Several etiologies of syringomyelia associated with Chiari malformation type I (CM-I) have been proposed. Insufficient CSF flow at the craniovertebral junction (CVJ) is a widely recognized cause for the development of a syrinx. Therefore, surgical strategies for treatment of these lesions are focused on restoring the normal CSF flow at the CVJ.

There are mainly two surgical strategies for normalizing the CSF flow in patients with CM: foramen magnum decompression (FMD) with removal of the outer dura mater layer, and FMD with duraplasty. In 1993, Isu et al. first reported on FMD with removal of the outer dura mater layer as a new surgical procedure for CM-I. Since then, this technique has gained attention as a minimally invasive procedure for the treatment of syringomyelia associated with CM-I. FMD with removal of the outer dura mater layer was initially described by Isu et al. in 1993 and has since been widely adopted as a minimally invasive surgical procedure for the treatment of syringomyelia associated with CM-I.
mater layer is associated with a longer operating time and lower rate of surgery-related complications, including CSF leakage, indicating minimally invasive surgery. However, a significant difference has been found in the clinical improvement rates in favor of FMD with duraplasty.10

Both surgical procedures involve dura mater manipulation at the CVJ for recovery of CSF flow. We have often experienced intra- and postoperative complications when performing these procedures at the CVJ. Postoperative restenosis is one of these complications that develops due to the “lax” duraplasty, which may result in bulging of the dura mater at the CVJ.3 We have encountered bulging lax dura mater in both surgical procedures. Moreover, we have sometimes experienced massive arterial and venous bleeding during surgery, particularly at the CVJ.

To reduce these surgical complications, it is essential to understand the microanatomy of the dura mater at the CVJ and spinal region. However, detailed information regarding the dura mater microanatomy at the CVJ is not available. The dura mater in this region has been thought to display dynamic morphological changes within an extremely short segment.3,11,12 We have already described the anatomical information of the cranial and spinal dura mater, but not of the CVJ dura mater.5,6 The microanatomy of the dura mater at the CVJ might reveal solutions to the aforementioned surgical challenges. The purpose of this study was to clarify the detailed and precise microsurgical anatomy of the dura mater at the CVJ for safe and effective surgical treatment, particularly for CM.

Methods

The IRB at Shinshu University School of Medicine approved this study protocol. The data were collected according to the principles of the Declaration of Helsinki.

This study entailed the dissection of 4 formalin-fixed, continuous, human cadaveric dura maters, extending from the posterior fossa to the C2 level. The age of the cadavers ranged from 88 to 94 years, and 2 were women and 2 were men (Fig. 1). After removing the occipital bone and C1 laminae, a dural incision was made to harvest the specimen (Fig. 2A and B). The specimens were cut in a parasagittal plane and embedded in paraffin. The 5-μm sections were stained with H & E and elastica Masson-Goldner (Fig. 2C). Figure 2D shows the relationships between the neural and bone structures and the dura mater. The number of arterial vascular structures with a diameter greater than 50 μm was calculated per 1 mm² in each area in the specimens stained with elastica Masson-Goldner.

We studied the following structural and topographical aspects of the dura mater in each region: 1) thickness, 2) morphological characteristics, and 3) vascular structures. The posterior cranial fossa was defined as the region between the tentorium cerebelli and the foramen magnum, the CVJ as the region from the foramen magnum to the upper border of the C1 laminae, and the spinal region was below the C1 level. The thickness of the dura mater was measured at 2 points in each region and the average was noted.

Results

Spinal dura mater was not obtained from case 1. Continuous dura maters for the CVJ were available in all 4 cadavers.

Thickness of the Dura Mater

The average thicknesses of the dura mater were 313.4 ± 137.0 μm, 305.15 ± 798.8 μm, and 866.5 ± 359.0 μm in the posterior cranial fossa, CVJ, and spinal region, respectively (Table 1). The posterior cranial fossa had the thinnest dura mater of all three regions studied. The spi-
nal dura mater was approximately 2 times thicker than the posterior fossa dura mater.

**Morphological Characteristics of the Dura Mater in Each Region**

The histological features of the dura mater in each region are summarized in Table 1. In the posterior cranial fossa, the dura mater was composed of two layers, inner and outer layers, which could be easily distinguished by the different arrangements of their constituent collagen fibers (Fig. 3A and B). At the CVJ, the dura mater was also composed of two layers. The dural inner layer at the CVJ was continuous with the dural inner layer of the posterior cranial fossa. Although the thickness of the dural inner

**TABLE 1. The anatomical features of the dura mater in each region**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Dura Mater Thickness (μm)</th>
<th>No. of Layers</th>
<th>Bulging of Dura Mater</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Posterior Fossa</td>
<td>CVJ</td>
<td>Spine</td>
</tr>
<tr>
<td>1</td>
<td>359</td>
<td>2470</td>
<td>2950</td>
</tr>
<tr>
<td>2</td>
<td>175</td>
<td>4492</td>
<td>447</td>
</tr>
<tr>
<td>3</td>
<td>458</td>
<td>2920</td>
<td>1010</td>
</tr>
<tr>
<td>4</td>
<td>185</td>
<td>2600</td>
<td>1120</td>
</tr>
<tr>
<td>Mean</td>
<td>313.4</td>
<td>3051.5</td>
<td>866.5</td>
</tr>
<tr>
<td>SD</td>
<td>137.0</td>
<td>798.8</td>
<td>359.0</td>
</tr>
</tbody>
</table>

NA = this specimen was not available in the spinal region.
Evaluating the degree of bulging of the dura mater was divided into two grades (yes and no).
layer at the CVJ was 2–3 times greater compared to that in the posterior fossa, the dural outer layer at the CVJ showed remarkable thickening (more than 10 times greater) compared to that in the posterior fossa. This thickening was largely caused by the presence of a large amount of tendon tissues of the rectus capitis posterior minor muscle (Fig. 3C and D). It was confirmed that the innermost part of the dural outer layer at the CVJ was continuous with the dural outer layer of the spinal region. In the spinal region, we could not separate the dura mater into two layers, because the constituent collagen fibers were arranged in the same direction (Fig. 3E).

At the foramen magnum level, bulging of the dura mater was observed in the subdural side of case 4 (Table 1, Fig. 3C). This was a small dural fold, which continued from the falx cerebelli, measuring approximately 2.48 mm in height (Fig. 3C, arrow). This bulging was observed in only 1 case in this study and recognized as an anomaly or variation. Histologically, it was a substructure of the inner layer of the dura mater. It contained a venous structure, which was proven by the presence of red blood cells and pacchionian granulation, thus allowing for CSF circulation (Fig. 3C, small asterisk). On the basis of these findings, the dural bulging was recognized as a marginal sinus around the foramen magnum.

Vascular Structures of the Dura Mater in Each Region

Blood vessels were scant in the dura mater of the posterior cranial fossa. In contrast, the CVJ dura mater had a well-developed vascular network (Fig. 4A). The network contained arteries, veins, and venous plexuses (Fig. 4B) located mainly between the inner and outer layers (Fig. 4B, asterisk). The numbers of vessels with a diameter greater than 50 μm were 0.37, 0.63, and 0.55 per 1 mm² in the posterior cranial fossa, CVJ, and spinal region, respectively. Large venous structures, including the venous plexus, were not found in the posterior cranial fossa or the spinal dura mater.

Discussion

This study showed that the structure of the dura mater changes dramatically in a very small area. In the posterior cranial fossa, the dura mater is very thin and consists of
two layers of collagen fibers oriented in different directions. At the CVJ, the dura mater becomes thicker, mainly due to the joining of tendon tissues from the rectus capitis posterior minor muscle. Finally, the spinal dura mater is the thickest, but constitutes a single layer of collagen fibers in the same direction. It is well established that the physical characteristics, for example, tensile strength and resistance to tearing forces, depend on the orientation of the collagen fibers. The spinal dura mater tears easily compared to the dura mater of the posterior cranial fossa and the CVJ. During surgery, neurosurgeons should pay careful attention to each part of the dura mater, which differs by person. In the spinal region, the dura mater is thick but comprises a single layer, which means that tearing is likely to occur. If a sharp needle is used after the intradural procedures, tears tend to occur easily. The thickness of the dura mater is irrelevant, and tears result in postoperative CSF leakage. To avoid dural tears, we always use titanium nonpenetrating titanium clips, which do not create any suture holes and are considered ideal for approximating the spinal dura mater. Especially in the CVJ, it is very important to know the characteristics of the dura mater, which displays dynamic morphological changes within an extremely short segment. To date, there have been few reports regarding the microanatomy of the dura mater of the posterior neck region and cranial dura mater. This is due to the difficulty in obtaining specimens, particularly at the CVJ, which has a complex anatomy and functionality, including a bony structure, thus allowing for complex morbidities.

Insufficient knowledge of the microanatomy of the dura mater at the CVJ may lead to ineffective surgical outcomes and complications. Among patients requiring surgery for CM, FMD with duraplasty or removal of the outer dura mater layer is the most common surgical procedure. Occasionally, restenosis occurs at the obex level postoperatively. One reason for postoperative restenosis is lax duraplasty, which may result from the bulging dura mater at the CVJ. The etiology of this dural bulging has remained unclear for some time.

On the basis of the microscopic findings, we determined that the dural bulging in the inner layer of the dura contained a marginal sinus. The dural fold, which bulged into subdural space, was found in only one of the specimens in this study. Although the marginal sinus forms at the embryonic stage and mostly regresses after infancy, it can persist beyond infancy in some people. Theoretically, it seems impossible to remove this bulging, if only removal of the outer dural layer or only craniectomy of the occipital bone is planned for the treatment of CM. This bulging is located in the subdural space in the inner layer of the CVJ dura mater. The dural fold containing a marginal sinus might be one of the reasons for the lax dura mater.

In addition, if the patient has a marginal sinus preoperatively, the surgical strategy regarding the dura mater can be altered. It is important to know whether the marginal sinus exists. However, patients with CM originally have a very tight CVJ, so the marginal sinus might be compressed by the neural tissue. Therefore, there is a possibility that the marginal sinus cannot be recognized preoperatively.

We hypothesize that the outstanding features include not only the drastic changes in the structures, such as the
thickness, number of layers of collagen fibers, and direction of the fibers, but also the presence of bulging of the dura mater and the “myodural bridge.”13,17-19 The “myodural bridge” was first described by Hack in 1995 and was thought to be related to chronic cervicogenic headaches.18,19 In the CVJ, the muscle fibers combine with the spinal dura mater to form the myodural bridge, which is a dense connective tissue bridge situated between the rectus capitis posterior minor muscle and the spinal dura. This structure plays an important role in CSF circulation and in the balance and coordination of the entire musculoskeletal system.17 This myodural bridge retracts the dura mater dorsally at the CVJ. In CM surgery, the myodural bridge is always removed and the tension to the dura mater may be reduced. It might also cause the lax dura mater.

There have been many reports in recent years regarding the presence of arteriovenous fistulae at the CVJ.1-20 Our study showed that the CVJ dura mater is rich in vascular structures, compared to that in the posterior cranial fossa and spinal region. Although the etiology is still unclear, the well-developed vascular network might contribute to this pathology.

When compared with the intracranial dura mater, the dura mater at the CVJ had characteristic microstructures. The CVJ dura mater was the most mobile part among the areas studied. The thickness was 3 and 5 times that of the dura in the spinal region and posterior cranial fossa, respectively. Moreover, this layer always contained the muscle fiber from the cranium. It may be the strongest in terms of tensile strength and resistance to tearing forces. These dural structures contribute to the complex morbidities of the CVJ, even if they have a complicated anatomy and functionality, including a bony structure. Thus, the dura is quite thick in this region, and vascular clips are often needed to obtain good hemostasis when operating in this area.

There is a limitation to this study. Most patients with CM-I who undergo surgery are younger than the cadavers used in our study (age range 88–94 years). However, we aimed to obtain fundamental information about the structure of the dura mater in the CVJ before we accounted for these pathological conditions.

Conclusions

In this study, we verified that the structure of the dura mater differed in the posterior cranial fossa, CVJ, and spinal cord. The CVJ dura mater has a complex anatomical structure and functionality. Additionally, the dura mater at the CVJ displayed dynamic morphological changes within an extremely short segment in this study. The characteristic anatomical features of the CVJ dura mater are not similar to those in the cranial and spinal regions. Dural bulging in the CVJ was determined to be the venous sinus. During surgery in the CVJ, different procedures should be used because of the specific microsurgical anatomy of the CVJ. Neurosurgeons should be aware of this strategy to ensure safe and effective surgical treatment.

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References

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The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Supplemental Information
Previous Presentations
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Correspondence
Kiyoshi Ito: Shinshu University School of Medicine, Matsumoto, Japan. kitoh@shinshu-u.ac.jp.