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Computed tomography perfusion evaluation after extracranial–intracranial bypass surgery

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ABSTRACT

Objective: Perfusion imaging is increasingly used for postoperative evaluation of extracranial to intracranial (EC–IC) bypass surgery. Altered hemodynamics and delayed arrival of the contrast agent in the area fed by the bypass can influence perfusion measurement. We compared perfusion asymmetry obtained with different algorithms in EC–IC bypass surgery patients.
Methods: We retrospectively identified all patients evaluated with computed tomography perfusion (CTP) between May 2007 and May 2011 after EC–IC bypass surgery at our institution. CTP images were analyzed with three perfusion algorithms that differ among their ability to anticipate for delayed arrival time of contrast material: the delay-sensitive first-moment mean transit time (fMTT), the semi-delay-sensitive standard singular value decomposition (sSVD) and the delay-insensitive block-circulant SVD (bSVD). The interhemispheric difference in bolus arrival time (ΔBAT) was determined to confirm altered hemodynamics. Interhemispheric asymmetry in perfusion values (mean transit time (MTT) difference, cerebral blood flow (CBF) ratio and cerebral blood volume (CBV) ratio) was compared between the three algorithms. Presence of a new infarct in the treated hemisphere was evaluated on follow-up imaging and perfusion asymmetry was compared between patients with and without infarction.
Results: Twenty-two patients were included. The median interhemispheric difference in ΔBAT was 0.98 s. The median MTT difference was significantly smaller when calculated with the delay-insensitive algorithm than with the other algorithms (0.44 s versus 0.90 s and 0.93 s, $p < 0.01$). The CBF ratio was similar for all algorithms (111.98 versus 112.59 and 112.60). The CBV ratio was similar for all algorithms (113.20 versus 111.95 and 113.97). There was a significant difference in MTT asymmetry between patients with and without infarction with the delay-insensitive algorithm only (1.57 s versus 0.38 s, $p = 0.04$).
Conclusion: In patients with EC–IC bypass surgery, delay-sensitive algorithms showed larger MTT asymmetry than delay-insensitive algorithms. Furthermore, only the delay-insensitive method seems to differentiate between patients with and without infarction on follow-up.

1. Introduction

Extracranial to intracranial (EC–IC) bypass surgery is a procedure to help divert, augment or restore cerebral blood flow in patients with Moyamoya disease, internal carotid artery occlusion or otherwise untreatable intracranial aneurysms [1]. In this procedure a branch of the external carotid artery (usually the superficial temporal artery) is connected to an intracranial branch of the internal carotid artery (usually the middle cerebral artery), either directly or via a venous graft. A possible complication of the procedure is hypoperfusion, due to bypass occlusion or stenosis [2,3], which may result in infarction in the treated hemisphere. Computed tomography (CT) angiography (CTA) is frequently performed to evaluate postoperative bypass patency. However, lack of information regarding the direction of flow in the vascular structures [4,5], small lumen sizes and artifacts from surgical clips make the evaluation challenging. In addition to CTA, CT perfusion (CTP) imaging can be used to assess bypass functionality with cerebral perfusion measurements in the hemisphere supplied by the EC–IC bypass. In this way bypass functionality can be evaluated directly

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after surgery and new ischemic events may thereby be detected at an early stage.

With CTP imaging, cerebral blood volume (CBV), mean transit time (MTT) and cerebral blood flow (CBF) are typically assessed. These hemodynamic parameters are estimated using perfusion algorithms that are 'delay-insensitive' or 'delay-sensitive' depending on the vendor or software package used. The perfusion algorithms that are commonly used are based on the direct assessment of kinetic parameters or are based on singular-value decomposition (SVD). SVD based algorithms estimate CBF, CBV and MTT by deconvolving the change in concentration with an arterial input function (AIF). The standard SVD (sSVD) is a semi- or one-way 'delay-sensitive' method because the calculation will fail if the contrast bolus to the tissue arrives before the contrast bolus has arrived to the vessel where the arterial input function was selected, whereas the block-circulant SVD (bSVD) is insensitive to delayed arrival of contrast agent by using circular deconvolution instead of linear deconvolution [6]. Direct assessment of kinetic parameters and sSVD based algorithms are favorable among vendors because it requires less computations time than bSVD based algorithms. However, bSVD algorithms are favorable when there is a possibility of delayed arrival of the contrast agent.

An important implication of EC–IC bypass surgery is that arrival of the contrast agent to the treated hemisphere is altered (i.e. delayed) compared to the untreated hemisphere due to a longer path length. As a result, delay-sensitive algorithms may under- or overestimate perfusion parameters in the treated hemisphere. This may cause unnecessary concern regarding the functionality of the bypass. To the best of our knowledge, the difference in effects of bypass surgery on delay-sensitive and delay-insensitive algorithms for CTP has not previously been studied.

In this study, we hypothesized that in patients with an EC–IC bypass cerebral perfusion values are under- or overestimated in the treated hemisphere when using delay-sensitive perfusion algorithms compared to delay-insensitive algorithms. Additionally, we hypothesize that EC–IC patients that later develop an infarct in the treated hemisphere can be distinguished early from patients that do not develop an infarct using postoperative CTP evaluation.

2. Materials and methods

2.1. Subjects

The local institutional ethics review board approved the retrospective study and waived the requirement for informed consent. We retrospectively identified all patients older than 18 years of age that were treated between May 2007 and May 2011 at our institution with EC–IC bypass surgery for Moyamoya disease, internal carotid artery disease or otherwise untreatable intracranial aneurysms, and post-surgical CTP and CTA imaging (group 1). From this group we identified a subgroup of patients (group 2) with post-surgical CTP and CTA imaging within 6 days, and additional follow-up with non-contrast enhanced CT imaging >3 days after post-surgical imaging. Patient gender, age, surgery indication, and previous history of cerebral infarction or hemorrhage were collected for all subjects.

2.2. Imaging protocol

CTP studies were obtained using a Philips Brilliance 16-slice (2 patients), a Philips Brilliance 64-slice (14 patients), or a Philips iCT 128-slice (6 patients) CT scanner (Philips Healthcare, Best, Netherlands). For the CTP, 40 ml of non-ionic contrast agent (Iopromide, Ultravist, 300 mg iodine/ml, Schering, Berlin, Germany) followed by 30–40 ml saline was injected intravenously at a rate of 5 ml/s using a Stellant Dual CT injector (Medrad Europe BV, Beek, the Netherlands). One image was acquired every 2 s during 60 s. Scan parameters were: 16 mm × 0.75/64 mm × 0.625/128 mm × 0.625 mm collimation, 80 kVp, 150 mAs, 512 × 512 matrix, 200 mm field-of-view. The CTP scan covered a 2.4 cm (16 slice), 4 cm (64 slice) or 6.7 cm (128 slice) slab selected at the level of the basal ganglia.

For the CTA scan 70 ml of non-ionic contrast agent was injected into the cubital vein; 50 ml at a rate of 5 ml/s, followed by a 40 ml saline flush at a rate of 4 ml/s. Scanning was performed with: 80/120 kVp, 300/100 mAs (depending on the presence of neurosurgical clips or coils), 16 mm × 0.75/64 mm × 0.625/128 mm × 0.625 mm collimation, 512 × 512 matrix, 200 field of view, slice thickness 0.67 mm, reconstruction increment 0.33 mm. The CTA was planned from the level of C2 to the vertex.

Additional follow-up imaging was done with non-contrast CT (NCT) with the following imaging parameters: 120 kVp, 250 mAs, collimation 16 mm × 0.75/64 mm × 0.625/128 mm × 0.625 mm collimation, 512 × 512 matrix and 220 mm field of view.

The total radiation dose of an imaging protocol in our institution comprising NCT, CTP and CTA is less than 7 mSv.

2.3. Image processing

CTP data were transferred to an image processing workstation, to process the CTP data into descriptive maps using a free available software package developed by the Acute Stroke Imaging Standardization (ASIST) workgroup (perfusion mismatch analyzer, PMA version 3.3) [7]. Three types of perfusion algorithms were compared that differ in their sensitivity to delayed arrival of the contrast agent: the bSVD, which is described as a contrast delay-insensitive algorithm [8]; the sSVD, which is theoretically semi- or one-way delay-sensitive (the calculation will fail if the contrast bolus to the tissue arrives before the contrast bolus has arrived to the vessel where the arterial input function was selected); and the first moment MTT (fMTT) algorithm, which determines the MTT by the difference in first moment (equivalent to the center of gravity) of the tissue concentration curves and arterial time attenuation curves [9,10]. The latter in particular does not take possible delays into account and is used in several commercially available software packages. With the fMTT method, CBV was calculated as the area under the gamma variate fitted time concentration curve (AUC), MTT was calculated as the time when half the signal change has been observed (mean) as measured by the fitted gamma function, the relative time-to-peak $T_{\max}$ was calculated as the difference between the physiological parameters time to peak (TTP) and bolus arrival time (BAT), and cerebral blood flow (CBF) was calculated as the ratio of CBV to MTT for each pixel according to the central volume principle. For the convolution algorithms bSVD and sSVD, the MTT was defined as the first moment of bolus arrival and the CBF is determined from the maximum value of the residue function ($R(t)$) and the corresponding time-to-peak of impulse response function and $R(t)$ as $T_{\max}$ [11]. The MTT for the sSVD is defined as the first moment of $R(t)$, whereas the MTT for the bSVD was defined as the highest peak of $R(t)$ [12]. Vascular pixels were defined as those with CBV values larger than 5 ml/100 g and were automatically eliminated from the perfusion maps (default in the ASIST software). Voxels containing bone or cerebrospinal fluid were excluded based on their CT number. Patient movements were corrected using the rigid registration method available in the software package. The software automatically determines the AIF by first identifying multiple (10) AIF locations based on histogram analysis on the following kinetic parameters: maximum contrast enhancement value ($C_{\max}$); TTP; and MTT. After determination of a fixed number of AIF pixels by varying thresholds on the three kinetic parameters, all