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MR Assessment of the Normal Position of the Spinal Cord in the Spinal Canal

J. Holsheimer, J. A. den Boer, J. J. Struijk, and A. R. Rozeboom

PURPOSE: To investigate intradural geometry, which strongly influences the effects of epidural spinal cord stimulation. **METHODS:** Axial MR images with turbo spin-echo were made of 26 healthy subjects at C-4 through C-6, T-5 and T-6, and T-11 and T-12, at T-11 and T-12 both in the supine and the prone position. Measurements were made of the dorsomedial and the ventromedial cerebrospinal fluid layer and the anteroposterior and transverse sizes of both the spinal cord and the dural sac. The samples of all variables were analyzed statistically. The distance between spinal and vertebral midline was also determined. **RESULTS:** The dorsal cerebrospinal fluid layer was 1.5 to 4.0 mm at C-4 through C-6 and 4.0 to 8.5 mm at T-5 and T-6. At T-11 it was 2.0 to 6.0 mm in the supine position and was increased by approximately 2.2 mm in the prone position. At T-12 these values were 1.5 to 4.5 mm and approximately 3.4 mm, respectively. Differences between the spinal and vertebral midline up to 1.5 to 2.0 mm occurred in approximately 40% of the images. **CONCLUSIONS:** Because there are variations of the dorsal cerebrospinal fluid layer among subjects by more than a factor of 2, and significant variations of the mediolateral position of the spinal cord, information on these parameters in patients will be essential for the optimal application of epidural spinal cord stimulation.

Index terms: Meninges; Spinal cord, anatomy; Spine, magnetic resonance; Spine, special procedures

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The anteroposterior and transverse sizes of the spinal cord have been assessed by autopsy (1), (postmortem) myelography (2–4), computed tomographic myelography (5–7), and magnetic resonance (MR) imaging (8). Most studies were confined to the vertebral levels C-4 through C-6, and only few presented some data on the anteroposterior size of the dural sac (2–4, 7).

The thickness of the dorsal cerebrospinal fluid (CSF) layer between dura mater and spinal cord (dorsomedial layer) is an important parameter in epidural spinal cord stimulation, as was suggested by clinical experience (Spincemaille GH, Wittens CH, Electrical Stimulation of the Spinal Cord, the Phenomenon of Changing Paresthesias, presented at the International Congress on Epidural Spinal Cord Stimulation in Movement and Vascular Disorders, Groningen, The Netherlands, 1989) and predicted by computer modeling (9, 10). When the epidural spinal cord stimulation contacts are positioned at the (radiologic) midline of the spine, paresthesia are symmetrical in only 27% of the patients (11), possibly because of an asymmetrical position of the spinal cord in the dural sac. To improve the computer model, developed for the prediction of the effects of epidural spinal cord stimulation and as a tool for the design of new electrodes, data on dorsomedial layer and on transverse asymmetry are essential. Therefore, we undertook an MR study on healthy subjects. We focused on three vertebral levels: midcervical (C-4 through C-6), midthoracic (T-5 and T-6), and low thoracic (T-11 and T-12). To obtain a good contrast between spinal cord, cere-

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brospinal fluid, dura mater, and epidural space, we used strongly T2-weighed turbo spin-echo scans.

The position of the cord in the dural sac, and thus the dorsomedial layer, may vary with a subject's position. Low thoracically there was a large difference when subjects were turned from supine to prone position. At the midthoracic kyphosis the spinal cord almost touched the ventral dura mater when subjects were in the supine position. Therefore, when turning to the prone position a significant change in cord position at T-5 and T-6 is unlikely. Because the cervical spine has two degrees of freedom, it was difficult to examine the cervical dorsomedial layer in a well-defined position of the neck among subjects. Therefore, transverse scans of the subjects in the supine position were made at all three vertebral levels and in the prone position only at T-11 and T-12.

In this investigation we not only measured dorsomedial layer from the turbo spin-echo images, but also the anteroposterior and transverse sizes of the spinal cord and the dural sac. The data from all subjects were analyzed statistically.

Materials and Methods

MR Protocols

Twenty-six healthy male volunteers (19 to 38 years) participated in this MR study. A sagittal survey scan and axial scans at C-4 through C-6, T-5 and T-6, and T-11 and T-12 were made in the supine position, followed by a survey and an axial scan at T-11 and T-12 in the prone position. During the cervical scans the neck was in a straight position. The whole procedure took approximately 1 hour for each subject and was executed on a 1.5-T MR system.

Two standard protocols were used for the sagittal surveys, and another two were developed for the axial scans. The cervical survey scan was made with a flexible, circular surface coil (C1 coil, 170 mm diameter) and the others with a body coil. The sagittal surveys were used to identify the vertebrae and to select the positions and orientations of the axial scans.

Each axial scan had six sections, covering the vertebrae C-4 through C-6, T-5 and T-6, and T-11 and T-12, respectively, resulting in two or three sections at each vertebra. Each series of six sections had the same orientation, perpendicular to the (average) direction of the posterior border of the corresponding vertebral bodies. All axial scans were made with the C1 coil, centered carefully at the scanning area. For data acquisition strongly T2-weighed turbo spin-echo scans were used, having sufficient signal-to-noise ratios and only minor CSF flow artifacts. This technique is similar in design to rapid acquisition with relaxation enhancement (12). Different sequences were used for axial scans in the supine and the prone positions.

Turbo Spin-Echo Scan Technique

The turbo spin-echo sequence for the supine position had the following parameter values: 4000/168/8 (repetition time/echo time/excitations), turbo factor of 24, field of view of 153 mm, matrix of 256 × 256, section thickness of 5.0 mm, and section separation of 5.5 mm. The scanning time was approximately 4.5 minutes and the resolution was 0.6 mm. Using this sequence in the prone position at T-11 and T-12 would give useless scans, because of breathing movements. Therefore, a second sequence was selected in which a single section could be scanned while breath was held for approximately 14 seconds. The parameter values of this turbo spin-echo sequence were as follows: 2300/168/2, turbo factor of 64, field of view of 256 mm, matrix of 256 × 256, half-scan, linear K_y-value order (phase-encode gradient), section thickness of 8.0 mm, and section separation of 2.5 mm. The six sections were scanned sequentially at intervals of approximately 20 seconds, and the resolution was 1.0 mm. Although the quality of the prone sections was less than those made in the supine position (Figs 1C and 1D), this was not a problem. Because the sections at T-11 and T-12 in the prone and the supine positions were made at identical vertebral positions, the high-quality supine images could be used in the evaluation of the prone images.

The system accuracy was tested by measurement of the size of a cylindrical vessel placed inside a standard test phantom. The observed error was between 0% and +2% in both transverse and anteroposterior directions. No correction for this error was attempted. The stability of the system adjustment was tested on a weekly basis, using the manufacturers periodic test protocol. The variation of the adjustment had a standard deviation of 0.3%. A few subjects were scanned more than once in the same or in different sessions. The images were identical, which means that differences were less than 3%.

Image Evaluation

All axial turbo spin-echo images were enlarged such that hard copies of 2.00 times the real size were obtained. The following variables were measured from all axial images in the supine position: anteroposterior size of the spinal cord (SCap), transverse size of the spinal cord (SCtr), anteroposterior size of the dural sac (Dap), transverse size of the dural sac (Dtr), dorsomedial CSF layer (DL), and ventromedial CSF layer (VL) (Fig 1E). All measurements were rounded off at 0.5 mm. The contours of the spinal cord and the dural sac of each image at T-11 and T-12 in the supine position were drawn on a transparency and overlead on the corresponding image in the prone position, to measure the shift in position of the spinal cord inside the dural sac. When the spinal cord had an asymmetrical position as referred to the vertebral midline, this (transverse) asymmetry was also quantified. At each vertebral

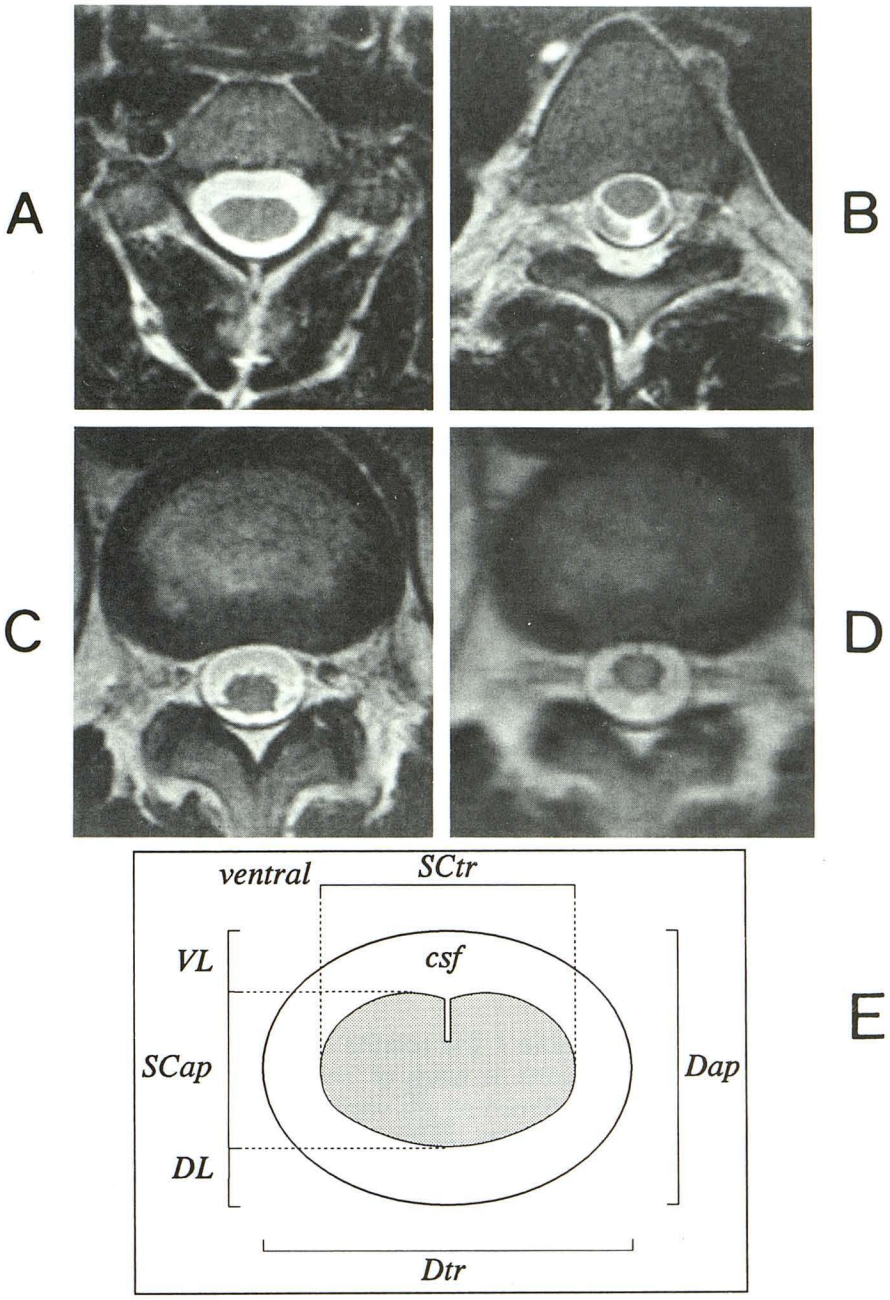

Fig. 1. Axial turbo spin-echo images at C-4 (*A*), T-5 (*B*), and T-11 in supine (*C*) and in prone position (*D*). *C* and *D* are from the same subject. *E*, Variables measured from images (see text). *VL* indicates ventromedial CSF layer; *SCap*, anteroposterior size of the spinal cord; *DL*, dorsomedial CSF layer; *SCtr*, transverse size of the spinal cord; *Dtr*, transverse size of the dural sac; *Dap*, size of the anteroposterior size of the dural sac.

level the values of each variable from two or three adjacent sections of a subject were averaged and rounded off at 0.5 mm. Because of movement artifacts some images, primarily cervical ones, lacked sufficient quality to allow a reliable measurement of all variables. These values were discarded.

Statistical Analysis

Variables from the sample of subjects were analyzed statistically for a generalization toward the population parameters of these variables. From each variable at each vertebral level the values from the sample of subjects (n) were used to calculate the mean (m), the standard deviation (SD), and the skewness (sk) as the estimates of the mean (μ), SD, and degree of symmetry of the distributions of these parameters in a population of healthy subjects. The 95% confidence interval of μ and the variation of samples were also determined.

The SD estimated from a sample with data x_i (i = 1, 2, 3, . . . n) is:

$$1) \qquad SD = \sqrt{\frac{\sum_{i=1}^{n} (x_i - m)^2}{n - 1}}.$$

Assuming a normal distribution of x_i, the $100(1-\alpha)\%$ confidence interval of the mean (μ) is given as:

$$2) \qquad \mu = m \pm SD \frac{t_{\alpha/2}}{\sqrt{n}},$$

TABLE 1: Sample size (n), mean (m), SD, and skewness (sk) of the variables indicated in Fig 1E; 10% and 90% values of the DL distributions (m, SD, and 10% to 90% in mm)

		n	m	SD	sk	10%–90%	n	m	SD	sk
		Dorsomedial layer (DL)					Ventromedial layer (VL)			
CSF layer	C-4	24*	2.6	0.9	0.85	1.5–4.0	24*	3.4	1.2	0.30
	C-5	23*	2.6	0.9	0.46	1.5–4.0	23*	3.8	1.1	0.12
Supine	C-6	24	2.2	0.7	0.70	1.5–3.0	22	4.6	1.2	−0.41
	T-5	26*	5.8	1.8	0.80	4.0–8.5	26*	1.5	0.5	1.15
	T-6	26*	5.8	1.8	1.05	4.0–8.5	26*	1.6	0.5	1.08
	T-11	25	3.6	1.6	0.67	2.0–6.0	25	4.0	0.9	0.36
	T-12	26	3.0	1.1	0.27	1.5–4.5	26	6.1	1.2	0.62
Prone	T-11	25	5.8	1.6	0.35	4.0–7.5	...	...	...	...
	T-12	26	6.4	1.3	−0.36	4.5–8.0	...	...	...	...
		Anteroposterior size of spinal cord (SCap)					Transverse size of spinal cord (SCtr)			
Spinal cord	C-4	24	7.3	0.6	−0.02		24*	13.6	1.1	−0.29
	C-5	22*	6.9	0.6	−0.19		23*	13.4	1.1	−0.46
	C-6	23*	6.7	0.6	0.06		22	13.0	1.1	−0.61
	T-5	26*	5.9	0.6	0.03		24*	8.5	0.7	−0.11
	T-6	26*	5.9	0.7	−0.12		26*	8.3	0.6	−0.43
	T-11	25	6.7	0.7	0.17		25*	9.1	0.7	−0.10
	T-12	26	7.0	0.5	0.15		26*	9.1	0.7	0.98
	LuE	25	7.4	0.6	0.38		26	9.6	0.6	0.95
		Anteroposterior size of dural sac (Dap)					Transverse size of dural sac (Dtr)			
Dural sac	C-4	24*	13.3	1.4	0.71		21*	20.4	2.0	0.78
	C-5	23*	13.4	1.5	0.39		19*	20.6	2.0	0.09
	C-6	24*	13.4	1.4	0.57		18*	20.7	2.1	0.72
	T-5	26*	13.4	1.7	0.79		23*	14.8	1.9	0.55
	T-6	26*	13.2	1.8	0.94		26*	14.8	1.9	0.70
	T-11	25	14.5	1.6	0.18		25	17.8	1.9	0.23
	T-12	26	16.0	1.7	−0.01		26	20.1	2.0	−0.11

Note.—* indicates variables with similar distributions.

where $t_{\alpha/2}$ is the upper $\alpha/2$ point of the t distribution with n−1 degrees of freedom (13). The following values of $t_{\alpha/2}/\sqrt{n}$ were used to calculate the 95% confidence interval of μ: 0.47, 0.45, 0.44, 0.43, 0.42, 0.41, and 0.40 for n = 20, 21, . . . 26, respectively.

Because several samples had a clearly asymmetrical distribution, we also estimated the skewness of the distributions using the (dimensionless) moment coefficient of skewness (14):

$$3) \qquad sk = \frac{\sum_{i=1}^{n} (x_i - m)^3}{SD^3 \cdot n}.$$

A distribution was assumed to have a positive skewness if sk was 0.6 or greater and negative if sk was −0.6 or less. These threshold values are arbitrarily chosen.

The variation of a sample is related to the SD and was defined as the 10% to 90% interval of its cumulative distribution.

The Wilcoxon signed-rank test was used to determine whether or not samples of a variable at two vertebral levels belong to the same distribution, by comparing pairs of data from each subject. Pairs of data of two variables X and Y were used to calculate the correlation coefficient (r) of these variables (13):

$$4) \qquad r(X, Y) = \frac{m(XY) - m(X) \cdot m(Y)}{SD(X) \cdot SD(Y)},$$

in which m(XY) is the mean of the product of X and Y.

Results

In Table 1 the results of the statistical analysis of all data at each of seven vertebral levels are shown. From all six variables shown in Figure 1E the sample size, the mean, the standard deviation, and the skewness are presented, as well as the 10% and 90% values of the dorsomedial layer distributions. The maximum size of the spinal cord at T-11 and T-12, representing the maximum size of the lumbar enlargement (LuE), is also given. In several cases the m values of a variable at neighboring vertebrae were within the reciprocal 95% confidence intervals of μ, and the distributions had similar SD and sk values. These variables were assumed to have similar distributions and are indicated by an asterisk in Table 1. In several cases these distributions were joined in the histograms of Figures 2–5.

Thickness of the CSF Layers

In a supine position the dorsomedial layer was smallest at the midcervical level and largest at the midthoracic level (Table 1). At C-6 the dorsomedial layer was significantly smaller than at

C-5 and C-4 (signed-rank test). At the low thoracic level the dorsomedial layer strongly depends on the position of the body. At T-11 the m value increased by 2.2 mm when subjects were turned from the supine to the prone position; at T-12 the increase was 3.4 mm. In the supine position most distributions of the dorsomedial layer had a positive skewness (sk $\geq$ 0.6).

The SD and variation values of the dorsomedial layer were also smallest at C-4 through C-6 and largest at T-5 and T-6 (Table 1 and Fig 2A). The shift in dorsoventral position of the spinal cord (prone-supine) at T-11 had a distribution with variation of 2.0 mm and sk of 0.85 (Fig 3C).

At T-5 and T-6 the ventromedial layer had a small mean, little variation (1.5 mm), and a positive skewness (Table 1 and Fig 2B). The distributions at C-4 through C-6 and T-11 were almost symmetrical ($-0.6 < sk < 0.6$).

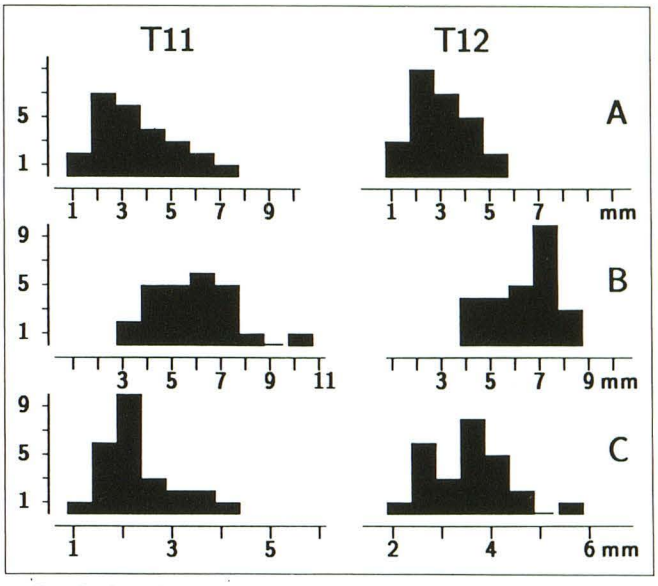

Fig. 3. Distributions of dorsomedial CSF layer at T-11 and T-12 in supine position (*A*), in prone position (*B*), and the difference between A and B (*C*).

Size of the Spinal Cord

The spinal cord had the smallest mean size at T-5 and T-6 and the largest one at C-4 (Table 1). Variation of SCap and SCtr was fairly constant among spinal levels (variation approximately 1.5 mm; SD 0.6 to 0.7 mm), except for the (large) cervical SCtr (variation approximately 2.5 mm; SD 1.1 mm) (see C-6 in Fig 4B).

At T-12 the spinal cord size varied strongly in 23 of 26 subjects, because of the variable vertebral position of the conus medullaris. Data related

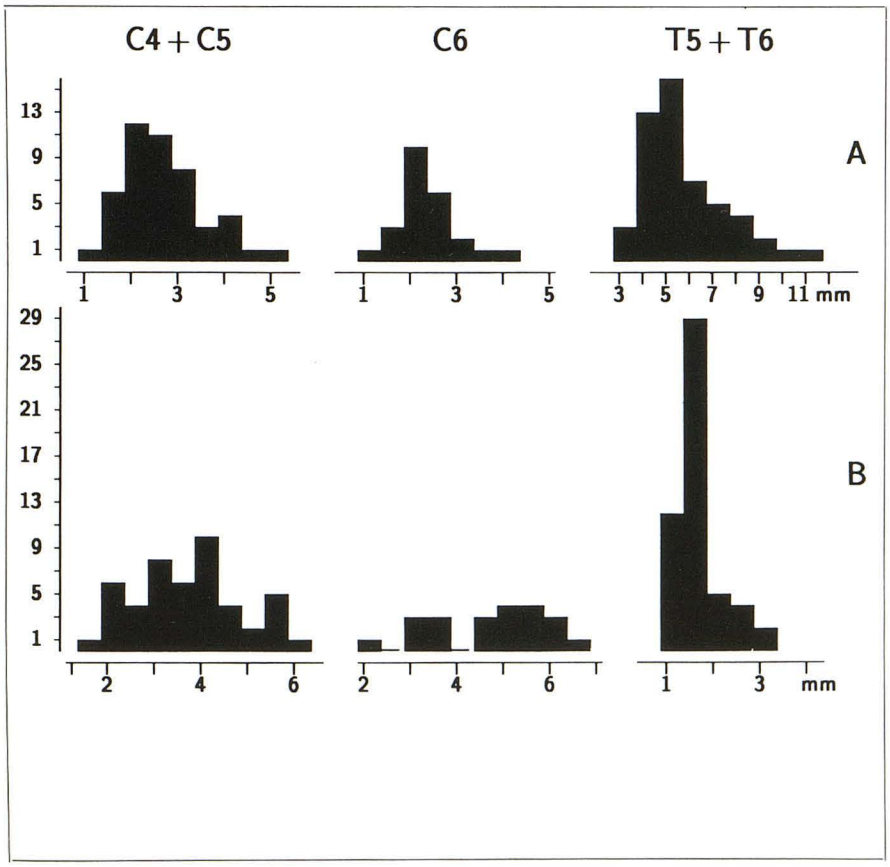

Fig. 2. Distributions of dorsomedial CSF layer (*A*) and ventromedial CSF layer (*B*) in supine position.

to the conus (caudal to the maximum size at T-12) were excluded from calculation of the SCap and SCtr parameters at T-12 in these subjects. The maximum values at T-12 of each subject were used to calculate the statistical parameters of the maximum size of the lumbar enlargement (LuE in Table 1).

Most distributions of SCap and SCtr were almost symmetrical ($-0.6 < sk < 0.6$). SCtr only had a negative skewness at C-6 and a positive one at T-12 and LuE (Table 1 and Fig 4B).

Size of the Dural Sac

The means of Dap at C-4 through C-6 and T-5 and T-6 were the same (approximately 13.4 mm), but the mean cervical Dtr was larger than the midthoracic one (approximately 20.6 mm and 14.8 mm, respectively). The mean size of the dural sac increased significantly from T-11 to T-12. Both Dap and Dtr varied strongly in comparison with SCap and SCtr. Variations were 2.5 to 5.0 mm and 4.5 to 5.0 mm for Dap and Dtr, respectively. Part of the distributions of Dap and Dtr had a positive skewness (Table 1 and Fig 5).

Correlation Between Variables

Because the dorsomedial layer is related to other variables (dorsomedial layer = Dap − SCap − VL), we calculated the correlation coefficients of Dap with both the dorsomedial layer and SCap at all vertebral levels. A fairly high value was only found for the dorsomedial layer and Dap at T-5 and T-6 ($r = .85$). The other values were small ($r < .65$).

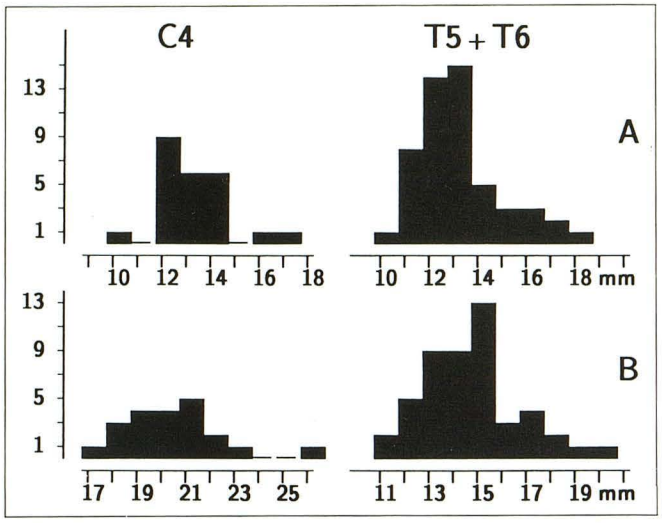

Fig. 5. Distributions of dural sac size: Dap (*A*) and Dtr (*B*).

Fig. 5. Distributions of dural sac size: Dap (*A*) and Dtr (*B*).

Asymmetrical Position of the Spinal Cord

At all three spinal areas studied we found that approximately 40% of the subjects had an asymmetrical position (right or left) of the spinal cord, although in some cases it was difficult to determine the position of the spinal cord midline as referred to the vertebral midline, because of asymmetrical vertebrae or a slight torsion of the spinal cord. Moreover, the mediolateral position of the spinal cord could vary by 0.5 to 1.0 mm within a few centimeters of its length. The maximum asymmetry was distributed as follows: 1.0 mm (five subjects), 1.5 mm (five), and 2.0 mm (one) at C-4 through C-6; 0.5 mm (four), 1.0 mm (four), 1.5 mm (two), and 2.0 mm (one) at T-5 and T-6; and 0.5 mm (six) and 1.0 mm (four) at T-11 and T-12. A statistical analysis of the distributions has not been made, because the number of data was too small.

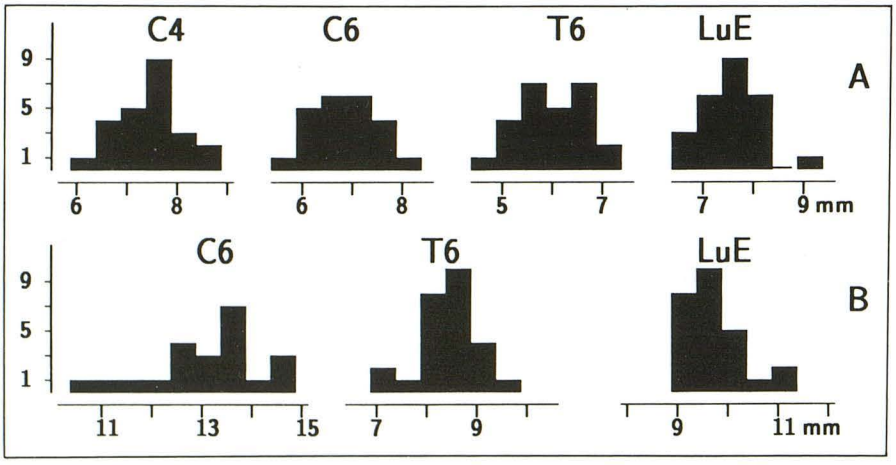

Fig. 4. Distributions of spinal cord size: SCap (*A*) and SCtr (*B*).

Comparison with Data from the Literature

Data from the literature were available of both SCap and SCtr at C-4 through C-6, T-5 and T-6, and T-12, and of Dap at C-4 through C-6. In Table 2 values of m and SD are presented. In the right outermost columns the corresponding 95% confidence intervals of μ and the SD values from our data are shown. The myelographic data of SCap and SCtr from Di Chiro and Fisher (2) were corrected for the discrepancy with their anatomical measurements (SCap was divided by a factor of 1.2 and SCtr by 1.1).

Discussion

Samples of various geometric data at seven vertebral levels have been measured and analyzed statistically. Strongly T2-weighted turbo spin-echo sequences were used, because this MR technique combines sufficient contrast and signal-to-noise ratio with acceptable scan time and little CSF flow artifacts. The reported disadvantage of this method to the conventional one (15) is not applicable, because we were not interested in gray-white matter differentiation. Although the measurement data were rounded off at 0.5 mm, the errors will not influence the mean of the samples if we assume that these errors are distributed homogeneously over the interval (−0.25 mm, +0.25 mm). The contribution of these errors to SD will be 0.15 mm (0.5 mm/$\sqrt{12}$), which is small in comparison with the SD values of all samples (Table 1). The error of the MR system was less than 3% and can be neglected if we take into account the 95% confidence intervals of μ of all variables.

Size of Spinal Cord and Dural Sac

Data from the literature regarding the size of the spinal cord and the dural sac were compared with the results of our study (Table 2). The m values of spinal cord anteroposterior and transverse sizes from Skalpe and Sortland (4) (myelography), Yu et al (6), and Penning et al (7) (CT myelography), and of its transverse size from Elliott (1) (autopsy) and Sherman et al (8) (MR) are all within the 95% confidence intervals of the means of our data. The SD values of our samples of spinal cord size were similar to most values from literature: anteroposterior is 0.5 to 0.7 mm (3, 4, 6), and transverse is 1.0 to 1.4 mm (5, 6, 8). The ratio mean SCap/mean SCtr at C-4 through C-6 calculated from our data and those of Thijssen et al (5), Yu et al (6), and Penning et al (7) was approximately 0.52. Elliott (1), Di Chiro and Fisher (2), Nordqvist (3), and Sherman et al (8), however, found a larger ratio (approximately

TABLE 2: Mean (m) and SD values of spinal cord and dural sac size (in mm) from literature

Reference		1	2	3		4		5		6		7	8		Present Study	
		m	m	m	SD	m	SD	m	SD	m	SD	m	m	SD	95% confidence interval of μ	SD
Spinal cord																
C-4	anteroposterior	...	8.8	9.6	0.6	7.1	0.6	6.0	0.75	7.1	0.8	...	8.7	0.9	7.0–7.6	0.6
	transverse	...	14.6	14.7	...	...	...	11.7	0.95	13.8	1.2	...	14.0	1.1	13.2–14.1	1.1
C-5	anteroposterior	7.7	8.7	9.5	0.7	6.9	0.5	6.2	1.15	6.9	0.7	7.1	8.3	0.9	6.6–7.2	0.6
	transverse	13.2	14.5	15.0	...	...	...	11.8	1.35	13.4	1.3	13.8	13.9	1.0	13.0–13.9	1.1
C-6	anteroposterior	...	8.4	9.2	0.6	6.9	0.5	6.4	1.35	6.8	0.6	...	7.9	0.8	6.4–7.0	0.6
	transverse	...	14.1	14.6	...	...	...	10.5	1.15	12.6	1.4	...	13.2	1.0	12.5–13.5	1.1
T-5–T-6	anteroposterior	6.5	7.5	7.5	0.4	...	...	...	...	...	...	...	...	...	5.6–6.1	0.7
	transverse	8.0	8.6	9.7	...	...	...	...	...	...	...	...	...	...	8.1–8.5	0.6
T-12	anteroposterior	8.0	9.5	9.6	0.7	...	...	...	...	...	...	...	...	...	6.8–7.2	0.5
	transverse	9.6	9.8	9.7	...	...	...	...	...	...	...	...	...	...	8.8–9.4	0.7
Subjects (n)		98	14	saggital 43–57 coronal 6–18		17		20		36		28	66		26	
Dural sac																
C-4	anteroposterior	...	14.3	11.8	1.1	14.9	0.75	...	...	...	...	...	...	...	12.7–13.9	1.4
C-5	anteroposterior	...	14.7	11.8	1.2	14.4	0.7	...	...	...	...	11.9	...	...	12.7–14.0	1.5
C-6	anteroposterior	...	14.5	11.7	1.2	14.2	0.35	...	...	...	...	...	...	...	12.8–14.0	1.4
Subjects (n)			18	42–51		17						28			24	

0.61). In the postmortem studies (1–3) the larger size and larger ratio can be caused by decompression of CSF in the spinal canal and/or (anisotropic) swelling of the spinal cord. Different sizes and ratios also can be related to different positions of the cervical spine, although in that case the transverse area should be constant. If this area is estimated by the product of the means of SCap and SCtr, there is a good fit of our values with those of Elliott (1), Yu et al (6), and Penning et al (7) (86 to 101 mm^2), whereas Di Chiro and Fisher (2) and Sherman et al (8) got slightly larger values (104 to 128 mm^2). Because Elliott and Sherman et al found similar areas but ratios different from other authors (6, 7; this study), the position of the cervical spine during their measurements may have been different. The increase of spinal cord size from C-6 to C-4, found by most authors (2, 3, 6, 8) and in this study, is related to the cervical enlargement. Mean values of cervical Dap varied strongly among authors (2–4, 7) and were not in the 95% confidence intervals of our μ values.

Although the distributions of SCap were almost symmetrical, SCtr, Dap, and Dtr had skew distributions at various vertebral levels (Table 1). Except for a single negative value ($sk \leq -0.6$), all these distributions had a positive skewness ($sk \geq 0.6$). Some distributions had one or two extreme values (C-6 in Fig 4B; C-4 in Figs 5A and 5B), causing the large skewness, because their contribution $(x_i - m)^3$ is large (see formula 3). If this type of distribution is excluded, only skew distributions of SCtr at LuE (Fig 4B) and of Dap and Dtr at T-5 and T-6 (Figs 5A and 5B) are left. Probably some developmental mechanism sets a lower limit to the size of these structures or restricts their outgrowth in a majority of the (male) population.

Thickness of the CSF Layers

No published data of the dorsomedial layer and its variation with subject position was found. In the supine position most distributions of the dorsomedial layer had a positive skewness, indicating some factor setting a lower limit to the dorsomedial layer larger than zero. Cervically this factor can be the presence of dorsal roots or the arachnoid. Midthoracically the skew distribution of the dorsomedial layer results from the distribution of Dap (see below). In the prone position the dorsomedial layer was increased at T-11 (m = 2.2 mm) and at T12 (m = 3.4 mm). This large shift in anteroposterior position of the caudal spinal cord may result from both gravitation and a lack of stabilizing force imposed by the dorsal and ventral roots, because of the longitudinal orientations of spinal roots in this area.

The small size and positive skewness of the midthoracic ventromedial layer are caused by the ventrally directed mechanical force imposed on the spinal cord by the kyphosis of the thoracic vertebral column. This force exceeds the dorsally directed gravitation when subjects are in a supine position.

Correlation Between Variables

In general, little correlation exists between variables at the same vertebral level, except for the dorsomedial layer and Dap at T-5 and T-6. A relatively high correlation was expected, because the distribution of Dap has a mean of almost twice and an SD of three times the corresponding values of SCap. Moreover, the ventromedial layer is small and has little variation (Fig 2B). Therefore, the variation of the dorsomedial layer among subjects is correlated with the variation of Dap. Both distributions have the same SD (1.8 mm) and skewness (0.8 to 1) (Table 1 and Figs 2A and 5A). The average relation between the midthoracic dorsomedial layer (DL) and Dap is:

$$DL = Dap - 7.4 \text{ (mm)}, \quad 5)$$

in which the constant is the mean sum of the ventromedial layer and SCap at T-5 and T-6. The variation of this sum (10% to 90%) is ± 0.6 mm.

Asymmetrical Cord Position

Asymmetrical spinal cord positions were fairly common (approximately 40%) in the group of healthy male subjects (19 to 38 years of age) and varied up to 1.5 to 2.0 mm. This transverse asymmetry may be caused by a minor degree of scoliosis, different lengths of right and left roots, or other intradural asymmetries. In patients with spinal deformations the percentage and magnitude of asymmetry will be even larger. Asymmetrical cord positions, asymmetry of vertebrae, and incidental torsion of the spinal cord are probably the main causes of the frequent asymmetrical or even unilateral paresthesia when epidural spinal cord stimulation electrodes are at the radiologic midline (9–11).

In conclusion, it was found that the dorsomedial CSF layer varies among subjects by more

than a factor 2 at all three vertebral levels. At the low thoracic level the dorsomedial layer also increases by 2.2 to 3.4 mm when subjects turn from a supine to a prone position. Moreover, the spinal and vertebral midlines may differ by up to 1.5 to 2.0 mm in each direction. The results of this study are relevant for the analysis of the effects of epidural spinal cord stimulation and for the optimization of the design of epidural leads. The optimal lead geometry will be related to the dorsomedial layer, whereas its optimal position is related to the midline of the spinal cord. Because of the large variation of the thickness of the dorsomedial layer among subjects, leads with different geometries should be developed. To select the optimal lead for any patient, it will be necessary to measure the dorsomedial layer before implantation. MR imaging, using a turbo spin-echo sequence as presented in this paper, has been shown to be a fast and accurate method for these measurements.

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