Aneurysm Surgery with Preoperative Three-Dimensional Planning in a Virtual Reality Environment: Technique and Outcome Analysis

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■ OBJECTIVE: **Aneurysm surgery demands precise spatial understanding of the vascular anatomy and its surroundings. We report on a decade of experience planning clipping procedures preoperatively in a virtual reality (VR) workstation and present outcomes with respect to mortality, morbidity, and aneurysm occlusion rate.**

■ METHODS: **Between 2006 and 2015, the clipping of 115 intracranial aneurysms in 105 patients was preoperatively planned with the Dextroscope, a stereoscopic, patient-specific VR environment. The outcome data for all cases, planned and performed in 3 institutions, were analyzed based on clinical charts and radiologic reports.**

■ RESULTS: **Eighty-five incidental, unruptured aneurysms in 77 patients were electively planned and treated surgically. Mortality was 0% and morbidity (modified Rankin Scale score >2) was 2.6%. The rate of complete aneurysm obliteration on postoperative imaging was 91.8%. In addition, 30 aneurysms were treated in 28 patients with previous subarachnoid hemorrhage. Mortality in these cases was 3.6%, morbidity (modified Rankin Scale score >2) 7.1%, and the rate of complete aneurysm clipping was 90%.**

■ CONCLUSIONS: **Meticulous three-dimensional surgical planning in a VR environment enhances the surgeon's spatial understanding of the individual vascular anatomy and allows clip preselection and positioning as well as anticipation of potential difficulties and complications. VR planning was associated, in this multi-institutional series, with excellent clinical outcomes and rates of complete aneurysm closure equivalent to benchmark cohorts.**

INTRODUCTION

The clipping of an intracranial aneurysm is a delicate maneuver in a complex, three-dimensional (3D) space. Long before placing a clip, the unique architecture of an aneurysm needs to be understood in its three-dimensionality. This includes the shape and size of the neck and dome of the aneurysm as well as its relationship to feeding and draining vessels and neighboring structures. This spatial construct must be understood from an intraoperative perspective, allowing anticipation of the most suitable sizes, shapes, and positions of clips and also taking into account the limitations of the surgical corridor. PACS (Picture Archiving and Communication System) workstations or the planning software of neuronavigation systems are able to show images of an aneurysm and its surroundings. However, the surgical corridor, dependent on other intracranial or bony structures, cannot be reliably simulated with these systems and it is thus sometimes difficult to conceive the spatial relations of the aneurysm as it will appear in the surgical view.

We have been working with the Dextroscope virtual reality (VR) neurosurgical planning system for more than a decade.[1-5] It shows multimodality, patient-specific, tomographic imaging data in a 3D

Key words
- Clipping
- Dextroscope
- Intracranial aneurysm
- Outcomes
- Surgical planning
- Virtual reality

Abbreviations and Acronyms
3D: 3-Dimensional
CT: Computed tomography
CTA: Computed tomography angiography
DSA: Digital subtraction angiography
MCA: Middle cerebral artery
MRA: Magnetic resonance angiography
MRI: Magnetic resonance imaging
mRS: Modified Rankin Scale
VR: Virtual reality
WFNS: World Federation of Neurological Surgeons

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stereoscopic environment and enables its manipulation through a spatial, handheld interaction interface. A variety of tools for segmentation and virtual drilling, suctioning, and measuring are available. Although the technology of the Dextroscope and its application in a variety of neurosurgical procedures has been extensively described,[1-5] there have been no reports regarding the outcomes associated with regular use of the system. We report here the clinical and radiologic results of Dextroscope-based planning in aneurysm surgery in a series of 105 patients with 115 aneurysms treated at 3 institutions.

METHODS

Patients

Between 2006 and 2015, the surgical repair of 115 aneurysms in 105 patients was planned with the Dextroscope in neurosurgical departments at 3 institutions: University Hospital Mainz, Germany (2006—2015), University Hospital Zurich, Switzerland (2009—2011), and Hirslanden Hospital, Zurich, Switzerland (2012—2015). The decision whether to use the Dextroscope for the planning of a clipping procedure was made by the respective lead neurosurgeon. All patients who underwent aneurysm clipping planned in advance with the Dextroscope were included.

Data Acquisition for Planning

Magnetic resonance imaging (MRI) studies were acquired as 3D fast gradient-recalled echo sequences covering the whole brain (matrix, 512 × 512; field of view, 24—26 cm; slice thickness, 1—2 mm). Magnetic resonance angiography (MRA) studies were acquired in 3D time-of-flight mode (1-mm slice thickness with 0.5-mm overlap). MRAs of the patients operated at Hirslanden Hospital were all acquired with contrast enhancement. Computed tomography (CT) angiography (CTA) was acquired as axial contiguous series with 0.5-mm to 0.8-mm slice thickness.

Technical Setup

Surgical planning was carried out with the Dextroscope, a stereoscopic visualization and planning workstation described previously.[1,2,4-6] The underlying philosophy is to use natural 3D hand movements instead of the mouse and keyboard to work with computer-generated 3D data. In the Dextroscope used in Mainz, the user manipulates a reflection of 3D data by reaching behind a mirror into a virtual workspace containing the patient-specific 3D data and a surrounding set of 3D planning tools. For the cases planned and operated on in Zurich, a modified version of the Dextroscope was used, consisting of a stereoscopic liquid crystal display monitor on which 3D patient data are showed within a floating 3D workspace. Wearing polarizing glasses, the user looks ahead into the monitor while working with the virtual image using handheld, tracked, 3D manipulation tools (Figure 1). Software tools for data loading, 3D reconstruction, segmentation, and surgical planning were common to both systems[6] and the overall surgical planning experience differed little.

Surgical Planning

VR model preparation, including 3D segmentation of imaging data, was performed either by the operating surgeon or the assisting neurosurgical resident. MRI or CT data were transferred

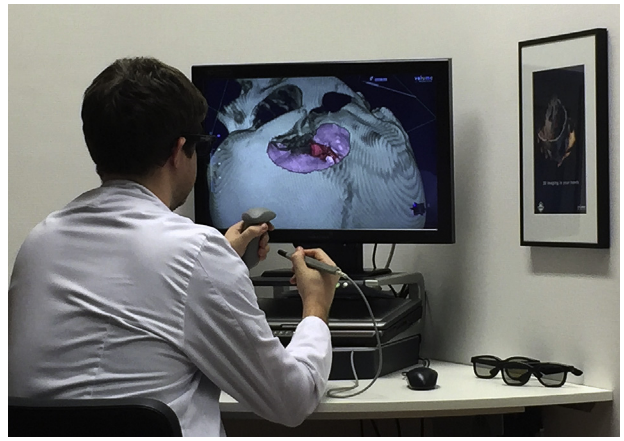

Figure 1. The Dextroscope in use at Hirslanden Hospital, Zurich. The surgeon wears polarizing glasses and interacts with the segmented, patient-specific imaging volume shown on a stereoscopic screen using electromagnetically tracked handheld controls.

in DICOM (Digital Imaging and Communications in Medicine) format to the planning station either via the hospital network or via portable media. Coregistration and volumetric reconstruction of MRI and CT data were performed automatically.[2,4] A variety of software tools were available for thresholding, coloring, and transparency modulation. Manual segmentation tools allow the 3D delineation of structures that cannot be segmented on the basis of grayscale thresholds, such as cranial nerves. A measuring tool allows the drawing of lines between any 2 points in 3D space and is used for determining the dimensions of an aneurysm neck or the lengths of clip arms. For 32 cases in Mainz planned after 2012, a selection of virtual clips and clip holders were available. This selection was achieved by acquiring CT scans of a selection of 64 closed aneurysm clips and 1 clip holder (Yaşargil and Lazic standard and mini clips set [Aesculap, Tuttlingen, Germany]). Volumetric representations of the clips and clip holder were generated and this allowed virtual positioning of the closed clips over the aneurysm. Neither opening nor closing of the clips nor tissue deformation could be simulated. Voxel editing tools allowed for the simulation of a craniotomy. A computer-generated crosswire simulated the focal point of a microscope and a magnification tool simulated the microscopic view into the surgical corridor.

In all cases, the lead neurosurgeon personally conducted the planning 1—24 hours preoperatively. In most of the elective cases, planning was performed the evening before the day of surgery. In all cases, screenshots of the simulated intraoperative view were acquired during the planning procedure and were available electronically in the operating room during the operation. After planning, the data of all cases remained on the Dextroscope for documentation purposes.

Retrospective Analysis

The patients' demographics and the details of the planning procedure (date and time of planning, imaging data imported,