The role of dynamic contrast-enhanced magnetic resonance imaging in the diagnosis and management of patients with vascular malformations

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Objective: Vascular malformations are uncommon but may confer significant morbidity. Limitations in diagnosis and treatment result from inadequate classification schema and diagnostic algorithms. The crucial distinction is between high-flow and low-flow lesions because this informs prognosis and treatment. This study assessed the utility of dynamic contrast-enhanced magnetic resonance imaging (dceMRI) in distinguishing high-flow from low-flow lesions, a technique that has previously not been widely applied or evaluated in this patient population.

Methods: A prospective database of all patients referred to the multidisciplinary vascular malformation team at our institution was reviewed from January 2006 to June 2010. dceMRI was obtained on each patient to determine flow characteristics and lesion extent. Additional studies were used as indicated. Catheter-based arteriography was performed when high-flow lesions were identified with the intention of intervening or to distinguish between high-flow and low-flow lesions when MRI was indeterminate. A triage algorithm was used to stratify patients and formulate therapeutic goals. We analyzed the accuracy of dceMRI in identifying high-flow and low-flow lesions.

Results: The study included 122 patients (aged <1 to 70 years) comprising 52 males (42.6%) and 70 females (57.4%). Pain (72 patients; 59%) and swelling (88 patients; 72.1%) were the most common presenting symptoms. All patients underwent dceMRI. Of these, 68 had confirmatory imaging (n = 15) or intervention (n = 53). The dceMRI was able to definitively and correctly distinguish high-flow from low-flow lesions in 57 studies, for an accuracy rate of 83.8%. In the remaining 11 studies, dceMRI correctly queried flow status but not definitively, and confirmatory angiography was required.

Conclusions: Using a diagnostic tool designed to identify key clinical characteristics, we were able to successfully distinguish between high-flow and low-flow vascular malformations using dceMRI alone in 83.8% of patients, minimizing the need for unnecessary invasive catheter-based procedures. (J Vasc Surg 2012;56:757-64.)

Vascular malformations affect only 0.8% to 1% of the population but are occasionally life-threatening and are often associated with significant lifelong morbidity.1 In general, vascular anomalies can be classified as vascular tumors or vascular malformations. Hemangiomas are the most common vascular tumor. These are present at birth, are proliferative lesions, and usually involute spontaneously during childhood.2 Vascular malformations are also present at birth and grow at a rate similar to the patient or may not become clinically evident until later in life. Malformations have normal endothelial cells and are not proliferative lesions; however, they never regress but rather tend to progress over the patient’s lifetime.2

The diagnosis and treatment of vascular malformations can best be accomplished when lesions are classified by their vascular composition (arterial, venous, lymphatic, or combined) and flow dynamics (high or low flow). The most commonly used classification scheme to date was devised in Rome in 1996 by the International Society for the Study of Vascular Anomalies (ISSVA), which delineates vascular tumors from malformations, with an emphasis on vascular characteristics.3-6 Prognosis and treatment of vascular malformations depend primarily on the velocity of flow within the lesion.7 Low-flow vascular malformations are usually treated with transcutaneous sclerotherapy or surgical resection, or both, whereas patients with high-flow lesions usually require transarterial catheter-based interventions or surgical resection, or both. Limitations in diagnosis and treatment of these complex lesions are largely due to inadequate classification schema and lack of consistent algorithms for diagnostic evaluation. If the diagnosis of low flow can be established without the use of catheter-based arteriography, these patients may be spared the expense, risk, and inconvenience of a catheter-based study.

In this study, we propose a simplified diagnostic and treatment algorithm based on vessel and flow characteristics within the lesion that is used for therapeutic decision making. We further assess the utility of dynamic contrast-enhanced magnetic resonance imaging (dceMRI) in distin-
Fig 1. This practical scheme to classify vascular anomalies is designed to evaluate patients and formulate diagnostic and therapeutic goals. It focuses on the distinctions that are clinically relevant: tumors vs malformations and high flow vs low flow. AVM, Arteriovenous malformation.

guishing between high-flow and low-flow lesions as a means to optimize treatment and outcome for patients. This noninvasive diagnostic modality, inadequately described in the current body of literature with regard to vascular malformations, differs from standard MRI in that it provides images analogous to conventional digital angiography. As such, key vascular components are enhanced, which may provide better definition and more accurate differentiation between high-flow and low-flow lesions than conventional MRI.

METHODS

This research was conducted with the approval of the Institutional Review Board of Duke University Medical Center, Durham, NC.

Patient selection. Medical records of patients treated by the multidisciplinary vascular malformation team at Duke University Medical Center from January 2006 to June 2010 were retrospectively analyzed. This team consists of vascular surgeons, pediatric surgeons; adult and pediatric orthopedic surgeons, plastic surgeons, hematologists, dermatologists, and ophthalmologists; and diagnostic and interventional radiologists. The team meets monthly to review patients.

The database is prospectively maintained and included 122 patients with the diagnosis of vascular malformation at the time of review. All patients were evaluated by a member of the vascular malformation team before being presented at the multidisciplinary conference. The focused data points in this database were patient demographics, comorbidities, presenting symptoms, physical examination findings, imaging modalities used, including diagnosis, interventions used, and outcomes.

Classification of lesions. A diagnostic algorithm was created and served as a tool to evaluate patients and formulate therapeutic goals (Fig 1). In accordance with the ISSVA classification, this schema differentiates first between vascular tumors and malformations, both under the umbrella diagnosis of vascular anomalies.9 Vascular malformations were subdivided further into high-flow and low-flow lesions. Low-flow lesions were separated into venous, lymphatic, and combined lesions. High-flow lesions include an arterial component. Patients with vascular tumors were excluded from consideration in this study. Patients were stratified into their respective lesion group based on definitive imaging modalities, in particular dceMRI.

Radiographic workup. A dceMRI was obtained for every patient deemed a candidate for intervention to determine flow characteristics and extent of the lesion. Imaging was principally performed on 1.5T scanners (78.7% on 1.5T scanners; 21.3% on 3T scanners; Avanto [Siemens Medical Systems, Malvern, Pa] or Signa hdx [General Electric Healthcare, Piscataway, NJ]). Multiplanar T1-weighted spin echo and T2-weighted fast spin echo or fast short-tau inversion recovery (STIR) images were initially obtained. Slice thickness, spatial resolution, matrix, and coil selection were dependent on the area to be imaged and the scanner used. A power injector was used to administer 5 to 20 mL (gadolinium-diethylenetriaminepentaacetate or gadolinium-benzylxypropionictetraacetate) of contrast intravenously. Image acquisition extended from the arterial to the late venous phase using time-resolved imaging of contrast kinetics (General Electric), time-resolved echo-shared angiographic technique (Siemens), or time-resolved angiography with stochastic trajectories (Siemens) dynamic sequences.3,8,9 Effective image temporal resolution was 3 to 8 seconds. Finally, postcontrast T1-weighted spin echo images were acquired.

After acquisition, images were reviewed on a Centricity picture archiving and communication system workstation (General Electric). The dynamic acquisitions produced multiple image volume sets, each at a different time point. Each volume was converted to a maximum-intensity projection, which was displayed in a fashion such that vessel and lesion enhancement were the only structures visualized. The appearance is analogous to a display of a conventional digital angiogram with background subtraction. Individual studies and volume sets were interrogated on a Vitrea three-dimensional workstation (Vital Images, Minnetonka, Minn) as needed. Besides defining the extent of the abnormality, the interpretations included information about the type of vascular malformation as well as the flow velocity (fast/high or slow/low) within the lesion.

If the dynamic gadolinium-enhanced sequences identified flow within the lesion at or preceding the visualization of arterial flow within normal vessels, the lesion was considered to be a high-flow lesion. The presence or absence of early venous return from veins draining the lesion or true immediate arterial venous shunting (ie, an arterial venous malformation) through the lesion was commented on. If the lesion was not apparent on the dynamic gadolinium-enhanced images until the capillary phase, or more typically the venous phase, as determined by a comparison with visualization of normal vessels, the lesion was considered to be a low-flow abnormality. Prominent venous draining vessels were also commented on.

Additional imaging studies were obtained on an individual basis when indicated. Specifically, catheter-based
arteriography was performed when high-flow lesions were identified with the intention of intervening or to distinguish between high-flow and low-flow lesions when dceMRI was indeterminate. Ultrasound (US) imaging and computed tomography (CT) were also used, although to a lesser extent, to supplement our understanding of the lesion (eg, to better evaluate for orbital involvement). We specifically analyzed the accuracy of dceMRI in identifying and differentiating high-flow vs low-flow lesions compared with this study’s gold standards: angiography, CT, US imaging, or findings during therapeutic procedures. If a patient had more than one vascular malformation, the dceMRI protocol did not change; however, multiple acquisitions were required.

Although multiple imaging modalities are available and provide useful data, dceMRI provides the most critical information, especially regarding a lesion that will be treated surgically. The dceMRI not only determines hemodynamic quality but also demonstrates the true extent of the lesion as well as the soft tissue compartments involved, all of which become important in planning the surgical approach. US imaging and other noninvasive studies can often determine flow quality with less financial expense; however, the critical lesion anatomy is often not obtained.

RESULTS

During the 54-month review period, 122 patients with vascular malformations were identified and reviewed at a monthly multidisciplinary vascular malformation meeting. Patient demographics included 52 males (42.6%) and 70 females (57.4%). Patient ethnicity varied: 71.3% were white, followed by 13.9% African American and 5.5% Hispanic. At the time of review, patients were an average age of 26.5 years (range, <1-70 years), with onset of symptoms at age 9.3 years. Patients presented with a variety of symptoms, including 72 (59%) with pain, 88 (72.1%) with subjective evidence or confounding issues that precluded a definitive diagnosis and as such were considered indeterminate. In addition, lesions were successfully treated without complications of arterial sclerosant injection.

In 46 of these 68 cases (67.6%), dceMRI definitively diagnosed low-flow lesions. Flow characteristics were validated as correct in each instance at the time of percutaneous intervention in 42 lesions or with US imaging in two lesions and with CT in two lesions (Table). Another eight cases were considered likely to be low-flow lesions at the time of dceMRI interpretation, but there was insufficient confidence or confounding issues that precluded a definitive diagnosis and as such were considered indeterminate. These eight cases necessitated catheter-based arteriograms, which confirmed the suspicion of low-flow physiology within all eight. Percutaneous interventions for the 54 dceMRI-diagnosed low-flow lesions, including those that required a secondary diagnostic modality, used US or fluoroscopic guidance, at which time none of these lesions was found to have a high-flow component.

The lack of communication with the arterial system was determined in several ways. In lesions treated with US or fluoroscopic guidance, the absence of pulsatile back bleeding at the time of access ruled out a high-flow component. In addition, lesions were successfully treated without complications of arterial sclerosant injection.

The dceMRI study correctly and definitively diagnosed 11 of 14 high-flow lesions (78.6%) in these 68 cases. These were typically followed with catheter-based arteriograms to

Fig 2. A variety of diagnostic studies were used, including dynamic contrast-enhanced magnetic resonance imaging (dceMRI) in 122 patients (100%), ultrasound (US) imaging in 17 (13.9%), catheter-based arteriography in 13 (10.7%), and computed tomography (CT) in eight (6.6%).
confirm the diagnosis and for intervention, as indicated. Although suggestive of high-flow lesions in the remaining three cases, confidence in the dceMRI findings was insufficient for a definitive diagnosis and diagnostic arteriography was requested. The final diagnosis was correct in each of these three presumed high-flow lesions. Further, 100% of the 14 presumed high-flow lesions did have high-flow physiology at the time of intervention.

When considering the 68 lesions with objective proof of hemodynamic physiology, dceMRI correctly and definitively diagnosed lesion flow in 57. Although none of the dceMRI indeterminate interpretations was actually incorrect, if we consider them all incorrect for statistical purposes, dceMRI was able to definitively distinguish slow-flow from fast-flow lesions with an overall accuracy rate of 83.8%. Again, making the worst-case assumption that all indeterminate interpretations were incorrect, the sensitivity and specificity of dceMRI for diagnosing high-flow lesions in these 68 cases was 78.6% and 85.2%, respectively. The positive predictive value was 57.9% and the negative predictive value was 93.9% for high-flow lesions diagnosed by dceMRI. Using the same assumptions, dceMRI was 85.2% sensitive and 78.6% specific for diagnosing low-flow lesions, with a positive predictive value and negative predictive value of 93.9% and 57.9%, respectively.

Of the seven high-flow lesions in which no intervention was implemented, two patients (28.6%) are currently considering therapy, two (28.6%) were advised against intervention because their lesions were relatively asymptomatic, one patient’s (14.3%) socioeconomic status prohibited an intervention, and one patient (14.3%) was lost to follow-up. The remaining patient (14.3%) patient died of a suspected pulmonary embolus after a diagnostic arteriogram to further evaluate the flow characteristics within a high-flow femoral malformation. This patient, whose high-flow lesion was an isolated finding, had no history of deep venous thrombosis and the results of a hypercoagulable workup were within normal limits.

Table. Objective evidence of dynamic contrast-enhanced magnetic resonance imaging (dceMRI) accuracya

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Statistical definitions

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<tr>
<td>Indeterminate</td>
<td>False negative</td>
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<td>True positive</td>
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HFVM, High-flow vascular malformation; LFVM, Low-flow vascular malformation; NPV, negative predictive value; PPV, positive predictive value.
aTo assess proof of flow quality determined by dceMRI, 68 dceMRI-diagnosed lesions underwent secondary imaging modalities or intervention/surgery. Accuracy, sensitivity, specificity, PPV, and NPV of dceMRI are indicated. Criteria for each statistical calculation are also included.

DISCUSSION

Vascular anomalies can be of the tumor or malformation type. The most common type of vascular tumor is a hemangioma, which presents at birth or within the first several weeks of life, may range from mild to life-threatening in nature, depending on its location, and is typically small and involves the skin. They grow rapidly over the course of the first several years and then universally involute spontaneously during childhood. The management of such lesions may include observation alone, medical therapy with steroids or propranolol, or even surgical resection, depending on the severity of the lesion, the area involved, and the extent of the residual irregularity during or after the involution stage. Vascular malformations, by contrast, are present at birth but may not be clinically evident immediately and never undergo spontaneous regression.

Unfortunately, lack of awareness of these distinctions and persistence of an archaic, eponymous naming system has interfered with appropriate and timely recognition of the nature of these lesions and therefore referral to a specialist. In fact, Konez et al reported nearly half of the patients referred to a vascular malformation specialist by providers relatively unfamiliar with the disease had been previously diagnosed inaccurately.
Almost 30 years ago, Mulliken and Glowacki\textsuperscript{13} classified vascular lesions based on endothelial characteristics. This classification was updated in 1996 by Mulliken and Young,\textsuperscript{18} which includes specific diagnoses. To date, there have been a number of other modifications and updates.\textsuperscript{19-22} These classification systems continue to evoke confusion in arriving at a proper diagnosis.\textsuperscript{23}

Contemporary studies have successfully proposed classification schemes that assist in confirming a named diagnosis.\textsuperscript{24} To date, the most commonly used classification scheme, which was devised in Rome in 1996 by the ISSVA, delineates vascular tumors from malformations, with an emphasis on vascular characteristics.\textsuperscript{3-6} However, deriving a treatment plan from even this criteria remains challenging.\textsuperscript{25}

Although the ISVVA classification scheme has been validated and is clinically applicable, our intention was to streamline this widely used classification scheme to create a therapy-directed treatment algorithm based on flow characteristics and hemodynamic physiology.\textsuperscript{26} Here, we demonstrate the utility of this application of the prior ISSVA classification scheme. The simple and practical diagnostic schema proposed and used in this study focuses on arriving at diagnoses stratified by basic lesion characteristics and flow qualities, which is the foundation for which prognosis and treatment can be formulated. The classification algorithm presented in this study was not compared with historic classification systems, including the ISSVA schema, with regard to patient outcomes; however, the current schema is built on and simplified from the ISSVA system, and we suspect they have similar utility.

The ability to distinguish between high-flow and low-flow lesions when using noninvasive imaging modalities is essential when the goal is to avoid unnecessary invasive catheter-based procedures. In fact, distinguishing a high-flow lesion from a low-flow lesion is more important for prognostic and therapeutic purposes than determining the particular makeup of the lesion (arterial vs venous vs lymphatic).\textsuperscript{10,12,27-29} Multiple diagnostic modalities can be used to evaluate vascular malformations and confirm the initial clinical diagnosis. US imaging, CT scans, catheter-based angiography, and MRI are often used, alone or

\begin{figure}[h]
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\includegraphics[width=\textwidth]{fig3.png}
\caption{A low-flow vascular malformation is seen in conventional and dynamic contrast-enhanced magnetic resonance imaging. \textbf{A,} A short-tau inversion recovery (STIR) image of a low-flow vascular malformation. \textbf{B-D,} A low-flow vascular malformation is seen in early arterial through late venous phase dynamic contrast-enhanced magnetic resonance imaging.}
\end{figure}
combined, to identify the lesion and its vascular characteristics. US imaging is an inexpensive and readily available tool to investigate vascular malformations but is often unable to demonstrate the true extent of the lesion. dceMRI yields more information, including flow characteristics, soft tissue involvement, and the relationship to normal anatomy. Although not the scope of this study, a number of studies have summarized the findings for each modality.

Specific to MRI, the parenchymal portions of vascular lesions are quite bright on T2-weighted images, and the extent of tissue involvement is readily depicted when T1 and T2 (or STIR) images are acquired. Low-flow malformations characteristically have increased intraluminal signal on T2-weighted images (Fig 3). There is likely an intraluminal signal on the T1-weighted images as well. These lesions enhance with contrast and typically do not contain flow voids. A low signal in such malformations is concerning for thrombosis. A very focal area of signal abnormality may also represent a phlebolith. High-flow arteriovenous malformations typically do contain flow voids that can be observed on T1- and T2-weighted images, distinguishing them from low-flow lesions. Dilated feeding arteries and draining veins with a paucity of venous lakes are also indicative of high-flow lesions (Fig 4).

However, distinguishing between low- and high-flow lesions is often unclear using the simple imaging techniques and rules described above. Many particulars can mitigate these observations; for example, a vessel that courses within an imaging plane may produce an intraluminal signal despite fairly rapid flow, falsely suggesting a low-flow lesion. As such, dceMRI using techniques, such as TRICKS (time-resolved imaging of contrast kinetics) and TREAT (time-resolved echo-shared angiographic technique), are required to accurately assess flow within the lesion. These techniques have the added advantage of being able to delineate dominant or multiple feeding vessels in these lesions, potentially facilitating intervention.

In 2002, Rijswijk et al published prospective data that resulted from blinding two independent observers as they reviewed conventional MRI and dceMRI studies performed on patients with clinically suspected high-flow vas-

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**Fig 4.** A high-flow vascular malformation is seen in conventional and dynamic contrast-enhanced magnetic resonance imaging. **A,** A short-tau inversion recovery (STIR) image of a high-flow vascular malformation. **B-D,** A high-flow vascular malformation is seen in early arterial through late venous phase dynamic contrast-enhanced magnetic resonance imaging.
cular malformations. All patients underwent dceMRI as well as diagnostic angiography. This group observed an increase in the specificity of MRI from 24% to 33% to 95% with the addition of dynamic contrast-enhanced sequences. Although the Rijswijk study included only 27 patients, our study of 122 patients, 68 with objective confirmation, confirms with overwhelming evidence that dceMRI is the diagnostic study of choice. In our study group, clinically relevant high-flow lesions were never missed on dceMRI: none of the dceMRI-diagnosed low-flow vascular malformations treated invasively had a high-flow component, and flow quality of indeterminately diagnosed low-flow vascular malformations was confirmed with secondary studies. dceMRI alone proved sufficient to diagnose flow characteristics in at least 83.8% of patients. The location of the lesion does not appear to correlate with a resulting indeterminate dceMRI, and there were no obvious patient-specific or lesion-specific characteristics that predicted indeterminate imaging studies.

The dceMRI data were used to determine and implement appropriate lesion management, as described in the Appendix (online only). The hemodynamic and anatomic characteristics determined by dceMRI allowed for implementation of catheter-based embolization for high-flow lesions, or transcutaneous sclerotherapy for low-flow lesions, with or without surgical resection, depending on the extent of the lesion, cystic quality, and involvement of vital structures. In the setting of determinate studies, dceMRI diagnoses provided sufficient evidence to intervene without further investigation. However, indeterminate dceMRI results were always followed with secondary imaging (ie, diagnostic angiography) in patients requiring invasive treatment. Because this was not the focus of this study, a separate publication will include a comprehensive review of management strategies with respect to patient outcomes and response to treatment.

Catheter-based procedures have traditionally been the standard of reference for assessing vascular malformations; however, such procedures are not entirely benign and entail some risk to the patient. Complications observed with endovascular procedures occur in 1.5% to 9% of patients and include groin hematoma, pseudoaneurysm, arteriovenous fistula, acute arterial occlusion or thrombosis, embolic events, and infection. Although some of these complications can be managed conservatively, ~11% of groin hematomas and 61% of pseudoaneurysms will necessitate another procedure or perhaps an operation. Subjecting patients to these risks, albeit small, adds to the morbidity of the vascular lesion from which they are already suffering. In this study, dceMRI was able to obviate more invasive diagnostic imaging in 83.8% of the cases. When dceMRI is not definitive in assessing flow status, arteriography can then be performed not only to confirm the diagnosis but also to provide an opportunity to intervene in the case of high-low abnormalities. Such an approach avoids unnecessary diagnostic arteriograms in most patients.

This study has several limitations. First, because Duke University Medical Center is a referral center, many of the patients discussed at our monthly multidisciplinary conference already carry a diagnosis and are in need of treatment or have already undergone multiple and often excessive or unnecessary imaging studies that may or may not have led to an accurate diagnosis. Imaging studies from other facilities were reviewed by the team radiologist and were available when dceMRI studies were protocolled and interpreted.

Further, only symptomatic patients underwent interventions; therefore, the conclusions drawn by the imaging studies regarding a particular lesion were not always confirmed because treatment was not always performed. In fact, to definitively confirm the diagnosis arrived at by dceMRI, each patient should have undergone catheter-based angiography. However, this was not feasible due to the retrospective nature of this study and may not be acceptable in future studies because of the added risk intrinsic with the procedure.

The most obvious shortcoming of this study is that patients were retrospectively analyzed. A prospective study that obtains conventional and dceMRI sequences, and perhaps conventional angiograms, on every patient to be reviewed blindly by expert radiologists in this field may more definitively assess the utility of dceMRI to accurately distinguish high-flow from low-flow vascular malformations.

CONCLUSIONS

Management of vascular malformations requires an accurate diagnosis before intervening. The correction of hemodynamic abnormalities, particularly in high-flow lesions, must occur before functional or cosmetic procedures can take place. Based on the results of this study, we propose dceMRI as the mainstay of diagnostic evaluation for patients with suspected vascular malformations. Information obtained from such imaging allows the patient to be stratified into a high-flow or low-flow vascular malformation group based on a simplified diagnostic stratification scheme, such that an appropriate therapeutic plan can be formulated and unnecessary invasive testing can be avoided in most patients. Although the primary focus of this study was on the utility of dceMRI to differentiate between high-flow and low-flow vascular malformations, future directions will include a comprehensive institutional review of management strategies with respect to patient outcomes and response to treatment.

This study would not have been possible without the care and commitment of Carol Fisher, who serves as the Multidisciplinary Vascular Malformation Team Coordinator, as well as Jovan Markovic, MD, for his contributions to the vascular malformation database.

AUTHOR CONTRIBUTIONS
Conception and design: ML, CES, CKS
Analysis and interpretation: ML, CES, CKS
REFERENCES


APPENDIX (online only).

Brief description of treatment algorithm. Once a patient is diagnosed with a vascular malformation and further stratified as having a high-flow or low-flow lesion, a discussion is held with the patient regarding prognosis and treatment options. Similar to the absolute and relative indications for treatment outlined by Lee et al, only patients who are symptomatic are considered candidates for invasive therapy given the potential for additional morbidity related to any intervention.

In our practice, symptomatic low-flow lesions (venous, lymphatic, or combined) are treated with ultrasound or fluoroscopic-guided percutaneous foam or liquid sclerotherapy (sodium tetradecyl sulfate, polidocanol, or ethanol, or a combination) or surgical resection, or both. Low-flow lesions that are superficial, localized, microcystic or septated, and encapsulated are typically excised, primarily because the sclerosant does not distribute homogenously throughout the lesion, whereas diffuse, extensive, macrocystic lesions involving multiple tissue planes or vital structures (ie, nerves) are treated with sclerotherapy because excision is often unfeasible. The sclerosant of choice is typically physician-dependent, but most lesions are treated with sodium tetradecyl sulfate or polidocanol (81.6% foam vs 18.4% ethanol). It is not uncommon for patients to require multiple sclerotherapy sessions until satisfactory improvement or resolution of symptoms is attained.

High-flow lesions, however, are typically treated with transarterial catheter-based techniques (also often requiring multiple sessions) that result in significant obliteration of the lesion’s central component without compromising inflow access, with or without subsequent surgical resection.