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Arteriovenous Malformation Model for Training and Research

Charles W. Kerber, Stephen T. Hecht, and Kimberly Knox

PURPOSE: To develop an arteriovenous malformation (AVM) model for teaching embolization techniques and for researching and developing new interventional devices. **METHODS:** Open pore cellulose sponges 2 to 5 cm in diameter were coated with a watertight elastomer. One to three afferent tubes (arteries) and one large efferent tube (vein) allowed insertion of the model into a circuit of pulsatile, flowing, non-Newtonian fluid. Using fluoroscopy and angiographic imaging, five neuroradiologists practiced occluding the AVM nidus with a variety of techniques and cyanoacrylate mixtures. **RESULTS:** The model appeared and behaved like a human brain AVM. Attempts to teach liquid adhesive techniques were successful, and though they were stressful for the trainee, failure had none of the disastrous sequelae that attend training with human subjects. **CONCLUSION:** The AVM training and research model is of value in introducing physicians to the techniques needed for endovascular cyanoacrylate therapy: it allows users to develop skills at their own rates, and permits safe "failure-mode" learning.

Index terms: Arteriovenous malformations, cerebral; Interventional neuroradiology, models

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If the treatment of aneurysms is a battle
Then the treatment of AVMs is a war.
Renato da Pian, MD*

Positive outcomes of cerebral arteriovenous malformation (AVM) treatment, as in warfare, are favored by outstanding equipment and keenly focused, intensive training. Warfare has been simulated accurately in many fashions, but human cerebral AVM therapy has suffered from a paucity of simulation systems. Prior to the elegant work of Massoud et al (1, 2), there was no realistic or feasible AVM animal model. Kerber and Flaherty (3) and Bartynski et al (4) have described handmade in vitro models that simulate the feeding arteries, nidus, and draining vessels of a cerebral AVM, but those model systems have never been widely used, perhaps because their production is laborious, they are not standardized, and, to date, they are not commercially available. To be useful for training, research, and development, the models must be uniform in their dimensions, geometry, and flow behavior. We have recently created a standard, accurate, commercially available AVM model system (Mark I AVM Model, Golden Pacific Arts, San Diego, Calif) for use in training, proficiency maintenance, and device and technique development.

Materials and Methods

The nidus of the AVM simulator was an open pore cellulose sponge (mean pore diameter, 3.9 mm; standard deviation, 1.7 mm), trimmed to volumes ranging from 5 to 50 cm^3 (2- to 5-cm diameter). A single large (4.5- or 6.5-mm) wax wire (simulating the vein) and one to three smaller (2.6-mm) wax wires (simulating feeding arteries) were attached to the sponge with small amounts of an adhesive elastomer. A larger (5.2-mm) wax wire was used as the proximal arterial pedicle that gave rise to the feeding arteries. After the elastomer cured, the entire model was repeatedly coated with a mixture of the elastomer and

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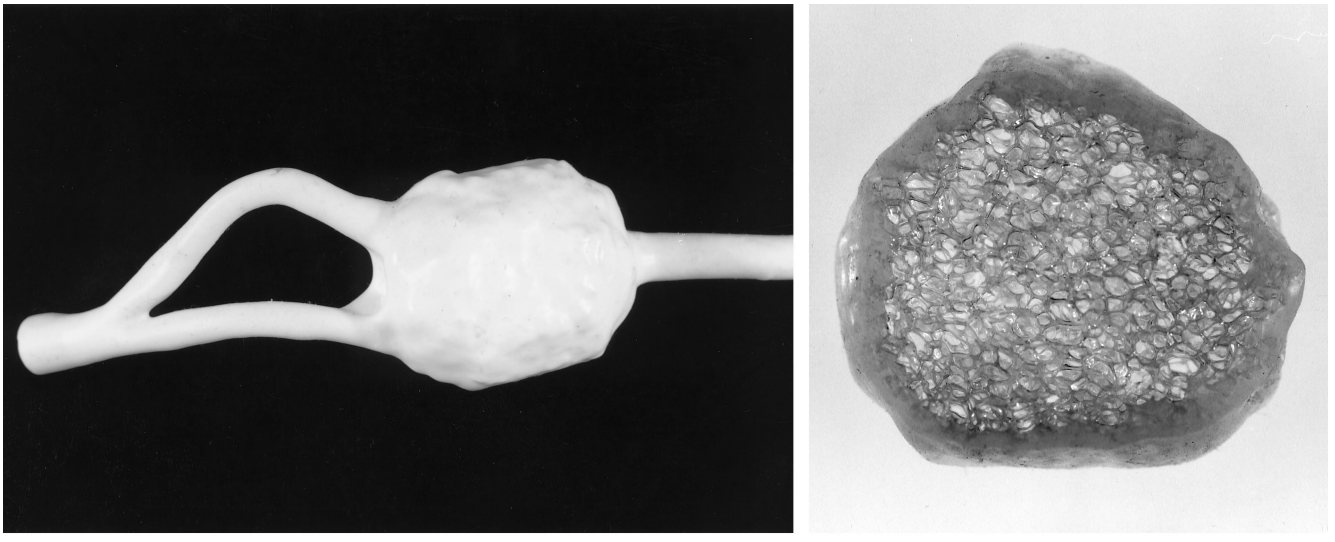

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Fig 1. *A*, An overview of an AVM model that has two afferent limbs and a solitary draining vein. Radiolucent elastomer covers the nidus. Fluid flows from left to right.

B, Cross section of the nidus (sponge).

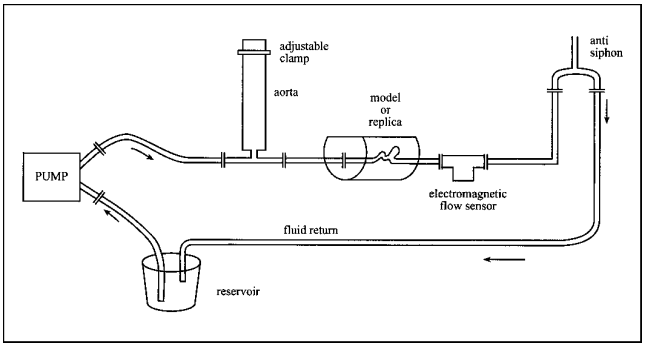

Fig 2. The circuit of flowing fluid. The pump provides the force that makes the fluid flow and is volume adjustable. The expansion chamber, also adjustable, gives the operator the ability to modify flow volume profiles (eg, to damp perturbances and ensure diastolic flow). The model lies within a water-filled plastic cradle. The cradle and water provide some X-ray beam attenuation. The antisiphon valve is the means of controlling efferent limb pressure. The electromagnetic low sensor can be placed either proximal or distal to the model. Flow data are then transmitted to a strip chart recorder.

hexanes. After polymerization, the wax was removed by thermal and chemical means (Fig 1). The model was pressure tested for leaks and then incorporated into a circuit of flowing fluid (Fig 2). The model has been used with continuous fluid flow and with pulsatile flow. Continuous flow was provided by an immersible, centrifugal pump (Model 1A-MD-1, March Mfg, Inc, Glenville, Ill). Pulsatile flow was provided by a programmable pump (Model 1421, Harvard Apparatus, South Natick, Mass). Within the circuit, between the pump and the model, there was an expansion chamber that simulated the damping action of the aorta.

The expansion chamber can be adjusted to yield flow and velocity profiles similar to those in the human intracerebral vasculature. The circuit also contained a pressure relief overflow bypass vent, which diverted the flow of fluid into the reservoir when the AVM model was occluded, preventing damage to the pump and/or rupture of the circuit when the AVM became totally occluded during practice therapy. Measured flow rates through the model system ranged from 150 to 400 mL/min, correlating to flow velocities of 22 to 70 cm/s, respectively.

The circuit can be perfused with an optically clear non-Newtonian fluid with flow properties similar to those of human blood (NNF Solutes, Golden Pacific Arts). The fluid was rendered alkaline to pH 10.5 $\pm$ 0.5 with sodium hydroxide. The high pH of the fluid caused cyanoacrylates to polymerize in the model system at rates similar to polymerization rates observed in human blood. When even more realism was desired, heparinized swine blood was used to perfuse the circuit.

After evaluation during experimental angiographic conditions to simulate liquid adhesive embolization, we injected cyanoacrylates mixed with ethiodized oil (Ethiodol, Savage Laboratories, Melville, NY) into the afferent vessels. Three different cyanoacrylates were evaluated (*N*-butyl [from two different manufacturers] and one isobutyl homologue). The ratio of ethiodized oil to cyanoacrylate ranged from 1:1 to 3:1. The ethiodized oil was added to the cyanoacrylate to render it radiopaque and to prolong its polymerization time, as undiluted cyanoacrylate tends to polymerize nearly instantaneously as it exits the catheter, resulting in undesirably proximal vascular occlusion. To simulate actual human brain embolization conditions further, the cyanoacrylate mixture was injected through various commercially available microcatheters. After angiography and before liquid adhesive embolization, the

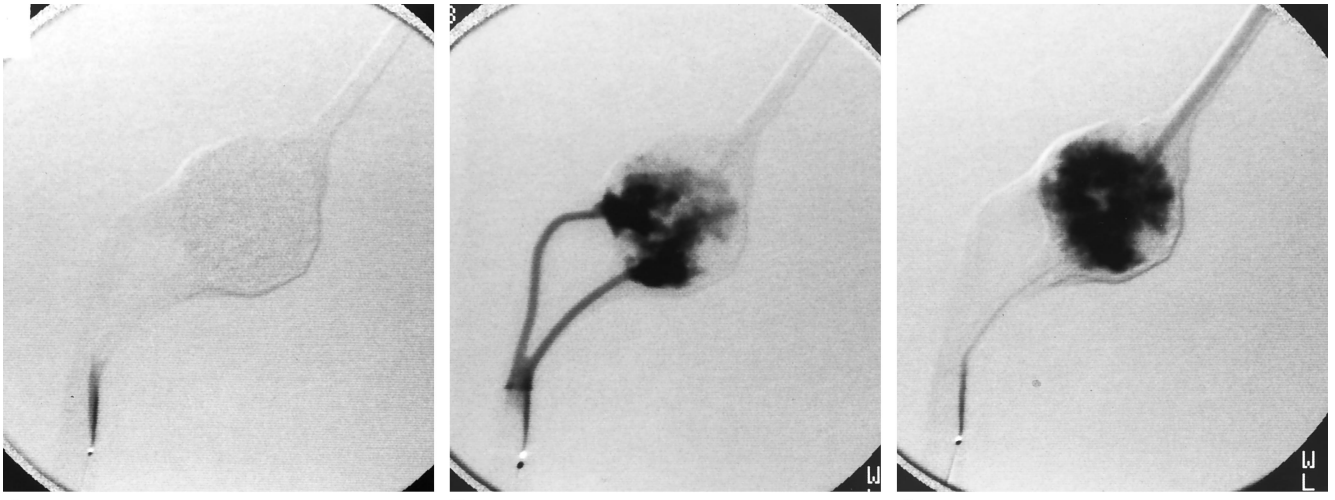

Fig 3. Digital subtraction angiogram, four frames per second. Total flow, Q = 250 mL/min.
A, At time zero, a microcatheter placed proximal to the origin of the two feeding arteries begins to inject the contrast agent.
B, At 0.25 seconds, the nidus fills.
C, At 0.50 seconds, the contrast agent appears in the vein.

catheter system was flushed and externally rinsed with 5% dextrose in water.

Results

To simulate angiography, the model was initially evaluated with fluoroscopy and digital subtraction angiography (LUA, General Electric, Milwaukee, Wis). Contrast material was injected into the system via a microcatheter, with the tip either in the afferent vessel proximal to its division (global angiography) or in one of the afferent branches distal to the division (superselective angiography). The global and superselective types of angiograms generated images that both statistically and dynamically appeared subjectively comparable to the angiographic appearance of human brain AVMs (Fig 3). The time courses of opacification during afferent vessel injection, nidus filling, and efferent vessel drainage were similar to those observed during superselective angiography of human brain AVMs.

The behavior of the model system during liquid adhesive embolization closely paralleled conditions observed during embolization of human brain AVMs. During more than 30 glue infusions by five different operators (whose experience ranged from trainee to more than 20 years), a qualitative spectrum of results was obtained, ranging from subjectively bad results (eg, total proximal feeder occlusion with gluing of the catheter into the afferent artery [Fig 4A] or traversal of the liquid adhesive through the nidus to completely occlude the efferent vein) to subjectively good results (eg, occlusion of the nidus and removal of the catheter with no residuum of cyanoacrylate left in the afferent artery) (Fig 4B). Novice users of cyanoacrylate experienced rapid learning curves, with early efforts tending toward poor results and later efforts tending toward better results. While embolizing the model system, all operators, whether novice or expert, experienced sympathetic discharge symptoms (eg, tachycardia, diaphoresis, and tremulousness) exactly duplicating the symptomatology encountered by interventional neuroradiologists during liquid adhesive embolization of human brain AVMs.

Discussion

Liquid adhesive embolization of human brain AVMs was first performed more than two decades ago (5, 6). In the intervening years, techniques and materials have evolved and improved, and the utility of embolization for the treatment of human brain AVMs has been acknowledged. There is now a substantial demand for interventional neuroradiologists who are well trained in the use of liquid adhesives, as this is a time-consuming and stressful endeavor, owing to the relative rarity of brain AVMs and the potential for life-threatening complications that accompanies the use of any embolic material, particularly the inexpert use of liquid adhesives.

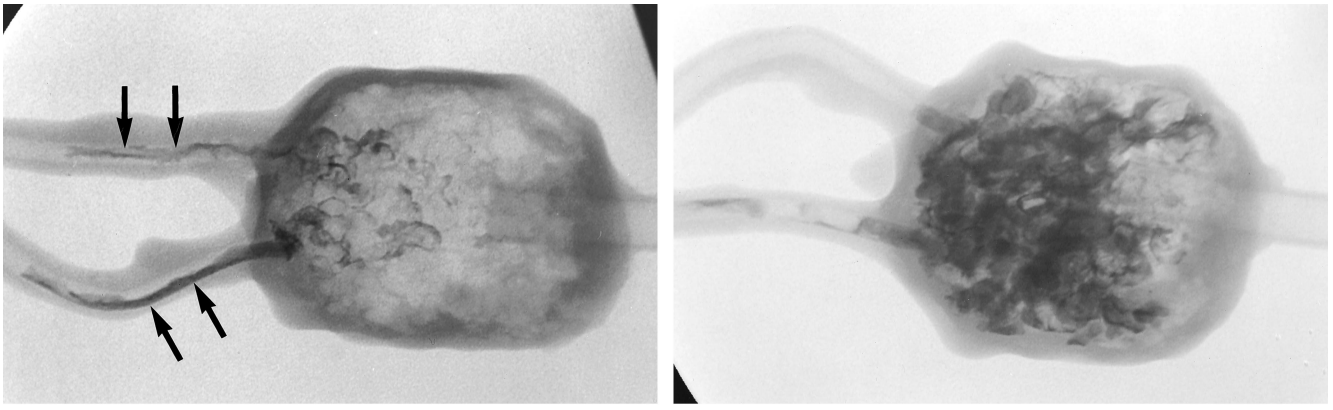

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Fig 4. *A*, Radiograph of unsuccessful first treatment. Note complete proximal pedicle occlusion (*arrows*).
B, After five additional training sessions, posttreatment radiograph shows satisfactory penetration of the nidus by the glue.

A first-time solo interventional procedure in which liquid adhesive is used to treat a live human patient is always a severely stressful event; however, stress levels can be substantially decreased if the novice has practiced the liquid adhesive infusion enough times on a realistic simulator. Model systems, both animal and inanimate, are extraordinarily useful in the training of interventional neuroradiologists. The advantages of inanimate model systems include reduced expense and lowered demand for animal models.

The standardization inherent in a model (eg, same resistance, same inflow and draining vessel dimensions, and so on) is extremely useful. If the model is standard, then the operator can vary liquid adhesive injection techniques and know that the differences in results obtained relate to changes in the delivery of the material rather than to differences in the model's ability to accept the material. Similarly, if different materials are being evaluated with a standard technique, a standardized model will highlight intrinsic differences in the materials.

Model systems are also useful to experienced interventional neuroradiologists. For example, after a long interval between liquid adhesive procedures, models can be used to regain proficiency; further, the characteristics of new materials can be compared with those of known materials in a standardized model before using them in a human subject.

Finally, a standardized model system is useful in the research and development processes that are integral to the development of new materials and techniques. The physical characteristics and immediate performance of multiple iterations can be evaluated and compared in a cost-effective fashion in inanimate models.

In conclusion, we have found this training and research model of value in introducing physicians to the techniques needed for endovascular cyanoacrylate therapy. More important, the model allows each person to develop skills at a customized rate, and has permitted safe "failure-mode" learning.

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