(Review of intraoperative durotomy, management strategies, and current advances in treatment)

Review of Intraoperative Durotomies in Spinal Surgery and its management strategies with Current Advances in Treatment

Abstract

Intraoperative durotomies (in spinal surgeries) can have potentially serious consequences if not appropriately addressed. They result from an opening in the dural-arachnoid membrane around the spinal cord, cauda equina or nerve root sleeve. Most causes are iatrogenic, and if not properly addressed or go unnoticed, patients may present with complications such as postural headache, wound breakdown, meningitis, and even death. Magnetic resonance imaging is the diagnostic study of choice, with treatment options ranging from observation, bed rest, and/or epidural blood patch to lumbar subarachnoid drainage, and surgical repair.

Key Words: intraoperative durotomy, management, treatment

Abbreviations: cerebrospinal fluid leak (CSF), magnetic resonance imaging (MRI), computed tomography (CT), valsalva maneuver (VM), polyethylene glycol (PEG), epidural blood patch (EBP)

INTRODUCTION

Intraoperative durotomies, whether incidental or intentional, can result in potentially significant complications. Recent advancements in technology and research have given spine surgeons numerous options for both intraoperative dural repair and managing postoperative cerebrospinal fluid (CSF) leaks. Intraoperative durotomies are normally considered on a spectrum, ranging from spinal pseudomeningocele to CSF fistula with CSF leak (which will be referred to as CSF leak in this paper-can). Most investigators agree a pseudomeningocele is an extravasated collection of extradural CSF. It can be contained within a fibrous capsule with or without an arachnoid-lined membrane (Reference?). If the extradural fluid communicates with another cavity, such as the pleura, or if a direct communication to the outside exists, this is when it is considered a CSF fistula. The underlying principle of a dural opening needing to be present is believed to be the foundational reason for the existence of this condition (Sentence correction). By far, the most common cause is iatrogenic, resulting from a dural tear during spinal surgery. Intraoperative treatment of intentional and incidental durotomies through a variety of synthetic or autologous materials as well as postoperative CSF leak management strategies including conservative measures, epidural blood patches, CSF diversion therapies, and definitive surgical repair will be discussed in the present review.

Epidemiology

Iatrogenic intraoperative durotomy can be encountered incidentally or intentionally.For example, when accessing intradural tumors, the dura is intentionally opened, in a planned manner and primary repair via suturing is typically intended. If not properly addressed, this can increase the risk of postoperative CSF leaks. Incidental durotomies are more challenging to treat since they result in more complicated tears. Intraoperative incidental durotomies are common, especially during lumbar laminectomy[1–4]. Rates of incidental durotomy in lumbar descectomy have been reported in the literature to occur from 0.5% (in lumbar discectomy) to 35% in a single retrospective study[5,6]. Understandably, durotomy rates vary with the surgical technique employed, for example, open versus a minimally invasive surgical approach. In one meta-analysis it was found that a durotomy rate ranged from 2%-20% in open surgical technique for lumbar degenerative conditions, and approximately ~7% in minimallyinvasive techniques[7]. The incidence of intraoperative incidental durotomy in cervical spine surgery is considerably lower compared to thoracic or lumbosacral surgeries[8,9]. Presumably, this is due to the fact that surgeons are more likely to manipulate the dura around the cauda equina,and that there are probably a higher number of laminectomies performed in the lumbar region[10,11].The incidence of CSF leak in elective anterior cervical spine surgery ranges from 0.3%-21.4%[12,13]. This is appreciated to be higher with patients suffering from ossified posterior longitudinal ligament (4.5%-32%)[14–16]. Cervical laminectomy and corpectomy have also been associated with the development of postoperative pseudomeningocele[17–19]. In one study of 286 patients with ossification of the ligamentum flavum, one-third were reported to have durotomies, but the literature on this is sparse[9,13]. It is more likely that the real incidence is unknown as many cases are self-limited and asymptomatic[2].

Pathophysiology

Iatrogenic intraoperative durotomy may or may not be associated with an arachnoid tear, but a dural tear is necessary to have a durotomy. If the arachnoid is not violated, the herniation of CSF and arachnoid membrane tends to resemble a sac with some arguing that this condition should be a “true meningocele”[20]. If the CSF extravasates through a dural-arachnoid tear into the surrounding soft tissue, eventually leading to afibrous capsule, it is termed a pseudomeningocele[21,22].In both conditions there is no communication with another cavity or the outside world.

The debate also exists when it comes to factors contributing to persistent communication. Items that have been evaluated are the amount of CSF leak and/or whether the arachnoid layer is violated or intact but with herniation. In order to discuss the aforementioned fact, it is important to further delineate the continuum with another term known as the pseudocyst. If the arachnoid mater is intact then this is coined the pseudocyst and results in accumulation of CSF via a ball-valve mechanism[10,23]. Arachnoid mater violations where CSF can directly flow into the extradural tissue forms the false cyst or pseudomeningocele. CSF extravasations, if small, are believed to be self-limited as reabsorption is more likely[24].This is why the true incidence of intraoperative durotomy is unknown since many cases are likely asymptomatic[2].With a pseudomeningocele this is less likely, as in some cases, the extravasated CSF causes reactive changes in the postoperative bed of the paraspinal musculature, leading to non-resorption of the fluid[18,25,26]. The vast majority of intraoperative durotomies that lead to pseudomeningocele occur in the lumbar spine because this part of the spine is under higher pressure compared to cervical or thoracic areas[27].

Clinical manifestations

Intraoperative durotomy may present in a variety of ways. As previously stated, in the case of a small unnoticed durotomy, most are asymptomatic and self-limited[2,24]. When symptoms do occur they can include, pseudomeningocele, leaking from wound, dizziness, nausea, postural headaches, vertigo, neck pain, diplopia, photophobia, tinnitus, and blurred vision[28]. Other more serious complications, especially when CSF communicates with the outside world, include wound breakdown, meningitis, hydrocephalus, arachnoiditis, and most grave, *death*[29].

The time interval for symptom onset ranges from immediate post-operatively to years after surgery[21]. Pseudomeningoceles typically appear as a fluctuant mass that can enlarge with Valsalva causing maneuvers[30]. Sometimes pain can be elicited from palpation of the pseudomeningocele[31]. An actual CSF leak can be identified by clear, colorless fluid from an opening in the wound[32].A cloudier, red or xanthochromic appearance can occur suggesting an infection, presence of blood, or seroma which can complicate idenitification[32].At times, patients may report the return of their preoperative symptoms which can range from radiculopathy to myelopathy or spinal cord injury believed to be caused by the herniation of nerve tissue[3,17–19,31,33–39]. Patients may also present with intracranial hypotension symptoms including photophobia, cranial nerve palsies, and tinnitus[40,41].

DIAGNOSTICS

Diagnosis is confirmed via magnetic resonance imaging (MRI) with history and physical examination narrowing down one's differential.

MRI

Imaging the spine is the initial step, with the signal following that of CSF on all sequences. A region of hypointensity on T1-weighted images and hyperintensity on T2-weighted images is seen[37,42]. MRI is particularly helpful as it can delineate the location of the issue, sometimes showing the level of communication with the dura and can characterize any internal components of the sac. If the cranium is incidentally imaged, findings of intracranial hypotension can be seen which include a subdural fluid collection, intracranial meningeal enhancement, and caudal displacement of cerebellar tonsils[5] further narrowing down ones differential.

Computed tomography (CT) and CT myelogram

CT scanning can help better delineate bone than MRI, allowing for improved visualization of a pseudomeningocele/cyst or fistula/leak relative to a surgical site. The introduction of a myelogram, which involves performing a CT scan of the spine after intradural administration of contrast, can identify the presence of a pseudomeningocele or pseudocyst by showing it filling with the administered contrast orbt? demonstrating active extravasation at the dural defect[43].

Beta 2-Transferrin

If a fistula/leak is present and direct visualization of clear fluid is noted from a defect in the wound, analysis can be done by looking for Beta 2-Transferrin within a sample of the leaking fluid. Beta 2-Trasnferrin is a protein found only in CSF[44(pp2-)]. Less than 1 mL is needed to test for Beta 2-Trasferrin. Via electrophoresis, one can appreciate 2 bands where one is for Beta 1-Transferrin and the other for the Beta 2-Transferrin isoform which arises from Beta 1-Transferrin. This is relative to serum or another body fluid which would only have a Beta 1-Transferrin band.

Caution must be taken with results interpretation as false positives can occur. In certain patients with specific genetic variations[45] and/or certain medical conditions like alcoholism, cirrhosis, rectal cancer, or rare glycoprotein metabolism disorders[45]. Non-CSF fluid can be mistaken for CSF. To combat this, false interpretation can be avoided by simultaneously testing other body fluids obtained in the same patient for Beta 2-Trasnferrin to ensure they are different in comparison. Careful attention to clinical history and comparison patterns of CSF with other body fluids will aid in making an accurate interpretation in unusual cases.

INTRAOPERATIVE MANAGEMENT

When a dural violation is appreciated, the first and foremost effort should be primary closure to prevent future complications. The goal, though debatable, is to achieve a "watertight" closure of the dura[46]. This is often difficult, especially for incidental intraoperative durotomies due to the unique biomechanical properties of dura mater which can be fragile or if the tear occurred at an inaccessible location. It is, for this reason that the ultimate goal should be to contain neural elements and prevent pseudomeningoceles/cyst or CSF fistulas/leak.

If a tear is easily accessible, primary repair is generally recommended. If it is not accessible, then observation, sealants, or CSF diversion maneuvers are used[47,48]. Since several items exist to bring dura together, ranging from sutures to synthetic patches/grafts, it is helpful to organize primary repair strategies into 3 categories: sutures, sealants, and patches/grafts[5,49–53]. Currently, no official consensus exists between which is the most ideal.

Sutures

Spine surgeons almost universally rely on non-absorbable sutures. The 4 main suture materials include: Nurolon, Prolene, Gore-Text, and Silk.

Nurolon is braided and comprised of long-chain aliphatic polymer of Nylon 6 or 6.6. It has been reported to elicit minimal acute inflammation, maintaining 81% tensile strength at 1 year and decreasing to 66% at 11 years[54].

Prolene is a monofilament comprised of an isotactic crystalline stereoisomer of polypropylene, a synthetic linear polyolefin. It does not adhere to tissues and does not cause an inflammatory reaction. Tensile strength is reportedlymaintained for up to 2 years[55].

Gore-Tex is a microporous monofilament made of expanded polytetrafluoroethylene (cPTFE). It has a beneficial structure that allows it to have a needle attached that is the diameter of the thread, thus reducing CSF leak at suture sites[56,57].

Lastly, silk was routinely used in earlier neurosurgical literature but has been mentioned less in the past several decades. It is technically non-absorbable but becomes proteolyzed with time and can be undetectable at a 2-year mark[58].

The literature around suturing techniques is sparse though some do exist. The conclusions are mixed and make it challenging for one to make a definitive statement about what technique is best. One article found that in a small linear incision, simple interrupted silk suturing was superior to running, running locked, or interrupted vertical mattress techniques[59]. To that end another paper studied Prolene and compared simple running to interrupted and found no change in difference between CSF leak[60].

A similar statement can be made about suture type when it comes to selecting one of the 4 aforementioned non-absorbable sutures. Biomechanical studies with Gore-Tex found that up to a mean CSF peak pressure of 34 cm H2O can be observed prior to CSF leakage recognition with its use when compared to Nurolon which had a mean CSF peak pressure of only 21 cm H2O. This same study found also that it still remained superior when examined across suturing techniques (running, locked continuously, and interrupted)[61]. In regards to Prolene another study showed that in cadaveric specimens it too had a higher mean pressure threshold when compared to Nurolon[62]. No studies currently exist giving a direct comparison between Gore-Tex and Prolene.

Ultimately a decision around the best suture or suture technique remains a challenging one and we advocate for using the material one is most comfortable, familiar, and has had the most success with in the past as surgeon experience has been shown to impact outcomes[63].

After completing a primary closure one should test for a persistent CSF leak via aValsalva maneuver (VM) where the anesthesiologist increases the intrathoracic pressure. The VM can be performed simply by switching the ventilator to manual ventilation, fully closing the adjustable pressure-limiting valve, increasing the fresh gas flow, and squeezing the breathing circuit bag for 15-20 seconds to generate the needed VM pressure which is around 40 mmHg intrathoracic pressure[64]. Its usefulness is more convincing during intraoperative durotomy repair but one should be mindful that rare complications have been reported, ranging from stroke and retinopathy to pneumothorax[64]. Clinical judgement should prevail when deciding to perform a VM.

Grafts/Patches

If an intraoperative durotomy is not ideal for a primary closure, for example, such as a far lateral one, or when neural elements become compressed, dural grafts or patches are useful options. Numerous materials can act as dural substitutes. Ideally the goal is to restore the continuity of dura mater to minimize CSF leak by mimicking the compliance of dura while being biologically inert[65]. Currently the options fall into 4 categories, with those being: autograft, allograft (i.e. cadaveric dura), xenograft (animal-derived), and synthetic materials. Surgicel is sometimes used to augment some dural repairs as well.

In the autologous family the options during spinal surgery typically include fascia lata, fat issue and muscle.

Some commonly used xenografts or synthetic material include the following: Durasis, DuraGaurd/Matrix, Durepair, Alloderm, Preclude, and Neuro-Patch. The xenografts:DuraGen, DuraMatrix, and Derepair, are all type I Collagen matrixes made from bovine Achilles tendon.

DuraGen has been shown to have 20% more conformability than DuraMatrix while DuraMatrix has a 50 times lower liquid permeability[66,67]. DuraGen has the most published data[68]and also widely utilized foir(correction)dural repair. An interesting property of DuraGen is its secondary hemostatic capabilities: its porosity allows platelets and fibroblasts to infiltrate, forming fibrin clots and laying down natural collagen fibers, which help prevent CSF leakage and initiate dural repair[69]. DuraGen has also been show to completely resorb within 1 year[69]. It is reported to have no inflammatory response, a 1.9% infection rate, and a 2.1% leakage rate[70].

Durerepair (correction)is made up of type I and III collagen and is produced by bovine skin[71]. Biomechanical studies show it having up to 4 times more tensile strength than cranial dura mater[72].

Durasis is made from porcine small intestinal submucosa. It manages to keep the cells extracellular membrane intact as it is harvested by removing the cells between the mucosal and muscular layer. Because of this notion, it contains collagen, bioactive proteins, and cytokines that guide host-tissue remodeling[73]. In 2007 it was demonstrated to have comparable rates of infection, CSF leak, and meningitis with that of other comparable dural substitutes of that time (Reference?).

DuraGuard is made from bovine pericardium that is cross-linked with glutaraldehyde. It has been reported to have superior tear resistance and tensile strength making suturing to it more feasible.

Alloderm is made from human donor skin which contains no cellular tissue but retains its biochemical and structural components[74]. It has been shown to become vascularized and integrated with native dura[74].One study showed a reoperation rate for CSF leak in Chiari decompression surgery of 2.2% when compared to DuraGaurd, DuraGen, and Durepair which had a 17.1% rate(Reference?).

Lastly, Preclude is made of inert polytetrafluoroethylene and elastomeric fluoropolymer in a 3-layer construct[75] and Neuro-Patch is made of microporous fleece from polyester urethane that also supports fibroblastic proliferation[76]. Interestingly in a study looking at postoperative adhesions and fibrosis-induced spinal cord tethering between Surgicel, Durasis, DuraGen, and Preclude, it was appreciated that DuraGen caused the least amount of local inflammation in the subarachnoid and Preclude generated the most[69].

Sealants

If a VM maneuver reveals a persistent CSF leak after a primary closure and after a graft/patch is attempted, a sealant can be placed over the area of the leak. Despite animal studies suggesting sealant alone can withstand high hydrostatic pressures[14,77,78], some remain in situ for only up to10-14 days[79], thus it must be supplemental to a patch or graft.

Two types of sealants are commercially available which fall into the category of either absorbable: synthetic consisting of polyethylene glycol (PEG)-based polymers or fibrin-based (from allogenic or autogenic fibrinogen in combination with thrombin and other hemostatic factors) categories. Both can be found in liquid or patch form.

Subtypes of fibrin-based sealants and liquid glue formulations include Tisseel or Tissucol, Evicel, and dry patch products, called Tachosil and Tachocomb. Literature around fibrin-based sealants has been mixed (References?). Their ability to augment sutures or aid in achieving "watertight" dural closure was found not to significantly decrease CSF leak when compared to sutures alone[80]. Although this was a retrospective study with inherent limitations, it is relevant as no randomized controlled trials exist looking at intraoperative durotomies during spinal surgery and the use of fibrin-based sealants. An interesting fact about the make of these agents is that they are technically useful as hemostatic agents as well.

Tisseel has 2 components: human fibrinogen and aprotinin, and human thrombin and calcium chloride dihydrate[81]. When mixed via the application tip during use, a fibrin clot is formed that adheres and provides hemostasis to tissues. Evicel is made from human plasma and also has 2 components: Biological Active Component 2 (largely cryoprecipitate) and thrombin.

Subtypes of synthetic PEG-based sealants include: DuraSeal Exact and Adherus. Both work in the form of hydrogels to minimize mass on the spine. DuraSeal, the predecessor to DuraSeal Exact, was reported to swell once applied[82,83]. In regards to efficacy, a randomized controlled trial looking at incidental and intentional spinal durotomies showed no significant difference in CSF leakage or superficial skin infection rates between the standard of care and DuralSeal Exact (reference?). FDA-approved secondary agent for dural closure in the spine is currently only applicable for DuralSeal Exact[84]. Regardless of the use of dural sealant, effective primary closure of the defect is critical to prevent further CSF extravasation.

If after use of these items proves there to be a residual CSF leak, some authors describe keeping a subfascial drain that would normally be placed intraoperatively for a longer period of time but keeping it "off suction" for several more days until drainage slowed[85].

POSTOPERATIVE PSEUDOCYST/PSEUDOMENINGOCELE/ CSF FISTULA/LEAK TREATMENT

Conservative Therapy

If an intraoperative spinal durotomy could not be closed "watertight" or went unnoticed and the patient exhibited any of the before-mentioned symptoms, preventing pseudomeningocele formation/controlling CSF leak relies on manipulating differences in subarachnoid and epidural pressure to impede flow[86]. The literature is mixed on bed rest/Trendelenburg positioning if primary closure was attempted for a lumbar durotomy. Bed rest is traditionally prescribed as a standard approach for the management of dural tears[87]. The rationale behind this approach is that the orthostatic position increases the hydrostatic pressure of the CSF and consequently may worsen the leakage[88]. Multiple survey-based studies conducted over the last decade indeed confirm this preference in the spine surgery community, with up to 89% of surgeons in favor of prolonged bed rest in this patient population[89–92]. The data supporting this approach, however, is composed of case series describing patients successfully treated with prolonged bed rest, without a control group of alternative options[93].A recent meta-analysis from 2023 found in patients with incidental durotomies during spine surgery, who underwent primary closure, early mobilization may reduce pulmonary complications compared to prolonged bed rest, without a significant difference between groups in the incidence of CSF leak or the need for additional surgical durotomy repair(reference?). Although prolonged bed rest is traditionally prescribed following a dural tear, it is not without risks. Surgeons should use this strategy with caution, given the risk of the aforementioned postoperative complications[94]. This result was also confirmed by the one randomized control trial to date that looked at this question in lumbar surgical patients who had primarily repaired intraoperative durotomies and was included in the meta-analysis[95]

If a primary closure was not performed because the durotomy was unnoticed, and the patient is exhibiting symptoms, it is reasonable to try Trendelenburg positioning/bedrest for a short course of 1 to 3 days in someone with a suspected lumbar durotomy. Direct pressure at the site of durotomy with a pressure dressing or brace may counteract egress through the area of least resistance as well[52]. Interestingly in the cervical spine, Kim et al published a report where a polycarbonate face mask was able to apply pressure on the cervical wound and resolved a refractory pesudomeningocele[52]. If the durotomy occurred inthe cervical or thoracic spine, primary closure was not attempted, and the patient is symptomatic, elevation of the head of the bed is reasonable for 1 to 3 days.

Inhibiting CSF formation with acetazolamide has been described in a randomized control trial to stop CSF leak in cranial patients[96] but the literature is limited regarding its use in spinal patients.

Non-conservative therapy

If a CSF leak persists, the patient has a pseudomeningocele/cyst with subjective symptoms, non-conservative therapies should be discussed which include epidural blood patch, CSF diversion measures, and re-operation for residual or previously unnoticed intraoperative durotomy identification and primary closure attempt/reattempt.

Epidural blood patch

Epidural blood patch (EBP) is a procedure in which the patient's blood is injected into the epidural space. It is thought that the blood forms a clot over the dural tear, allowing the heading of the dura, as well as raising extradural pressure relative to the subarachnoid pressure in turn decreasing the efflux CSF gradient[97]. Limited cases are described stating the efficacy of EBP in resolving pseudoemingoceles[98]. Skepticism, however, exists among spine surgeons as no robust large studies have been done[97,99,100].

CSF diversion

There is a paucity of literature describing CSF diversion therapy via a subarachnoid drain, normally placed in the lumbar region, after intraoperative spinal durotomy, but the benefit and timing are not as clear. In the cases of a large pseudomeningocele, it has been shown that they are best treated by a combination of primary closure and implantation of a subarachnoid drain[10]. If placed, it has shown efficacy at an output rate of 5-10 mL/hr for 3-5 days as a primary tool or supplement to other measures[101]. Lumbar subarachnoid drainage has been reported to have a complication rate of up to 44% with symptoms ranging from headache and nerve root pain to subdural hematoma, pneumocephalus, and meningitis[102]. These are important to consider when choosing to use a lumbar subarachnoid drain.

Lastly, there have been reports of a lumbo-peritoneal shunt being used to successfully treat a pseudomeningocele and CSF fistula/leak[103–106]. However, this should only be a consideration after an attempt at a primary closure has failed.

CONCLUSION

There are many options for the repair of intraoperative durotomies that can be utilized. Iatrogenic causes are common, and the goal when identified is to achieve "watertight" closure of dura with sutures whenever possible. Dural sealants and patches/grafts may be used as adjuncts. MRI is the neurodiagnostic modality of choice for diagnosis. If a durotomy goes unnoticed or a "watertight" closure cannot be achieved, and the patient becomes symptomatic, several conservative therapies are available. These include bed rest and head-of-bed elevation (depending on whether the durotomy is in the cervicothoracic or lumbar region), pressure dressing, epidural blood patch, and lumbar subarachnoid drain placement. If these measures fail, re-operation to obtain a primary closure should be attempted/reattempted. In rare cases, the placement of a ventriculo-peritoneal or lumbo-peritoneal shunt may be considered.

REFERENCES

1. Jones AA, Stambough JL, Balderston RA, Rothman RH, Booth RE. Long-term results of lumbar spine surgery complicated by unintended incidental durotomy. *Spine (Phila Pa 1976)*. 1989;14(4):443-446. doi:10.1097/00007632-198904000-00021
2. Lee KS, Hardy IM. Postlaminectomy lumbar pseudomeningocele: report of four cases. *Neurosurgery*. 1992;30(1):111-114. doi:10.1227/00006123-199201000-00020
3. O'Connor D, Maskery N, Griffiths WE. Pseudomeningocele nerve root entrapment after lumbar discectomy. *Spine (Phila Pa 1976)*. 1998;23(13):1501-1502. doi:10.1097/00007632-199807010-00014
4. Oppel F, Schramm J, Schirmer M, Zeitner M. Results and Complicated Course after Surgery for Lumbar Disc Herniation. In: Wüllenweber R, Brock M, Hamer J, Klinger M, Spoerri O, eds. *Lumbar Disc Adult Hydrocephalus*. Vol 4. Advances in Neurosurgery. Springer Berlin Heidelberg;

1977:36-51. doi:10.1007/978-3-642-66578-3_9
5. Mayfield FH, Kurokawa K. Watertight closure of spinal dura mater. Technical note. *J Neurosurg*. 1975;43(5):639-640. doi:10.3171/jns.1975.43.5.0639
6. Rodriguez-Olaverri JC, Zimick NC, Merola A, et al. Comparing the clinical and radiological outcomes of pedicular transvertebral screw fixation of the lumbosacral spine in spondylolisthesis versus unilateral transforaminal lumbar interbody fusion (TLIF) with posterior fixation using anterior cages. *Spine (Phila Pa 1976)*. 2008;33(18):1977-1981. doi:10.1097/BRS.0b013e31817ecc01
7. Ghobrial GM, Theofanis T, Darden BV, Arnold P, Fehlings MG, Harrop JS. Unintended durotomy in lumbar degenerative spinal surgery: a 10-year systematic review of the literature. *Neurosurg Focus*. 2015;39(4):E8. doi:10.3171/2015.7.FOCUS15266
8. McMahon P, Dididze M, Levi AD. Incidental durotomy after spinal surgery: a prospective study in an academic institution. *J Neurosurg Spine*. 2012;17(1):30-36. doi:10.3171/2012.3.SPINE11939
9. Williams BJ, Sansur CA, Smith JS, et al. Incidence of unintended durotomy in spine surgery based on 108,478 cases. *Neurosurgery*. 2011;68(1):117-123; discussion 123-124. doi:10.1227/NEU.0b013e3181fcf14e
10. Weng YJ, Cheng CC, Li YY, Huang TJ, Hsu RWW. Management of giant pseudomeningoceles after spinal surgery. *BMC Musculoskelet Disord*. 2010;11:53. doi:10.1186/1471-2474-11-53
11. Hawk MW, Kim KD. Review of spinal pseudomeningoceles and cerebrospinal fluid fistulas. *Neurosurg Focus*. 2000;9(1):e5. doi:10.3171/foc.2000.9.1.5
12. Cammisa FP, Girardi FP, Sangani PK, Parvataneni HK, Cadag S, Sandhu HS. Incidental Durotomy in Spine Surgery: *Spine*. 2000;25(20):2663-2667. doi:10.1097/00007632-200010150-00019
13. Tani T, Ushida T, Ishida K, Iai H, Noguchi T, Yamamoto H. Relative safety of anterior microsurgical decompression versus laminoplasty for cervical myelopathy with a massive ossified posterior longitudinal ligament. *Spine (Phila Pa 1976)*. 2002;27(22):2491-2498. doi:10.1097/00007632-200211150-00013
14. Epstein NE, Hollingsworth R. Anterior cervical micro-dural repair of cerebrospinal fluid fistula after surgery for ossification of the posterior longitudinal ligament. Technical note. *Surg Neurol*. 1999;52(5):511-514. doi:10.1016/s0090-3019(99)00135-4
15. Macdonald RL, Fehlings MG, Tator CH, et al. Multilevel anterior cervical corpectomy and fibular allograft fusion for cervical myelopathy. *J Neurosurg*. 1997;86(6):990-997. doi:10.3171/jns.1997.86.6.0990
16. Smith MD, Bolesta MJ, Leventhal M, Bohlman HH. Postoperative cerebrospinal-fluid fistula associated with erosion of the dura. Findings after anterior resection of ossification of the posterior longitudinal ligament in the cervical spine. *J Bone Joint Surg Am*. 1992;74(2):270-277.
17. Cobb C, Ehni G. Herniation of the spinal cord into an iatrogenic meningocele. Case report. *J Neurosurg*. 1973;39(4):533-536. doi:10.3171/jns.1973.39.4.0533
18. Goodman SJ, Gregorius FK. Cervical pseudomeningocele after laminectomy as a cause of progressive myelopathy. *Bull Los Angeles Neurol Soc*. 1974;39(3):121-127.
19. Maiuri F, Corriero G, Giamundo A, Donati P, Gambardella A. Postoperative cervical pseudomeningocele. *Neurochirurgia (Stuttg)*. 1988;31(1):29-31. doi:10.1055/s-2008-1053895
20. Rinaldi I, Peach WF. Postoperative lumbar meningocele. Report of two cases. *J Neurosurg*. 1969;30(4):504-507. doi:10.3171/jns.1969.30.4.0504
21. Miller PR, Elder FW. Meningeal pseudocysts (meningocele spurius) following laminectomy. Report of ten cases. *J Bone Joint Surg Am*. 1968;50(2):268-276. doi:10.2106/00004623-196850020-00005
22. Pagni CA, Cassinari V, Bernasconi V. Meningocele spurius following hemilaminectomy in a case of lumbar discal hernia. *J Neurosurg*. 1961;18:709-710. doi:10.3171/jns.1961.18.5.0709

23. Hyndman OR, Gerber WF. Spinal extradural cysts, congenital and acquired; report of cases. *J Neurosurg*. 1946;3(6):474-486. doi:10.3171/jns.1946.3.6.0474
24. Tsuji H, Handa N, Handa O, Tajima G, Mori K. Postlaminectomy ossified extradural pseudocyst. Case report. *J Neurosurg*. 1990;73(5):785-787. doi:10.3171/jns.1990.73.5.0785
25. Bhatoe HS. Postoperative lumbar pseudomeningocele. *J Indian Med Assoc*. 1995;93(7):280, 282.
26. Pau A. Postoperative "meningocele spurius". Report of two cases. *J Neurosurg Sci*. 1974;18(2):150-152.
27. Cervical cerebral spinal fluid pressure. *The Spine Journal*. 2002;2(2):34-35. doi:10.1016/S1529-9430(01)00257-1
28. Deyo RA, Cherkin DC, Loeser JD, Bigos SJ, Ciol MA. Morbidity and mortality in association with operations on the lumbar spine. The influence of age, diagnosis, and procedure. *J Bone Joint Surg Am*. 1992;74(4):536-543.
29. Couture D, Branch CL. Spinal pseudomeningoceles and cerebrospinal fluid fistulas. *Neurosurg Focus*. 2003;15(6):E6. doi:10.3171/foc.2003.15.6.6
30. Rocca A, Turtas S, Pirisi A, Agnetti V. Iatrogenic lumbar pseudomeningocele. *Zentralbl Neurochir*. 1986;47(4):311-315.
31. Aldrete JA, Ghaly R. Postlaminectomy pseudomeningocele. An unsuspected cause of low back pain. *Reg Anesth*. 1995;20(1):75-79.
32. Huff T, Tadi P, Weisbrod LJ, Varacallo M. Neuroanatomy, Cerebrospinal Fluid. In: *StatPearls*. StatPearls Publishing; 2024. Accessed July 20, 2024. http://www.ncbi.nlm.nih.gov/books/NBK470578/
33. Burres KP, Conley FK. Progressive neurological dysfunction secondary to postoperative cervical pseudomeningocele in a C-4 quadriplegic. Case report. *J Neurosurg*. 1978;48(2):289-291. doi:10.3171/jns.1978.48.2.0289
34. Hadani M, Findler G, Knoler N, Tadmor R, Sahar A, Shacked I. Entrapped lumbar nerve root in pseudomeningocele after laminectomy: report of three cases. *Neurosurgery*. 1986;19(3):405-407. doi:10.1227/00006123-198609000-00011
35. Helle T, Conley FK. Postoperative Cervical Pseudomeningocele as a Cause of Delayed Myelopathy. *Neurosurgery*. 1981;9(3):314-316.
36. Horowitz SW, Azar-Kia B, Fine M. Postoperative cervical pseudomeningocele. *AJNR Am J Neuroradiol*. 1990;11(4):784.
37. Hosono N, Yonenobu K, Ono K. Postoperative cervical pseudomeningocele with herniation of the spinal cord. *Spine (Phila Pa 1976)*. 1995;20(19):2147-2150. doi:10.1097/00007632-199510000-00014
38. Rinaldi I, Hodges TO. Iatrogenic lumbar meningocoele: report of three cases. *J Neurol Neurosurg Psychiatry*. 1970;33(4):484-492. doi:10.1136/jnnp.33.4.484
39. Wilkinson HA. Nerve-root entrapment in "traumatic" extradural arachnoid cyst. *J Bone Joint Surg Am*. 1971;53(1):163-166.
40. Bell WE, Joynt RJ, Sahs AL. Low spinal fluid pressure syndromes. *Neurology*. 1960;10:512-521. doi:10.1212/wnl.10.5.512
41. Hochman MS, Naidich TP, Kobetz SA, Fernandez-Maitin A. Spontaneous intracranial hypotension with pachymeningeal enhancement on MRI. *Neurology*. 1992;42(8):1628-1630. doi:10.1212/wnl.42.8.1628
42. Schumacher HW, Wassmann H, Podlinski C. Pseudomeningocele of the lumbar spine. *Surg Neurol*. 1988;29(1):77-78. doi:10.1016/0090-3019(88)90127-9
43. Lauer KK, Haddox JD. Epidural blood patch as treatment for a surgical durocutaneous fistula. *J Clin Anesth*. 1992;4(1):45-47. doi:10.1016/0952-8180(92)90120-p
44. Ryall RG, Peacock MK, Simpson DA. Usefulness of beta 2-transferrin assay in the detection of cerebrospinal fluid leaks following head injury. *J Neurosurg*. 1992;77(5):737-739. doi:10.3171/jns.1992.77.5.0737
45. Sloman AJ, Kelly RH. Transferrin allelic variants may cause false positives in the detection of cerebrospinal fluid fistulae. *Clin Chem*. 1993;39(7):1444-1445.

46. Barth M, Tuettenberg J, Thomé C, Weiss C, Vajkoczy P, Schmiedek P. Watertight dural closure: is it necessary? A prospective randomized trial in patients with supratentorial craniotomies. *Neurosurgery*. 2008;63(4 Suppl 2):352-358; discussion 358. doi:10.1227/01.NEU.0000310696.52302.99
47. Hannallah D, Lee J, Khan M, Donaldson WF, Kang JD. Cerebrospinal fluid leaks following cervical spine surgery. *J Bone Joint Surg Am*. 2008;90(5):1101-1105. doi:10.2106/JBJS.F.01114
48. Kitchel SH, Eismont FJ, Green BA. Closed subarachnoid drainage for management of cerebrospinal fluid leakage after an operation on the spine. *J Bone Joint Surg Am*. 1989;71(7):984-987.
49. Eismont FJ, Wiesel SW, Rothman RH. Treatment of dural tears associated with spinal surgery. *J Bone Joint Surg Am*. 1981;63(7):1132-1136.
50. Foyt D, Johnson JP, Kirsch AJ, Bruce JN, Wazen JJ. Dural closure with laser tissue welding. *Otolaryngol Head Neck Surg*. 1996;115(6):513-518. doi:10.1016/S0194-59989670005-0
51. Levy DI, Sonntag VK. Titanium dural clip testing. Technical note. *J Neurosurg*. 1994;81(6):947-949. doi:10.3171/jns.1994.81.6.0947
52. Kerr E, Ripul P, Kim KD. Refractory Cervical Spinal Pseudomeningocele Successfully Treated with a Polycarbonate Face Mask: Technical Note. *JSM Neurosurgery and Spine*.
53. Shimada Y, Hongo M, Miyakoshi N, et al. Dural substitute with polyglycolic acid mesh and fibrin glue for dural repair: technical note and preliminary results. *J Orthop Sci*. 2006;11(5):454-458. doi:10.1007/s00776-006-1044-7
54. Dafford EE, Anderson PA. Comparison of dural repair techniques. *Spine J*. 2015;15(5):1099-1105. doi:10.1016/j.spinee.2013.06.044
55. Chu CC, Pratt L, Zhang L, Hsu A, Chu A. A comparison of a new polypropylene suture with Prolene. *J Appl Biomater*. 1993;4(2):169-181. doi:10.1002/jab.770040209
56. Miller CM, Sangiolo P, Jacobson JH. Reduced anastomotic bleeding using new sutures with a needle-suture diameter ratio of one. *Surgery*. 1987;101(2):156-160.
57. Dang MC, Thacker JG, Hwang JC, Rodeheaver GT, Melton SM, Edlich RF. Some biomechanical considerations of polytetrafluoroethylene sutures. *Arch Surg*. 1990;125(5):647-650. doi:10.1001/archsurg.1990.01410170095020
58. Gallini G, Pasqualini M. [Sutures in oral surgery]. *Attual Dent*. 1988;4(20):14-18.
59. Megyesi JF, Ranger A, MacDonald W, Del Maestro RF. Suturing technique and the integrity of dural closures: an in vitro study. *Neurosurgery*. 2004;55(4):950-954; discussion 954-955. doi:10.1227/01.neu.0000138441.07112.1b
60. Ebel F, Wanderer S, Beck J, Raabe A, Ulrich CT. The Optimal Dura Closure Technique and Material – An In-Vitro Evaluation. *J Neurol Surg A Cent Eur Neurosurg*. 2017;78(S 01):S1-S22. doi:10.1055/s-0037-1603847
61. Ghobrial GM, Maulucci CM, Viereck MJ, et al. Suture Choice in Lumbar Dural Closure Contributes to Variation in Leak Pressures: Experimental Model. *Clin Spine Surg*. 2017;30(6):272-275. doi:10.1097/BSD.0000000000000169
62. Bakhsheshian J, Strickland BA, Patel NN, et al. The use of a novel perfusion-based cadaveric simulation model with cerebrospinal fluid reconstitution comparing dural repair techniques: a pilot study. *Spine J*. 2017;17(9):1335-1341. doi:10.1016/j.spinee.2017.04.007
63. Kelz RR, Sellers MM, Niknam BA, et al. A National Comparison of Operative Outcomes of New and Experienced Surgeons. *Ann Surg*. 2021;273(2):280-288. doi:10.1097/SLA.0000000000003388
64. Kumar CM, Van Zundert AAJ. Intraoperative Valsalva maneuver: a narrative review. *Can J Anaesth*. 2018;65(5):578-585. doi:10.1007/s12630-018-1074-6
65. MacEwan MR, Kovacs T, Osbun J, Ray WZ. Comparative analysis of a fully-synthetic nanofabricated dura substitute and

bovine collagen dura substitute in a large animal model of dural repair. *Interdisciplinary Neurosurgery*. 2018;13:145-150. doi:10.1016/j.inat.2018.05.001
66. Integra. Stryker Promotional Material #9410-400-152 Rev. A. https://products.integralife.com/file/general/1453796534.pdf
67. Danish SF, Samdani A, Hanna A, Storm P, Sutton L. Experience with acellular human dura and bovine collagen matrix for duraplasty after posterior fossa decompression for Chiari malformations. *J Neurosurg*. 2006;104(1 Suppl):16-20. doi:10.3171/ped.2006.104.1.16
68. Integra. Integra Promotional Material#0179531-2.
69. Haq I, Cruz-Almeida Y, Siqueira EB, Norenberg M, Green BA, Levi AD. Postoperative fibrosis after surgical treatment of the porcine spinal cord: a comparison of dural substitutes. Invited submission from the Joint Section Meeting on Disorders of the Spine and Peripheral Nerves, March 2004. *J Neurosurg Spine*. 2005;2(1):50-54. doi:10.3171/spi.2005.2.1.0050
70. Integra. Integra Promotional Material #0069447- 3-EN. https://products.integralife.com/file/general/1518550095.pdf
71. McCall TD, Fults DW, Schmidt RH. Use of resorbable collagen dural substitutes in the presence of cranial and spinal infections-report of 3 cases. *Surg Neurol*. 2008;70(1):92-96; discussion 96-97. doi:10.1016/j.surneu.2007.04.007
72. Kizmazoglu C, Aydin HE, Kaya I, et al. Comparison of Biomechanical Properties of Dura Mater Substitutes and Cranial Human Dura Mater : An In Vitro Study. *J Korean Neurosurg Soc*. 2019;62(6):635-642. doi:10.3340/jkns.2019.0122
73. Hodde JP, Badylak SF, Brightman AO, Voytik-Harbin SL. Glycosaminoglycan content of small intestinal submucosa: a bioscaffold for tissue replacement. *Tissue Eng*. 1996;2(3):209-217. doi:10.1089/ten.1996.2.209
74. Bowers CA, Brimley C, Cole C, Gluf W, Schmidt RH. AlloDerm for duraplasty in Chiari malformation: superior outcomes. *Acta Neurochir (Wien)*. 2015;157(3):507-511. doi:10.1007/s00701-014-2263-x
75. Chappell ET, Pare L, Salehpour M, Mathews M, Middlehof C. GORE PRECLUDE MVP dura substitute applied as a nonwatertight “underlay” graft for craniotomies: product and technique evaluation. *Surg Neurol*. 2009;71(1):126-128; discussion 128-129. doi:10.1016/j.surneu.2007.08.041
76. Raul JS, Godard J, Arbez-Gindre F, Czorny A. [Use of polyester urethane (Neuro-Patch) as a dural substitute. Prospective study of 70 cases]. *Neurochirurgie*. 2003;49(2-3 Pt 1):83-89.
77. Cain JE, Rosenthal HG, Broom MJ, Jauch EC, Borek DA, Jacobs RR. Quantification of leakage pressures after durotomy repairs in the canine. *Spine (Phila Pa 1976)*. 1990;15(9):969-970. doi:10.1097/00007632-199009000-00024
78. Pomeranz S, Constantini S, Umansky F. The use of fibrin sealant in cerebrospinal fluid leakage. *Neurochirurgia (Stuttg)*. 1991;34(6):166-169. doi:10.1055/s-2008-1052082
79. Tisseel. Baxter Advanced Surgery. https://advancedsurgery.baxter.com/tisseel
80. Jankowitz BT, Atteberry DS, Gerszten PC, et al. Effect of fibrin glue on the prevention of persistent cerebral spinal fluid leakage after incidental durotomy during lumbar spinal surgery. *Eur Spine J*. 2009;18(8):1169-1174. doi:10.1007/s00586-009-0928-6
81. Baxter. HIGHLIGHTS OF PRESCRIBING INFORMATION. https://baxterpi.com/pi-pdf/Tisseel_PI.pdf
82. Mulder M, Crosier J, Dunn R. Cauda equina compression by hydrogel dural sealant after a laminotomy and discectomy: case report. *Spine (Phila Pa 1976)*. 2009;34(4):E144-148. doi:10.1097/BRS.0b013e31818d5427
83. Tseng WL, Xiao F. Duraseal thecal sac compression after lumbar discectomy causing radiculopathy. *Spine J*. 2015;15(8):1892-1893. doi:10.1016/j.spinee.2015.03.048

84. FDA. Premarket Approval (PMA). US Food & Drug Administration. https://www.accessdata.fda.gov/scripts/cdrh/
85. Sellin JN, Kolcun JPG, Levi AD. Cerebrospinal Fluid Leak and Symptomatic Pseudomeningocele After Intradural Spine Surgery. *World Neurosurg*. 2018;120:e497-e502. doi:10.1016/j.wneu.2018.08.112
86. Fang Z, Tian R, Jia YT, Xu TT, Liu Y. Treatment of cerebrospinal fluid leak after spine surgery. *Chin J Traumatol*. 2017;20(2):81-83. doi:10.1016/j.cjtee.2016.12.002
87. Hodges SD, Humphreys SC, Eck JC, Covington LA. Management of incidental durotomy without mandatory bed rest. A retrospective review of 20 cases. *Spine (Phila Pa 1976)*. 1999;24(19):2062-2064. doi:10.1097/00007632-199910010-00017
88. Khan MH, Rihn J, Steele G, et al. Postoperative management protocol for incidental dural tears during degenerative lumbar spine surgery: a review of 3,183 consecutive degenerative lumbar cases. *Spine (Phila Pa 1976)*. 2006;31(22):2609-2613. doi:10.1097/01.brs.0000241066.55849.41
89. Oitment C, Aref M, Almenawar S, Reddy K. Spinal Dural Repair: A Canadian Questionnaire. *Global Spine Journal*. 2018;8(4):359-364.
90. Clajus C, Stockhammer F, Rohde V. The intra- and postoperative management of accidental durotomy in lumbar spine surgery: results of a German survey. *Acta Neurochir (Wien)*. 2015;157(3):525-530. doi:10.1007/s00701-014-2325-0
91. Lewandrowski KU, Hellinger S, De Carvalho PST, et al. Dural Tears During Lumbar Spinal Endoscopy: Surgeon Skill, Training, Incidence, Risk Factors, and Management. *Int J Spine Surg*. 2021;15(2):280-294. doi:10.14444/8038
92. Gautschi OP, Stienen MN, Smoll NR, Corniola MV, Tessitore E, Schaller K. Incidental durotomy in lumbar spine surgery--a three-nation survey to evaluate its management. *Acta Neurochir (Wien)*. 2014;156(9):1813-1820. doi:10.1007/s00701-014-2177-7
93. Winter F, Hasslinger S, Frueh A, et al. Incidence, risk factors, and treatment of incidental durotomy during decompression in degenerative lumbar spine conditions. *J Neurosurg Sci*. 2023;67(4):507-511. doi:10.23736/S0390-5616.21.05404-7
94. Gomes FC, Larcipretti ALL, Elvir FAR, et al. Early ambulation versus prolonged bed rest for incidental durotomies in spine procedures: a systematic review and meta-analysis. *Neurosurg Rev*. 2023;46(1):310. doi:10.1007/s10143-023-02201-2
95. Farshad M, Aichmair A, Wanivenhaus F, Betz M, Spirig J, Bauer DE. No benefit of early versus late ambulation after incidental durotomy in lumbar spine surgery: a randomized controlled trial. *Eur Spine J*. 2020;29(1):141-146. doi:10.1007/s00586-019-06144-5
96. Abrishamkar S, Khalighinejad N, Moeim P. Analysing the Effect of Early Acetazolamide Administration on Patients with A High Risk of Permanent Cerebrospinal Fluid Leakage. *Acta Medica Iranica*. 2013;51(No 7).
97. McCormack BM, Taylor SL, Heath S, Scanlon J. Pseudomeningocele/CSF fistula in a patient with lumbar spinal implants treated with epidural blood patch and a brief course of closed subarachnoid drainage. A case report. *Spine (Phila Pa 1976)*. 1996;21(19):2273-2276. doi:10.1097/00007632-199610010-00019
98. Sandwell S, Walter K, Westesson PL. Pseudomeningocele Aspiration and Blood Patch Effectively Treats Positional Headache Associated With Postoperative Lumbosacral Pseudomeningocele. *Spine (Phila Pa 1976)*. 2017;42(15):1139-1144. doi:10.1097/BRS.0000000000002003
99. Maycock NF, van Essen J, Pfitzner J. Post-laminectomy cerebrospinal fluid fistula treated with epidural blood patch. *Spine (Phila Pa 1976)*. 1994;19(19):2223-2225. doi:10.1097/00007632-199410000-00018
100. Fridley JS, Jea A, Glover CD, Nguyen KP. Symptomatic postsurgical cerebrospinal fluid leak treated by aspiration and epidural blood patch under ultrasound guidance in 2 adolescents. *J Neurosurg Pediatr*.

2013;11(1):87-90. doi:10.3171/2012.9.PEDS12314

101. Shapiro SA, Scully T. Closed continuous drainage of cerebrospinal fluid via a lumbar subarachnoid catheter for treatment or prevention of cranial/spinal cerebrospinal fluid fistula. *Neurosurgery*. 1992;30(2):241-245. doi:10.1227/00006123-199202000-00015

102. Açikbaş SC, Akyüz M, Kazan S, Tuncer R. Complications of closed continuous lumbar drainage of cerebrospinal fluid. *Acta Neurochir (Wien)*. 2002;144(5):475-480. doi:10.1007/s007010200068

103. Duthel R, Nuti C, Motuo-Fotso MJ, Beauchesne P, Brunon J. [Complications of lumboperitoneal shunts. A retrospective study of a series of 195 patients (214 procedures)]. *Neurochirurgie*. 1996;42(2):83-89; discussion 89-90.

104. James HE, Tibbs PA. Diverse clinical applications of percutaneous lumboperitoneal shunts. *Neurosurgery*. 1981;8(1):39-42. doi:10.1227/00006123-198101000-00008

105. Katz SS, Savitz MH, Osei C, Harris L. Successful treatment by lumboperitoneal shunting of a spinal subclavicular fistula following thoracotomy. *Neurosurgery*. 1982;11(6):795-796. doi:10.1227/00006123-198212000-00014

106. Kitchen N, Bradford R, Platts A. Occult spinal pseudomeningocele following a trivial injury successfully treated with a lumboperitoneal shunt: a case report. *Surg Neurol*. 1992;38(1):46-49. doi:10.1016/0090-3019(92)90211-5

107.Karnati T, Kulubya ES, Kim KD. Advances in the Management of Spinal Durotomy. Medical Research Archives. 2020 Sep 28;8(9).