Delineating the Subarachnoid Space in the Adult Lumbosacral Spine Using Computed Tomographic Myelography: An Aid for Clinical Target Volume Delineation in Craniospinal Irradiation

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Abstract

Purpose: Our aim was to characterize the patterns of cerebrospinal fluid (CSF) extension in the lumbosacral spine using computed tomography (CT) myelograms to provide an evidence base for clinical target volume (CTV) definition in adults receiving craniospinal irradiation.

Methods and Materials: This was a retrospective analysis of diagnostic CT lumbar myelograms performed in 30 patients between the ages of 22 and 50. Lateral extension of CSF beyond the thecal sac was measured along each lumbar and sacral nerve root to the nearest millimeter, as was the distance of inferior extension of CSF beyond the caudal end of the thecal sac. Each patient’s lateral and inferior CSF extensions were mapped onto a standardized CT data set to create a model target volume in the lumbosacral spine that would contain the aggregate observed CSF distributions from the analyzed CT myelograms. The median extension distances, interquartile ranges, and 90th percentile for distance at each level were calculated.

Results: The median lateral extension of CSF along nerve roots beyond the thecal sac—as measured perpendicular to the longitudinal axis—increased from 0 mm (interquartile range [IQR], 0-4 mm) at L1 to 8 mm (IQR, 6-12 mm) at S1 and 0 mm (IQR, 0-0 mm) at S4. The 90th percentile ranged from 5 to 14 mm laterally, with a pattern partially extending into the S1 and S2 sacral foramen. Median CSF extension inferior to the caudal sac was 5 mm (IQR, 2-8 mm), with 90% of patients within 12 mm. An atlas was generated to guide CTV delineation for highly conformal radiation techniques.

Conclusion: These results provide information on patterns of CSF extension in the lumbosacral spine of adults and can serve as a model for CTV guidelines that balance comprehensive coverage of the CSF compartment while minimizing the dose to nontarget tissues.

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Introduction

Effective radiation therapy for certain tumors involving the central nervous system can require therapeutic radiation to the entire anatomic compartment containing the cerebrospinal fluid (CSF). This technique, known as craniospinal irradiation (CSI), is specifically employed in patients where tumor cells have been found in the CSF, imaging shows evidence of subarachnoid tumor spread, or the primary tumor is in a location and has a known natural history suggesting a high risk of occult spread via a CSF pathway. For this reason, accurate targeting of the CSF compartment is critical for successful outcomes. In patients with medulloblastoma treated with 2-dimensional irradiation techniques, inaccurate targeting of the cranial CSF compartment has been associated with increased recurrence rates.1

Historically, radiation targets were off bony anatomy seen on plain radiographs.2 However, in the modern era, the precision with which radiation can be delivered calls for a more accurate understanding of the anatomy of the subarachnoid space, especially in areas where unnecessarily large target volumes will increase exposure to normal tissues. In the lumbar spine, and sacrum specifically, overly generous radiation targets can potentially increase the dose to bone marrow and gonadal tissues.3,4 Previous research has established ranges of locational variation for spinal landmarks in the adult population5,6 and suggests that the use of computed tomography (CT) myelograms to pinpoint anatomic landmarks has the potential to improve the definition of target volumes and tailor CSI to a patient’s unique anatomy.5,7

Unfortunately, there is still no consensus on what defines the spinal CSF therapeutic clinical target volume (CTV).9 Many recent protocols still rely on language that focuses on field borders, which is a definition that does not accurately inform the volumetric anatomic targeting required for more sophisticated radiation delivery techniques, such as volumetric modulated arc therapy (VMAT) and inverse-planned spot-scanning proton therapy.10-12 Much of the disagreement centers on the extent to which lateral and inferior field borders should include the spinal nerves showing CSF extension. Although this debate existed in the era of less sophisticated radiation techniques, advances in radiation delivery and changes in targeting definitions require that it be readdressed.2 The 2018 International Society of Paediatric Oncology Europe (SIOPEN) Brain Tumor Group consensus guidelines recommend treating all of the subarachnoid space, including nerve roots laterally, while omitting the sacral canals. The inferior-most extent of the CTV was recommended to be the termination of the thecal sac.13 However, the need for more generous coverage inferior to this was implied in the protocol-specified fields of the Children's Oncology Group ACNS0331, which were set 2 cm inferior to the caudal end of the thecal sac.14

The purpose of this study was to use CT myelograms to provide detailed anatomic information about CSF patterns in the lumbosacral spine to move toward consensus in target volume delineation.

Methods and Materials

This study is a retrospective analysis of lumbar CT myelograms taken of 100 adult patients from the University of Utah health care system over the past 10 years for nononcologic reasons. Because this study posed little to no risk to human participants, the university’s institutional review board ruled it to be exempt from full board review. To minimize variations in spinal anatomy due to degenerative changes or surgeries, patients over the age of 50 were excluded, leaving 37 patients between the ages of 22 and 50 years. Within this remaining group, 5 were duplicates, and 1 patient never received a lumbar CT myelogram. One additional patient with severe dextroscoliosis and extensive surgical hardware was also omitted, leaving 30 patients in the final study group (20 women and 10 men).

Lateral CSF extension was measured beyond the thecal sac at L1, L5, and along the sacral nerve roots to the nearest millimeter, and the inferior extension distance was measured beyond the inferior termination of the thecal sac at midline. It should be noted that the sacral nerve root measurements did not necessarily occur at the level of their respective foramina. Each patient’s CSF lateral and inferior extensions were contoured onto a standardized CT image data set using Eclipse software (Varian Medical Systems, Inc, Palo Alto, CA), to recreate an aggregate mapping of the CSF distribution of the lumbar myelograms as closely as possible. If CSF extension could not be determined at a given spinal level because of the presence of surgical hardware or associated artifacts, the measurement for that particular level was classified “N/A.”

Statistical analysis

The median and upper and lower quartile ranges were calculated for each spinal level and for the inferior extension using Microsoft Excel (Microsoft Corporation, Redmond, WA). An additional set of contours comprehending all existing contours was made. Representative snapshots of CSF extension inferiorly and at each spinal level were
also taken both of the contours and of one of the patient’s CT myelogram images.

**Results**

Computed tomography myelograms demonstrated a variety of patterns of CSF in the lumbar spine and around sacral nerve roots. An example of CSF extending along sacral nerve roots and beyond the magnetic resonance imaging—visualized thecal sac is shown in Fig. 1. Lateral extension of CSF with interquartile ranges (IQRs) was measured to be a median of 0 mm (IQR, 0-4 mm) at L1; 3 mm (IQR, 0-5 mm) at L2; 5 mm (IQR, 3-7 mm) at L3; 6 mm (IQR, 4-8 mm) at L4; 8 mm (IQR, 3-9 mm) at L5; 8 mm (IQR, 6-12 mm) at S1; 0 mm (IQR, 0-7 mm) at S2; 0 mm (IQR, 0-2 mm) at S3; and 1 mm (IQR, 0-0 mm) at S4. There was no measurement of lateral extension at S5 (Table 1). Overall, CSF extended laterally a median of 3 mm (IQR, 0-7 mm) at all spinal levels, and 90% of lateral CSF extension was within 9 mm. Median CSF extension inferior to the caudal end of the dural sac was 5 mm (IQR, 2-8 mm; Table 1). The 90th percentile of lateral CSF extension reached 5 mm at L1, 7 mm at L2, 8 mm at L3, 9 mm at L4, 12 mm at L5, 14 mm at S1, 12 mm at S2, 5 mm at S3, and 1 mm at S4. The 90th percentile of CSF extension inferior to the caudal of the dural sac was 12 mm.

Examples of the individual and aggregated contours at each spinal level are shown in Fig. 2 alongside representative images from patient myelograms at the corresponding spinal level. An atlas containing a recommended

![Figure 1](image_url)

**Figure 1** Magnetic resonance (MR) and computed tomography (CT) myelogram images from a single patient showing limitations of MR imaging in fully characterizing the extent of the subarachnoid space in some patients. (A) Sagittal T2-weighted MR images of the lumbar spine show the thecal sac terminating at the S1/S2 interspace. (B) Reformatted sagittal images from a CT myelogram showing a thin wisp of contrast extending inferior to the thecal sac, corresponding to contrast around the filum terminale and sacral nerve roots that extends 12 mm inferiorly along the axis of the sacral canal. (C) Axial CT myelogram image at S2 spinal level.
standardized CTV using these data was generated (Appendix E1). Based on the measurements summarized in Table 1, we recommend that the CTV extend inferiorly 10 to 15 mm beyond the terminus of the thecal sac and include the nerve roots present in the sacral canal at those levels. One patient was found with CSF extension beyond the sacral foramen at the S2 level (Fig. 3), but given this atypical finding (a probable meningeal cyst) in only a single patient, we decided not to include the patient in the proposed CTV. Contrast enhancement along the S3 and S4 nerve roots outside the sacral canal (ie, in the sacral foramen) was not observed, but the pattern observed in several patients did include the S1 and S2 foramina partially.

While measuring the lateral CSF extension on the lumbar myelograms, we noted small wispy regions of extrathecal contrast spread caused by periprocedural myelogram contrast leakage (2 examples from the L2 and L3 levels of the same patient’s lumbar myelogram are shown in Fig. 4). The presence of trace extrathecal contrast leakage can be seen in the setting of myelography and did not represent the dural cuffing that was the focus of this study. These procedural artifacts should not be included in the field of treatment.

### Discussion

These results offer a starting point for understanding patterns of CSF extension in the lumbar and sacral spine. CSF extension beyond the thecal sac was observed at all levels of the lumbar spine, and there was extension into the S1 and S2 foramina anterolaterally and along S3 and S4 nerve roots inferiorly in the sacral canal. In the majority of cases, lateral CSF extension within the lumbar spine remained within 9 mm of the lateral edges of the spinal canal, and the inferior extension did not extend more than 12 mm inferior to the caudal end of the thecal sac or beyond the S3-S4 interspace. These findings are within similar recommendations to those for spinal CTVs found in The Children’s Oncology Group’s ACNS0331 protocol: within 5 mm of the lateral field margins and within 3 mm of the inferior field margins. They do, however, vary from the 2018 recommendations from the SIOPE Brain Tumor Group, which omitted the sacral canals from the spinal CTV. CSF was observed extending into the sacral foramina in these patients, more prominently at the S1-S2 spinal level.

However, the measurements in this study also illustrate the range of variability, both between patients and spinal levels. The degree of lateral CSF extension is not consistent across all lumbar and sacral spinal levels. Rather, it increased in magnitude from L1 to S1 toward a maximum distance between L5 and S1 before then dropping to a median of 0 mm at S2 through S4. This pattern is not unlike the natural increasing size of the lumbar vertebrae when moving caudally from L1 to S1. This trend is notable and may prove useful in refining the spinal CTV to maximize CSF coverage and minimize bone marrow irradiation. However, the trend is unidimensional; ventral-dorsal extension of CSF was not studied, and additional research is necessary to better characterize it in 3-dimensional space. Additionally, rare cases demonstrated sacral meningeal cysts extending more laterally along the nerve root (Fig. 3). Studies have shown the presence of these sacral meningeal cysts in approximately 5% of the population imaged for back pain. Because these findings are seen in the minority of patients, extending treatment further laterally along the nerve is not recommended.

This study was limited by focusing on a relatively young patient population to limit the effect of anatomic changes due to severe degenerative spinal disease.

### Table 1: Median and 90th percentile of CSF extension, laterally at each lumbosacral spinal level and inferior to the caudal end of the thecal sac

| Level | Median (mm) | Interquartile range (mm) | 90th percentile (mm) |
|-------|-------------|--------------------------|----------------------|
| L1    | 0           | (0, 4)                   | 5                    |
| L2    | 3           | (0, 5)                   | 7                    |
| L3    | 5           | (3, 7)                   | 8                    |
| L4    | 6           | (4, 8)                   | 9                    |
| L5    | 8           | (3, 9)                   | 12                   |
| S1    | 8           | (6, 12)                  | 14                   |
| S2    | 0           | (0, 7)                   | 12                   |
| S3    | 0           | (0, 2)                   | 5                    |
| S4    | 0           | (0, 0)                   | 1                    |
| Inferior distance | 5 | (2, 8) | 12 |

The lateral distances recorded for the sacral nerve roots were often superior to the corresponding foramen and often still within the spinal canal.
Although the greater standardization facilitated more accurate mapping of contours onto the standard CT model, the study could have benefited from relaxing the exclusion criteria to include a wider range of ages and possible anatomic variations. However, because craniospinal irradiation is less frequently used in elderly patients, this restriction in our study population is not likely to have significant clinical import. It is, however, important to note that these findings, which were developed in an adult population, would not translate quantitatively to the pediatric population, but the study does support the anatomic concept of treating laterally beyond the tubular thecal sac to include expected dural cuffing and, at least in a limited fashion, to cover a portion of the sacral nerve.

Figure 2  Individual and aggregated contours accompanied by computed tomography myelogram images highlighting cerebrospinal fluid extension at each spinal level.
roots, including a margin below the terminus of the thecal sac where CSF can continue along lower nerve roots for a short distance. Full target coverage of sacral nerve roots to where they exit the sacral foramina is unnecessary in most patients.

Some minor artifact caused by metal surgical hardware prevented lateral measurements in certain patients. This problem was specific to the L4 through S1 spinal levels where 3 patients’ dural cuffs could not be measured. There is also the possibility that the measurements and qualitative descriptors in this study could have overestimated the necessary therapeutic target for CSI. The pressure applied with the injection of the intrathecal contrast could have caused potential CSF spaces to open and become opacified, when in the normal physiological state they would have remained closed and not susceptible to CSF seeding from tumors. The opposite could also be true, namely that these contours could underrepresent the volume that should be treated in patients with a neoplastic process involving the CSF. In other words, imaging the CSF space in healthy individuals may not represent the most appropriate approach to understanding the optimal target volume in patients with CNS neoplasms. For example, arachnoid villi projecting from dural coverings of spinal nerve roots are permeable to colloidal particles and possibly red blood cells in a space where they are intimately associated with venous structures. In advanced disease states, such permeability might be altered to allow tumor cell trafficking and thus potentially require more generous target volumes. Patients with a higher neoplastic burden within the CSF can also have longitudinal infiltration along nerves. Such possibilities should be considered when designing CTVs in accordance with findings on magnetic resonance imaging (such as gross nerve enhancement, where margins may need to be larger) and individual disease burdens. Despite these limitations, these results advance the understanding of patterns of CSF extension and dural cuffing in the lumbosacral region in a way that may improve consensus for CSI target volumes in patients with CNS tumors.

Conclusion

We have demonstrated that the sensitivity of CT myelograms in identifying CSF extension along lumbar and sacral nerve roots is beneficial in developing evidence-based recommendations for CTV delineation in the lumbosacral spine for CSI in the modern radiotherapeutic era. This will allow for progress toward standardization of treatment delivery approaches that could improve the therapeutic ratio.

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Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.adro.2022.100994.

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