ELSEVIER

Seminars in
ROENTGENOLOGY

Interventional Radiology's Role in the Treatment of Pediatric Thoracic Disease

Jay H. Shah, MD,*,† and Morgan J. Whitmore, MD*

A wide array of thoracic diseases affects both the adult and pediatric populations alike. While many disease processes and treatment algorithms are similar among pediatric and adult patients, awareness of the pathologic differences and the unique challenges specific to pediatric interventions are critical for treatment success. Additionally, the over-arching principles of radiation safety and radiation awareness, summarized by "as little as reasonably achievable; ALARA" principles,[1-3] are especially important in the pediatric setting. As such, the judicious use of ionizing radiation and the preference for ultrasound-guided procedures over computed tomography (CT) creates a general distinction between thoracic procedures in the pediatric and adult populations.[2-5]

As the pediatric IR's role within multidisciplinary teams continues to expand, the need for expertise in both diagnostic and therapeutic interventions is of increasing importance. This manuscript aims to review the fundamental treatment considerations, techniques, and complications associated with minimally invasive procedures used to treat the most commonly encountered pediatric thoracic diseases.

Thoracic Biopsies

Although pediatric thoracic biopsies within the mediastinum, pleura, or lung parenchyma were traditionally performed via open or surgical methods, bronchoscopy, or video-assisted thoracoscopic surgery, the role for percutaneous interventional techniques has continued to expand. Specifically, as interventional procedural equipment and operator expertise has continued to evolve and improve, the interventionalists' role surrounding thoracic biopsies has also evolved from one of predominately surgical lesion localization to primary tissue sampling.[4,5] While no universally accepted operational standard exists, interdisciplinary societies have suggested that peripherally located thoracic lesions be targeted with percutaneous tissue sampling, while more central lesions be targeted from endobronchial approaches and endobronchial lavage.[6,7]

Indications for thoracic biopsies do not significantly vary between adult patients and pediatric patients. Fundamentally, thoracic biopsies can be separated into obtaining tissue for a malignant diagnosis, a benign diagnosis, or tissue sampling for culture.[8,9] While no absolute contraindications exist for percutaneous sampling, relative contraindications can be globally grouped into compromised respiratory function and intrinsic pulmonary diseases, including interstitial lung diseases, pulmonary arterial hypertension, technically challenging lesion locations (eg, target located centrally or near the diaphragm), coagulopathies, and positive pressure ventilation.[6,8-10]

After clinically deciding upon percutaneous tissue sampling, the technical aspects of approach and available equipment should be considered. In children, many peripheral lung lesions can be biopsied with ultrasound guidance (Fig. 1). Additionally, with the availability of cone-beam CT guidance (Fig. 2) in many IR suites, this modality allows IRs to perform percutaneous lung biopsies and potentially expose pediatric patients to less radiation as compared to similar procedures performed on conventional CT scanners.[11] In fact, a recent multi-institutional retrospective review of 37 pediatric lung biopsies performed with cone-beam CT guidance showed a diagnostic success rate of 89%.[12] While many different products and percutaneous sampling systems exist, the 2 main techniques are fine needle aspiration (FNA) and core needle biopsy. The decision to utilize 1 percutaneous sampling technique from the other is often multifactorial and dependent upon institutional resources, equipment availability,

*Department of Radiology and Imaging Sciences, Division of Interventional Radiology and Image-Guided Medicine, Emory University School of Medicine, Atlanta, GA.
†Department of Radiology and Imaging Sciences, Division of Pediatric Radiology, Emory University School of Medicine, Emory + Children's Pediatric Institute, Children's Healthcare of Atlanta at Egleston, Atlanta, GA.
Authors' Contributions: J.H.S. and M.J.W. were involved in the literature search, the writing of the article, and the manuscript preparation. Both authors approved the final manuscript.
No funding was received for this study.
There are no conflicts of interest with any authors.
Address reprint requests to Jay H. Shah, MD, Emory University School of Medicine, 1364 Clifton Rd NE, Suite D112, Atlanta, GA 30322. E-mail: jay.hemant.shah@emory.edu

https://doi.org/10.1053/j.ro.2019.06.009
0037-198X/

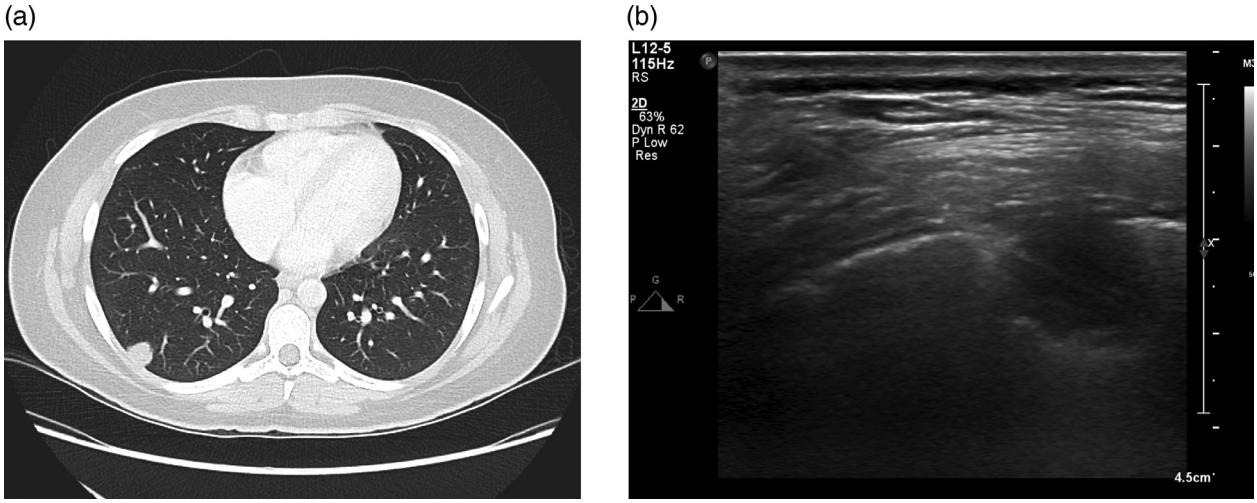

Figure 1 Seventeen years old female with a peripheral lung nodule detected on CT (a). Successful, diagnostic 18G core biopsy was performed of this lesion with ultrasound guidance (b).

and operator preference.[9] FNA utilized for the detection of malignancy has a high sensitivity of 82%-99%, high specificity of 86%-100%, and an overall accuracy of malignancy detection of 64%-97% in diagnosing lung cancer in adults. However, the FNA definitive benign diagnosis yield is only possible in approximately 20%-50% of cases.[9] Utilizing a core biopsy system increases the yield of benign diagnoses in approximately 52%-91% of cases, with similar specificity and sensitivity yields as FNA in malignancy detection.[9] A meta-analysis of multiple CT-guided percutaneous tissue sampling studies in the pediatric population demonstrated overall diagnostic yields of 77%-98% of lesions less than 2 cm and diagnostic yields of 90%-98% of lesions between 2 cm and 3 cm.[13] Importantly, many pediatric tumors require extensive tissue analysis that often necessitates more tissue than can be provided by FNA alone. Discussion with oncologists and pathologists prior to pediatric lung biopsy can provide appropriate insight into the amount of tissue that may be needed based on the suspected pathology and differential diagnosis.

While understanding percutaneous imaging techniques and diagnostic yields is important, anticipation and prompt recognition of complications is also critical to treatment success. Major complications surrounding thoracic percutaneous tissue sampling include pneumothorax and pulmonary hemorrhage.[7,9,13,14] Meta-analysis of pediatric data suggests the incidence of postprocedure pneumothorax ranging from 15% to 52%, and the incidence of pneumothoraces requiring chest tube insertion ranging from 2% to 8%.[13] Postprocedure complications are reduced by decreasing the total number of pleural transgressions by needle (including lung fissures), as well as limiting the overall distance of aerated lung crossed by biopsy needles.[9] Additionally, postbiopsy techniques such as rapid roll-over to procedure site down, normal saline tract sealant, collagen tract plug, blood patch in biopsy tract, and deep expiration/breath hold during needle extraction, have all been suggested to reduce the rates of postprocedure pneumothoraces.[15]

While the majority of pulmonary hemorrhage following percutaneous biopsy is minor and self-limiting, the incidence of pulmonary hemorrhage in the pediatric population after percutaneous tissue sampling ranges from 3% to 43%, with the incidence of symptomatic hemoptysis ranging from 2% to 11%.[13] Similar reports in adults suggest an incidence ranging from 4% to 27%.[9] The need to manage pulmonary hemorrhage through advanced airway management and endovascular interventions are uncommon but may be required in certain cases. Air embolism following percutaneous thoracic biopsy is a potentially serious, yet an exceedingly rare complication, that has been reported to occur in less than 1% of adults.[9] The incidence of pediatric air embolism following biopsy has not been reported. If air embolism is suspected, supportive care through supplemental oxygen and patient positioning to trap the air within the right side of the heart (left lateral decubitus) are recommended immediately.[16]

Despite the reported complications, percutaneous image-guided thoracic biopsies are considered both safe and effective in the pediatric population, and in many instances have become the standard of care.[4,5,13,17]

Pleural Space Interventions

A thin layer of normal fluid is located between the partial and visceral pleura of the lung, compromising what is known as the pleural space. While the pleural space is a potential space, certain diseases processes can cause an abnormal expansion of this space through the accumulation of transudative or exudative fluid, which may require intervention.[18]

Upon discovery of an abnormal pleural effusion, attempts at delineating the effusion into a transudative effusion or exudative effusion, can assist in diagnosis and help guide management.[19,20] Specifically, Light's criteria are a set of clinical rules which can be used to delineate between exudative and

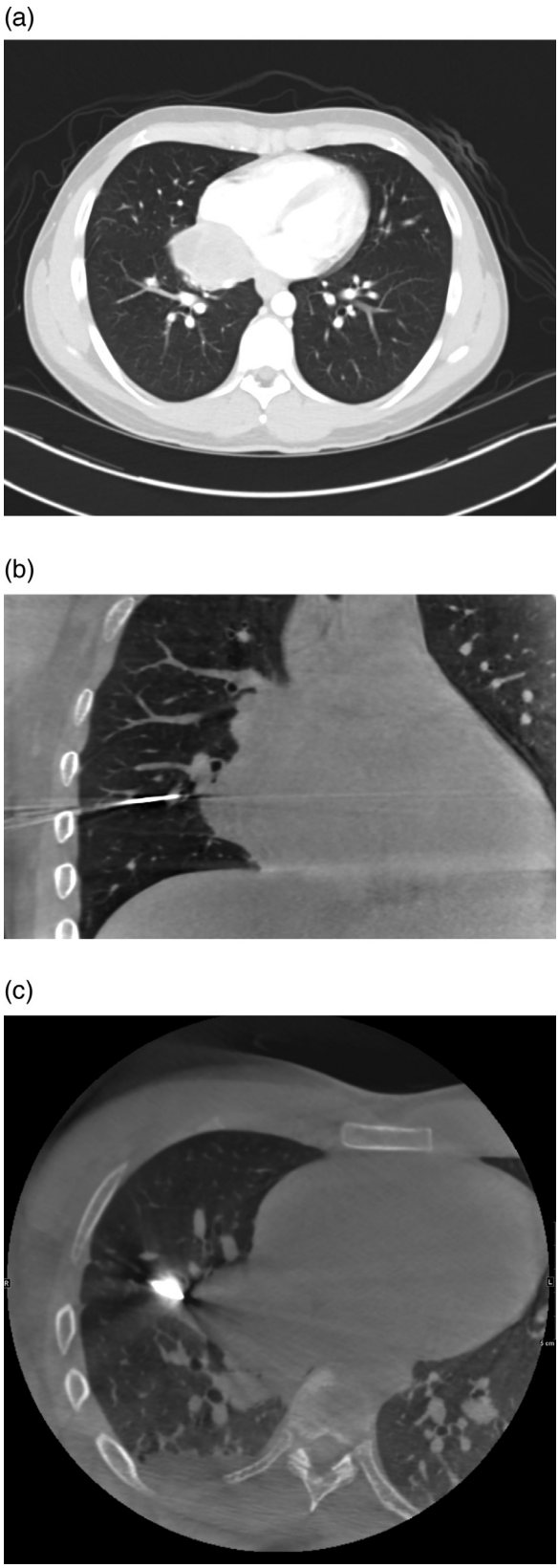

Figure 2 Nineteen years old male with prior Ewing's sarcoma and new mediastinal mass detected on CT (a). Using cone-beam CT guidance with live fluoro-navigational overlay (b,c), a coaxial biopsy guide needle could be advanced to the lateral margin of the mass. Eight 18-gauge cores were obtained successfully without complication.

transudative effusions.[19] One of the following is required to be true to fulfill the criteria for an exudative effusion[19,21]:

(1) The ratio of pleural fluid lactate dehydrogenase (LDH) to serum LDH must be greater than 0.6;
(2) Pleural fluid LDH to serum LDH (upper limit) ratio must be greater than 2/3;
(3) Ratio of pleural fluid protein to serum protein greater than 0.5.[19,21]

The most common cause of an abnormal pleural effusion in children is secondary to an infectious process, particularly parapneumonic effusions, which represent 50%-70% of all abnormal pediatric pleural effusions. Abnormal pleural effusions related to congestive heart failure and malignancy are uncommon in children and seen much more commonly in the adult population.[22]

Fundamentally, a pleural effusion occurs when pleural fluid production exceeds fluid filtration and elimination, through disturbances in the pleural Starling forces.[20] In regards to parapneumonic effusions, infectious microorganisms within the alveoli cause a granulocytic or white blood cell-mediated inflammatory response. Through this inflammatory process, multiple changes in the permeability and porosity of pleural and subpleural capillaries occur, resulting in the leakage of proteinaceous material and cells into the pleural space, effectively transforming a transudative fluid into an exudative fluid. If the infectious microorganism has not yet seeded the pleural fluid, by definition, the pleural fluid has become a sterile exudate. However, as the infection continues to progress and seed the pleural fluid, pro-coagulation factors, such as fibrin, can also begin to leak into the pleural space. As fibrin and collagen are deposited, and the infection within the pleural space becomes organized, loculations and a rind surrounding the purulent pleural fluid occurs. By definition, this organized collection of infected and purulent pleural fluid is consistent with an empyema.[21,23,24]

The sequela of untreated and ongoing thoracic infectious processes can result in significant morbidity, if not result in a terminal event for some patients. Specifically, as infected pleural effusions or an empyema becomes organized and loculated, the resultant damage can cause diminished parenchymal lung expansion, leading to a restrictive lung disease pattern. Moreover, extension of an infectious process centered within the pleural space into adjacent tissue planes, such as dissection of an empyema into the chest wall (empyema necessitans) or extension of the empyema into the adjacent lung parenchyma, can substantially increase morbidity in some patients.[21-26]

Pediatric IRs have a unique opportunity to mitigate morbidity and mortality by providing minimally invasive solutions to pediatric, pleural-based disease processes. Optimizing medical management prior to intervention is a general routine initial step, and pediatric pleural diseases are no different. Medical management of systemic disease processes, correction of electrolyte abnormalities, and modifying fluid volume status can all be utilized in the management of noninfectious pleural fluid

accumulation. However, medical management of pleural-based infectious disease processes is far less structured. Most clinicians agree that antibiotic therapy alone can often treat uncomplicated infectious pleural effusions, excluding those effusions that are causing significant mass effect or respiratory compromise.[20,21,23] Additionally, the American College of Chest Physicians advocates for initiating empiric antibiotic regimens prior to hematologic or pleural fluid culturing.[23,27-29] However, as infected effusions transform into organized infected fluid collections (empyema), antibiotic therapy alone may not be effective, and surgical or procedural interventions may be required.[23] Despite intervention in severe pleural-based infections, intravenous and oral antibiotic regimens must continue well past the afebrile period of illness.[22,23,27]

To supplement medical management, interventionalists have multiple percutaneous techniques at their disposal to assist in the management of pleural-based disease processes, which are described below.

Thoracentesis

Although numerous diagnostic and therapeutic indications exist for percutaneous pleural fluid needle aspiration, there are no established consensus guidelines for thoracentesis in children.[30] With the majority of pleural effusions within the pediatric population related to infectious etiologies, indications of intervention are related to draining or obtaining infected fluid for diagnostic and/or therapeutic purposes.[22,29,31]

Once the decision is made to intervene percutaneously in a patient's care, technical considerations of pleural-based interventions include imaging guidance, equipment, and approach. While thoracenteses have traditionally been performed without imaging guidance, the use of sonographic imaging guidance for thoracenteses and tube thoracostomy has been well established and demonstrated reduced rates of pneumothorax compared with the absence of imaging guidance.[31,32] A multitude of equipment exists to perform thoracenteses. At our institution, the most commonly utilized equipment includes a combination 5 French and 19-gauge needle-centesis catheter system positioned in the most dependent areas (containing the largest amount of pleural fluid). Of note, particular care is made of needle positioning during pleural entry in order to not transgress the visceral pleural, thereby minimizing the risk of postprocedure pneumothorax.[31] Following intervention, pleural fluid is often presented for laboratory analysis and culture, and postprocedure chest radiograph is performed to evaluate for postprocedure complications.[31]

Incidences of complications in the pediatric population remain unclear but can be interpolated from the adult literature. Specifically, pneumothorax is the most commonly encountered postprocedure complication following percutaneous needle access into the pleural space, with a reported incidence of up to 6%.[31,32] Additionally, complications of postprocedure hemorrhage and re-expansion pulmonary edema following thoracentesis are also uncommon within the adult population.[31]

Pig-Tail Catheters and Chest Tubes

First documented by Hippocrates in the fifth century, thoracic drainage has been a mainstay for the treatment of many pleural diseases, from empyema to hemopneumothorax.[33,34] Multiple technological advances surrounding catheter equipment have been made over time. Specifically, the size of the catheter equipment has evolved over time and remains an important consideration during interventions. Traditionally, catheters of sizes 14 French and smaller can be considered "small bore," while catheters larger than 14 French can be considered "large bore."[35] Interestingly, pig-tail catheters, as small as 5 French, have also been introduced to market — offering safer, less invasive insertion, which is particularly beneficial within the neonatal and infant population.[33,35,36] Larger bore tubes sometimes necessitate a surgical cutdown with blunt dissection and are more often placed by surgeons.[35]

Predictably, catheter size selection is often closely related to patient size and the indication for pleural catheter or tube placement. For simple pleural effusions and chylous effusions, pig-tail catheter insertion is effective and has a favorable safety profile in children greater than 5 kg.[37] For loculated pleural effusions and empyema, larger bore catheters are frequently used secondary to the viscosity of fluid attempting to be removed. Large bore, surgically placed thoracostomy tubes have been traditionally placed for this purpose in children. However, as intrapleural fibrinolytic regimens become more readily accepted, image-guided pig-tail drainage catheter placement is a reasonable initial approach.[37-40]

Complication rates surrounding pleural-based catheter placement is low, with pneumothorax and hemothorax representing the majority of postprocedure complications.[37]

Intrapleural Fibrinolysis

In dense collections such as complex effusions, or empyema, adjunct intrapleural fibrinolytic therapy is often necessary to ensure successful drainage. Historically, intrapleural fibrinolysis has involved off-label drug use of pharmacologic agents, which most commonly involved drugs such as streptokinase, urokinase, deoxyribonuclease, or tissue plasminogen activator (tPA).[39,41] The off-label use of tPA is currently the pharmacologic fibrinolytic agent of choice for intrapleural fibrinolysis.[42] Despite the variation of reported dosing regimens and techniques, the reproducibility and efficacy of intrapleural fibrinolysis has been established in the pediatric population.[39,43,44] Specifically, pediatric intrapleural fibrinolytic therapy remains a reasonable and efficacious treatment alternative to other invasive therapeutic surgical treatment options and has been shown to duration of shorten hospital stay.[42-45]

At our institution, intrapleural fibrinolysis is performed via infusion of 4-6 mg of tPA mixed in 10-20 mL of normal saline injected through pleural-based pig-tail catheter. In smaller children and infants, 0.6 mg/kg is the preferred dosing regimen of tPA, with a maximum tPA dose of 6 mg.[46] However, it should be noted that minimal literature support

exists for tPA dose limits for intrapleural use.[47] Once the dose of tPA has been selected, the tPA-saline mixture is injected through the catheter, which is then locked in place for 4-6 hours, allowing the tPA to dwell. Following this, the chest tube is opened and placed to low-suction or dependent gravity bag drainage. This protocol can be repeated, as needed, dependent upon the clinical scenario.[37,39-43,45]

Predictably, the complications surrounding intrapleural use of tPA are predominately surrounding postprocedural hemorrhage but occur with relative infrequency.[41,44] While few if any absolute contraindications exist for the intrapleural use of tPA, relative contraindications include risk of hemorrhage from recent trauma, surgery, other recent major bleeding events, and persistent coagulopathy.[44]

The efficacy and overall safety profile for pediatric intrapleural fibrinolysis is likely to continue to improve, as national and international societies continue to inform standardization and guidelines for clinicians.[42,43]

Indwelling Tunneled Pleural Drainage Catheters

Recurrent pleural effusions are a significant impediment to the quality of life for many patients and most commonly afflict children with metastatic cancer. These patients often require repeat thoracenteses and incur the risks associated with such repeat interventions, as described earlier. While other more invasive and definitive treatment options exist for recurrent pleural effusions, such as pleurodesis, the overall safety profile and potential complications associated with such interventions may not be acceptable for some patients and their families.[48]

Tunneled pleural drainage catheters are a reasonable palliative treatment alternative for recurrent pleural effusions, allowing ongoing pleural fluid removal from existing catheter access, with evidence from the adult literature supporting the efficacy and safety of use within the pediatric population.[49] Although studies specific to the pediatric population are limited by small sample sizes, the limited data do suggest tunneled pleural drainage catheters can be placed safely and allow for the more efficient management of refractory malignant pleural effusions in children.[50]

Two frequently used pleural drainage catheters are the Aspira system (Merit Medial, South Jordan, UT) and the PleurX system (Becton, Dickenson (BD) and Company, Franklin Lakes, NJ), which have both demonstrated safety and efficacy.[51] While these large, cuffed, soft catheters are frequently placed in adults, a pediatric-sized catheter equivalent does not currently exist. Therefore, these tunneled pleural drainage catheter systems must only be used in selective and appropriately sized children. Although the benefits of catheter placement usually outweigh the risks, attention should be given to the potential complications, which can include infection, malignancy tract seeding, catheter obstruction, leakage from the insertion site, and pneumothorax.[49]

Central Conducting Lymphangiography and Thoracic Duct Embolization

Image-guided thoracic duct embolization (TDE) is a minimally invasive alternative to surgical thoracic duct ligation. First performed by Dr Constantine Cope, the indications for TDE fundamentally include the management of lymphatic flow disorders.[52] TDE is most commonly performed for chylous leaks, which are typically classified as traumatic (surgery) or atraumatic (idiopathic, malignancy, cardiogenic, etc).[53] Additionally, congenital central conducting lymphatic disorders can also result in chylous leaks into the pleural space.[54] Furthermore, disorders such as plastic bronchitis, common in patients with Fontan physiology,[55,56] are also palliated by this procedure. TDE offers a safe treatment option with a technically high success rate for a variety of etiologies. TDE is attempted most often after patients are refractory to conservative therapies such as “medium chain triglyceride” diets, TPN, somatostatin analogues, pleurodesis, and percutaneous drainage.[52,57]

Fundamentally, lymphatic anatomy and drainage consists of a dendritic pattern of small lymphatic tributaries into a larger, dominant, and more centralized lymphatic system. There are generally 2 major lymphatic drainage pathways in humans. Specifically, the right side of the head, neck, upper extremity, and chest, including the lung and heart, all drain into the right lymphatic duct. The right lymphatic duct ultimately drains into the venous system at the confluence of the right internal jugular and right subclavian veins. The remaining lymphatic drainage of the body drains directly into the thoracic duct, located within the left chest or through the cysterna chyli (lymphatic drainage of the abdomen and lower extremities) and ultimately into the thoracic duct. Interestingly, the ostial insertion of the thoracic duct at the left internal and jugular venous confluence consists of 2 valves that prevent reflux of blood into the lymphatic system. The entire lymphatic system is tasked with the transit of 1-2 L of lymphatic fluid a day, the majority of which is of hepatic and intestinal origin.[58-60]

Nuclear scintigraphy was the historic mainstay of lymphatic imaging. Traditionally performed under moderate sedation and local anesthesia, Methylene blue dye (2.5% Patent Blue V Dye; Guerbet Laboratories, Aulnay-sous-Bois, France) was infiltrated within the web spaces along the dorsal aspect of the feet for surgical localization. Once lymphatic drainage was visualized through staining, fine needle access into the lymphatic drainage system was gained through surgical approach, where lipiodol or ethiodol was injected into the lymphatic drainage system, thereby causing lymphatic opacification during intermittent fluoroscopic exposures. This described method was utilized for diagnostic evaluation of the lymphatic system, assisting in the identification of chylous leaks, fistulae and was also utilized for surgical planning. Modified protocols of fluoroscopic lymphangiography have been well described in the literature, including ultrasound-guided injection of the inguinal lymph nodes with lipiodol, a

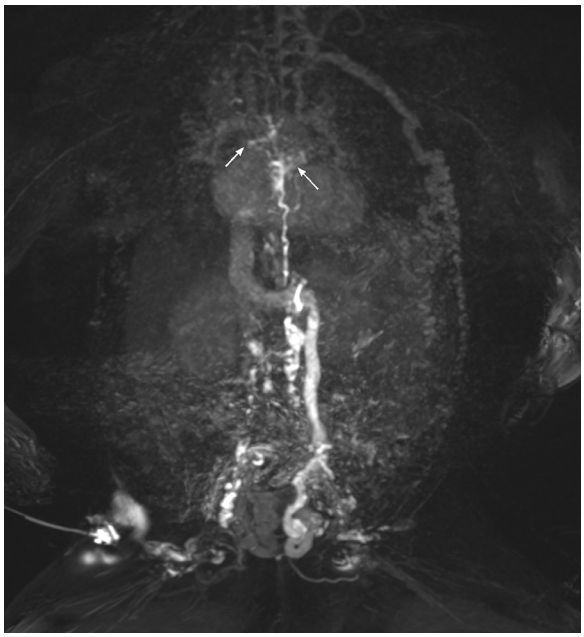

Figure 3 Diagnostic MR lymphangiogram in a 2-year-old with plastic bronchitis, extensive central chronic venous occlusion, and congenital pulmonary disease shows extravasation of gadolinium in the airways (arrows).

technique which expedites diagnostic lymphatic opacification, and offers a simpler target (access of inguinal lymph nodes over pedal lymphatics in children).[61-63]

More recently, magnetic resonance (MR) lymphangiography (Fig. 3) has gained rapid adoption as a problem-solving diagnostic tool for lymphatic flow disorders in children. While traditional lipiodol-based lymphangiography occasionally provides an additional therapeutic edge to a diagnostic evaluation for certain lymphatic disorders, such as chylothorax, the use of gadolinium-based contrast for MR lymphangiography has only demonstrated diagnostic capabilities.[54,63-66] Although a thorough discussion of the recommended techniques for MR lymphangiography has been previously described and is beyond the scope of this manuscript, MR lymphangiography has the capacity to provide highly sensitive, time resolved opacification of the lymphatic system that can accurately characterize a number of lymphatic anomalies and injuries.[54] Importantly, MR lymphangiography has become one of the primary diagnostic tools used in the diagnosis of congenital complex lymphatic disorders, such as generalized lymphatic anomaly, central-conducting lymphatic disorders, and kaposiform lymphangiomatosis.[52]

Following the identification of abnormal lymphatic flow or injury, TDE is an ideal therapeutic intervention, after more conservative treatment options have been exhausted. While numerous approaches for TDE exist, the most common approach includes percutaneous, transabdominal access into the cysterna chyli through a small gauge needle, such as a 22-gauge access needle, under fluoroscopic guidance following lipiodol-based lymphangiography. Once the cysterna chyli, classically located immediately anterior to the vertebral bodies at the L1 or L2 levels,[52,63] or another large lymphatic vessel is cannulated, attempts are made to gain microwire access into the lymphatic system and subsequently into the thoracic duct. After microwire access is achieved, catheter access into the system is attained, and contrast diagnostic lymphangiography can be performed. If clinically indicated, TDE can be executed through a microcatheter system placed coaxially through the access catheter. Embolotherapy can then be performed using a variety of embolics, which include both n-Butyl cyanoacrylate glue and/or embolization coils. More exhaustive discussions of TDE and further procedural details and options, including retrograde TDE embolization (Fig. 4), exist throughout the literature and are beyond the scope of this manuscript.[57-71]

The literature supporting pediatric TDE in the pediatric population is scarce and comprised mostly of case reports. One of the largest pediatric-only case series to date of central lymphangiography and intervention, consists of 11 pediatric patients undergoing 12 lymphangiographic interventions for chylothorax, chylous ascites, and chylopericardium, resulting in clinical success of 7 of the 11 children (64%) and only 3 minor complications.[72,73] A larger meta-analysis in the adult population evaluated 409 patients with chylothorax who underwent central lymphangiography and thoracic duct intervention, demonstrated pooled technical success rates of lymphangiography and TDE of 94.2% and 63.1%, respectively. Pooled data evaluating clinical success rates of lymphangiography, TDE, and thoracic duct disruption demonstrate rates of 56.6%, 79.4%, and 60.8%, respectively. Major complication rates were effectively low, with lymphangiographic and TDE reported complication rates of 1.9% and 2.4%, respectively.[74] Although pediatric percutaneous interventions for central lymphatic disorders are still early in development, the limited literature supports them to be considered effective and safe.

Pulmonary Arteriovenous Malformations

Pulmonary arteriovenous malformations (PAVMs), first described by Churton in 1897 following an autopsy,[75] are abnormal vascular connections between pulmonary arteries and pulmonary veins without a normal intervening capillary bed.[76,77] Although the overall prevalence of PAVMs is quite rare, the vast majority of PAVMs are associated with Hemorrhagic Hereditary Telangiectasias and are often diagnosed within the first 3 decades of life.[77-79] While many PAVMs are asymptomatic and sometimes incidentally discovered, the potential sequela of untreated PAVMs, including stroke, can cause significant morbidity and mortality. Importantly, patients with PAVMs in the setting of Hemorrhagic Hereditary Telangiectasias require genetic testing and extensive additional diagnostic work-up (including CNS imaging) that should be done at a multi-disciplinary referral center with experience diagnosing, working-up, and treating these patients.

Symptomatic PAVMs can vary widely, but clinical presentations of PAVMs can often be attributed to 3 fundamental physiologic processes, which include right-to-left shunting, abnormal vascularity leading to compromised vessel

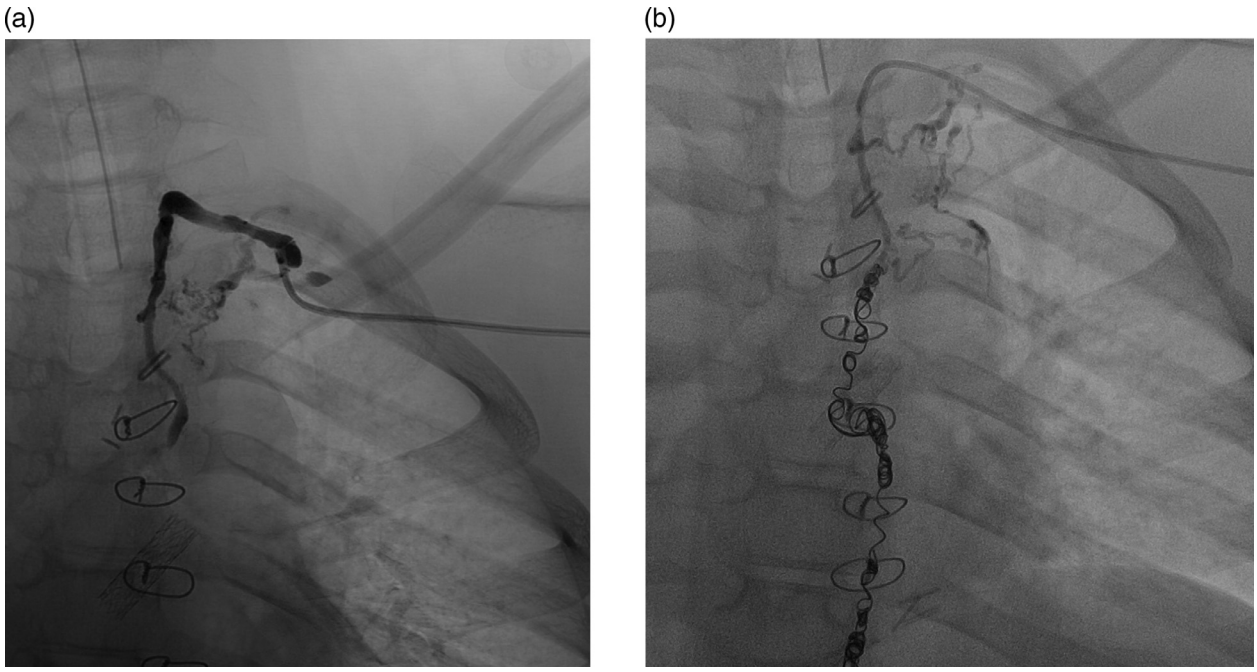

Figure 4 (a,b) Retrograde access into the thoracic duct was obtained in a 7-year-old patient with congenital cardiac disease, status post Fontan, with plastic bronchitis. The patient had undergone prior thoracic duct embolization precluding conventional antegrade, transabdominal route. A 4-French angled catheter was used to access the ostium of the thoracic duct (a). Using a 1.7F microcatheter and 0.014 microwire, caudal access into the thoracic duct was obtained. Embolization was performed with coils and glue (b).

integrity, and loss of the normal lung filtration process. Specifically, hypoxemia, cyanosis, platypnea, and congestive heart failure can often be attributed to the right-to-left shunting, while hemothorax and hemoptysis can be attributed to abnormal vessel integrity. Lastly, paradoxical emboli, stroke, and intracranial abscesses are caused by the loss of the normal lung filtration process.[77-79] Additionally, the severity of symptoms is often related to the size of right-to-left shunting or the number of PAVMs.

Many clinical tools exist for the diagnostic evaluation of PAVMs. Contrast echocardiography is an excellent screening tool for those patients suspected of having right-to-left shunts, with the sensitivity of detecting a right-to-left shunt approaching 100%.[77,78] Beyond screening, CT Angiography (CTA) is the most-common diagnostic modality for noninvasive evaluation of PAVMs.[77,78,80] Magnetic Resonance Imaging (MRI) is an alternative, less sensitive, diagnostic option for patients trying to minimize radiation exposure or who have iodinated contrast allergies.[77]

Despite the improvement in noninvasive diagnostic options, pulmonary angiography remains the gold standard for both pre- and post-treatment imaging, as it provides the most accurate assessment of vessel architecture, as well as establishes an avenue for potential therapeutic interventions.[77,78]

The decision to treat PAVMs, especially in the pediatric setting, can be nuanced. However, most agree that intervention is warranted for symptomatic patients and in cases where the feeding artery is greater than 2-3 mm.[77,78] Additionally, the decision to intervene is influenced by the morphology and classification of the PAVM. Specifically, PAVMs can defined as simple or complex, with simple PAVMs having a single feeding artery and draining vein and complex PAVMs containing 2 or more feeding arteries and/or draining veins.[77,78,80] Importantly, the decision to intervene should be made in conjunction with a multidisciplinary team.[80]

Percutaneous, endovascular embolization (Fig. 5) remains the mainstay of treatment for PAVMs,[77,78,80] with an overall technical success rate of greater than 95%.[78] In addition to executing the procedure safely, technical considerations regarding complete embolization of all feeding arteries, maximal preservation of normal lung parenchyma, and appropriate embolic device selection should be implored.[77,78,80] In regards to embolic device selection, multiple studies have demonstrated technical success achievement with both plugs and coils.[77,78,80,81] Importantly, detachable coils and plugs should be used in order to limit the risk of nontarget embolization. Within the pediatric population, both coil and plug embolization has been executed successfully.[79] Institutional protocols in the literature include percutaneous embolization for feeding arteries measuring 2 mm or more, in addition to high-grade diagnostic contrast echocardiogram.[82] Liquid embolics and particles should not be used to embolize PAVMs given the inherent presence of PAVM right-to-left shunting imminent risk of stroke and other complications from non-target systemic arterial embolization.[78,82,83]

Postintervention care and continued clinical follow-up is necessity following PAVM embolization. Immediately post-procedure care includes managing self-limiting pleuritic chest pain, which can be seen within the first 2 days of the procedure in up to 15%-31% of patients.[80] Additionally, recanalization and/or collateralization can be seen in 5%-19% of patients following PAVM embolization.[77] Therefore,

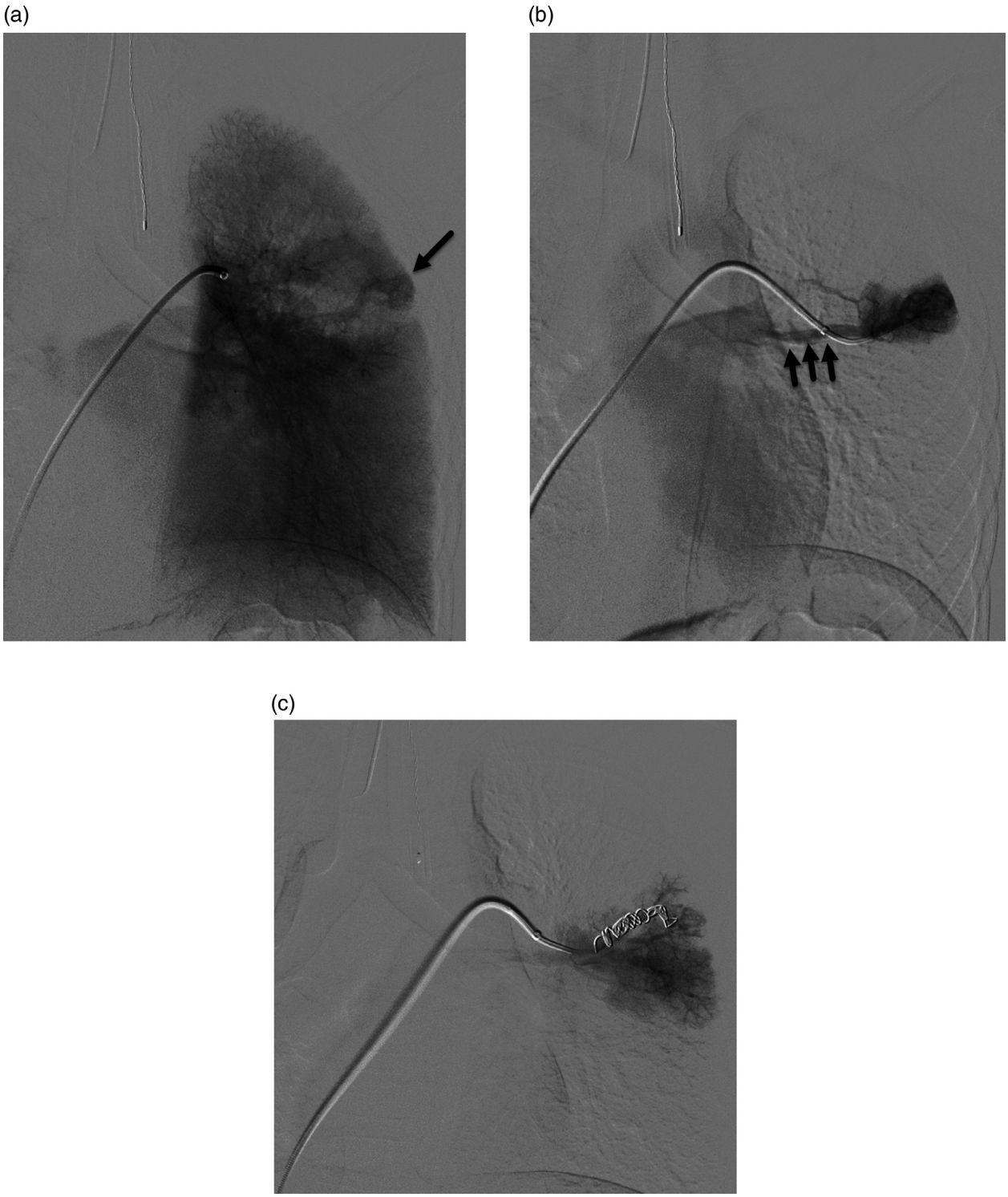

Figure 5 (a-c) Left pulmonary angiography (a) in a 9-year-old patient with hereditary hemorrhagic telangiectasia, hypoxia, and history of stroke shows a peripheral pulmonary AVM (black arrow). A long 6-French sheath was used to stabilize the system in the left pulmonary artery. A 4-French angled catheter and 0.035 wire obtained distal access directly proximal to the pulmonary AVM (b). Angiography (b) shows early venous drainage (black arrows). Section c shows the postembolization angiogram following deployment of a detachable 0.035 Retracta (Cook Medical, Bloomington, IN) with successful embolization of the AVM.

it is necessary that continued clinical screening and interval diagnostic imaging be used in order to evaluate for persistent PAVMs and development of new PAVMs. While there is no consistent data on imaging follow-up intervals, a follow-up CTA in 6-12 months and then every 3-5 years thereafter has been suggested.[77,80]

Bronchial Artery Embolization

Massive hemoptysis is a life-threatening event, which has controversial definitions, but quantitatively is characterized as more than 300 mL of blood in a 24-hour period in an adult,[84] or more than 8 mL/kg of blood in a 24-hour period in a child.[84-86] Additionally, massive hemoptysis can also be defined as hemoptysis causing significant cardiovascular instability or respiratory compromise, which includes hypotension as represented by systolic blood pressures of less than 90 mmHg in adults,[84] or age-height-gender adjusted hypotension in the pediatric setting of systolic blood pressures falling below the fifth percentile or 2 standard deviations below the mean,[87,88] as well as oxygen saturation levels (SpO_2) less than 60%. Moreover, the morbidity and mortality of massive hemoptysis is often not related to an exsanguination event, but rather an asphyxiation event,[85] necessitating the need for prompt recognition and early intervention.[86] In cystic fibrosis patients prone to hemoptysis, commonly with multidrug resistant sputum and severe lung disease, studies support bronchial artery embolization (BAE) to be a relatively safe and effective method to treat acute hemoptysis.[89,90]

Beyond recognizing and categorizing hemoptysis events, uncovering the etiology of hemoptysis is critical to the continued clinical management of patients. While the list of potential hemoptysis causing etiologies is vast, the most common etiology in the United States in children is sequela cystic fibrosis, with infectious or postinfectious etiologies, such as active tuberculosis or aspergillomas, being less common.[84] While uncovering the etiology of hemoptysis is important, diagnostic investigation should not impede rapid clinical evaluation and management of patients with hemoptysis, especially in the setting of massive hemoptysis.

Initial clinical management of patients with massive hemoptysis includes active resuscitation and airway management.[85] In scenarios of persistent clinical deterioration despite resuscitative measures and airway support, immediate intervention may be required in lieu of initial diagnostic evaluation. However, in controlled clinical scenarios, diagnostic imaging evaluation is often utilized. While no formal imaging paradigm has been suggested for hemoptysis, the American College of Radiology Appropriateness Criteria has suggested chest radiography as the most appropriate initial imaging modality of choice, followed by CTA of chest.[91] However, when evaluating the overall diagnostic accuracy of radiologic imaging in localization or etiology identification of hemoptysis, chest radiography has only been reported as high as 50%,[86] whereas CTA of the chest has been reported as high as 92%.[84] In many institutions, bronchoscopy is often a first-line resource for diagnostic evaluation, but the diagnostic accuracy of bronchoscopy in isolation is reported to be less than 50%.[86,92] However, when bronchoscopy is used in conjunction with CTA of the thorax, the diagnostic accuracy for pulmonary hemorrhage has been reported to be as high as 93%.[86,92] Lastly, when possible, laboratory sputum analysis should be performed for evaluation of underlying infections processes and/or malignancy.[86]

Following diagnostic evaluation, a targeted intervention should be performed for cessation of hemoptysis. While surgical approaches for hemoptysis were the primary interventions prior to 1970, BAE for hemoptysis, first described by Remy et al in 1974, is now commonly performed.[84-86,93] However, understanding bronchial vessel anatomy and embolic agent selection are 2 major technical factors that must be considered prior to BAE, in order to ensure a safe, effective, and durable intervention.

Although bronchial artery anatomy is widely variable, the bronchial arteries most commonly arise between the T5 and T6 levels of the descending thoracic aorta, with the right bronchial artery arising from a common intercostobronchial trunk and 2 left bronchial arteries arising directly from the aorta.[86] These bronchial arteries can often be seen on preprocedure imaging or during the endovascular intervention via an aortogram. However, nonbronchial systemic arteries can also supply abnormalities within the lung and can be a source of hemoptysis recurrence if not appropriately identified.[84,86] Specifically, in children with cystic fibrosis, bronchial artery anatomy can be widely variable and change over time in children that have had prior BAEs. Thus, whenever it is clinically feasible, the authors recommend a CTA for anatomical delineation of the bronchial arteries in all patients prior to BAE.

Embolic agent selection is a major technical consideration during BAE. Particles are the embolic agent of choice at many institutions given their accessibility, effectiveness, and ability to ensure repeat arterial access for future interventions.[85,86] Overall, particle size selection should be above 325 μm to avoid embolization through known broncho-pulmonary anastomoses, which can lead to inadvertent systemic arterial embolization causing stroke.[86] Traditionally, gelatin sponge and 350-500 μm polyvinyl alcohol were utilized. However, there is increasing use of tris-acyl microspheres, which have more uniform diameter and are less likely to clump compared to polyvinyl alcohol and gelatin[84-86] At the authors' institution, 500-700 μm tris-acyl microspheres are the preferred embolic agent when performing BAE.

Overall, immediate hemoptysis cessation clinical success of 73%-99% has been reported following BAE.[84-86] However, overall recurrence rates of 10%-57.5% have been reported, with the median time of recurrence between 6 months and 1 year.[84,86] Therefore, treating the underlying etiology of hemoptysis and close clinical surveillance are necessary. In fact, in children with cystic fibrosis, recurrence is expected.

Following the procedure, the most commonly reported complication is chest pain and dysphagia,[84,86] as branches of the bronchial arteries provide blood supply to a variety of organs including the esophagus and many pleural surfaces. However, the most feared complication is inadvertent embolization of an anterior spinal artery, causing spinal cord ischemia and transverse myelitis. The reported prevalence of spinal cord ischemia following BAE is 0.6%-6.5%, which can be minimized by more distal embolization within the bronchial arteries, recognition of blood vessels coursing medially toward the spine, and recognizing anterior spinal arteries demonstrating the classic "hairpin" configuration.[84-86]

Conclusion

As with all cutting-edge pediatric specialties, such as pediatric interventional radiology, understanding the historical origin and efficacy of therapy in adults informs contemporary practice in children. While safety and efficacy data are limited for many minimally invasive treatment options for thoracic diseases in children, the overall transition to minimally invasive techniques is informed by interpolated adult data, expert experience, and analysis of metadata. A thorough understanding of contraindications, and complication management should inform decision making, as more minimally invasive therapeutic options emerge for thoracic diseases in pediatric patients

References

1. Strauss KJ, Kaste SC: ALARA in pediatric interventional and fluoroscopic imaging: Striving to keep radiation doses as low as possible during fluoroscopy of pediatric patients-A white paper executive summary. J Am Coll Radiol 2006. https://doi.org/10.1016/j.jacr.2006.04.008
2. Sodhi KS, Krishna S, Saxena AK, et al: Clinical application of "Justification" and "Optimization" principle of ALARA in pediatric CT imaging: 'How many children can be protected from unnecessary radiation? Eur J Radiol 2015. https://doi.org/10.1016/j.ejrad.2015.05.030
3. Shah NB, Platt SL: ALARA: Is there a cause for alarm? Reducing radiation risks from computed tomography scanning in children. Curr Opin Pediatr 2008. https://doi.org/10.1097/MOP.0b013e3282ffafd2
4. Hardaway BW, Hoffer FA, Rao BN: Needle localization of small pediatric tumors for surgical biopsy. Pediatr Radiol 30:318-322, 2000. https://doi.org/10.1007/s002470050748
5. Cahill AM, Baskin KM, Kaye RD, et al: CT-guided percutaneous lung biopsy in children. J Vasc Interv Radiol 15:955-960, 2004. https://doi.org/10.1097/01.RVI.0000130814.63277.F2
6. Efrati O, Gonik U, Bielorai B, et al: Fiberoptic bronchoscopy and bronchoalveolar lavage for the evaluation of pulmonary disease in children with primary immunodeficiency and cancer. Pediatr Blood Cancer 48:324-329, 2007.
7. Manhire A, Charig M, Clelland C, et al: Guidelines for radiologically guided lung biopsy. Thorax 58:920, 2003. https://doi.org/10.1136/thorax.58.11.920. LP-936
8. Work-up P: IPEG guidelines for thoracoscopic biopsies in children. J Laparoendosc Adv Surg Tech A 15:95-97, 2005. https://doi.org/10.1089/lap.2005.15.95
9. Winokur RS, Pua BB, Sullivan B, et al: Percutaneous lung biopsy: Technique, efficacy, and complications. Semin Intervent Radiol 2013. https://doi.org/10.1055/s-0033-1342952
10. Sinha A, Narayan O, Cheesman E: Utility of open surgical lung biopsy in children. Eur Respir J 50(suppl 61):PA4159, 2017. https://doi.org/10.1183/1393003.congress-2017.PA4159
11. Acord M, Shellikeri S, Vatsky S, et al: Reduced-dose C-arm computed tomography applications at a pediatric institution. Pediatr Radiol 2017. https://doi.org/10.1007/s00247-017-3964-0
12. Shivaram GM, Gill AE, Monroe EJ, et al: Cone-beam computed tomography guidance with navigational overlay for percutaneous lung nodule biopsy. Pediatr Radiol 2019. https://doi.org/10.1007/s00247-018-4296-4
13. Han Y, Kim HJ, Kong KA, et al: Diagnosis of small pulmonary lesions by transbronchial lung biopsy with radial endobronchial ultrasound and virtual bronchoscopic navigation versus CT-guided transthoracic needle biopsy: A systematic review and meta-analysis. PLoS One 2018. https://doi.org/10.1371/journal.pone.0191590
14. Naumann H, Pittaway A, Lynn AM, et al: CT-guided percutaneous lung biopsy under general anesthesia: A pediatric case series and literature review. Paediatr Anaesth 2012. https://doi.org/10.1111/j.1460-9592.2011.03773.x
15. Huo YR, Chan MV, Habib A-R, et al: Post-biopsy manoeuvres to reduce pneumothorax incidence in CT-guided transthoracic lung biopsies: A systematic review and meta-analysis. Cardiovasc Intervent Radiol 2019. https://doi.org/10.1007/s00270-019-02196-8
16. Shaikh N, Ummunisa F: Acute management of vascular air embolism. J Emerg Trauma Shock 2009. https://doi.org/10.4103/0974-2700.55330
17. Hayes-Jordan A, Connolly B, Temple M, et al: Image-guided percutaneous approach is superior to the thoracoscopic approach in the diagnosis of pulmonary nodules in children. J Pediatr Surg 2003. https://doi.org/10.1016/jpsu.2003.50198
18. Hyeon Y: Management of pleural effusion, empyema, and lung abscess. Semin Intervent Radiol 28:75-86, 2011. https://doi.org/10.1055/s-0031-1273942
19. Light RW: Clinical practice: Pleural effusion. N Engl J Med 2002. https://doi.org/10.1056/NEJMcp010731
20. Adeyinka A, Kondamudi NP: Pleur Effusion Pediatr Malig 2019. https://www.ncbi.nlm.nih.gov/pubmed/29939542
21. Light RW: Pleural effusions. Med Clin North Am 2011. https://doi.org/10.1016/j.mcna.2011.08.005
22. Efrati O, Barak A: Pleural effusions in the pediatric population. Pediatr Rev 23:417-426, 2002. https://doi.org/10.1542/pir.23-12-417
23. Koegelenberg CFN, Diaconi AH, Bolligeri CT: Parapneumonic pleural effusion and empyema. Respiration 2008. https://doi.org/10.1159/000117172
24. Light RW, Girard WM, Jenkinson SG, et al: Parapneumonic effusions. Am J Med 1980. https://doi.org/10.1016/0002-9343(80)90460-X
25. Hoffer FA, Bloom DA, Colin AA, et al: Lung abscess versus necrotizing pneumonia: Implications for interventional therapy. Pediatr Radiol 1999. https://doi.org/10.1007/s002470050547
26. VanSonnenberg E, Wittich GR, Goodacre BW, et al: Percutaneous drainage of thoracic collections. J Thorac Imaging 1998. https://doi.org/10.1097/00005382-199804000-00002
27. Colice GL, Curtis A, Deslauriers J, et al: AACP Consensus statement: Medical and surgical treatment of parapneumonic effusions. Chest 2000. https://doi.org/10.1378/chest.118.4.1158
28. Chapman SJ, Davies RJO: Recent advances in parapneumonic effusion and empyema. Curr Opin Pulm Med 2004. https://doi.org/10.1097/01.mcp.0000129755.79467.67
29. Lewis RA, Feigin RD: Current issues in the diagnosis and management of pediatric empyema. Semin Pediatr Infect Dis 2002. https://doi.org/10.1053/spid.2002.127197
30. McGraw MD, Galambos C, Stillwell PC: Uremic pleuritis: A case report and review of recurrent exudative pleural effusions in children. Pediatr Pulmonol 2017. https://doi.org/10.1002/ppul.23708
31. Cantey EP, Walter JM, Corbridge T, et al: Complications of thoracentesis: Incidence, risk factors, and strategies for prevention. Curr Opin Pulm Med 2016. https://doi.org/10.1097/MCP.0000000000000285
32. Barnes TW, Morgenthaler TI, Olson EJ, et al: Sonographically guided thoracentesis and rate of pneumothorax. J Clin Ultrasound 2005. https://doi.org/10.1002/jcu.20163
33. Walcott-Sapp S, Sukumar M. A history of thoracic drainage: From ancient Greeks to wound sucking drummers to digital monitoring. CTSNET.ORG. https://www.ctsnet.org/article/history-thoracic-drainage-ancient-greeks-wound-sucking-drummers-digital-monitoring. Published 2015.
34. Lindskog G: Some historical aspects of thoracic trauma. J Thorac Cardiovasc Surg 42:1-11, 1961
35. Mahmood K, Wahidi MM: Straightening out chest tubes: What size, what type, and when. Clin Chest Med 2013. https://doi.org/10.1016/j.ccm.2012.11.007
36. Miller KS, Sahn SA: Chest tubes. Indications, technique, management and complications. Chest 1987. https://doi.org/10.1378/chest.91.2.258
37. Roberts JS, Bratton SL, Brogan TV: Efficacy and complications of percutaneous pigtail catheters for thoracostomy in pediatric patients. Chest 1998. https://doi.org/10.1378/chest.114.4.1116
38. Wei YH, Lee CH, Cheng HN, et al: Pigtail catheters versus traditional chest tubes for pneumothoraces in premature infants treated in a neonatal intensive care unit. Pediatr Neonatol 2014. https://doi.org/10.1016/j.pedneo.2014.01.002
39. Ahmed AH, Yacoub TE: Intrapleural therapy in management of complicated parapneumonic effusions and empyema. Clin Pharmacol Adv Appl 2010. https://doi.org/10.2147/CPAA.S14104

40. Monaghan SF, Swan KG: Tube thoracostomy: The struggle to the "standard of care." Ann Thorac Surg 2008. https://doi.org/10.1016/j.athoracsur.2008.08.006
41. Piccolo F, Popowicz N, Wong D, et al: Intrapleural tissue plasminogen activator and deoxyribonuclease therapy for pleural infection. J Thorac Dis 2015. https://doi.org/10.3978/j.issn.2072-1439.2015.01.30
42. Falsarella PM, Rocha RD, Rahal Junior A, et al: Minimally invasive treatment of complex collections: Safety and efficacy of recombinant tissue plasminogen activator as an adjuvant to percutaneous drainage. Radiol Bras 2018. https://doi.org/10.1590/0100-3984.2017.0086
43. Generali JA, Cada DJ: Alteplase: Pleural effusion (Parapneumonic) and empyema in children. Hosp Pharm 48:912-921, 2013. https://doi.org/10.1310/hpj4811-912
44. Israel EN, Blackmer AB: Tissue plasminogen activator for the treatment of parapneumonic effusions in pediatric patients. Pharmacotherapy 2014. https://doi.org/10.1002/phar.1392
45. Barthwal MS, Marwah V, Chopra M, et al: A five-year study of intrapleural fibrinolytic therapy in loculated pleural collections. Indian J Chest Dis Allied Sci 2016. PMID: 28368566
46. Taylor JL, Liu M, Hoff DS: Retrospective analysis of large-dose intrapleural alteplase for complicated pediatric parapneumonic effusion and empyema. J Pediatr Pharmacol Ther JPPT 2015. https://doi.org/10.5863/1551-6776-20.2.128
47. Forsey JT, Elmasry OA, Martin RP: Patent arterial duct. Orphanet J Rare Dis 2009. https://doi.org/10.1186/1750-1172-4-17
48. Hoffer FA, Hancock ML, Hinds PS, et al: Pleurodesis for effusions in pediatric oncology patients at end of life. Pediatr Radiol 2007. https://doi.org/10.1007/s00247-006-0392-y
49. Stokes LAS: Percutaneous management of malignant fluid collections. Semin Intervent Radiol 2007. https://doi.org/10.1055/s-2007-992328
50. Adams J, Auger J, Schiff D: Outcome of indwelling tunneled PleurXW catheter placement in pediatric and young adult patients with malignant effusions. Pediatr Blood Cancer 61:1118-1120, 2014
51. Gupta SS, Floudas CS, Chandra AB: A comparison between two types of indwelling pleural catheters for management of malignant pleural effusions. J Thorac Dis 2018. https://doi.org/10.21037/jtd.2018.05.57
52. Cope C: Management of chylothorax via percutaneous embolization. Curr Opin Pulm Med 2004. https://doi.org/10.1097/01.mcp.0000127903.45446.6d
53. Bhardwaj R, Vaziri H, Gautam A, et al: Chylous ascites: A review of pathogenesis, diagnosis and treatment. J Clin Transl Hepatol 2017. https://doi.org/10.14218/jcth.2017.00035
54. Chavhan GB, Amaral JG, Temple M, et al: MR lymphangiography in children: Technique and potential applications. RadioGraphics 2017. https://doi.org/10.1148/rg.2017170014
55. Schumacher KR, Stringer KA, Donohue JE, et al: Fontan-associated protein-losing enteropathy and plastic bronchitis. J Pediatr 2015. https://doi.org/10.1016/j.jpeds.2014.12.068
56. Rubin BK: Plastic Bronchitis. Clin Chest Med 2016. https://doi.org/10.1016/j.ccm.2016.04.003
57. Alejandre-Lafont E, Krompiec C, Rau WS, et al: Effectiveness of therapeutic lymphography on lymphatic leakage. Acta radiol 2011. https://doi.org/10.1258/ar.2010.090356
58. Hsu MC, Itkin M: Lymphatic anatomy. Tech Vasc Interv Radiol 2016. https://doi.org/10.1053/j.tvir.2016.10.003
59. Maclellan RA: The lymphatic system. Lymphedema Present Diagn Treat 2015. https://doi.org/10.1007/978-3-319-14493-1_1
60. Jesinger RA: Breast anatomy for the interventionalist. Tech Vasc Interv Radiol 2014. https://doi.org/10.1053/j.tvir.2013.12.002
61. Rajebi MR, Chaudry G, Padua HM, et al: Intranodal lymphangiography: Feasibility and preliminary experience in children. J Vasc Interv Radiol 2011. https://doi.org/10.1016/j.jvir.2011.05.003
62. Nadolski G, Itkin M: Thoracic duct embolization for the management of chylothoraces. Curr Opin Pulm Med 2013. https://doi.org/10.1097/MCP.0b013e3283610df2
63. Inoue M, Nakatsuka S, Yashiro H, et al: Lymphatic intervention for various types of lymphorrhea: Access and treatment. RadioGraphics 2016. https://doi.org/10.1148/rg.2016160053
64. Lee EW, Shin JH, Ko HK, et al: Lymphangiography to treat postoperative lymphatic leakage: A technical review. Korean J Radiol 2014. https://doi.org/10.3348/kjr.2014.15.6.724
65. Okuda K, Masuda K, Kawashima M, et al: Bronchial artery embolization to control hemoptysis in patients with Mycobacterium avium complex. Respir Investig 54:50-58, 2016. https://doi.org/10.1016/j.resinv.2015.08.004
66. Matsumoto T, Yamagami T, Kato T, et al: The effectiveness of lymphangiography as a treatment method for various chyle leakages. Br J Radiol 2009. https://doi.org/10.1259/bjr/64849421
67. Hsu CCT, Kwan GNC, Thompson SA, et al: Embolisation for pulmonary arteriovenous malformation. Cochrane Database Syst Rev 8: CD008017, 2012. https://www.cochranelibrary.com/cdsr/doi/10.1002/14651858.CD008017.pub2/epdf/abstract
68. Mittleider D, Dykes TA, Cicuto KP, et al: Retrograde cannulation of the thoracic duct and embolization of the Cisterna Chyli in the treatment of Chylous Ascites. J Vasc Interv Radiol 2008. https://doi.org/10.1016/j.jvir.2007.10.025
69. Srinivasa RN, Majdalany BS, Gemmete JJ, et al: Thoracic duct embolization: Analysis of practice patterns. Ann Vasc Surg 2018. https://doi.org/10.1016/j.avsg.2018.03.016
70. Chick JFB, VanBelkum A, Yu V, et al: Balloon-occluded retrograde abdominal lymphangiography and embolization for opacification and treatment of abdominal chylous leakage. J Vasc Interv Radiol 2017. https://doi.org/10.1016/j.jvir.2016.11.044
71. Chung A, Gill AE, Rahman FN, et al: Retrograde thoracic duct embolization in a pediatric patient with total cavopulmonary connection and plastic bronchitis. J Vasc Interv Radiol 2015. https://doi.org/10.1016/j.jvir.2015.07.023
72. Chick JFB, Gemmete JJ, Cline M, et al: Successful thoracic duct embolization for treatment of an iatrogenic left chylothorax in a neonate after repair of a tracheoesophageal fistula and esophageal atresia. J Vasc Interv Radiol 2017. https://doi.org/10.1016/j.jvir.2017.05.004
73. Majdalany BS, Saad WA, Chick JFB, et al: Pediatric lymphangiography, thoracic duct embolization and thoracic duct disruption: A single-institution experience in 11 children with chylothorax. Pediatr Radiol 2018. https://doi.org/10.1007/s00247-017-3988-5
74. Kim PH, Tsauo J, Shin JH: Lymphatic interventions for chylothorax: A systematic review and meta-analysis. J Vasc Interv Radiol 2018. https://doi.org/10.1016/j.jvir.2017.10.006
75. Churton T: Multiple aneurysms of pulmonary artery. Br Med J 1897. (1:1223)
76. Pollak JS, Saluja S, Thabet A, et al: Clinical and anatomic outcomes after embolotherapy of pulmonary arteriovenous malformations. J Vasc Interv Radiol 17:35-45, 2006. https://www.jvir.org/article/S1051-0443(07)60872-0/pdf
77. Cartin-Ceba R, Swanson KL, Krowka MJ: Pulmonary arteriovenous malformations. Chest 144:1033-1044, 2013. https://doi.org/10.1378/chest.12-0924
78. Abdel Aal AK, Eason J, Moawad S, et al: Persistent pulmonary arteriovenous malformations: Percutaneous embolotherapy. Curr Probl Diagn Radiol 47:428-436, 2018. https://doi.org/10.1067/j.cpradiol.2017.09.006
79. Abushaban L, Uthaman B, Cardiology DM, et al: Transcatheter coil closure of pulmonary arteriovenous malformations in children. J Interv Cardiol 2004. https://doi.org/10.1111/j.1540-8183.2004.00287.x
80. Chamarthy MR, Park H, Sutphin P, et al: Pulmonary arteriovenous malformations: Endovascular therapy. Cardiovasc Diagn Ther 2018. https://doi.org/10.21037/cdt.2017.12.08
81. Bailey CR, Arun A, Towsley M, et al: MVP™ Micro vascular plug systems for the treatment of pulmonary arteriovenous malformations. Cardiovasc Intervent Radiol 42:389-395, 2019. https://doi.org/10.1007/s00270-018-2106-x
82. Tau N, Atar E, Mei-Zahav M, et al: Amplatzer vascular plugs versus coils for embolization of pulmonary arteriovenous malformations in patients with hereditary hemorrhagic telangiectasia. Cardiovasc Intervent Radiol 2016. https://doi.org/10.1007/s00270-016-1357-7
83. Dalvi R: Pulmonary av malformations in hereditary hemorrhagic telengiectasis. In: 54th Annu Conf Indian Soc Haematol Blood Transfusion, Haematacon 2013 Mumbai India; 2013, 2013 http://dx.doi.org/10.1007/s12288-013-0303-y

84. Panda A, Bhalla AS, Goyal A: Bronchial artery embolization in hemoptysis: A systematic review. Diagnostic Interv Radiol 23:307-317, 2017. https://doi.org/10.5152/dir.2017.16454
85. Cody O'Dell M, Gill AE, Hawkins CM: Bronchial Artery Embolization for the Treatment of Acute Hemoptysis. Tech Vasc Interv Radiol 20:263-265, 2017. https://doi.org/10.1053/j.tvir.2017.10.006
86. Chun JY, Morgan R, Belli AM: Radiological management of hemoptysis: A comprehensive review of diagnostic imaging and bronchial arterial embolization. Cardiovasc Intervent Radiol 2010. https://doi.org/10.1007/s00270-009-9788-z
87. Shieh HH, Barreira ER, Bousso A, et al: Update of the pediatric hypotension graphic adjusted for gender and height percentiles: Systolic blood pressure for girls, 1 to 17 years old. Crit Care 2013 http://doi.org/10.1186/cc12636
88. Falkner B, Daniels SR: Summary of the fourth report on the diagnosis, evaluation, and treatment of high blood pressure in children and adolescents. Hypertension 2004. https://doi.org/10.1161/01.HYP.0000143545.54637.af
89. Brinson GM, Noone PG, Mauro MA, et al: Bronchial artery embolization for the treatment of hemoptysis in patients with cystic fibrosis. Am J Respir Crit Care Med 1998. https://doi.org/10.1164/ajrccm.157.6.9708067. PubMed: 9620932
90. Monroe EJ, Pierce DB, Ingraham CR, et al: An Interventionalist's guide to hemoptysis in cystic fibrosis. RadioGraphics 38:624-641, 2018. https://doi.org/10.1148/rg.2018170122
91. Ketai LH, Mohammed TLH, Kirsch J, et al: ACR appropriateness criteria® hemoptysis. J Thorac Imaging 2014. https://doi.org/10.1097/RTI.0000000000000084
92. Hirshberg B, Biran I, Glazer M, et al: Hemoptysis: Etiology, evaluation, and outcome in a tertiary referral hospital. Chest 1997. https://doi.org/10.1378/chest.112.2.440
93. Rémy J, Voisin C, Dupuis C, et al: Traitement des hémoptysies par embolization de la circulation systémique. Ann Radiol (Paris) 17:5-16, 1974. PMID: 4820232