Virtual Cerebral Aneurysm Clipping with Real-Time Haptic Force Feedback in Neurosurgical Education

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■ OBJECTIVE: **Realistic, safe, and efficient modalities for simulation-based training are highly warranted to enhance the quality of surgical education, and they should be incorporated in resident training. The aim of this study was to develop a patient-specific virtual cerebral aneurysm-clipping simulator with haptic force feedback and real-time deformation of the aneurysm and vessels.**

■ METHODS: **A prototype simulator was developed from 2012 to 2016. Evaluation of virtual clipping by blood flow simulation was integrated in this software, and the prototype was evaluated by 18 neurosurgeons. In 4 patients with different medial cerebral artery aneurysms, virtual clipping was performed after real-life surgery, and surgical results were compared regarding clip application, surgical trajectory, and blood flow.**

■ RESULTS: **After head positioning and craniotomy, bimanual virtual aneurysm clipping with an original forceps was performed. Blood flow simulation demonstrated residual aneurysm filling or branch stenosis. The simulator improved anatomic understanding for 89% of neurosurgeons. Simulation of head positioning and craniotomy was considered realistic by 89% and 94% of users, respectively. Most participants agreed that this simulator should be integrated into neurosurgical education (94%). Our illustrative cases demonstrated that virtual aneurysm surgery was possible using the same trajectory as in real-life cases. Both virtual clipping and blood flow simulation were realistic in broad-based but not calcified aneurysms. Virtual clipping of a calcified aneurysm could be performed using the same surgical trajectory, but not the same clip type.**

■ CONCLUSIONS: **We have successfully developed a virtual aneurysm-clipping simulator. Next, we will prospectively evaluate this device for surgical procedure planning and education.**

INTRODUCTION

In recent years, modalities for simulation-based training have been developed in many surgical fields. In neurosurgery, a highly complex surgical discipline, realistic opportunities to enhance the quality and efficiency of surgical education in a safe environment are highly warranted.[1] If adequate training models were integrated in daily routine, both resident education and patient safety would be further increased by improved preoperative planning and refined surgical skills.[2] After publication of the International Subarachnoid Aneurysm Trial, a case load reduction related to improved endovascular treatment options has occurred in cerebrovascular microsurgery.[3] Moreover, the remaining cerebral aneurysms have tended to be more complex and difficult to clip, requiring advanced surgical skills.[4-6] In turn, cerebrovascular "resident" training cases for young or otherwise less experienced neurosurgeons were encountered less frequently.[6] A virtual surgical simulator could thus be incorporated into the teaching of standard procedures in resident training. Moreover, even experienced neurosurgeons facing highly complex cerebrovascular cases will appreciate the

Key words
- Cerebral aneurysm
- Clipping
- Education
- Simulation
- Virtual reality

Abbreviations and Acronyms
3D: Three-dimensional
CTA: Computed tomography angiography
GPU: Graphics processing unit
ICG: Indocyanine green
MCA: Medial cerebral artery
WSS: Wall shear stress

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opportunity to refine technical skills or to review and discuss different surgical options in a safe environment.

Therefore, the aim of this study was to develop a patient-specific virtual aneurysm-clipping simulator with haptic force feedback and real-time deformation of the vessel and aneurysm wall during clipping. In addition, evaluation of the clipping procedure by blood flow simulation is integrated in this simulation software. Furthermore, the simulator was evaluated by 18 neurosurgeons at 2 institutions.

MATERIAL AND METHODS

From 2012 to 2016, a software system for virtual aneurysm clipping was developed at RISC Software (Hagenberg, Austria) in cooperation with the Department of Neurosurgery and Institute of Neuroradiology, Kepler University Hospital, Linz, Austria.[7] This study was approved by the local ethics committee.

Technical Implementation

For the technical implementation of the simulator, the main focus was to make both the haptic and visual feedback as realistic as possible. Therefore, we had to find a compromise between using a sophisticated physical model for the deformation of the arterial walls and keeping the computational complexity low enough to allow smooth interaction with the virtual blood vessel (i.e., maintain a frame rate greater than 20 Hz). We have chosen a finite element method that discretizes the elasticity equations of continuum mechanics, thus being much more realistic than, for example, simple mass spring models, but we assume a simplified isotropic linear material model, disregarding the layered structure, nonlinearity, and anisotropy of real arteries.[8] The values of Young's modulus E used in the literature range between 1 and 300 Mpa.[9,10] Because we are currently using one modulus for the whole mesh, including the artery and aneurysm wall in our simulations, we chose the value at the low end of the spectrum for E and $\nu = 0.45$ for the Poisson ratio.

We are using special numerical methods[7] to accelerate the finite element calculations and general-purpose computing on graphics processing units (GPUs) to increase the calculation speed. The computer used for the simulation is equipped with a discreet GPU used only for calculations to keep the main graphics card free for rendering the scene.

The three-dimensional (3D) models of the aneurysm geometries we use as training scenarios were generated from computed tomography angiography (CTA) or 3D rotational angiography. The use of a magnetic resonance angiography as source data is possible, but the contrast of the vessels in our virtual simulation is better when a 3D rotational angiography or CTA is used. We currently need approximately 1–2 hours to transfer a CTA or 3D rotational angiography image to this prototype simulator. We use another in-house software application (MEDVIS 3D)[11] to reconstruct the voxel volume and segment the region of interest. From these volume data, a triangle mesh of the blood vessel surface is created automatically and then a mesh for the arterial wall is then generated by specifying the thickness of the healthy artery and the aneurysm dome.

Virtual clips available in the simulator were manually modeled according to the product catalog of our project partner Aesculap AG (Tuttlingen, Germany). Our system provides 50 different clip types and sizes, including straight, curved, fenestrated, and mini clips. Opening and closing animations also had to be created for each one.

Apart from a physically correct wall movement, an accurate and fast collision detection and response is another vital ingredient for creating a convincing visual and haptic experience. We use the Bullet Physics Library,[12] an open source project used, for instance, in a National Aeronautics and Space Administration robotics toolkit for detecting collisions. This system has the advantage that it can use the exact geometry of the 3D models (i.e., triangle meshes describing the surface) to test for collisions, while still being fast enough to allow a smooth user interaction. As a response to the collision detection results (collision points and interpenetration vectors), we have to generate the boundary conditions for the wall displacement and calculate the force for the haptic feedback.

Blood Flow Simulation

A main part in the quantitative assessment of the training results is a numerical simulation of the altered blood flow through the treated aneurysm, which allows the calculation of the degree of an induced stenosis and the percentage of the remaining aneurysmal blood volume. This procedure is further complicated by the requirement for automatic generation of a smooth high-quality mesh for the interior of the clipped wall geometry.[7] The blood itself is modeled as an incompressible Newtonian fluid, for which we solve the Navier-Stokes equations with a finite element method, using state-of-the-art numerical methods on parallel GPU architectures.[11] To minimize the computation time, we assume a constant inlet velocity and ignore its pulsatile variation over time. The resulting flow can then be visualized as a vector field or via velocity streamlines. We also calculate the wall shear stress (WSS) acting on the surface of the fluid domain, which is an important biologic parameter affecting the vascular wall, with low WSS indicating increased risk of aneurysm growth and rupture, and high WSS facilitating the initial formation of an aneurysm.[13,14]

Illustrative Cases

In 4 selected cases, real-life microsurgical clipping of different medial cerebral artery (MCA) bifurcation aneurysms was performed and documented. Thereafter, we completed virtual aneurysm clipping using each patient's individual preoperative CTA examination. Surgical results of real-life and virtual aneurysm clipping were analyzed and compared regarding clip application, surgical trajectory, and blood flow simulation.

Evaluation

The virtual aneurysm-clipping model was also evaluated using a questionnaire with 12 questions on a 5-point Likert scale (strongly agree, agree, neutral, disagree, strongly disagree, or do not know; **Table 1**). Free-text responses were possible. Surgical experience in years was assessed for each participant. Hands-on experience was possible before the participants evaluated the simulator. Surgeons from 2 neurosurgical institutions (Department of Neurosurgery, Krankenanstalt Rudolfstiftung, Vienna, Austria, and Department