Original Article

Virtual Reality Planning of Microvascular Decompression in Trigeminal Neuralgia: Technique and Clinical Outcome

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Abstract

Background A neurovascular conflict (NVC) is considered the cause of trigeminal neuralgia (TN) in 75% of cases, and if so, a microvascular decompression (MVD) can lead to significant pain relief. A reliable preoperative detection of NVC is essential for clinical decision-making and surgical planning, making detailed neuroradiologic imaging an important component. We present our experiences and clinical outcomes with preoperative planning of the MVD procedure in a virtual reality (VR) environment, based on magnetic resonance imaging (MRI) including magnetic resonance angiography (MRA) and magnetic resonance venography (MRV) sequences.
Methods We analyzed the data of 30 consecutive MVDs in patients treated for TN, in a retrospective single-surgeon (R.A. Kockro) study. Out of the 30 cases, 26 were included. Preoperatively, MRA/MRV and MRI series were fused and three dimensionally reconstructed in a VR environment. All critical structures such as the trigeminal nerve as well as the arteries and veins of the cerebellopontine angle, the brainstem, the neighboring cranial nerves, and the transverse and sigmoid sinus were segmented. The NVC was visualized and a simulation of a retrosigmoid approach, with varying trajectories, to the NVC was performed. The intraoperative findings were then compared with the data of the simulation. The clinical outcome was assessed by a detailed review of medical reports, and follow-up-interviews were conducted in all available patients (20/26).
Results The VR planning was well integrated into the clinical workflow, and imaging processing time was 30 to 40 minutes. There was a sole arterial conflict in 13 patients, a venous conflict in 4 patients, and a combined arteriovenous conflict in 9 patients. The preoperative simulations provided a precise visualization of the anatomical relationships of the offending vessels and the trigeminal nerves as well as the surrounding structures. For each case, the approach along the most suitable surgical corridor was simulated and the exact steps of the decompression were planned. The NVC and the anatomy of the cerebellopontine angle as seen intraoperatively matched with the preoperative simulations in all cases and the MVC could be performed as planned. At follow-up, 92.3% (24/26) of patients were pain free and all the patients who completed

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- microvascular decompression
- trigeminal neuralgia
- virtual reality

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the questionnaire would undergo the surgery again (20/20). The surgical complication rate was zero.

Conclusion Current imaging technology allows detailed preoperative visualization of the pathoanatomical spatial relationships in cases of TN. 3D interactive VR technology allows establishing a clear dissection and decompression strategy, resulting in safe vascular microsurgery and excellent clinical results.

Introduction

Trigeminal neuralgia (TN) is defined as a facial pain syndrome characterized by episodes of paroxysmal, sharp-shooting, intense pain in one or more branches of the trigeminal nerve on one side of the face. Usually, the patients describe the pain level as worst possible pain that can often be triggered by speaking, eating, teeth brushing, touching, cold, etc.[1–3]

In approximately 75% of patients, a neurovascular conflict (NVC) is considered the etiology of TN, which can be caused by an arterial or venous conflict or both. In about three-fourths of these cases, the superior cerebellar artery (SCA) is the responsible vessel. In approximately 10 to 20%, a venous conflict alone is the underlying pathology. Apart from NVCs, other possible etiologies can be multiple sclerosis (MS) plaques in the pons, infectious lesions, tumors, or cavernomas in or near the location of the trigeminal brainstem nuclei or along the route of the trigeminal nerve.[2–6]

If an NVC is prevalent, surgical microvascular decompression (MVD) can be offered, if therapy by medication does not achieve a sustainable clinical success. Unlike drug medication and interventional options, surgical decompression addresses the cause of the neuralgia: the removal of the offending vessel from the nerve. Optimal preoperative neuroradiologic imaging is necessary to identify patients with NVCs who will most likely benefit from an MVD. However, some studies show the NVC cannot reliably be identified by preoperative magnetic resonance imaging (MRI) in all cases.[7–10] In their recent study, Hitchon et al were able to show a sensitivity and specificity of MRI for NVC of only 87 and 50%, respectively.[11]

Over the last decades, MRI techniques have shown great progress. Nowadays, T2-based 3D-DRIVE (driven equilibrium) and constructive interference in steady-state (CISS) sequences visualize nerval, vascular, and arachnoid structures in high resolution. MR angiography (MRA) and MR venography (MRV) provide a contrasted view of the vascular anatomy. Unfortunately, current radiology software usually displays different sequences only as separated series of two-dimensional (2D) image planes; some software allows three-dimensional (3D) reconstruction. However, proper tools for image fusion and segmentation of the trigeminal nerve, brainstem, and subarachnoid space including its vasculature are missing. Furthermore, software for radiologic and neuronavigation workstations is suitable for inspecting data rather than surgical planning since it is difficult to adjust trajectories and viewpoints according to the anticipated surgical scenario.

The Dextroscope (Volume Interactions PTE LTD, Singapore) is a virtual reality (VR) workstation that enables fusion, 3D reconstruction, and segmentation of patient-specific MRI and CT imaging series. The individual anatomy and prevalent pathologies can be explored in any angle by the use of handheld immersive image exploration tools, allowing the simulation of surgical steps via different trajectories.[12–15]

In this study, we present our experiences with the Dextroscope for preoperative planning of MVD in TN with respect to intraoperative findings and clinical outcome.

Methods

Patients

For the purpose of the study, 30 consecutive cases operated on for typical TN were analyzed in a single-surgeon study. The senior author (R.A. Kockro) was the lead neurosurgeon in all cases. Four cases were excluded due to other prevailing etiologies. Three patients harbored pontine MS plaques and one patient was diagnosed with a cluster headache. Out of the 26 patients, 15 were females and 11 were males with an age range of 26 to 89 years and mean age (±SD) of 62.04 (±17.51) years.

The clinical outcome was assessed by a detailed review of the medical reports as well as the conduction of phone interviews. The questionnaires included pre- and postoperative medication, pre- and postoperative pain levels, and whether they would undergo surgery again.

Imaging

In all patients, preoperative MRA, T2–3D-DRIVE or T2-CISS, and T1–3D-MPRAGE were acquired. MRA studies were acquired in 3D time-of-flight mode (1-mm slice thickness with 0.5-mm overlap) with contrast medium.

Technical Setup

The details of the Dextroscope imaging analysis have been previously described.[12,13,15,16] The concept is to use natural 3D hand movements instead of the mouse and keyboard to work with computer-generated 3D data. The patient-specific multimodal 3D data are displayed on a stereoscopic liquid crystal display monitor, seemingly “floating” within a virtual 3D workspace. Wearing polarizing glasses, the user looks ahead into the monitor while working with the virtual image using handheld, tracked, 3D tools for manipulation and exploration of the 3D graphical data (►**Fig. 1**).

Fig. 1 Dextroscope setup. The user wears polarizing glasses and interacts with the stereoscopic, segmented patient-specific imaging data using electromagnetically tracked handheld controls, thereby seemingly reaching into the 3D simulation scenario.

Preparation of Imaging Data

Source imaging series were imported in Digital Imaging and Communications in Medicine (DICOM) format to the Dextroscope, three-dimensionally reconstructed, and automatically fused. Various segmentation and volume exploration tools (cropping, voxel editing, threshold adjustment) were used to highlight the structures of interest. Each single MRI sequence served for a specific purpose. The trigeminal and vestibulocochlear nerves were extracted from CISS images. MRA/MRV served to segment arteries and veins around the trigeminal nerve and in the anatomical regions expected to be encountered during the surgical access (i.e., transverse and sigmoid sinus, petrosal or tentorial veins). T1–3D-MPRAGE served to segment the cerebellar surface and brainstem. The whole segmenting process usually required 15 to 20 minutes. After data preparation, the virtual image contained the trigeminal and vestibulocochlear nerve and all surrounding venous and arterial vasculature, the subarachnoid corridor between the posterior face of the petrous pyramid, the surfaces of pons and cerebellum, the transverse and sigmoid sinus, and the skin surface.

Surgery Planning

Using the Dextroscope volume exploration tools accessible within the virtual workspace, the multimodal 3D dataset was inspected and analyzed with the following purposes:

- Visualizing and understanding the three-dimensionality of the NVC.
- Visualizing the nuances of the possible surgical corridors taking into account the transverse and sigmoid sinus and petrosal and tentorial veins.
- Determining on the best surgical strategy.

The main phases of the surgical approach were simulated —skin incision, craniotomy, approach to the trigeminal neurovascular complex—with the aim to experience the accurate representation of the patient-specific anatomy as it would be encountered during surgery (see case illustration). Skin incision, craniotomy, and cerebellar retraction were simulated with the real-time voxel-editing tool. The site and extent of the retrosigmoid craniotomy was planned according to the best possible viewpoint for dissection. A computer-generated crosswire simulated the focal point of a microscope and a magnification tool simulated the microscopic view into the surgical corridor. The intraoperative view of the NVC and other relevant structures in the cerebellopontine (CP) angle could then be simulated and adjusted to obtain a thorough comprehension of all the important anatomical relationships. Altering the transparency of objects was used to see and understand the course of vasculature behind the trigeminal nerve or the curvature of the brainstem.

Preparation of the VR model, including 3D segmentation of imaging data, was done by either the operating surgeon or the assisting neurosurgical resident. In all cases, the lead neurosurgeon conducted the planning 24 hours preoperatively, mostly in the evening before the day of surgery. In all cases, screenshots of the simulated intraoperative views were acquired during the planning procedure. They were available electronically in the operating room during the operation. After planning, the data of all cases remained on the Dextroscope for documentation purposes.

Surgery

All the patients were operated in park-bench position and with image-guided navigation. After a linear skin incision, a burr hole and craniotomy were performed. Its position was chosen according to the surgical simulation. After arachnoid dissection, the trigeminal nerve and the offending vessel were exposed and in all cases a Teflon pad was placed in between. The surgical site was inspected with an endoscope (Storz, Tuttlingen, Germany) before and after the placement of the Teflon pad.

Results

Preoperative Planning and Intraoperative Findings

In all the patients, the Dextroscope allowed accurate visualization and comprehension of the characteristics of the NVC. This included the display of involved vessels and the precise spatial relationships between nerve and vessel(s) from various surgical perspectives. There was a sole arterial conflict in 13 patients and a sole venous conflict in 4 patients, while in 9 cases there was a combined arteriovenous conflict. The SCA was the offending vessel in 76.92% (20/26) of cases. A combined SCA and vertebral artery conflict and an anteroinferior cerebellar artery (AICA) were responsible once each. The spatial architecture of each NVC, as seen from a surgical perspective, exactly matched the preoperative simulation. In all cases, the preoperatively determined surgical trajectory, that is, placing the corridor more superior below the tentorium or inferiorly along the CP angle, proved to be intraoperatively successful.

Clinical Outcome

The mean (±SD) follow-up was 38.35 (±19.22) months and a phone interview was conducted in 20 of 26 patients. Six patients could not be reached; in such cases, the clinical outcome was assessed by analyzing the discharge and outpatient reports. The preoperative pain levels on the numerical rating scale (NRS) were on average 9.3 (±0.8). All patients had undergone therapy with pain modulating analgesics. Five of 26 patients had one or several interventions before surgery—1 patient had undergone thalamotomy, 1 patient had undergone a previous MVD, 1 patient had undergone glycerol injections as well as a balloon compression of the gasserian ganglion, and 2 patients had undergone several thermocoagulations. At follow-up, which was either the phone interview or the last available medical report, 92.3% (24/26) of patients were pain free and all patients (20/20) who participated in the interview stated that they would undergo the surgery again. No patient had a neurologic deficit as a surgical complication.

Illustrative Case 1

A 57-year-old woman was experiencing right-sided trigeminal pain (NRS 8/10), mainly in the V2 and V3 territory, triggered by chewing and hot and cold beverages. Multiple regimes of medical treatments with carbamazepine, phenytoin, and pregabalin did not lead to a satisfactory reduction of pain and caused side effects like fatigue, drowsiness, and electrolyte imbalances. The MRI series showed an SCA with multiple contact points with the trigeminal nerve (**►Fig. 2A**). The simulation in the Dextroscope revealed a descending SCA with a triple-loop configuration, contacting the nerve at three points, two of which located close to the nerves' entry into the brainstem. At the most anterior contact point, the vessel caused a slight lateral bulging of the nerve (**►Fig. 2C**). The simulation revealed that the best supracerebellar surgical trajectory started 5-6 millimeters posterior to the angle of the transverse and sigmoid sinus (**►Fig. 2B**). Intraoperatively, the appearance of the NVC exactly matched the preoperative Dextroscope simulation—a triple looping SCA branch with triple contact at the medial face of the trigeminal nerve (**►Fig. 2D**). Two Teflon pads, one medial and one lateral, were placed to separate the nerve from the entire course of the vessel (**►Fig. 2E**). Immediately postoperatively, the patient was pain free and able to completely phase out the analgesics within 2 weeks.

Illustrative Case 2

A 62-year-old man presented with a long-lasting history of right-sided TN. Several years earlier, a thalamotomy had been performed in another institution, which resulted in 3 years of pain relief. After pain reoccurrence, several combinations of analgesics were unsuccessful. MRI was performed. The Dextroscope simulation based on MRI, MRA, and MRV showed an arterial conflict caused by a downward loop of the SCA (**►Fig. 3B**). In addition, a large petrosal vein was directly in contact with the nerve at its inferior and lateral face (**►Fig. 3B**). The best-suited craniotomy was simulated (**►Fig. 3A**). Intraoperatively, the spatial architecture matched the planning scenario. The SCA loop behind the nerve could be freed and mobilized from its pocket position between the nerve and the brainstem and was positioned near the tentorium and attached to it by fixing a Teflon pad with fibrin glue over it (**►Fig. 3C–E**). This resulted in a free space between the Teflon pad and the nerve (**►Fig. 3E**). In addition, a Teflon pad was placed between the nerve and the petrosal vein (**►Fig. 3E**). The patient was pain free after surgery without the need for medication.

Discussion

Neurosurgery is a planned intervention into a complex anatomical space—especially in the area of the skull base. The individual characteristics of a spatial conflict between the trigeminal nerve and one or several blood vessels may be

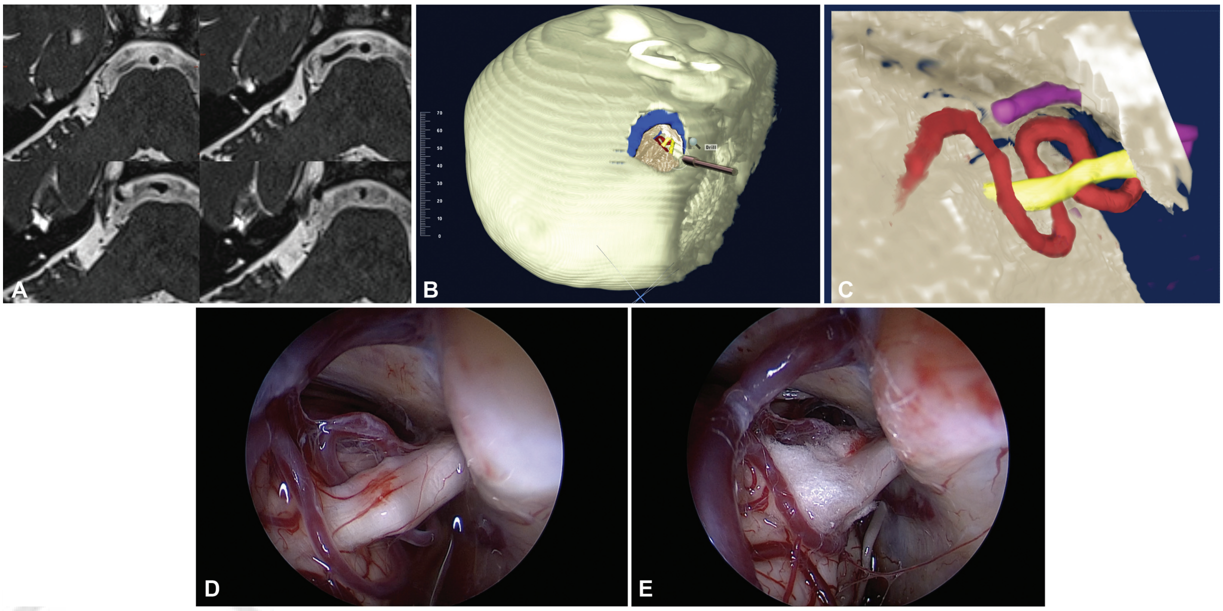

Fig. 2 Illustrative case 1. (**A**) Axial constructive interference in steady-state (CISS) magnetic resonance imaging (MRI) showing the right trigeminal nerve and a looping superior cerebellar artery (SCA) with several contact points (left upper image, most superior, and right lower image, most inferior). (**B**) Simulation of the right retrosigmoid mini-craniotomy with the virtual drill tool. Transverse and sigmoid sinus in *blue*, cranial nerves V and VII/VIII in *yellow*, looping SCA in *red*, and adjacent petrosal vein in *blue*. (**C**) Simulation of the close-up view of the neurovascular conflict. After a proximal inferior loop, the SCA (*red*) curves upward and presses on the trigeminal nerve (*yellow*) medially, causing a slight bulging of the nerve. It then forms a loop superiorly, followed by another inferior loop and thereby causing two more conflicts at the root entry zone. A prominent petrosal vein (*blue*) is located adjacent to the SCA superiorly. (**D**) Endoscopic inspection. Note the similarity to the preoperative simulation with triple-loop configuration and the slight bulging of the nerve. (**E**) Endoscopic inspection after two Teflon pads have been placed, one on the medial face of the nerve and the second near the brainstem laterally.

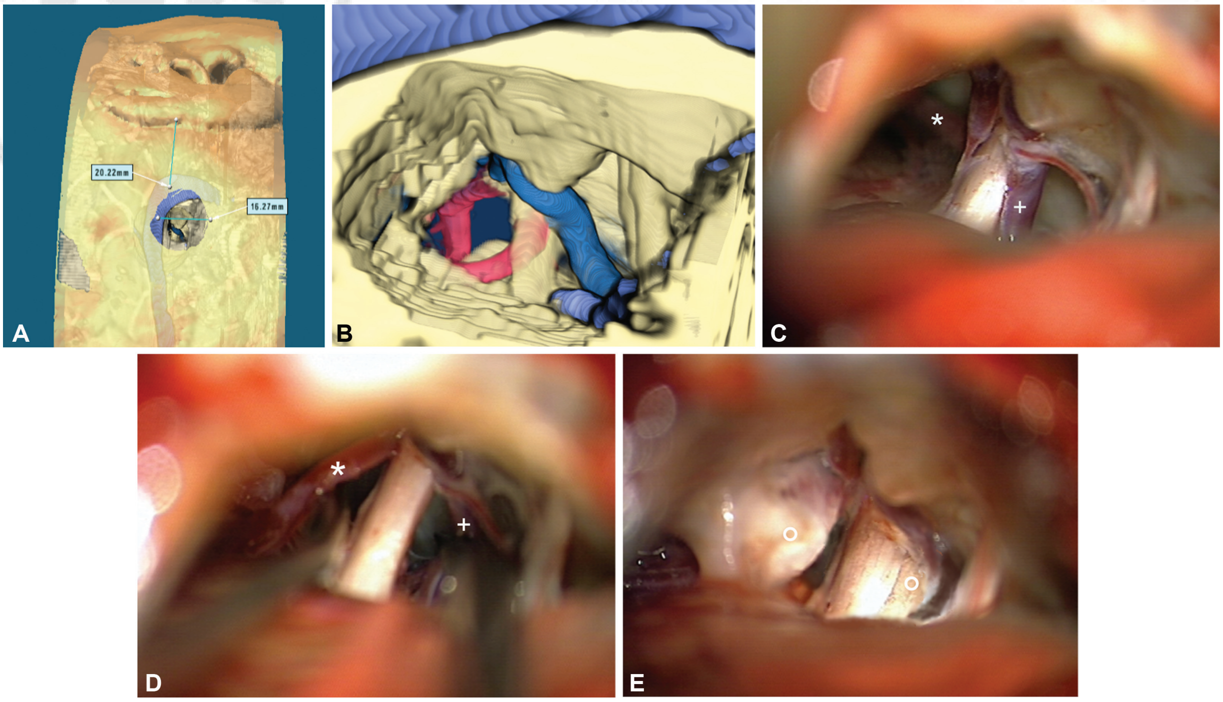

Fig. 3 Illustrative case 2. (**A**) Planning of the mini-craniotomy in the angle of the transverse and sigmoid sinus in *blue*. (**B**) Simulation of the intraoperative sight. The trigeminal nerve (*yellow*) is rendered semi-transparently, revealing the position of the superior cerebellar artery (SCA) loop (*red*), which is causing nerve compression near the root entry zone. A prominent petrosal vein (*blue*) is attached to the nerve inferiorly and laterally. (**C**) Microscopic view. The proximal portion of the SCA loop is visible (*) as well as the venous structures (+). (**D**) The SCA loop is mobilized behind the nerve and positioned next to the tentorium. (**E**) A Teflon pad (°) and fibrin glue fixed the SCA loop to the tentorium, creating a free space, separating it from the nerve. A second Teflon pad (°) had been placed between the nerve and the large petrosal vein.

a predictive factor for the success of surgical treatment as well as recurrence after MVD.[6,17] For these reasons, since the first studies of Sobel et al[18] and de Lange et al,[19] who used cerebral angiography and computed tomography to infer the existence of an NVC, there has been a continuous effort to optimize its preoperative visualization. Detailed preoperative analysis of the pathoanatomical spatial relationships of the surgical target region naturally leads to better conceptualizing of a surgical plan and anticipating possible difficulties.

The Dextroscope, a stereoscopic visualization and surgical planning system with VR features for interaction with 3D imaging data,[15] has been shown to be a tool that may improve surgical planning as well as clinical outcome, especially in the field of skull base and vascular surgery.[12–14,16,20] We have been using this system to plan the surgical procedure of MVD in a series of 30 consecutive patients suffering from TN.

Neurovascular Conflict Description

With improvement of imaging technology, the focus has shifted from mere identification of the conflict to its accurate depiction[7–10,21–27] to, in recent years, its 3D description.[23,26,27] Using the Slicer software (Surgical Planning Laboratory, Harvard University, Boston, Massachusetts, Unites States), Han et al[28] and Shi et al[29] report 100 and 93% consistency between 3D preoperative imaging and intraoperative findings with respect to NVC detection. Satoh et al,[26] Takao et al,[27] and Akimoto et al[23] report 100% consistency using a variety of 3D image reconstruction software such as virtual cisternography and virtual endoscopy. In our series, the consistency between the preoperative simulation using the Dextroscope and the intraoperative findings of the NVC was 100% as well. It is difficult to compare the different studies presented in the literature given the heterogeneity of the MRI sequences and 3D reconstruction software. Theoretically, since 3D image software does simply reconstruct 2D MRI source images, no difference is to be expected—in other words, what can be seen on 2D MR images should also be seen after 3D reexamination of those same source images, provided the software does not eliminate image information during the reconstruction process. However, different imaging series focus on the visualization of the different structures involved in the NVC and, in our experience, the inspection of the segmented data as a combined 3D object reveals more information than looking at the individual image series. In essence, one would probably not miss the existence of an NVC by not using the Dextroscope, but one would most likely miss a significant degree of comprehension of its spatial architecture (see Illustrative Case 1; ►**Fig. 2A–E**).

Du et al[30] used the Dextroscope for preoperative examination of the NVC in 6 cases of TN and 10 cases of hemifacial spasm. They report full consistency between the planning and intraoperative findings. However, their use of MRA as the sole imaging modality as a basis for 3D reconstruction limited the display of nonvascular structures and required the use of contour editing tools to segment the nerves and display them as separate objects. No data on clinical outcome is provided.

In our series, we have used T2–3D-DRIVE or T2-based CISS sequences for visualization of the brainstem and cranial nerves.[31] The sharp contrast of these series allows fast and accurate segmentation of cranial nerves within the subarachnoid cisterns by template-based setting of the signal-intensity threshold. With respect to visualization of the vasculature, the contrast-enhanced MRA sequences resulted in venous and arterial display of even small vessels down to a diameter of 1 to 2 mm. The brainstem and cerebellar surface were autosegmented by an algorithm based on erosion and dilation. The preparation of a multimodality 3D model, floating within the virtual workspace of the Dextroscope and ready for surgical planning, typically took approximately 30 minutes.

Planning of the Microvascular Decompression

In any surgical procedure, knowing the individual anatomy of the surgical target zone is imperative. The surgical path and the location of delicate structures potentially at risk must be perfectly clear. For this purpose, the mental establishment of a 3D map of the individual anatomy of the patient based on the study of preoperative imaging is a key process, which should be completed long before skin incision. It was shown previously that the preoperative 3D simulation of neurosurgical procedures enhances confidence and reduces exploratory dissection[12,14] In a series of 115 cases of aneurysm surgery, which were meticulously planned with the Dextroscope, it was shown that the surgical morbidity and mortality, as well as the rate of complete aneurysm occlusion, were largely superior to the data published in controlled trials like international study of unruptured intracranial aneurysm (ISUIA), unruptured cerebral aneurysm study Japan (UCAS), the barrow ruptured aneurysm trial (BRAT), or international subarachnoid aneurysm trial (ISAT).[16]

In comparison to surgical planning with 2D imaging series, the Dextroscope offers two main advantages:

- It permits to co-register and segment and therefore simultaneously displays several different imaging modalities. This allows combining the informative value of each of them.
- It displays the segmented multimodal data as stereoscopic virtual object, floating within a 3D user interface and therefore allowing very intuitive and yet detailed spatial exploration.

The planning of the surgery usually started by examining the virtual object with handheld volume exploration tools like zooming, cutting, or see-through tools. The conflict and the anatomy of the posterior fossa were inspected from any angle. Individual anatomical variations of the posterior cranial fossa can increase the complexity and therefore the risk of complication of MVD: venous anatomy, size of cisterns, depth of the posterior fossa, or proximity of the cranial nerve VII to VIII complex to the trigeminal nerve. Not all of these features can be directly assessed on standard 2D images. As an example, Sade and Lee[32] found a correlation between the tentorial angle and the intraoperatively measured distance between the facial–acoustic complex and the trigeminal nerve. In the Dextroscope, however, the distance between the facial–acoustic complex and the trigeminal nerve, as well as any other relevant dimension (width of the cisternal compartments, working depth and width), can be directly assessed at one glance.

Once the nature of the neurovascular conflict was clear, the surgical planning focused on the surgical strategy. The conflict was visualized exactly as it will appear intraoperatively. While editing the transparency of the nerve or by switching on or off various segmented objects, it is possible to understand exactly which structures lie behind or in front of the nerve and what their exact relationship is to it.

As outlined in ►**Figs. 2B, C** and **3A, B**, all the critical steps of MVD may be simulated preoperatively. By altering the transparency of the skin, the course of the transverse and sigmoid sinus can be visualized in relation to external anatomical landmarks, like the ear and the inion as well as to the surgical target zone around the trigeminal nerve. This results in accurate planning of the size and shape of the craniotomy, even without having an intraoperative navigation system available. With respect to the actual vascular decompression procedure, the most critical information is the preoperative anticipation of the course of the offending vessel(s). Like in ►**Fig. 2C**, the offending vessel may be the SCA or one of its branches. From a surgeon's perspective, it may form a loop behind the nerve and then continue its course around the brainstem and cerebellar surface. A branching of the vessel may or may not be present at this portion of the artery and surrounding veins may hinder an approach from certain trajectories. Precise knowledge and anticipation of the anatomical situation and a clear plan from which angle to approach the nerve–vessel complex—for example, more caudally or rather along the tentorium—clearly simplifies the surgery. It facilitates straightforward dissection with little exploratory maneuvers and guesswork and allows anticipating the positioning and the size and shape of Teflon pad(s). In our series, all surgeries were performed exactly as planned. Endoscopic exploration was used in all cases, confirming the anticipated anatomical situation without revealing additional findings causing nerve compression. We used intraoperative navigation (Curve, BrainLab, Munich, Germany and StealthStation, Medtronic, Minneapolis, USA) in all cases with the main purpose to define the position of the craniotomy with respect to the transverse and sigmoid sinus.

Clinical Outcome

Several studies regarding the clinical outcome of MVD in case of TN have been conducted. Barker et al[6] report in a series of 1,185 patients complete pain relief in 75% of cases at 1 year and 64% at 10 years, while 9% experienced partial response at 1 year and 4% at 10 years. Tyler-Kabara et al[33] present similar data with a 73% pain-free rate at 5 years after MVD for typical TN. Other, smaller, studies have presented data ranging from 60 to 80% complete pain relief with an average follow-up between 1 and 9.7 years. Most pain recurrences appeared within the first 2 postoperative years.[34–42]

In our series, 92.3% of all patients were pain free at the last documented patient contact with an average follow-up of 38.4 months. No patient developed pain after having been pain-free initially.

The above-mentioned studies report surgical complication rates between 1 and 15%, while the morbidity in our series was 0%.

We believe that our good clinical results are related to our precise preoperative planning. Every neurovascular conflict is unique and so is the optimal surgical corridor and strategy to untangle it—taking into account all its surrounding structures. Relying mainly on exploratory dissection requires larger arachnoid opening and tissue retraction, increasing the risk of stretching and sheering of cranial nerves and the rupture of vessels, including bridging veins. In addition, conflicting vessels in blind spots, for example, close to the brainstem or behind the far side of the trigeminal nerve might be missed.

The precise 3D anticipation of the anatomical situation, especially beyond the visible surgical field, is a key advantage and preoperative imaging is the only data available to establish a surgical strategy. The 3D display options of radiologic workstations and navigation systems allow displaying imaging a data only in a rather simplified way with limited tools of structural segmentation and image fusion. Depth perception is poor due to monoscopic display and, furthermore, these systems lack options to simulate and adjust intraoperative viewpoints.

Making full use of preoperative imaging means extracting and understanding its spatial information related to key considerations of the surgery: the architecture of the conflict and its appearance from a surgical perspective, branching vessels, width of the subarachnoid space, necessary dissection to free the nerve, distance to other cranial nerves, positioning and size of the pad, venous anatomy nearby or along the tentorium, and location and extent of craniotomy. The Dextroscope with its VR features of interaction and display integrates all this information and presents it in its inherent 3D form. In our experience, the fully interactive, spatial and stereoscopic nature of this planning process creates an unambiguous and clear anatomical reference that leads to precise anticipation of the intraoperative scenario. The anatomical clarity of the VR display is especially useful when discussing surgical concepts with residents and students.

Limitations and Outlook

Although this study is the first of its kind to report not merely on technical aspects but also on clinical outcome after VR surgical planning for MVD, the results should be interpreted with caution since the study is retrospective and lacks control groups.

One limitation of the Dextroscope is the missing simulation of intraoperative brain shift. However, the retraction of the cerebellum during the retrosigmoid approach can be simulated with a voxel-editing tool, which turns voxels along the anticipated space created by retraction into a transparent mode. The most appropriate surgical corridor according to the characteristics of the conflict and the individual anatomy of the patient can thus be analyzed, that is, along the tentorial and petrosal surface of the cerebellum. Future software will need to address the simulation of tissue deformation due to cerebrospinal fluid (CSF) removal, retraction, or the use of instruments. Combined with haptic feedback devices, these VR environments would become ever more faithful to the surgical reality—turning the actual surgery largely into a déjà vu experience while optimizing outcome and patient safety.

Conclusion

The planning of MVD surgery in the VR environment of the Dextroscope is feasible in a clinical setting and provides accurate and useful information for the development of a clear surgical strategy. This enhances intraoperative confidence, minimizes exploratory dissection, and facilitates accurate placement of a Teflon pad. Compared with the literature, our postoperative rates of pain relief were excellent and we did not encounter any complications. Meticulous 3D surgical planning is an invaluable component of cerebrovascular and skull base surgery.

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Conflict of Interest
None declared.

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Ethics
According to the Swiss Ethics Committee, Zürich, the project does not qualify within the scope of the Human Research Act and therefore does not require the approval of the Ethics Committee.

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