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Clinical Study

Quantitative assessment of hemodynamic changes during spinal dural arteriovenous fistula surgery

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ABSTRACT

We aimed to evaluate the efficacy of FLOW 800 (Carl Zeiss Meditec, Jena, Thuringia, Germany) with indocyanine green (ICG) videoangiography for the quantitative assessment of flow dynamics in spinal dural arteriovenous fistula (dAVF) surgeries. We prospectively enrolled nine patients with spinal dAVF diagnosed within the past year and performed FLOW 800 analyses using ICG videoangiography before and after surgical obliteration of the fistula. A color-coded map was semi-automatically generated by FLOW 800 and used for high-resolution visualization of the vasculature and instant interpretation of the dynamic flow changes. The FLOW 800-specific hemodynamic parameters were employed for real-time measurements of parenchymal perfusion alterations. Overall, 18 intraoperative FLOW 800 analyses using ICG videoangiography were performed in nine patients. The color-coded map aided the detection and complete obliteration of the fistulas in all patients and the results were verified by postoperative spinal digital subtraction angiography. The transit time parameter was significantly shorter in the preobliteration phase than in the postobliteration phase ($p < 0.01$), the rise time parameter exhibited the same pattern ($p = 0.08$) and maximum intensity and blood flow index were not significantly different between these phases. FLOW 800 with ICG videoangiography provided an intuitive and objective understanding of blood flow dynamics intraoperatively and enabled easy and confident identification and treatment of this pathology. The FLOW 800-specific hemodynamic analyses provided additional perfusion information that enabled real-time measurements of parenchymal perfusion alterations. FLOW 800 with ICG videoangiography is useful for intraoperative quantitative assessment of flow dynamics, facilitating safety and confidence in the treatment of spinal dAVF.

1. Introduction

Spinal dural arteriovenous fistulas (dAVF) are the most common spinal vascular malformations and the principle behind the surgical treatment of this specialized pathology lies in the accurate identification and disconnection of the fistulous site without compromising normal blood flow [1–4]. However, surgery for the abnormal, tortuous and dilated conglomerate of vessels poses a challenge. Indocyanine green (ICG) videoangiography was first described by Raabe et al. in 2003 and is now well established as a useful adjunct in vascular neurosurgery [4–13]. However, ICG cannot provide quantitative information about blood flow dynamics and the interpretation of the results depends only upon the rate of vessel filling and shades of grey that are directly inspected. Recently, a further extension of this technique termed FLOW 800 (Carl Zeiss Meditec, Jena, Thuringia, Germany) was introduced and this extended technique has been used for analytical color visualization and objective evaluation of fluorescence video obtained from microscope-integrated intraoperative ICG angiography [14]. Previous studies have reported the initial use of this technique primarily with cerebral arteriovenous malformations (AVM), extracranial-intracranial bypasses and vein sacrifice surgeries and the results have been promising [8,15–22]. However, the value of FLOW 800 for the determination of perfusion and flow changes during spinal dAVF surgery remain unclear. In the present study, we present our experience of a nine patient series in which we used FLOW 800 analysis with ICG videoangiography to evaluate the applicability of this new technique for the quantitative assessment of flow dynamics and objective measurement of parenchymal perfusion during spinal dAVF surgery.

2. Materials and methods

2.1. Patient population

Between June 2013 and February 2014, nine consecutive patients with spinal dAVF were treated by surgical obliteration in

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our department. Details of the patient demographics, presenting symptoms and neuroimaging findings are listed in Table 1. Preoperative MRI and spinal digital subtraction angiography (DSA) were routinely performed in all nine patients to confirm the diagnoses. None of the patients underwent preoperative embolization. All patients received postoperative DSA to verify the intraoperative findings based on FLOW 800 with ICG videoangiography.

2.2. ICG videoangiography and FLOW 800

ICG videoangiography was performed using a commercially available operating microscope (Zeiss OPMI Pentero; Carl Zeiss Meditec) equipped with the INFRARED 800 infrared fluorescence detection hardware and the FLOW 800 software. At the time of angiography, a standard dose of ICG dye (0.1 mg/kg body weight, 25 mg dissolved in 5 ml of saline) was administered intravenously through a central line. Fluorescence intensities were detected by the camera and measured in arbitrary intensity units [AI]. The FLOW 800 analysis tool was used to calculate the fluorescence intensities and delay times and subsequently display them in two respective 2D tissue maps. Color-coded maps provided an overview of the flow dynamics using different colors for differentiation and an intuitive color scale that marked early fluorescence (starts in red and late starts in blue) and maximum intensity maps provided a summary overview (irrespective of the moment in time) of the maximum fluorescence level achieved during the observation period.

2.3. Quantitative analysis of the FLOW 800-specific hemodynamic parameters

The ICG time intensity curves were measured in freely definable regions of interest (ROI) and analyzed using the FLOW 800 microscope-integrated software. The following FLOW 800-specific hemodynamic parameters were selected for this study: maximum fluorescence intensity (peak fluorescence value of the time intensity curve); rise time (time interval between the point at which 10 and 90% of the maximum fluorescence intensity were reached); transit time (time difference between the maximum fluorescence in an artery and the spinal cord parenchyma); blood flow index (BFI; ratio of the maximum fluorescence intensity to the rise time). All of these parameters were measured before and after surgical obliteration of the fistula and a subset of the values were semi-automatically generated by the FLOW 800 software.

2.4. Statistics

All values are given as the mean ± the standard deviation. The FLOW 800-specific parameters were compared with paired t tests. The statistical analyses were performed using SPSS statistical software (version 16.0; IBM Corporation, Armonk, NY, USA). Statistical significance was defined as $p < 0.05$.

3. Results

A total of nine patients were prospectively enrolled in this study (six men, three women) with a median age of 48 years (range: 39–61). Detailed patient data are listed in Table 1. Overall, 18 intraoperative FLOW 800 analyses using ICG videoangiography were performed in the nine patients. Each procedure added an additional 6.2 ± 1.1 min of surgical time. FLOW 800 with ICG videoangiography helped to successfully identify the fistulous site and verify its obliteration in all patients and the results were confirmed by postoperative DSA. The neurological outcomes observed in this study are consistent with those of our previous experiences. Seven patients exhibited improvements in function and two patients remained stable. The mean follow-up was 8.9 ± 3.0 months.

FLOW 800-specific hemodynamic analyses were achieved in all patients. The calculated hemodynamic parameters are summarized in Table 2. The maximum intensity of the draining vein significantly decreased from 387.43 ± 146.92 to 95.35 ± 23.65 AI during the post-occlusion phase ($p < 0.01$) while the maximum intensity of the proximal spinal cord tissues increased from 263.53 ± 105.63 to 321.72 ± 119.48 AI ($p = 0.29$). The transit time from the reference artery to the proximal spinal cord tissues significantly decreased from 1.86 ± 0.67 to 0.72 ± 0.27 s ($p < 0.01$) and the rise time of the proximal spinal cord tissues decreased from 7.41 ± 1.72 to 6.04 ± 1.43 s ($p = 0.08$).

3.1. Patient 1

A 45-year-old man presented with a 1 year history of progressive paresthesia in the lower extremities and acute urinary incontinence. T2-weighted MRI revealed signal changes with serpiginous flow voids in the spinal canal that were suggestive of a spinal dAVF (Fig. 1A). Conventional spinal angiography confirmed this diagnosis and revealed a fistula being fed by the left T5 artery (Fig. 1B). Intraoperatively, after the opening of the dural mater, an initial ICG videoangiography with subsequent FLOW 800 analysis was performed (Fig. 1C, D). Using the color-coded map, the fistulous site was easily identified in red and the draining vein was visualized in an orange-to-green gradient (Fig. 1E). The surgical procedure was uneventful. Bipolar cauterization was performed to occlude and disconnect the fistulous site. Afterward, a second FLOW 800 analysis with ICG videoangiography suggested the complete obliteration of the fistula. In the FLOW 800-specific hemodynamic analysis, five ROI (one fistulous point, one draining vein, one spinal cord artery defined as the reference artery and two spinal cord tissues [one proximal and one distal]) were manually selected and used to construct time intensity curves before and after the surgical obliteration of the fistula (Fig. 1F, G). The maximum

Table 1
Characteristics of the spinal dural arteriovenous fistula surgery patient population

Patient	Age, years/sex	Spinal location	Presentation	Postoperative DSA	Follow-up, months	Improvement
1[a]	45/M	T5	Progressive myeloradiculopathy, urinary incontinence	Complete occlusion	13	Yes
2	57/M	T6	Progressive myeloradiculopathy	Complete occlusion	12	No
3	54/F	T12	Progressive myeloradiculopathy, urinary incontinence	Complete occlusion	11	Yes
4	61/M	L1	Back pain, urinary incontinence	Complete occlusion	11	Yes
5	39/F	T5	Progressive myeloradiculopathy, urinary incontinence	Complete occlusion	9	Yes
6	43/M	T8	Progressive myeloradiculopathy	Complete occlusion	7	No
7	49/M	T9	Progressive myeloradiculopathy	Complete occlusion	6	Yes
8	44/M	L3	Progressive myeloradiculopathy	Complete occlusion	6	Yes
9	40/F	S1	Progressive myeloradiculopathy, urinary incontinence	Complete occlusion	5	Yes

[a] Patient 1 is the illustrative case.
DSA = digital subtraction angiography, F = female, M = male.