Magnetic Resonance Imaging of Cerebrospinal Fluid Volume and the Influence of Body Habitus and Abdominal Pressure

Quinn H. Hogan, M.D.,* Robert Prost, B.S.,† Alexander Kulier, M.D.,‡ Mary Lou Taylor, Ph.D.,§ Spencer Liu, M.D.,¶ Leighton Mark, M.D. #

Background: Although the cerebrospinal fluid (CSF) is the pathway of anesthetic delivery and the diluent for neuraxially administered drugs, little is known about its volume, including variability among individuals, longitudinal distribution, or influence of body habitus. Models made to investigate subarachnoid anesthetic distribution lack valid dimensions. CSF volume was measured in volunteers, and the effect of obesity and abdominal compression on CSF volume was evaluated using magnetic resonance imaging.

Methods: Low thoracic and lumbosacral axial magnetic resonance images of 25 healthy volunteers were obtained at 8-mm intervals by fast spin-echo sequence, which highlights CSF. A repeat image series was performed in 15 subjects during external abdominal compression. In two subjects, images were obtained without compression for the entire vertebral column. Dural sac and spinal cord areas were determined in a blinded fashion for each image using video/digital analysis. Area of the sac minus area of the cord constituted area of CSF and roots ("CSF/root"); this area multiplied by 8 mm resulted in CSF/root volume per section.

Results: There is great interindividual variability in CSF/root volume. From the T11–T12 disc to the sacral terminus of the dural sac, the mean volume for all subjects is 49.9 ± 12.1 ml (mean ± SD; range 28.0–81.1 ml). This volume was significantly less in relatively obese subjects (42.9 ± 9.5 ml) than in non-obese subjects (53.5 ± 12.9 ml). Abdominal compression decreased CSF/root volume by 3.6 ± 3.2 ml. Sections through intervertebral foramina showed the biggest decrease with abdominal compression, with a lesser change in sections with veins and no change in the absence of these anatomic features. Total vertebral CSF/root volume in two subjects was 94.84 and 120.01 ml, respectively.

Conclusions: CSF volume is widely variable between individuals. The decreased CSF volume that results from increased abdominal pressure, such as with obesity or pregnancy, may produce more extensive neuraxial blockade through diminished dilution of anesthetic. The mechanism by which increased abdominal pressure decreases CSF volume is probably inward movement of soft tissue in the intervertebral foramen, which displaces CSF. (Key words: Anatomy; vertebral column. Anesthetic techniques: epidural; spinal.)

THE cerebrospinal fluid (CSF) is the diluent for drugs delivered by a subarachnoid route. Local anesthetics are typically administered in concentrations 100-fold greater than the minimum effective concentration (C₉₀) for neural blockade (e.g., about 0.025–0.05% for lidocaine¹), and the degree of subsequent dilution can be expected to determine distribution of blockade. The site of action for epidurally administered local anesthetics is also predominantly within the subarachnoid space.² Despite the obvious importance of CSF volume, it has not been adequately measured. Of particular practical interest are the range and variability of CSF in the lower spine, where most epidural and spinal anesthetics are performed, as well as the clinical influences on CSF volume that might predict anesthetic response. Models of the subarachnoid space have been used to analyze anesthetic distribution,³ but they lack validation because volumes are not known and the axial section area is assumed constant over the length of the model.

Previous findings indicate that aspects of body habitus may influence distribution of neuraxial anesthetics. For
example, the extent of anesthetic distribution after injection of a fixed dose of epidural or subarachnoid local anesthetic is highly variable, yet block produced in each individual is consistent. Also, blockade is predictably more extensive in obese subjects and in pregnancy. One explanation is that individuals differ in their CSF volume and that pregnancy and obesity are accompanied by a decreased CSF volume. We therefore determined CSF volume in volunteers with different body habitus using a new method of magnetic resonance imaging (MRI) that allows clear identification of the CSF with short acquisition times while avoiding ionizing radiation or subarachnoid contrast injection. Because the dural sac is known to be easily compressible during brief maneuvers, such as Valsalva or jugular compression, we hypothesize that tonic influences of body habitus are accompanied by a shift in the range of CSF volumes and that abdominal compression will duplicate these changes.

Methods

After institutional review board approval and with the subjects’ written consent, 25 healthy paid volunteers without back complaints or previous surgery were studied. Their height and weight were measured as well as waist and hip circumferences. Imaging was performed using a 1.5T Signa MRI system (General Electric, Milwaukee, WI) with the subject in the supine position with the knees slightly flexed on a wedge for comfort. After obtaining a midline sagittal scout view (fig. 1), serial fast spin echo images of the lower spine were obtained in the axial plane at 8-mm intervals (fig. 2; appendix).

In ten normal subjects (six men, four women), this was the only image sequence obtained. Fifteen other subjects (all men) were recruited into the study because of moderate obesity (n = 8) or slim build (n = 7). In these subjects, imaging was performed before and during abdominal compression with care not to move the subject between imaging sessions so that images would be obtained at precisely the same levels. During the second series of images, abdominal compression was produced by inflation of an empty 5-l irrigation solution bag to a pressure of 20 mmHg while being constrained against the subject’s abdomen with a 36 cm-wide circumferential binder. This pressure resulted in a sensation of fullness, such as after a large meal, but was not uncomfortable and did not limit ventilation.

Two subjects had further series of images to portray the entire vertebral canal up to the foramen magnum. This was performed without abdominal compression.

Images were printed on x-ray film using constant display parameters (window and level) and were analyzed by a single investigator (Q.H.H.). During quantification, the images were encoded and randomized to blind the investigator to the source of the image with regard to subject habitus and the presence or absence of abdominal compression. The area of the dural sac was determined using an image-processing system (Image Pro Plus v1.0, Media Cybernetics L.P., Silver Spring, MD).

The transilluminated magnetic resonance image was photographed by a video camera and digitized for computer analysis. No image enhancement techniques were applied. The inner aspect of the dural margin was traced and the surrounded area computed for each image. The area of the spinal cord was similarly measured at levels where it appeared. No attempt was made to measure nerve roots. Where CSF in the dural sleeve at the intervertebral foramen was contiguous with the rest of the CSF, it was included in area measurement. Where the nerve root fully occupied the exiting dural sleeve at the intervertebral foramen, the CSF outline followed the medial aspect of the nerve roots rather than the

Fig. 1. Sagittal magnetic resonance imaging of lower thoracic and lumbar sacral vertebral column illustrating typical levels of subsequent axial imaging. Scale bar = 5 cm.
Fig. 2. Representative images by axial fast spin-echo magnetic resonance imaging. (A) Section through the L1–L2 intervertebral foramen at baseline (BL) and during abdominal compression (AC). Anterior is up, and the scale bar is 1 cm in this and other images. The bright area is CSF, and roots are represented by multiple low-intensity defects in the CSF. Dural area at this level decreased from 2.71 to 2.56 cm² with compression, with evident inward movement of foraminal contents (arrows). Dorsal root ganglia are evident in the intervertebral foramina, and the conus medullaris/filum terminale is seen in the midst of the roots. The darkening of the CSF during abdominal compression represents flow artifact due to increased longitudinal CSF movement. (B) Section through the L3 vertebral body and venous plexus in the anterior epidural space (arrows) before (BL) and during (AC) abdominal compression (same subject as A). Dural area at this level decreased from 2.72 cm² to 2.49 cm² with compression. There is displacement of the anterior dural sac posteriorly by the expanded veins during abdominal compression. (C) Section through the L5–S1 intervertebral foramen before (BL) and during (AC) abdominal compression (same subject as A). Expansion of the anterior epidural space and inward movement of the foramen contents cause decreased volume of the dural sac. Dural area decreased from 2.59 to 2.15 cm² with compression.

results in the volume of CSF plus nerve roots, was determined and termed CSF/root volume. Dependence of CSF/root volume on height, body mass index (BMI; weight divided by height squared in kg/m²), and waist/hip ratio (waist circumference divided by hip circumference) in all 25 subjects was examined by simple regression.

To generate average axial section areas for sites along the length of the dural sac at anatomically relevant longitudinal locations, a normalization process was employed. This was necessary because images were obtained at 8-mm intervals without reference to anatomic segmentation, thus slices in different subjects would not necessarily fall at the same sites, and the number of slices per anatomic interval is not necessarily comparable between subjects. Two reference points, the T11–T12 disk and the L5–S1 disk, were identified in the image series of each subject. The distance between these points was divided into 18 equal intervals (bins), and area measurements were grouped from images within the longitudinal range of each bin and an average area calculated for the bin. Other bins of equal longitudinal dimension extended above T11–T12 and below L5–S1. By this approach, average distribution of dural sac area by longitudinal position was generated for slim, obese, and all subjects. Longitudinal distribution of axial section area before and after abdominal compression was generated by bin.
To examine the validity of the imaging and digital quantification of the images, a phantom was constructed of an uncooked pork roast with a 20 ml saline-filled syringe wedged within it. The area of fluid inside the syringe on axial section images was measured using the system described above and compared to the area calculated from measurement of internal syringe diameter determined by caliper.

Averages of parameters for which a single value was determined in each individual (weight, height, waist, and hip measurements and volume calculations) were compared by single-tailed $t$ test. Means are presented with standard deviation for variability within a group of individual data points and with standard error for variability of a group of means. A three-way (one between, two within factors) univariate analysis of variance for repeated measures (SuperANOVA, Abacus, Berkeley, CA) was performed on areas (e.g., of dura and CSF/roots). On main effects and interactions with significant F-values, comparisons of specific means were one by denominator adjusted $t$ tests.

**Results**

Age and height are comparable for all subjects, slim subjects and obese subjects (table 1). The BMI and waist/hip ratio were significantly larger in the obese subjects compared to slim subjects.

The overall mean CSF/root volume inferior to the T11–T12 disk for all subjects was $49.9 \pm 12.1$ ml (mean $\pm$ SD) with a range of 28.0–81.1 ml. Dural volume and CSF/root volume were larger in slim subjects when compared to obese subjects. Abdominal compression produced a comparable decrease in CSF/root volume in slim and obese subjects, with an average decrease in all subjects of $3.6 \pm 3.2$ ml.

The complete data set of dural sac and cord areas for all individuals is shown in figure 5, illustrating the interindividual variability of these measures. The distance between the longitudinal references for normalization (the T11–T12 disk and the L5–S1 disk) ranged from 18.8 to 22.4 cm. Longitudinal distribution of average axial section area at sites along the length of the dural sac are shown in figure 4, comparing all (fig. 4A), and slim and obese subjects (fig. 4B). The section area in obese subjects is less than in slim subjects throughout the length of the lumbar and sacral dural sac. Figure 4C shows the change in dural area during abdominal compression according to longitudinal site. The great-
MRI MEASUREMENT OF CSF VOLUME

Fig. 3. Area determinations for dural sac and cord of all subjects. Great interindividual variability is evident.

est changes were in the lower lumbar and sacral segments.

There was a dependence of CSF/root volume on BMI ($r = 0.40, P < 0.05; \text{fig. 5}$) but no significant regression of CSF/root volume with either height or waist/hip ratio.

Table 2 shows that there were no differences in axial section area according to whether the section contained intervertebral foramen, obvious veins, or neither. Also shown is the change in volume during abdominal compression attributable to sites with vein, foramen, or neither. There is a greater volume decrease in sections at the site of intervertebral foramina than in sections with vein or neither, and the decrease at sites with veins exceeds that at sites with neither foramen nor vein.

The results of the evaluation of the complete dural sac in two subjects are shown in table 3 and figure 6. The total CSF/root volume is 94.8 and 120.0 ml, of which about 40% resides in the region inferior to the T11-T12 disc studied in the other subjects.

The average difference between duplicate determinations of axial areas from the images was 1.48 ± 0.13%, and the coefficient of correlation between duplicate determinations was $r = 0.9972 ± 0.0005$. Repeat measures of the axial section area of the magnetic resonance images of the phantom differed from the area by caliper by an average of 0.01 cm$^2$ (using the absolute value of differences for averaging). This represents an error of 0.4%. The intraabdominal pressure change produced by abdominal compression was determined in a single subject (BMI 23.3 kg/m$^2$) by esophagogastroduodenoscopy; resting intragastric pressure of 7 mmHg increased to 15 mmHg with compression by the method used during imaging.

Discussion

The principal findings of this study are the wide variability in spinal CSF volume, a lower average CSF volume in subjects with high BMI, and a decrease in CSF volume during static abdominal compression. Previous studies have used myelography to examine dural sac diameter$^{10-18}$ and cord dimensions.$^{19}$ While these and autopsy studies$^{20}$ largely are consistent with the current findings, area and volume determinations could have been derived only by secondary calculations using assumptions about dural and cord shape. On the other hand, our technique using MRI gives direct imaging of axial areas in living subjects.

A similar MRI technique has been used by other investigators to evaluate CSF volume.$^{21}$ They found CSF volumes between T2 and S1 vertebral levels of 42.2–80.0 ml using a technique in which the image pixels with intensities in the range typical for CSF were sorted by histogram from those of the rest of the area of interest. Although this was done to exclude nerve roots from CSF volume determination, we chose not to use this technique. Because the size of the nerve roots approximates the resolution of MRI, a large error is introduced by volume averaging, in which the intensity of a pixel that includes an interface between the two structures is intermediate between the densities of adjacent structures. Also, the effect on volume determinations of viewer controls$^{22}$ is magnified by evaluating many interfaces. Furthermore, the threshold of image intensity for inclusion of a pixel as CSF is inevitably arbitrary to some degree because these boundary effects, movement artifact from CSF pulsation, and chemical shift artifact produce variable image intensity within the CSF (fig. 2). The method used in the current study, in which borders of dura and cord were outlined on the basis of previous anatomic work,$^{23}$ minimizes these sources of error because dural boundaries are clearly seen.

We determined the combined volume of CSF and roots and have no means of separating root volume from the data in this study. However, examination of root volume in fresh autopsy specimens$^{24}$ provides an esti-
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Fig. 4. Average axial section areas along the length of the vertebral column are shown for (A) CSF/root area for all subjects; (B) CSF/root area for slim and obese subjects (*significant difference between slim and obese at that level; \( P < 0.05 \)); and (C) dural area before and during abdominal compression (*significant difference between control and compressed at that level; \( P < 0.05 \)). Values are mean ± SE.

Fig. 5. Dependence of CSF/root volume on body mass index (\( r = 0.40; P < 0.05 \)).

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ulate of 7.31 ± 0.33 ml volume of roots inferior to the T11–T12 disk. This is about 15% of the total dural sac volume not occupied by cord below T11–T12 and results in an estimate of an average CSF volume of 42.6 ml below T11–T12, with a range of 20.7 ml to 73.8 ml. This 3.6-fold difference is remarkable, especially in that the subjects were selected from a normal pop-
MRI MEASUREMENT OF CSF VOLUME

Table 2. Dura Area and Dura Volume Change with Compression, According to Anatomic Features Present in the Section

<table>
<thead>
<tr>
<th></th>
<th>All Levels</th>
<th>Foramen</th>
<th>Vein</th>
<th>Neither</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dura area (cm²)</td>
<td>2.2 ± 0.12 (average)</td>
<td>1.99 ± 0.11†</td>
<td>2.25 ± 0.11</td>
<td>2.17 ± 0.12</td>
</tr>
<tr>
<td>Dura volume change (ml)</td>
<td>-3.76 ± 0.86 (total)</td>
<td>-2.35 ± 0.43†</td>
<td>-1.28 ± 0.32*</td>
<td>-0.46 ± 0.20</td>
</tr>
</tbody>
</table>

Values are mean ± SE.
† P < 0.05 versus Foramen.
* P < 0.05 versus Vein.

sure has been shown to increase linearly with increased body weight. Because abdominal compression produces a comparable increase in intraabdominal pressure, this is a suitable analog for the study of intraabdominal mechanics of obese subjects. Our finding that abdominal compression also decreases CSF/root volume therefore supports elevated intraabdominal pressure as the mechanism of decreased CSF in obese subjects. We expected CSF/root volume also to show dependence on waist/hip ratio, which, when high, indicates preferential abdominal obesity. That this did not prove to be so may result from skeletal contributions to the waist/hip ratio that do not affect intraabdominal pressure.

The CSF reduction produced by external abdominal compression (3.6 ml) is less than the difference between obese and slim subjects (10.6 ml). This may be due to lower abdominal pressures in our compression model than with obesity, although the gastric pressure achieved by compression in the one subject tested by manometry is typical of obese subjects in another study with weights of 113–205 kg. Also, brief compression may have a diminished effect compared to persistent increase, as with obesity. Alternatively, factors associated with obesity other than increased abdominal pressure may contribute. The effect of obesity is seen throughout the lumbosacral spine, whereas external compression produced volume loss mostly at sacral levels.

The greatest change in CSF volume during abdominal compression was found at sites in which intervertebral foramina were present. This is probably because of displacement of foraminal contents (mostly fat) inward as retroperitoneal pressure increases with abdominal pressure (fig. 2A) and is the principal mechanism for CSF volume decrease with abdominal compression by the method in this study. A lesser change was seen at sites with veins but no foramina (fig. 2B), possibly because of altered venous flow patterns. Although there is no direct evidence for it, the common explanation of extensive block in conditions associated with increased abdominal pressure is epidural venous distension, which in turn is thought to compress the dural sac. The findings of this study do not support this mechanism as the primary cause of decreased CSF volume. Although direct pressure focused on the vena cava by a gravid uterus might produce venous obstruction and epidural venous distension, it is unlikely that a global and uniform pressure increase in the abdomen would greatly alter venous flow because pressure also will increase in the spinal canal.

A decreased CSF volume with elevated abdominal pressure, such as with obesity or pregnancy, is a possible mechanism for more extensive spinal and epidural blockade in such subjects. External abdominal compression similar to our study results in extending blockade after intrathecal tetracaine in nonpregnant subjects to a degree comparable to blockade achieved in pregnant subjects. Also, high epidural pressures result in more extensive epidural blockade. It is unlikely that epidural fat increases with obesity, but other factors contributing to higher blocks during

<table>
<thead>
<tr>
<th>Subject No.</th>
<th>BMI</th>
<th>Waist/Hi Ratio</th>
<th>Cervical Volume (ml)</th>
<th>Thoracic Volume (ml)</th>
<th>Lumbar Volume (ml)</th>
<th>Sacral Volume (ml)</th>
<th>Total Volume (ml)</th>
<th>% Below T11/T12</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>22.79</td>
<td>0.95</td>
<td>21.15</td>
<td>41.13</td>
<td>30.52</td>
<td>2.03</td>
<td>94.84</td>
<td>40.76</td>
</tr>
<tr>
<td>2</td>
<td>23.25</td>
<td>0.86</td>
<td>33.25</td>
<td>46.24</td>
<td>35.67</td>
<td>4.85</td>
<td>120.01</td>
<td>38.85</td>
</tr>
</tbody>
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pregnancy and in stout patients may include a higher needle insertion site because of change in body contours and increased neural sensitivity to local anesthetics in pregnancy.\(^3\)

Only the change in CSF area for the entire axial cross-section of the subarachnoid space was examined in our study. The nerve root cuff in the intervertebral foramen, a possibly important site of epidural anesthetic action, will be most directly affected by pressure changes. Therefore, a proportionately greater change in the CSF volume of this subarachnoid cul-de-sac can be expected, decreasing anesthetic dilution.

Measurement of the complete dural sac in two subjects showed that a substantial portion of the entire CSF/root volume is in the immediate area of spinal and lumbar epidural injection (fig. 6). Prompt buffering of anesthetic effect by dilution is produced by this fortuitous accumulation of CSF at the most frequent site of neuraxial injection. Diminished CSF content at mid-thoracic segments probably contributes to the increased efficacy of epidural local anesthetic injected at those levels by causing less dilution of anesthetic. Our finding of decreased dural area in the midthoracic vertebral column is in agreement with measurements of the vertebral canal, which also follows this pattern.\(^3\)

Our findings can be summarized as showing tremendous variability in CSF volume and a typically smaller CSF volume in obese subjects. Because similar changes take place with external abdominal compression, increased abdominal pressure is probably the agent causing CSF decrease. Increased abdominal pressure in turn acts to decrease CSF volume mostly by displacing tissue into the vertebral canal through the intervertebral foramina rather than by changing venous volume. The data presented here will aid in designing more accurate subarachnoid space models for determining distribution of intrathecal medication. Further study will test whether CSF volume can predict the distribution of anesthesia after neuraxial local anesthetic administration.

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Appendix

A single magnetic resonance imaging acquisition produces a series of individual images in the same orientation. For this study, images were obtained using a four-coil phased array dedicated spine imaging coil. Acquisition parameters were as follows: repetition time 5,500 ms; effective echo time 133 ms; echo train length 8; 42 images; field of view 16 cm; three excitations; image matrix 256 × 256; 3-mm slices with 5-mm interslice spacing; and 16 kHz receiver bandwidth. All images were generated in an axial plane and were therefore in a consistent orientation parallel to each other but not necessarily perpendicular to the axis of the vertebral canal or dural sac. The data that resulted from each magnetic resonance imaging acquisition was a sequence of axial images at 8-mm intervals with a pixel size of 0.625 × 0.625 mm.