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Assessing surgical treatment outcome following superficial temporal artery to middle cerebral artery bypass based on computational haemodynamic analysis

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ABSTRACT

To estimate haemodynamic modification of Internal Carotid Artery (ICA) after bypass surgery using computational fluid dynamic (CFD) technology and thereby aid in our understanding of the influence of hemodynamic parameters on the outcomes of bypass operations. 18 patients who underwent superficial temporal artery to middle cerebral artery bypass and encephaloduromyosynangiosis (EDMS) surgery were included. Reconstructed three-dimensional vessel geometries from MRA were segmented to create computational domains for CFD simulations. All cases were classified as three groups according to the proportion of the MCA area of distribution supplied by revascularization: A, more than two thirds; B, between two-thirds and one-third; and C, less than one-third of the MCA distribution. Pre-operative and follow-up haemodynamic parameters, especially volume flow rate and pressure drop index (PDI) in ICA were compared. For all cases, PDI and volume flow rate in the surgical-side ICA decreased significantly at follow-up ($P < 0.05$). For the cases of group A, volume flow rate in surgical-side ICA decreased by average 24.2%, whilst for the cases of group B and C, flow rate reduced by 10.5% and 3.7%, respectively. An average PDI for cases in group A was −1.67 mmHg, conversely average PDI values of group B and C were −0.53 and 0.82 mmHg, respectively. The remodelling of ICA after bypass was associated with reduction in the volume flow rate and pressure drop. Good correlation with angiographic grading suggested that CFD might play a critical role as a quantitative haemodynamic technique for predicting treatment outcome during the follow-up of MMD patients.

1. Introduction

Moyamoya disease (MMD) is characterized by stenosis or occlusion at the terminal internal carotid artery (ICA) or proximal portions of anterior cerebral arteries (ACA) and middle cerebral arteries (MCA). It leads to formation of a fine vascular network at the base of brain which looks like “puff of smoke” in angiogram, which is why it is named moyamoya (puff of smoke in Japanese) disease (Kuroda and Houkin, 2008). Arterial stenosis around the circle of Willis induces blood flow reduction in the brain and formation of fragile moyamoya vessels (Iwama et al., 1997). There exist two peaks of distribution of age at onset and the clinical features differ substantially between children and adults. Generally, adult patients with MMD usually present with intracranial hemorrhage, whereas most pediatric cases have cerebral ischemia.

Surgical revascularization, including direct methods, e.g. superficial temporal artery – middle cerebral artery (STA-MCA) bypass, and indirect methods, e.g. encephaloduroarteriosynangiosis (EDAS), encephalomyosynangiosis (EMS), encephaloduromyosynangiosis (EDMS) and multiple burr holes surgery are common treatments for reconstructing cerebral blood flow of MMD patients. Many observational studies indicated that direct and/or indirect bypass could reduce the risk of cerebral ischemic stroke by flow augmentation for patients with MMD (Hoshino et al., 2006; Sasoh et al., 2003; Takagi et al., 1997). One randomized control trial (RCT) study was also reported to confirm that extracranial to intracranial (EC-IC) bypass surgery can help decrease the rate of recurrent bleeding (Miyamoto et al., 2014). Angiographic diminishment of moyamoya vessels was observed after EC-IC bypass surgery, which was regarded to result in decreased haemodynamic stress to pathological

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moyamoya vessels (Houkin et al., 2004; Jiang et al., 2014; Miyamoto et al., 2014).

Computational fluid dynamics (CFD) technology has been applied widely in many cerebrovascular diseases for quantitative haemodynamic analysis, especially for aneurysms and intracranial artery stenosis (Lee et al., 2013; Wong and Poon, 2011; Zhang et al., 2012). In the past, CFD techniques have been employed to look into maintaining the patency of high flow bypass (Sia et al., 2012). Our previous study revealed STA-MCA bypass has a characteristic auto-remodelling after surgery using CFD (Zhu et al., 2014). The decrease of ICA pressure drop index (PDI) was also observed at follow-up after indirect bypass surgery (Karunanithi et al., 2014). In this study, we are trying to estimate the haemodynamic modification of ICA after combined STA-MCA bypass and EDMS surgery by using CFD technology and to verify whether haemodynamic parameters correlate with treatment outcome.

2. Materials and methods

2.1. Subjects

18 patients were diagnosed with MMD and treated with combined STA-MCA bypass and EDMS in Huashan Hospital from 2010 to 2013. MMD was diagnosed according to the criteria of the Research Committee on Spontaneous Occlusion of the Circle of Willis (Moyamoya Disease) of the Ministry of Health and Welfare, Japan (Fukui, 1997). The circle of Willis was incomplete and bypass surgery was performed on one hemisphere for each patient. All patients were routinely examined by Magnetic Resonance Angiography (MRA) and duplex ultrasonography preoperatively and at follow-up. The study was approved by ethical committees of Huashan Hospital, Fudan University and Macquarie University. Written informed consent was obtained from each patient.

2.2. Surgical procedures

Surgical intervention for MMD was indicated after comprehensively evaluating the digital subtraction angiography (DSA), clinical manifestations and brain perfusion or metabolic findings in our department, detailed surgical indications were described before (Jiang et al., 2014; Xu et al., 2012). Anterior and/or posterior branch of STA were anastomosed to the cortical branch of MCA in end-to-side fashion using a single 10-0 nylon suture. EDMS, the indirect bypass procedure has been described in our previous study (Xu et al., 2012). Fifteen cases were operated by Professor B Xu, and three cases were operated by Professor Y.X Gu.

2.3. MRI scanning and ultrasonography

MRA scans (4 slabs , 40 slices per slab; TR, 22 ms; TE, 4.2 ms; flip angle, 18; matrix size, 365 × 384; slice thickness 0.5 mm; field of view 181 × 200 mm^2) were obtained with 3.0 T MR Systems console (Verio, Siemens Medical Systems, Erlangen, Germany).

Duplex ultrasonography was performed to measure the blood flow of ICA using an L9-3 linear probe (bandwidth, 3–9 MHz) (bandwidth, 1–5 MHz) on a high-end ultrasound device (Philips Healthcare, Andover, MA) (Wang et al., 2014).

2.4. CFD modelling

Three-dimensional (3D) geometries of ICA were reconstructed and segmented by using a commercial software package - MIMICS (Materialise' Interactive Medical Image Control System, Belgium) to create domains for CFD computation. Instead of using "global smoothing", we used manual "local smoothing" to keep the 3-D geometry as realistic as possible. Mesh generation yielded elements ranging from 0.8 to 1.4 million. The conservation equations for 3D steady flow with rigid walls were solved by using the ANSYS CFX 15.0, a finite-volume-based CFD solver (ANSYS Inc., Canonsburg, PA, USA). Patient specific inflow boundary conditions of blood flow were measured by duplex ultrasonography. A zero static pressure was specified as outlet boundary condition. Blood flow was modelled as a laminar Newtonian fluid with a density and dynamic viscosity of 1050 kg m^{-3} and 0.0032 Pa s, respectively.

2.5. Pressure drop index (PDI)

PDI was calculated as the difference in pressure reduction along the ICA at pre-operation and follow-up. PDI can be calculated using the formula

$$PDI = \Delta P_f - \Delta P_p = [(P_{if} - P_{of}) - (P_{ip} - P_{op})] \quad (1)$$

where ΔP_f and ΔP_p are the calculated pressure reduction at follow-up and pre-operation respectively.

P_{if} and P_{of} are the follow-up pressure values calculated at the inlet and outlet sections, respectively, and P_{ip} and P_{op} are the pre-operative pressure values calculated at the ICA inlet and outlet, respectively as shown in Fig. 1. The positions of proximal (inlet) and distal (outlet) planes where we measured the pressure values are the same between pre-operative and follow-up models. All units are in mmHg.

2.6. Inflow conditions and volume flow rate change

Velocities were measured at the proximal end of ICA by ultrasonography and were used as inflow conditions in CFD simulation. The volume flow rate of ICA was measured by utilising the mass flow from CFD. The percentage of volume flow rate change was calculated by using the formula

$$\text{Percentage of volume flow change} = (F_f - F_p)/F_P * 100\% \quad (2)$$

where F_p and F_f are the measured mass flow of ICA at pre-operation and follow-up respectively.

2.7. Angiographic treatment outcome

All cases are classified as three groups according to angiographic outcomes from surgery by the criteria proposed by Matsushima (Matsushima and Inaba, 1984). This grading was the proportion of the MCA area of distribution supplied by the surgical revascularization: A, more than two thirds of the MCA distribution; B, between two thirds and one third of the MCA distribution; and C, less than one third of the MCA distribution. The angiographic treatment outcome was evaluated by 2 independent neurosurgeons that were blinded to this study.

2.8. Statistical analysis

The normality of haemodynamic parameter distributions was checked. Mean and standard deviation were calculated to represent the normal variable, and non-normal distribution variables were represented as median and quartile. Two-tailed paired Student's t-test was applied to compare the results of pre-operative and follow-up parameters both in the surgical side and non-surgical (contralateral) side of ICA. Nonparametric analysis was used among non-normal variables. A significance

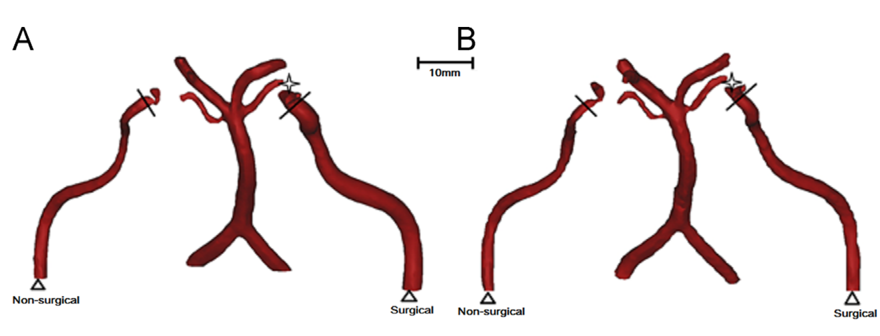

Fig. 1. Illustration of planes for pressure measurement in the pre-operative and follow-up CFD models. Inlet measurement plane is marked with triangle, outlet measurement plane is labelled using black line. The asterisks indicated the location of bifurcation.