Surgical Management of Chest Wall Sarcoma

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KEYWORDS

• Chest wall sarcoma • Chondrosarcoma • Osteosarcoma • Ewing sarcoma
• Chest wall resection

KEY POINTS

- Chest wall sarcoma is a rare cancer due to a heterogenous collection of histologies. Multidisciplinary management in centers experienced in these pathologies is optimal.
- There are many opportunities for scientific investigation to answer basic questions about chest wall sarcoma management including treatment components, treatment sequence, optimal margin, and optimal reconstruction.
- Incomplete excisions, often during incisional biopsies, require reexcision of the entire surgical bed, and radiation should be considered as an adjuvant.
- The general principle of 2 cm margin for low-grade tumors and 4 cm margins for high-grade tumors still applies, although data supporting this approach are very limited.

INTRODUCTION

In 2020, there will be an estimated 13,130 cases of soft tissue sarcoma and 3600 cases of bone sarcoma (BS) in adults and children in the United States, with approximately 7100 deaths.[1,2] Overall, sarcoma cancers account for less than 1% of adult malignancies and 15% to 20% of pediatric malignancies. Most sarcomas arise de novo and not from premalignant lesions. A review of 4500 soft tissue sarcomas suggested that approximately 1 in 5 soft tissue sarcomas occur in chest wall/torso location, with the majority presenting in the lower and upper extremities.[3] Those patients presenting with chest wall tumors can present in a variety of ways, with the most common presentation being that of a palpable and symptomatic mass. The manner of treatment is largely dictated on tumor location, biological risk (ie, tumor size, grade, histology), and metastatic status at presentation. Risk factors that have been associated with lower overall survival include margin status, age, grade of the tumor, and radiation-associated histology.[4,5] Although BS and soft tissue sarcoma histologies

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follow many commonalities with regard to diagnosis and treatment, a variety of histologies should be highlighted and will be a focus in this review.

More common in the chest wall are nonsarcoma etiology malignancies (direct invasion breast cancers, metastatic disease, plasmacytomas) and benign entities (enchondroma, fibrous dysplasia, osteochondroma, aneurysmal bone cysts, eosinophilic granulomas, desmoid fibromatosis) that comprise additional chest wall neoplastic processes.[6] Although surgical intervention can be entertained in many of these diagnoses, understanding the natural history of common chest wall nonsarcoma origin tumors is important when guiding treatment considerations.

The purpose of this review is to highlight chest wall malignancies (and select benign entities) with a focus on chest wall sarcoma and discuss appropriate preoperative workup, neoadjuvant therapy, the oncologic resection, and definitive reconstructive methods.

Initial Evaluation

Imaging

An magnetic resonance scan (MRI) of the primary site of concern (with and without intravenous contrast) is best for extremity sarcoma, whereas computed tomography (CT) scan has long been advocated as an appropriate choice in chest wall and retroperitoneal sarcoma investigation. MRI of the chest wall can be considered when assessing for soft tissue edema. This may help delineate the "reactive zone" of a sarcoma where microscopic "satellite" cells may be found or may have utility for identify "skip" lesions in the ribs or sternomanubrial/clavicular anatomy in the setting of BS. A CT of the chest should be obtained for staging of all soft tissue sarcomas and BS. Intravenous contrast is useful in studying the relationship of a tumor with vascular structures, as well as delineating possible hilar or mediastinal lymphadenopathy. PET scans should not be obtained routinely in patients with isolated or metastatic soft tissue sarcoma, although PET imaging has been shown to be useful in prognostication, grading, and determining response to chemotherapy in tumors greater than 3 cm, high grade, and deep to fascia.[7] Trends are shifting in Ewing sarcoma toward higher utilization of PET-CT imaging, with recent literature suggesting that PET-CT scan imaging may be able to avoid the need for bone marrow biopsy in Ewing sarcoma staging.[8,9] PET-CT has also been shown to add insight into distinguished neurofibromas from possible transformed malignant peripheral nerve sheath tumors (MPNST) in the setting of NF-1.[10–12] The role of PET scan should be discussed at a multidisciplinary sarcoma conference in individual cases.

A nonexhaustive list of previously described common entities for chest wall sarcomas include liposarcoma, rhabdomyosarcoma, leiomyosarcoma, synovial sarcoma, undifferentiated pleomorphic sarcoma (formerly malignant fibrous histiocytoma), angiosarcoma, MPNST, Ewing sarcoma, osteosarcoma, and chondrosarcoma. Special circumstances for advanced imaging do apply for certain tumor histologies[13,14]:

- Myxoid/round cell/liposarcoma—as per National Comprehensive Cancer Network guidelines, a dedicated spine imaging (MRI or CT) is recommended. PET-CT imaging as a standalone has lacked as a sufficiency screening tool in this variant, which has tendency for extrapulmonary metastases.[15] Contrast is recommended to decipher enhancement pattern of possible metastasis versus benign elements such as a Schmorl node or hemangioma. CT abdomen/pelvis is also recommended for these subtypes. Evidence does suggest that PET-CT scans and MRIs alone can be useful in finding metastatic foci. An argument

can be made that combining a whole-body MRI and PET capability with a PET-MRI can look not only at the spine but also at other extrapulmonary locations that myxoid liposarcoma can be predisposed toward.[15–19]

- Angiosarcoma—historically, central nervous system imaging has been recommended, in the form of either a CT head or a brain MRI. A recommendation is to obtain an MRI of the brain (or CT head if MRI is contraindicated) based on clinical suspicion. A CT abdomen/pelvis is recommended, in addition to a CT chest.
- Dedifferentiated liposarcoma—a CT chest/abdomen/pelvis is recommended.
- Leiomyosarcoma—CT abdomen/pelvis imaging is recommended. PET-CT imaging can be ordered on a case by case basis due to clinical concerns. These will be taking origin from smooth muscle, likely of vascular origin in the chest. Vascular invasion on final pathology review is an important prognostic detail.
- "RACES" sarcomas—although uncommonly noted to disseminate through lymphatic channels as hematopoietic dissemination is mainstay for sarcoma histologies, several sarcomas have a rare but known predisposition toward lymph node dissemination (*RACES*—*R*habdomyosarcoma, *A*ngiosarcoma, *C*lear Cell Sarcoma, *E*pithelioid Sarcoma, *S*ynovial Sarcoma). A clinical lymph node examination is mandatory, as well as CT abdomen/pelvis imaging. Any suspicion on clinical examination should mandate a sentinel lymph node biopsy and PET-CT imaging (whole body).
- Ewing sarcoma—evolving evidence supports the use of PET-CT whole-body imaging as part of the preoperative workup, in addition to a CT chest. If the PET-CT does not show increased avidity in the marrow, then a bone marrow biopsy is not necessary. If a PET-CT is either not approved or shows marrow avidity, then a Bone marrow biopsy is necessary to prove marrow dissemination.
- Osteosarcoma—whole-body bone scan is recommended, in addition to the CT chest. An MRI chest with and without contrast may be helpful in looking for "skip" metastases in the bone or for soft tissue edema extent when planning oncologic resection margins.
- Chondrosarcoma—whole-body bone scan is recommended, in addition to the CT Chest. An MRI chest with and without contrast may be helpful in looking for "skip" metastases in the bone or for soft tissue edema extent when planning oncologic resection margins.
- Plasmacytoma—a skeletal survey is recommended over a whole-body bone scan, in order to appropriately understand distant bony involvement.

Several benign and nonsarcoma malignant tumors should also have special considerations when determining an appropriate preoperative workup:

- Osteochondroma—in the setting of multiple osteochondromas, suspicion for multiple hereditary exostosis (MHE) should be had. A skeletal survey can be ordered to look at all major bones (long and flat bones) in order to obtain a baseline for comparison purposes in the future. The risk of malignant transformation, even in syndromic MHE, is low (~1%).[20] A CT chest can help prove marrow confluence between the tumor and the adjacent bone.
- Desmoid tumor—in the young patient, Lynch syndrome/familial adenomatous polyposis should be ruled out with germline testing and tumor genetic testing. A family history with suspicion for colon cancer should trigger a referral for colonoscopy. An MRI with and without contrast is helpful for looking at characteristic "dark T1, dark T2" signal suggested for fibrotic makeup of the tumor.

- Aneurysmal bone cyst—an MRI with and without contrast is helpful when suspected. This can show "fluid-fluid" levels characteristic of this diagnosis, as well as look for more aggressive features that may suggest concern for a telangiectatic osteosarcoma.
- Solitary fibrous tumor—a CT chest is recommended, and if pathology is concerning for a high-risk stratification (**Box 1**), then a CT abdomen/pelvis is recommended.[21]

Echocardiogram

All patients with anticipated anthracycline-based agents (ie, doxorubicin or adriamycin) should have an echocardiogram to assess left ventricular ejection fraction (before receiving doxorubicin) due to the risk of development or worsening of congestive heart failure.

Laboratory assessment

Baseline laboratories, specifically a complete metabolic panel and complete blood count should be performed on all patients. In addition, suspicion for a plasmacytoma should also include a serum and urine electrophoresis.

Biopsy

If imaging does not clearly delineate a diagnosis (ie, benign lipoma, osteochondroma, fibrous dysplasia, chondrosarcoma, etc.), then a carefully planned biopsy is necessary. Importantly, such interventions should be performed along planned the future resection axis with minimal dissection and careful attention to hemostasis. Although tumor tract seeding is extremely rare with needle biopsy and correlates with the size of the needle,[22] large hematoma formation by a poorly planned biopsy has the potential to affect surgical planning and functional outcome. Strictly for diagnostic purposes, a needle biopsy is favored over an incisional or excisional biopsy in most of the cases.

Best practice for all potential sarcomas (retroperitoneal, head and heck, extremity/trunk) supports biopsy procedures at the facility where definitive care will most likely take place, in an effort to prevent complication.[23,24] The literature strongly favors treatment of sarcomas in a "centralized" fashion, where referral to a high-volume center has lower local recurrence risk, more reliable margin status, lower amputation rates, improved survival with high-grade tumors, lower complication and mortality rates, and more reliable administration of appropriate adjuvant therapies.[23–25] Given the rarity of this disease, pathologic diagnosis should be confirmed by a pathologist who is an expert in the assessment of sarcoma due to concerns regarding higher false-negative rates from less-experienced pathologists.[26]

Box 1
Features associated with malignant behavior for solitary fibrous tumors

Size greater than 10 cm

Greater than 4 mitoses/10 HPFs

Increased nuclear pleomorphism

Increased cellularity

Tumor necrosis

Abbreviation: HPF, high-power field.

Data from Refs.[73,74]

With regard to those soft tissue sarcomas that have a higher predisposition to lymph node metastases (**Box 2**), a sentinel lymph node (SLN) biopsy should be performed on all patients with palpable lymphadenopathy or advanced imaging showing pathologic enlargement of lymph nodes in the same drainage pattern as the sarcoma in question. Those patients without clinical or radiographic evidence of lymphadenopathy with the aforementioned diagnoses should be decided upon on a case-by-case basis, given lack of good evidence for an SLN biopsy as a routine practice.

Pathology

Sarcomas are rare cancers with more than 50 to 75 different histologic subtypes classified by the World Health Organization. Soft tissue and bone malignancies are graded by the FNCLCC grading system, which is a 3-grade system (low, intermediate, and high).

Immunohistochemistry and molecular genetic studies are frequently used to classify bone and soft tissue sarcomas. Immunohistochemistry is generally useful in delineating the line of differentiation of the tumor, which is the basis of classifying bone and soft tissue tumors (eg, skeletal muscle differentiation for rhabdomyosarcoma). In addition, some immunohistochemical markers (eg, STAT6 in malignant/benign solitary fibrous tumor, MUC-4 in low-grade fibromyxoid sarcoma, INI-1 loss in epithelioid sarcoma) and gene fusions (eg, *EWSR1-FLI1* in Ewing sarcoma) are pathognomonic or strongly suggest many entities. Looking for additional fusion partners in order to aid with diagnosis, as well as to identify potential targets with immunotherapy or targeted therapy should be discussed on a case-by-case basis. Specific to chest wall sarcomas, past studies show most of the chest wall tumors undergoing surgical excision to be high-grade malignancies.[4]

Preoperative Planning

The foundation of an effective treatment plan begins with appropriate preoperative assessment. The cornerstone of this assessment is obtaining the correct diagnosis. As mentioned previously, the use of core needle biopsies as opposed to incisional biopsies is desirable, as it limits potential spillage of tumor cells and contamination of surrounding tissue. Once the diagnosis is determined, discussion in a multidisciplinary setting specializing in sarcoma is important to assure the appropriate staging evaluation and treatment sequence. This process can be facilitated by the use of institution- or society-derived care paths to assure standardization of care and avoidance of unnecessary tests.

Physiologic assessment of the patient can be performed as a concurrent process. A standard thoracic surgical evaluation including pulmonary function tests, a functional test such as a 6-minute walk test, and cardiac risk assessment is advisable. Functional

Box 2
Sarcomas requiring lymph node assessment

*R*habdomyosarcoma

*A*ngiosarcoma

Clear cell sarcoma

*E*pithelioid sarcoma

*S*ynovial sarcoma

testing is desirable to assess the patient's strength and ability to recover from a significant physiologic insult including loss of chest wall function. Assessment of secretion management, diaphragm function, and patient vigor are required to counsel the patient on risks of postoperative atelectasis, which could lead to repeated invasive procedures such as toilet bronchoscopy, reintubation, and respiratory failure. A history of vocal cord dysfunction or aspiration should be investigated to identify patients at higher risk for postoperative respiratory complications.

Surgical planning revolves around determining the size of the chest wall defect, the skin defect, the means of reconstruction, and the need for additional soft-tissue coverage. Consultation with a Plastic Surgeon may be necessary to plan out various soft tissue coverage strategies including rotational flaps and free flaps with muscle and skin.

Surgical Treatment—Soft Tissue Sarcoma

The generally accepted rule of thumb for resection of chest wall sarcomas is based on tumor grade: 4 cm margins for high-grade lesions and 2 cm margins for low-grade lesions (with some exceptions such as desmoid tumors).[27] The data, however, to support this rule of thumb are rather sparse. One of the early landmark studies is a single-center retrospective series from the Mayo Clinic where King and colleagues[28] demonstrated that a greater than 4 cm margin was associated with a 5-year survival of 56% as opposed to 29% in patients with a 2 cm margin ($P<.06$). This univariate analysis did not account for tumor size, grade, or histology (nor did it reach statistical significance) yet the 4 cm margin became widely accepted, given the paucity of available data. A more contemporary series from Shewale and colleagues[4] included 121 patients with primary chest wall sarcoma over a 15-year period. This study did not specifically study margin length but rather divided patients into 3 groups: R0, R1, and R2 resections. Multivariable analysis identified tumor grade (hazard ratio [HR] 15.21; 95% confidence interval [CI] 3.57–64.87; $P<.001$), incomplete resection (R1; HR 3.10; 95% CI 1.40–6.86; $P = .005$; R2 HR 5.18; 95% CI 1.91–14.01; $P = .001$), and increasing age (HR 1.02; 95% CI 1.01–1.03; $P = .002$) to be independently associated with worsened overall survival. Interestingly, in this analysis, tumor histology, induction chemotherapy, and large tumor size did not achieve significance. An analysis by Scarnecchia and colleagues[29] similarly identified R0 resection to be an independent predictor of survival following chest wall resection (HR 5.6; 95% CI 2.95–11.93; $P<.001$). This analysis notably combined primary tumors of the chest wall with lung cancer with chest wall involvement, primary tumors being roughly 25% of the entire population. A 2015 cohort of 65 chest wall sarcomas (Ewing sarcoma and chondrosarcoma histologies excluded) showed a reduction of local recurrence and distant metastases in patients with stage IIb and stage III disease with the addition of radiation therapy and chemotherapy, respectively, at 5- and 10-year endpoints.[30]

Histology-dependent soft tissue sarcoma excisions and margin measurements are controversial. Histologies that are more infiltrative in nature, such as myxofibrosarcoma, dedifferentiated liposarcoma, or dermatofibrosarcoma protuberans variants, may require more extensive margin planning at the offset to account for the microscopic infiltrative extensions.

Although other studies exist on this topic, generally the small size, retrospective nature, heterogeneity of histologies included in the studies and heterogeneity of variables included in analyses make it challenging to draw definitive conclusions regarding optimal margin determination. What should be noted, however, is the currently accepted practice in extremity soft tissue sarcoma to pursue limb salvage over radical resection, thus potentially sacrificing the traditional "wide margins."

This approach has been noted to be associated with higher rates of local recurrence but not overall survival, thus emphasizing the importance of systemic control of the disease with evolving systemic therapies.[31,32]

A further challenge in the chest is the lack of data on long-term functional outcome, which is well described in the orthopedic population. This prevents analysis of risk:benefit with radical resections. We are therefore left to conclude that there are no data that strongly recommend a change in the generally accepted practice of 2 cm for low-grade and 4 cm for high-grade chest wall tumor resection. The authors suspect that broader margins are more likely to assure an R0 resection, as we have limited capability to perform frozen section analysis of chest wall specimens. Conceptually, a reasonable alternative would be a delayed reconstruction with "fast tracked" pathologic analysis; however, this could potentially increase risk of prosthetic infection, a potentially devastating complication. Better imaging and understanding of different histologies may allow us, in the future, to tailor margins more effectively and thus potentially decrease postoperative respiratory complications and improve long-term functional results.

Surgical Treatment—Bone Sarcoma

For BS excision, a negative surgical margin has been reported as a key indicator toward effecting both local recurrence and overall survival prognosis. Literature has suggested tumor necrosis following neoadjuvant chemotherapy and pleural involvement to be potentially predictive for overall survival outcome, but due to the rare nature of this histology previous studies are not statistically powered to definitively answer the question of factors that are clearly linked to overall survival.[33] Histology-specific considerations are as follows:

- *Chondrosarcoma* is traditionally considered a radio-resistant and chemo-resistant histology, with up front wide surgical margin excision the standard of care. Prior studies have shown excellent survival with R0 excision in chondrosarcoma. With achieved negative margins (R0), chondrosarcoma has shown 5-year overall survival of up to 100% in grade 1 and 2 tumors.[34] Overall 10-year survival is affected when a local recurrence occurs.[35]
- *Ewing sarcoma* has generally been thought of as a histology that benefits from multimodal treatment, including surgery in combination with either radiation therapy or chemotherapy. In the large chest wall Ewing sarcoma multicentric German registry study, surgery versus radiation and surgery treatment did not show benefit from local recurrence if the initial excision was R0.[36] Radiation has shown benefit as an adjuvant treatment with chemotherapy and surgery in those patients who were identified to have low tumor necrosis following en bloc excision pathology review.[33,37] Controversy exists as to whether or not the entire rib seen as the epicenter should be excised, although no definitive evidence has pointed toward a survival advantage with full rib resection versus partial rib resection.
- *Osteosarcoma* is generally a histology where surgery and chemotherapy are a mainstay. Low-grade osteosarcomas are rare in the chest wall, with additional histologies such as chondroblastic osteosarcoma showing little anticipated response to induction chemotherapy (behaving similar to chondrosarcoma histologies). Generally, a survival advantage exists with skeletal osteosarcoma by combining surgery and chemotherapy. The role of radiation therapy is more controversial with osteosarcoma, generally reserved for palliative situations. No literature specifically looking at a homogenous osteosarcoma chest wall population exists.

- *Radiation-induced sarcomas* (RIS) generally occurs in the setting of radiation to the chest wall for breast cancer, lung cancer, or non-Hodgkin lymphoma, in as short a latency period as 3 years following radiation and a median of 10 to 15 years.[33,37–39] Wide excision is the gold-standard treatment of RIS of the chest wall, with relatively poor local recurrence and overall survival prognosis. The role of chemotherapy and radiation therapy are controversial, and literature is limited in proving their benefit.

Incomplete Excisions

When a sarcoma is incompletely removed, oftentimes because a sarcoma is not suspected at the time of surgery, an immediate referral to a tertiary care sarcoma center is recommended. No prior studies evaluating this scenario in chest wall tumors exist, but a mixture of extremity and trunk populations has been published. Current rates of incomplete excision rates range from 18% to 53%, with most literature ~30%. Depending on location of the lesion, these will require reexcision of the contaminated sarcoma bed ± radiation therapy used as an adjuvant treatment. Without reexcision, those sarcomas with microscopically or macroscopic positive margins may have recurrence rates as high as 70% to 90%.[40–42] Microscopic disease has been noted in 14% to 74% of reexcised tumor specimens.[43] Although a properly reexcised soft tissue sarcoma bed has not been reliably linked with adverse overall survival effect, reexcision is generally associated with greater financial burden cost and more morbidity at the time of surgery.[44,45]

Surgical treatment—nonsarcoma neoplasms

Surgical resection considerations should be taken into account for different histologies.

- *Benign tumors* such as fibrous dysplasia, enchondromas, or osteochondromas can be safely observed to prove stability. Surgical excision is considered for symptomatic tumors or tumors that show aggressive feature transformation with serial imaging. Eosinophilic granulomas (aka Langerhans cell histocytosis) often can seem aggressive and may require biopsy. The biopsy manipulation itself has been shown to be curative, as well as observation, steroid injections, or surgical curettage.[46]
- *Desmoid tumors (extraabdominal)* generally should not undergo surgical intervention, given the prohibitively high risk of local recurrence that approaches 100% after even an R0 resection. R0 and R1 margins have not shown a predictable difference in determining local recurrence risk. Consensus and recent publications have pushed toward nonoperative, and even observation, treatments.[47,48] Antiinflammatories, antihormonal medications, and a variety of chemotherapy regimens have all shown sporadic benefit. Surgery and radiation are often reserved as last-line treatments unless there is an impending life-threatening mass effect on a nearby vital structure. Minimally invasive options, such as cryoablation or magnetic resonance–guided high-frequency ultrasound have been described as showing benefit from presenting progression.[49,50]
- *Plasmacytomas*, if identified to be isolated (normal bloodwork, bone survey, and/or marrow studies), should be considered for a side excision. Sarcoma margin literature cannot be extrapolated to this histology, and consideration of preserving as much anatomy as possible while still obtaining an R0 resection should be made.
- *Aneurysmal bone cysts* have historically been described in extremity and spine literature as being amendable to open intralesional approaches and bone

grafting. The "curopsy" has also been described, as similar to an eosinophilic granuloma, where the simple irritation from the biopsy can stimulate resolution of the lesion.[51] Recently, CT-guided injections of doxycycline—an agent that acts as a sclerosing/irritant chemical—has shown great promise in preventing the need for surgery.[52,53]

Surgical Reconstruction

Large, single-center case series from major institutions such as Mayo Clinic,[54,55] Emory University,[56] Memorial Sloan Kettering,[57] and MD Anderson[58,59] comprise the most often referenced studies on chest wall resection and reconstruction. Each center has developed a particular and nuanced approach with some overlapping similarities, but in general there is no unified consensus or clear superiority regarding many of the technical aspects such as type of mesh to implant or the use of rigid versus flexible prosthesis for chest wall stabilization (**Table 1**).

There is general agreement in underlying guiding principles behind chest wall reconstruction should be to stabilize the thorax to achieve (1) optimal respiratory function; (2) protection of underlying organs; and (3) acceptable cosmetic outcome. A multidisciplinary approach to these often complex patients is essential. Below is a stepwise approach to devising a plan for chest wall resection, which will ultimately be colored by surgeon preference and available resources.

Is reconstruction necessary?

Some chest wall defects do not necessarily require reconstruction. The 2 major, interrelated factors are size and location of the defect. Many investigators agree that reconstruction is not necessary for defects smaller than 5 cm in any location or up to 10 cm if protected by the scapula and there is no risk of scapular entrapment. With respect to location, Scarnecchia and colleagues[29] defined "critical areas" of the chest that require skeletal reconstruction as anterior or lateral chest wall and defects of 3 or more ribs not covered by scapula. In their study of 71 patients undergoing chest wall resection, 41 had a defect in a critical area. Skeletal stabilization was inversely correlated with acute respiratory complications and flail chest. Without reconstruction in a critical area, 100% of patients had respiratory complications versus 5.7% in reconstructed patients.

Should rigid or flexible material be used?

The ideal characteristics of a prosthesis include the following: (1) sufficient stability to abolish paradoxic chest movement; (2) malleable to allow shaping; (3) ability for host tissue ingrowth/incorporation; (4) resistant to infection; (5) radiolucent; (6) cost permissive; and (7) durable with long-term mechanical integrity.[60,61] In addition, choice of prosthesis is an important component in the concept of "biomimesis" where the natural biological form and function of the chest wall are recreated.[62]

The only definitive conclusions that can be summed from the literature are that there is no perfect prosthetic material (**Table 2**) currently available and that any type of prosthetic material (rigid or flexible) can be used successfully in experienced hands.[54,57,59,61]

Flexible materials are the simplest to implant but sacrifice rigidity, which is optimal for preservation of respiratory mechanics. Porous materials seem to have the advantage of the capability for tissue ingrowth and thus greater resistance to infection. In the authors' experience, the lack of tissue incorporation of polytetrafluoroethylene (PTFE) leads to more frequent reintervention for infection. Methacrylate is the most common material used for rigid reconstruction of the chest wall. The creation of a composite of

Table 1
Examples of center-dependent preferences for chest wall resection

	# Pts	*Prosthesis* Flexible/ Rigid/ None	*Skeletal Rsxn* Rib Rsxn Sternal Rsxn	Pulmonary Complications	ID Complications	
Scarnecchia et al,[29] 2018, JTD	71	Prosthesis: 33 (49.3%) None: 36 (41 critical/30 noncritical)	Ribs mean 3 (2–6) Sternal rsxn: Total: 6 Partial: 4	10 pts (14%) In critical area: Recon: 5.7% Non: 100% Flail: 9 (6 non-recon)	No infection of chest wall prosthesis observed/ reported	Periop mortality: NR Morbidity: 45% R0 = 76%, 5-y OS 67% R1 = 24%, 5-y OS: 15%
Spicer et al,[59] 2016, Annals	427	Flex: 345 Rigid: 82 None: 20	Ribs—median Flex: 3 (1–6) Rigid: 3 (1–8) Sternal rsxn: Flex: 24 (6.9%) Rigid: 9 (11%)	102 (24%) Flex: 78 (22%) Rigid: 24 (29.3%) *P*=NS	Wound infect 12 (2.8%) Empyema 3 (0.7%)	30 d mortality: 1% 60 d mortality: 6% Median survival: 40 mo Preop: 12 • None for infected mesh • 1 broken strut • 11 = recurrence
Kachroo et al,[75] 2012, J Thor Oncol	51	Flex: 24 Rigid: 18 None: 9	Ribs—avg 3.7 (1–10)	2 (3.9%) Combo lung: 14 pt (27%)	Wound infection 2 (4%) Empyema 1 (2%)	Mortality: 0% Morbidity: 10 (20%)
Hanna et al,[76] 2011, Surgery	37	Flex: 18 Rigid: 0 None: 19	Ribs 3 or more: 38% Sternal rsxn: Total: 8 pt (22%) Partial: 1 pt (3%)	Combo lung rsxn: 3 pt (8%)	Wound infection 2 pt (5%) Remove prosthesis: 1 pt (5.5%)	Mortality: 0%

Weyant et al,[57] 2006, Annals	262	Flex: 97 Rigid 112 None: 53	Ribs—median Flex: 3 (1–6) Rigid: 3 (1–8) None: 3 (1–4) Sternum: 49 pts Total: 6 (2.3%) Partial: 34 (14%) Manubrium: 9 (34)	29 *(11%)* *Flex: 7* *Rigid: 8* [a]*P = NS* *7 of 10 deaths*	Wound infection 14 (5.3%) Flex: 3 Rigid: 9[a] Remove prosthesis Flex: 4 (4.1%) Rigid: 5 (4.5%)	Mortality: 3.8% Morbidity: 33.2% CWR + lung rsxn: mortality 5.6% • Pneumonectomy 44% Multivariate: Age (10-y increments) Lobe/pneumonectomy Size of defect
Mansour et al,[56] 2002, Annals	200	Flex: 82 Rigid: 11 None: 43	Ribs - Mean 4 (2–9) Sternal rsxn: 56 pts Total: 16 (8%) Hemi: 18 (9%)	38 pts (20%) Combo lung rsxn: 34%	Wound infection: (5%) • Remove prosthesis: 5%	Mortality: 7% Morbidity: 24% Immediate closure: 195
Walsh et al,[58] 2001, JTCVS	51	Flex: 16 Rigid: 18 None: 17	Ribs—avg 3.8 (1–9) Sternal resection: Total: 6 Partial: 5	4 pts (7.8%)	Wound infection: 3 (5.8%) Remove prosthesis: 2	Mortality: 0% Morbidity: 24%
Lardinois et al,[77] 2000 Annals	26	Flex: 0 Rigid: 2 None: 0 Flap: 17 (65.4%)	Rib rsxn—mean 4 (3–8) Sternal rsxn: 10 pt Total: 4 Partial 6	1 pg (3.8%) Combo lung-CWR: 12 (46%) • Pneumo-nectomy 2 Concordant chest movement: 92%	Wound infection: 2 (8%) Remove prosthesis: 2 (8%)	Mortality: 0% Morbidity: 22%

(*continued on next page*)

Table 1
(*continued*)

	# Pts	*Prosthesis* Flexible/ Rigid/ None	*Skeletal Rsxn* Rib Rsxn Sternal Rsxn	Pulmonary Complications	ID Complications	
Deschamps et al,[55] 1999, JTCVS	197	Flex: 197 Rigid: 0 None: 0	Rib rsxn—Median 3 (1–8) Sternal rsxn Total: 7 Partial: 46	48 pts (24.4%) Combo lung rsxn: 58 pts (29.4%) • Pneumo-nectomy: 13 pts, 4 of 8 deaths (50%)	Wound infection: 9 (4.6%) • Remove prosthesis: 3 pts (2.5%) (no subsequent recon) • 3 w/contaminated wound preop	Mortality: 4.1% Morbidity: 46.2% • Lung rsxn sig assoc with mortality ($P = .0002$) • 4 of 8 deaths after pneumonectomy
Arnold & Pairolero,[54] 1996, Plast Recon Surg	500	Flex: 171 Rigid: 14 None: 315	Ribs avg: 3.9 Sternal rsxn: 231 pts	Tracheostomy: 23 pt (4.6%)	Remove prosthesis: 1 pt (only with MMA)	Mortality: 3.0%

Abbreviations: Avg, average; CWR, chest wall resection; MMA, methyl methacrylate; Preop, preoperative; Rsxn, resection.
[a] Rigid higher wound versus non, $P = 0.05$.
Data from Refs.[54–59,75–77]

Table 2
Prosthetic options for chest wall reconstruction

	Flexible	Rigid
Porous	Polypropylene • Marlex; Davol & Bard, Cranston, RI • Prolene; Ethicon Inc, Sumerville, NJ Polyglactin • Vicryl; Ethicon Inc, Somerville, NJ	Titanium mesh
Nonporous—synthetic	Polytetrafluoroethylene (PTFE)	Methyl methacrylate Titanium plates
Nonporous—Biologic	Acellular dermis • Cadaveric human • Porcine • Bovine Acellular pericardium • Bovine	Cadaveric homografts

methacrylate with porous mesh permits customized solutions. Similar to PTFE, methacrylate does not incorporate into the surrounding tissue and thus is at increased risk of wound seroma and infection. Wound complications are reported in 10% to 20% of patients with methacrylate prostheses; 5% ultimately require removal of the prosthesis.[63] The rigidity of methacrylate furthermore can be problematic in the environment of dynamic chest wall. This can lead to stress fractures and pain with breathing. Titanium mesh plate remains are gaining popularity as alternatives for rigid chest wall reconstruction. Of note, these applications remain "off label" and should be approached with caution. Rib plating systems, for instance, generally are restricted to traversing fairly small unsupported gaps in bone. The long-term stability and durability of plates over large bone gaps is unknown.

Use of muscle flaps

Most of the investigators advocate for ensuring that reconstruction of a chest wall defect includes the use of well-vascularized, myocutaneous tissue. This can be in the form of local advancement flaps (eg, pectoralis muscle for sternal defects) or distant transfer using pedicled, rotational, propeller, or free flap techniques.[64,65] The goals are to provide complete cutaneous coverage, obliterate dead space, prevent development of seromas, and optimize tissue ingrowth and mesh incorporation to minimize risk of infection.[54,66] Myocutaneous flap selection needs to be carefully planned with consideration for operative positioning, flap viability, and available conduits following radical tumor resection.

ADJUVANT RADIATION THERAPY

Radiation treatment can be considered as an adjuvant therapy for chest wall sarcomas. A 2020 review of the National Cancer Database of 1215 patients with primary chest wall sarcoma suggested a 20-month improvement in survival in those patients who received adjuvant radiotherapy, with high-grade tumors seeing the most benefit.[67] Local recurrence rates have generally been thought to be positively affected with radiation used in soft tissue sarcoma, allowing for potentially closer margins.[68,69] More controversy surrounds the role of radiotherapy with bone sarcoma. With Ewing sarcoma, radiotherapy has not shown consistent benefit in improving local control in the setting of a negative margin.[36] In a heterogenous population of 65 chest wall sarcoma patients,

radiotherapy was associated with improved disease-free survival, with improved trends in mortality within patients undergoing chemoradiation + surgery as compared with surgery alone.[30]

ADJUVANT SYSTEMIC THERAPY

Despite numerous clinical trials and meta-analyses of these trials, the role of adjuvant chemotherapy in patients with soft tissue sarcoma of the extremity and chest wall has not been established, particularly with overall survival as the endpoint. Specific to chest wall literature, a single-institution 20-year experience, looking back at 65 patients with chest wall soft tissue sarcoma (only one BS included in the series), the authors showed 5- and 10-year disease-free survival improvement with the addition of chemotherapy, radiation therapy, or a combination of both to an index surgical operation.[30] Given the small numbers and heterogeneity of the histologies, definitive regimen recommendations could not be made. There is no proved role for chemotherapy in the treatment of chondrosarcoma. Ewing sarcoma has perhaps the strongest insight into systemic therapy. A pediatric oncology group review of 98 patients aged 30 years or older with Ewing sarcoma of the chest treated in 2 multiinstitutional trials concluded that neoadjuvant multiagent chemotherapy improved the likelihood of obtaining an R0 excision and decreased the likelihood for needing adjuvant radiotherapy.[70] Prior studies have shown the risk of radiation-associated malignancy higher in the child and adolescent population.[71] Osteosarcoma, as Ewing sarcoma, has shown improved survival with the addition of multiagent therapy as a gold standard, although clear margin resection of axial location skeletal osteosarcomas continues to be important for prognosis.[72] No chest wall location–specific recommendations for chemotherapy exist.[13]

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