Intraoperative computed tomography angiography with computed tomography perfusion imaging in vascular neurosurgery: feasibility of a new concept

Clinical article

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**Object.** In vascular neurosurgery, there is a demand for intraoperative imaging of blood vessels as well as for rapid information about critical impairment of brain perfusion. This study was conducted to analyze the feasibility of intraoperative CT angiography and brain perfusion mapping using an up-to-date multislice CT scanner in a prospective pilot series.

**Methods.** Ten patients with unruptured aneurysms underwent intraoperative scanning with a 40-slice sliding-gantry CT scanner. Multimodal CT acquisition was obtained in 8 patients consisting of dynamic perfusion CT (PCT) scanning followed by intracranial CT angiography. Two of these patients underwent CT angiography and PCT 2 times in 1 session as a control after repositioning cerebral aneurysm clips. In another 2 patients, CT angiography was performed alone. The quality of all imaging obtained was assessed in a blinded consensus reading performed by an experienced neurosurgeon and an experienced neuroradiologist. A 6-point scoring system ranging from excellent to insufficient was used for quality evaluation of PCT and CT angiography.

**Results.** In 9 of 10 PCT data sets, the quality was rated excellent or good. In the remaining case, the quality was rated insufficient for diagnostic evaluation due to major streak artifacts induced by the titanium pins of the head clamp. In this particular case, the quality of the related CT angiography was rated good and sufficient for intraoperative decision making. The quality of all 12 CT angiography data sets was rated excellent or good. In 1 patient with an anterior communicating artery aneurysm, PCT scanning led to a repositioning of the clip because of an ischemic pattern of the perfusion parameter maps due to clip stenosis of an artery. The subsequent PCT scan obtained in this patient revealed an improved perfusion of the related vascular territory, and follow-up MR imaging showed only minor ischemia of the anterior cerebral artery territory.

**Conclusions.** Intraoperative CT angiography and PCT scanning were shown to be feasible with short acquisition time, little interference with the surgical workflow, and very good diagnostic imaging quality. Thus, these modalities might be very helpful in vascular neurosurgery. Having demonstrated their feasibility, the impact of these methods on patients’ outcomes has now to be analyzed prospectively in a larger series. (DOI: 10.3171/2009.9.JNS081255)

**Key Words** • intraoperative computed tomography • computed tomography angiography • perfusion computed tomography • vascular neurosurgery • aneurysm

**Abbreviations used in this paper:** ACoA = anterior communicating artery; CBF = cerebral blood flow; CBV = cerebral blood volume; DS = digital subtraction; MCA = middle cerebral artery; PCT = perfusion CT; ROI = region of interest; TTP = time to peak.

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This article contains some figures that are displayed in color online but in black and white in the print edition.
Intraoperative CT angiography and PCT imaging of the blood flow is very short. Hence, there is a need for an intraoperative diagnostic tool examining cerebral perfusion even in distant regions within a very short acquisition time.

In addition, intraoperative proof of complete occlusion of the aneurysm is needed especially in very complex malformations, which currently account for a higher percentage of surgical series since the introduction of endovascular occlusion techniques.

Because of its technical refinement, CT angiography has been shown to be a reliable method for assessing clipped aneurysms as well as the primary imaging modality for diagnostic imaging of cerebral aneurysms. In addition, in some institutions PCT has replaced DS angiography as the primary diagnostic tool for the detection of perfusion deficits caused by vascular stenosis or vasospasm.

This prospective pilot study was performed in a series of consecutive patients who presented with unruptured aneurysms. The primary goal was to evaluate the feasibility and imaging quality of intraoperative CT angiography and PCT using a new multislice intraoperative CT scanner. Additional aims of this study were the development of a standard setup for CT imaging during the operative procedure and the evaluation of workflow.

Methods

Patient Population

Between December 2007 and February 2008, 10 consecutive patients (2 men and 8 women, age range 42–61 years [mean 50 years]) with unruptured aneurysms underwent surgery performed by a single surgeon (C.S.) and comprise this study. There were 11 total aneurysms that were distributed as follows: MCA (in 8 patients), ACoA (in 2), and posterior inferior cerebellar artery (PICA) (in 1 patient). In 1 patient, aneurysms were located at the MCA and ACoA.

Informed consent was obtained from all patients according to the neurosurgical and radiological departments’ conditions. Data storage as well as monitoring of radiation exposure was performed according to the legal requirements of the state and the board of physicians.

Setup of Operating Room

In a preexisting operating room, a sliding-gantry 40-multislice CT scanner (SOMATOM Sensation Open Sliding Gantry, Siemens Medical Solutions) with an 82-cm bore diameter was installed on rails, which had been mounted into the floor of the operating room. The patient is positioned on a radiolucent adjustable, flexible operating table.

Workflow

After final positioning of the patient on the operating table and fixing the head in the radiolucent clamp, a safety check was done. Therefore, the gantry was moved over the patient without scanning to detect and avoid any collision of the gantry and table or patient during the operative procedure. After successful completion, the gantry position for scanning was saved. Thus later on, after having been tilted during the surgical procedure, the table could be moved back automatically to the saved scanning position at any time, allowing collision-free scanning.

Due to the extra large bore diameter of 82 cm, any positioning of the patient except the sitting one was possible. The arrangement of instrument tables, an operating microscope, and equipment for neuromonitoring and anesthesiology, as well as positioning of the surgeon, assistant, and scrub nurse were maintained as usual.

For intraoperative scanning, all brain retractors were removed from the headholder ring as well as all metal-containing instruments in the vicinity of the scanned area. The patient was then covered with an additional sterile drape after the table was repositioned to the saved scanning position as mentioned above. After scanning, the additional drape was removed, the table was tilted if necessary, and the surgical procedure was resumed. Image analysis with a special focus on residual aneurysm parts and impaired brain perfusion was performed by the...
neuroradiologist, and it was discussed with the neurosurgeons directly after the scan.

**Image Acquisition**

After the above-mentioned scanning preparations consisting of sterile drape placement, retractor removal, a test run of the gantry movement, and connecting the contrast injector tube to a central or peripheral venous catheter of an appropriate lumen (≥ 20 gauge), all personnel left the operating room. The scanner console and the console of the contrast injector were installed in a separate room next to the operating room with a direct view of the operating room through a lead-glass window and a monitor view of a video camera system mounted in the operating room showing the backside view of the gantry, which was not visible through the lead-glass window. A neuroradiologist, the neurosurgeons, and the anesthesia team observed the patient throughout the imaging process. First, a scout CT scan of the head and upper neck was obtained, and scan ranges for CT angiography (C-1 to vertex) and PCT scanning (1 cm superior to the aneurysm clip with a distance of at least 1 cm to the head clamps) were planned. To obtain the best results for CT angiography, that is, high-contrast attenuation values in the cerebral arteries and low overlay in the veins and sinuses, a bolus tracking technique was used for CT angiography, and PCT scanning was performed after CT angiography. For contrast agent bolus tracking, a CT slice, roughly at the level of the carotid bifurcations, was obtained every second with a start delay of 8 seconds after injection of contrast material had commenced to monitor the contrast agent arrival at the cervical arteries. The CT angiography was then started manually when significant contrast attenuation was recognized on the monitoring scans. Caudocranial CT angiography started at C-1 and moved to the vertex using a collimation of 40 × 0.6 mm at 120 kV, 120 mA, pitch 1.1, and rotation time of 1 second, resulting in a normalized effective dose of ~ 0.5 mSv. Automated contrast agent injection was done by using a dedicated weight-adapted protocol (contrast agent 1.35 ml/kg body weight [Imeron 300, Bracco-Altana-Pharma], iodine 0.4 g/kg body weight at an injection rate of 6.0 ml/second followed by 100 ml saline at 6.0 ml/second). For PCT scanning, a 28.8-mm-thick slice was acquired every second over a period of 40 seconds using 80 kV and 200 mA with a collimation of 24 × 1.2 mm, resulting in a normalized effective dose of ~ 3.2 mSv. Perfusion scanning started 5 seconds after injection of 50 ml contrast agent (Imeron 300) at 7 ml/second and a saline flush of 50 ml at 7 ml/second.

Reconstruction of the CT angiography raw data was then performed in a standardized fashion. Axial reformations with a slice thickness of 1.0 mm and an increment of 0.75 mm and maximum intensity projections (MIPs) in axial, coronal, and sagittal orientations with a slice thickness and increment of 2.5 mm. The thin axial slices were then loaded into a standard 3D workstation (syngo MultiModality Workplace [MMWP], Siemens Medical Solutions) installed next to the scanner console, allowing cross-sectional viewing of multiplanar reconstructions in sliding thin-slab technique as well as reconstructions using volume-rendering technique.

Perfusion analysis was performed using standard, vendor-provided PCT analysis software installed on the scanner and the workstation. Color-coded parameter maps of CBF, CBV, and TTP were calculated.

**Image Reading**

The quality of all images was assessed in a blinded consensus reading by an experienced neurosurgeon and an experienced neuroradiologist at the end of the study period. A 6-point scoring system ranging from excellent to insufficient was used for quality evaluation of PCT scanning (in 12 cases) and CT angiography (in 8).

**Results**

**Workflow**

After adaptation of the protocol for intracranial CT imaging, the following optimal workflow could be achieved. Removal of the brain retractors from the Budde-Halo ring (these are the only metal-containing components), draping the patients, and bringing the table to the saved scanning position (see above) took 3 minutes. Subsequently, CT imaging and automated contrast agent and saline injection were performed within 90–120 seconds, and 3D postprocessing of the CT angiography data set as well as the analysis of the dynamic perfusion data could be achieved in ~ 3 minutes. Meanwhile, the drape was removed from the patient, and surgery could be resumed. Thus, the entire procedure caused a discontinuation of the surgical procedure of ~ 8–9 minutes altogether. Initially, at the beginning of the learning curve concerning this part of the workflow, it took ~ 20 minutes. Intraoperative workflow and sterility of the operating field were not affected in any case due to unexpected collision of the table or patient and CT gantry. Application of the contrast medium, scanning, and workup of the data set generating CT angiography and PCT were performed by a neuroradiologist (D.M.).

**Computed Tomography Angiography**

Thirteen CT angiograms were obtained in both ACoA and MCA aneurysms and in 2 PICA aneurysms. All CT angiograms were obtained after aneurysm clipping (all patients underwent preoperative DS angiography). In 2 patients, 2 CT angiograms were obtained because repositioning of the clip was necessary. The quality of all 8 CT angiography data sets were rated excellent or good; thus, all CT angiography investigations were found to be of a sufficient quality for an unrestricted evaluation (Fig. 2).

In another patient, CT angiography revealed a remnant of the aneurysm sac opposite to the surgeon’s viewing direction (data not shown). This partial occlusion was successfully corrected thereafter by clip repositioning. Even in a case in which 5 clips had to be placed for total occlusion of 2 aneurysms, imaging quality was not affected (Fig. 3).

**Perfusion CT Scanning**

The image quality of 10 of 11 PCT parameter maps
Intraoperative CT angiography and PCT imaging

was rated as good or excellent. In 1 data set, massive streak artifacts induced by a pin that was accidentally included into the scanning range made reliable perfusion analysis impossible.

In a case of an aneurysm in the ACA territory, CT angiography displayed an insufficient perfusion of both A2 segments (due to hypoplasia of the contralateral A1, both A2 segments were perfused by the ipsilateral A1). Perfusion CT with subsequent generation and analysis of the colored perfusion parameter maps of CBV, CBF, and TTP revealed an ischemic perfusion deficit (Fig. 4b). In this patient, a pathological delayed TTP (47.6%) was shown at the territory of the contralateral ACA. An ROI was manually drawn around this territory including gray and white matter of the left frontal lobe. The ROI analysis in which the ischemic ROI was mirrored over the midline of brain to the corresponding area in the nonischemic hemisphere revealed a combination of a reduced CBF (−31.9%) and a reduced CBV (−2.2%) representing a classic pattern of an ischemic, but not yet infarcted, brain territory. On this occasion, a partial clip stenosis that had not been detected before (even using micro-Doppler ultrasonography) could be corrected. In a second PCT scan obtained directly after repositioning of the clip, the ischemic values had become nonischemic, only slightly delayed, and well-compensated perfusion values. Three days after surgery the patient showed no clinical deficit.

Clinical Outcome

No temporary or permanent morbidity or mortality was observed in this series. There were no minor or major adverse events related to the administration of the iodine contrast agent (for example, allergic or anaphylactic reac-

tions, extravasation, interference with anesthesia, or impairment of renal function) observed by serum creatinine sampling and clinical observation in a time period of 7 days after surgery.

Discussion

In neurovascular surgery, the risk of creating iatrogenic brain ischemia because of unintentional occlusion of a vessel or partial stenosis by a clip is a relevant risk. Moreover, in complex aneurysms, incomplete occlusion of the sac with remnants that are difficult for the surgeon to notice can occur. Thus, intraoperative immediate information about the perfusion status of the normal vessels and the related neural tissue as well as the malformation itself is warranted to react timely to prevent permanent ischemic deficits or reoperations due to insufficient clipping. Numerous efforts have been made to solve this problem.

Intraoperative catheter angiography, whether conventional or DS angiography, requires a high technical and logistic method, and an adequate system within the operating room is expensive. In addition, the method is time-consuming and inherits a considerable risk even in experienced hands. As a consequence, this technique should be restricted to very complex cases such as those involving certain giant aneurysms. Even in highly specialized centers, the technique has not been widely used. On the other hand, quantitative and time-resolved assessment of perfusion in defined brain areas is more precisely done by PCT scanning.

Micro-Doppler ultrasonography was introduced into the operating room after the acceptance of transcranial Doppler ultrasonography as a noninvasive method to ob-
Fig. 4. a: Normal PCT after clipping of a right-sided MCA aneurysm. b: A PCT obtained in a patient with an ACoA aneurysm. Analysis of CBV, CBF, and TTP revealed an ischemic perfusion deficit due to unexpected stenosis after clipping. After repositioning of the clip, subsequent PCT showed improved parameters. MIP = maximum intensity projection; MTT = mean transit time.
Intraoperative CT angiography and PCT imaging
tain indirect information about the brain’s circulation in cases of suspected or proven vasospasm. However, although being a low-cost method that is rather easy to handle, it has some inherent limitations. First, it only measures blood flow velocity, which does not necessarily correlate with perfusion or regional blood volume. Therefore, only the patency of vessels can be estimated to a certain extent. Second, although it is user-friendly, the probe has to be put on the vessel at specific angles, which allows little variation, thus limiting in its use especially in cases of very tortuous vessels or rather narrow surgical fields.

Some centers use electrophysiological monitoring during cerebral aneurysm surgery. However, this method allows only indirect identification of already significant cerebral ischemia with conceptual limitations concerning the modalities used (for example, somatosensory evoked potential, motor evoked potential, phase reversal, and so on) and does not provide information about stenosis of adjacent vessels, critical perfusion limits of tissue at risk, or the completeness of aneurysm occlusion. Furthermore, the results show a wide variability and might be affected by anesthesia. Moreover, especially during surgery for posterior fossa aneurysms, electrophysiological monitoring may show false-negative results in regard to the monitoring of regional ischemia.

A new, elegant intraoperative imaging method is provided by intraoperative fluorescence angiography using indocyanine green as an intravascular dye that reflects fluorescent light detected by a specially designed filter system incorporated in the operating microscope. It has the potential to be a true “online” method, being replicable and delineating even very small vessels and persistent low-flow circulation in aneurysms. However, since this concept is based on the reflection of light, only vessels or parts of vascular lesions exposed to the emitted light can fluoresce, whereas hidden vessels or those covered by brain tissue cannot. Moreover, as all the other methods mentioned so far, no data can be provided about regional perfusion, especially whether a critical threshold toward “tissue at risk” might be reached.

Intraoperative MR imaging, which has elicited a lot of interest as a sophisticated intraoperative imaging technology, could provide perfusion as well as diffusion mapping. Despite the use of titanium clips, however, clip artifacts omit any information in the vicinity of the clip. This excludes MR imaging from being an ideal technology for intraoperative neurovascular imaging and is why MR imaging has not gained widespread acceptance as a noninvasive imaging modality for postinterventional control in neurovascular diseases as compared with, for example, CT angiography.

Computed tomography angiography performed with modern multislice scanners is able to depict vascular structures with a submillimeter spatial resolution even in a 3D mode. Very short imaging acquisition times, rather low radiation exposure, and limited amounts of contrast medium needed are further reasons why CT angiography is increasingly accepted as a diagnostic modality for aneurysms as well as for treatment planning and postinterventional controls. Hence, this technology could be very beneficial for neurovascular surgery once brought into the operating room, even more so since most recent software packages allow quantification of cerebral perfusion, and CBV is displayed in a color-coded mode.

The aim of this pilot series was to investigate whether intraoperative CT could meet these demands. Our focus was on the issues of practicability and gaining of useful information in due time within an intraoperative surrounding. We chose to clip unruptured aneurysms because we wanted to explore this technology under optimal surgical conditions, first to stepwise go through a learning curve without any additional risk for patients. Potential influence of subarachnoid hemorrhage–related clinical factors such as brain edema, vasospasm, or subarachnoid blood layers on imaging quality should be evaluated in additional prospective studies.

Intraoperative CT angiography and PCT were not only shown to be feasible even in a complex operating room surrounding with a rather short and quick learning curve, but also (although not being the primary goal of this study) both modalities proved to be very efficient in short-term decision making about the necessity of clip replacement in due time to prevent iatrogenic ischemia as well as incomplete aneurysm occlusion. The benefits of this modality over DS angiography, which carries an estimated risk of 0.5–2% of iatrogenic complications (such as dissections of the vessel wall or emboli), include minimal interference with the regular surgical workflow, minimal interruption of the surgical procedure, and no radiation exposure to the personnel. Moreover, there is no need for additional catheter angiography. The mean effective dose of the CT angiography was 0.47 mSv, and the mean effective dose of PCT scanning was 3.22 mSv. Overall, the mean effective dose of intraoperative CT angiography plus PCT was 3.69 mSv, which is comparable to values of a typical 4-vessel angiogram given in the literature of 3.6 mSv. Thus, in addition to other indications in which intraoperative CT scanning could be of value (for example, neurosurgery of the skull base and the spine), CT angiography and PCT scanning should now be evaluated prospectively further on in terms of efficacy to lower the incidence of surgical morbidity in neurovascular diseases.

Conclusions

In this prospective pilot study, in a series of consecutive patients presenting with unruptured aneurysms, intraoperative CT angiography and PCT scanning were shown to be feasible with a short acquisition time, little interference with the surgical workflow, and very good diagnostic imaging quality. Thus, intraoperative multislice CT scanning may be very helpful in vascular neurosurgery. Having demonstrated their feasibility, the impact of intraoperative CT angiography and PCT scanning on patients’ outcomes has to now be analyzed prospectively in a larger series of different neurovascular procedures.

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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