

# Rectus Capitis Posterior Minor

## *Histological and Biomechanical Links to the Spinal Dura Mater*

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**Study Design.** Serial histological investigation was performed on 10 cadaveric specimens and biomechanical tests were performed on five specimens, both focused on the tissue connexion between the rectus capitis posterior minor (RCPMi) and the spinal dura.

**Objective.** This study had two components: to clarify the microscopic structure of the tissue link between RCPMi and the dura mater, and to evaluate the mechanical role of this tissue complex.

**Summary of Background Data.** Dissection-based and imaging-based reports have suggested a connective tissue link between the RCPMi and the dura mater at the posterior-atlanto-occipital (PAO) level. Existence of this link, and properties, remain unclear.

**Methods.** Histological investigation: RCPMi muscles, their bony attachments, PAO space, and adjacent spinal dura mater were resected from 10 cadavers. Tissues were subdivided into medial and lateral parts. Serial histological sections were prepared to cover maximum surface area; Masson trichrome stain was used to evaluate the tissue connection. Biomechanical investigation: individualized RCPMi muscles from five cadavers were detached from their origin. Each muscle was loaded incrementally up to 2 kg, with the cervical spine hyperextended. Using a structured light scanner, the dura mater was scanned for each loaded state. Comparison between unloaded and each loaded scanned surface quantified the displacement of the dura mater.

**Results.** Histological investigation confirmed the existence of a connective tissue link between the RCPMi and the dura mater.

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The biomechanical testing suggests that this tissue link complex can reduce the bulging of the dura mater into the spinal canal, caused during hyperextension, by  $53.4\% \pm 6.9\%$  under RCPMi loading.

**Conclusion.** This histological investigation clarified the structure of the tissue link between the RCPMi and the dura mater. The biomechanical testing indicated a potential mechanical function of the RCPMi in regards to the spinal dura mater, which may include a stabilizing role of the dura mater during neck extension.

**Key words:** biomechanical testing, cervical dura mater, mechanical influence of muscles, mechanical influence of soft tissue, rectus capitis posterior minor, serial histological sections.

**Level of Evidence:** N/A

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The rectus capitis posterior minor (RCPMi) is a deep suboccipital muscle that originates from the inferior nuchal line and inserts onto the posterior tubercle of the atlas. This small muscle has been of interest since Hack *et al*<sup>1</sup> described a dense connective tissue structure linking this muscle to the posterior-atlanto-occipital membrane (PAOM), named the myodural bridge and also known as a connective tissue bridge.

The PAOM has been described by Hack *et al*<sup>1</sup> and Mitchell *et al*<sup>2</sup> as a membrane extending from the cephalic border of the posterior arch of the atlas, to the posterior edge of the foramen magnum. According to Hack *et al*,<sup>1</sup> this membrane is fused to the spinal dura mater by fine connective tissue elements, forming a PAOM-spinal dura complex (PAOM-SDC) that may function as a membranous unit. Other authors found a connective tissue bridge between the RCPMi and PAOM, but could not explain the relation between the PAOM and the spinal dura mater.<sup>3</sup> In contrast, Nash *et al*<sup>4</sup> questioned the existence of the PAOM and discussed the possibility of a misinterpretation of the PAOM as a deep and lateral portion of the RCPMi tendon and fascia.

Since the findings of Hack *et al*<sup>1</sup> investigations of the myodural bridge, there have been attempts to clarify its function and potential clinical implication in chronic cervicogenic headaches.<sup>2,3,5–8</sup> The role and structure of the PAOM and the connective tissue bridge from the RCPMi

remain unclear. Detailed serial histological investigation, along with biomechanical testing, may help to establish a link between the RCPMi and the dura mater.

This study had two objectives: to describe the posterior-atlanto-occipital (PAO) space using serial histological sections, clarifying the connective tissue link between the RCPMi and the spinal dura mater; and to evaluate the mechanics of the tissue bridge connection between the RCPMi and the cervical dura mater.

## MATERIALS AND METHODS

### Dissection Approach

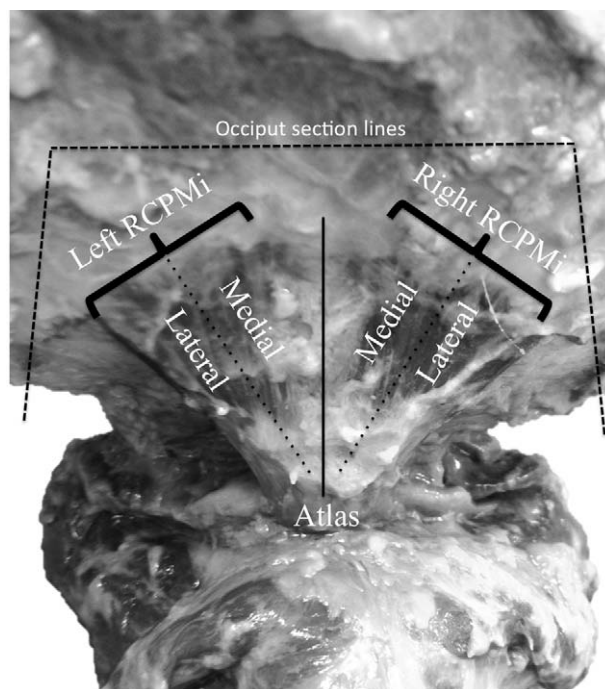
With approval from the relevant institutional review board, five embalmed cadavers and four fresh-frozen cadavers were acquired for the histological investigation; five fresh-frozen cadaveric head and necks were acquired for biomechanical investigation. For all specimens, the calvarium was removed using a Stryker autopsy saw (model 0295-270; Stryker, Kalamazoo, MI) and the brain was resected at the pons/medulla oblongata interface to expose the dura mater. The cervical spine was sectioned at the zygapophysial joints and intervertebral disc at the fifth and sixth cervical vertebrae level. Following the dissection method of Kahkeshan and Ward,<sup>8</sup> the rectus capitis posterior major and minor, obliquus capitis inferior, and obliquus capitis superior were identified and cleaned.

### Histological Investigation

For the nine specimens used for the histological investigation, the occipital bone and suboccipital muscles were harvested by performing an oblique cut on the occipital bone, from the lateral aspect of the obliquus capitis superior down to the posterolateral aspect of the foramen magnum. A meticulous dissection isolated the RCPMi. The occipital bone and the lateral aspect of the posterior arch of the atlas were cut to harvest the RCPMi muscles, their bony attachments, and the adjacent dura mater (Figure 1).

Tissue samples were fixed with 4% formaldehyde freshly prepared from paraformaldehyde for 48 hours, then placed in a 10% ethylenediamine tetracetic acid (EDTA) solution. The EDTA solution was changed weekly until complete decalcification of the bony components (18 weeks). The decalcified bones were cut through the mid-sagittal plane with a razor blade to separate the two RCPMi muscles. Each muscle and bony attachment was carefully sectioned longitudinally into medial and lateral samples (Figure 1).

Specimens were dehydrated with a series of graded ethanol solutions and cleared in toluene before being embedded in paraffin wax, this preserving the spatial relationship between C0 and C1 and with the medial aspect as the sectioning face. To cover a maximal surface area, serial sections 6- $\mu$ m-thick were cut using a manual microtome. One section was kept every six sections, to be mounted on a



**Figure 1.** Dissection for histology investigation: RCPMi's were isolated whereas other suboccipital muscles were resected. The dash line represents the section lines of the occipital bone for harvesting the RCPMi. The atlas was cut at the lateral aspect of the posterior arch of the atlas. Once fixed and decalcified, the RCPMi were separated for histology. The mid-sagittal separation of the two RCPMi is illustrated by the sagittal line while the dotted lines represent the separation of muscle into lateral and medial samples. RCPMi indicates rectus capitis posterior minor.

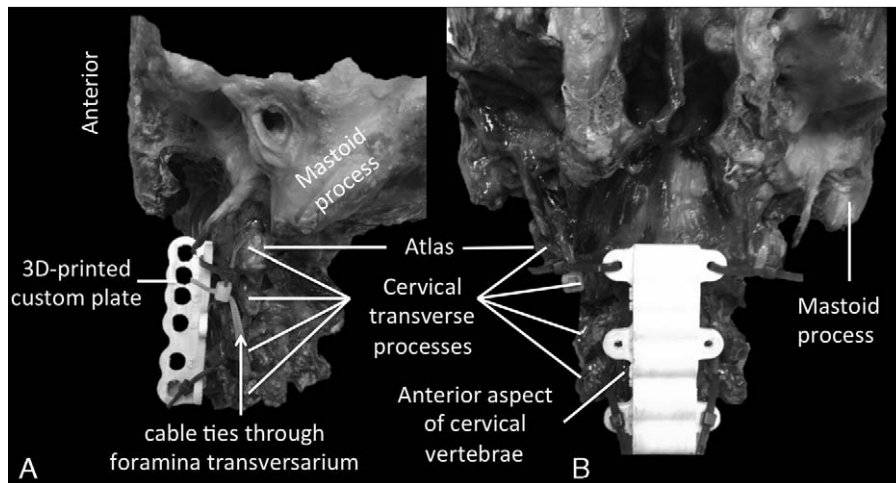
super frost microscope slide. Masson's trichrome (Staining Kit no.: 87019; Fisher Scientific Co., Nepean, Ottawa, Canada) was used to stain the collagen organization of the PAO region and to evaluate the connective tissue relation between the RCPMi and the spinal dura mater.

### Data Analysis for Histology Investigation

Each histological serial section was examined using light microscopy. Detailed descriptions of the collagen distribution and organization of the PAO region were recorded and verified by three independent investigators.

### Biomechanical Investigation

For each of the five samples used in the biomechanical section of this study, the bony anatomy of the cervical spine was cleaned of all soft tissue to isolate the RCPMi muscles. The cervical spine was stabilized using cable ties through the foramina transversarium and then fixed onto a custom-made plastic plate (Figure 2), designed to allow static neck extension positioning. For complete immobilization of the skull during the trials, holes were drilled on each side, at the pterion and the posterior-parietal-squamous suture, to anchor the skull onto a platform. The design of this platform allowed then to move the cervical spine from neutral to extension with respect to the immobilized skull (Figure 3).



**Figure 2.** Dissection for biomechanical investigation: figures showing a dissection of a frontally sectioned skull. The cervical spine was stabilized using cable ties through the foramina transversarium and then fixed onto a 3D-printed custom plate to allow static positioning. **A**, Lateral view. **B**, Anterior view.

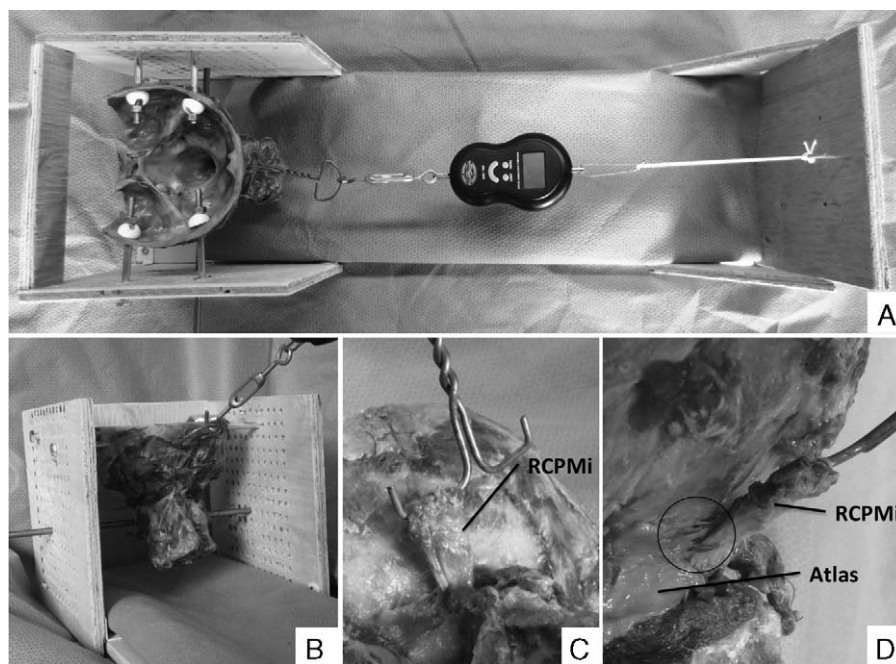
**Muscle Loading**

Each individual muscle was detached from its occipital origin and sutured to a wire frame using 3.0 Ethibond suture wire. The wire frame was supported by a cable tensioned by a turnbuckle for loading. A portable electronic scale, fixed to the turnbuckle and the testing platform, quantified the loading. Static loads were applied to the muscle in a quasiphysiological direction at 1.5 N, and between 2.5 N and 20.0 N in increments of 2.5 N; this loading protocol was chosen to respect the reported peak force of the muscle, 46 N,<sup>9</sup> based on the 50th percentile male physiological cross-sectional area<sup>10</sup> and by preliminary test.

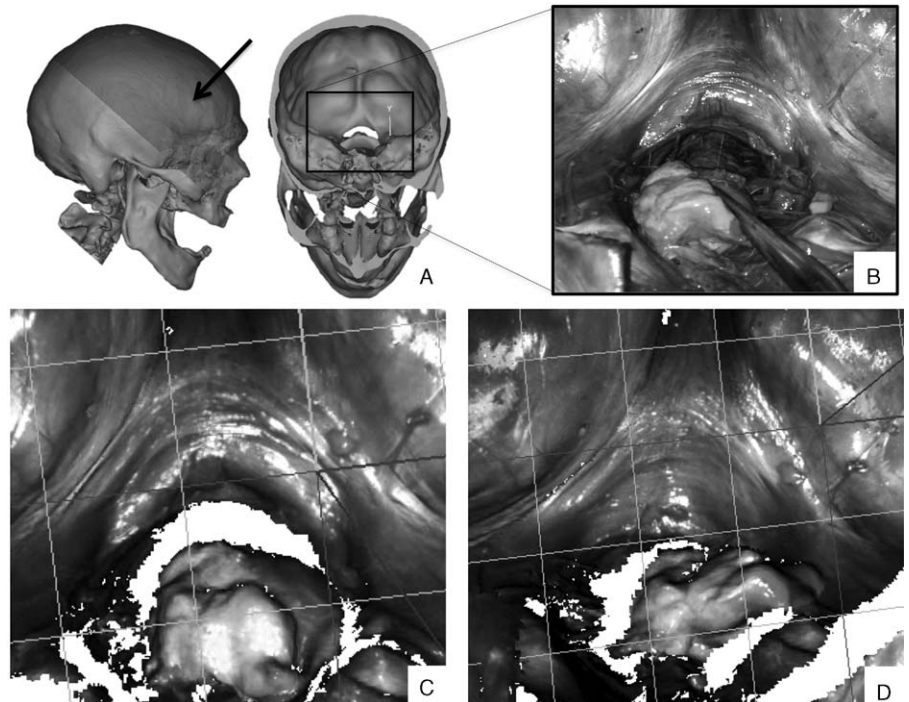
**Image Acquisition**

Displacement of the dura mater between neutral spine position and at hyperextension for each loaded states was

measured by 3D surface scanning. The 3D geometry of the surface of the dura mater at the atlanto-occipital region was acquired using a handheld structured-light scanner (Artec Spider; Artec Group, Palo Alto, CA). Structured-light scanning is a technique for accurately creating 3D surface models by projecting a known pattern of light onto the object, then capturing and analyzing the distortion of the pattern using a camera system. It has been used and validated for soft tissue morphology recording for clinical and for research.<sup>11,12</sup> The reported 3D resolution of this surface scanner is 0.1 mm, with a 3D point accuracy of up to 0.05 mm. Scans were acquired at a working distance of 17 to 30 cm and contained 170 ± 70 frames, obtained at seven frames per second. To evaluate the accuracy of the scanned model in the given setup, we compared virtual dimensions of the hexagon nuts used to hold the specimen to physical measurements made



**Figure 3.** Skull was mounted onto a platform designed to move the cervical spine from neutral to extension in respect to an immobilized skull (A). A metal rod was inserted into the drilled sides of the platform and into the 3D-printed custom plate attached to the anterior aspect of the cervical vertebrae to immobilize the cervical spine in the desired positioning (A and B). A portable electronic scale, fixed to the turnbuckle and the testing platform, was used to quantify the loading (A). Each RCPMi muscle was detached from its occipital origin and sutured to a wire frame (B and C). Static loads were applied to the muscle in a quasiphysiological direction (C and D). Picture of the connective tissue bridge during muscle loading (D). RCPMi indicates rectus capitis posterior minor.



**Figure 4.** A, Superior view on skull and ROI of the dura mater at the atlanto-occipital level. B, Photograph of the ROI at hyperextended cervical spine position showing bulging of the dura mater into the spinal canal at ROI. C, Scan of the ROI at hyperextended position. D, Scan of the ROI at neutral cervical spine position. ROI indicates region of interest.

with a precision caliper. The average deviations of 0.14 mm confirmed that the scanner was operating within the factory specifications. The scanned geometry at neutral and hyperextended cervical spine position were used as references for comparison (Figure 4).

### Image Processing

Using the scanner's software (Artec Studio 9.2), the scans were processed and exported as a triangulated surface mesh. For each specimen, meshes corresponding to loaded states were registered to the unloaded reference states using a paired-point followed by a surface registration in commercial software (Materialise, Leuven, Belgium).

### Data Analysis

For each point in the region of interest in a registered mesh, the distance to the corresponding surface of the reference mesh was determined. Displacement from the two compared surfaces was calculated from the 95th percentile of the global distance measured. A 3D color topographic map was generated to illustrate the magnitude of this residual distance to allow visual assessment of the distribution of any displacement of the dura mater.

## RESULTS

### Histological Investigation

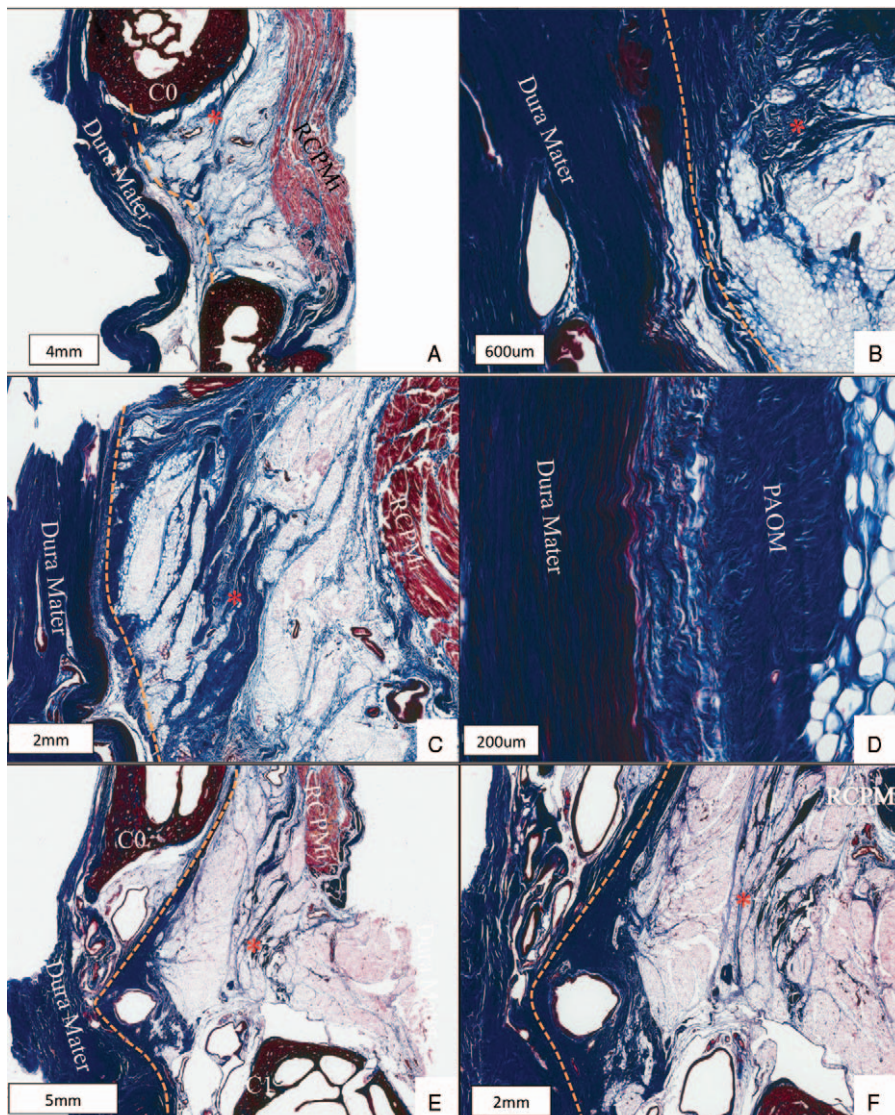
#### Description of the PAO Space: at the Medial Aspect of RCPMi

At the most medial aspect of the RCPMi, a collagen network composed of well-defined and well-oriented collagen fibers,

forming fine collagen bundles, was present in the PAO space. The collagen bundles originated from the periosteum of the external surface of the occiput, and the perimysium and endomysium of the RCPMi (Figure 5A). The collagen network inserted and contributed to a thin longitudinally organized collagen layer that ran parallel and superficial to the dura mater: the PAOM. This membrane layer originated from the periosteum of the inferior surface of the occipital bone and inserted onto the anterior surface of the posterior arch of the atlas. The PAOM and the dura mater were in contact in the most cephalic region of the PAO; however, they became distinct caudally (Figure 5B). There was no evidence of a full connection between the PAOM and the dura mater at the most medial aspect of the RCPMi in the PAO space.

#### Description of the PAO Space: At the Middle Aspect of the RCPMi

At the middle aspect of the RCPMi, the PAOM became thicker and distinctive in the PAO, preserving its longitudinal orientation in parallel and superficial to the dura mater (Figure 5C). At this level, the PAOM mainly originated from the periosteum of the inferior and external surface of the occiput from the posterior aspect of the foramen magnum. Collagen fibers and bundles from the ventral aspect of the RCPMi were more evident, forming a distinctive connective tissue inserting onto and contributing to the PAOM. In the cephalic portion of the PAO, the PAOM and dura mater were connected by a collagen interface. The direct connection was composed of less densely organized collagen fibers and undulating fibers, suggesting the presence of elastin (Figure 5D). However, the dura mater and PAOM remained separated in the most caudal region of the PAO space.



**Figure 5.** Histological section of the PAO space stained with Masson's trichrome. **A** and **B**, Originate from the medial aspect of the RCPMi. **A**, A fascia-like collagen network, known as the connective tissue bridge (\*), is originating from the periosteum of the external surface of the occipital bone (C0) and from the endo and perimysium of the RCPMi. It is inserting onto the superficial aspect of the PAOM (- - -). **B**, The dura mater and the PAOM are intimate to one another in the cephalic region and appear connected. They become more distinct caudally and show no evidence of connection with one another. **C** and **D**, Originate from the middle aspect of the RCPMi. **C**, The PAOM (- - -) is thicker, more defined, and is longitudinally oriented parallel to the dura mater. The collagen fibers from the RCPMi are more distinct, forming the connective tissue link (\*) that connects onto and appears to contribute to the thickening of the PAOM. The PAOM and dura mater are contiguous with one another in the cephalic region and get more distinct caudally. **B**, The interface between the PAOM and dura mater is composed of less densely organized and wavy collagen fibers directly connecting them together. **E** and **F**, Originate from the lateral aspect of the RCPMi. **E**, The PAOM (- - -) is originating from the external surface of the occiput and is distinct from the connective tissue bridge and dura mater. The PAOM is in contact with the dura mater only in the caudal region. The connective tissue bridge from the RCPMi is present and well-defined and its collagen fibers are oriented towards the anterior aspect of the posterior arch of the atlas. The direct connection of this collagen network and the PAOM is absent. **F**, Thin collagen fibers originating from the PAOM are fanning out into an adipocyte rich tissue. The PAOM is no longer inserting onto the anterior aspect of the posterior arch of the atlas but seems to blend into the dura mater at the level of the atlas. PAO indicates posterior-atlanto-occipital; PAOM, posterior-atlanto-occipital membrane; RCPMi, rectus capitis posterior minor.

### Description of the PAO Space: At the Lateral Aspect of the RCPMi

At the lateral aspect of the RCPMi, the PAOM was distinct from the connective tissue bridge and the dura mater. The PAOM originated uniquely from the external surface of the occiput and no longer from the inferior surface of the mentioned bone. In the most cephalic part of the PAO space, the contact between the dura mater and the PAOM was lost, yet they remained in contact caudally (Figure 5E). At this lateral level of the PAO space, a collagen network originating from the ventral aspect of the RCPMi was still present and well-defined, but diminishing. The collagen fibers were oriented more vertically toward the ventral aspect of the posterior arch of the atlas. The direct connection of the collagen network from the RCPMi and the

PAOM was lost laterally and gradually replaced by thin collagen fibers, distributed in a fan-shaped pattern into the rich adipose tissue of the PAO space (Figure 5F). The PAOM no longer inserted onto the anterior aspect of the posterior arch of the atlas, but seemed to blend into the spinal dura mater at approximately the level of the posterior arch of the atlas.

### Biomechanical Investigation

During hyperextension, the dura mater at the atlanto-occipital level bulged  $3.1 \pm 0.8$  mm into the spinal canal, compared with neutral spine position (Table 1). On every tested sample, increasing the static load of individualized muscle amplified the posterior displacement of the dura mater (Figure 6) with an approximately linear relationship. At

**TABLE 1. Dura Mater Displacement (mm) at the Atlanto-Occipital Level Compared With Neutral Spine Position**

|                                      | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 | Mean ± SD    |
|--------------------------------------|------------|------------|------------|------------|------------|--------------|
| Anterior bulging                     | 2.67       | 2.07       | 3.25       | 3.07       | 4.36       | 3.08 ± 0.84  |
| Posterior displacement, left muscle  | 0.84       | 1.34       |            | 1.98       | 1.88       | 1.51 ± 0.53  |
| Posterior displacement, right muscle | 2.26       | 1.12       | 1.54       | 1.56       | 2.01       | 1.70 ± 0.44  |
| Average of posterior displacement    | 1.55       | 1.23       | 1.54       | 1.77       | 1.94       | 1.61 ± 0.46  |
| % Bulging reduction                  | 58.00      | 59.25      | 47.28      | 57.74      | 44.52      | 53.36 ± 6.90 |

Anterior bulging was measured during hyperextension spine position. The posterior dura mater displacement is reported at maximal static muscle loading (20 N). Left muscle of specimen 3 served to establish the loading protocol and therefore has been removed from the pool.

maximum loading, the highest posterior displacement measured was 2.3 mm and the total average over specimens was  $1.6 \pm 0.5$  mm. The posterior displacement was ipsilateral with the loaded muscle. The 3D color topographic maps showed that, generally, the maximal posterior displacement of the dura mater was located laterally to the mid-sagittal line. Figure 7 illustrates a typical result of posterior displacement under load.

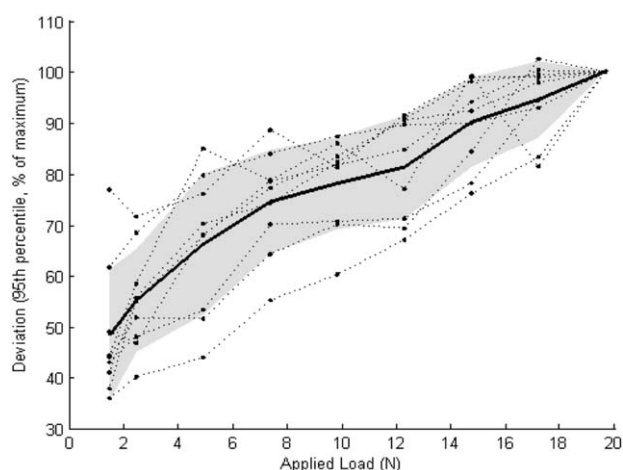
**DISCUSSION**

The histological investigation supported the concept of the connective tissue bridge and the PAOM. The connective tissue bridge was mostly present on the middle aspect of the RCPMi, where it had a fascia-like insertion onto the PAOM. The PAOM and the spinal dura mater were connected to one another by a fine connective tissue interface. This detail supported the findings of the PAOM-SDC highlighted by

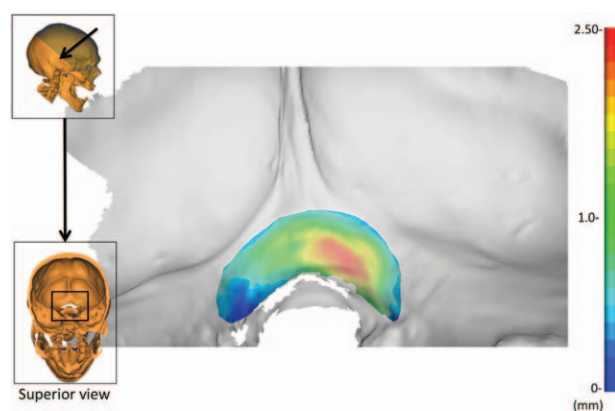
Hack *et al.*<sup>1</sup> Our findings support Hack *et al.*<sup>1</sup> in the description of the fascial bridge between the RCPM and the PAOM.

**Posterior-Atlanto-Occipital Membrane**

The PAOM originated from the periosteum of the occipital bone, with its external and inferior surface at the postero-medial aspect of the foramen magnum. More laterally, the PAOM originated from the external surface of the occiput. Midway to the RCPMi, the PAOM and the spinal dura mater were connected to one another by a fine connective tissue interface, giving the PAO dura mater a thicker appearance compared to its anterior aspect, as found by Hack *et al.*<sup>1</sup> and supported by Taylor.<sup>13</sup> Our histology suggests that this thickness could be attributed to the tissue bridge blending into the PAOM of the PAOM-SDC. At the most lateral aspect of the RCPMi, the PAOM was decreasingly evident until its complete absence more laterally, implying the loss of connection with the dura mater.



**Figure 6.** Displacement-force plots for nine RCPMi muscles, normalized to displacement at maximum load. The mean normalized displacement is plotted in bold, with a standard deviation about the mean shown by the shaded region. The highest displacement measured was 2.3 mm. Displacement at maximum load average  $1.6 \pm 0.5$  mm. RCPMi indicates rectus capitis posterior minor.



**Figure 7.** Representative 3D color topographic maps illustrating the magnitude of displacement of a left loaded RCPMi. The general localization of the maximal posterior displacement of the dura mater was located laterally to the mid-sagittal line, ipsilateral with the loaded muscle. RCPMi indicates rectus capitis posterior minor.

### Connective Tissue Bridge

The spatial relationship between C0 and C1 was preserved during the positioning of the samples in paraffin wax. The PAO space description is based on histology observation and therefore could vary from *in vivo*.

A connective tissue bridge connecting the perimysium of the ventral aspect of the RCPMi to the PAOM was observed throughout the entire width of the RCPMi, being more prominent at the middle aspect of the muscle. As described by Nash *et al*,<sup>4</sup> the collagen network of the connective tissue bridge in the PAO space was well-defined and showed a clear orientation from postero-cephalic to antero-caudal. Previous work found that structural fibers increase in thickness and density and are oriented in the direction of load acting on them, suggesting a mechanical role in tensile-force transmission.<sup>14-16</sup> The connective tissue bridge fibers' orientation was distinctively defined, suggesting a potential mechanical influence in their patterning. This collagen organization could suggest a mechanical link between the RCPMi to the PAOM-SDC.

The fibers of the connective tissue bridge inserted onto and participated in the PAOM thickening. The attachment of the connective tissue fibers onto the PAOM was a fascia-like connection. No trace of either tendinous tissue or a direct link from the RCPMi to the dura mater could be found, as suggested by some authors.<sup>4,6</sup>

### Mechanical Role of the RCPMi With Spinal Dura Mater

For each individual muscle used in the biomechanical section of this study, statically loading of the RCPMi produced a quasilinear relationship of increasing posterior displacement of the dura mater. This posterior displacement reduced the bulging of the dura mater into the spinal canal, during hyperextension, by  $53.4\% \pm 6.9\%$ . The distribution of displacement of the dura mater highlighted by the 3D color topographic maps suggested that the localization of displacement occurred approximately at the middle aspect of the RCPMi (Figure 7). This region corresponds to the histological description of the localization of the connective tissue bridge insertion onto the PAOM. These results suggest that the RCPMi could have a mechanical effect on the spinal dura mater, such as a protective and mechanically supportive role; this theory was previously proposed as preventing or restraining the bulging of the dura mater into the spinal canal or impingement during head extension, as advanced by Hack *et al*<sup>1</sup> and supported by other authors.<sup>8,13,17,18</sup>

The length of the muscle in extension and neutral position and its displacement during loading were not controlled or measured in this study. This could be an avenue for future work on how mechanical forces are transmitted from the RCPMi to the dura mater.

Despite the limited number of specimens, and the quasiphysiological muscle loading direction, which could have affected the dura mater displacement results, these findings provide evidence of an anatomical link of the RCPMi with

regard to the spinal dura mater and of a mechanical role of the RCPMi on the dura mater.

### CONCLUSION

Histological investigation supported the concept of the connective tissue bridge and the PAOM. The connective tissue bridge had a fascia-like insertion onto the PAOM. The PAOM and the spinal dura mater were connected to one another by a fine connective tissue interface. The orientation of the connective tissue bridge fibers and direct linear relationship of posterior displacement of the dura mater with increasing static loads all support the theory that the RCPMi could have a mechanical influence on force distribution in regard to the spinal dura mater, such as a protective and mechanically supportive role. These results may provide anatomical and physiological information of the craniocervical junction for helping understanding the pathogenesis of cervicogenic headaches.

### Key Points

- ❑ The rectus capitis posterior minor muscle has a connective tissue link to the spinal dura mater at the craniocervical junction.
- ❑ As measured by structured light surface mapping, static loading of the RCPMi produced posterior displacement of the dura mater.
- ❑ These findings may provide insights into understanding the pathogenesis of cervicogenic headache.

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