

## Flow-independent dynamics in aneurysm (FIDA): pressure measurements following partial and complete flow impairment in experimental aneurysm model

Shahram Majidi, MD<sup>\*</sup>, Masaki Watanabe, MD, Saqib A Chaudhry, MD, and Adnan I Qureshi, MD

*Zeenat Qureshi Stroke Research Center, University of Minnesota, Minneapolis, MN*

### Abstract

**Background:** There have been growing concerns regarding delayed aneurysm rupture subsequent to the flow-diverting stent deployment. Therefore, more investigations are needed regarding hemodynamic changes secondary to flow-diverting stent deployment.

**Objective:** To study intra-aneurysmal and perianeurysmal pressures after partial and complete flow impairment into the aneurysm.

**Methods—**A silicone model of an 8-mm-sized aneurysm (neck diameter: 5 mm, vessel size: 4 mm) was used. The aneurysm wall was encapsulated and sealed within a 5 ml syringe filled with saline and a pressure sensor guide wire (ComboWire, Volcano Corp.) to detect pressure changes in the perivascular compartment (outer aneurysm wall). A second pressure sensor guide wire was advanced inside the aneurysm sac. Both pressure sensors were continuously measuring pressure inside and outside the aneurysm under pulsatile flow under the following conditions: 1) baseline (reference); 2) a 16 mm by 3.75 mm flow-diverting stent (ev3/Covidien Vascular, Mansfield, MA) deployed in front of the aneurysm; 3) two flow-diverting stents (16 mm by 3.5 mm) were deployed; and 4) a covered stent (4 mm by 16 mm VeriFlex coronary artery stent covered with rubber sheet) was deployed.

**Results:** Mean ( $\pm$ SD) baseline pressures inside and outside the aneurysm were 53.9 ( $\pm$ 2.4) mmHg (range 120–40 mmHg) and 15.4 ( $\pm$ 0.7) mmHg (range 40–8mmHg), respectively. There was no change in pressure inside and outside the aneurysm after deploying the first and second flow-diverting stents (partial flow impairment) and it remained at 53.9 ( $\pm$ 2.7) mmHg and 14.9 ( $\pm$ 1) mmHg for the pressure inside and outside the aneurysm, respectively. The pressure recording from outside the aneurysm dropped from 15.4 ( $\pm$ 0.7) mmHg to 0.3 ( $\pm$ 0.7) mmHg after deploying the covered stent (complete flow impairment). There was no change in pressure inside the aneurysm after deploying the covered stent. Mean ( $\pm$ SD) pressure within the aneurysm was 55.1 ( $\pm$ 1.7) mmHg and it remained 54.7 ( $\pm$ 1.7) mmHg after covered stent deployment.

**Conclusion:** Our findings suggest a major discordance between the pressures within the aneurysm and partial or complete flow impairment (flow independent). The outer wall pressure is reduced after covered stent placement. These finding may assist clinicians in better understanding of aneurysm hemodynamics and rupture after flow-diverting stent deployment.

### Keywords

Aneurysm; hemodynamics; intra-aneurysmal pressure; perianeurysmal pressure; flow-diverting stents; covered stent

### Background

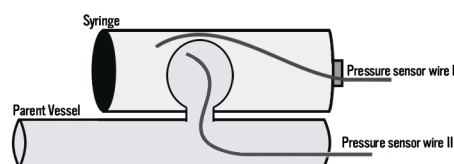
Endovascular intracranial aneurysm treatment has evolved during the last decade from using coil emboliza-

tion alone to additional parent vessel reconstruction through flow-diverting stents. Flow diversion with high-density braided stents is a hemodynamic approach for the exclusion of the aneurysm from the circulation

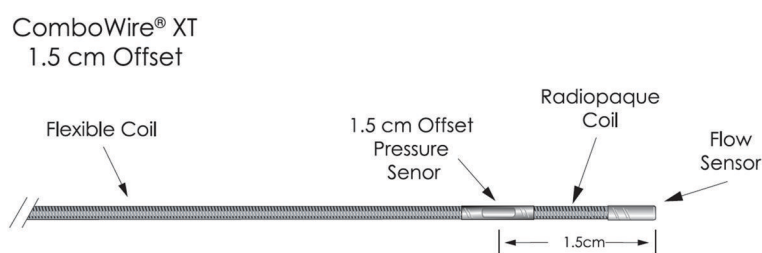
Published September, 2014.

All Rights Reserved by JVIN. Unauthorized reproduction of this article is prohibited

\*Correspondence to: Shahram Majidi, M.D.



**Figure 1.** Placement of pressure sensor guide wires in perianeurysmal space (ComboWire I) and within intra-aneurysmal space (ComboWire II).



**Figure 2.** ComboWire® XT Guide Wire, Volcano Corporation, Rancho Cordova, CA.

through redirecting blood flow away from the aneurysm and subsequent induction of thrombosis formation inside the aneurysm [1,2]. Flow diversion technique has been demonstrated as a promising approach for the treatment of wide neck and/or giant aneurysms [3,4]. Despite the promising initial results, there have been growing concerns regarding delayed aneurysm rupture subsequent to the flow-diverting stent deployment [5]. Therefore, more investigations are needed regarding intra-aneurysmal and perianeurysmal hemodynamic changes secondary to flow-diverting stent deployment, which are still not fully understood.

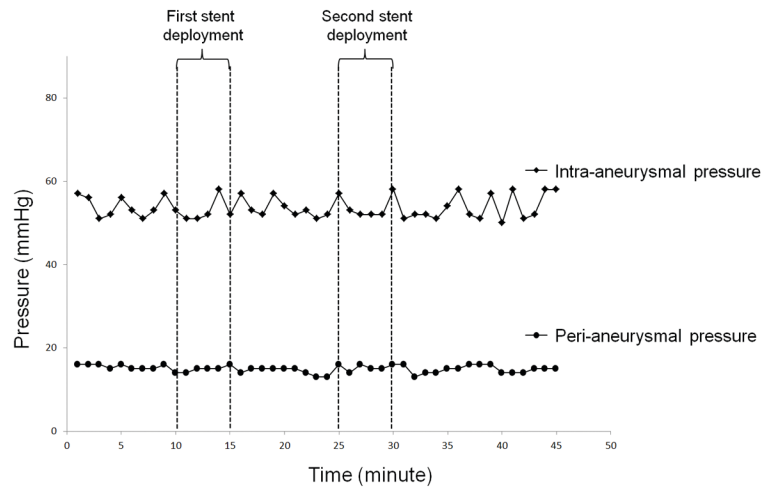
In this study, we investigated perianeurysmal and intra-aneurysmal pressures changes after partial and complete flow impairment into the aneurysm by using flow-diverting and covered stents.

## Materials and Methods

A silicone model of an artery with aneurysm was used; the parent vessel diameter was 4 mm; and aneurysm neck, neck to dome and the aneurysm width dimensions were 5, 8.2, and 8 mm, respectively. A 5-mm hole was made in the wall of the barrel of 5 ml syringe and the

aneurysm was encapsulated within the barrel through the hole. Then, the hole and the plunger of the syringe were sealed using silicone glue. A hemostasis valve was connected to the hub of the syringe, and the volume of the barrel of the syringe surrounding the aneurysm was filled with water. Then, a dual-sensor guide wire (ComboWire® XT Guide Wire, Volcano Corporation, Rancho Cordova, CA) was passed through the hemostasis valve into the syringe and touched the aneurysm wall from outside (Figure 1). ComboWire has a pressure sensor built 1.5 cm from the tip of the wire and a Doppler velocity sensor at the tip of the wire (Figure 2). The flow-velocity measurement mode was disabled during the experiment and only pressure measurement capacity was used.

The silicone model was connected to a pulsatile fluid pump. Through a 5F guiding catheter, another ComboWire guide wire was introduced into the vessel and advanced into the aneurysm until the pressure sensor was placed inside the aneurysm (Figure 1). While the fluid pump was off, the pressure sensors both outside and inside the aneurysm were calibrated to zero values. Subsequently, the fluid pump turned on in the pulsatile mode, and the pressure inside and outside the aneurysm continuously was recorded for 10 min for baseline meas-



**Figure 3.** Intra-aneurysmal and perianeurysmal pressures before and after the deployment of one and two flow-diverting stents. There were no significant changes in either of the pressures after the stents deployment.

urements. A second set of measurements of the pressure inside and outside the aneurysm was performed after a 16 mm by 3.75 mm flow-diverting stent (ev3/Covidien Vascular, Mansfield, MA) was deployed across the aneurysm neck by using microcatheter under direct visualization. After recording the pressures inside and outside the aneurysm for 10 min following the stent deployment, a second flow-diverting stent (16 mm by 3.5 mm) was deployed in the same fashion and the pressures were monitored for another 15 min. Both stents were retrieved and the pressure sensors were retained in the primary positions. A third set of measurements for the pressures inside and outside the aneurysm was performed after a covered stent was deployed in front of the aneurysm. The covered stent was made through covering a 4 mm by 16 mm VeriFlex coronary artery stent (Boston Scientific, Natick, MA) with rubber tubular sheet. The pressures were recorded for 15 min following the deployment of the covered stent.

### Statistical analysis

The pressures were expressed as mean  $\pm$  standard deviation (SD). The pressure measurements (mean arterial pressure) at every 10-s interval were used to calculate the mean pressures. The baseline mean pressures inside and outside the aneurysm were compared with corresponding pressures after: 1) deployment of one flow-diverting stent; 2) deployment of two flow-diverting stents; and 3) deployment of one covered stent. The mean values were compared using Wilcoxon–Mann–Whitney test. The SAS 9.3 software (SAS Institute, Cary, NC) was used for the statistical analysis.

## Results

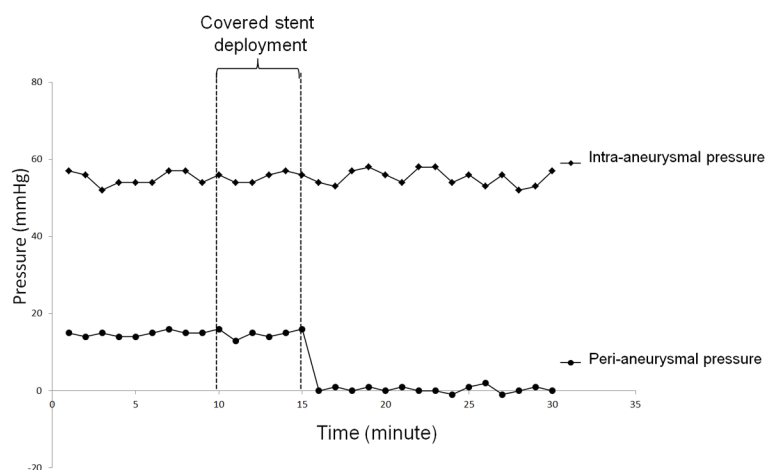
Baseline pressures within and outside the aneurysm were measured for 10 min before deploying the stent. The mean ( $\pm$ SD) baseline pressure within and outside the aneurysm were 53.9 ( $\pm$ 2.4) mmHg and 15.4 ( $\pm$ 0.7) mmHg, respectively.

### Effect of flow-diverting stents deployment

There was no significant change in pressures within and outside the aneurysm after the first Pipeline stent deployment as the mean ( $\pm$ SD) intra-aneurysmal and perianeurysmal pressures recorded continuously for 15 min following the stent deployment were 53.6 ( $\pm$ 2.3) mmHg and 14.6 ( $\pm$ 1) mmHg, respectively ( $p = 0.8$ ). Similarly, there was no significant change in intra-aneurysmal and perianeurysmal pressures after the deployment of the second Pipeline stent. The mean ( $\pm$ SD) intra-aneurysmal pressure recorded for 15 min after the second stent deployment were 53.9 ( $\pm$ 2.7) mmHg and the perianeurysmal pressure remained at 14.8 ( $\pm$ 1) mmHg ( $p = 0.9$ ). Figure 3 shows perianeurysmal and intra-aneurysmal pressure readings during this part of the experiment.

### Effect of covered stent deployment

Intra-aneurysmal and perianeurysmal pressures were continuously measured for 10 min before deploying the covered stent. The baseline means ( $\pm$ SD) intra-aneurysmal and perianeurysmal pressures were 55.1 ( $\pm$ 1.7) mmHg and 15.4 ( $\pm$ 0.7) mmHg, respectively. The pressures recorded during the stent placement and after



**Figure 4.** Intra-aneurysmal and perianeurysmal pressures before and after the deployment of the covered stent. Perianeurysmal pressure abruptly dropped after the stent deployment, whereas the intra-aneurysmal pressure remained unchanged.

placement for 15 min. There was no significant change in intra-aneurysmal pressure after the covered stent deployment and the mean ( $\pm$ SD) pressure after the procedure was 54.7 ( $\pm$ 1.7) mmHg ( $p = 0.9$ ). In contrast, perianeurysmal pressure significantly dropped abruptly after the covered stent placement to 0.3 ( $\pm$ 0.7) mmHg ( $p < 0.0001$ ). Figure 4 shows intra-aneurysmal and perianeurysmal pressures before and following the covered stent deployment.

## Discussion

Hemodynamic parameters of aneurysm play a critical role in aneurysm growth and rupture. In-depth analysis of these parameters is both clinically relevant and critical with increasing use of hemodynamic approaches such as flow diversion technique for the treatment of complex aneurysms. In our experiment, we observed that intra-aneurysmal pressure is independent of intra-aneurysmal flow status. We also found discordance between intra-aneurysmal and perianeurysmal pressures in certain settings. After the partial impairment of the flow into the aneurysm by using one and two flow-diverting stents, the intra-aneurysmal pressure remained unchanged in comparison with baseline measurement. Even after complete flow impairment into the aneurysm through a covered stent, the intra-aneurysmal pressure did not change. The perianeurysmal pressure reading demonstrated significant reduction after the deployment of the covered stent.

Despite encouraging long-term results in aneurysm obliteration after placement of flow-diverting stents, occurrence of early aneurysm rupture after the treatment

has prompted question regarding the intra- and perianeurysmal pressure effects of flow diversion [6,7]. Complete aneurysm occlusion following flow-diverting stent deployment in clinical studies takes place after a delay extending from a few weeks to months suggesting delayed thrombosis but no acute major pressure changes [2,8]. Lylyk *et al* [3] reported the use of flow-diverting stents in 63 intracranial aneurysms, and found that the rate of complete occlusion was only 56% at 3 months which increased to 95% at 12 month followup. Anecdotal reports have confirmed the lack of any acute pressure reduction within the aneurysm following the deployment of one flow-diverting stent [9,10]. Shobayashi *et al* [10] investigated intra-aneurysmal pressure changes following Neuroform EZ self-expanding aneurysm neck bridging stent (Stryker Neurovascular, Fremont, CA) and Pipeline embolization device deployment in a computation model of large internal carotid artery aneurysm. They demonstrated that the intra-aneurysmal pressure remained unchanged after deploying both stents. In fact, the stents only reduced flow velocity inside the aneurysm. They concluded that until flow-diverting stents with capabilities to reduce intra-aneurysmal pressure and induce faster thrombosis become available, concomitant coil embolization of the aneurysm may be a valid approach to protect the aneurysm from the delayed rupture. Cezbral *et al* [8] investigated the intra-aneurysmal pressure in seven cases of intracranial aneurysms treated with flow-diverting stent deployment by using Computational analysis of the model of the procedures. They found that intra-aneurysmal pressure increased after the deployment of the stents in three cases all them had postprocedural ruptures. In the remaining four cases

without aneurysmal rupture, the intra-aneurysmal pressure was not affected by stent deployment.

Our experiment demonstrated that intra-aneurysmal pressure remains unchanged following deployment of one or multiple flow-diverting stents. The lack of pressure change is consistent with a previous study [11] that demonstrated in the presence of any flow into-and-out of the aneurysm, the aneurysm sac is part of the fluid-coupled system and the pressure inside the aneurysm can remain as high as the parent artery pressure. On the other hand, intra-aneurysmal pressure after complete occlusion of the aneurysm neck is the function of pressure transmission through the covered stent [12]. In our experiment, there was no decline in the intra-aneurysmal pressure after covered stent deployment. A previous study [13] found that upon using stiffer material with less compliance to form the covered stent, the intra-aneurysmal pressure decreases following the stent deployment. The pressure transmission through the parent artery wall can explain the discordance between the intra-aneurysmal and the perianeurysmal pressure changes after covered stent deployment.

Our study has several limitations. First, the study was performed in *in-vitro* setting by using a silicone model of aneurysm which may not adequately replicate the compliance of arterial wall. Second, we investigated only the intra-aneurysmal and perianeurysmal pressure in a relatively small aneurysm model. The model is reflective of the majority of intracranial aneurysms but may not have all the characteristics of giant wide-neck aneurysms. Finally, we did not use different types of covered stents to test the impact of different materials with different compliance on the intra-aneurysmal pressure changes.

## Conclusion

In summary, with all the findings, one can argue that a prominent component of intra-aneurysmal pressure dynamics is independent of flow status into the aneurysm. Even after complete flow occlusion into the aneurysm, the intra-aneurysmal pressure remains high and comparable with pressure within the parent vessel that makes the aneurysm vulnerable to possible delayed rupture. Our findings supports the technical approach of coil placement into the aneurysm prior to flow-diverting stent deployment to protect aneurysm from early rupture, as it has been proposed by Siddiqui *et al* [14].

## References

1. Turjman F, Acevedo G, Moll T, Duquesnel J, Eloy R, Sindou M. 1993; Treatment of experimental carotid aneurysms by endoprosthesis implantation: preliminary report. *Neurological research* 15:181–4.
2. Kulcsar Z, Houdart E, Bonafe A, et al. 2011; Intra-aneurysmal thrombosis as a possible cause of delayed aneurysm rupture after flow-diversion treatment. *AJNR American journal of neuroradiology* 32:20–5.
3. Lylyk P, Miranda C, Ceratto R, et al. 2009; Curative endovascular reconstruction of cerebral aneurysms with the pipeline embolization device: the Buenos Aires experience. *Neurosurgery* 64:632–42. discussion 42—3 quiz N6
4. Kallmes DF, Ding YH, Dai D, Kadirvel R, Lewis DA, Cloft HJ. 2009; A second-generation, endoluminal, flow-disrupting device for treatment of saccular aneurysms. *AJNR American journal of neuroradiology* 30:1153–8.
5. D'Urso PI, Lanzino G, Cloft HJ, Kallmes DF. 2011; Flow diversion for intracranial aneurysms: a review. *Stroke; a journal of cerebral circulation* 42:2363–8.
6. Nelson PK, Lylyk P, Szikora I, Wetzel SG, Wanke I, Fiorella D. 2011; The pipeline embolization device for the intracranial treatment of aneurysms trial. *AJNR American journal of neuroradiology* 32:34–40.
7. Turowski B, Macht S, Kulcsar Z, Hanggi D, Stummer W. 2011; Early fatal hemorrhage after endovascular cerebral aneurysm treatment with a flow diverter (SILK-Stent): do we need to rethink our concepts? *Neuroradiology* 53:37–41.
8. Cebal JR, Mut F, Raschi M, et al. 2011; Aneurysm rupture following treatment with flow-diverting stents: computational hemodynamics analysis of treatment. *AJNR American journal of neuroradiology* 32:27–33.
9. Schneiders JJ, Van Bavel E, Majoie CB, Ferns SP, van den Berg R. 2013; A flow-diverting stent is not a pressure-diverting stent. *AJNR American journal of neuroradiology* 34:E1–E4.
10. Shobayashi Y, Tateshima S, Kakizaki R, Sudo R, Tanishita K, Vinuela F. 2013; Intra-aneurysmal hemodynamic alterations by a self-expandable intracranial stent and flow diversion stent: high intra-aneurysmal pressure remains regardless of flow velocity reduction. *Journal of neurointerventional surgery* 5:38–42.
11. Parodi JC, Berguer R, Ferreira LM, La Mura R, Schermerhorn ML. 2001; Intra-aneurysmal pressure after incomplete endovascular exclusion. *Journal of vascular surgery* 34:909–14.
12. Gawenda M, Knez P, Winter S, et al. 2004; Endotension is influenced by wall compliance in a latex aneurysm model. *European journal of vascular and endovascular surgery: the official journal of the European Society for Vascular Surgery* 27:45–50.
13. Gawenda M, Jaschke G, Winter S, Wassmer G, Brunkwall J. 2003; Endotension as a result of pressure transmission through the graft following endovascular aneurysm repair—an in vitro study. *European journal of vascular and endovascular surgery: the official journal of the European Society for Vascular Surgery* 26:501–5.
14. Siddiqui AH, Kan P, Abula AA, Hopkins LN, Levy EI. 2012; Complications after treatment with pipeline embolization for giant distal intracranial aneurysms with or without coil embolization. *Neurosurgery* 71:E509–13. discussion E13