Robotically Facilitated Parafasicular Microsurgery to a Brain Arteriovenous Malformation in a Paediatric Patient

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Purpose of the article:
We report what we believe is the first application of robotically constrained image-guided surgery to approach a fistulous micro-arteriovenous malformation in a highly eloquent location.
Drawing on institutional experience with a supervisory-control robotic system, a series of steps were devised to deliver a tubular retractor system to a deeply situated micro-arteriovenous malformation. The surgical footprint of this procedure was minimised along with the neurological morbidity. We hope that our contribution will be of assistance to others in integrating such systems given a similar clinical problem.

Clinical Presentation:

A right-handed nine-year old girl presented to her local emergency department after a sudden onset of severe headache accompanied by vomiting. An intracranial haemorrhage centred in the right caudate nucleus body with intraventricular extension was evident and she was transferred urgently to the regional paediatric neurosurgical centre, where an external ventricular drain (EVD) was sited
A digital subtraction angiogram demonstrated a small right hemispheric arteriovenous shunt irrigated by peripheral branches of the middle cerebral artery & a robotically facilitated parafasicular microsurgical approach was performed to disconnect the arteriovenous malformation.

Conclusion:

We describe the successful microsurgical in-situ disconnection of a deeply-situated, fistulous micro-AVM via a port system itself delivered directly to the target with a supervisory-control robotic system. This minimised the surgical disturbance along a relatively long white matter trajectory and demonstrates the feasibility of this approach for deeply located arteriovenous fistulae or fistulous AVMs.

Running title:

Robotically Facilitated AVM microsurgery

Keywords:

Robotic, Arteriovenous, microsurgery, Neuronavigation, Neuromate®

Background and Importance.

We report what we believe is the first application of robotically constrained image-guided surgery to approach a fistulous micro-arteriovenous malformation in a highly eloquent location.

Endovascular and radiosurgical treatments will frequently offer a minimally invasive alternative to microsurgery for intracranial arteriovenous shunts. This case illustrates a rare situation where these alternatives were not considered optimal. Drawing on institutional experience with a supervisory-control robotic system used in our functional and epilepsy program, a series of steps were devised to deliver a tubular retractor system to a deeply situated micro-arteriovenous malformation. The surgical footprint of this procedure was thus minimised along with the neurological morbidity. We describe the adaption of the existing tool holder to make this feasible in the hope it will be of assistance to others in integrating such systems given a similar clinical problem.

Clinical Presentation.

History.

A right-handed nine-year old girl presented to her local emergency department after a sudden onset of severe headache accompanied by vomiting. On arrival she was not eye-opening, localising with the right side only and making incomprehensible sounds. She was sedated, intubated, ventilated, and transferred to the CT scanner.

She had no previous medical history with no contributary family history of cerebrovascular disease. No cutaneous stigmata of neurological disease were found on examination.

An intracranial haemorrhage centred in the right caudate nucleus body with intraventricular extension was evident (Figure 1), and she was transferred urgently to the regional paediatric neurosurgical centre, where an external ventricular drain (EVD) was sited to assist in the management of intracranial hypertension. CT angiography was non-diagnostic.

A digital subtraction angiogram including super-selective microcatheter angiography via the M3 branches of the middle cerebral artery demonstrated a small right hemispheric arteriovenous shunt irrigated by peripheral branches of the middle cerebral artery and draining centrally via the thalamostriate vein ultimately to the Galenic system (Figure 2). No other cerebrovascular lesions were demonstrated. There may be a tiny, diffuse nidus proximal to the origin of the draining vein. Our evaluation was that this constituted a Spetzler-Martin Grade 3 (S1 E1 V1), Spetzler-Ponce Class B and Lawton-Young Supplemental Grade 5 (SM3+2) fistulous micro-arteriovenous malformation. It could be argued that the angioarchitecture should be regarded as a subpial arteriovenous fistula, but we submit the distinction has no particular implications for the natural history or therapeutic strategy in this particular case.

This lesion was not deemed favourable for endovascular embolisation by transarterial or transvenous routes. An additional external opinion from another paediatric neurovascular service concurred with that opinion.

With the EVD in-situ and strict blood pressure control, her sedation was gradually weaned. She recovered consciousness quickly with a left hemiparesis that improved rapidly over a few days. Once the blood in her ventricles had cleared, the drain was removed. By ten days since her haemorrhage she was independently mobile with mild left-sided dyspraxia and short-term memory impairment. She was discharged pending further investigation and opinions.

The lesion was re-evaluated with further angiography once the local mass effect had abated in case this had compressed part of a nidus on the initial angiography. No significant architectural changes to the description above were found. Inevitably with the resolution of the haematoma the surgical target had become very small (Figure 3).

Microsurgical treatment was felt to be of relatively high risk given the minute size and eloquent location of this arteriovenous shunt in a by-now neurologically intact child. Her case was discussed at the regional radiosurgical multi-disciplinary team meeting, but it was agreed there that stereotactic radiosurgery was not optimal given the fistulous architecture as well as the recent history of haemorrhage. It was again agreed that this lesion was not amenable to endovascular treatment.

It was decided to surgically target the arteriovenous transition point at the formation of the draining vein, via a pre-planned parafascicular trajectory utilising a tubular retraction system designed to minimise trauma to the adjacent white matter. In an attempt to maximise accuracy, we utilized a robotic system which has become the standard means of delivery for deep brain stimulation electrodes and intracranial recording electrodes in our department.

After several rehearsals with a phantom model the series of surgical steps described below was settled upon. Patient informed consent was obtained for surgery including photography and scientific submission. Ethics committee approval was not required as this was not a part of any research study.

Operative Procedure

Under general anaesthesia the patient was positioned prone with her head fixed slightly rotated in the Leksell Frame (Elekta Ltd, Crawley, UK). A CT scan was performed with the O-Arm (Medtronic UK) and registered using the Neurolocate 3D system (Renishaw, Gloucestershire, UK). This scan was fused with pre-operative CT, MR structural and diffusor tensor imaging to plot a parafascicular trajectory to target (Figure 4). The Neuromate Robot (Renishaw, Gloucestershire, UK) was brought into the field (Figure 5) A ventricular catheter was placed over a Neuroguide (R) Guide Rod (Renishaw, Gloucestershire, UK) and advanced to the target. Subsequently, it was secured in place as a fiducial (Figure 6).

The patient was transferred to the angiography suite where digital subtraction angiography confirmed placement of the catheter at target (Figures 7a and 7b). Returning to the operating room she was repositioned with the head held in Mayfield pins and an adjacent and converging course was plotted to deliver a 12x70 mm *Viewsite Brain Access System* (VBAS) port (Vycor Medical Inc., Boca Raton, FL, USA) to the same target at which time the orange ventricular catheter could be clearly seen through the transparent wall of the port.

The arterialised vein was identified within the white matter just ahead of the port, coagulated and divided (Figures 8a and 8b).

Postoperatively, the patient had no new neurological deficits. She was discharged home after short in-hospital stay. At 6 months follow up, Digital subtraction angiogram study confirmed complete extirpation of the arteriovenous malformation (Figures 9a and 9b).

Methods:

A comprehensive literature search was performed to determine if there had been previous reports of this technology being applied to definitively treat an arteriovenous shunt in the brain. PubMed, Ovid MEDLINE, Embase and Cochrane library databases from database inception until November 2021 to identify relevant articles were interrogated. Google scholar was searched as a supplementary source. Appropriate keywords and MeSH terms were used to identify all studies: ("Intracranial Arteriovenous Malformations"[MeSH Terms] OR "Arteriovenous Malformations"[MeSH Terms] OR "arteriovenous*"[Title/Abstract]) AND ("robotic surgical procedures/adverse effects"[MeSH Terms] OR "robotic surgical procedures/classification"[MeSH Terms] OR "robotic surgical procedures/economics"[MeSH Terms] OR "robotic surgical procedures/instrumentation"[MeSH Terms] OR "robotic surgical procedures/methods"[MeSH Terms] OR "robotic surgical procedures/mortality"[MeSH Terms] OR "robot*"[Title/Abstract]).

Experimental, In-vitro, animal studies and non-English language papers were excluded as were studies pertaining exclusively to robotically-assisted radiosurgery, tumour surgery or endovascular treatment. Five papers met the inclusion criteria (1 literature review, 3 Cohort studies and 1 case report).

Discussion.

The introduction of robotic stereotaxy has generally been predicated on minimising human error in following a pre-determined trajectory while guiding or constraining the human hand. Robotic surgical systems are broadly classified as(Nathoo *et al.* 2003)(Faria *et al.* 2015) :

Telesurgical (Controller/Responder): A manipulator tool is remotely and directly controlled by the surgeon.

Shared-control*:* The control over movement is shared with the human surgeon subject to steady-hand manipulation or active-restrain of surgical movement within the defined field

Supervisory-Control*:* The robotic movement is pre-programmed offline by the operator, allowing autonomous movement during the programmed procedure

Literature Review

The Unimation PUMA (Programmable Universal Machine for Assembly) industrial robot was the first used for CT guided stereotactic biopsy of a deep intracerebral lesion. Although needle advancement and biopsy were achieved manually, the capacity of a robot to accurately position the biopsy needle was a technological first(Kwoh *et al.* 1988).

Gonen L et al.(Gonen *et al.* 2017) described five brain AVM surgeries in their series where visualization was robotically controlled on an integrated arm.

Chakravarthi S et al.(Chakravarthi *et al.* 2018) reported a similar application of robotically controlled visualization (ROVOT-m; Synaptive Medical, Toronto, Canada) to direct the delivery of a tubular port to one pedicle of a pial occipital arteriovenous malformation.

The novel aspect to our case in the cerebrovascular setting is that the subcortical corridor was entirely constrained by the robotic system once programmed unlike the reports cited above. No other surgical corridor was available to reach the malformation. We have institutional experience with image-guided delivery of retractor ports to subcortical vascular malformations assisted by robotically controlled exoscopes. The procedure described in this report further reduced the variation from the planned trajectory inevitable with a manually directed placement and is therefore likely to have minimized the trauma to neurological tissue adjacent to the VBAS port.

In open cerebrovascular applications shared-control systems have yet to develop to a point where there is demonstrable advantage over conventional microscopic/ 3D exoscopic bimanual surgical techniques. Robotically assisted visualisation has made its way into clinical practice to complement conventional microsurgical technique (Bohl *et al.* 2016)(Belykh *et al.* 2018). Robotic manipulators or effectors have generally been limited to haematoma evacuation and the degree to which they add significant value in that scenario remains undetermined (Swaney *et al.* 2013)(Burgner *et al.* 2013). More commonly they have been utilised to steady and manoeuvre endo-, exo- and microscopic imaging systems.

Transoral resections of retropharyngeal, glottic, abdominal and mediastinal vascular malformations utilising telesurgical robotic systems have been reported (Sasankan *et al.* 2021)(Fuglsang and Kjærgaard 2018)(Zdanski *et al.* 2017)(Ferrell *et al.* 2014)(Chen *et al.* 2020). These authors have documented the feasibility of secure haemostasis although many cases are relatively low-flow veno-lymphatic malformations and/or are amenable to adjunctive embolisation. Thus, the operating conditions in such cases may not reflect what is optimal in addressing an arteriovenous malformation within the brain and the very limited tolerance of neurological tissue for retraction or resection.

In principle the surgical procedure for our patient was straightforward. This was a micro-AVM with a tiny, diffuse nidus facilitating a shunt via a single deep draining vein. It was located in highly eloquent white matter. The strategy we favour in that situation is of *in-situ* disconnection with division of the draining vein at its "transition point" from the nidus. This technique has been described in detail by other authors(Velat *et al.* 2012)(Han *et al.* 2015) and we had previously used it with gratifying results in highly-eloquent arteriovenous shunts of the brain and spinal cord.

The challenge lay with obtaining access to this lesion to afford disconnection as it did not present to a pial surface and the patient was neurologically intact. A transcortical transventricular route afforded access only to the more distal part of the draining vein (the *thalamostriate vein*) in the lateral ventricle wall. Following that vein transependymally from that route would transgress the posterior limb of the internal capsule. A parafasicular transcortical trajectory offered a safer course but at the expense of a much longer white matter corridor.

Stereotactic approaches are well established in functional neurosurgical procedures such as deep brain stimulation (DBS) and stereo-electroencephalography (SEEG) electrode implantation. They are well suited to deliver a fiducial close to very small anatomical lesions such as this vascular malformation. In our own experience with the Neuromate® robot in children undergoing implantation of DBS electrodes, the mean target point error was 1.69 mm(Furlanetti *et al.* 2021). This degree of precision allows a fiducial to be placed with confidence at close proximity to a deeply seated lesion to enable microsurgical dissection, and provides a direct corridor which minimises tissue manipulation on the way in.

An advantage of robotic technology over conventional frames is the requirement for fewer manual calculations and intraoperative adjustments, which may reduce additional errors and improve accuracy(Neudorfer *et al.* 2018). The Neurolocate 3D® registration system is a frameless platform that registers the position of the robot arm directly to the head without reliance on a stereotactic frame, allowing ease in patient positioning without impact on accuracy for cases such as this which required a prone position with the head rotated to facilitate better access to perform the craniotomy. In this case the Leksell Frame served as a rigid head holder rather than as a stereotactic apparatus. Use of the most rigid head-holding system available is necessary to maximise accuracy with this robotic system. An adaption of the Sugita Frame is also available for this application. A major disadvantage of this arrangement is the fixed head position and the inability to alter this during surgery.

Our decision to place a catheter fiducial and confirm localisation with intraoperative angiography reflected firstly, a degree of caution and secondly, the requirement to transfer to an adjacent dedicated biplanar angiography suite. This step could be dispensed with in a hybrid operating room equipped with biplanar facilities and the VBAS port delivered, secured and angiography immediately carried out.

Catheter angiography at six months postoperatively confirmed continued exclusion of the arteriovenous shunt by which time our patient had returned to normal physical activities and full-time education.

Conclusion.

We describe the successful microsurgical in-situ disconnection of a deeply-situated, fistulous micro-AVM via a port system facilitated by a supervisory-control robotic system. This minimised the surgical disturbance along a relatively long white matter trajectory and demonstrates the feasibility of this approach for deeply located arteriovenous fistulae or fistulous AVMs. We anticipate that the development of dedicated tool holders for the delivery of access ports and integration with hybrid-neurovascular operating facilities will offer lower morbidity microsurgical options for such lesions than has been the case to date.

Disclosures:

Funding: No funding was received for this research.

Conflict of Interest: No Conflicts of Interest:

Ethical approval: This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent: Informed consent was obtained from all individual participants included in the study.

Details of Previous Presentation:
This case was presented in abstract as a part of:
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Daniel C Walsh
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Fig 1: Post-operative CTH showing an external ventricular drain (EVD) in situ following the acute presentation with right caudate nucleus intracranial haemorrhage with intraventricular extension.

Fig 2: A digital subtraction angiogram demonstrating a small right sided arteriovenous shunt irrigated by peripheral branches of the middle cerebral artery and draining centrally via the thalamostriate vein to the vein of Galen.

Fig 3: T2 weighted MRI brain showing resolution of the previously described haemorrhage rendering the surgical target very small.

Fig 4: pre-op planning after fusion of CT, MR structural and diffusor tensor imaging to design a parafascicular approach utilising a tubular retraction system simulation model.

Fig 5: Panoramic view of the operative room showing the Robot (Renishaw, Gloucestershire, UK) and the O-Arm (Medtronic UK) around the operating table to which the patient was fixed in a prone position using Leksell Frame (Elekta Ltd, Crawley, UK).

Fig 6: ventricular catheter placement over a Neuroguide (R) Guide Rod (Renishaw, Gloucestershire, UK).

Fig 7a and 7b: Intra op digital subtraction angiography confirming placement of the ventricular catheter at the designated target.

Fig 8a and 8b: The arterialised vein identified within the white matter just ahead of the port using Indocyanine green angiography (ICG), coagulated and divided.

Fig 9a and 9b: Digital subtraction angiogram showing complete resolution of the avm during both arterial & venous phase.