Evaluation of the Intracranial Flow Alteration during Manual Syringe and Continuous Pump Aspiration

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Goals: While mechanical thrombectomy (MT) has been shown to be effective in the treatment of acute large vessel occlusions, adjunctive measures, such as balloon guide catheters (BGC) and aspiration techniques, are utilized heterogeneously. Clarifying the effects of aspiration applied to the anterior cerebral circulation with proximal flow arrest can shed light on embolic protection during MT. *Materials and Methods:* Manual and pump aspiration were applied through a BGC in a synthetic cerebrovascular model with a 60 ml syringe and a Penumbra pump, respectively. Flow direction was observed during the procedure with fluorescent particles and ultraviolet light. Flow rates were monitored at the simulated internal carotid artery and middle cerebral artery (MCA). *Findings:* Both aspiration methods produced retrograde flow in all the modeled cerebrovascular segments. In the syringe aspiration methods, an interval phase occurred during the experimental trial in which suction forces paused and MCA flow became anterograde through posterior communication artery collateral circulation. *Conclusion:* Flow patterns vary with different methods of aspiration. With proximal flow arrest, continuous aspiration methods induce constant retrograde flow in all vessels, whereas manual aspiration demonstrates various flow changes, including periods of anterograde flow during the procedure, which may be less effective at distal re-embolization prevention.
Key Words: Balloon guide catheter—aspiration—mechanical thrombectomy—stroke

Introduction

Since the validation of mechanical thrombectomy (MT) for the treatment of acute large vessel occlusion, there have been continued efforts to identify optimally effective neuroendovascular recanalization procedures.[1] Adjunctive techniques, such as proximal flow arrest with a balloon guide catheter (BGC), a variety of aspiration methods, and various device combinations, have been employed in attempts to reduce distal re-embolization during MT.[2] We sought to understand the focal effects on the intracranial circulation of various aspiration methods applied to a BGC providing proximal flow arrest, as used in the MT practice at some centers. This information will allow for further understanding of the tools available for re-embolization protection and in devising new procedural techniques.

Materials and Methods

We utilized a synthetic cerebrovascular model that simulated a complete circle of Willis including 4 inflow

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channels correlating to the bilateral vertebral arteries and internal carotid arteries (ICA). The first and second segments of the bilateral middle cerebral (M1 and M2) and anterior cerebral arteries (A1 and A2), as well as posterior communicating arteries (PCoA) and anterior communication artery (ACoA) were all represented. Normal saline was circulated via a pulsatile pump to simulate cardiac output at a rate of 0.875 liters per minute with 50 pulses per minute. Fluid was maintained at 37°C. Fluorescent particles were used to observe the circulation under ultraviolet light (UVL). Two PXL Clamp-on Tubing Flowsensors (Transonic, Ithaca, NY) provided quantitative flow measurements at the petrous ICA and M2 segments (Fig 1).

An 8 French Flowgate-2 BGC (Stryker, Fremont, CA) was placed into the modelled distal left cervical ICA. After inflating the balloon to vessel occlusion, we applied the 2 methods of aspiration through the BGC: manual aspiration with a 60 ml syringe and continuous aspiration using a Penumbra pump (Penumbra Inc., Alameda, CA). Each method was performed 2 times.

The technique of aspiration for each methods was as follow:

(1) Syringe aspiration - Two 60 ml syringes and a stopcock were used to aspirate through the BGC. The plunger of the first syringe was fully withdrawn and held. After 60 ml of fluid was withdrawn into the first syringe, the stopcock was closed and then reopened after the second syringe was connected and the plunger fully withdrawn and held. The procedure concluded after a total of 120 ml was aspirated.

(2) The Penumbra aspiration pump was connected with the entire length of its standard tubing to the BGC and aspiration was performed at −20 in Hg.

The intracranial flow was visualized using fluorescent particles under UVL and each test was video recorded for qualitative evaluation. The direction of flow (anterograde, retrograde, "to and fro", and stagnation) in each simulated intracranial segment (proximal ICA below the level of PCoA, communicating segment ICA, ICA terminus, and ipsilateral A1, A2, M1, and M2) was determined. Quantitative flow-rates were measured at the proximal intracranial ICA and ipsilateral M2 throughout each test.

Results

The syringe aspiration flow changes showed a bimodal flow pattern consisting of 2 high flow aspiration phases, each tapering as the syringe neared completion, and a low flow interval phase corresponding to the exchange of the syringes. In these 2 aspiration methods, the retrograde flow rate gradually decreased toward the end of each aspiration. The pump aspiration showed uniform,

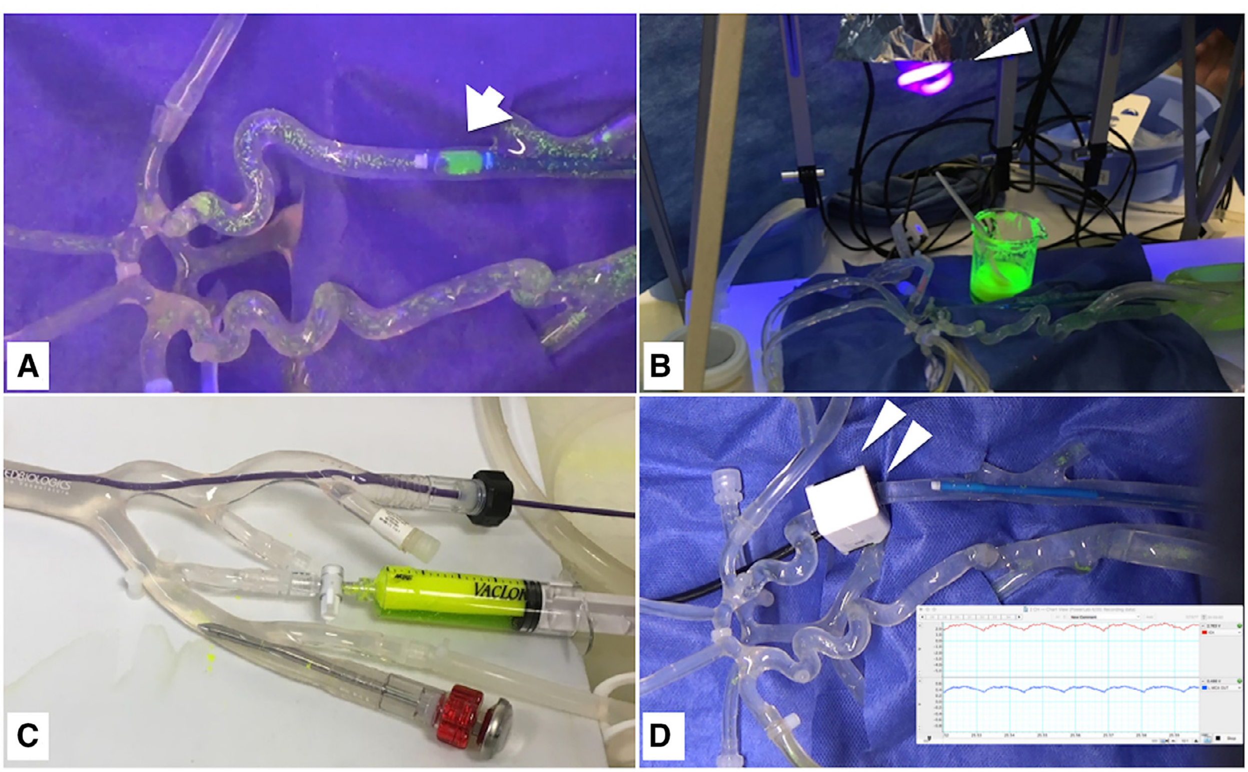

Figure 1. *Overview of the synthetic cerebrovascular model. A. Vascular model with fluorescent particles under ultraviolet light to visualize the circulation flow. BGC (white arrow) was placed in the proximal ICA. B. Ultraviolet light (white arrowhead) was used to visualize the fluorescent particles. C. The fluorescent particle was injected through the femoral artery of the vascular model. D. Flow sensor was attached to the vascular model. Two PXL Clamp-on Tubing Flowsensors (Transonic, Ithaca, NY) were used to detect the flow rate at the ICA (white double arrowhead) and ipsilateral M2 (not shown). Abbreviations: BGC, balloon guide catheters; ICA, internal carotid artery.*

monophasic retrograde flow during the continuous aspiration (Fig 2). The average flow rates of retrograde fashion during the aspiration phase at distal ICA and M2 were 228 ml/min and 104 ml/min in manual aspiration, and 232 ml/min and 108 ml/min in pump aspiration, respectively. During the interval phases, M2 flow was seen to reverse from retrograde to anterograde, with an average flow rate of 150 ml/min during manual aspiration (Fig 3).

At the initiation of all the procedures, both aspiration methods resulted in retrograde flow in all the intracranial segments during the aspiration phases. During the interval phase (seen in manual aspiration methods only), different alterations were observed in the various intracranial segments: Anterograde flow in distal ICA, ipsilateral A2, M1, and M2 segment, "to and fro" pattern in ipsilateral A1, and stagnant in the proximal intracranial ICA (Fig 4). The recorded movies with fluorescent particles and UVL are shown in Supplemental Video 1, and the movies with flow monitoring are show in in Supplemental Video 2.

Discussion

With the thorough integration of MT into acute ischemic stroke care, continued efforts aim to further maximize treatment effectiveness and identify optimal procedure techniques and strategies. A significant focus of this effort has been directed towards reduction of distal embolism during clot removal.

To this effort, BGC have become a mainstay of many MT techniques, with multiple studies demonstrating improved recanalization rates and positive effect on functional outcomes. A subgroup nonrandomized analysis of the North American Solitaire Acute Stroke registry found an improved complete recanalization rate with BGC (thrombolysis in cerebral infarction (TICI)) 3; 53.7% versus 32.5%) and that BGC use was independently associated with a good clinical outcome (modified Rankin Scale ≤2; odds ratio 2.5, 95% confidence interval 1.2-4.9).[3] Interestingly, there was no difference in radiographically apparent distal and/or new territory emboli, although a higher rate of TICI 2b suggests that distal stagnation of flow may be attributable to microembolic material. Velasco et al. found BGC to be associated with superior procedural results when used during MT, such as more successful recanalization rate (89.2% versus 67.9%), one-pass recanalization rate (63.7% versus 35.8%), and shorter procedure time (20.5 versus 41.0 minutes).[4] In this study, manual aspiration via a 50 ml syringe was applied twice to the BGC during clot removal, as performed in our studied syringe aspiration technique.

Aspiration through a BGC serves a different role than the distal aspiration techniques that utilize suction

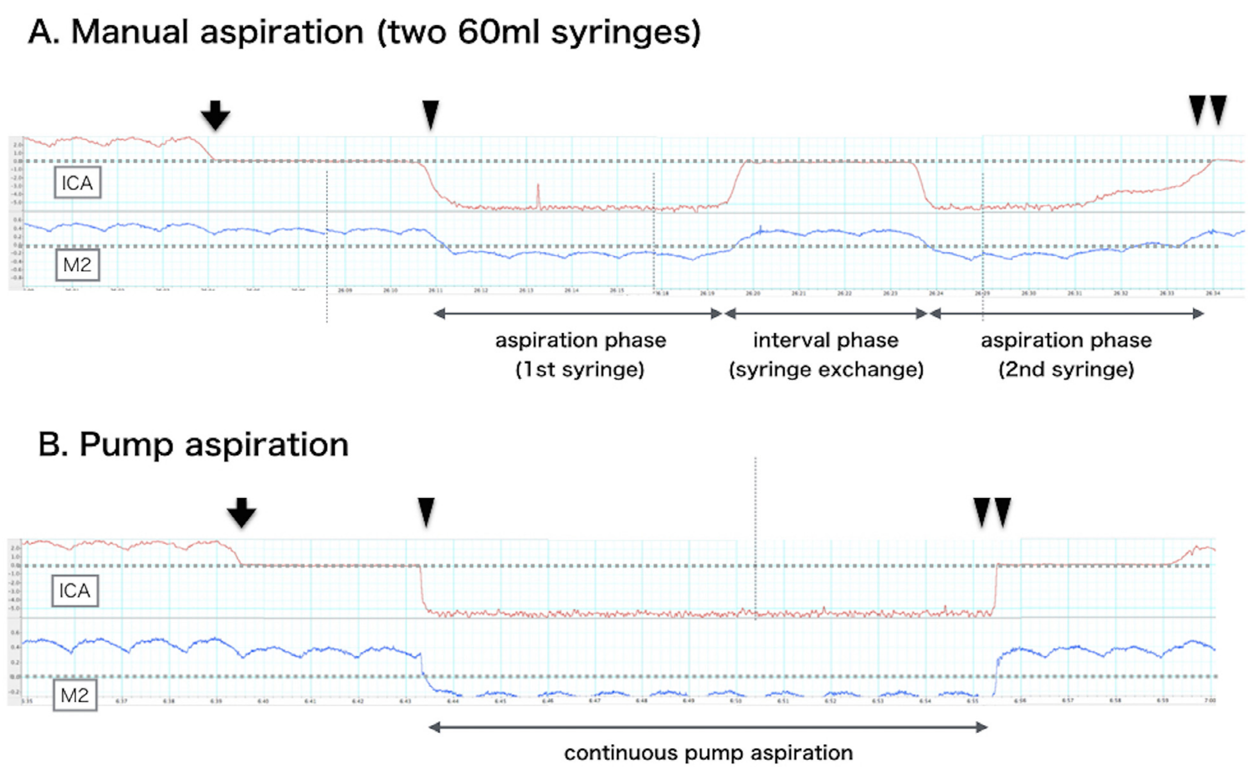

Figure 2. *Flow rate graphs. The X axis represents time and the Y axis is for the flow rates, represented in voltage. One voltage is equivalent to 400 ml/min in our model. In each method, timings of the procedure are shown as follows: balloon inflation (black arrow), aspiration initiation (black arrowhead), aspiration discontinuation (double black arrowhead). Dotted lines indicate the baseline, and waves above and below the dotted lines mean anterograde and retrograde flow, respectively. A. Flow rate recorded during the manual aspiration method using two 60 ml syringes. Note that the flow in M2 became anterograde during the interval phase (syringe exchange). B. Flow rate recorded during the pump aspiration. Throughout the procedure, M2 flow remained retrograde.*

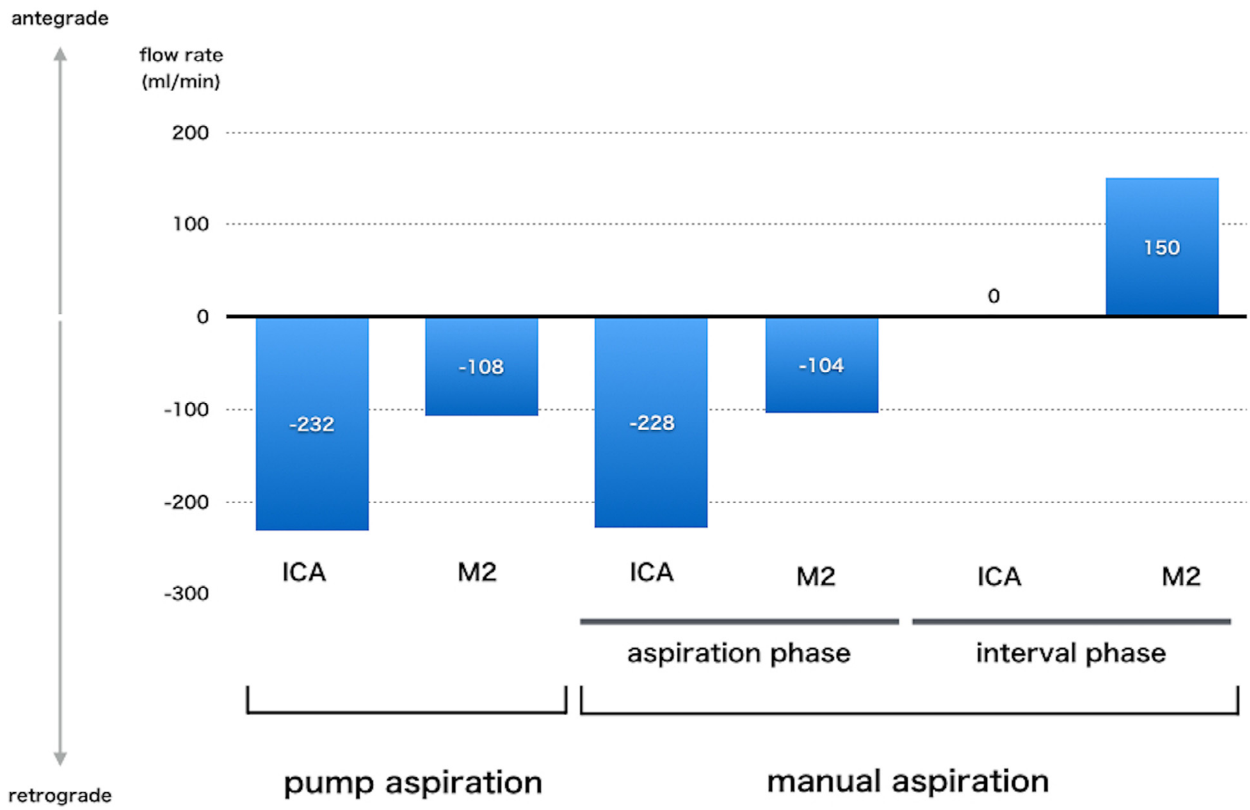

Figure 3. *Average flow rate in each method during aspiration and interval phase. Flow rate measured at the distal ICA and the M2 segment is shown in the graph. With pump aspiration, uniform retrograde flow was observed throughout the procedure at both the distal ICA and the M2 segment. With manual aspiration, retrograde flow equivalent to pump aspiration was observed during aspiration phase; however, antegrade flow occurred in the M2 segment during interval phase. Abbreviation: ICA, internal carotid artery.*

through a large bore intracranial catheter to engage the clot for extraction.[5-7] During clot engagement, no suction effect is experienced by the intracranial blood flow as the catheter should be occluded with clot. Alternatively,

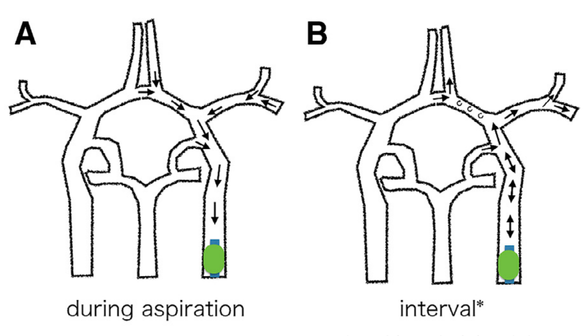

Figure 4. *Schematic illustration of intracranial flow during the aspiration and the interval phase. Arrows represent the direction of the flow observed by the fluorescent-backlight model. The two-headed arrow indicates a "to and fro" pattern. A. During the aspiration phase in each method, flow in all segments showed retrograde flow. B. During the interval phase, flows in distal ICA, ipsilateral MCA and ipsilateral A2 became anterograde due to collateral flow through the ACoA and PCoA. Flow in the A1 segment demonstrated a "to and fro" pattern. Abbreviations: ACoA, anterior communication artery; ICA, internal carotid artery; MCA, middle cerebral artery; PCoA, posterior communicating arteries;*

when aspiration is applied to the BGC, as recommended in the ESCAPE trial and utilized in the stentriever arm of the initial ADAPT evaluation, flow reversal is intended to evacuate fragmented clot to prevent re-embolization.[6,8] This phenomenon was observed in a porcine model with radiopaque thrombus shearing when being pulled into a BGC, and aspiration then retrieved all fragments.[9] These 2 aspiration strategies come together in the SAVE technique, although it utilizes aspiration proximally through a non-BGC.[5]

Maus et al. notes that an advantage of their SAVE technique, over other described local aspiration techniques, is that while others utilize proximal flow arrest via a BGC to limit re-embolization, they cannot control for the effect of collateral flow through the A1 segment as proximal aspiration can.[5] While this postulate appears logical, our data demonstrated a different effect. During aspiration through the BGC, retrograde flow was observed in all the intracranial segments of our competent circle of Willis cerebrovascular model, as expected. During the interval phases of the manual aspiration method, anterograde flow in distal ICA, ipsilateral A2, M1, and M2 segment, "to and fro" pattern in ipsilateral A1, and stagnant in the proximal intracranial ICA was observed (Fig 4). It appears that anterograde flow through the distal ICA was propagated from the posterior circulation through the PCoA and into the MCA, while A1 appeared stagnant due to competing flow from the ACoA complex. During MT, clot fragments may be present in the distal ICA and MCA, and poised to be propagated into the distal vasculature. Our segmental qualitative flow analysis during proximal flow arrested aspiration and during interval periods of the manual suction method adds to the previously published in-vitro studies. Using a synthetic vascular model simulating MT procedures with suction to a BGC versus non-BGC, Chueh et al. found BGC use significantly reduced the formation of certain distal emboli, as well as resulted in significantly higher retrograde flow rates than when applied to a conventional guide catheter.[10]

In many of these described experiments, aspiration through the BGC was performed with a variety of different syringes, and also in clinical practice, the widely used Penumbra pump is often utilized for this purpose. With the influence of these different methods of aspiration not having been fully evaluated, we sought to test a variety of methods of suction to the BGC. We applied 2 different aspiration methods to a BGC within the distal cervical ICA of the synthetic cerebrovascular model with a complete Circle of Willis. Continuous aspiration using a Penumbra pump at is −20 in Hg produced retrograde flow uniformly in all the ipsilateral intracranial arteries throughout the test, whereas manual aspiration method using two 60 ml syringes resulted in an interval phase of absent suction and restored anterograde flow while exchanging 2 syringes despite the utilization of a stopcock on the BGC. While only 60 ml syringes were tested in this study, we postulate that smaller volumes syringe, which are more common in the clinical and procedural setting, would fill more quickly and then cease to provide suction force. This may require more syringe changes or result in a lack of suction, either potentially resulting in an increase in total interval phase. While the comparative effectiveness of syringe and pump aspiration has been shown previously in a rigorous biomechanical evaluation by Simon and Grey, our study demonstrates that when using syringe aspiration, the timing to change syringes, if needed, could play a crucial factor on control of distal re-embolization.[11] Ideally, one should time the "pulling" of the stentriever with the syringe aspiration of BGC to avoid having to change syringes while the stentriever is going around the ICA bifurcation and PCoA.

While our study was intended to shed light on the flow changes that occur in each vessel segment to help guide future development of thrombectomy techniques, the following limitations must be considered: A limited number of trials were performed in each scenario (two), and while results were the same each time, further studies of this nature would be useful to confirm our findings. Although constant retrograde flow is proposed to have advantages in preventing embolic shower, a risk of additional cerebral ischemia due to flow reversal should be taken into consideration. The Penumbra pump is not approved to be used for aspiration through a BGC and could possibly cause excessive blood loss. For both of these reasons, we suggest considering that aspiration through the BGC be limited to only the brief interval of clot extraction. Finally, our study design did not include an occlusive thrombus and/or simulation of a thrombectomy procedure. While efficacy of aspiration methods through a BGC during a thrombectomy should be examined in-vivo, we feel that our data has clinical relevance, as there is often reestablished flow through a clot once a stentriever is deployed or around a clot, once extraction has begun, which is the proposed phase of the thrombectomy procedure that aspiration should be applied.

Conclusion

Aspiration through a BGC can have different effects on flow in the ipsilateral intracranial arteries, depending on the method of suction application. Continuous aspiration allows for uniform flow reversal during MT. Manual aspiration methods should be applied at the time of clot retrieval to avoid interval phases where anterograde flow may be re-established through communicating arteries, potentially propagating embolic material distally.

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Disclosures

DKL is a paid consultant for Stryker. All other authors (HO, YM, AM, JC, DMH) have no conflicts of interest to disclose.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi: 10.1016/j.jstrokecerebrovasdis.2019.05.015.

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