Three-dimensional Magnetic Resonance Image of structures enclosed in the spinal canal relevant to anesthetists and estimation of the lumbosacral CSF volume


Abstract: Three-dimensional (3D) image-reconstruction of structures inside the spinal canal certainly produces relevant data of interest in regional anesthesia. Nowadays, all hospital MRI equipment is designed mainly for clinical diagnostic purposes. In order to overcome the limitations we have produced more accurate images of structures contained inside the spinal canal using different software, validating our quantitative results with those obtained with standard hospital MRI equipment.

Neuroanatomical 3D reconstruction using Amira® software, including detailed manual edition was compared with semi-automatic 3D segmentation for CSF volume calculations by commonly available software linked to the MR equipment (MR hospital). Axial sections from seven patients were grouped in two aligned blocks (T1 Fast Field Eco 3D and T2 Balance Fast Field Eco 3D - resolution 0.65 × 0.65 × 0.65 mm, 130 mm length, 400 sections per case). T2 weighted was used for CSF volume estimations.

The selected program allowed us to reconstruct 3D images of human vertebrae, dural sac, epidural fat, CSF and nerve roots. The CSF volume, including the amount contained inside nerve roots, was calculated. Different segmentation thresholds were used, but the CSF volume estimations showed high correlation between both teams (Pearson coefficient = 0.98, p = 0.003 for lower blocks; Pearson 0.89, p = 0.042 for upper blocks). The mean estimated value of CSF volume in lower blocks (L₃-S₁) was 15.8 ± 2.9 ml (Amira® software) and 13.1 ± 1.9 ml (software linked to the MR equipment) and in upper blocks (T₁₁-L₂) was 21 ± 4.47 ml and 18.9 ± 3.5 ml, respectively. A high variability was detected among cases, without correlation with either weight, height or body mass index. Aspects concerning the partial volume effect are also discussed.

Quick semi-automatic hospital 3D reconstructions give results close to detailed neuroanatomical 3D reconstruction and could be used in the future for individual quantification of lumbosacral CSF volumes and other structures for anesthetic purposes.

Key words: Spinal canal, cerebrospinal fluid, epidural fat, dural sac, nerve roots, volumetric image reconstruction, three-dimensional MRI.

INTRODUCTION

In recent years, the demand for 3-D computerized tomography and magnetic resonance image (MR) reconstruction have significantly increased thanks to improvements achieved in identification of e.g. vascular, bone, ureteral structures. In spite of their enormous potential in clinical diagnosis, anesthesiologists rarely make use of these resources for reasons of limited time available to spend in other departments such as radiology, lack of funds or poor infrastructure.

Cerebrospinal fluid (CSF) volume measurements at lumbosacral level are relevant in anesthesia (1-6), (the extent of spinal blockade is influenced by CSF volume) and in oncology (where

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chemotherapy treatment is similarly affected). Previously, invasive techniques such as myelography have been used to measure CSF volumes (7, 8) although Magnetic Resonance Imaging (MRI) allows non invasive estimation of CSF volumes from human axial images under physiological and pathological conditions (6-11). In those studies, anesthesiologists had worked in partnership with neuroradiology staff and reconstructed CSF volumes at lumbosacral level of the spinal canal using integral hospital image reconstruction equipment. However, estimations of CSF volume were performed by single teams and MR images processed had lower resolutions than those presently available.

Three-dimensional MRI reconstruction is undoubtedly a useful adjunct in anesthesia as it may contribute to more accurate identification of structures relevant in regional anesthesia such as spinal meninges, spinal nerve roots, cauda equina, CSF distribution or dural sac and its contents. In an attempt to improve accuracy of image reconstruction of structures specifically relevant to neuraxial blockade, it has been necessary to find commercially available software, adapting parameters to identify preferentially neuraxial structures.

Modern MR equipments and new 3D reconstruction software may be used routinely in the near future for calculations of CSF and other structures. However, there are a number of factors involved in the image analysis that may affect the final volume calculation and should be taken into account.

In this study, we reconstructed CSF images as these are the only structure within the spine that had undergone previous analytic reconstruction including volume measurements. These data enable comparative evaluation of methodology applied by different authors (9-11).

The purpose of our descriptive study was:
1) preliminary study and evaluation of the suitability of 3D MR image reconstruction of specific structures enclosed in the vertebral column relevant to anesthesiologists;
2) comparison of two methods for estimation of lumbosacral CSF and root volumes based on high resolution MR images: Semi-automated 3D reconstructions through the software linked to the MR equipment and other specific software for 3D anatomic image reconstruction (Amira®) (12-14) combined with detailed manual edition by a neuro-anatomical team; and 3) analyse factors that influence decisions which affect CSF volume calculations based on MRI.

METHODS

The study was approved by “Grupo Hospital Madrid Clinical Research Ethics Committee” and consent was obtained from seven patients who were being treated at the Pain Unit Service, having symptoms of low back pain, without a history of previous spinal pathology or surgery as evidenced by normal MR lumbar images. Patient demographics, including age, gender, height, weight and body mass index (BMI), were recorded (Table 1).

MR image scans were performed on seven patients in the supine position, placing a support below the popliteal fossa to produce slight knee flexion. Lumbar MRI scans on a 1.5 T Scanner Philips Intera®, Software 1.1 (Philips Medical System. The Netherlands) using a 3D fast spin echo (3D FSE), acquiring T1 and T2 weighted sequences. The MRI standard settings were modified to obtain an isometric voxel (volumetric picture element, representing a value on a regular grid in the three dimensional space) configuration and 50% average overlapping between acquired data. The axial sections were divided in two co-aligned blocks (block length 130 mm). The sequence configuration of T1 Fast Field Echo 3D was: FOV 230 mm., 205 × 256 matrix, 160 contiguous sections per block, thickness per section/distance between sections 1.8/-0.9 mm, nominal voxel size 0.9 mm × 0.9 mm × 0.9 mm, TR 32 msec, TE 4.6 msec, NSA 1. The sequence configuration of T2 Balance Fast Field Echo 3D was: FOV 230 mm, 246 × 352 matrix, 200 sections per block, thickness per section/distance between sections 1.3/-0.65 mm, TR 7.7 msec, TE 3.8 msec, NSA 1. The sequence obtained by T1 Fast Field Echo sequence allowed detailed 3D reconstruction of spinal cord and nerve root structures. The sequence obtained by T2 weighted provides helpful data for CSF volume determinations, due to its better discrimination of CSF from spinal cord and spinal nerve roots.

Sequence acquisitions were grouped in two aligned adjacent blocks, rendering 3D images of the spinal canal, extending from lowest end of the dural sac to the lower thoracic vertebrae, including the entire lumbosacral portion. The upper level varied among cases (T10 or T11) depending on the height of patients, leading to differences in thoracic levels included within the 130 mm length of the upper block. Sections obtained were contiguous between adjacent voxels but also between blocks.

After image reconstruction, quantitative CSF volume measurements were calculated using

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different semi-automated methods by two independent teams. One team used the software linked to the MRI scanner which took approximately 30 minutes to process the data for each patient. The other team processed the data in a Neuroanatomy Laboratory, using Amira® software (Mercury Co, Boston, USA) and, in addition, expert manual delimitation of structures such as the dural sac and spinal nerve roots in each image. This method produced highly accurate models but took longer for processing the data (about ten hours per case).

**Image Reconstruction and CSF Volume Calculation with conventional software linked to the MR (Hospital MR Team)**

The software used for data processing and CSF volume calculation was linked to the MR by a reconstructing protocol common in Hospital MR equipment. T2 MR images were exported in DICOM format to a View Forum Work Station (Philips Release 2.5.3.0 2007. Philips Medical System, The Netherlands B.V. Veemplius-4-6 PC Best). MR images showed a gray scale range of 0-3000. The CSF volume of interest (VOI) was reconstructed from segmentation thresholds adapted to each patient that selected CSF voxels in MR images (Fig. 1). Then, a brief manual segmentation was done reviewing and selecting among voxels that had been initially excluded or included according to their relation to the structure examined. Three-dimensional (3D) volume rendering of the lumbar intrathecal CSF space was performed and the total volume of CSF for the selected area was calculated (Fig. 1).

**Table 1**

<table>
<thead>
<tr>
<th>Case</th>
<th>Gender</th>
<th>Age (years)</th>
<th>Height (m)</th>
<th>Weight (kg)</th>
<th>BMI (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Female</td>
<td>24</td>
<td>1.60</td>
<td>68</td>
<td>26.6</td>
</tr>
<tr>
<td>2</td>
<td>Female</td>
<td>34</td>
<td>1.70</td>
<td>80</td>
<td>27.7</td>
</tr>
<tr>
<td>3</td>
<td>Male</td>
<td>36</td>
<td>1.82</td>
<td>94</td>
<td>28.4</td>
</tr>
<tr>
<td>4</td>
<td>Female</td>
<td>35</td>
<td>1.70</td>
<td>70</td>
<td>24.2</td>
</tr>
<tr>
<td>5</td>
<td>Male</td>
<td>45</td>
<td>1.84</td>
<td>78</td>
<td>23.0</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>58</td>
<td>1.62</td>
<td>61</td>
<td>23.2</td>
</tr>
<tr>
<td>7</td>
<td>Female</td>
<td>24</td>
<td>1.68</td>
<td>95</td>
<td>33.7</td>
</tr>
</tbody>
</table>

BMI: body mass index.

**Fig. 1.** — Semiautomatic 3D reconstruction of CSF lumbar-sacral volume through software linked to the MR equipment. Anterior and posterior views of the caudal (1) and rostral (2) blocks.

**Image Reconstruction and CSF Volume Calculation with AMIRA® software and expert image delimitation.**

MR images were exported from the hospital equipment to the neuroanatomic equipment in DICOM format, which preserves spatial coordinates. Data processing was performed by the software AMIRA® v4.1 (Mercury Co, Boston, USA) installed in a graphic station Dell Precision. This software is designed for viewing and analysis of biomedical images, allowing volumetric reconstruction.
After transferring the data, the following steps were taken:

1) VOI delimitation of the dural sac: 2) validation of the 3D reconstruction of the dural sac; 3) second segmentation to separate the CSF space and spinal nerve roots.

1) In order to determine the VOI of the dural sac the T2 sequence was used and the threshold segmentation adapted in each case to preferentially select CSF. This was followed by interactive segmentation (automatic selection among contiguous voxels with similar gray values), separating thus the different tissues enclosed in the dural sac. Manual editing was performed to reclassify voxels when needed.

2) A surface model was generated to obtain validation of the dural sac VOI. Later, the 3D model of the dural sac and the axial plane of the MR image were overlapped to identify differences between their respective external contours (Fig. 2). Only when the selected section and the MR did not coincide, the VOI was manually processed and the procedure repeated once again.

3) A second segmentation was applied exclusively to the region of the MR image enclosed in the dural sac VOI. Processed images showed a gray scale range between 0-3000. A segmentation threshold was chosen to separate the spinal nerve roots of the cauda equina along the entire portion of the vertebral canal from the CSF inside the dural sac. CSF found inside the dural sleeves was measured and its corresponding value was included in the VOI.

Throughout the reconstruction, each section was examined and a manual voxel selection of intermediate gray ranges was performed, following criteria of similarity among gray values from delimited structures, and in relation to their anatomic position.

Validation of Image Reconstruction in both Methods: Phantom Study

Two water phantoms containing 100 ml of water were constructed to simulate the dural sac in the spinal canal and to validate the accuracy of the volume measurement technique. Volume calculations were performed on the reconstructed images of both water phantoms. The real water volume of both phantoms was determined from the difference in weight obtained while being filled with water and after being cleaned with acetone and left to dry. Each weight was measured on an analytical balance (Ohaus® Adventure™, Dublin, Ireland, measurement error ± 0.1 mg.). These phantoms had a width of 36 mm and a length of 150 mm. Acquisitions were taken using the same sequences and placing the phantom between the legs of a patient to obtain about 5 to 10 cm of muscle around the phantom. Both phantoms were placed in a parallel axis. The percentage between calculated and real volumes was determined (Table 2).

Data Analysis

An Excel database was created and the data processed using the program SPSS 10.0. Pearson’s correlation coefficient was estimated for weight, height, BMI and CSF values in those cases that shared similar vertebral levels (inferior blocks of cases 3 to 7). Total CSF values and thresholds were compared with the paired Student’s t-test.
after testing for the normality of variables, using Kolmogorov-Smirnov test.

**3D Image reconstruction of other relevant structures**

With the application of this methodology it is feasible to produce reconstructed MR images of other relevant structures such as vertebrae, intervertebral ligaments, epidural fat, spinal nerve roots in the cauda equina and dural sleeves.

**RESULTS**

Volumes for two phantoms were determined in both MR equipments. The neuroanatomist team estimated in 98.97-101.51% the water volume and the hospital equipment provided an estimation of 94.96-103.27%, resulting thus in a precision of 98.50-98.97% and 94.26%-96.82%, respectively (Table 2).

In five of the seven patients, the CSF volume was reconstructed in two blocks that extended from sacral levels, up to thoracic vertebra T 10 -T 11 , depending on the patients height. In the other two cases, the reconstruction was performed in a single block extending from sacral levels to the lumbar vertebra L2.

CSF volume estimations from both teams are shown in Table 3. The mean value of CSF volume in lower blocks extending from L3 to S1 was estimated 15.8 ± 2.9 ml (Amira® software) (Fig. 3), and 13.1 ± 1.9 ml (software linked to the MR equipment) (Fig. 1). In blocks reaching T11, the mean value of CSF volume was 18.9 ± 3.5 ml (software linked to the MR equipment) and 21 ± 4.47 ml (Amira® software). Positive correlation between the teams was significant for CSF volume calculated values (Pearson 0.982, p = 0.003 for lower blocks ; Pearson 0.891, p = 0.042 for upper blocks). No significant correlation was found between CSF volume and weight (Pearson = -0.081 and 0.41 ; p = 0.884 and p = 0.493 in Amira® software - software linked to the MR equipment respectively) or BMI (Pearson = -0.102 and 0.244 ; p = 0.87 and 0.693 in Amira® software – software linked to the MR equipment respectively).

Significant differences in the segmentation thresholds were found between the two teams (p = 0.003 for lower blocks and p = 0.030 for upper blocks, Table 3). Differences in mean CSF volume calculations between both teams were 2.76 ± 1.13 ml in lower blocks (p = 0.003) and 3.2 ± 2.17 ml in higher blocks (p = 0.042). In those two cases where a single block was studied, differences in the mean CSF volume were 0.3 ml and 3 ml respectively.

There was a 36-39% difference in CSF volume between the case with lowest CSF volume and the case with the highest CSF volume (Amira® software - software linked to the MR equipment respectively), although differences in height, weight and BMI (Table 1) were of lesser magnitude for the same cases (11.9%, 21.7% and 0.9% respectively).

**Image reconstruction of other relevant structures**

The application of this method allowed us to produce qualitative and quantitative reconstructed images of supraspinous ligaments, interspinous ligaments, flaval ligament (Fig. 4), and location distribution and relationships of epidural fat (Fig. 5). Other relevant structures such as nerve roots in cauda equina and their relationships with neighboring structures (Fig. 5). The possibility of qualitative and quantitative volumetric studies has been confirmed. The values of calculated volumes for each structure were not included as this was not the aim of our study.

**DISCUSSION**

This study clearly demonstrated the suitability of 3D MR Image reconstruction of most structures...
enclosed in the spinal canal specifically relevant in neuraxial anesthesia through Amira® software. The great advantage of this method which uses a commercial software program is its availability to research teams lacking access to hospital MR equipment. It enables 3D image reconstruction of structures such as epidural fat, dural sac, dural sleeves and nerve roots in the cauda equine allowing extremely accurate and detailed anatomical representation of each of these structures with obvious benefits in clinical diagnosis of neuraxial blockade complications and improvement of anesthetic techniques. Another advantage is also the data obtained during reconstruction such as measurements, volumes and relationships with neighboring structures. Lastly, in the future, setting up a validated method will allow comparisons among studies from different authors. This study shows the potential of this technology in improving the knowledge of the lumbosacral region relevant to anesthesiologists and other specialists.

Although MRI provides a noninvasive means to measure the volume of anatomical structures such as spinal CSF or spinal nerve roots, the final calculations may vary when different observers and software are used in spite of processing the same data saved in DICOM files. The selection of the contours of the structure under study requires a good anatomical knowledge and evaluation of the aspects involved in neuroimage analysis. The neuroanatomical team had advanced experience in neuroimaging and quantification (12-14). Image reconstruction CSF volume calculation and the factor under analysis that influence decisions which affect CSF volume calculations were

Table 3
Cerebrospinal fluid volume estimations by two methods in two blocks. Threshold segmentation values chosen in each case by both teams

<table>
<thead>
<tr>
<th>CASE</th>
<th>Amira® software</th>
<th>Software linked to the MR equipment</th>
<th>Difference</th>
<th>Amira® software</th>
<th>Software linked to the MR equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ml</td>
<td>ml</td>
<td>ml</td>
<td>Threshold</td>
<td>Threshold</td>
</tr>
<tr>
<td>1. Lower block L₂-S</td>
<td>20.7</td>
<td>17.7</td>
<td>3.0</td>
<td>140</td>
<td>452</td>
</tr>
<tr>
<td>2. Lower block L₂-S</td>
<td>23.7</td>
<td>22.9</td>
<td>0.8</td>
<td>160</td>
<td>514</td>
</tr>
<tr>
<td>3. Lower block L₂-S</td>
<td>14.7</td>
<td>12.6</td>
<td>2.1</td>
<td>268</td>
<td>431</td>
</tr>
<tr>
<td>4. Lower block L₂-S</td>
<td>19.8</td>
<td>15.3</td>
<td>4.5</td>
<td>766</td>
<td>1140</td>
</tr>
<tr>
<td>5. Lower block L₂-S</td>
<td>18.0</td>
<td>14.9</td>
<td>3.4</td>
<td>713</td>
<td>1191</td>
</tr>
<tr>
<td>6. Lower block L₂-S</td>
<td>12.5</td>
<td>11.0</td>
<td>1.5</td>
<td>700</td>
<td>1154</td>
</tr>
<tr>
<td>7. Lower block L₂-S</td>
<td>14.3</td>
<td>11.7</td>
<td>2.6</td>
<td>582</td>
<td>1247</td>
</tr>
</tbody>
</table>

Fig. 4. — 3D MR images reconstructed. Amira® software. A: human dural sac. B: Ligamentum flavum.

Fig. 5. — 3D MR images reconstructed. Amira® software. A: Distribution of nerve roots. B: Distribution of epidural fat.
In our study, we assessed the accuracy of two software programs in estimating cranial spinal fluid (CSF) volume using MRI. For each patient, CSF volume was estimated using different criteria and equipment, with patient characteristics recorded for basic descriptive purposes. No significant correlation was found between variables such as height (1.62-1.84 m), weight (68-95 kg) and BMI (23-33.7 kg.m$^{-2}$) measured at T10 or T11, depending on the height of the patient. CSF volume was estimated in 30.18 $\pm$ 5.9 ml and 36.14 $\pm$ 6.7 ml by the respective teams, with maximum and minimum values summed to 113%.

In the higher block of the study, the difference in estimated CSF volumes was reduced to 27.9% and the total CSF volume difference was only 5.5 ml among four vertebral segments. Both, the accurate phantom estimates, high correlation in volume estimates but the significant differences between the selected thresholds suggest that decision making rather than imprecision of the method itself, is the relevant factor that explains the differences.

Factors such as acquisition configuration, magnetic field, type and position of the antenna, but also CSF pulsating movement, patient morphology influence the range of gray values involved in each MR image set. However, segmentation thresholds are specifically selected later in each case during imaging analysis and probably constitute the most important factor affecting 3D reconstruction and CSF volume estimations. Furthermore, the appearance of the voxels in the borderlines of the structures of interest may be affected by the so called “partial volume effect”: when the same voxel is shared by two structures, its final gray value results from the average gray values of both structures. The setting of segmentation threshold determines how these voxels are interpreted either, as CSF, nerve root or dural sac. The gray scale range of the complete image is between 0-3000 but this range is reduced in areas involving nerve roots and on the edges of the dural sac.

The Amira® software team selected low segmentation thresholds assuring specific selection of nerve roots and considering that the rest of the content of the dural sac was CSF. However, voxels surrounding roots, with a close gray range, affected by the partial volume effect, were considered as CSF, leading to a possible slight overestimation of CSF volume. Low thresholds coincide also with the interface between CSF and the dural sac boundaries and they had to be manually modified to avoid misclassification as nerve root structures. Exhaustive work is required to supervise and manually correct each of the 400 slices per case of the T2 sequences. In this way, the process achieved high image discrimination in areas with irregularity, where CSF and nerve roots are difficult to delineate due to their proximity, like in the conus medullaris area.

In the past, CSF volume measures were based on data obtained by qualitative studies such as myelography (7, 8), measuring diameters of the dural sac and spinal cord sizes (19, 20, 21). CSF volume estimations from MRI have been performed by Fink et al. (9), Hogan et al. (10), Higuchi et al. (3) and Sullivan et al. (11). However, recent advances involving thinner slices, higher image resolutions and analysis with specific 3D reconstruction software, allow more precise determinations.
from each corresponding surface, CSF volumes were calculated. It was not possible for Fink (9) and Hogan (10) at that time, to extract volumes corresponding to spinal nerve roots and the result was an overall estimation inside the dural sac. Fink et al. (9) calculated values for CSF volume of 42.2-80.0 ml in an area extending from T2 to S1; Hogan et al. (10) estimated values for CSF volume of 49 ± 12.1 ml in an area extending from T12-T1 and the lowest limit of the dural sac. Sullivan et al. (11) estimated a CSF volume of 35.8 ± 10.9 ml (range 10.6-61.3 ml) between a perpendicular plane in the intervertebral midpoint of T12-L1, and the lowest limit of the dural sac. The results presented here are within the range reported previously, although, divergences between the studied vertebral levels and between the group of blocks processed, may lead to differences in overall results.

In this study, high resolution MR images (slices at 0.65 mm intervals) most probably improved the precision of our estimated values comparing to previous calculations, where the interval between segments were larger, i.e. 1 mm (Sullivan et al. (11)), 5 mm (Higuchi et al. (4)), (Fink et al. (9)) and 8 mm (Hogan et al. (10)). Due to such high resolution, the image sets had to be grouped in two aligned blocks of 200 sections in order to include all lumbosacral segments. Other relevant aspects of high resolution MRI are that the number of voxels affected by the "partial volume effect" is more reduced, diminishing the imprecision during threshold segmentation and volume estimations. This last aspect has not been analyzed in previous studies, nor have such estimates been compared by two independent teams. The amount of work involved in detailed manual anatomical analysis of 400 slices per patient, limited study to a reduced number of cases, but enough for a basic statistical comparison between both teams.

The software linked to the MR equipment chose higher segmentation thresholds to discriminate areas of CSF, excluding nerve root and dural sac structures. The reconstructions were performed by a technician in radiology with eight years of experience and dedication in medical MR reconstruction. However, detailed image delineation was influenced by common hospital time limitation. The overall volume including nerve roots and spinal cone, separated as a block from the CSF volume, may have been overestimated resulting in an underestimated CSF volume.

Even if manually obtained estimates of CSF volume that were slightly overestimated and the semiautomatic hospital estimates were underestimated, real CSF volume values would be expected to be included between both estimations.

**Conclusion**

Volume estimations from MR images depend on the MR equipment and on the decisions taken during the process of image segmentation. Reconstruction from MR images is a useful non-invasive research technique to measure, CSF, epidural fat, or other volumes, although the potential benefits of its precision and resolution need complementary assessment. Nevertheless, it is interesting to note manual anatomic delimitation in high resolution MR imaging provides very accurate CSF calculations while faster semi-automatic procedures may reach comparable results.

Three-dimensional image reconstruction techniques constitute a unique resource in research at present and clinical practice in the future to obtain anatomical accurate CSF volume measurements and other structures enclosed in the spinal canal that would lead to significant advances in regional anesthesia. Anesthesiologists but also oncologists, physiologists and neuroradiologists, may better understand the physiological, pharmacological and pathological implications, as well as those derived from surgical techniques, of reconstructed structures.

**Acknowledgments**

The authors are grateful to Olga Fuentes for her contribution in the image processing, Human Anatomy and Embryology Unit, Faculty of Medicine, Universitat de Barcelona.

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