T he STA-MCA bypass is an appealing microanastomotic procedure initially developed and described by Yaşargil and colleagues in 1967. At present, there are 3 overall accepted indications: to achieve perfusion in distal MCA branches when iatrogenic vessel occlusion cannot be avoided for various reasons, to improve brain perfusion in moyamoya disease, and to augment hemispheric perfusion in major vessel occlusion with hemodynamic insufficiency. Although the microanastomosis itself is a highly sophisticated procedure on small structures, the need to intraoperatively evaluate suitable recipient vessels requires a considerable frontotemporal craniotomy to expose a wide area of the distal sylvian fissure.

The introduction of 3-T MR imaging in the clinical diagnostic routine at major neurovascular centers has tremendously improved the preoperative evaluation of potentially suitable recipient arteries. Nevertheless, the preoperative selection of appropriate donor and recipient...
vessels, and thus the tailoring of an ideally located craniotomy based on MR imaging and digital subtraction angiography data, remain challenging. In the current study we describe the application of a 3D virtual reality planning system based on 3-T MR angiography and its consequences for preoperative planning and an intraoperative strategy without stereotactic neuronavigation guidance.

**Methods**

A 3D virtual reality planning tool (Dextroscope, Volume Interactions, Bracco AMT, Inc.) was applied in 5 consecutive STA-MCA bypass procedures between July and December 2008. The system’s influence on the surgical procedure was evaluated with special attention to the selection of the recipient vessel, localization of the donor artery, and size and location of the craniotomy.

**Patient Population**

All patients were men between the ages of 56 and 67 years (average age 62 years) who had suffered an ICA occlusion (3 left side, 2 right side). Of these 5 patients, only 1 had a history of a small MCA infarct. This patient and 3 others suffered from recurrent TIA symptoms. An impaired O\textsubscript{2} reserve capacity was found using duplex ultrasonography under CO\textsubscript{2} exposition in all 4 patients. The fifth patient was subjected to deep brain stimulation of the subthalamic nucleus for essential tremor. In the work-up for the procedure, occlusion of the right ICA and a 10-mm ACoA aneurysm were incidentally found. As there was no right posterior communicating artery, the patient depended on cross-flow via the ACoA. A prophylactic STA-MCA bypass was performed in this patient followed by endovascular coil occlusion of the ACoA aneurysm. The clinical situation, radiological images, and the surgical findings were prospectively analyzed for all patients.

**Three-Dimensional Virtual Reality Planning**

Preoperatively, all patients underwent MR imaging in a 3-T unit (Magnetom Trio system with TrioTim syngo MR B12 software, Siemens Medical Solutions). Using a 32-channel head coil, magnetization-prepared rapid acquisition gradient echo (MPRAGE) sequences (TR 24 msec, TE 4.4 msec, flip angle 15°, matrix 640 × 564, slice thickness 0.49 mm, slice gap 0.49 mm) were created. Computed tomography 3D datasets with a slice thickness of 0.5 mm were obtained to assess bony structures. Radiological data were integrated into a 3D virtual reality planning system (Dextroscope). The planning tool, its applications, and the advantages and disadvantages in general neurosurgery have been discussed in detail elsewhere.\textsuperscript{2,3} In brief, 3-T MR images, time-of-flight MR angiograms, and cranial CT images were fused, and a 3D virtual reality model was generated. Skin surface, skull surface, and extra- and intracranial arteries as well as the cortical brain surface were displayed in detail in a 3D configuration. The surgical approach was visualized virtually, and the anatomical relationships of structures of interest were presented by different values of translucency (Fig. 1).

Anatomical findings in each individual were analyzed in detail, and the surgical steps of the upcoming procedure were simulated. The optimal STA branch for a donor vessel was identified, as was its course in relation to anatomical landmarks and auxiliary lines. The optimum recipient vessel, usually the M\textsubscript{1} or M\textsubscript{2} segment, was chosen based mainly on its caliber and superficial location. The size and location of the craniotomy as well as the length of the skin incision were determined by the proximity of the selected donor and recipient vessels. With the system’s “surface ruler” mode, we calculated the size and localization of the calculated craniotomy as well as the length and localization of the skin incision in relation to given anatomical landmarks and constructed auxiliary lines. A virtual line extending from the corner of the patient’s eye to the upper point of attachment of the ear served as the auxiliary line, and a second line marking the course of the donor STA branch served as the skin incision line. Angles and measurements were transferred to each patient’s skin (Fig. 2 and Table 1). Three-dimensional virtual reality planning was performed without any difficulties in all 5 cases.

**Specific Surgical Procedure**

After marking the auxiliary lines and the size of the
Minimally invasive bypass using 3D virtual reality planning

craniotomy on the skin according to the preoperative 3D virtual reality planning data, shaving was restricted to a narrow strip along the intended skin incision. After disinfecting the skin and draping with the aid of microscopy, the incision was made at the intended location directly atop the selected STA branch. In each case, the vessel was identified in absolute accordance with the preoperative plan and subsequently prepared by preserving a 5-mm tissue sheath around it. After splitting the temporalis muscle, we used a high-speed drill to create a bur hole as a starting point for a small osteoplastic craniotomy with a mean diameter of 22 mm (range 20–25 mm). The dura was preserved in all cases. After opening the dura, the recipient vessel was identified in all 5 cases in exact agreement with the presurgical plan despite the limited exposure of the brain surface through the minimal osteoplastic craniotomy (Fig. 3). All anastomotic procedures were performed without any difficulties through the small approach. Good anastomotic flow, as assured by either indocyanine green angiography or micro-Doppler ultrasonography, was observed in each case.

General Surgical Technique and Follow-Up

After inducing a state of general anesthesia, the patient was placed supine with the head turned. The subsequent anastomosis site was determined as the highest point of the surgical field to avoid CSF accumulation during the procedure. The skin was incised and the extracranial donor artery was prepared. After splitting the temporalis muscle and the temporal craniotomy, the recipient artery was selected. A temporary aneurysm clip was placed on the STA, which was then cut distally, followed by flushing with a heparinized saline solution. The artery tip was stripped and incised to create a fish-mouth opening. After placing temporary clips on the recipient artery, a longitudinal arteriotomy at least twice as long as the diameter of the vessel was performed. After placing 2 stay sutures, anastomosis was accomplished using 10-0 nylon sutures in an interrupted fashion. Anastomotic flow was assured with either indocyanine green angiography or micro-Doppler ultrasonography. The dura mater was loosely readapted, followed by a layer of Gelfoam. The bone flap was fixed with titanium pins after drilling an

![Fig. 2. Preoperative determination of the skin incision and craniotomy site. A: Image depicting the auxiliary line drawn from the corner of the eye to the upper point of attachment of the ear. The craniotomy center is assigned based on a second perpendicular auxiliary line (distance from ear rim to rectangle 14.93 mm, length of second auxiliary line 40.75 mm). B: Image showing identification of the ideal position and length of the skin incision on top of the selected STA branch with a third auxiliary line (angle to first line 114.57°, distance from ear rim 25.07 mm, length 45.06 mm). C: Drawing of first auxiliary line, craniotomy site, and skin incision on the patient’s skin according to the preceding calculations (superimposition with Dextroscope donor and recipient vessels for orientation).](image-url)
adequate gap for the donor vessel. The temporalis muscle was also loosely readapted around the vessel. The skin closure was outlined with sub- and intracutaneous interrupted sutures. Postoperatively, the patients underwent CT angiography and duplex ultrasonography during the hospital stay, followed by duplex ultrasonography every 3 months thereafter.

Results

The Dextroscope was applied without any difficulties in all 5 cases. After specific virtual reality planning, the surgical procedures were performed without neuronavigation.

All microanastomoses were performed without major restrictions associated with the limited approach. In all cases, the appropriate donor and recipient vessels were found exactly where expected based on the virtual reality simulation procedure, without the addition of Doppler probes or stereotactic neuronavigation. Subsequent enlargement of the craniotomy was not necessary. Perioperative complications like epidural or subdural hematoma, wound-healing disorders, CSF leakage, infarctions, or wound infections were not observed. Postoperative courses in all 5 patients remained uneventful. During the hospital stay, all anastomoses were patent as shown by CT angiography and duplex ultrasonography (Fig. 4). Thus far, the mean follow-up has been 3.4 months (range 1–6 months). All bypasses have remained open on duplex ultrasonography follow-up studies.

Discussion

The STA-MCA bypass is a well-established revascularization procedure to augment moderate flow in well-selected cases. It is known for its rather low rate of perioperative complications. Nevertheless, the disproportion of the size of the standard craniotomy and the subsequent tissue trauma to the very small area actually required for the microsurgical anastomosis is quite striking. Historically, when preoperative evaluation was based on digital subtraction angiography studies alone, the standard craniotomy was placed around the supposed area of the distal sylvian fissure and was made large enough to choose a dedicated recipient artery within the exposed surgical field. Often, the course of the STA branch was determined using a Doppler probe.

Using time-of-flight MR angiography with a 3-T unit, small arteries with a diameter of ~1 mm, especially in distally located MCA segments, can be depicted with excellent quality. With these volumetric imaging data, stereotactic neuronavigation procedures can be applied to STA-MCA bypass procedures and have been described as helpful in reducing the size of the craniotomy. The use of a 3D virtual reality simulation tool is a somewhat
Minimally invasive bypass using 3D virtual reality planning

different approach to a reduction in craniotomy size. With plain preoperative evaluation of the anatomical findings and auxiliary line calculations on the skin surface, it was possible to forgo the use of stereotactic navigation systems while achieving comparable accuracy. Furthermore, the 3D virtual reality planning facilitated perioperative workflow and shortened the procedure in the operating theater. In all 5 cases, even the use of a Doppler probe was not required to localize the course of the donor branch. The described technique provides a safe and reliable means of minimizing the skin incision and dissection of the STA donor branch as well as limiting the incision of the temporalis muscle and the size of the craniotomy, and thus exposure of the cortical surface. Three-dimensional virtual reality planning is helpful in designing minimally invasive intracranial procedures. Its benefits are not limited to vascular processes but are also applicable in skull base surgery, glioma surgery, or even spinal surgery. The main advantage of 3D virtual reality planning is the verisimilitude of the preoperative 3D model; the consequent intraoperative “déjà-vu” feeling enhances surgical confidence. In all procedures planned with the Dextroscope, the chosen surgical strategy proved to be the correct choice. Three-dimensional virtual reality models of a patient allowed quick and easy understanding of complex intracranial lesions.7,11

In cavernoma surgery a 3D virtual reality model enables the surgeon to preoperatively visualize the cortical surface with its gyral and sulcal patterns including the cortical vessels. A very precise image of what the surgeon will see after the craniotomy is created by the additional display of the skull and the skin. A surgical corridor to reach the cavernoma can be defined after virtual reality visualization of the pathoanatomical situation. Finally, the optimally suited craniotomy can be defined and measured. The measured size and position of the craniotomy and distance to the cavernoma and images of the cortical surface can be easily transferred to the operating room either electronically or as printouts and serve as a “storyboard” for surgery.12

We see further potential for this technique in planning AVM surgery. The possibility of displaying the complex angioarchitecture of an AVM with its feeding vessels, nidus, and draining veins might be advantageous as compared with information provided by conventional angiography or MR imaging. With these traditional methods, the 3D aspect of an AVM can only be understood after a meticulous and time-consuming learning process. Using a 3D virtual reality planning system would offer the possibility of directly visualizing these complex vascular malformations and thus make the chore of planning a surgical intervention easier and more intuitive.

In the current series of STA-MCA bypass surgeries, operative complications like epidural or subdural hematoma, wound-healing disorders, CSF leakage, seizures, stroke, or wound infections were not observed. However, our experience is limited to 5 surgical cases so far. At this point no definite conclusions can be drawn. Nevertheless, some theoretical advantages and disadvantages of the technique should be addressed at this point in our surgical experience.

Particular advantages of the technique are as follows: First, no additional intraoperative neuronavigational guidance is required with the 3D virtual reality planning. Because the set up for neuronavigation requires additional time in the surgical theater, the periprocedural time with the virtual reality technique would be shortened given the absence of stereotactic guidance. Furthermore, since preoperative 3D virtual reality planning is accomplished the day before surgery, no intraoperative dysfunction of the technique can occur; that is, the success of the surgical procedure does not depend on the functioning of a neuronavigational system. Second, perioperative complications of the standard STA-MCA bypass procedure have been reported in the literature as 2.4–4.2% operative morbidity and 1–4.2% deaths.1,5,9,13,18 Amending the approach to a minicraniotomy of ~ 20 mm in diameter could further reduce the risk of periprocedural complications such as epidural and subdural hematomas. Additionally, the minimally invasive approach could significantly reduce arachnoidal scarring in the exposed area. Third, the exact preoperative selection of optimal donor and recipient vessels might lead to less extensive vessel preparation and thus result in optimal bypass function.

Disadvantages of the technique include the additional amount of time required for the 3D virtual reality planning and, more importantly, in the event of injury to either the STA or the MCA during the approach, the possibility of switching to another vessel as the donor or recipient is very limited.

In all, we consider 3D virtual reality planning a useful and supportive technique that allows STA-MCA bypass surgery via a minimally invasive approach. Further studies are required to gather more experience with this technique before definite conclusions can be drawn.

Conclusions

In this article, we described a minimally invasive STA-MCA bypass procedure. With the application of a 3D virtual reality planning system (Dextroscope), the extent of the skin incision and tissue trauma as well as the size of the bone flap was significantly reduced. The closest point of the appropriate donor branch of the STA and the most suitable recipient M3 or M4 segment could be figured out preoperatively with high accuracy, and the STA-MCA bypass could be safely and effectively performed through an optimally located minicraniotomy with a mean diameter of 22 mm without the necessity of stereotactic guidance.

Disclaimer

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

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