Case series

Definitive treatment of seizures due to hemimegalencephaly in neonates and young infants by transarterial embolization: technical considerations for 'endovascular embolic hemispherectomy'

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ABSTRACT

Background This case series describes the technical considerations and effectiveness of 'endovascular embolic hemispherectomy' for the treatment of medically intractable seizures in neonates and young infants with hemimegalencephaly (HME) and in whom surgical hemispherectomy is not a viable option.

Methods This is a descriptive review of the endovascular technique used to treat consecutive pediatric patients with serial transarterial embolization for intractable seizures due to HME between 2018 and 2022. Clinical presentation, endovascular procedural details and complications, and efficacy were examined.

Results Three infants (13-day-old, 13-week-old and 15-day-old) with HME and intractable seizures underwent a total of 10 transarterial embolizations. Anticipated intraprocedural events included vasospasm and focal subarachnoid hemorrhage in all three infants, effectively controlled endovascularly, and non-target embolization in one infant. No infants had symptomatic intracranial hemorrhage or femoral artery occlusion. EEG background quiescence and seizure cessation was achieved after the final stage of embolization in all patients. All infants were discharged home from the neonatal ICU (median length of stay 36 days, range 27–74 days) and remain seizure-free to date (4 years, 9 months, and 8 months). None have developed hydrocephalus, required surgical hemispherectomy or other neurosurgical interventions.

Conclusion Endovascular hemispherectomy can be safely used to provide definitive treatment of HME-related epilepsy in neonates and young infants when intraprocedural events are managed effectively. This less invasive novel approach should be considered a feasible early alternative to surgical hemispherectomy. Further studies are needed to enhance the safety profile and to assess long-term neurodevelopmental outcome and durability of freedom from seizures.

INTRODUCTION

Hemimegalencephaly (HME) is a rare hamartomatous congenital brain malformation that involves unilateral asymmetric lobar or hemispheric enlargement. Cortical abnormalities include polymicrogyria, lissencephaly and variable degrees of heterotopia caused by a combination of neural proliferation and cell migration dysfunction.[1] Neurologic features are dominated by epilepsy, severe psychomotor retardation, contralateral hemiparesis and homonymous hemianopia.[2] Seizure onset is generally before 6 months of age (mean onset <1 month),[3] typically refractory to multiple anti-seizure medications (ASMs), and can evolve to epileptic encephalopathy. This unrelenting seizure activity is associated with up to 20% risk of mortality[4–6] and impairs cognitive and functional brain development reported in one series of a 10-point developmental quotient decline for each month delay.[7]

Anatomic or functional hemispherectomy are established neurosurgical treatment options and are recommended for effective seizure control and improved neurodevelopmental outcome in patients with HME. Early hemispherectomy in the neonate, however, is also associated with high surgical risks[8] including significant intraoperative blood loss, coagulopathy, and intraoperative death. Given these risks and association with longer hospitalization and high mortality,[7 9 10] most neurosurgeons defer surgical hemispherectomy until the patient is at least 8 weeks old. This delay comes at a significant neurocognitive cost as the uncontrolled seizures during this time of deferred surgery have a deleterious effect on future neurocognitive outcome.

Our group first described staged transarterial embolization to achieve rapid seizure reduction in neonates awaiting anatomic hemispherectomy for drug-resistant epilepsy due to HME.[11] We now propose endovascular hemispherectomy as a valid and preferred alternative approach to anatomic or functional hemispherectomy in newborn and early infants who are too young for surgical hemispherectomy. We describe our endovascular approach and experience in three recent cases, approved by the IRB as part of our Pediatric Epilepsy Research Consortium (protocol 02383).

CASE SERIES

Case 1

A 3.42 kg girl born at 39 weeks and 1 day from an uncomplicated pregnancy presented with clinical

Table 1 Anti-seizure medication regimens before and after embolization

Case no	Regimen prior to embolization	Regimen after embolization
1	Phenobarbital, fosphenytoin, levetiracetam, topiramate, oxcarbazepine, midazolam infusion	Levetiracetam, oxcarbazepine, clobazam, vigabatrin
2	Phenobarbital, fosphenytoin, levetiracetam, lacosamide, vigabatrin, lorazepam	Phenobarbital, levetiracetam, topiramate, vigabatrin
3	Phenobarbital, fosphenytoin, levetiracetam, topiramate, midazolam infusion	Phenobarbital, levetiracetam, topiramate

seizures on the first day of life (DOL). Seizures rapidly progressed despite phenobarbital, levetiracetam, fosphenytoin, and topiramate. Brain MRI revealed left HME. She became increasingly encephalopathic from daily seizures and multiple ASMs. Surgical options were discussed but were not considered safe given her age and weight. Her parents elected to pursue endovascular hemispherectomy to maximize her developmental potential. She was transferred to our center on DOL 8.

The seizures originated predominantly in the left posterior region with a baseline seizure burden of 1–10 electrographic seizures per hour despite five ASMs and a continuous midazolam infusion (table 1). After multidisciplinary consensus within our level IV Comprehensive Pediatric Epilepsy Center and extensive family discussions, she underwent staged transarterial embolization beginning at DOL 13. Branches of the left posterior cerebral artery (PCA) followed by the branches of the left middle cerebral artery (MCA) were sequentially embolized with n-butyl cyanoacrylate (NBCA). After the third embolization in this first stage, subtle vasospasm was noted in the temporo-occipital branches of the left MCA on the microcatheter injection (figure 1). After the microcatheter was withdrawn slightly proximally, a small amount of focal contrast extravasation was identified on the repeat microcatheter injection, and this was immediately glued. No hemodynamic changes were observed. Control angiography via the left internal carotid artery (ICA) was performed and showed no residual contrast extravasation, and the remainder of the anterior cerebral artery (ACA) and MCA branches were patent. One week later, the second stage of embolization was performed for the remaining left PCA branches as well as left ACA branches. Nine days later (DOL 29), the third (final) stage of embolization for the remaining left ACA was completed. The proximal A2 was coiled to prevent non-target embolization of liquid embolic to the contralateral ACA territory (figure 2).

The patient tolerated her embolization sessions well and the seizures stopped midway during the third stage of embolization with significant attenuation of all EEG activity over the abnormal left hemisphere. Her femoral arteries remained patent, documented by femoral ultrasounds after each stage. Post-embolization brain MRI confirmed complete embolization of the entire left hemisphere, sparing the basal ganglia. To date, she is seizure-free after more than 4 years and has not required anatomic hemispherectomy or other neurosurgical procedures.

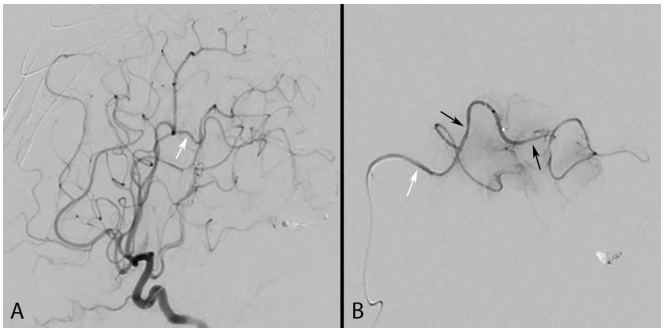

Figure 1 Subtle vasospasm in case 1. Lateral views from (A) the left internal carotid artery and (B) the left temporo-occipital branches of the left middle cerebral artery show subtle vasospasm (black arrows). After withdrawing the microcatheter to the slightly more proximal location (white arrows), small focal contrast extravasation was identified and immediately controlled without complications.

Case 2

A 4.36 kg boy was born at 37 weeks and 5 days by scheduled cesarean section after late prenatal studies revealed right HME and right ventriculomegaly. Postnatal evaluation was significant for right facial lipomatous hypertrophy and brain MRI for right HME involving the basal ganglia, cerebellum, and vermis due to a mosaic PIK3CA mutation. Focal motor seizures started on DOL 1 and were refractory to phenobarbital, levetiracetam, and lacosamide (table 1). Infantile spasm was diagnosed on DOL 37 and was refractory to high-dose prednisolone and vigabatrin. A ventriculoperitoneal shunt was placed on DOL 79. He presented to us on DOL 84 for a second opinion. The parents elected to pursue endovascular hemispherectomy rather than functional hemispherectomy.

Our comprehensive evaluation confirmed the studies performed by the local specialists, which showed decompression of the right obstructive hydrocephalus, ruled out vascular malformations to the brain and spine, and uncovered adrenal insufficiency. His seizure burden was 4–7 clusters of spasms per

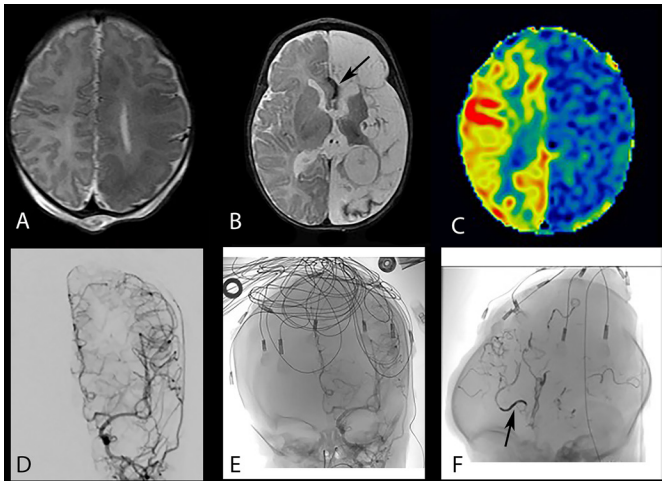

Figure 2 MRI and angiographic images before and after embolization in case 1. (A) Axial T2 image before embolization shows the enlarged dysplastic left cerebral hemisphere. (B) Axial T2 image 5 weeks after embolization shows the coils (arrow) in the left A2 segment, left hemispheric cystic encephalomalacia, preservation of the basal ganglia, and compensatory enlargement of the left lateral ventricle. (C) Axial CBF shows diffuse left hemispheric hypoperfusion. (D) Frontal projection from a left common carotid artery angiogram shows an elongated left middle cerebral artery. (E,F) Frontal and lateral unsubtracted views show the difference between optimal (F) and suboptimal (E) EEG wire placement. Coils in the left A2 segment (arrow) are seen in (F).

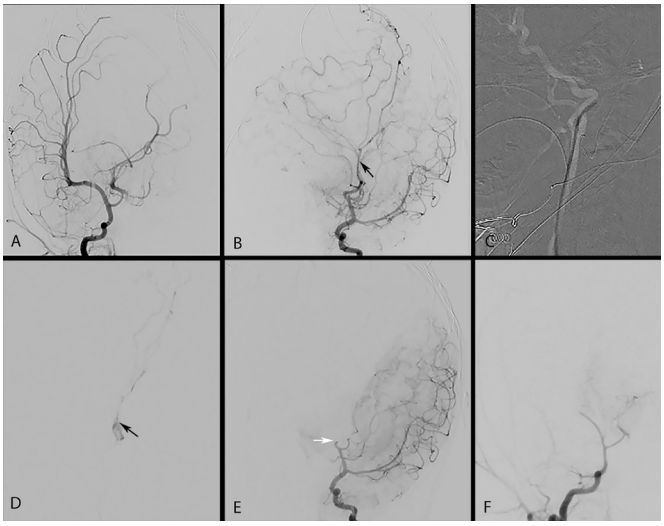

Figure 3 Frontal and lateral angiographic views in case 2. Anteroposterior views from (A) right and (B) left internal carotid artery (ICA) angiograms showing the right anterior cerebral artery (ACA) and posterior cerebral artery (PCA) territories displaced across the midline. A hypoplastic right A1 segment is present. (C) Lateral view from a left cervical ICA roadmap showing a 4 Fr catheter placed in the cervical ICA proximal to the marked tortuosity. (D) Microcatheter injection at the right A2–A3 junction shows a small focal area of contrast extravasation (arrows in D and B for reference) which was embolized with n-butyl cyanoacrylate. Control angiograms via the left ICA (E) and right ICA (F) show no residual contrast extravasation, occlusion of the right ACA at the A2 segment (white arrow), and preservation of the left ACA and MCA.

day and one focal motor seizure per hour. His interictal EEG was significant for hypsarrhythmia on the right.

He underwent three stages of embolization on DOL 99 (14 weeks), 106, and 111. During the first stage, mild vasospasm was noted during a microcatheter injection after the second embolization of the right PCA territory. The vasospasm was effectively treated by slowly infusing 1 mL of 0.1 mg/mL nicardipine IA through the microcatheter. No hemodynamic changes were observed. Multiple branches of the right MCA and remaining PCA were embolized uneventfully during the second stage. The final stage of embolization for the right ACA was targeted via the left ICA due to the hypoplastic right A1 segment. Vasospasm was again noted after one glue embolization and was treated with 1 mL of nicardipine IA. During the second glue embolization of the anterior internal frontal branch of the right ACA, reflux of glue on the distal microcatheter tip was noted. After removing the microcatheter, control angiography showed a small amount of contrast extravasation at the right A2–A3 junction. IV protamine was administered and a new microcatheter, which was already prepared on the back sterile table, was rapidly advanced to the point of extravasation at the A2–A3 junction and this was glued (figure 3). No residual contrast extravasation was noted from the left ICA angiogram. The right ICA was then catheterized to ensure no residual flow to the distal right ACA from the right. He remained hemodynamically stable and tolerated the procedure well.

Seizures stopped during the third stage of embolization with attenuation of all EEG activity over his right hemisphere after a few days. Post-embolization brain MRI confirmed complete right hemisphere embolization with preservation of the basal ganglia. He was discharged home 13 days later and remains seizure-free (to date 9 months).

Case 3

A 3.22 kg girl was born at 39 weeks and 5 days by scheduled cesarean section after an unremarkable pregnancy. Focal motor seizures started at 2 hours of life and were refractory to phenobarbital and levetiracetam (table 1). She had right facial lipomatous hypertrophy and postnatal imaging revealed right HME. The parents elected to pursue endovascular hemispherectomy for treatment. She was transferred to us on DOL 12.

After comprehensive evaluation, she underwent four stages of embolization on DOL 15, 20, 28, and 33. The right MCA and PCA were targeted during the first and second stages. During her second stage, focal contrast extravasation was noted during a microcatheter injection in the anterior temporal artery. This was immediately glued without associated hemodynamic changes or complications. The PCA and ACA territories were embolized during her third and fourth stages and were complicated by small areas of non-target embolization in the left PCA and ACA territories. She also demonstrated moderate vasospasm that was responsive to IA nicardipine. The patient remained hemodynamically stable during all four stages of embolization and tolerated the sessions well.

Her hourly seizures stopped after the third stage and attenuation of all EEG activity over her right hemisphere occurred after the fourth stage. Genetic studies confirmed mosaic PIK3CA mutation. Post-embolization brain MRI confirmed right hemisphere embolization. She was discharged home 15 days later and remains seizure-free (to date 8 months).

BEFORE THE PROCEDURE

A multidisciplinary surgical epilepsy evaluation is performed for neonates or very young infants with HME referred for refractory epilepsy. The team includes a comprehensive level IV pediatric epilepsy program with pediatric epileptologists and pediatric epilepsy neurosurgeons, pediatric neurointerventional radiology, level IV neonatal intensive care unit (NICU), and neonatal neurocritical care to review outside clinical history and diagnostic work-up. Our criteria for infants to be considered potential candidates for endovascular hemispherectomy were to have refractory epilepsy, age or weight considered high risk for standard neurosurgical hemispherectomy, absence of medical conditions to substantially increase the hematologic risk associated with an endovascular approach, and absence of genetic conditions associated with severely limited neurodevelopmental outcome. Candid family discussions of the natural history of HME-related epilepsy and neurodevelopmental outcome, and risks and benefits of medical, neurosurgical, and endovascular options are essential to an informed consent process. The risks of endovascular hemispherectomy via transarterial embolization including femoral arterial occlusion, uncontrolled hemorrhage, non-target embolization, and death must be explicitly discussed.

Potential candidates are then transferred for a comprehensive preoperative medical and epilepsy evaluation. Medically optimizing seizure control and obtaining high-resolution anatomic and vascular brain images are prioritized. Hematology, endocrinology, genetics, ophthalmology, and anesthesiology evaluations are completed to fully assess risks. Brain MRI and MRA of the head and neck are obtained to identify anatomic variants, vascular loops or marked tortuosity, and to delineate the arterial distribution prior to angiography. The enlarged cerebral hemisphere distorts the vascular territories. Of note, the PCA and ACA territories can be markedly displaced across the midline,

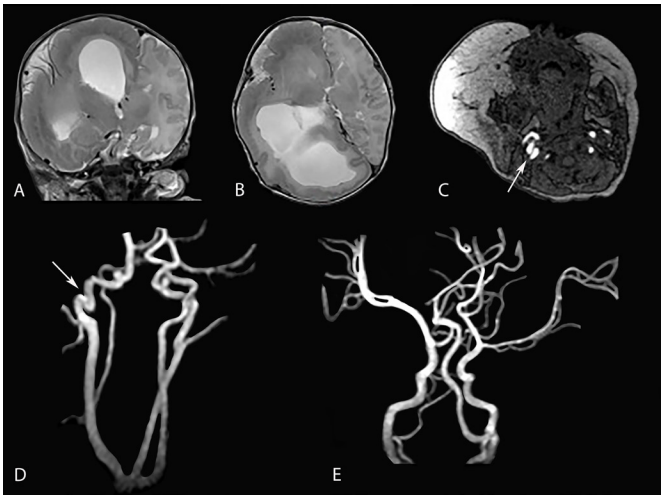

Figure 4 Pre-procedure MRI and MR angiography (MRA) images from case 2. (A) Coronal and (B) axial T2 images show a dysplastic right cerebral hemisphere with ipsilateral ventriculomegaly, midline shift, and mass effect on the contralateral hemisphere. Axial time-of-flight MRA (C) and maximum intensity projection MRA images of the neck (D) and head (E) show the vascular loop of the right internal carotid artery, tortuosity of the cerebral vessels, and variant anatomy, all important considerations for embolization.

projecting over the contralateral hemisphere on the frontal angiographic views (figure 4).

PROCEDURAL CONSIDERATIONS

Anesthesia

The procedure is performed under general endotracheal anesthesia. A pediatric anesthesiologist accustomed to intubating and managing neonates with multiple drug infusions and potential hemodynamic fluctuations is critical. Atraumatic intubation is essential to reduce the risk of airway trauma associated with successive procedures over a few weeks. Sevoflurane can be used for rapid induction; however, isoflurane is preferred to maintain anesthesia as it is less epileptogenic.[12] The procedure should be reviewed with the anesthesiologist, including potential complications and mitigation strategies, ASM dosing regimen, line placement to minimize excess wires around the head and neck, use of a paralytic, and temperature and mean arterial pressure goals (table 2).

Temperature control

Body heat is quickly lost in young infants and deliberate efforts to maintain normothermia (36–37°C) must be made. The baby should be kept covered as much as possible while in the angiography suite with a tabletop warmer and supplemental external warming device. Core temperature should be assessed using a rectal probe rather than an esophageal probe to minimize additional radiopaque devices in the head and neck region.

EEG

EEG leads are placed on the scalp in the NICU prior to angiography with wires arranged to optimize views of the cerebral hemisphere (figure 2) without obscuring angiographic views. Continuous EEG monitoring by the epilepsy and neonatal neurocritical care teams throughout the procedure helps guide the real-time response to anesthesia and to seizures provoked by embolization.

Table 2 Intraoperative checklist

Intraoperative checklist	
Anesthesia	**Radiation**
GETA: isoflurane	Grids out
Paralytic, no antibiotics	Pediatric low-dose protocol
Discuss frequent breath holds, MAP and temperature goals, ASM administration	
	Heparin
Monitoring devices	1000 units per 1 L NS flush bag
Blood pressure cuff	No IV heparin bolus after arterial access
Arterial line	Have protamine available
O_2 saturation probe	Check baseline activated clotting time after femoral access
EKG and EEG leads	
Temperature probe (rectal)	**Recovery plan**
No Foley	Keep intubated, return to NICU

ASM, anti-seizure medication; GETA, general endotracheal anesthesia; MAP, mean arterial pressure.

Positioning, supplies, and preparation

Radiation scatter grids should be removed and a pediatric low-dose protocol selected.[13] While creating and storing baseline cerebral frontal and lateral working projections, the positions of the endotracheal tube, EEG and EKG leads should be checked, adjusting as needed to optimize visualization during subsequent catheter navigation. All catheters and supplies including microcatheters and a separate glue table should be prepared. Our current practice is to have a second microcatheter flushed and prepared on the sterile table, rendering rapid microcatheter availability if needed immediately. Contrast syringes should be filled using dilutions of 50% (1:1 contrast to saline ratio) or less, as contrast administration is limited in a 3–4 kg neonate (~4–6 mL/kg maximum).[14] This should all be prepared prior to obtaining femoral arterial access, thereby limiting the sheath duration time in the femoral artery.

Circulating heparin in young infants can markedly prolong the activated clotting time (ACT), especially for long procedures with flush lines infusing the femoral sheath, guide catheter, and microcatheter. Administer 1000 units of heparin for each 1 L normal saline bag. An IV heparin bolus is not administered after femoral arterial access is achieved.

Femoral access

Successfully obtaining femoral arterial access in infants <3 months of age is technically challenging and must be performed cautiously.[14 15] Ultrasound using a high-frequency small-footprint linear array transducer (ie, hockey-stick probe) is helpful to assess size and patency of the common femoral artery and to guide the single wall puncture using a 21G needle. The hub of the needle should be checked to ensure pulsatile arterial flow and a portion of the 0.018 inch guidewire should be gently advanced, recognizing that the included guidewire (eg, 40 cm for a 4 Fr Prelude Ideal sheath, Merit Medical) is nearly the average length of a full-term neonate. Wire advancement should be without resistance and position can be confirmed with fluoroscopy. If arterial access is not achieved after two attempts, ultrasound may show vasospasm that is unlikely to resolve immediately and accessing the contralateral femoral artery should be considered instead. Check an ACT after arterial access, minimizing the volume collected from the femoral sheath. Gently flush the 4 Fr arterial sheath

with heparinized saline and connect to a pressurized heparinized saline flush bag with an intervening flow limiter to prevent inadvertently infusing a large volume of heparinized saline.

Catheter choice and positioning

A 4 Fr catheter is advanced over a 0.035 inch guidewire and the right or left common carotid artery is selectively catheterized. Biplane roadmap of the neck is performed, and the catheter can be advanced over saline into the ICA proximal to any vascular loops often encountered in neonates and young infants (figures 3 and 4). A 4 Fr catheter situated proximally in the cervical ICA does not provide a rigid support system that one may be accustomed to for neurointerventions in adults and older teenagers; however, the risks of ICA vasospasm or dissection are less with this position and, more often, it is sufficient for distal intracerebral microcatheter navigation.

Choose microcatheters that will enable the safest intracerebral arterial navigation and allow for the type of embolic agent chosen (eg, NBCA or coils). A 1.2 Fr (Magic, Balt) microcatheter over an 0.008 inch microwire works well for distal navigation in small cerebral arteries; however, marked tortuosity extracranially and intracranially can make its use more challenging. When slightly more support is desired, yet still in a highly trackable low-profile system, a 1.7 Fr (Prowler 10, Cerenovus) microcatheter over a 0.014 inch or 0.010 inch microwire is an effective option. In scenarios most commonly in the proximal ACA, where coils rather than NBCA are likely to be used because of the potential for non-target embolization to the contralateral hemisphere with a liquid embolic agent, a 1.7 Fr microcatheter with a slightly larger inner diameter (0.017 inch Echelon 10, Medtronic) works well and can accommodate a wide array of coils and NBCA.

Choosing which arterial territory to target

The first stage of embolization should target the brain region with dominant seizure activity on EEG (typically the most dysplastic region on MRI) and lowest risk for cerebral herniation from cerebral edema (typically PCA and posterior MCA). In all our cases, seizure activity was greatest posteriorly; thus, the PCA territories were targeted during the first embolization sessions. When reviewing the pre-procedure MRA, assess the presence and size of the posterior communicating artery (PCOM). In all cases, the PCA territory could be accessed from the ICA, across the PCOM. This has the following advantages: (1) the ICA is typically larger than the vertebral artery; (2) the relative guide catheter position can be placed higher in the ICA than in the vertebral artery; and (3) the ICA injection can opacify both anterior and posterior circulations, allowing for flexibility in choosing which vessels to embolize and eliminating the need to navigate through the basilar artery.

Embolization goals and techniques

Extensive familiarity and proficiency with standard techniques for transarterial NBCA embolization is required. Disruption of cortical epileptiform activity is the goal, to be accomplished via intentional widespread arterial territorial infarction with sufficient embolic distribution throughout the hemisphere such that adjacent pial or external carotid artery collaterals do not revascularize the embolized arterial territory. The aim is to preserve the parent ICA, A1, M1, and P1 segments while achieving hemispheric embolization.

A 1:5 ratio of NBCA:ethiodized oil prolongs polymerization time without high viscosity and enhances distribution into small cortical vessels. A technique to aid in distal NBCA distribution is a modification of the 5% dextrose (D5) push, in which approximately 0.3 mL of NBCA is injected in the microcatheter followed immediately by D5 (in a 3 mL syringe), infused through the microcatheter rather than the guide catheter. Care must be taken to avoid reflux on the microcatheter. A second technique for efficient embolization is the 'glue pull' technique in which the microcatheter is carefully withdrawn during the glue embolization from its position after distal glue distribution and polymerization to a more proximal predetermined stopping point. Care must be taken to withdraw the microcatheter before glue refluxes on the microcatheter tip and to stop injecting before any large target branches to prevent blocking access to those arteries for subsequent catheterization. As with all glue embolizations, remove redundant loops in the microcatheter prior to pulling.

INTRAOPERATIVE EVENTS: RISKS, COMPLICATIONS, AND MITIGATION STRATEGIES

The setting of intentionally creating large arterial territorial strokes in neonates and very young infants with intractable seizures, distorted cerebral arteries due to HME, and intrinsically abnormal blood vessels due to associated genetic abnormalities (eg, PIK3CA) is a unique one. This high-risk scenario is compounded by the fragility and small caliber of the cerebral blood vessels in the neonatal period, which nearly reach adult size by 5 years of age,[16] and the tortuosity that must be navigated by the microcatheter to reach the distal locations in each arterial tree. Risks of vasospasm, hemorrhage, and non-target embolization must be considered and prepared for in advance to reduce the conversion risk of an intraoperative event into a potentially life-threatening complication.

Vasospasm

Vasospasm has been described as a frequent occurrence in pediatric neurointervention. It can be minimized by choosing a flexible, soft guide catheter and positioning its tip in the cervical ICA below the invariably present ICA vascular loop (figure 3). As discussed above, although this position provides less support than a more distal position, it is less traumatic to the ICA. After the first or second transarterial embolization, subtle vasospasm can be detected either at the guide catheter tip in the cervical ICA and/or intracerebrally. In our experience, vasospasm has been observed more frequently in these cases than in other cases of neonatal neurointervention, such as in vein of Galen embolization. In addition, despite the apparent small difference in age, our observations suggest that neonates exhibit more vasoreactivity after the creation of strokes than infants closer to 3 months of age. Given the high frequency of vasospasm we have observed, nicardipine (0.1 mg/mL) is readily available during the case for limited IA infusion through the guide catheter and/or microcatheter, depending on the vasospasm location. 1 mL (0.1 mg) infused over a few minutes is often sufficient to relieve the observed vasospasm without associated hemodynamic changes.

Hemorrhage

Contrast extravasation, indicative of active bleeding, is a dreadful observation and one must be prepared to handle this finding expeditiously. Standard neurointerventional techniques (table 3) can help to minimize the risk of this event. If this is encountered during the microcatheter injection of contrast prior to embolization, alert the anesthesia team, administer IV protamine (3–5 mg, depending on the duration of the case and expected ACT level), maintain normothermia, preserve the microcatheter

Table 3 Endovascular reminders

Careful smooth navigation through the cerebral vasculature	Anticipate and control the natural forward motion of the microcatheter during microwire removal, simultaneously withdrawing the microcatheter as needed to maintain the desired position
Use small-caliber soft-tipped microcatheters and microwires	Avoid/minimize NBCA reflux along the microcatheter tip
Reduce redundancy in the microcatheter prior to removing the microwire	Pull the microcatheter after NBCA embolization carefully, acknowledging that the vessels are elongated and distorted

NBCA, n-butyl cyanoacrylate.

position and inject the NBCA under negative roadmap guidance to control the area of extravasation. After occluding the rupture point, continue to infuse the NBCA while withdrawing the microcatheter until an intact vascular lumen is observed. The focal hemorrhage must be controlled effectively and quickly. If this is encountered during the control angiographic run after embolization (figure 3D), efficient microcatheter navigation to the site of hemorrhage should be performed followed by NBCA embolization. As discussed above, we typically have a second microcatheter prepared on the back table to facilitate prompt use if needed. The critical care neonatal neurology and epilepsy teams are simultaneously monitoring the EEG and may instruct anesthesia to administer additional ASM. On return to the NICU, a stat cranial ultrasound is performed to assess the hemorrhage which, if well controlled, is nearly imperceptible. Fresh frozen plasma is prophylactically administered preoperatively and post-microhemorrhages to minimize bleeding as the coagulation pathway is not yet mature in neonates.

Non-target embolization

A liquid embolic agent has the advantage of widespread distribution, which is also a disadvantage when adjacent vascular territories in the contralateral hemisphere are also supplied. Use caution when embolizing in the ACA territory, ensuring only the ipsilateral ACA territory is perfused. Consider coil embolization for the more proximal ACA (eg, A2) to limit the risk of non-target embolization.

POST-PROCEDURE CONSIDERATIONS AND TIMING BETWEEN EMBOLIZATIONS

Check an ACT prior to removing the femoral sheath, as IV protamine may need to be administered to reduce the ACT to less than 200 s. Apply manual compression, avoiding prolonged excessive pressure, to achieve hemostasis and ensure normothermia is maintained, as hypothermia makes achieving hemostasis challenging. A femoral arterial ultrasound can be obtained in the NICU between serial embolization sessions to demonstrate femoral artery patency. The patient will remain intubated and transported to the NICU, where a NICU post-embolization pathway is instituted.

In addition to continuous EEG monitoring, imaging after embolization includes daily cranial ultrasounds to monitor for bleeding and cerebral edema and an MRI/MRA on post-procedure day 4 to plan for the next stage of embolization. The time between each embolization session is based on the risk of cerebral herniation secondary to cerebral edema and adverse events such as intracranial hemorrhage. After each embolization, we wait a minimum of 4–5 days before the next embolization session to allow for reduction in cerebral edema as well as time for cerebral volume loss, which significantly reduces the risk of herniation after subsequent embolizations.

DISCUSSION

There is an unmet clinical need to control drug-resistant seizures in neonates and young infants with HME. This rare population of pediatric patients is generally considered ineligible for surgical hemispherectomy and has limited other therapeutic options. The significance of early intervention that offers the possibility of reducing or eradicating seizures during a critical time of neurodevelopment, in which no curative option exists, has prompted our group to consider innovative techniques to address this problem.

Embolization as an adjunct to surgical hemispherectomy for HME was first described by Mathis *et al* in 1995[17]. They described a newborn with HME and seizures identified at DOL 17. They performed serial transarterial embolizations of the ACA, MCA, and then PCA territories at 10-week intervals, respectively, beginning first at 10 weeks of age using particles and PVA. They demonstrated the feasibility of the technique and initial seizure control; however, they noticed recanalization of the previously embolized ACA territory over the treatment course and seizure recurrence. Their patient underwent anatomic hemispherectomy at 14 months of age. Our group was the first to describe staged transarterial embolization with NBCA in two infants treated between 7 and 9 weeks of age,[11] prior to anatomic hemispherectomy at 4 months and 18 weeks, respectively. Including our initial experience,[11] we have treated a total of seven neonates and young infants by serial transarterial embolization. The initial embolization procedures were performed as an adjunct to neurosurgical hemispherectomy and, in 2018, we began to consider embolization as a primary method for early seizure control in neonates and young infants with HME (n=3). These latter patients, described here, have had embolization as a primary therapy and have not required surgical hemispherectomy, not developed hydrocephalus, and remain seizure-free to date. Intraoperative events are frequent, yet when timely identified and addressed, the risk of conversion to complication is low.

We have demonstrated feasibility and efficacy of the technique, yet many questions remain regarding the optimal embolic agent, precise location for level of occlusion in the MCA, ACA, and PCA, and the number of and time interval between embolization sessions. The endovascular goals are to create the outcome of an anatomic hemispherectomy by effectively devascularizing the abnormal affected hemisphere. This could be stated as preserving the proximal circle of Willis (A1, M1, and P1 segments) and devascularizing everything distally such that there is no cortex or brain parenchyma remaining to generate epileptic activity. We have accomplished the hemispheric devascularization by typically starting in more distal locations—for example, M3 or M4 branches—and embolizing with the techniques described above. It is unclear, however, if the same degree of cortical disruption and hemispheric stroke resulting in cystic encephalomalacia can be created with embolization from more proximal locations. What is evident is that the endovascular creation of a complete hemispheric stroke, 'endovascular hemispherectomy', is a potentially highly effective and minimally invasive treatment option that acutely stops seizures in neonates and young infants with HME.

CONCLUSION

In our limited cohort of neonates and young infants with HME and drug-resistant seizures, endovascular hemispherectomy is feasible and safe when intra-procedural events are managed

expeditiously. This effective, minimally invasive, novel approach acutely stops seizures in this rare population. Additional studies, however, are needed to assess the durability of freedom from seizures, long-term neurodevelopmental outcome, and to enhance the safety profile of this potentially transformative technique.

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Ethics approval This retrospective case series was approved by the IRB as part of our Pediatric Epilepsy Research Consortium (protocol 02383). The purpose of this study is to create a record-based research database of patients diagnosed with epilepsy and to track their response to any form of treatment prescribed by the neurologist or epileptologist caring for their epilepsy. Protected Health Information was not disclosed but permission to share the case was obtained from the patients' parents. Participants gave informed consent to participate in the study before taking part.

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