Cerebrospinal fluid leaks after spine tumor resection: avoidance, recognition and management

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Abstract: Post-operative CSF leaks are a known complication of spine surgery in general, and patients undergoing surgical intervention for spinal tumors may be particularly predisposed due to the presence of intradural tumor and a number of other factors. Post-operative CSF leaks increase morbidity, lengthen hospital stays, prolong immobilization and subject patients to a number of associated complications. Intraoperative identification of unintended durotomies and effective primary repair of dural defects is an important first step in the prevention of post-operative CSF leaks, but in patients who develop post-operative pseudomeningoceles, durocutaneous fistulae or other CSF-leak-related sequelae, early recognition and secondary intervention are paramount to preventing further CSF-leak-related complications and achieving the best patient outcomes possible. In this article, the incidence, risk factors and complications of CSF leaks after spine tumor surgery are reviewed, with an emphasis on avoidance of post-operative CSF leaks, early post-operative identification and effective secondary intervention.

Keywords: Durotomy; cerebrospinal fluid leak; spine tumor; duraplasty; dural repair

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Introduction

Cerebrospinal fluid (CSF) leaks are a known complication of spine surgery, and an effective protocol for prevention, recognition and treatment of postoperative CSF leakage is essential to avoiding a cascade of associated adverse outcomes, such as durocutaneous fistula, wound infection (1-5), intracranial hemorrhage (6-12), arachnoiditis (13,14), nerve root incarceration/strangulation (15,16) and meningitis (3-5,17). Unintended durotomies are reported to occur in up to 16% of spine surgeries in several large series (14,15,18-38), with smaller series reporting even higher incidences (39). While unintended durotomies may lead to longer operative times, a delay in mobilization after surgery, and occasional nerve root injury or neurological deficit (30,31), the majority of incidental durotomies are identified and addressed intraoperatively without the need for reoperation or further intervention, and evidence regarding the overall effect of incidental durotomy on long term patient outcomes are conflicting (19,22,40-42). The adverse outcomes of perhaps greater interest are post-operative CSF leaks that require secondary intervention and lead to CSF-leak-related sequelae after spine surgery, as these are a source of considerable patient morbidity and economic burden (43,44).

Patients undergoing surgical intervention for spinal tumors would seem particularly prone to the development of post-operative CSF leaks due to a number of factors, including: (I) the variable presence of an intradural tumor component requiring durotomy as a part of the intervention, (II) deficits in wound healing capability as a result of malnutrition, complex wounds, medical comorbidities, extended use of high-dose steroids or the need for adjuvant chemoradiotherapy, and (III) the use of anterior/ventral approaches to the spine which may create communications between the subarachnoid space and negative pressure potential spaces (e.g., the pleural cavity).

Inappropriately managed CSF leaks subject spine tumor patients to a number of associated complications, lengthened hospital stays, the need for additional interventions, increased health care costs (43,44), and the propensity for tumor seeding (4,45,46). Early identification and treatment of CSF leaks is necessary to avoid compounding the risks of spine tumor surgery and achieving the best possible patient outcomes. The goal of this article will be to review the literature on post-operative CSF leaks after surgical intervention for spinal tumors—with an emphasis on avoidance, recognition and effective management.

Incidence and risk factors

The reported incidence of CSF leak requiring intervention after spinal tumor surgery varies widely (0–28.6%) (3-5,47-67), but a review of the recent literature would suggest that the overall incidence after surgery for both intradural and extradural pathologies is relatively low (68-77) (mean, 6.6%±5.8%; *Tables 1,2*).

A number of factors predisposing to unintended durotomy during spine surgery for degenerative pathology have been described, including advanced patient age (26,30,78,79), resident involvement (34,38), history of prior surgery in the same region (36,38,79-81), length of surgery (78), lumbar spine surgery (compared with cervical and thoracic) (38,79), and synovial cyst pathology (30).

Risk factors for the development of post-operative CSF leak requiring intervention after spine surgery, however, are not well defined. In patients undergoing resection of extradural tumors, unintended durotomy is necessary—but not sufficient—for the development of a post-operative CSF leak. Effective closure of dural defects should prevent extradural CSF egress, and wound closure and wound healing are likely fundamental to the prevention of cutaneous CSF fistulae.

Several authors have suggested that minimally invasive surgical (MIS) approaches to spine tumor resection—and other MIS spine surgeries—lead to lower rates of post-operative symptomatic CSF leakage, despite the increased difficulty of primary dural closure through an MIS approach (65,68,70,82-84). This finding is said to be a consequence of the limited soft-tissue exposure and relative absence of "dead space" resulting from MIS approaches, wherein the absence of dead space leads to a relative increase in epidural pressure, "tamponading" the epidural space and preventing epidural CSF egress (84). Applied to open spine tumor resections, these principles would suggest that meticulous closure of not only the dural defect, but of all surgical layers, would decrease the risk of pseudomeningocele development and other manifestations of post-operative CSF leak by decreasing dead space. By extension, perioperative radiotherapy/chemotherapy delivery (85), high-dose steroids, elevated intracranial pressure related to leptomeningeal-disease-related hydrocephalus or intracranial metastases, and comorbidities that delay wound healing would seem likely to elevate the risk of post-operative CSF leak; evidence that speaks to these issues is difficult to find.

Avoidance of unintended durotomy

In intradural spine tumor surgeries, durotomies are inevitable, but avoiding unintended durotomies when resecting epidural spine tumors is the first step in the prevention of post-operative CSF leak. Data from the degenerative spine literature suggest that the Kerrison punch is the tool most likely to cause unintended durotomies, followed by the high-speed drill (26,30). Unintended durotomies have also been reported with greater incidence in surgeries for synovial cysts (30) and revision surgeries (36,38,78-81). Many of these durotomies could likely be prevented through adherence to fundamental surgical principles, such as: (I) adequate visualization of tissues before tissue removal, (II) adequate dissection of tissue planes before tissue removal, and (III) in revision cases or cases in which normal tissue planes are distorted/adherent, beginning with dissection of "normal" tissue planes before proceeding toward adherent/distorted planes.

Epidural spine tumors may be adherent to the dura, distorting normal tissue planes and making dissection difficult. It may be beneficial in these cases to dissect tumor away from the dura in a medial-to-lateral and cranial-to-caudal direction to prevent inadvertent nerve root injury, which could be a source of CSF leak as well as pain or neurological deficit. Additionally, in cases in which a nerve

Table 1 Reported cases of post-operative CSF leakage requiring secondary intervention after surgical intervention for extradural spinal tumors

Author (reference number)	Year	N	Histology	Location (spinal region)	Location with respect to dura	Approach	Unintended durotomy [N (%)]	Post-operative CSF leak requiring intervention [N (%)]	Intervention for CSF leak	CSF-leak-related complications [N (%)]
Akeyson and McCutcheon (67)	1996	25	Metastasis	Thoracolumbar (100%)	Extradural	Single-stage posterior spondylectomy	ND	4 (16.0)	Lumbar drainage and/or reoperation (N=2), wound reinforcement (N=2)	ND
Gokaslan *et al.* (72)	1998	72	Metastasis	Thoracic	Extradural	Transthoracic vertebrectomy	ND	2 (2.7)	ND	ND
Fourney *et al.* (3)	2001	26	Metastasis (N=15), sarcoma (N=10), ganglioneuroblastoma (N=1)	Thoracolumbar (100%)	Extradural	Single-stage circumferential	ND	2 (7.8)	Lumbar drainage	Meningitis [1 (3.8)]
Jackson *et al.* (73)	2001	107	Renal cell carcinoma metastasis	Occipitocervical (1.8%), cervical (6.5%), cervicothoracic (4.7%), thoracic (37.4%), thoracolumbar (17.8%), lumbar (26.2%), lumbosacral (5.6%)	Extradural	Anterior, posterior or circumferential	ND	2 (1.9)	ND	ND
Wiggins *et al.* (74)	2001	47	Metastasis (N=31), primary benign (N=10), primary malignant (N=6)	Thoracic (78.7%), upper lumbar (21.3%)	Extradural	Anterior thoracolumbar or costotransversectomy	4 (8.5)	3 (6.4)	Reoperation	ND
Zileli *et al.* (75)	2003	34	Primary sacral tumors, multiple histologies	Sacral	Extradural	Multiple	ND	1 (2.9)	Lumbar drainage	ND
Holman *et al.* (76)	2005	139	Metastasis	Lumbar	Extradural	Anterior, posterior or circumferential	ND	5 (3.6)	Reoperation and/or lumbar drainage	Wound infection (3 [2.2])
Barrenechea *et al.* (77)	2007	7	Chordoma	Cervical	Extradural	Anterolateral	ND	2 (28.6)	Lumbar drainage	ND
Chaichana *et al.* (47)	2008	78	Metastasis	Cervical (24%), cervicothoracic (9%), thoracic (60%), thoracolumbar (5%), lumbar (29%)	Extradural	Anterior (35.9%), posterior (55.1%), anteroposterior (9%)	ND	3 (3.8)	ND	ND

Table 1 (*continued*)

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Author (reference number)	Year	N	Histology	Location (spinal region)	Location with respect to dura	Approach	Unintended durotomy [N (%)]	Post-operative CSF leak requiring intervention [N (%)]	Intervention for CSF leak	CSF-leak-related complications [N (%)]
Williams *et al.* (48)	2009	44	Prostate metastasis	Cervical (2.3%), cervicothoracic (2.3%), thoracic (6.8%), thoracolumbar (25%), lumbar (9.1%), lumbosacral (2.3%), multifocal (45.5%)	Extradural	Posterior (40%), anterior (30%), circumferential (30%)	3 (6.8%)	1 (2.3)	Reoperation	ND
Laufer *et al.* (4)	2010	39	Metastases (reoperation)	Cervical (7.7%), thoracic (66.7%), lumbar (23%), sacral (2.6%)	Extradural	Posterolateral approach	3 (7.7)	1 (2.6)	Reoperation	Malignant pleural effusion [1 (2.6)]
Chong *et al.* (49)	2012	105	Metastasis	Thoracic (100%)	Extradural	Single-stage posterior approach; Corpectomy in 91.4%	ND	4 (3.8)	Reoperation	ND
Fang *et al.* (50)	2012	41	Solitary metastasis	Thoracolumbar (100%)	Extradural	Total en bloc spondylectomy (N=17), mini-open anterior corpectomy (N=24)	ND	1 (2.4)	ND	ND
Feiz-Erfan *et al.* (51)	2012	25	Metastasis	Sacral	Extradural	Posterior	ND	4 (16.0)	ND	ND
Sciubba *et al.* (52)	2016	60	Osteosarcoma (N=13), chondrosarcoma (N=12), Ewing sarcoma (N=7), other sarcoma (N=28)	Cervical (18.3%), thoracic (35%), lumbar (13.3%), sacral (33.3%)	Extradural	Sacrectomy (N=7), hemisacrectomy (N=7), en bloc spondylectomy (N=13), en bloc resection posterior elements (N=10), other (N=23)	ND	5 (8.3)	ND	ND
Yanamadala *et al.* (53)	2017	16	Chordoma (N=13), chondrosarcoma (N=3)	Cervical (18.7%), thoracic (31.3%), lumbar (43.8%), sacral (6.2%)	Extradural	Circumferential decompression and fusion	6 (37.5)	1/13 (7.6)	ND	ND

CSF, cerebrospinal fluid; ND, no data; NA, not applicable.

Table 2 Reported cases of post-operative CSF leakage requiring secondary intervention after surgical intervention for intradural spinal tumors

Author (reference number)	Year	N	Histology	Location (spinal region)	Location with respect to dura	Approach	Unintended durotomy [N (%)]	Post-operative CSF leak requiring intervention [N (%)]	Intervention for CSF leak	CSF-leak-related complications [N (%)]
Jenkinson *et al.* (5)	2006	115	Meningioma (N=36), schwannoma (N=23), ependymoma (N=21), astrocytoma (N=7), other (N=28)	Cervical (27.8%), thoracic (38.3%), thoracolumbar (8.7%), lumbar (24.3%), craniocervical (0.9%)	Intradural extramedullary (66.1%), intramedullary (33/9%)	Posterior (laminectomy)	NA	12 (10.4)	ND	Meningitis [5 (4.3)]
Setzer *et al.* (54)	2007	80	Meningioma	Cervical (21.3%), cervicothoracic (7.5%), thoracic (60%), thoracolumbar (7.5%), lumbar (3.8%)	Intradural extramedullary	Posterior (laminectomy, hemilaminectomy, costotransversectomy)	NA	2 (2.5)	ND	ND
Nakamura *et al.* (55)	2008	68	Ependymoma (N=33), astrocytoma (N=23), hemangioblastoma (N=12)	Cervical (44.1%), cervicothoracic (27.9%), thoracic (23.5%). conus medullaris (4.5%)	Intramedullary	Posterior (laminectomy, laminoplasty)	NA	2 (2.9)	Lumbar drainage	ND
Sacko *et al.* (56)	2009	102	Meningioma	Cervical (10.8%), cervicothoracic (3.9%), thoracic (85.3%)	Intradural extramedullary	Posterior or posterolateral	NA	1 (0.98)	Lumbar drainage	ND
Song *et al.* (57)	2009	12	Meningioma (N=4), schwannoma (N=4), epidermoid cyst (N=2), arachnoid Cyst (N=1), ependymoma (N=1)	Cervical (8.3%), thoracic (58.3%), lumbar (33.3%)	Intradural extramedullary	Posterior (laminectomy)	NA	2 (16.7)	Lumbar drainage	ND
Halvorsen *et al.* (58)	2010	86	Ependymoma	Cervical (16%), thoracic (16%), conus medullaris (33%), filum terminale (35%)	Intradural	ND	NA	5 (5.8)	Reoperation and/or lumbar drainage	Meningitis [1 (1.2)]
McGirt *et al.* (59)	2010	238	Ependymoma (N=69), schwannoma (N=55), meningioma (N=37), astrocytoma (N=23), other (N=54)	Cervical (24%), cervicothoracic (11%), thoracic (26%), thoracolumbar (14%), lumbar (24%)	Intradural extramedullary (43%), intramedullary (57%)	Posterior (laminectomy *vs.* laminoplasty)	ND	18 (7.6)	ND	ND
Lu *et al.* (60)	2011	27	Meningioma (N=9), schwannoma (N=7), ependymoma (N=3), other (N=8)	Thoracolumbar (100%)	Intradural	Posterior (mini-open *vs.* open)	NA	1 (3.7)	Reoperation	ND
Mannion *et al.* (61)	2011	11	Schwannoma (N=9), meningioma (N=2), ependymoma (N=2)	Cervical (9%), thoracic (54.5%), lumbar (54.5%)	Intradural extramedullary	Minimally invasive posterior	NA	1 (9.1)	Resutured wound	Wound infection [1 (9.0)]

Table 2 (*continued*)

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Author (reference number)	Year	N	Histology	Location (spinal region)	Location with respect to dura	Approach	Unintended durotomy [N (%)]	Post-operative CSF leak requiring intervention [N (%)]	Intervention for CSF leak	CSF-leak-related complications [N (%)]
Iacoangeli *et al.* (62)	2012	65	Meningioma	Cervical (18.5%), thoracic (81.5%)	Intradural extramedullary	Posterior (open *vs.* minimally invasive)	NA	5 (7.7)	ND	ND
Chowdhury *et al.* (63)	2013	15	Schwannoma	High cervical	Extradural (13.3%), intradural extramedullary (46.7%), intra-extradural (40%)	Midline Posterior	ND	2 (13.3)	Resutured wound and lumbar drainage (N=1), Reoperation (N=1)	ND
Tarantino *et al.* (64)	2014	107	Schwannoma (N=51), meningioma (N=33), ependymoma (N=11), other (N=12)	ND	Intradural extramedullary	Posterior (laminectomy, hemilaminectomy, costotransversectomy)	ND	5 (4.7)	ND	ND
Halvorsen *et al.* (71)	2015	131	Nerve sheath tumor	Cervical (30%), thoracic (17%), lumbosacral (53%)	ND	Posterior (laminectomy, laminoplasty)	ND	4 (3.1)	Reoperation and/or lumbar drainage	Meningitis [1 (0.8)]
Raygor *et al.* (65)	2015	51	Schwannoma (N=20), meningioma (N=12), ependymoma (N=11), other (N=8)	Thoracic (33.4%), thoracolumbar (9.8%), lumbar (47%), lumbosacral (9.8%)	Intradural extramedullary	Posterior (open *vs.* minimally invasive)	NA	3 (5.9)	Lumbar drainage	ND
Turel *et al.* (66)	2015	164	Schwannoma (N=110), meningioma (N=31), other (N=26)	Cervical (26.3%), cervicothoracic (3%), thoracic (43.1%), thoracolumbar (4.2%), lumbar (23.4%)	Intradural extramedullary	Posterior (hemilaminectomy)	ND	3 (1.8)	Resutured wound and/or lumbar drainage	ND
Wong *et al.* (68)	2015	45	Nerve sheath tumor (N=28), meningioma (N=10), other (N=4)	Cervical (24.4%), thoracic (20%). lumbar (53.3%), lumbosacral (2.2%)	Intradural extramedullary	Posterior (open *vs.* minimally invasive)	NA	3 (6.7)	Reoperation	ND
Raco *et al.* (69)	2017	173	Meningioma	Cervical (14.4%), cervicothoracic (15.6%), thoracic (68.6%), thoracolumbar (1.2%)	Intradural extramedullary	Posterior (Laminotomy or hemilaminectomy)	NA	3 (1.7)	Lumbar drainage	None
Formo *et al.* (70)	2018	83	Schwannoma (N=49), meningioma (N=18), ependymoma (N=10), other (N=6)	Cervical (10.8%), thoracic (27.7%), thoracolumbar junction (6%), lumbar (49.4%), sacral (6%)	Intradural	Posterior (hemilaminectomy)	NA	3 (3.6)	ND	ND

CSF, cerebrospinal fluid; ND, no data; NA, not applicable.

root must be intentionally sacrificed to achieve surgical goals, it is important that this is done in a controlled manner, wherein the root sleeve is ligated securely proximal to the dorsal root ganglion and cut—rather than avulsed—in order to prevent CSF leaks.

Many reported cases of unintended durotomy occur during bony removal. Although a large proportion of unintended durotomies are caused by Kerrison rongeurs (26,30), the high-speed drill is another unfortunate source of CSF leaks and neurological injury. Great caution should of course be taken when using a high-speed drill in all cases, and especially when aggressive, cutting bits are employed. Ultrasonic osteotomes (84) have been purported by some to be less likely to penetrate the spinal dura, but others have found the rate of incidental durotomy with ultrasonic osteotomes to be statistically equivalent to that seen with high-speed drills (86).

Finally, in some cases, post-operative CSF leaks occur in the absence of recognized intraoperative durotomies (6.8–25%) (13,84,87). The underlying cause of such "occult" leaks is unclear. They may be the result of small durotomies occurring intraoperatively with an initially intact arachnoid layer which later ruptures or herniates into the epidural space as an arachnoid-lined, CSF-filled cyst (14). This highlights the importance of diligent inspection of the dura prior to closure. Alternatively, they may occur post-operatively as a result of dural penetration by bony spicules (88,89), in which case they might be prevented by meticulous removal of all epidural protuberances prior to closure.

Recognition of post-operative CSF Leaks

Ideally, recognition of CSF leaks should begin intraoperatively. Unintended durotomies may be recognized not only by the emanation of spinal fluid into the surgical field, by often by a sudden increase in epidural venous bleeding and decrease in thecal sac turgor. In the case of intended durotomies, failure of primary closure may be recognized intraoperatively as persistent CSF egress, a finding that may be elicited more readily with a Valsalva maneuver.

Post-operatively, suspicion for CSF leak may be initially raised by a number of factors, including patient symptoms (e.g., postural headache, axial pain, recurrence of preoperative symptoms), unexpectedly high outputs from wound drainage systems, a palpable fluid collection on physical exam, neurologic deficits (38), or drainage of clear fluid from the wound, any of which may justifiably prompt post-operative imaging (e.g., MRI). The large majority of contained pseudomeningoceles are asymptomatic and likely go unrecognized, but cases of radiculopathy and myelopathy due to compression of neural elements by a pseudomeningocele have been reported (14). Retropleural pseudomeningoceles have also been reported, particularly when transthoracic approaches are used (*Figure 1*) (90-92).

In cases of post-operative fluid collections or elevated output from subfascial drains of undetermined etiology, testing for beta-2-transferrin, a protein found almost exclusively in CSF, can be used to differentiate post-operative CSF leaks from seromas and other fluid collections (90–94% sensitive, 98–100% specific) (93).

Complications of CSF leak after spine surgery

A multitude of complications have been reported to occur in association with spinal CSF leaks, including infectious complications (e.g., meningitis, arachnoiditis, wound infections), delayed wound healing, complications of intracranial hypotension (e.g., intracranial hemorrhage, cranial nerve palsies), and neurological deficits related to compression or incarceration of neural elements, among others.

Subarachnoid-cutaneous fistulae prevent normal tissue opposition, impair wound healing and also lead to increased risks of meningitis and wound infection (1-5,17), although the precise incidence of these complications in patients with CSF leaks after spine surgery is unclear. Data from the traumatic cranial CSF leak literature report a 10–19% incidence of fulminant meningitis in patients with persistent or occult CSF leakage (94-96), although this may not be generalizable to the spinal surgery patient population. Lin *et al.* performed a retrospective review of 20,178 patients undergoing spinal surgery at a single institution, reporting that 21 patients (0.10%) developed post-operative meningitis. All 21 patients underwent lumbar spinal surgery for degenerative indications, and incidental durotomy was reported to have occurred in each case, although only 11 of the 21 patients suffered from post-operative CSF leakage, and the incidence of durotomy and/or postoperative CSF leak in the other 20,157 patients was not reported. All 21 patients recovered with antibiotic therapy, although 3 patients required reoperation for repair of the dural defect (17). Arachnoiditis has also been reported to occur in the setting of post-operative CSF leaks, presumably as a consequence of blood products being introduced

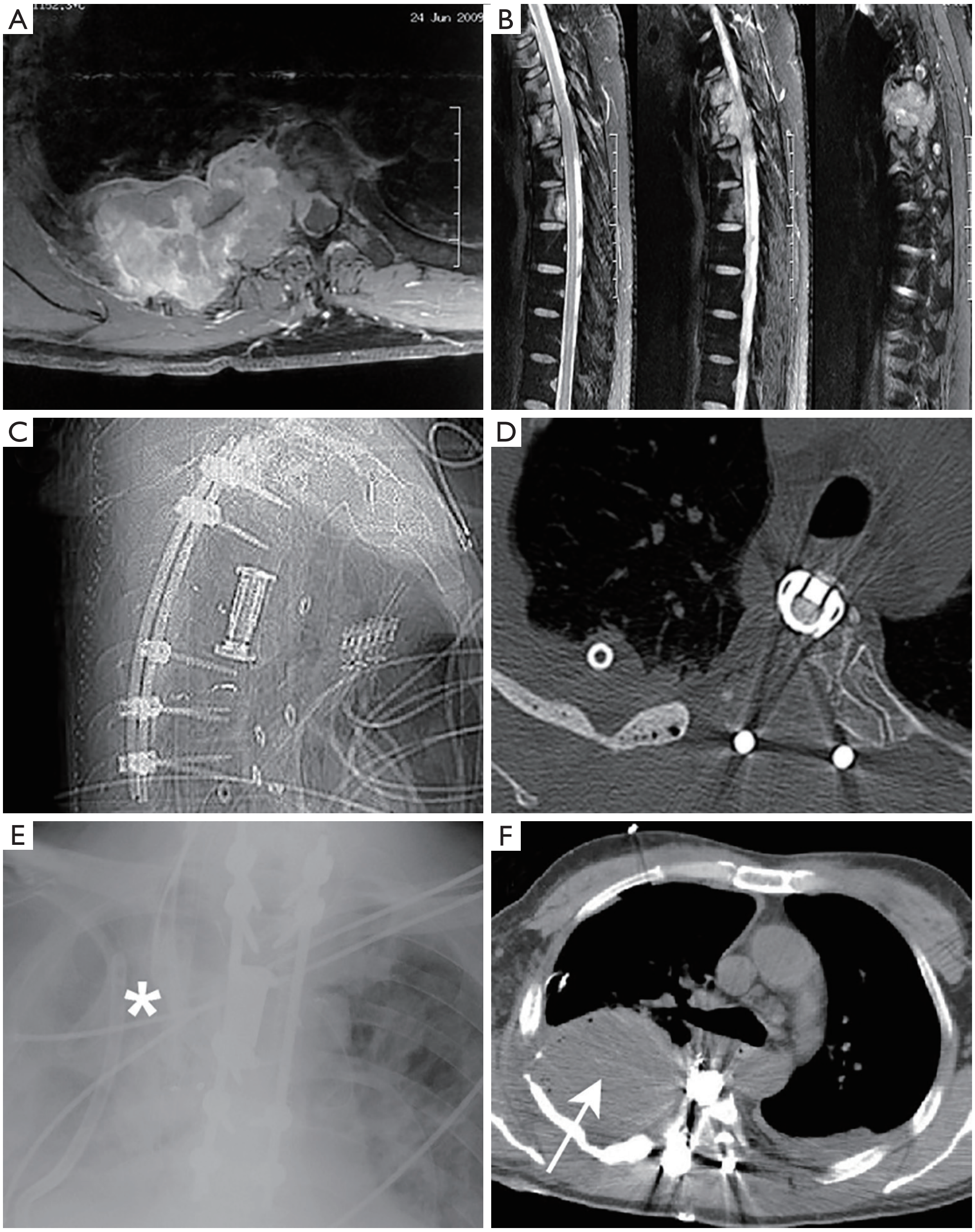

Figure 1 Pre- (A,B) and post-operative (C-F) films of a patient with a thoracic epidural mass who underwent a circumferential approach for tumor resection and posterior instrumentation. The anterior portion of the surgery was complicated by unintended durotomy, although the site of durotomy was not easily visible/accessible at the time of surgery and was not primarily repaired. Post-operatively the patient developed a large right-sided pleural effusion requiring chest tube placement (E, asterisk; F, arrow). Chest tube drainage was positive for beta-2-transferrin. The patient subsequently underwent re-exploration and durotomy repair with a favorable long-term outcome.

into the subdural space or infection/inflammation (97). Several authors have also reported nerve root incarceration/strangulation and even spinal cord herniation through a dural defect, leading to pain and neurological deficits (13-16).

Intracranial hypotension is another consequence of persistent CSF leakage, and may lead not only to postural headaches, but also intracranial hemorrhage, cerebellar herniation and cranial nerve deficits (7-12,14,98). Intracranial hemorrhage is thought to occur in the setting of CSF leakage due to CSF hypovolemia and resultant caudally oriented mechanical forces exerted on the brain when in an upright posture, which presumably leads to occlusion or tearing of bridging veins and subsequent venous infarct/hemorrhage (8,10). Cerebellar hemorrhage has been reported to occur with an incidence of 0.8% after all lumbar spine surgeries (i.e., whether complicated by durotomy or not) (12), and poorly controlled CSF diversion through lumbar drains and unmonitoring subfascial drain output in the setting of a durotomy may exacerbate the risk (7).

Tumor seeding is a complication of post-operative CSF leakage unique to patients undergoing resection of malignant spinal tumors (4,45). Tumor seeding is known to occur with CSF diversionary procedures (99), and remote tumor spread via CSF pathways is a known phenomenon in malignant brain tumors and intradural spine tumors (100,101). Such an event has been only rarely reported after extradural spine tumor resection in the setting of an unintended durotomy (46). Currently, the incidence of intradural tumor seeding as a consequence of CSF leak after spine tumor surgery remains unclear.

Finally, there is evidence from several series that CSF leaks may impair bony fusion in spine surgeries for which arthrodesis is a goal, either through the displacement of bone graft or impairment of the cellular signaling cascades necessary for bony growth and fusion (102). Other studies have failed to corroborate this finding, however (19).

Direct repair materials and techniques

Primary repair of durotomies intraoperatively—when feasible—is recommended to prevent post-operative CSF leaks, yet direct durotomy repairs have been reported to fail in 5–9% of cases (103,104). A variety of dural repair materials and techniques may be used depending on surgeon preference, durotomy location and the morphology of the durotomy (e.g., linear tear *vs.* large defect). Repair of linear, accessible durotomies, including those intentionally created for resection of intradural tumors, is typically undertaken with suture. The comparative effectiveness of various suture materials and techniques in durotomy repair is a somewhat controversial issue, with several studies reporting that an interrupted closure is most effective (105,106), other studies showing similar outcomes with interrupted and running techniques (107,108), and still others reporting that interrupted repairs leak at lower pressures than running-locking repairs (109). While some studies have found that less CSF leakage is seen with prolene suture than silk/nurolon/surgilon (107), others have reported that Gore-Tex suture provides the more watertight closure, owing to the absence of a disparity between the diameters of the suture needle and thread (108). Several authors have reported that in suture with a large needle-to-thread diameter ratio (e.g., prolene, nurolon), CSF leakage is often seen through the suture holes themselves despite an otherwise adequate closure, with nurolon/surgilon leaving a greater dural defect than prolene at the site of the suture hole (107). The needle-to-thread diameter ratio for Gore-Tex suture is close to 1, which is thought to lead to a smaller defect at the suture hole site and less CSF leakage through suture holes (108).

Primary closure of durotomies may be made difficult by durotomy location (e.g., ventral or far-lateral durotomies), presence of a large dural defect, poor tensile strength of the dura, and minimally invasive techniques which limit exposure and access. In cases of far-lateral or ventral durotomies, some authors have advocated the creation of an additional dorsal durotomy, through which the far-lateral defect can be more easily visualized and plugged with autograft (e.g., fat, muscle, fascia) or sutured (14,110). Others have recommended the use of autograft or blood-soaked gelfoam supplemented with a dural sealant in cases of durotomies that cannot be repaired primarily due to limited visibility or access (67,72,103,111,112). Some authors have also reported that titanium clips (68,113), or even aneurysm clips (114), may increase the ease of watertight durotomy closure in cases of minimally invasive or otherwise limited access.

A variety of dural patch graft materials—including autograft, allograft, and both suturable and non-suturable grafts—have been utilized for repair of large dural defects or cases in which the dura cannot be primarily approximated without undue tension on the dural edges or excessive stenosis of the thecal sac. Little consensus or objective evidence exists of one material's superiority over another, especially with regard to the repair of spinal dural defects (115). A variety of concerns have been raised regarding the use of non-autologous grafts (e.g., allografts, xenografts, synthetic grafts), including graft dissolution, encapsulation, foreign-body or inflammatory reactions, infection, hemorrhage, and excessive scarring and adhesion formation (115-121), while the use of autologous grafts may require an additional incision and additional operative time for harvest and may be of variable suitability and effectiveness in preventing post-operative CSF leaks (122). Although available studies seem to indicate that the risk of wound infection, post-operative CSF leak, and other complications are greater with the use of non-autologous dural substitutes, further study is needed (117,123,124).

Tissue sealants are also frequently used to augment dural repair and decrease dead space within a wound. Animal studies have demonstrated that dural sealants lead to improvements in hydrostatic strength of a primary dural repair (109), but a benefit has not been consistently evidenced in human clinical studies (125-129). A multitude of sealants have been utilized for augmentation of spinal durotomy repair with variable success (25,107), and little evidence exists to recommend one sealant over another. Some authors have reported improved CSF leak indices in patients in whom a primarily repaired durotomy is augmented with polyethylene glycol (PEG) hydrogel sealants as opposed to fibrin glue sealants (130), although certain PEG hydrogel formulations have a documented capacity to expand and cause neural compression (107,131,132).

Wound closure

A meticulous wound closure is an important part of any surgical procedure, but in patients with durotomies, in particular, wound closure may have a considerable effect on the clinical outcome. As mentioned previously, several authors have demonstrated a decreased risk of postoperative CSF leak requiring intervention in patients undergoing minimally invasive resections of intradural spine tumors, a finding perhaps attributable to the differential dead space resulting from open *vs.* minimally invasive approaches (65,68,70,82-84).

The Hagen-Poiseuille law asserts that the laminar flow of an incompressible, Newtonian fluid with a constant viscosity between two given points is proportional to differential pressures between these two points and the amount of resistance to flow between the points (133). Although the flow of CSF from the subarachnoid space into the extradural space is likely to be turbulent and not entirely laminar, the principles of the law may still provide insight into the pathophysiology of postoperative CSF leaks and the relative success of our interventions to prevent or treat these leaks (103). Reduction of flow through an open dural defect could theoretically be slowed by reduction of intracranial/intrathecal pressure (e.g., treatment of intracranial hypertension or placement of subarachnoid drains), increasing epidural pressure (e.g., by elimination of dead space), or increasing resistance to flow through the defect (e.g., by way of suture, sealants). The goals of wound closure should thus be to eliminate dead space and to create resistance to flow.

The preferred method for elimination of dead space is through meticulous closure of surgical layers. Muscle is the predominant material present in the subfascial space, and thus muscle layers should be approximated, or overlapped through fascial undermining techniques, if feasible. The deep thoracodorsal fascia possesses the greatest tensile strength of all layers closed after spine surgery, and thus provides the greatest resistance to CSF flow. The deep thoracodorsal fascia should be approximately tightly, with closely-spaced, heavy suture (103,134). The skin is not a particularly effective barrier to CSF, and is also highly vascular. Although some have reported success with oversewing a wound after a durocutaneous CSF fistulae develops, the tension that must be placed on the skin in order to prevent CSF flow places the skin edges at risk of ischemia. Others have also reported success with the use of skin sealants (e.g., Dermabond) to arrest a durocutaneous CSF fistulae (135), but in the authors' experience and that of others (13), this is typically insufficient.

Post-operative positioning

Another controversial matter is that of patient positioning after a durotomy. Conventional wisdom suggests that patient positioning (e.g., flat for lumbar durotomies, upright for cervical durotomies) after a spine surgery complicated by durotomy will decrease the CSF pressure at the site of the durotomy (Bernoulli's law) (136), thus decreasing the flow of CSF through the dural defect (Poiseuille's law) (133), but the available evidence is conflicting. A number of authors have reported successful prevention of post-operative CSF leaks requiring intervention after lumbar durotomy when a patient is positioned flat until symptoms (e.g., postural headache) resolve (1–3 days) (25,137-139), but several series have documented similar outcomes with a shortened—or altogether abandoned—period of bedrest (140-143). Given that multiple complications have been reported to result from the aforementioned period of bedrest, including pulmonary, urinary, and cardiac complications, as well as deep venous thrombosis (143), it would seem beneficial for patients to be allowed to mobilize early after a durotomy, but further study regarding the effect on outcomes is needed.

Cerebrospinal fluid diversion

CSF diversion may be employed as a primary (e.g., after a durotomy, in order to prevent post-operative CSF leak) or

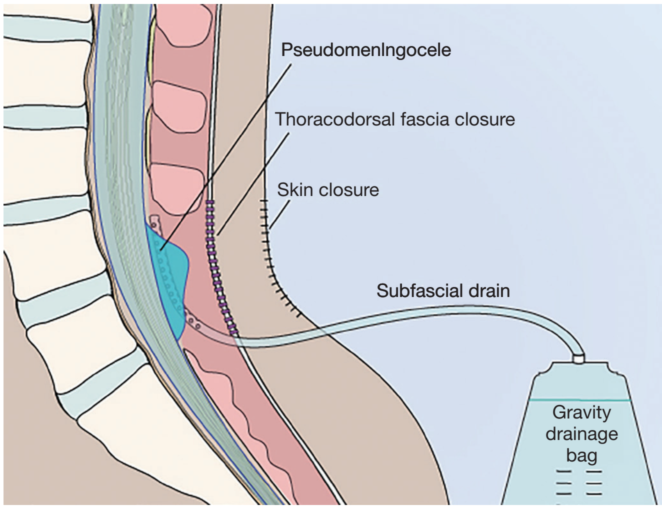

Figure 2 An illustration depicting the use of subfascial drainage in the prevention of post-operative CSF leaks. The subfascial drain is connected to a Becker bag or other form of gravity drainage, and the output is closely monitored and the bag height titrated to avoid overdrainage. Prolonged subfascial diversion of spinal fluid provides time for the thoracodorsal fascia and skin to heal. After drain removal, epidural and subarachnoid pressure are said to equalize, arresting flow through the dural defect and allowing the dural defect to heal secondarily. CSF, cerebrospinal fluid.

secondary (after a post-operative CSF leak has developed) intervention for the prevention and treatment of CSF leaks after spine surgery. As discussed previously, Poiseuille's law dictates that reduction of CSF flow through an open dural defect can be slowed by reduction of intracranial/intrathecal pressure by way of lumbar or intraventricular CSF diversion. In patients with underlying intracranial hypertension, prolonged CSF diversion may be indicated in the form of a ventriculoperitoneal or lumboperitoneal shunt. In many cases, however, temporary drainage (e.g., 5–7 days) via a lumbar subarachnoid catheter is sufficient to allow a dural defect to heal (reported success rate: 85–94%) (103,144,145). The number of days and volume of lumbar drainage required for healing of the dural defect, however, is not well defined. It has been suggested that a drainage volume of 120–360 mL/day for 3–5 days confers a 90–92% success rate in the treatment of a CSF fistula (146), but little high-level evidence exists. Complications associated with lumbar drainage—both minor (e.g., headache, nerve root irritation) and major (e.g., meningitis, intracranial hemorrhage, cranial nerve palsy, retained catheter fragments, spinal hemorrhage) have been reported to occur in up to 44% of cases (103,147-151).

Some authors have reported favorable outcomes with prolonged subfascial/epidural drainage or chest tube drainage (in cases of ventral durotomies after anterior approaches to the thoracic spine) in lieu of a subarachnoid drain (103,152-155). While this would theoretically encourage continued CSF flow through a dural defect, temporary subfascial CSF diversion would allow the fascia time to heal, and after drain removal, the subfascial pressure and intrathecal pressure are said to equalize, leading to indirect slowing of CSF leakage and eventual secondary healing of the dural defect (*Figure 2*) (152-154). These subfascial drains are typically used without suction (to allow the subarachnoid pressure to dictate the amount of drainage) with the collection bag maintained at the level of the dural defect (to avoid overdrainage by siphoning), although some authors have reported that the use of half-suction or even full suction is relatively safe (153). Several series have suggested the optimal length of subfascial drainage for the prevention of post-operative CSF leak is 7–17 days (152,154).

Epidural blood patch

A number of authors have reported good results with epidural blood patches as a treatment for symptomatic pseudomeningocele after spine surgery (7,93,137,138,156). Similar to the mechanism of action reported for dural sealants, epidural blood patches are said to provide coverage of the dural defect while also filling epidural dead space and increasing epidural pressure, thus providing resistance to continued CSF egress. Some suggest placement of an epidural blood patch adjacent to a recent surgical site to avoid overly deep or superficial injection (93), but ultrasound guidance has also been reported to assist with accurate placement of an epidural blood patch in the setting of post-surgical anatomical changes (156).

Conclusions

Post-operative CSF leak is a known complication of spine surgery. Patients undergoing resection of spine tumors may be particularly susceptible due to number of patient and pathology-related factors. Intraoperative identification of inadvertent durotomies and meticulous primary repair is preferred, but in cases of failed primary repair or unidentified durotomies, early post-operative recognition and secondary intervention may protect patients from CSF-leak-related complications, obviate the need for revision surgery and lead to improved patient outcomes.

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Footnote

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