ORIGINAL RESEARCH

IS FlowMap, a novel tool to examine blood flow changes induced by flow diverter stent treatment: initial experiences with pipeline cases

Aichi Chien, Fernando Viñuela

Division of Interventional Neuroradiology, David Geffen School of Medicine at UCLA, Los Angeles, California, USA

Correspondence to
Professor A Chien, Division of Interventional Neuroradiology, David Geffen School of Medicine at UCLA, 10833 LeConte Ave, Box 951721, Los Angeles, CA 90095, USA; aichi@ucla.edu

Received 30 November 2012
Revised 14 January 2013
Accepted 15 January 2013

ABSTRACT

Background Intracranial aneurysm flow diverting stents are a new endovascular treatment option for wide neck and large/giant aneurysms. Since August 2011, our center has integrated flow diverting stents into aneurysm treatment management. To further understand the effects of flow diverting stents, we developed the intracranial stent flow mapping program, which allows detailed, case by case, examination and comparison of blood flow changes within an aneurysm before and after stent treatment.

Methods The Intracranial Stent Flow Mapping program (IS FlowMap) utilizes algorithms detecting movement changes between consecutive images. Sequences of catheter angiograms capturing the movement of injected contrast were used to map flow patterns and examine aneurysmal flow before and after stent implantation.

Results A pilot study of this new technique in flow diverter (FD) stent treated aneurysms was performed. Four clinical aneurysms (two wide neck and two giant aneurysms) were analyzed by IS FlowMap. The characteristics of redirected flow in cases treated with one stent or two overlapping stents in the reconstructed vessels are presented. Distinct differences in flow impingement on the aneurysm wall, aneurysmal inflow, and flow circulation before and after FD stent treatment were found.

Conclusions We present a novel approach to map blood flow motion within aneurysms and have shown the feasibility of the technique in clinical aneurysms. This new technology can help monitor flow changes induced by stents and study the relationship between the modified flow and treatment outcome.

INTRODUCTION

Flow diverter (FD) stents present an alternative treatment for aneurysms unsuitable for traditional methods, such as endovascular coiling or surgical clipping. The treatment uses high mesh density stents to reconstruct the diseased parent vessel and reduce blood flow within the aneurysm, excluding the aneurysm from the circulation and facilitating progressive thrombosis within it.[1–3] Since August 2011, our center has integrated flow diverting stents into the endovascular therapy of wide neck, large, and fusiform aneurysms.

Although it has been indicated that changes in the blood inflow and circulation patterns underlie stent induced aneurysmal clot formation, we found that the flow changes induced by the FD stent were difficult to visualize and compare.[4] To analyze flow and circulation patterns and associated aneurysm clot formation and clinical outcome, we have developed a new blood flow analysis tool—Intracranial Stent Flow Mapping program (IS FlowMap)—which allows detailed examination and comparison of the flow changes for individual aneurysms. In this paper, using this new technology, we present a pilot study of the flow changes in aneurysms which were treated with FD stents.

METHOD

The IS FlowMap program was developed to assist the measurement of flow changes in aneurysms due to stents.[5] IS FlowMap analyzes the movement of injected contrast and is based on technology to detect motion in a series of images. It is a well studied and validated numerical method which, among other applications, is used to detect motion in airborne images for military purposes and to map the velocity of ocean currents using continuous satellite images.[6–9]

To compare the flow changes in FD treated cases, we utilized cerebral angiogram images that capture contrast flow within aneurysms for IS FlowMap flow motion detection.[10] Because the variation in contrast intensity in the angiogram results from the blood flow motion, blood flow velocity in the aneurysm can be measured by the spatial and temporal changes of the image intensity as[5]:

$$I_x V_x + I_y V_y = I_t \qquad (1)$$

where I_x and I_y are the contrast intensity changes in x and y coordinates (the spatial changes in intensity). I_t is the contrast intensity change in different image frames (the temporal change in intensity). V_x and V_y are the flow velocity in the x and y directions.

The DICOM images of injected contrast entering the aneurysm dome were applied as the input for the flow mapping analysis.[10] Comparison of the contrast intensity changes between two consecutive frames was performed by IS FlowMap. Measurement of the intensity change in the image—I_x and I_y, and the intensity change between two frames—I_t was then applied based on (1). Finally, based on the trajectory of V_x and V_y, the blood flow motion within the aneurysm was mapped.[11]

The study was approved by institutional review board review. Four aneurysm cases (two wide neck and two giant aneurysms) which were treated with Pipeline (EV3, Irvine, California, USA) FD stents were analyzed to study the changes in flow before

To cite: Chien A, Viñuela F. *J NeuroIntervent Surg* Published Online First: [*please include* Day Month Year] doi:10.1136/neurintsurg-2012-010613

and after stent treatment. Sequences of cerebral angiograms which were routinely used to assist the embolization procedure were archived into a Dell 490 workstation to measure flow.

Cerebral angiograms for each aneurysm were acquired before and after stent deployment using a Philips Integris System (Philips Healthcare, The Netherlands). All of the angiograms were performed using standard cerebral angiogram protocols. Images were captured at 6 frames/s and contrast injection rates were set as 6 ml/s from the internal carotid artery with image resolution of 0.18 mm×0.18 mm×1.0 mm per voxel.

RESULTS

Changes in flow characteristics from FD stent treatment obtained using IS FlowMap are shown in figures 1–4. In each figure, the columns are, from left to right: the original angiogram used as input for the IS FlowMap, the flow impingement direction, and a velocity vector plot presenting the aneurysmal flow pattern. The flow impingement on boundaries including the aneurysm wall, vessel wall, and FD stents is denoted with a color wheel, where the impingement direction corresponds to the position of the color on the wheel.[12] For example, flow impingement to the left will be indicated by a red color. The vector plot, which depicts the dynamics of the flow motion, helps compare the inflow pattern and flow circulation within the aneurysm.[11] The location of stents is highlighted using yellow lines in the left image. One of the cases (case No. 4) was treated with two overlapping stents, and green lines were used to indicate the location of the second stent.

Case No. 1 is a 9.55 mm, wide neck aneurysm located at the distal left vertebral artery. Figure 1a-1 and 1b-1 show the angiogram before and after FD treatment, respectively. Before FD treatment, the flow impingement was directed toward the aneurysm proximal wall (figure 1a-2, red arrow). After treatment, the curvature of the vertebral artery changed. Aneurysmal inflow was redirected away from the proximal wall of the aneurysm and the flow impingement toward the proximal wall was reduced (figure 1b-2, red arrow). We also identified the inflow impingement on the jailed microcatheter which was later used to deploy embolization coils in the aneurysm dome. The yellow arrows in figure 1a-3 and 1b-3 indicate the inflow changes before and after stenting, respectively. The outflow changed from toward the distal artery (black arrow in figure 1a-3) and became directed through the stent by the stent mesh (black arrow in figure 1b-3).

Case No. 2 is a wide neck, irregular shaped, multi-blebs aneurysm (maximum dimension 14 mm) located at the left internal carotid artery ophthalmic artery region (figure 2). The angiograms were taken during endovascular treatment with catheters in place. The difference in vessel boundary at the neck can be seen from plots of the flow forces at the vessel wall in figure 2a-2 and 2b-2 (white arrows), indicating a well defined reconstructed vessel boundary at the aneurysm neck after FD stent treatment. The stent redirected the outflow along the reconstructed parent artery (figure 2a-3 and 2b-3 red arrows). The inflow within the aneurysm also changed. We observed reduced flow in one of the blebs of the aneurysm (yellow arrows in figure 2a-3 and 2b-3); moreover, a new circulation was formed in the distal sac after stenting (black arrow).

Case No. 3 is a 23 mm giant aneurysm located at the left carotid artery–ophthalmic artery region. Flow characteristics before and after FD stents treatment are shown in figure 3. A nearly vertical inflow jet seen in the original angiogram (figure 3a-1) diminished after stenting (figure 3b-1). However, flow impingement on the apex and distal wall remained unchanged (figure 3a-2 and 3b-2, white arrows). We found clear flow velocity vector changes near the inflow jet (figure 3a-3 and b-3,

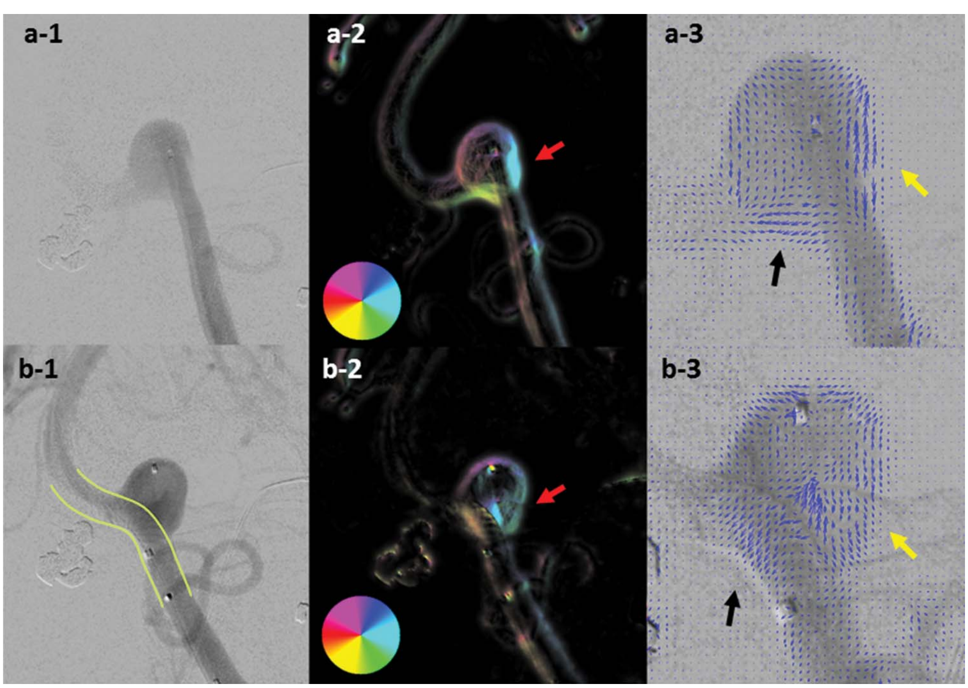

Figure 1 Inflow and outflow pattern changes in a 9.55 mm wide neck vertebral artery aneurysm before (a) and after (b) the flow diverter (FD) stent implant. Flow impingement at the aneurysmal proximal wall (red arrow in a-2) was reduced after the FD implant (b-2). The flow velocity vector plot (right column) shows changes in the aneurysmal inflow (yellow arrows) and outflow (black arrows) before (a-3) and after (b-3) the FD stent was implanted.

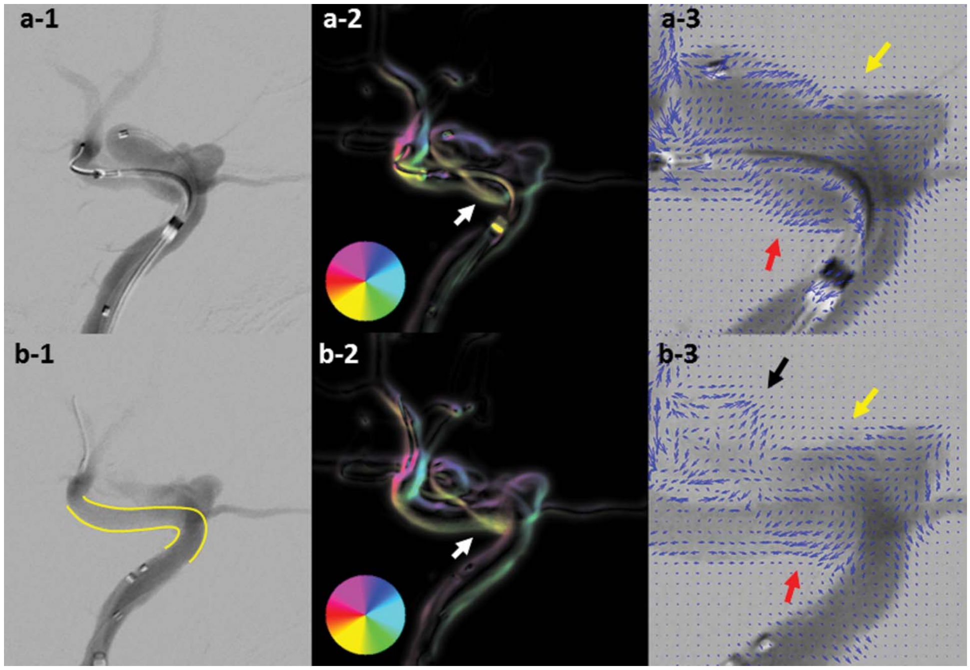

Figure 2 A new reconstructed flow boundary and different aneurysmal circulation in a 14 mm wide neck multi-blebs internal carotid artery aneurysm after the flow diverter (FD) stent was implanted. (a) and (b) are before and after the FD stent was implanted, respectively. The reconstructed vessel which creates a new flow impingement boundary can be observed at the area of the aneurysm neck (white arrows in a-2 and b-2). The flow velocity vector plot (a-3 and b-3) shows distinct changes in the aneurysmal inflow and outflow (yellow and red arrows) as well as the new circulation formed (black arrow) after the FD stent was implanted.

red arrows). A new recirculating flow appeared after stent treatment from the reduced inflow jet to the proximal end of the aneurysm wall (figure 3b-3, yellow arrow).

Case No. 4 is a 26.1 mm giant aneurysm located at the right cavernous segment of the internal carotid artery. The aneurysm was treated with two Pipeline stents—the first stent was 25 mm and the second stent was 14 mm, deployed coaxially. Figure 4 shows blood flow (figure 4a) before treatment, after placing the first stent (figure 4a), and after placing the second stent (figure 4a). Before treatment, blood flow in the aneurysm produced a

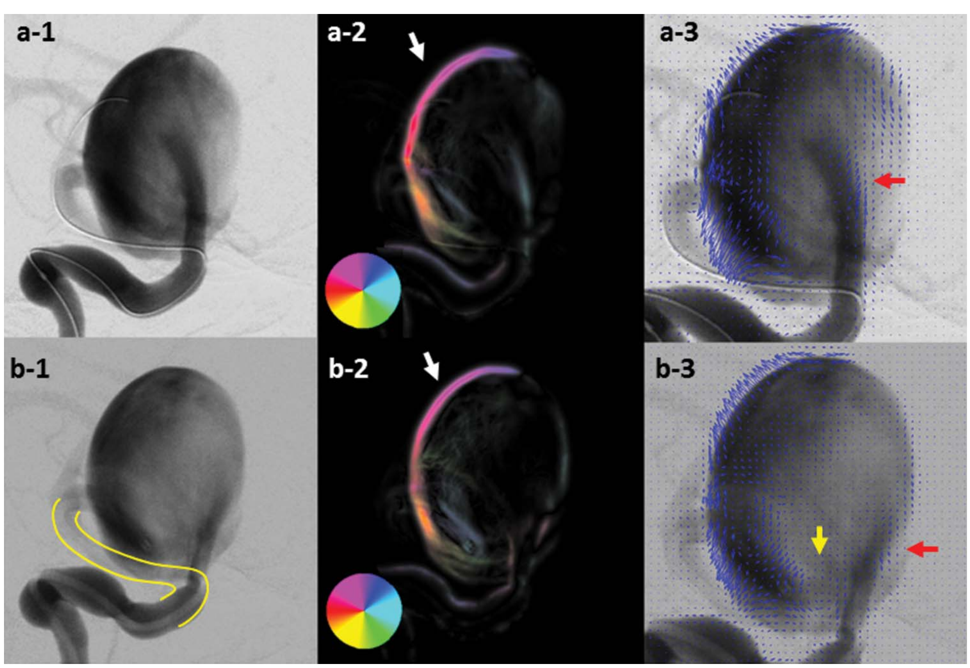

Figure 3 Inflow changes and new circulation formed in a 23 mm giant internal carotid artery aneurysm comparing the blood flow pattern before (a) and after (b) the flow diverter (FD) stent was implanted. A nearly vertical inflow jet is seen in the original angiogram (a-1). After the stent was implanted, although the vertical inflow diminished (b-1), flow impingement on the apex and distal wall remained unchanged (white arrows in a-2 and b-2). In the flow velocity vector plot, changes in inflow are denoted with red arrows (a-3 and b-3) and a new circulation formed after FD implantation is indicated by a yellow arrow.

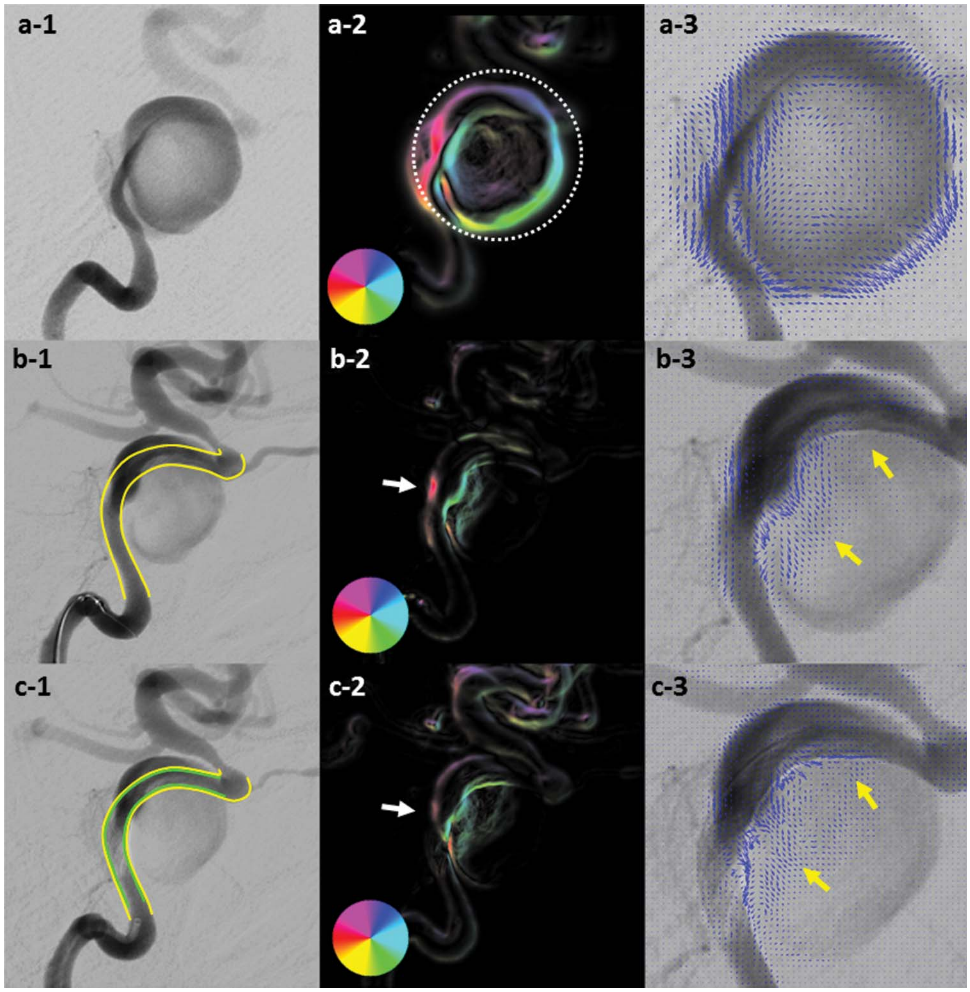

Figure 4 Distinct changes in blood flow pattern before treatment (a), after a first flow diverter (FD) stent is implanted (b), and after overlapping with a second FD stent in a 26.1 mm giant internal carotid artery aneurysm. Yellow lines in b-1 and c-1 indicate the location of the first stent. Green lines denote the position of the second stent: (a-2) shows the blood flow impinging in a radial direction toward the entire aneurysm wall before the treatment. It was reduced immediately after the first stent was implanted (b-2). The flow vector plot shows the clear flow direction changes after the first and second FD stents were implanted (yellow arrows in b-3 and c-3).

uniform, radial flow force acting on the aneurysm wall (figure 4a-2, dotted circle)—the color at the aneurysm wall follows the same order as the color wheel, indicating the eccentric flow impingement in a radial direction toward the entire aneurysm wall. With the first stent, the flow impingement became localized (figure 4b-2, white arrow) and the flow directions within the aneurysm changed completely (figure 4b-3, yellow arrows). After deploying the second stent, this impingement decreased and the flow was further redirected along the reconstructed parent artery. Yellow arrows in figure 4c-3 show less flow entering the aneurysm, as the flow was increasingly directed along the reconstructed parent artery after placement of the second stent.

DISCUSSION

Since FD stents were introduced for aneurysm treatment, encouraging treatment outcomes have been found in many centers.[1 2 13] These new treatment devices present a new option for aneurysm patients and, at the same time, a new task for the scientific community to analyze related clinical data and assist treatment planning. Inspired by such needs, researchers have proposed different approaches to study the effects of flow diverting stents.[14] In the original research on endovascular stent induced aneurysmal clot in a canine model, Wakhloo *et al*[4] suggested that the mechanism inducing clot formation may relate to changes in the inflow zone and circulation pattern within the aneurysm. In this paper, we presented a novel flow mapping technology (IS FlowMap) which allows comparison of these key flow changes in individual aneurysms before and after FD stent treatment.

The fundamental principle of FD stent treatment is a device with a mesh designed to disrupt the hemodynamics within the aneurysm and consequently promote progressive thrombosis. However, there is limited information about the relationship between aneurysmal flow changes induced by FD and aneurysmal clot formation in humans, due to a lack of methodology. Further understanding of FD stent induced thrombogenesis and the healing process in clinical practice is of great interest.[15–19]

Cerebral angiography is the gold standard for interventional procedures. Sequences of contrast flow images are critical tools for endovascular treatment planning and they are usually stored and archived as a part of the clinical record. IS FlowMap, which utilizes angiogram data without additional procedures, directly measures flow from clinical images. Since it does not simulate flow, IS FlowMap avoids the multi-scale simulation problem of sub-millimeter stent meshes, and their combination with vessel geometry.[11 20] It does not require a three-dimensional reconstruction process for the aneurysm shape nor use of virtual stenting to position the stents, as do previously published aneurysm hemodynamic simulations with stents.[21] This direct flow analysis technology contributes to a fast turnaround time for IS FlowMap—average flow analysis time from raw images to flow results is less than 30 min. Moreover, as opposed to virtual stenting using pretreatment aneurysm geometry to study flow changes due to stents, IS FlowMap analyzes the flow for the clinically deployed stent shape, taking into account morphological changes of the parent artery due to interventional procedures commonly seen in FD treatment, such as in case Nos 1 and 2 (figures 1 and 2, respectively).

IS FlowMap was developed to rapidly analyze FD stent treated cases to understand the flow changes in different aneurysms. However, because IS FlowMap is impartial to the details of a particular device, it can likely be useful to analyze other treatments than FD stents. Development of quantitative analysis based on this technology, such as quantifying the reduction in aneurysmal flow, will be helpful to perform comparative studies in large clinical series Moreover, future research to investigate the relationship between flow changes and clot formation within aneurysms using follow-up data will be helpful to understand the progressive influence of FD devices in vivo and assist future advancement of FD devices.

CONCLUSION

We have presented a novel approach to map blood flow movement within aneurysms that utilizes cerebral angiograms to visualize and analyze flow motion, and may be helpful to future quantification of flow changes during FD stent treatment. We demonstrated the feasibility of the technique and analyzed the flow changes in clinical aneurysms which were treated using FD stents.

Contributors Both authors made substantial contributions to conception and design; acquisition of the data, or analysis and interpretation of the data; drafting the article or revising it critically for important intellectual content; and final approval of the version to be submitted.

Funding This research was supported in part by a UCLA Radiology Exploratory Research Grant (#120003).

Competing interests None.

Ethics approval The study was approved by the institutional review board.

Provenance and peer review Not commissioned; externally peer reviewed.

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