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METHODS

Spinal tumor embolization: benefit for surgical resection

Krisna Maddy[1], Delano Trenchfield[1], Henson Destine[1], Vanesha Waiters[2], Daniel Nwatu[1] and Brandon Lucke-Wold[3]*

[1]University of Miami Miller School of Medicine, Miami, FL, United States
[2]Morehouse School of Medicine, Atlanta, GA, United States
[3]Department of Neurosurgery, University of Florida, Gainesville, FL, United States

***Correspondence:**
Brandon Lucke-Wold,
brandon.Lucke-Wold@neurosurgery.ufl.edu

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The embolization of hypervascular spinal tumors preoperatively has shown to be a worthwhile adjunctive procedure to minimize the elevated risks associated with surgical resection, such as intraoperative blood loss and its associated complications. Resection of these hypervascular tumors is necessary for local tumor control, reduction in patient-reported pain, improved neurological functioning, and spinal stability. This adjunctive procedure has been associated with improved surgical outcomes and easier facilitation of surgical resection. As such, we provide a review of the current literature examining the employment of this technique. Specifically, this article (a) reviews the techniques of embolization, with anatomical considerations of the arterial framework of the spinal network; (b) relativizes and outlines the post-embolization management of spinal tumor resection; (c) provides a critical outlook on the reported benefit of preoperative embolization before surgical resection with support from clinical studies in the literature; and (d) discusses the efficacy and reliability of provocative testing and post-procedural management and follow-up. Ultimately, a thorough and updated review of preoperative spinal tumor embolization and its clinical benefits will summarize the current fund of knowledge and encourage future research toward continued improvements in patient outcomes for those needing to undergo surgical resection of spinal lesions.

Keywords: spinal tumors, spinal lesions, embolization, hypervascular, blood loss, transarterial

Introduction

Spinal is a minimally invasive procedure involving injecting embolic agents to occlude small tumor vessels of hypervascular spinal lesions, intending to promote devascularization and reduced blood flow to decrease the risks of diffuse bleeding (1). In 1974, Benati et al. first introduced trans-arterial embolization of spinal lesions in four cases involving a spinal cord angioma, a hemangioma, a glomus tumor of the petrosal bone, and a dural vascular malformation of the occipital bone (2). With recent medical advances, embolization has become a standard adjunctive procedure used to treat spinal tumors (3–5). Metastases most commonly invade the spine and are 20 times more likely to develop than primary spinal tumors. These metastatic lesions are often hypervascular and increase the complexity of interventions. However, embolization can be performed for an array of spinal tumors and at various time points, whether delayed, isolated, or as a preoperative intervention strategy(6). The literature primarily reports on thoracic and lumbar spine tumors, with very few studies exclusively focused on embolization for cervical spinal tumors.

To date, several reports have showcased positive outcomes when embolization is utilized preoperatively (7). Advances in interventional techniques and rapidly evolving technology with microcatheters, microwires, embolic agents, and digital subtraction imaging have contributed to the evolution and impact of this procedure (7). Quality improvement guidelines for percutaneous transcatheter embolization in the literature support embolization as an optimal treatment choice for many vascular anomalies.

We have advanced and will continue to advance our comprehension of the clinical benefits of spinal tumor embolization for surgical resection. However, while there is much in the literature regarding specific uses of spinal embolization, there need to be more comprehensive reviews overviewing the clinical relevance of the procedure. As such, we aimed to remedy this gap in the literature by highlighting the technical approaches of tumor embolization, its indications, and the timing of post-embolization lesion resection. Additionally, we provide a detailed overview of the breadth of benefits of tumor embolization and comment on its complications. We end our review by discussing provocative testing and guidelines for post-embolization management.

The utility of preoperative embolization

Indications

Spinal tumors are currently managed with procedures involving decompression, tumor resection, and additional stability of the spinal column with instrumentation. However, when tumors are deemed hypervascular, the risks of intraoperative bleeding substantially increase, potentially resulting in severe hemorrhage, increased operative difficulty, discontinuation of surgery, and greater overall risks of adverse events. Hypervascular spinal tumors, which are classified as benign, primary malignant, or metastatic, represent a major indication of the utility of preoperative transarterial embolization (**Table 1**). Respectively, 40, 85, and 60% of these tumor types are shown to be hypervascular (8, 9). Furthermore, embolization can contribute to tumor shrinking, which may facilitate the likelihood of complete resection (10). Other potential situations to consider preoperative embolization include radical exposure, intralesional curettage, or piecemeal removal (11).

TABLE 1 | Vascular lesions of the spinal column.

Benign	Malignant	
	Primary	**Metastatic**
Hemangiomas	Ewing sarcoma	Hepatocellular carcinoma
Aneurysmal bone cyst	Osteogenic sarcoma	Multiple myeloma
Osteochondroma	Chondrosarcoma	Thyroid carcinoma
Osteoid osteoma	Hemangiopericytoma	Renal cell carcinoma
Osteoblastoma	Chordoma	Breast cancer
Paraganglioma	Plasmacytoma	Sarcoma
Giant cell tumor	Giant cell tumor	Melanoma
Chondromas	Lymphoma	Neuroendocrine tumor

Characterization of hypervascularity

Assessment of hypervascularity is an essential aspect of determining eligibility for tumor embolization and may be identified or predicted in several ways. One such method is by clinical findings, illustrated by inflammation in soft tissue such as erythema, induration, and puckering (12). Furthermore, suspicions should be raised for purely lytic tumors, lesions exhibiting growing on serial imaging, and tumors aggressively disrupting peripheral anatomic structures, including the blood supply (e.g., the vertebral or segmental arteries), all of which are known to increase perioperative blood loss. Imaging findings indicating rapid growth may also predict hypervascularity. It is relevant to note that findings on PET scans and MRIs are not always predictive, but embolization is likely necessary for tumors that demonstrate elevated contrast enhancement, considerable signal voids, or intralesional hemorrhage (13). However, some agree that angiography is the only method that can adequately identify lesions for which embolization is beneficial (12, 14).

The practice of embolization in hypovascular spine tumors is still poorly established due to a lack of consensus. Patsalides et al. demonstrated no differences in the mean estimated blood loss (EBL) between the embolized and tumors that are not embolized with low hypervascularity for cervical spine tumors (15). Yoo et al. (16) analyzed intraoperative and perioperative blood loss and the number of required transfusions in patients receiving surgical management for hypovascular spine tumors. They reported that embolization does not lessen perioperative blood loss, but results in reduced intraoperative bleeding and number of transfusions. On the other hand, Gong et al. (14) found that preoperative embolization doesn't lead to decreased bleeding intraoperatively for hypervascular spine tumors. Hence, further research is necessary to help dictate the role of embolization in managing hypovascular spine tumors.

Embolization techniques and considerations

Anatomical considerations

It is imperative to lead our review with a description of the spine's microvascular anatomy (1). At various levels along the spinal cord, segmental arteries branch into radiculomedullary arteries and then anastomose with the anterior and posterior spinal arteries (**Figure 1**). The radiculomedullary arteries supply blood to the dura, spinal roots, and wall of the vertebar surrounding the spinal canal (1, 17). The site of origin of radiculomedullary arteries becomes important when considering spinal embolization. If the artery's takeoff originates within proximity of a

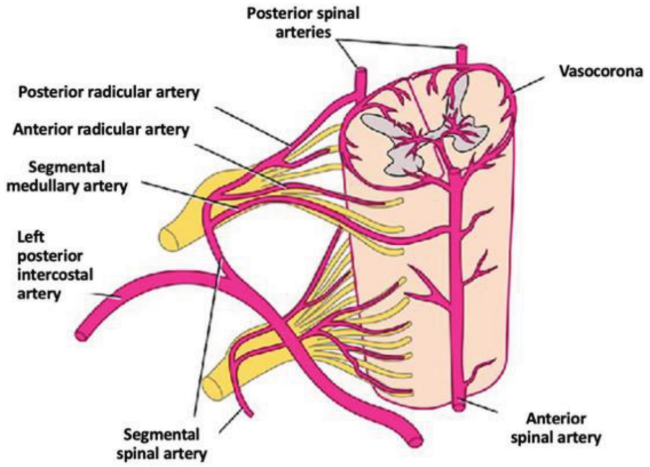

FIGURE 1 | Arterial vasculature of the spinal cord. Adapted from Guerrero-De León et al. (65).

hypervascular spinal tumor and the catheter is not advanced beyond this site, there is a risk of non-targeted embolization of the artery (1). Although rare, non-volitional embolization of a radiculomedullary artery can lead to devastating consequences such as spinal cord ischemia or infarction (7). Intersegmental anastomoses also exist between neighboring segmental arteries, granting access to the spinal arteries from different levels (1, 18). Thus, even if a super selective arterial approach is used, it is imperative to investigate the microvascular anatomy two levels above and below the hypervascular lesion to rule out the risk of embolic material shunting to an adjacent vertebral level (1).

Superselective catheterization is not always an option in the presence of feeding arteries. Alternatively, the microcatheter can be advanced past the feeding arteries, followed by the placement of micro-coils in the segmental artery to avoid subsequent embolization of normal tissue. Embolization is then carried out proximally to the feeding arteries (7). This is known as the flow-controlled technique, where arterial inflow is not occluded. Instead, blood flow and perfusion pressures allow for the transport of embolic agents into the lesion (19). Ideally, the embolic agent should infiltrate the capillary bed of the lesions for complete and permanent vessel occlusion.

Greater caution may be necessary when the cervical spine region as there are significantly heightened risks of embolization of cervical spine tumors compared to thoracic or lumbar spine tumors. Cervical spinal tumors are characterized by more complex vascular anatomy (20, 21). Their arterial supply may originate from vertebral, external carotid, or subclavian artery branches. In addition to embolizing radiculomedullary arteries, embolic agents may obstruct intracranial vasculature via pathways from the vertebral artery or carotid artery anastomoses (22). Tumor-feeding arteries from the vertebral artery are usually short and tortuous, which leads to high degrees of difficulty catheterizing selectively without embolic agent reflux. Therefore, although somewhat similar embolization techniques are employed in cervical and thoracic or lumbar spinal lesions, they can be applied very differently (23).

Limitations of angiography

While angiographic evaluation remains the standard modality for obtaining high-resolution spinal vascular anatomy imaging, they are limited in their ability to completely visualize the microvascular infrastructure given the small size and overlapping nature of the spinal arteries (7). Thus, not identifying a radiculomedullary artery on angiographic evaluation does not rule out its presence. Many articles have mentioned that spinal cord infarction can occur even when spinal branches are not visualized on an angiographic examination (24). Prior reports have suggested that the placement of coils at the origin of radiculomedullary arteries may be protective; however, there continues to exist a risk of spinal cord ischemia, particularly with insufficient collateral blood supply (3).

Complete vs. partial tumor embolization

Embolization is often categorized as either complete or incomplete. The literature reports that a range of 50–86% of embolizations are complete (25, 26). The most likely reason for incomplete embolization is neighboring radiculomedullary arteries, but there are several other potential causes, which include catheter-induced dissection of feeding arteries, instability of the position of the catheter, and difficulty of selective catheterization (7).

Embolic agents

Coils

While this represents the simplest and most safe technique, there is an elevated risk of tumor revascularization (1). Hence, coil embolization is best utilized for hypovascular tumors. When coils are used alone, embolization is not as effective due to proximal vessel occlusion only. Berkefeld et al. did not identify any differences in intraoperative bleeding in patients undergoing coil embolization versus those who did not (1). Coils also block access that may be of future necessity in cases of tumor recurrence, subsequent surgery, or re-embolization. However, coils can protect uninvolved distal vessels and occlude worrisome anastomoses.

Liquid agents

These agents deeply penetrates lesion and achieves rapid and permanent embolization, unlike coil embolization (27). However, liquid agents have posed significant challenges

due to its liquid state, which increases likelihood of non-targeted embolization (28). Hence, embolization requires experience and technical expertise to minimize neurologic complications and necrosis.

Ethanol deeply penetrates where it is injected due to its low viscosity. While its use may lead to extensive necrosis, it can be valuable for the treatment of malignant spine lesions. There is little concern for recanalization as complete occlusion lasts up to 3 months after embolization (29). Ethanol is less frequently used compared to other embolic agents due to common occurrences of complications.

NBCA quickly polymerizes into a solid when it encounters blood or saline. However, its mechanism of action may result in gluing of the microcatheter within the cast or avulsions of the feeding artery with catheter removal. As a result, injection needs to be quick and continuous, possibly diminishing delivery precision (30).

Onyx decreases the risks of catheter adherence and allows for embolization with fewer catheterizations. Catheter withdrawal is much safer despite incidences of substantial reflux. As injection does not need to be as quick, the use of angiographic assessments and better control of delivery overall are advantages of using this embolic agent (31).

Particulate agents

Particulate agents are the most utilized embolic agents. For ideal outcomes, these agents should be non-biodegradable, deformable, and homogeneously shaped (2). While smaller particles are more effective due to farther penetration, particles greater than 100 μm should be used as they are less likely to cause ischemia and/or necrosis (7). Augmenting coils with particle significantly improves tumor penetration, leading to greater devascularization and inhibition of early revascularization. Nevertheless, only incomplete embolization can be achieved, as particles can impact critical anatomic structures (32).

PVA particles were previously the most common agent due to their inertia, non-absorbability, and occlusion of tumor vessels at the capillary bed (32). However, drawbacks of this embolic agent are its irregular surface, size variability, and ability to swell when suspended in a contrast agent, leading to unintended aggregation. Consequently, this increases the rates of obstructed catheters and recanalized capillary beds (2).

Trisacryl gelatin microspheres, on the other hand, are non-resorbable, homogenous, deformable, and precisely calibrated. Compared to PVA particles, these agents do not aggregate and result in even deeper penetration (33). During embolization, fluoroscopic guidance is utilized, and injection is administered slowly and intermittently until or near stasis. To monitor any potential opening of anastomotic channels and flow diversion to the spinal cord, angiograms should be obtained at regular intervals throughout the embolization procedure (7).

Altogether several factors such as size of the vessel, intended duration of occlusion, tumor etiology, and surrounding tumor environment should be considered when choosing the appropriate embolic agent (34). As such, preoperative spinal embolization will continue to see advances as new agents and techniques evolve in the surgical space.

Clinical outcomes after tumor embolization

As we have outlined, several techniques and indications exist for spinal tumor embolization. Next, we discuss the clinical benefits of this procedure as reported in the primary literature, with benefits ranging from pain improvement as a palliative measure to significant decreases in blood loss intraoperatively. Overall, the use of preoperative embolization resulted in more favorable outcomes (6, 35–37).

Benefits

Delayed embolization is primarily used for symptomatic alleviation following treatment failure (38). This form of embolization allows for pain relief and improved neurological symptoms in patients with spinal tumors that have either failed therapy or were diagnosed as unresectable (38). Through tumor necrosis and shrinkage, palliative embolization results in a reduction of the mass effect of spinal tumors, alleviates spinal cord compression, and reduces damage to adjacent normal tissues (38). Relief typically lasts for 3–9 months following embolization (7).

Isolated embolization is pursued with curative intentions in patients with specific primary benign spinal tumors (7). These patients undergo serial embolization that ultimately stops tumor growth and development, creates tumor ossification, and resolves their symptoms.

The use of preoperative embolization to facilitate surgical resection is of greater importance (3, 4, 36, 39). Tumor excision without the utility of embolization may result in extensive bleeding, leading to severe hemorrhage and increased transfusion requirements, (3, 4, 36, 39). In addition, certain tumor types, such as spinal metastases from renal cell carcinoma, are correlated with greater risks of hemorrhage and several reports have shown success in the reduction of blood loss with preoperative embolization (4, 40, 41). Increased blood loss can cloud the surgical field and consequently increase operative times, complications intraoperatively, post-operative hematoma formation and infections, and hindered wound healing (4, 6, 36, 38). The addition of preoperative embolization within spinal tumor management mitigates these issues by reducing intraoperative bleeding and subsequently decreasing the aforementioned complications (4, 36, 38–40, 42).

Several studies in the spine oncology literature affirm the positive effect of embolization in regard to surgical blood loss. Clausen highlights these benefits with findings of significantly reduced operative length of time and loss of blood in hypervascular metastases that underwent preoperative embolization (43). A comprehensive review by Ozkan et al. states that patients who undergo spinal tumor surgery without preoperative embolization accrue an EBL between 4,350 and 8,750 mL compared to an EBL of 300 to 4,300 mL for patients who undergo spinal tumor surgery with preoperative embolization (7). Hess et al. reported a more favorable post-operative hemoglobin in those patients undergoing preoperative spinal embolization for patients with spinal metastases versus those patients who did not undergo embolization (44). Findings of studies reporting clinical outcomes are summarized in **Table 2**.

Westbroek et al. did not identify any differences in blood loss after complete embolization vs. near-complete embolization. Kato et al. performed a study, for which complete embolization was categorized by occlusion greater than 90% and partial embolization was 90% or less (45). They identified no differences in intraoperative blood loss, and multiple studies report similar results (5). One study reported that embolization greater than 80%, did not reduce blood vs. partial embolization (3). Tan et al. found conflicting results in their study, however. They showed that complete embolization, characterized by occlusion greater than 80%, led to less blood loss (46). Interestingly, they did not find any differences when occlusion was less than 50% vs. 50–80%. Possible hypotheses for the differences in findings in these studies may be due to the heterogeneity of embolization degree classification or the evolution of new embolization techniques. It is important to note that severe intraoperative bleeding may following complete embolization, and in particular during an anterior approach to access the intended surgical site (4). Moreover, although more blood loss may be encountered after partial embolization than complete embolization, partial or incomplete embolization is still more efficient in the reduction of intraoperative blood loss (3–5, 35, 36, 38, 47).

In addition to the completeness of embolization, Ladner et al. suggest that the embolization technique also affects efficacy. The authors reported significantly lower blood loss and intraoperative transfusion requirements with dual-lumen balloon catheters as opposed to non-dual-lumen catheters (39). Kobayashi et al. expanded this to include surgical invasiveness as a limiting factor to the clinical benefit of embolization (5). The authors found that surgical invasiveness, as evaluated by a validated scoring index, significantly correlated with both intraoperative blood loss and transfusion necessities (5).

Risks of neurologic injury

Despite the plethora of benefits surrounding embolization for spinal tumors, the procedure carries important risks, such as the possibility for neurological injury. Accidental embolization of spinal arteries can lead to severe sequelae such as paralysis, anesthesia, sexual dysfunction, and loss of bladder and bowel control (36). Preoperative embolization is contraindicated for patients with uncorrectable coagulopathy

TABLE 2 | Summary of clinical studies and major reported findings examining clinical outcomes for preoperative spinal embolization ahead of surgical resection.

Reference	Reported benefit
Hess et al. (44)	Reduction in blood loss of 2,088 mL and more favorable post-operative hemoglobin after preoperative embolization
Kato et al. (45)	IBL of 520 mL after embolization vs. 1,128 mL without embolization for spinal metastasis
Clausen et al. (43)	Reduced operative times and IBL with preoperative embolization for hyper-vascular metastases, although average IBL did not differ between embolization group (618 mL) and control group (735 mL)
Ozkan and Gupta (7)	30–50% reduction in IBL post-embolization.
Luksanapruksa et al., (35)	Preoperative embolization reduced average IBL by an average of 1,226.9 mL (889.9 mL for the mixed tumor group and 2,931.3 mL for the renal cell carcinoma metastases group)
Manke et al., (25)	The average IBL for the embolized group was 1,500 mL while IBL for the non-embolization group averaged 5,000 mL.
Gao et al., (40)	In patients with hypervascular tumors treated with preoperative embolization, there was a significant decrease in IBL (−1,171.49 mL), transfusion requirements (−3.13 units), and operative time (−33.91 min).
Awad et al., (36)	A significant reduction in blood loss was seen for lesions that achieved embolization over 90% (average of 1,391 mL for lesions over 90% embolization and 2,296 mL for lesions under 90%).
Kobayashi et al., (5)	Patients with tumor invasiveness under 10 reported significantly reduced blood loss (1,315 mL) vs. patients between 10 and 20 (2,695 mL) and patients over 20 (3,905 mL).
Westbroek et al., (4)	Complete embolization (1,625 mL) and near-complete embolization (2,021 mL) demonstrated reduced blood loss compared to partial embolization (4,009 mL). No differences between complete and partial embolization were identified.
Patsalides et al., (15)	Reduced estimated blood loss in patients undergoing embolization for hypervascular cervical spine tumors (1,717 mL) compared to those who did not (722 mL).

IBL, intraoperative blood loss.

and renal failure (7). Major complication rates are relatively low if embolization is performed by experienced professionals with thorough pre-procedure imaging (36, 38). The reported risk of neurological complication following preoperative embolization is under 2% if performed by an expert clinician. Likewise, Kobayashi reported presentation of irreversible neurologic complications following embolization due to cord ischemia (5).

A comprehensive neurological examination should be administered immediately after embolization for prompt evaluation and recognition of potential complications outside of the expected recovery course; modest swelling of tumor and compression of the spinal cord are common after embolization and solely require inpatient monitoring in case of progression (36, 38). Post-embolization syndrome is the most common complication, presenting in 18–86% of patients. It presents with systemic symptoms such as localized pain, headache, malaise, nausea and vomiting, low-grade fever, and leukocytosis likely in response to the release of necrosis byproducts and inflammatory factors (38).

In summary, the clinical benefits of spinal tumor embolization have been well documented. Despite the low rate of complications seen within many studies, embolizations are complex procedures and require an experienced interventionalist to ensure successful implementation. Next, we discuss the outcomes of surgical resection following embolization.

Post-embolization surgical resection

While the benefits of preoperative embolization are extensive, there are no well-defined academic standards on the timeline of preoperative embolization and subsequent planned surgical resection. Understanding the pathophysiological requirements of hypervascular tumors is relevant to this discussion on the optimal schedule of preoperative embolization. Hypervascular tumors can lead to timely involvement of collateral blood flow (48). Metastatic tumors also tend to create arteriovenous shunts thus, early drainage could aid in reducing intraoperative loss as the tumor has more time after embolization to adapt (48). Thus, this pathophysiological mechanism underlies several reports in the literature proposing earlier rather than delayed post-embolization surgical resection.

Several studies point to optimal minimization of blood loss (4, 38, 49) (**Table 2**). This 3-day period is reported to minimize other operative complications such as potential revascularization or added spinal cord compression due to tumor edema, increased tumor volume, or hemorrhage (13). Others have proposed a 24-h window between embolization and surgical resection to reduce the risk of developing tumor edema from collateral formation and revascularization or post-embolization syndrome (7). Additionally, combined coil and particle embolization demonstrated an added benefit of inhibiting rapid revascularization if surgery was to be delayed (1).

Another group reported two cases of preoperative embolization prior to tumor resection at different time points but similar positive patient outcomes (50). The first case was of osteoblastoma located at the T2 posterior vertebral arch, with concern for bleeding into the spinal canal. Following complete devascularization, partial tumor resection was performed 36 h later with no post-operative neurological deficit or complications (50). The second case was that of a 68-year-old with plasmacytoma of the L4 vertebra. Successful total surgical resection was done 48 h following embolization without any complications (50).

To better understand the association between delayed surgical intervention following embolization and intraoperative blood loss, Kato et al. examined blood loss during spinal metastasis in 65 posterior palliative decompression surgical procedures from 2004 to 2012 (45). They found that patients who had complete preoperative embolization and surgery within the same day (less than 24 h) had significantly less intraoperative blood loss and decreased perioperative transfusion requirements compared to those patients undergoing surgical 1 day after embolization (45). Thus, their recommendation was to perform surgical resection on the same day of embolization to maximize the clinical benefits of reduced blood loss and lesser perioperative transfusion requirements.

Another important consideration is the biochemical properties of the embolization agents that are being used. For example, PVA and gelatin sponge have been can be damaged by enzymatic pathways as early as 7 and up to 21 days post-embolization (51). This property raises concern for early vessel recanalization, given that the intravascular thrombus can begin to degrade within 24 h of embolization (52). The implications of this have been studied by Gellad et al who recommended that surgery should be executed within 1 day following embolization using a gelatin sponge to avoid recanalization (49). In their series of 24 patients with spinal metastasis, those who underwent surgery after 1 day of complete embolization had, on average, about a half-reduction in blood loss (49).

Wilson found no disparity in estimated blood loss when surgical resection was done within 2 days vs. greater than 2 days following embolization (26). Interestingly Çelebioğlu et al. reported a waiting period of 6 to 12 h within a 24-h period following embolization as a practical time interval for surgical resection. The authors echoed that an earlier time interval maximizes operative results while minimizing risks of neurological complications and otherwise (53).

Most studies in the literature support early versus late surgical resection following spinal tumor embolization. While few studies report no significant differences, this overview highlights the need for consolidated academic

guidelines based on these reported clinical studies, which describe the ideal scheduling timeline and approach for surgical resection to ensure that the full benefits of spinal tumor embolization are realized in the clinical setting.

Provocative testing

Pharmacological provocative testing is an intraoperative neurophysiological monitoring (IONM) technique commonly utilized by neuroradiologists and neurosurgeons to mimic and assess the risk of proposed endovascular interventions (54). In the endovascular treatment of hypervascular tumors, pharmacological provocative testing is used as an intra-operative adjunct to angiographic evaluation to identify vessels and anastomoses that supply eloquent functional territories of the spine (54). This monitoring technique is essential for predicting the safety of arterial embolization and minimizing post-procedural complications (**Figure 2**). The standard protocol for provocative pharmacologic testing suggests super selective catheterization of the vessel of interest followed by lidocaine or sodium amytal injection (55). Lidocaine, which blocks axonal conduction, is recommended for arteries with extra-axial destination, while sodium amytal, which blocks neural activity, is recommended for arteries with intra-axial trajectories (56). If the catheterized artery connects with a spinal artery, the patient will experience changes in neurological status, including transient lower extremity paresis or paralysis (55). As such, a positive test warrants repositioning of the catheter beyond the spinal artery anastomosis and repeat testing (55). Alternatively, a fiber or liquid coil can be used to protect the normal territory (57) (**Figure 3**).

The previously described technique requires patient participation through verbalization of acute neurological changes. Thus local anesthesia and conscious sedation are utilized to assess the neurological status (58). Contrarily, some institutions will opt to use general anesthesia to regulate patient breathing and attain high-quality intraoperative images (58). In the setting of general anesthesia use, IONM with somatosensory evoked potentials (SSEPs) and muscle motor evoked potentials (mMEPs) to assess the patient's neurologic response to provocative testing (55). SSEPs are produced by bilaterally stimulating the posterior tibial and median nerves using electric current (57). SSEPs are recorded through corkscrew electrodes placed on the scalp across the sensory cortex. MMEPs are prompted by transcranial electrical stimulus of the motor cortex using a corkscrew electrode strip (57). Potentials are recorded from needle electrodes in the anterior tibialis and thenar muscles (57). Under general anesthesia, a positive amytal or lidocaine provocative test under general anesthesia would appear as more than a 50% decrease in SSEP amplitude or mMEP disappearance, suggesting vascular communication to the posterior and anterior spinal cord, respectively (58, 59).

Several retrospective studies demonstrate that provocative pharmacologic testing along with intraoperative neurophysiologic monitoring have a high negative predictive value (55, 60). Kothbauer et al. reported that the sensitivity of muscle motor evoked potentials to detect motor deficit post-operatively was 100% and specificity 91% (61). In the retrospective analysis, none of the patients with stable mMEPs following provocative testing developed post-operative motor deficits. In 2021, Tong et al. exhibited in a prospective study between 2018 and 2020 that the negative predictive value of provocative testing was 97.9%, in which the single false negative results in post-operative hemorrhage but the other cause did not lead to post-operative neurologic deficit (60).

Katsuta et al. questioned whether pharmacologic provocative testing overstimulated clinical results when an embolization did not cause catastrophic consequences despite a positive lidocaine injection test with bilateral lower extremity sensorimotor deficits and SSEP amplitude depression (62). Furthermore, Katasuta hypothesized that because liquid lidocaine can spread through any vascular network, it is not comparable to embolic particles that may vary in size (62). Berkefeld et al. similarly questioned the certainty of pharmacologic provocative testing with lidocaine noting the role of collateral arteries during embolization (1). In the pre-embolization phase, Berkefeld et al. noted that blood flows directly to the hypervascular tumor. However, collateral branches to adjacent segments, with contributions to spinal arteries, may spontaneously open during the embolization phase (1). Pre-embolization provocative testing

FIGURE 2 | Pathway for utilization of provocative testing results in surgical planning.

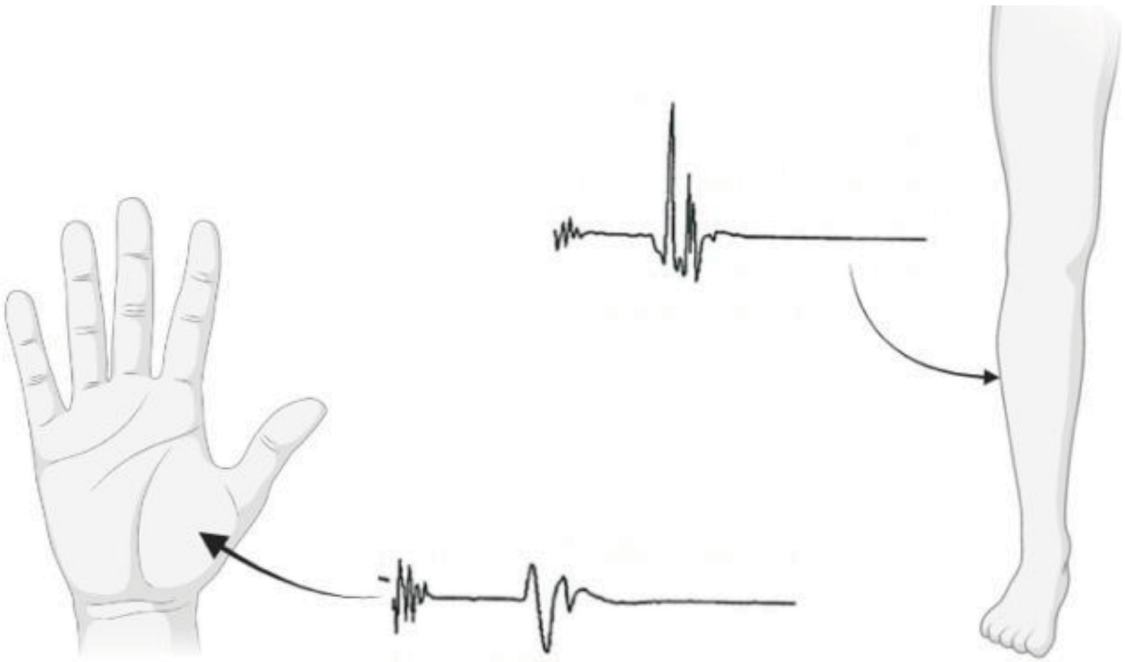

FIGURE 3 | Muscle responses during provocative testing are typically measured using needle electrodes, which can be placed at the anterior tibialis bilaterally, thenar muscles, and/or toe abductors (57).

would not be able to predict this, resulting in deleterious effects. Thus, provocative testing should only be utilized with angiographic evaluation and clinical monitoring to ensure the safety of spinal embolization.

Post-embolization follow up

Post-operative management and monitoring

Immediately following spinal embolization, a neurological examination ought to be completed to identify immediate complications (7). Post-operative management for all patients should then involve transfer to an intensive care unit for hemodynamic control and surveillance of neurological status (58). Hypotensive or hypertensive events in the post-embolization period are not uncommon due to vascular occlusion and may lead to deleterious neurological effects (58). A patient's neurological status may also be compromised by post-embolization tumor swelling with successive spinal cord compression. In the event of post-embolization syndrome, given that the condition is self-limiting, the recommended treatment is supportive, such as analgesia and intravenous fluids (63).

Follow-up

Following hospital discharge, a 30-day follow-up should be completed, either as an outpatient or a telephone visit, to assess for resolution or recurrence of presenting symptoms and the presence of complications, such as new neurological deficits, signs of pain and infection, and early or delayed recurrence of hematoma. Follow-up imaging with a CT scan and/or an arteriogram may be done to evaluate disease progression and stabilization (64). Embolization may be performed every 2–4 months until resolution of the hypervascular tumor has been achieved, or the patient's radiographic and clinical signs improve (64). Lin et al. reported that most patients demonstrated significant radiographic improvement in response to tumor embolization (64). Radiographic and clinical improvements were sustained in 50% of giant cell spinal tumor patients one to two decades post-embolization. One patient developed tumor recurrence 10 years post-embolization but likely developed a rare, aggressive form causing widespread metastasis post-embolization (64).

Conclusion

Our understanding of the role of spinal tumor embolization has continued to expand in the literature. As we have presented, the techniques of tumor embolization largely rely on technical and clinical expertise, with consideration for the arterial vasculature of the spinal cord. The indications for tumor embolization can vary widely, but its benefits have been echoed in the literature for reducing the risk of operative bleeding and improving overall patient outcomes. Notably, the implementation of provocative testing has allowed for an even more pragmatic approach to risk

stratification, and guidelines for follow-up management published in the literature allow for ensured patient safety. With further study, the exploitation of spinal tumor embolization will hopefully result in successfully improved clinical management strategies. As endovascular technologies continue to expand, the benefits of this procedure will undoubtedly continue to grow in the clinical space.

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