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Cerebrospinal fluid volume and nerve root vulnerability during lumbar puncture or spinal anaesthesia at different vertebral levels

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SUMMARY

Cerebrospinal fluid (CSF) and nerve root volumes within the lumbosacral dural sac were estimated at various vertebral levels, in an attempt to determine any possible relevance to the incidence of nerve root trauma during lumbar puncture or spinal anaesthesia. Magnetic resonance images from seven patients were studied. Volumes were calculated by semi-automatic threshold segmentation combined with manual editing of each slice. The mean dural sac volume from S1 to T12 was 42.8±5.8 ml and the mean CSF volume 34.3±5.1 ml with the mean root volume being 10.4±2.2 cm^3. The mean CSF volume per vertebral segment ranged from 4.3±0.7 ml at L5, to 5.8±2.5 ml at L1, with high inter-individual variability. The mean root volume ranged from 0.6±0.1 cm^3 at L5 to 2.4±0.5 cm^3 at T12.

The conus medullaris was located at L1 in four of the five patients scanned at upper lumbar levels, and at the lower border of L2 in the other. Vulnerability to nerve root damage was expressed as the Vulnerability Index (%), being defined as the ratio of root volume to dural sac volume (CSF volume + root volume). The value ranged between 7 and 14% at L5, increasing rostrally to 30 to 43% at T12. Caution is obviously required in high punctures to avoid contact with the conus medullaris, but the cauda equina is also vulnerable to contact with more caudal punctures and had a Vulnerability Index of about 25% at L4, that increased rostrally.

Key Words: lumbar puncture, spinal anaesthesia, cerebrospinal fluid, 3D magnetic resonance imaging

Paraesthesiae produced during subarachnoid puncture for diagnostic, therapeutic or anaesthetic purposes are a relatively common complaint. The incidence of paraesthesiae varies between 0.9 and 18%, depending on a variety of factors[1-5] and adverse consequences are difficult to predict.

Lumbar puncture and subarachnoid blocks are commonly performed below the vertebral level at which the conus medullaris is expected to be located. The L4/5 interspinous space is usually identified after drawing a line between the iliac crests[6]. In lumbar punctures where cerebrospinal fluid (CSF) is removed, clinicians tend to select lower lumbar levels where fewer nerve roots are found and paraesthesiae are less likely to result. However, no in vivo studies have previously quantified the relationship between CSF volume and the volume of nerve roots at different levels of the lumbar spine. This could be indicative of the vulnerability to needle contact at particular levels.

The aim of this study was to determine the volumes of both CSF and nerve roots within the human lumbar dural sac and estimate the degree of vulnerability at different vertebral levels.

METHODS

After patient consent and approval by the Clinical Research Ethics Committee at Madrid Hospital Group we studied magnetic resonance images (Philips Intera 1.5, Team Software 1.1, Tesla, Madrid, Spain) from seven patients suffering low

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back pain, with absence of morphological changes in their neuroradiological reports. Images were obtained following placement of the patients in the supine position with slight flexion of their knees and a support under the popliteal fossae. For the three-dimensional (3D) reconstruction and volume calculations of CSF and nerve roots, images from a T2 Sequence Balance were used, in view of its ability to preferentially distinguish the spinal cord and spinal nerve roots from CSF (see Appendix for technical details).

Three-dimensional reconstruction

Magnetic resonance imaging (MRI) images were exported from the hospital equipment in DICOM format, which preserved spatial data and co-ordinates, then imported through Amira 4.1 software (Mercury Co., Boston, USA) to a Dell Precision graphic station. The software allowed visualisation, volumetric reconstructions and volume calculations from the images, which showed a range of gray between 0 and 3000 approximately, varying slightly between patients. For 3D reconstruction, the volume of interest (VOI) of the dural sac was initially determined by using the T2 sequence and applying a segmentation threshold that discriminated in favour of CSF. This was followed by interactive segmentation (automatic selection between similar and adjacent gray levels) in order to select nerve tissue contained within the dural sac. Then, a surface model was generated, the 3D model of the dural sac and the axial plane of the MRI image being overlapped (Figure 1A). If the external contours of the dural sac VOI did not coincide with the MRI image, the VOI was manually corrected and the procedure repeated. Then a further segmentation process selecting CSF was applied exclusively to the dural sac VOI, which preserved the structural continuity of the roots within the cauda equina and the lower portion of the spinal cord (Figures 1B to 1D).

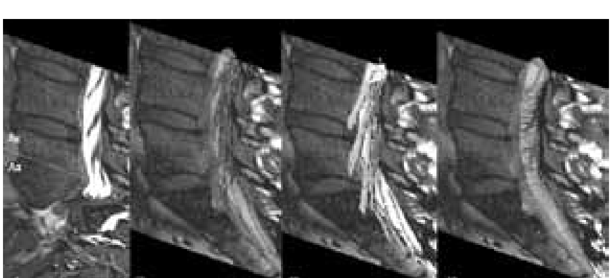

FIGURE 1: A) Dorsolateral oblique view of two orthogonal MRI sections (sagittal [sg] and axial [ax] case 3) including the dural sac limit. B) Three-dimensional reconstruction of CSF volumes. C) Nerve root volumes. D) Dural sac.

Finally the completed reconstruction was divided into different vertebral segments. Horizontal planes drawn from the posterior midpoint of the intervertebral discs, identified in the sagittal plane, were considered as reference points for delimiting vertebral levels (Figure 2A). Sacral levels were considered as a single unit. MRI images are composed of voxels, each representing a cube in 3D space. All voxels of the reconstruction between two adjacent segments were reclassified into two new VOIs (CSF and nerve roots) at each of the vertebral levels examined (Figures 2B and 2C). The conus medullaris volume was considered within the root volume.

Data analysis

The Vulnerability Index was defined as the ratio of root volume to dural sac volume (the latter being composed of root volume + CSF volume), expressed as a percentage. The mean odds ratio of the Vulnerability Index at different spinal levels relative to L5 (Vulnerability Index at level/Index at L5) was also determined.

RESULTS

Dividing the images into co-aligned blocks of 130 mm in length allowed the visualisation of segments extending from the L5/S1 intervertebral disc up to T11/12 (Figure 1) in five of our patients (cases 3 to 7). In the other two (cases 1 and 2), scanning of the upper lumbar spine (L1/L2) was not clinically indicated.

The mean total volume of the reconstructed dural sac in comparable S1 to T12 segments (cases 3 to 7) was 42.8±5.8 (range 33.2 to 48.9) ml, the

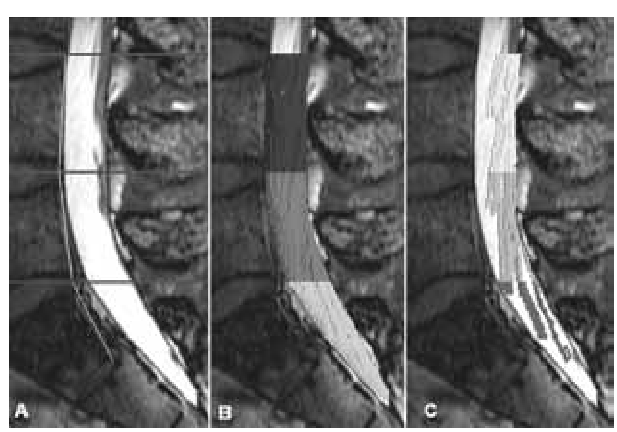

FIGURE 2: A) Median sagittal MRI section (case 3). Vertical lines: distance between the posterior midpoints of the intervertebral discs. Horizontal lines: horizontal planes originating in the same posterior midpoints of the intervertebral discs, used as limits for the different vertebral segments. B) Lateral view of CSF Volumes of Interest. C) Root volumes of interest at L4-S1.

mean volume of CSF was 34.3±5.1 ml and the mean volume of the nerve roots 10.4±2.2 ml[3] (Table 1). The conus medullaris was found at the midpoint of L1, in two of the five patients scanned at the upper lumbar levels. It reached the caudal end of L1 in two other individuals and the caudal end of L2 in one (Table 2.)

The mean volume of CSF at each vertebral level studied was approximately 5 ml with a wide range of results between the different levels, but also between various individuals at the same level (3.5 to 7.6 ml at L1, and 3.1 to 6.0 ml at L4, for example, Table 1). The Vulnerability Index was estimated as 12.1±1.8% at L5, and increased up to 34.0±5.3% at T12 (odds ratio related to L5 1.8, 2.2, 2.2, 2.4, 2.8 at L4, L3, L2, L1 and T12 respectively, Table 2). Maximal Vulnerability Index was approximately 40% in segments above L3 in certain individuals (36% at L3, 38.9% at L2, 39.2% at L1 and 42.9% at T12).

DISCUSSION

Measurement of the relative volumes of CSF and spinal nerve roots in the cauda equina within the dural sac in this small number of patients has allowed us to estimate the relationship between these volumes at several intervertebral levels. To our knowledge

TABLE 1

Cerebrospinal fluid and root volumes in ml/vertebral segment from sacral to lower thoracic segments (T12)

	Age, y	Height, m	BMI, kg/m^2	V_{CSF}/V_{root}	Sacral to lower thoracic segments†					
				S	L5	L4	L3	L2	L1	T12
Patient 1, F	26	1.60	26.6	1.2/0.0	4.5/0.3	5.8/1.0	6.2/1.7			
Patient 2, M	36	1.70	27.7		7.3/1.1	6.0/2.0	5.0/2.5			
Patient 3, M	38	1.82	28.4	2.9/0.1	4.9/0.7	5.1/1.4	4.3/2.4	5.1/3.2	5.0/2.9*	3.5/2.6*
Patient 4, F	35	1.78	24.2	1.9/0.1	4.0/0.6	5.0/1.1	5.6/1.3	6.0/1.5	6.2/2.1*	4.4/2.2*
Patient 5, M	47	1.84	23.0	2.4/0.0	5.2/0.5	5.9/1.0	5.3/1.5	7.0/1.4	7.6/1.7*	6.2/2.6*
Patient 6, M	60	1.62	23.2	2.6/0.0	3.4/0.5	3.1/1.2	3.7/1.4	4.6/1.6*	3.5/2.3*	3.4/1.4*
Patient 7, F	26	1.68	33.7	2.0/0.0	4.1/0.5	4.2/1.4	4.3/1.8	5.4/2.3	6.5/2.7*	5.9/3.0*
Patients 3-7§										
Mean V_{CSF}				2.4	4.3	4.7	4.6	5.6	5.8	4.7
SD				0.4	0.7	1.0	0.7	0.9	1.5	1.3
Mean V_{root}				0.1	0.6	1.2	1.7	2.0	2.3	2.4
SD				0.0	0.1	0.1	0.4	0.7	0.4	0.5

† Numbers are represented as V_{CSF}/V_{root}. * Includes spinal cord volume. § Mean and SD based on cases with full data (patients 3 to 7). BMI=body mass index, V_{CSF}=cerebrospinal fluid volume, V_{root}=root volume, F=female, M=male, SD=standard deviation, S=sacral roots.

TABLE 2

Vulnerability Index, calculated as the % ratio of root volume (including conus medullaris when present) to dural sac volume (V_{CSF} + V_{root}), and odds ratio relating the index to the value at L5. The vertebral level of the distal end of the conus is also indicated

	Vulnerability Index, L5	End of conus medullaris, L4	L3	L2	L1	T12	Vertebral level
Patient 1	7.0	15.6	21.9				
Patient 2	14.0	25.6	33.6				
Patient 3	13.5	21.6	36.0	38.9	37.3	42.9	Caudal L1
Patient 4	12.8	18.1	19.1	19.9	26.0	33.7	Caudal L1
Patient 5	9.1	15.0	21.9	16.7	18.5	29.6	Mid L1
Patient 6	13.4	28.2	27.6	25.7	39.2	30.2	Caudal L2
Patient 7	12.0	25.1	29.8	29.9	29.2	33.8	Mid L1
Mean*	12.1	21.6	26.9	26.2	30.1	34.0	
SD*	1.8	5.3	6.6	8.7	8.5	5.3	
OR related to L5		1.777	2.212	2.158	2.474	2.803	

* Mean and SD based on cases with full data (Patients 3 to 7). V_{CSF}=cerebrospinal fluid volume, V_{root}=root volume, SD=standard deviation, OR=odds ratio.

this is the first study that has estimated both CSF and nerve root volume, providing detailed data per segment based on MRI. Neuroanatomical manual handling of data from MRI images is considerably time-consuming, but allows high accuracy, as suggested by our precise phantom volume estimation (see Appendix).

Previous calculations made reference exclusively to total CSF volume in the lumbosacral region. Our CSF volume estimations are within the range of those obtained by other authors[7-10]. However it should be noted that our image resolution was higher, while the distance between MRI images was less (0.65 mm as compared to 5[7,9], 1[10] or 8 mm[8]), resulting in much higher precision.

Our Vulnerability Index expressed the proportion of dural sac occupied by nerve roots, the mean value being 12% at L5 but increasing up to 34% at T12. This figure may be relevant to the risk of contacting a nerve root during lumbar puncture or spinal anaesthesia.

Our cases were studied in the supine position, whereas patients are usually in a lateral decubitus or sitting position for subarachnoid puncture. The effects of a change in posture on the position of the cauda equina have been studied using MRI[11]; the lateral decubitus position with fully flexed legs creates a free zone in the posterior subarachnoid space[12,13], with anterior displacement of the cauda equina, which may also be displaced to the dependent side[12,13]. These anatomical movements almost certainly increase the safety of low punctures in the lateral position, and the relative CSF and root volumes that we found may help contribute to a safe insertion approach. Spinal flexion has not been proven to give extra protection against spinal cord or nerve root contact or damage as the caudal or rostral displacement of the conus is not consistent[14]. As computed tomography or MRI scanning is rarely performed in the sitting position, there is no knowledge of the effect of this posture on the position of the conus or cauda equina.

The finding that the conus medullaris was at L1 in four of our five patients scanned at upper lumbar levels was similar to previous studies[15]; while the remaining patient, who had the conus at the caudal end of L2, might be at increased risk from a high puncture.

Given the variability of the location of the intercristal line (line of Tuffier[6]), there may be errors when identifying the intervertebral spaces in up to 30% of patients[16]. One study reported the use of an interspace higher than planned in 51% of cases[17] and the possibility of inadvertent damage to the conus[18] must be considered with these high punctures. Above L3, we found a Vulnerability Index of approximately 30% in most individuals, increasing to 43% at T12 in one patient. These findings provide another reason for proceeding with caution during subarachnoid puncture; to limit potential risk to the cauda equina nerve roots or the conus.

Due to the painstaking nature of the work required in 3D neuroanatomical studies[19-21], the number of cases we studied was low, but nevertheless sufficient to demonstrate the large variation in CSF volumes. The results suggest a low correlation between the parameters examined, for example CSF volume and spinal or body measurements. This might be improved by increasing the sample size, but the results probably arise from natural inter-individual anatomical variability. Future studies including patients with varying pathologies might help us to understand the influence of different disease processes on CSF volume and the spread of subarachnoid local anaesthetic solutions. In addition, as a research project, CSF volume could be calculated for patients having routine lumbosacral MRI as 3D reconstruction software is commonly attached to the equipment. Benefits such as a better understanding of lumbosacral anatomy and the dilution of local anaesthetics in CSF could result, ultimately leading to improved block efficiency and safety.

CONCLUSION

This anatomical imaging study has allowed us to estimate the location and size of structures that might be exposed to needle trauma at the intervertebral levels where lumbar puncture or spinal anaesthesia is performed. With diagnostic procedures it would be advisable to select more caudal vertebral levels. If aiming for the L2/L3 interspace for spinal anaesthesia, a level often considered safe with respect to neural injury, it must not be forgotten that it remains possible to inadvertently puncture the conus medullaris causing neurological damage, particularly if the vertebral level identified is incorrect.

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APPENDIX

Magnetic resonance imaging and processing

The configuration selected for the MRI T2 Sequence Balance 3D Fast Field Echo was: CDV 230, matrix 246×352, thickness section/space between sections: 1.3/-0.65, isometric voxel size 0.65×0.65×0.65 mm, TR 7.7 msec, TE 3.8 msec. NSA 3. A total of 400 sections per patient were distributed in two adjacent aligned blocks (200 sections/block) with a length of 130 mm to achieve reconstruction from the end of the dural sac up to the lowest visualised thoracic vertebra. Our methodology was validated by a volumetric study of two 36×150 mm phantoms, each containing 100 ml of water measured on an analytical balance (Ohaus, Adventure TM, measurement error ±0.1 mg). The phantoms were placed between the folds of both thighs. Volume estimates carried out after 3D image reconstruction (3D volume calculated/phantom weight) matched in 98.97 and 101.51% respectively. The acquisitions were grouped in two co-aligned blocks sharing a single axis.

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