3D Interactive Model of Lumbar Spinal Structures of Anesthetic Interest

Alberto Prats-Galino[1], Miguel A. Reina[2*], Marija Mavar Haramija[1], Anna Puigdellivol-Sánchez[1], Juan A. Juanes Méndez[3], José A. De Andrés[4]

[1] Laboratory of Surgical NeuroAnatomy, Human Anatomy and Embryology Unit, Faculty of Medicine, Universitat de Barcelona, Barcelona, Spain.

[2] Department of Clinical Medical Sciences and Applied Molecular Medicine Institute, CEU San Pablo University School of Medicine and Department of Anesthesiology, Madrid-Montepríncipe University Hospital, Madrid, Spain.

[3] VisualMed System Group, University of Salamanca, Spain

[4] Management Department. General University Hospital. Valencia, Spain.

[*] Correspondence to: Miguel A. Reina. MD, PhD, Department of Clinical Medical Sciences and Applied Molecular Medicine Institute, CEU San Pablo University School of Medicine, Department of Anaesthesiology, Madrid-Montepríncipe University Hospital, c/Valmojado , 95 1º B, 28047 Madrid, Spain. Phone: 34 636 62 94 91 FAX E-mail: miguelangel@perticone.e.telefonica.net

Abstract.

Introduction: A 3D model of lumbar structures of anesthetic interest was reconstructed from human Magnetic Resonance (MR) images and embedded into a Portable Document Format file, which can be opened by freely available software and used offline.

Materials and methods: MR images were analyzed using specific 3D software platform for biomedical data. Models generated from manually delimited volumes of interest and selected MR images were exported to Virtual Reality Modeling Language format and were included in a PDF document containing JavaScript-based functions. The 3D file and the corresponding instructions and license files are freely available at http://diposit.ub.edu/dspace/handle/2445/44844?locale=en.

Results: The 3D PDF document includes reconstructions of vertebrae, intervertebral disks, ligaments, epidural and foraminal fat, dural sac and sleeves, sensory and motor cauda equina roots, anesthetic approaches (epidural medial, spinal paramedical and radicular paths) as well as a predefined sequential educational presentation. Zoom, 360º rotation, selective visualization and transparency graduation of each structure and clipping functions are available. Familiarization requires a few minutes.

Conclusions: The document’s easy use may facilitate anatomical and anesthetic teaching, demonstration of patient information and visualization of frequent complications.

Key words: magnetic resonance imaging; three-dimensional PDF; lumbosacral region; user-computer interface; anatomical models

Introduction

The demand of 3D reconstruction in computed tomography and magnetic resonance imaging (MRI) has significantly increased during the last years, but in spite of its enormous potential in clinical diagnosis, it's not widely used in anesthesiology. The small number of combined anesthetic, radiologist and anatomical studies could be the reason. 3D MRI could undoubtedly be a useful complementary approach as it may facilitate the visualization of structures relevant in regional anesthesia.

We have previously published cauda equina nerve roots vulnerability rates (Prats-Galino et al., 2012a) based on 3D reconstructions of lumbosacral CSF and root volumes of human patients MR images. However, the direct interaction with the 3D models is now possible without the use of commercial software.

At present, 3D models obtained from cross-sectional images can be embedded in Portable Document Format (PDF) files, becoming a powerful tool for clinical, educational and research purposes (Phelps et al., 2012). Some 3D based on experimental animals have been developed and presented in PDF format (Ruthensteiner et al., 2008; de Boer et al., 2012); such technology has been also implemented to study the developing human heart (Sizarov et al., 2012) and the adult human liver (Mutter et al., 2010) as examples. Human 3D resources based on images from dissections of the Visible Human Project (Ackerman et al., 1995) are available (NLM, 2013). Other commercial 3D programs combine anatomic Visible Human images with MR or TC images: Voxel-man 3D-Navigator (Höhne, 2001). Furthermore, 3D PDF resources from the Korean visible body, based on images of sections of a whole male cadaver, are now freely available (Sin et al., 2012). Here, we propose the first 3D PDF supported model for lumbosacral neuraxial structures of interest in anesthesia, specifically relevant to neuraxial blockade, based on human MR images.

This model could be of interest in educational programs, allowing teaching neuraxial anatomy and regional anesthesia, as well as visual aid in the development of new approaches in regional anesthetic techniques and surgical procedures. It can also be used to assist in the education of patients about their spinal pathology. Finally, it can also be used as a source of support in research programs.

Our aims were to develop a model from lumbosacral human MR images that could be examined through easily available software, free of charge, allowing interaction with those models. Such software should not require previous specialized knowledge in informatics and should be available for offline use for most users on their own computers, to allow widespread use.

Materials and Methods

This work was based on data obtained in previous studies from DICOM files, whose dural sac results, MR setting details and basic 3D reconstruction have been partly published (Prats-Galino et al., 2012a). The research line was approved by "Grupo Hospital Madrid Clinical Research ethics Committee" and consent was obtained from patients who were being treated at the Pain Unit Service, having symptoms of low back pain, with absence of morphological changes in their MR neuroradiological reports. One of the models obtained has been studied here in more detail.

The methodology of this study can be divided into 3 main steps (Figure 1): a) data acquisition, b) image processing (segmentation and surface reconstruction) and c) 3D PDF document creation.

Lumbar MRI scans were performed 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 sequence obtained by T1 Fast Field echo allowed detailed 3D reconstruction of ligaments, bones, dural sac and sleeves while T2 weighted sequence was used for volume determinations of CSF, spinal cord and cauda equina structures.

MR images were exported from the hospital equipment to the neuroanatomic laboratory in DICOM format, which preserves spatial coordinates. Data processing was performed by the software AMIRA® v5.2 (Mercury Co, Boston, USA), installed on a graphic station (Dell Precision 690). This software is designed for visualization and analysis of biomedical images, allowing volumetric reconstruction.

The image processing steps are the summarized in Figure 2:

1.) MR images in different planes, saved in DICOM format on the MR equipment, are imported to AMIRA software

2.) The images in the three orthogonal planes -axial (a), sagittal (b) or coronal (c)- are segmented by manual delimitation of Volumes of Interest (VOI) of structures such as vertebrae, intervertebral discs, ligaments, epidural fat, dural sac and a preliminary 3D visualization (d) is prepared for revision of the correspondence between each model contours and its corresponding structure in the MR images. Steps may be repeated until accurate adjustment is reached.

3.) 3D appearance results from triangulation by marching cubes algorithm (a), that leads to the corresponding shaded 3D surface model (b).

4.) To allow a quick interactive movement of the model, the number of triangles is reduced (final resolution about 0.01cm2 per triangle) and a whole structure smoothing is applied (a), resulting in a simplified 3D surface appearance (b).

Once the 3D reconstruction has been finalized, 3D models and MRI slices (13 mm intervals for axial and coronal slices and 6,5 mm for sagittal slices) were exported to Virtual Reality Modeling Language (VRML) file format. VRML files are then imported to 3D Reviewer® (Tetra4D, Seattle, USA; Figure 2.5) to generate a file in U3D format, which contains graphic components that are compatible with PDF documents. The accessory plug-in '3D PDF converter' (Tetra4D) allows the embedding of the U3D files in a 3D area of a PDF file by Acrobat XI Pro, that was used to define the 3D PDF interface.

Results

The PDF file with the 3D model and an instructions file (Figure 3) are available at the University of Barcelona public repository (http://diposit.ub.edu/dspace/handle/2445/44844?locale=en). These files were translated to seven foreign languages in order to facilitate their international diffusion and can be accessed from the same repository. The files are distributed under an international Creative Commons Attribution-Noncommercial-Share Alike license, which requires attribution to the authors, that allows derivate works without commercial use, provided that is shared like the present license. Source code and model geometry are not public and cannot be accessed or modified.

The resulting 3D PDF file and the corresponding instructions file must be downloaded and saved in the same folder. When clicking on the 'help' button in the 3D PDF (Figure 3.15), the instructions file contents will be opened off-line in the computer's internet browser. The instructions file may also be opened separately by a PDF reader.

The model allows interactive visualization of the 3D reconstructed structures, such as vertebrae, intervertebral disks, ligaments (flavum, supraspinous and interspinous), epidural and foraminal fat, dural sac and sleeves, sensory and motor cauda equina roots, and needles simulating common anesthetic approaches (epidural medial, spinal paramedical and radicular approach paths). Furthermore, it includes axial, sagittal and coronal MR planes.

The appearance of the PDF 3D interface (Figure 3) is shown at the beginning of the instructions file. Clicking on blue labels 1-15 within the instructions file leads to the explanations of different button functions (Fig 3.1-15).

The model rotates 360º with the left mouse button. Zoom is adjustable by the right mouse button and a scroll wheel. Pre-defined axial, sagittal and coronal views are offered as reference. Partial transparency effects (Fig 3.5; Fig 4a) and selective visualization of each structure are possible (Fig 3.3-4; Fig 4b, c, d), including anesthetic paths (Fig 5), as well as clipping of the entire model in the three axis (Fig 3.10-12; Fig 6). Different axial, sagittal, and coronal MR planes may be visualized either independently or in combination (Fig 3.8-9; Fig 7). Predefined scenes are provided, and can be displayed sequentially to facilitate an educational presentation, showing progressive appearance of the spine, ligaments, epidural fat, dural sac and sleeves and sensory and motor cauda equina nerve roots (Fig3.13; Fig 8).

Discussion

Three-dimensional image reconstruction techniques are widely used in research, in clinical practice for pre- and intra-operative visualization of MRI data (Fedorov et al., 2012) and in anatomical teaching: commercially available 3D anatomical software may be based on models built from imaging data (Primal Pictures, 2005) or on drawn illustrations (A.D.A.M., 2013). Furthermore, a whole body 3D interactive model, based on TC and MR images, photographs of real tissues and atlases, is partially available free of charge (Zygote Media Group, 2012). Most of those products include 3D interactive models of bones, muscles, blood vessels, nerves, brain structures and viscera.

After developing several 3D models to facilitate brain understanding for neuroanatomical teaching (Prats-Galino et al., 2003), improving neuroimaging interpretation (Ruisoto et al., 2012), participating in research assessment (Padros et al., 2010; Soria et al, 2011; Prats-Galino et al, 2012) and enhancing surgical approaches (de Notaris et al., 2010) or surgical training (de Notaris et al., 2013), our focus has now shifted to 3D reconstruction of lumbosacral structures of anesthetic interest, specifically relevant in neuraxial anesthesia.

3D surface reconstruction from MR images of most structures enclosed in the spinal canal was made through commercial software (Amira®), which also allowed measurements of the volumes of the reconstructed structures and enhances visualization of the relationship between neighboring structures after detailed manual delineation of semiautomatic reconstructions from human 2D MR images. However, its cost and learning curve hinders its widespread use by anesthesiologists to develop interactive 3D models. The final outcome, the resulting 3D PDF model presented here, was later developed to allow accurate and detailed anatomical representation of each of the structures involved in neuraxial blockade.

The advantages of the presented software, regarding the anatomical commercial software mentioned above, are the free availability and the anatomical detail based on human MR images, focused in lumbar anesthetic approaches. 3D model was embedded in a standard

PDF file format that can be opened by freely available programs (Acrobat Reader XI or posterior). The PDF format of the document simplifies its use, portability, compatibility and storage as the file size can be compressed. For the moment, 3D PDF documents are not supported in mobile devices (tablets and smartphones).

The document is intuitive and doesn't require any special informatics knowledge of the user who may be familiarized with the interface in a few minutes. Instructions may be easily visualized through the 'help' button. Furthermore, it contains predetermined 3D views, with partial visibility of the structures for a sequential educational presentation: general view of the spine and anatomy of vertebrae, different paths of the anesthetic approaches for epidural blocks, progressive appearance of ligaments, epidural fat, dural sac and sleeves and cauda equina sensory and motor nerve roots. The human MR images from which the 3D model was reconstructed are also visible in three planes.

Altogether, this model may be of special interest for anesthesiologists and anesthesiology teaching and it can be used free of charge by every physician.

Conclusion

An intuitive 3D PDF interactive anatomical model allows the visualization from any perspective of lumbar structures of interest in neuraxial anesthesia, including MR planes, facilitating anatomical and anesthetic research, teaching programs and patient communication, without the need for deep previous informatics knowledge.

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Figure Legends

Figure 1. Process flow diagram. The software used to perform each step is indicated on the left.

Figure 2. 3D PDF development steps.

Figure 3. Instructions file screenshot showing the PDF file interface. (1) Screen working area. (2) Predefined frontal, lateral, dorsal and coronal views. Structures listed in the drop down menu (3), are visualized after confirmation in the check box (4), while arrows (5) allow different degrees of their transparency. All the structures may be also displayed together (6) or hidden (7). Axial, sagittal and coronal magnetic resonance images may be displayed (8) and it's possible to navigate among them (9). Clipping is available (10) in three planes (11) and allows moving along successive cuts in each plane (12). Predefined views with the progressive appearance of the different structures are presented (13). Checkbox (14) disables the automatic selection of clicked structures and button (15) opens the instructions file.

Figure 4. Partial visualization of the anatomical structures. The user may select which structures are shown. Some examples are provided: a) Transparentation of L4. b) L4 may be hidden to allow better visualization of intervertebral discs, dural sac and sleeves. c) L3 is selectively hidden and the model rotated to allow visualization of the epidural medial approach. d) Dural sac can be hidden to enhance visualization of cauda equina sensory (blue) and motor nerve roots (red).

Figure 5. Needles in the common anesthetic approaches: epidural medial, spinal paramedial and radicular approach paths.

Figure 6. Clipping in axial (a), sagittal (b) and frontal (c) planes.

Figure 7. MR planes may be visualized, hidden or rotated together with the model.

Figure 8. Predefined models for an educational presentation. The sequence shows progressive appearance of spine together with the medial spinal approach (a), ligaments (b), fat (c), dural sac (d) and sensory (e) and motor (f) roots.