Vein of Galen malformations are congenital lesions that result from the abnormal persistence of the median prosencephalic vein. This vein is normally present for the first few weeks of life and usually involutes, eventually regressing to form the great cerebral vein of Galen. However, in vein of Galen malformations, arterial feeders from the choroid artery can bypass the capillary system and empty directly into the anterior portion of the vein of Galen. Ultimately this process forms a persistent abnormal dilation and gives rise to the classic malformation.17 This aneurysmal dilation can cause severe developmental derangements in the neonatal population, such as high-output heart failure, fetal hydrops, cyanosis, respiratory distress, and renal failure.6 These systemic complications are due to increased venous drainage from the high-flow vascular malformation, which causes increased preload and ultimately pulmonary hypertension and heart failure. Infants can present with signs and symptoms of hydrocephalus as the vein of Galen malformation can compress the cerebral aqueduct. Infants typically present with increasing head circumference and at times developmental delay.6,8

Medical management can only temporize symptomatology but can be useful in neonates who are not yet stable enough or lack a mature enough vascular system to undergo open surgical or endovascular intervention. Historically, these malformations were almost universally fatal, and up to 100% mortality with either medical or surgical management has occurred in reported case series.9 With advances in endovascular treatments, such as coils, glue, and Onyx (Medtronic) liquid embolic agent, this rare disease has become more survivable with improved results.1,4,5,11 However, one of the difficulties that remains in endovascular treatment is the delicate deployment of these thrombotic materials into a high-flow system without propagation of the material to unwanted downstream locations.

Adenosine is a purine nucleotide that is the first-line pharmacological treatment for supraventricular tachycardias that cause hemodynamic instability in infants as well as adults.2,13 When given as a bolus dose, adenosine inhibits adenylyl cyclase, causing a hyperpolarization of the sinus and atrioventricular nodes. This can lead to cardiac standstill, which allows the atrioventricular node to reset.13 Although the use of adenosine to induce hypotension has been described in open cerebrovascular surgery since the 1980s,12,13 more recently endovascular procedures have adopted the same technique for the repair of thoracic aortic aneurysms, coronary artery stenting, and embolization of arteriovenous malformations.13,14 Multiple studies have
demonstrated that the use of adenosine for treatment of arrhythmias or in endovascular procedures in the pediatric population is both safe and effective.\textsuperscript{2,3,13} Although the technique of adenosine-induced cardiac standstill to aid in the endovascular treatment of vein of Galen malformations has been previously reported in adults,\textsuperscript{16} it has not been previously described in infants. We present here 3 instances of the use of adenosine to induce cardiac standstill in 2 infants who underwent endovascular embolization of their high-flow arteriovenous shunts.

**Case Presentations**

**Case 1**

This male infant was diagnosed with a “midline brain cyst” on prenatal ultrasonography. Despite this finding, his birth was unremarkable at 38 weeks of gestation. He was normocephalic, was neurologically intact for age, and had no signs of high-output cardiac failure or end-organ dysfunction. MRI and MR angiography (MRA) demonstrated a 10-mm left anterior frontal lobe venous aneurysm supplied by an enlarged frontopolar branch of the left anterior cerebral artery (ACA), with 2 large varices within the drainage pathway (Fig. 1A). The patient developed progressive enlargement of the venous aneurysm, enlargement of the lateral ventricles, and frank macrocephaly. At 6 months of age, he had successful coil embolization of the main arterial feeder arising from ACA. This significantly slowed the filling of the vein of Galen malformation, and follow-up imaging showed reduction in size of the malformation (Fig. 1B).

At 12 months of age, the patient underwent further endovascular treatment. The fistulous point arising from the ACA was accessed with a Marathon (Medtronic) microcatheter. Onyx 34 was slowly injected to embolize the arterial feeder, but because of the high-flow nature of the vascular malformation, an Onyx plug did not form. Several boluses of adenosine were administered in progressively larger doses to assess sensitivity and tolerability. Finally, a 5-mg bolus of adenosine (0.5 mg/kg) was sufficient to induce a few seconds of cardiac standstill. This allowed a small Onyx plug to develop, and after return to baseline cardiac function, a second 5-mg bolus was administered, allowing a larger Onyx plug to develop. This was then pushed anterograde into the fistulous point and achieved successful occlusion of the feeding vessel (Fig. 1C). Later, at 30 months of age, the patient underwent endovascular treatment of the fistulous point arising from the middle cerebral artery. Again, because of the high-flow nature of this lesion, initial efforts at creating an Onyx plug failed and again progressively larger doses ranging from 1 mg to a maximum of 0.5 mg/kg of adenosine were administered to achieve brief cardiac standstill and allow formation of an Onyx plug (Fig. 1D). The patient tolerated both procedures well, without neurological or cardiac adverse events. His progressive hydrocephalus and macrocephaly stabilized (Fig. 2), and he continued to develop normally until his last follow-up visit at 3 years of age.

**Case 2**

This male infant was found at birth to have pulmonary hypertension and early congestive heart failure. On further workup, a high-flow fistulous connection with an arterial feeder arising from the right posterior cerebral artery (PCA) and draining into a dilated persistent vein of Galen was found on MRI (Fig. 3A and B). Initially,
the child appeared neurologically intact for age and was
temporized with sildenafil for his pulmonary hyperten-
sion; however, at 12 weeks of age, his cardiorespiratory
function began to deteriorate, and neurosurgical interven-
tion was more urgently needed. During angiography, it
was clear that coils would not stay in place because of the
high-flow nature of the fistula (Fig. 3C). An initial attempt
at Onyx embolization failed, and Onyx was embolized
downstream into the distal venous system. Progressively
larger doses of adenosine were used, ranging from 1 mg
to finally a bolus of 0.5 mg/kg, which was sufficient to
induce brief cardiac standstill, allowing successful coil
embolization of the large PCA feeder. Residual flow was
still detected, so Onyx 34 was used to completely occlude
the fistulous connection (Fig. 3D). Despite his cardiorespi-
atory decompensation, the patient tolerated the adenosine
boluses and the procedure well, without neurological or
cardiac complications. His respiratory and heart function
improved immediately, and at his most recent follow-up
visit, at 3 years of age, he was developing normally with-
out any neurological or cardiorespiratory issues. MRI/
MRA demonstrated stable appearance of the vasculature
without evidence of hydrocephalus (Fig. 4).

Discussion

When left untreated, congenital vein of Galen malfor-
mations that present in the neonatal period are associated
with high morbidity and mortality, particularly when pa-
tients present early with high-output cardiac failure. Often,
surgery cannot be delayed until these neonates are large
efficient to tolerate open surgery. Additionally, open sur-
gery to obliterate these lesions can be associated with mor-
tality rates up to 91% in newborns. Consequently, endo-
vascular approaches, despite being associated with poorer
outcomes when performed in neonates, have become the
first-line method of definitive treatment. Recent improve-
ments in microcatheters and wires and development of
liquid embolic materials have improved outcomes signifi-
cantly. A recent meta-analysis of patients with vein of
Galen malformations showed that the mortality rate for
patients who underwent embolization was 10%, whereas
that for patients who did not have embolization was 47%. In
our experience with treating vein of Galen malfor-
mations, the main limitation relates to the high-flow ar-
teriovenous shunting associated with these lesions. Endo-
vascular embolization can be difficult because both Onyx
and detachable coils have poor stability within the high-
flow fistulous target. These difficulties have been reported
in other studies, and one group described the use of aden-
osine for the treatment of the high-flow fistulous point in
an adult patient with vein of Galen malformation. Another
group reported the use of rapid ventricular pacing to
reduce mean arterial pressure and blood flow to treat a
posterior choroidal fistulous connection in an infant with a
vein of Galen malformation. In both studies, decreasing
the flow was necessary for the safe embolization of the
fistulous connection.

Here, we present 3 instances in 2 infants where adeno-
sine-induced cardiac standstill allowed the controlled and
safe embolization of the high-flow fistulous connection
associated with vein of Galen malformations. The admin-
istration of adenosine was well tolerated, with spontane-
ous return of normal sinus rhythm and blood pressure, and
without adverse cardiac side effects. This was demonstrat-
ed even in our second patient, who developed cardiopul-
monary decompensation prior to endovascular treatment.
Embolization of his fistula resulted in almost immediate
resolution of his cardiopulmonary insufficiency. This is
consistent with previous reports showing that adenosine-

FIG. 3. Case 2. Vein of Galen malformation supplied largely by an enlarged branch arising from the right PCA. A and B: Axial
t1-weighted contrast-enhanced MR images showing the enlarged PCA feeder with the enlarged vein of Markowski. C: Left
vertebral artery angiogram demonstrating the high-flow shunting from the PCA branch, with early drainage into the dilated venous
system. D: Postprocedure angiogram demonstrating excellent Onyx embolization of this PCA feeder.

induced cardiac standstill is well tolerated in neonates and young infants.7,13

Conclusions
Vein of Galen malformations are associated with high rates of morbidity and mortality, particularly when they present in the neonatal period. Although medical management can help alleviate symptoms, obliteration of the high-flow fistula may be urgently required when medical management fails and cardiorespiratory decompensation develops. Here, we present an endovascular approach using adenosine-induced cardiac standstill to allow the safe and controlled embolization of the high-flow arteriovenous shunts associated with these aggressive lesions in infants.

References

Disclosures
Dr. Taussky reports a consultant relationship with Medtronic.

Author Contributions
Conception and design: all authors. Acquisition of data: all authors. Analysis and interpretation of data: all authors. Drafting the article: Yoon, Scoville. Critically revising the article: Taussky. Reviewed submitted version of manuscript: all authors. Study supervision: Taussky.

Correspondence
Philipp Taussky: University of Utah Health Care, Salt Lake City, UT. neuropub@hsc.utah.edu.