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Induction of Brain Arteriovenous Malformation in the Adult Mouse

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Summary

Brain arteriovenous malformations (bAVM) are tangles of abnormal, dilated vessels that directly shunt blood between the arteries and veins. The pathogenesis of bAVM is currently unknown. Patients with hereditary hemorrhagic telangiectasia (HHT) have a higher prevalence of bAVM than the general population. Animal models are important tools for dissecting the disease-etiopathogenesis and for testing new therapies. Here, we introduce a method that induces the bAVM phenotype through regional deletion of activin-like kinase 1 (*Alk1*, the causal gene for HHT2) and vascular endothelial growth factor (VEGF) stimulation.

Keywords

Arteriovenous malformation; Activin-like kinase 1; Angiogenesis; VEGF; Hereditary hemorrhagic telangiectasia; Mouse model

1. Introduction

Arteriovenous malformations (AVM) are tangles of abnormal, dilated vessels that directly shunt blood between the arteries and veins without a true capillary bed. It is a common phenotype in patients with hereditary hemorrhagic telangiectasia (HHT). The two main subtypes of HHT are: (a) HHT1, caused by loss-of-function mutations in the endoglin (*ENG*), a type III transforming growth factor-beta (TGFβ) coreceptor; (b) HHT2, caused by mutations in activin-like kinase 1 (*ALK1* or *ACVRL1*) gene, a type I TGFβ signaling receptor. Compared to the general population, the prevalence of bAVM in HHT1 (*ENG*) is 1000-fold higher, and in HHT2 (*ALK1*), 100-fold higher (10/100,000) (1).

Brain AVM accounts for 1–2% of all strokes (2). The malformed vessels are fragile and prone to rupture, and rupture of bAVM can lead to intracranial hemorrhage and serious neurological disability or death. The risk of intracranial hemorrhage of bAVM is about 2–4% per year (2). Patients with unruptured bAVM can develop many neurological symptoms, e.g., seizures and headache. The pathogenesis of bAVM is currently unknown (3). To better understand the underlying mechanisms of bAVM formation, it is critical to establish reproducible and reliable animal models that mimic both macroscopic and microscopic

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morphological features of the human bAVM lesional phenotype, including large dysplastic, tangled vessels and arteriovenous shunting.

Previous studies have shown that homozygous deletion of *Alk1* and endoglin results in embryonic lethality (4, 5). Interestingly, induction of *Alk1* gene deletion at the adult stage leads to AVM formation only in small intestinal, pulmonary and uterine vessels, but not in the brain (6). Our group has previously shown that vascular endothelial growth factor (VEGF) stimulation in adult *Alk1* or *Eng* heterozygous mice results in vascular abnormalities at the capillary level (7–9), which supports the response-to-injury paradigm. Thus, other than genetic modification, environmental stimulus might also be involved in the onset of bAVM formation in adults. We have successfully induced the AVM phenotype in the adult mouse brain through regional *Alk1* deletion in combination with VEGF stimulation (10).

2. Materials

2.1. Animals

Adult *Alk1*$^{2f/2f}$ mice (exons 4–6 flanked by loxP sites) (11).

2.2. Viral Vectors

1. Adenoviral vector with cytomegalovirus (CMV) promoter driving Cre recombinase expression (Ad-Cre, Vector Biolabs, Philadelphia, PA, USA).
2. Control adenoviral vector with green fluorescent protein expression (Ad-GFP, Vector Biolabs).
3. Adeno-associated viral vectors expressing vascular endothelial growth factor (AAV-VEGF) packaged in AAV serotype 1 capsid (12–14).
4. Adeno-associated viral vectors expressing β-galactosidase (AAV-LacZ) (12–14).

2.3. Viral Vector Injection

1. Isoflurane (Abbott Laboratories, Abbott Park, IL, USA).
2. 30% oxygen/70% nitrogen.
3. Anesthetic vaporizer and flowmeter (Dragerwerk AG, Lübeck, Germany).
4. Stereotactic frame (David Kopf Instruments, Tujunga, CA, USA).
5. Homeothermic temperature system (Harvard Apparatus, Holliston, MA, USA).
6. Hot Bead Sterilizers (Fine Science Tools, Foster City, CA, USA).
7. Rechargeable Cordless Micro Drill (Stoelting, Wood Dale, IL, USA).

2.4. Assorted Surgical Instruments

1. FS-2, 4-0 black silk suture (Henry Schein Inc., Indianapolis, IN, USA).
2. Microdissecting tweezers (Roboz Surgical Instruments, Gaithersburg, MD, USA).

3. McPherson-Vannas microdissecting scissors (Roboz Surgical Instruments).
4. Hamilton syringe (World Precision Instruments, Sarasota, FL, USA); forceps (Roboz Surgical Instruments).

2.5. Latex Vessel Casting

1. 25-gauge 5 ml syringe (Becton Dickinson, Franklin Lakes, NJ, USA).
2. Blue latex dye (Connecticut Valley Biological Supply Co., Southampton, MA, USA).
3. 4% Paraformaldehyde (Fisher Scientific, Pittsburgh, PA, USA).
4. Methanol (Fisher Scientific).
5. Benzyl alcohol (Fisher Scientific).
6. Benzyl benzoate (Fisher Scientific).
7. Microscope (Leica MZFL III microscope, Leica Microsystems Inc, Buffalo Grove, IL, USA).

2.6. Determining Dysplasia Index

1. Fluorescein-lycopersicin esculentum lectin (Vector Laboratory, Burlingame, CA, USA).
2. Leica CM1900 Cryostat (Leica Microsystems Inc).
3. Fluorescent microscope.

3. Methods

3.1. Stereotactic Injection of Viral Vectors into the Basal Ganglia (see Note 1)

1. This protocol was approved by the Animal Care Committee of the University of California, San Francisco.
2. Following induction of anesthesia with 5% isoflurane, eight-week old $Alk1^{2f/2f}$ mice were placed in a stereotactic frame (David Kopf Instruments) with a mouth holder. The anesthesia was maintained with 1.5% isoflurane.
3. A 1-cm midline skin incision at the top of the head was made to expose the sagittal suture and bregma.
4. A burr hole was drilled in the pericranium 2 mm lateral to the sagittal suture and 1 mm posterior to the coronal suture.
5. A 10 μl Hamilton syringe (World Precision Instruments) was slowly inserted into the left caudate nucleus at a depth of 3.0 mm under the dura (*see* Note 2).

[1]The vectors can also be injected into other brain regions, such as the cortex, to induce the AVM phenotype.
[2]During viral injection, fix the mouse head in a horizontal position, and insert the needle perpendicularly into the surface of the dura. Needle insertion at an angle will affect the lesion location, or may even inject into the brain ventricle.

6. A 2 μl viral suspension containing 2 X 10^7 plaque forming unit (PFU) Ad-Cre and 1 μl containing 2 X 10^9 genome copies (gcs) of AAV-VEGF were injected into the right basal ganglia at a rate of 0.2 μl per minute using a ultra-micro pump (World Precision Instruments). For control group, Ad-GFP and AAV-LacZ were used.
7. The needle was retained in the brain for 10 minutes, and then slowly withdrawn over a 5-minute period (*see* Note 3).
8. The skin wound was closed with a 4-0 suture.
9. Brain sections were collected for analysis eight weeks later (*see* Note 4).

3.2. Analysis

Visualizing malformed vessels in the brain is the first step to confirm the successful induction of the AVM phenotype. There are different techniques to visualize cerebral vasculature in small animals, including casting vessels with microfil (10, 15) or latex. Latex perfusion is the usual choice to display the AVM-like phenotype, since the particles in the latex dye are too big to pass through the capillaries.(6) Latex will present in the veins after intra-artery infusion when there is direct flow between arteries and veins (i.e., AV shunting, a major characteristic of AVM). Latex perfusion was first described by Coyle and Jokelainen (16) and later modified by Maeda et al (17). It is liquid rubber that solidifies after the vasculature is filled.

Lesion volume measurement and dysplastic vessel index quantification (the number of vessels larger than 15 μm/200 vessels) (8–10, 18–20) are methods to evaluate the severity of the phenotype, enabling quantitative measurement of cerebrovascular abnormality, which could provide critical outcome evaluation in innovative brain vascular malformation therapies.

3.3. Vessel Casting with Latex Perfusion

1. Deep-anesthesize the mice with isoflurane. Open the abdominal and thoracic cavities and expose the heart.
2. Cut both left and right atria. Slowly inject 1 ml blue latex dye (Connecticut Valley Biological Supply Co.) into the left ventricle with a 25-gauge 5 ml syringe (*see* Note 5).
3. Remove the brain and fix with 4% paraformaldehyde overnight.
4. Dehydrate the brain tissue using methanol series (50%, 75%, 95%, and 100% methanol, 24 hours for each concentration).
5. Clarify the brain with benzyl alcohol/benzyl benzoate (1:1 ratio).

[3]After viral injection, it is critical to retain the needle in the brain for 10 minutes, and then slowly withdraw the needle. Pulling the needle out too fast could lead to the virus leaking out.

[4]Other than Ad-Cre-mediated regional gene deletion, *Alk1* can be conditionally deleted in adult mice, either systemically or tissue/cell-specifically by crossbreeding *Alk1*$^{2f/2f}$ mice with transgenic mouse lines that express inducible cre-recombinase. Brain AVM phenotype can be induced in mice that have systemic/endothelial specific *Alk1* gene deletion through intra-brain injection of AAV-VEGF.

[5]For latex perfusion, make sure that the latex is fresh and that no solidified cluster has formed.

6. Cut the brain coronally using a razor blade. Image the brain AVM vessels under the microscope (Fig. 1).

3.4. Lesion Volume Quantification

1. After imaging the latex-perfused brain slide, rehydrate the brain tissue and snap-freeze in dry ice.
2. Coronally section the brain serially into 50 μm-thick sections using a Leica CM1900 Cryostat (Leica Microsystems Inc). Section the entire brain AVM lesion region.
3. Under a 5X microscope objective lens, image both the AVM lesion side and the contralateral corresponding region.
4. Quantify the latex area using NIH Image 1.63 software after binary (Fig. 2).
5. Based on known section thickness, estimate the volume by summing serial volumes. This method is adapted from what we have used for quantifying infarct volume in mice with middle cerebral artery occlusion (MCAO) (21).

3.5. Capillary Density and Dysplasia Index Quantification (see Note 6)

1. Eight weeks following viral injection, perfuse the mice with cold 1X PBS through the left ventricle of the heart, using a Masterflex Pump Controller (Cole Parmer Instrument, Vernon Hills, IL, USA) at 4 ml/min.
2. Harvest the brain sections and snap-freeze in dry ice.
3. Coronally slice the brain serially at 20 μm thickness using a Leica CM1900 Cryostat (Leica Microsystems Inc).
4. Choose two sections per mouse, one mm rostral and one mm caudal of the injection site, for vessel staining using fluorescein-lycopersicin esculentum lectin (1:200, Vector Laboratory) (Fig. 3; *see* Note 7).
5. Under a 20X microscope objective lens, capture three areas (to the right and left of and below the injection site) of each section. In each image, count total vessel number and vessels with diameter larger than 15 μm using NIH Image 1.63 software. Calculate vascular density for each animal as the mean of the total vessel number obtained from the six images taken under 20X microscope objective lens. Calculate dysplasia index as the number of vessels with a diameter larger than 15 μm per 200 vessels.

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[6]Vessels can also be visualized by perfusing fluorescent-labeled lectin through intravenous injection.
[7]The sections can be stained with endothelial-specific antibodies, such as anti-CD31 antibody.

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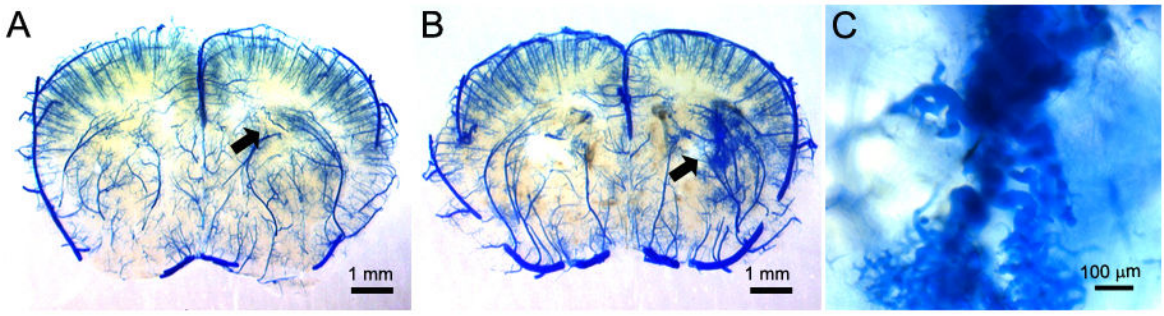

Figure 1.

Vessel casting by latex perfusion shows the AVM lesion. (A) No abnormal vessels were detected in the brain of wild-type mouse around the vector injection site (arrow). Scale bar: 1 mm. (B) AVM phenotype was detected around the vector injection site of 8-week old *Alk1*$^{2f/2f}$ mouse (arrow). Scale bar: 1 mm. (C) High magnification of the injection area shows the abnormal vascular structure. Scale bar: 100 μm.

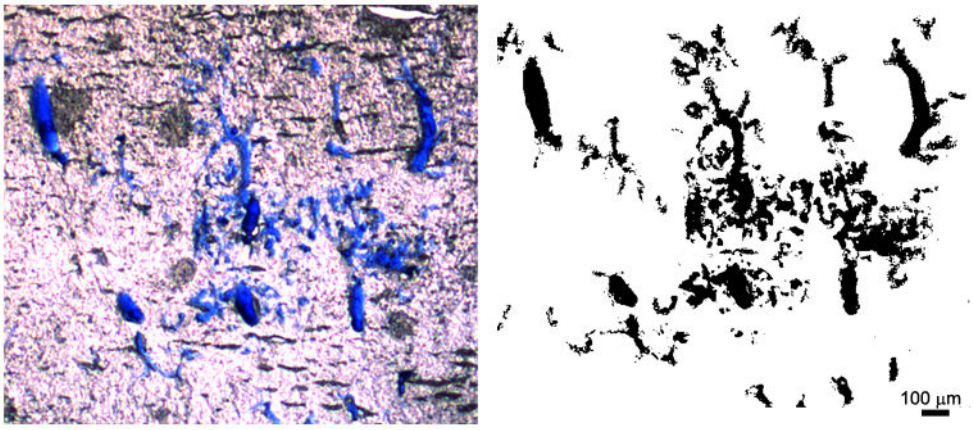

Figure 2.

An example of blue latex section image (left), and an image after binary (right). Scale bar: 500 μm.

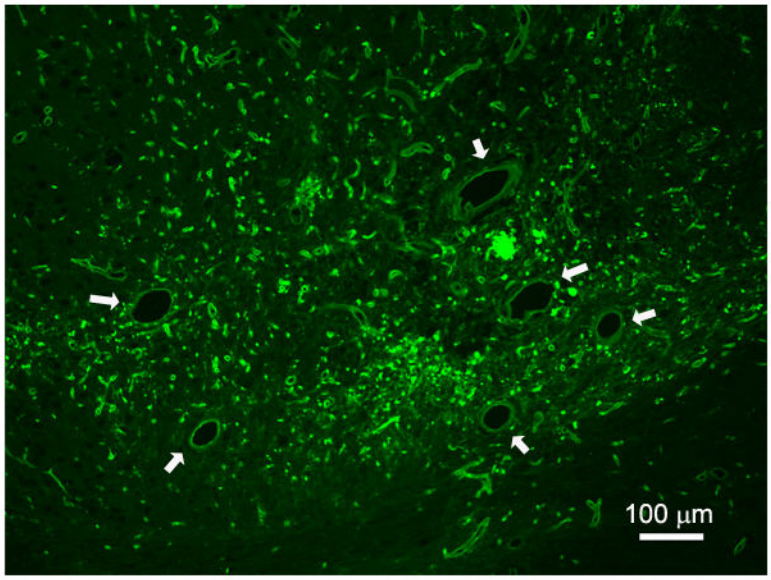

Figure 3.

Representative image of a brain section with lectin staining. *Alk1*$^{2f/2f}$ mouse received 2 × 10^7 PFU Ad-Cre and 2 X 10^9 gcs of AAV-VEGF in the basal ganglia for eight weeks. A cluster of dysplastic vessels formed in the viral injection site (white arrows). Scale bar: 100 μm.