</th>
</tr>
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<tbody>
<tr>
<td>orientation</td>
<td>axial &amp; coronal</td>
<td>axial</td>
<td>axial</td>
</tr>
<tr>
<td>TR (msec)</td>
<td>11.46</td>
<td>6490</td>
<td>10,000</td>
</tr>
<tr>
<td>TE (msec)</td>
<td>5.73</td>
<td>98</td>
<td>103</td>
</tr>
<tr>
<td>slice thickness (mm)</td>
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<td>5</td>
<td>5</td>
</tr>
<tr>
<td>no. of slices</td>
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<td>25</td>
<td>25</td>
</tr>
<tr>
<td>distance factor (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>field of view (mm)</td>
<td>200</td>
<td>200</td>
<td>230</td>
</tr>
<tr>
<td>acquisitions</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>flip angle (*)</td>
<td>70</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>matrix</td>
<td>$224 \times 512$</td>
<td>$245 \times 512$</td>
<td>$245 \times 512$</td>
</tr>
<tr>
<td>voxel size (mm)</td>
<td>$0.8 \times 0.4 \times 0.7$</td>
<td>$0.7 \times 0.4 \times 5.0$</td>
<td>$0.7 \times 0.4 \times 5.0$</td>
</tr>
<tr>
<td>SNR</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

* FLAIR = fluid-attenuated inversion-recovery; SNR = signal/noise ratio.
Technical Prerequisites for Image Processing

In this study, we used the programs SegMed and QVis (IRIX version: VisMed), which was developed at the Computer Graphics Group and the Neurocenter of the University of Erlangen. Whereas SegMed is used for an initial coarse and explicit segmentation of larger structures, QVis/VisMed provides interactive direct volume rendering by hardware-supported 3D texture mapping. Both applications can be used with the operating systems Linux and Irix (SGI Unix), whereas QVis is also available for Microsoft Windows; furthermore, QVis is available as open source code. Direct volume renderings based on standard PCs (Intel Pentium IV processor, 2.0–2.4 GHz, minimum RAM 512–1024 MB) were used for interactive 3D visualization. The PCs should be equipped with an appropriate graphics card supporting 3D texture mapping (NVIDIA GeForce3 or GeForce4 with 128 MB graphics memory).

Steps Needed for Segmentation

The combination of explicit and implicit segmentation for the delineation of all important target structures is the basis for this approach (Fig. 1). In our first step, we applied semiautomatic explicit segmentation to separate the CSF that included all nerves and vessels (subvolume 1) and the brainstem (subvolume 3) from the remaining imaging data (subvolume 0). Because the vessels and cranial nerves within the space of the CSF are represented in the same range of intensity values by using the MR CISS sequence, a further step of coarse and explicit labeling is required to separate the nerves (subvolume 2). There is a hierarchy of the subvolumes that makes the explicit segmentation easier: subvolume 2 (representing the nerves) has the highest priority, followed by subvolume 1 (CSF including all vascular structures), and subvolume 3 (containing the brainstem).

Later in the study, implicit segmentation was used based on individual look-up tables for color and opacity values in all of these subvolumes. The remaining surrounding structures are suppressed by assigning full transparency with a further look-up table. Altogether, from a technical point of view, this is a single look-up table in relation to the texture mapping subsystem of the graphics hardware, which is divided into four parts. The actual assignment of color and opacity values to the intensity values of the MR data is then performed with four individual transfer functions (red, green, blue, and opacity) for each subvolume (Fig. 2), which supports interactive manipulation and adjustment of the settings. Using this approach, a clear 3D visualization of the important structures is obtained.

Noise Reduction. The noisy character of MR imaging data is reduced with so-called anisotropic diffusion, which results in more homogeneous areas, while preserving anatomical boundaries (Figs. 1 and 2a).

Morphological Filtering. To simplify the explicit segmentation of the CSF volume, including the vascular structures, morphological filtering with a 3D gray value closing operation is applied. This operation results in the removal of hypointense signals within the hyperintense CSF. Consequently, the CSF is formed into a more compact body with a clear border, which can be extracted as a preformed mask from the surrounding structures. The spherical filter kernel must be smaller than the surrounding structures and greater than the targeted cranial nerves and vessels. Therefore, we used a radius of 2 (Figs. 1 and 2b).

Volume Growing. The definitive extraction of the CSF is performed using volume growing; user-defined bounding boxes are applied to accelerate this process. These boxes provide subsequent rectangular areas restricting the growing process, which are finally linked together (Fig. 2c). Additionally, the growing within a bounding box requires...
an upper and lower threshold that is selected close to the signal intensity of the structure of interest. The segmented "closed" CSF volume serves as a mask for labeling the original MR CISS data for volume rendering (Fig. 2d).

**Manual Labeling.** The differentiation between cranial nerves and vessels is performed by labeling. Due to the necessity for profound anatomical knowledge, so far this has been achieved manually. In contrast, the segmentation of the brainstem is easily obtained using volume growing because the already existing mask of the CSF volume as well as a simple lateral and dorsal restriction with a bounding box to serve as a boundary (Fig. 2e and f).

**Attributing.** At the end, the original MR CISS data set is attributed using four different tags according to the segmented subvolumes, as follows: Tag 0 for the background (including the surrounding structures), Tag 1 for the CSF volume including the vessels, Tag 2 for the cranial nerves, and Tag 3 for the brainstem.

**Visualization Process**

During the visualization process each segmented subvolume of the original MR CISS data is assigned a different color (Figs. 1 and 3). We have chosen white or light blue as the background color, light gray for the brainstem, red for the vessels, and yellow for nerves. These colors are most familiar for these anatomical structures in the medical field. Anatomical structures that are of no interest and are unsegmented (subvolume 0) were made completely transparent (opacity 0), giving optimal visual access to the volume of the CSF space that included all vascular structures (subvolume 1), nerves (subvolume 2), and the brainstem (subvolume 3).

Adjusting the transfer functions of the volume-rendering application, the vessels (subvolume 1) and the nerves (subvolume 2) are delineated using implicit segmentation (Fig. 3). This is achieved by mapping the low signal intensity values representing vessels and nerves to high opacity values (opaque representation) and the high signal intensity of the CSF to low opacity values (transparent representation). Further assistance is achieved using predefined settings of the transfer functions (Fig. 3) for each subvolume, which are adjusted solely by minor manipulation operations. The histogram of signal intensities displayed within the transfer function editor serves as an additional source of information in this process. A range of transfer function settings was evaluated and the most appropriate served as a template function (Fig. 3).

**Results**

**Image Processing, Technical Aspects**

Anisotropic diffusion and subsequent morphological filtering ensured a fast and reliable extraction of the CSF space in front of the brainstem. Small vessels and nerves
were automatically covered by this mask. Larger hypointense structures such as the basilar artery were included in a manual editing process because their diameter was larger than the selected filter kernel \( r = 2 \). With respect to image processing, manual labeling is allowed for structures completely surrounded by CSF. This is also valid for structures of equal intensity values that are attached to each other as long as the contours do not fuse completely. Vessels that were closely attached and running for a distance at the surface of the brainstem could not be delineated because of contour fusion. During the volume-growing procedure it is important to choose an appropriate lower-intensity threshold for CSF to avoid including low-intensity voxels of the surrounding surfaces (skull base and brainstem). After extracting the CSF space the segmentation of the brainstem was performed with no problem in all cases because of the predefined hierarchy between the respective subvolumes. This semiautomatic segmentation procedure ensures a comparatively fast and in addition a robust preprocessing of the imaging data with immediate visual control and low computational costs at each step. The integration of the expert’s knowledge within this highly specialized task leads to robust results.

The visualization with direct volume rendering was per-

**Fig. 3.** Charts and 3D reconstructions showing implicit segmentation: the example for interactive allocation and adjustment of color and opacity/ transparence values for the CSF subvolume. The effect of the different adjustments of the functions on the visualization is demonstrated. For all subvolumes (cranial nerves, brainstem) such transfer functions had to be adjusted. Once the optimal adjustments had been found, they were used as standard templates for all visualizations, ensuring comparability among all cases. a: An MR CISS image with the respective transfer functions prior to adjustment. b: For the subvolume of the CSF space the color red is allocated and the maximum opacity is used for all signal intensities; the subvolume appears as a compact body. c: The color red is adjusted to the hypointense signals of the vessels and the hyperintense signals have no red allocation; the opacity is adjusted high for all signals in the subvolume. d: Adjusting the color value and the value for opacity to the hypointense signal, the vessels can be delineated and the hyperintense CSF appears transparent.
formed interactively by using the 3D texture mapping capabilities of the graphics cards. The adjustment of transfer functions was a time-consuming task at the beginning. After some training and the development of optimized settings, which were applied as template functions as the study progressed, this procedure was considerably accelerated. This template was applied to all data, ensuring comparable visualization results. A bright color (light blue or white) was chosen for the background, which provides sufficiently high contrast even for structures at the margin of the 3D object (Figs. 3–6).

Clinical Application

For all patients MR imaging data were obtained that were sufficient in quality for segmentation and subsequent visualization. The time needed for all MR measurements is approximately 30 minutes. The preparation of the data and the subsequent processing, including segmentation and visualization, took approximately 2 to 4 hours. The examination comprises the whole posterior fossa and the structural relationships at the surface of the brainstem from the fifth cranial nerve to the ninth/tenth nerve complex. It was possible to delineate the trigeminal nerves, the facial and vestibulocochlear nerves, and the glossopharyngeal–vagal complex in all cases (Figs. 3–6). The abducent nerve was visualized in 49 of 55 patients. To differentiate between cranial nerves and vessels, the straight course of the nerves through the CSF from the REZ or RExZ at the brainstem to the foramen at the skull base was used as an orientation marker for the segmentation process (Fig. 2). The affected cranial nerve and its structural relationships were carefully analyzed with regard to the presurgical planning. Intraoperative photomicrographs showed that 3D visualization revealed no unexpected relationships regarding the surgical anatomy (Figs. 4–6).

During exploration of the affected nerve in the cerebellopontine angle, in four patients with trigeminal neuralgia very small veins were observed that were attached to the brainstem and nerve; these veins traversed the surface of the pons for quite a distance. These vessels were not visible on the initial MR slice images because the low signal at the surface prohibited their differentiation from the brainstem surface. Due to their small size, these veins did not leave a distinct contour at the surface of the brainstem (contour fusion, see Fig. 7f). In patients with hemifacial spasm the RExZ of the facial nerve at the brainstem was visualized in all cases and the complex relationship of the PICA or the AICA to the nerve were demonstrated. Differentiation between the seventh and eighth cranial nerves was possible in 40 (cave bilateral evaluation) of 55 cases examined in this study. In 12 patients with hypertension we observed typical loops at the ventral/axillary side of the glossopharyngeal–vagal complex on the left side (Fig. 6). One patient dis-
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Discussed

Our strategy is the first standardized, robust method for the comprehensive 3D visualization of the neurovascular relationships in the posterior fossa. This method has been applied in clinical routine in 55 cases and has proven to be effective and practicable. It is based on CISS MR imaging sequences, which have the specific advantages of the highest resolution and lowest signal artifacts from pulsating CSF of the modalities that are currently available. There is great controversy about the imaging of neurovascular relationships at the surface of the brainstem, and the studies presented so far result in divergent conclusions, especially for the detection of neurovascular compression.

This controversy resembles the discussion when Jannetta introduced his concept of neurovascular compression as the cause of hyperactive cranial nerve dysfunction syndromes. It was difficult for Jannetta and other advocates of this hypothesis to convince the skeptics.

... regarding vascular and other abnormalities in problems of cranial nerves, there was little acceptance for this concept until recently. Several reasons for this lack of acceptance may be given. 1) Incomplete verification by others: few neurosurgeons ventured safely and comfortably into the cerebellopontine angle. 2) Relatively primitive technology: lighting and instrumentation were not highly sophisticated. Magnification techniques were not used outside the laboratory except... 3) Inadequate documentation of finding. ...21

The main problem with understanding the very complex anatomy when using a 2D presentation is the mental reconstruction of 3D objects, which mainly depends on the power of the observer’s imagination. To overcome the limitations of 2D representations of volume data, 3D visualization based on direct volume rendering has been applied.

An important advantage of this strategy is that the tiny target structures are delineated with implicit segmentation.
This advance is achieved with transfer functions, which assign color and opacity values to the original intensity values of the MR data (Fig. 2). As a further important prerequisite, interactive manipulation of the transfer functions and the objects within a 3D viewer is provided using standard PC graphics hardware for acceleration.

It requires quite a lot of training time to be able to interpret the original slice images correctly. Whereas nowadays the concept of neurovascular compression as an underlying principle of the so-called hyperactive cranial nerve dysfunction syndromes is generally accepted among neurosurgeons, the understanding of neurovascular compression is different and is still not uniform. What are the characteristics of neurovascular compression? The term neurovascular compression includes a wide spectrum of contacts between vessels and cranial nerves. Nevertheless, there are several specific common characteristics of neurovascular compression. First, the location of the contact is important in addition, the anatomical appearance of a loop is a convex course toward the nerve and the brainstem. Especially for neurovascular compression in arterial hypertension, Naraghi and colleagues described three anatomically distinct types for the courses of the vessels. Looking for and counting contacts between vessels and nerves is not enough to describe or detect neurovascular compression. This is the main reason the results in several studies indicated no difference between patients with hypertension and normal individuals. Moreover, it is important to have infor-
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Fig. 7. Images demonstrating limitations of the method. Low blood flow resulting in hyperintense signals on MR CISS images leads to a limited visualization of the vessel. a–d: Images demonstrating an increasing signal within the vertebral artery (VA) (va, yellow arrows) at the ventrolateral medulla. The VA is visible in the MR CISS. e: Visualization shows a very unclear course (green arrows). Although one knows that there must be a VA, any further editing is regarded as an unacceptable manipulation. An “honest” visualization should be used within its methodological abilities. Similarly, although one knows that the course of the vessel at the surface follows the dotted line (pink arrows), the vessel cannot be delineated clearly and manual editing is considered to be an unacceptable manipulation. f: Schematic explanation of contour fusion: consecutive slice images demonstrating the effect when a vessel runs close to the surface of the brainstem.

Intraoperative photomicrographs and video documentation served as the basis for verifying the 3D visualization results. This comparison showed that our method is in fact able to demonstrate the relationships correctly (Figs. 4–6). There were no unforeseen findings in which the preoperative images were completely different from reality. The

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Conclusions

Our method can be regarded as a first step for a better preoperative setup in cases of difficult anatomical relationships. We think that applying this method to other regions can also serve as a valuable assistance. Clinical controversies about the concept of neurovascular compression and especially the association of neurovascular compression and arterial hypertension can be reevaluated and resolved.

The ability to manipulate the 3D representations interactively provides the surgeon with an excellent intraoperative, real-time virtual view of the anatomy corresponding to the surgical field (Figs. 4–6). Questions about the course of the vessels in the depth or those lying behind a structure (Fig. 5d, e, g, and h), which are difficult to inspect with the coaxial view of the microscope, could be answered with intraoperative interactive virtual endoscopy. Approaches for the fusion of the 3D representations produced and the real intraoperative view should be a further step. The introduction of the interactive use of 3D visualization during surgery is a logical move toward fusion of the virtual space and the real physical space by superimposing 3D visualizations into the microsurgical field of view.

Acknowledgments

Ramin Naraghi and Peter Hastreiter contributed equally to this study.

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