

ORIGINAL COMMUNICATION

3D Interactive Model of Lumbar Spinal Structures of Anesthetic Interest

ALBERTO PRATS-GALINO,¹ MIGUEL A. REINA,^{2,3*} MARIJA MAVAR HARAMIJA,¹
ANNA PUIGDELLIVOL-SÁNCHEZ,¹ JUAN A. JUANES MÉNDEZ,⁴ AND JOSÉ A. DE ANDRÉS^{5,6}

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

²Department of Clinical Medical Sciences and Applied Molecular Medicine Institute, CEU San Pablo University School of Medicine, Madrid, Spain

³Department of Anesthesiology, Madrid-Montepíncipe University Hospital, Madrid, Spain

⁴VisualMed System Group, Human Anatomy Department, University of Salamanca, Salamanca, Spain

⁵Surgical Specialties Department, University of Valencia School of Medicine, Valencia, Spain

⁶Anesthesia Critical Care and Pain Management Department, Valencia General University Hospital, Valencia, Spain

A 3D model of lumbar structures of anesthetic interest was reconstructed from human magnetic resonance (MR) images and embedded in a Portable Document Format (PDF) file, which can be opened by freely available software and used off-line. The MR images were analyzed using a 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 presented in a PDF document containing JavaScript-based functions. The 3D file and the corresponding instructions and license files can be downloaded freely at <http://diposit.ub.edu/dspace/handle/2445/44844?locale=en>. The 3D PDF interactive file includes reconstructions of the L3–L5 vertebrae, intervertebral disks, ligaments, epidural and foraminal fat, dural sac and nerve root cuffs, sensory and motor nerve roots of the cauda equina, and anesthetic approaches (epidural medial, spinal paramedial, and selective nerve root paths); it also includes a predefined sequential educational presentation. Zoom, 360° rotation, selective visualization, and transparency graduation of each structure and clipping functions are available. Familiarization requires no specialized informatics knowledge. The ease with which the document can be used could make it valuable for anatomical and anesthetic teaching and demonstration of patient information. *Clin. Anat.* 28:205–212, 2015. © 2014 Wiley Periodicals, Inc.

Key words: magnetic resonance imaging; anatomical reconstruction; 3D PDF; lumbosacral region; nerve roots; epidural fat

INTRODUCTION

The demand for 3D reconstruction in computed tomography and magnetic resonance imaging (MRI) has increased significantly during recent years, but despite its enormous potential in clinical diagnosis it is not widely used in anesthesiology. This could be because the aggregate number of anesthesiological, radiological, and anatomical studies is small. 3D MRI could undoubtedly be a useful complementary

Contract grant sponsor: Marató TV3 Grant Project 411/U/2011.

*Correspondence to: Miguel A. Reina. MD, PhD, Department of Clinical Medical Sciences and Applied Molecular Medicine Institute, CEU San Pablo University School of Medicine and Department of Anaesthesiology, Madrid-Montepíncipe University Hospital, c/Valmojado, 95 1° B, 28047 Madrid, Spain.
E-mail: miguelangel@peticone.e.telefonica.net

Received 30 July 2014; Revised 25 September 2014; Accepted 30 September 2014

Published online 28 October 2014 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/ca.22479

approach because it can facilitate the visualization of structures relevant to regional anesthesia.

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

At present, 3D models obtained from cross-sectional images can be embedded in Portable Document Format (PDF) files, making them a powerful tool for clinical, educational, and research purposes (Phelps et al., 2012). Some 3D images based on experimental animals have been developed and presented in PDF format (Ruthensteiner and Heb, 2008; de Boer et al., 2012); similar technology has been used to study, e.g., the developing human heart (Sizarov et al., 2012) and the adult human liver (Mutter et al., 2010). Human 3D resources based on images from dissections in the Visible Human Project (Ackerman et al., 1995) are available (NLM, 2013). Other commercial 3D programs combine anatomical Visible Human images with MR or TC images: Voxelman 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 (Shin 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 (Prats-Galino et al., 2014).

This model could be useful in educational programs, allowing neuraxial anatomy and regional anesthesia to be taught and providing a visual aid for the development of new approaches to regional anesthetic techniques and surgical procedures. It could also be used to assist in educating patients about their spinal pathology. Finally, it could 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 users to interact with them. To enable usage to be widespread, such software should not require previous specialized knowledge in informatics and should be available for offline use on most users' own computers.

MATERIALS AND METHODS

This work was based on data obtained in previous studies from DICOM files, of which the 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 being treated at the Pain Unit Service for symptoms of low back pain, with no 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 three main steps (Fig. 1): data acquisition, image

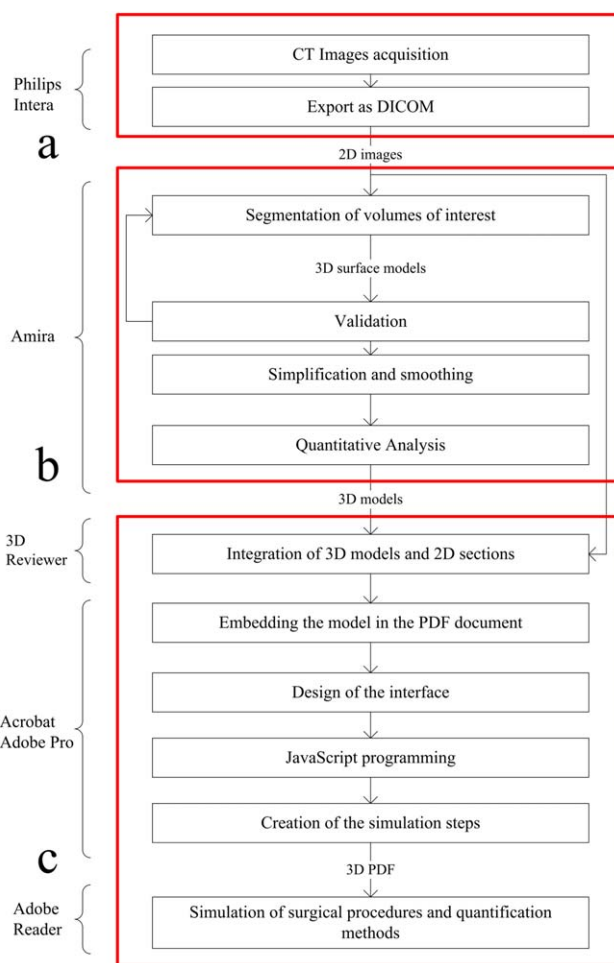


Fig. 1. Process flow diagram: (a) data acquisition, (b) image processing, (c) 3D PDF technology. More detail about each step is provided for readers interested in creating interactive 3D files for themselves. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

processing (segmentation and surface reconstruction), and 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 the T1 Fast Field echo allowed ligaments, bones, dural sac, and nerve root cuffs to be reconstructed in detail in 3D, while the T2 weighted sequence was used to measure the volumes of CSF, spinal cord, and cauda equina structures.

MR images were exported from the hospital equipment to the neuroanatomical laboratory in DICOM format, which preserves spatial coordinates. Data were processed by the software AMIRA[®] v5.2 (Mercury Co, Boston, MA) installed on a graphic station (Dell Precision 690). This software is designed for visualizing and analyzing biomedical images, making volumetric reconstruction possible.

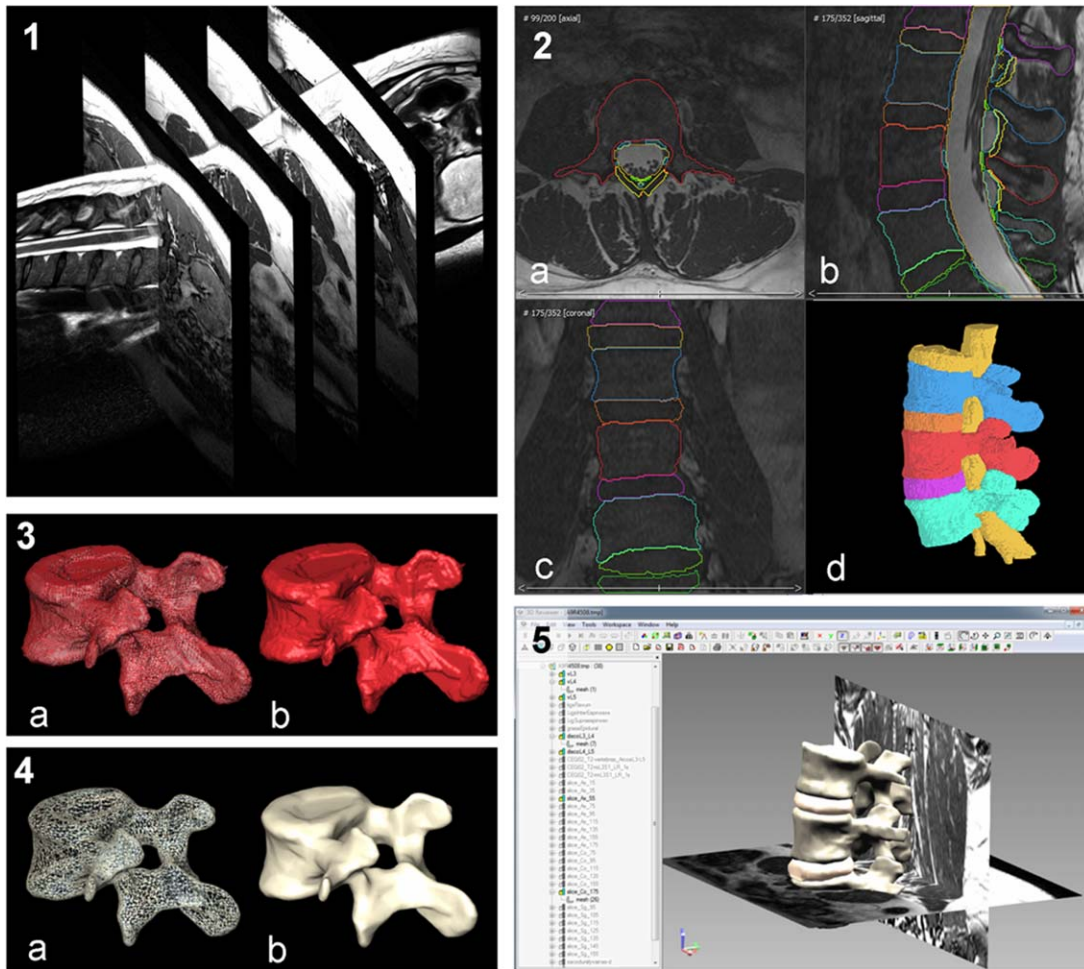


Fig. 2. 3D PDF development steps. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The image processing steps are 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) and coronal (c)—are segmented by manual delimitation of volumes of interest (VOI) of structures such as vertebrae, intervertebral discs, ligaments, epidural fat, and dural sac, and a preliminary 3D visualization (d) is prepared for revising the correspondence between the contours of each model and its corresponding structure in the MR images. Steps can be repeated until accurate adjustment is reached.
3. The 3D appearance results from triangulation by the marching cubes algorithm (a), which generates the corresponding shaded 3D surface model (b).
4. To allow for a quick interactive movement of the model, the number of triangles is reduced (final

resolution about 0.01 cm^2 per triangle) and the whole structure is smoothed (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. The VRML files were then imported to 3D Reviewer[®] [Tetra4D, Seattle, WA; Fig. 2(5)] to generate a file in U3D format, which contains graphic components compatible with PDF documents. The accessory plug-in “3D PDF converter” (Tetra4D) allows the U3D files to be embedded in a 3D area of a PDF file by Acrobat XI Pro, which was used to define the 3D PDF interface.

RESULTS

The PDF file with the 3D model and an instructions file (Fig. 3) are available for download at the University of Barcelona public repository (<http://diposit.ub>).

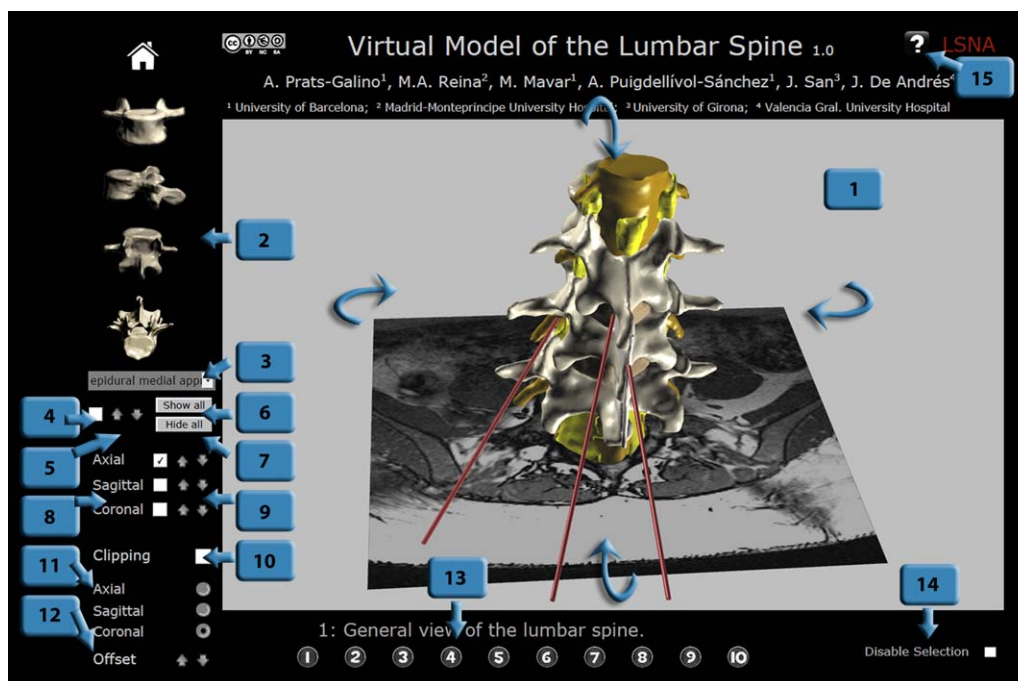


Fig. 3. Instructions file screenshot showing the PDF file interface. (1) Screen working area. (2) Predefined frontal, lateral, dorsal, and coronal views. Structures listed in the drop down menu (3) are visualized after confirmation in the check box (4), while arrows (5) allow different degrees of transparency to be chosen. The structures can all be displayed together (6) or hidden (7). Axial, sagittal, and coronal magnetic resonance images may be displayed (8) and navigation among them is possible (9).

edu/dspace/handle/2445/44844?locale=en). These files were translated into seven foreign languages to facilitate their international diffusion and the translations 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 and allows derivative works to be created if they are not for commercial use, provided they are shared, like the present license. The 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 on a desktop computer. In order to achieve its full functionality, the 3D PDF file has to be opened in Acrobat Pro XI or Acrobat Reader XI on the user's computer, not with an internet browser. The instructions file is opened by clicking on the "help" button in the 3D PDF [Fig. 3(15)], after which it appears offline in the computer's internet browser. It can also be opened separately by a PDF reader (Acrobat Reader).

The model allows for interactive visualization of the 3D-reconstructed structures such as vertebrae, intervertebral disks, ligaments (flavum, supraspinous, and interspinous), epidural and foraminal fat, dural sac

and nerve root cuffs, sensory and motor nerve roots of the cauda equina, and needles simulating common anesthetic approaches (epidural medial, spinal paramedial, and selective nerve root approach paths). Furthermore, it includes the axial, sagittal, and coronal MR planes.

The appearance of the PDF 3D interface (Fig. 3) is shown at the beginning of the instructions file. Clicking on blue labels 1–15 within the instructions file opens the explanations of different button functions [Fig. 3(1–15)].

The model rotates 360° using the left mouse button. Zoom can be adjusted with the right mouse button and a scroll wheel. Pre-defined axial, sagittal, and coronal views are offered as reference [Fig. 3(2)]. Partial transparency effects [Figs. 3(5) and 4a] and selective visualization of each structure are possible [Figs. 3(3,4) and 4b–4d], including anesthetic paths (Fig. 5), and the entire model can be clipped in the three axes [Figs. 3(10–12) and 6]. Different axial, sagittal, and coronal MR planes can be visualized either independently or in combination [Figs. 3(8,9) and 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, nerve root cuffs, and sensory and motor cauda equina nerve roots [Figs. 3(13) and 8].

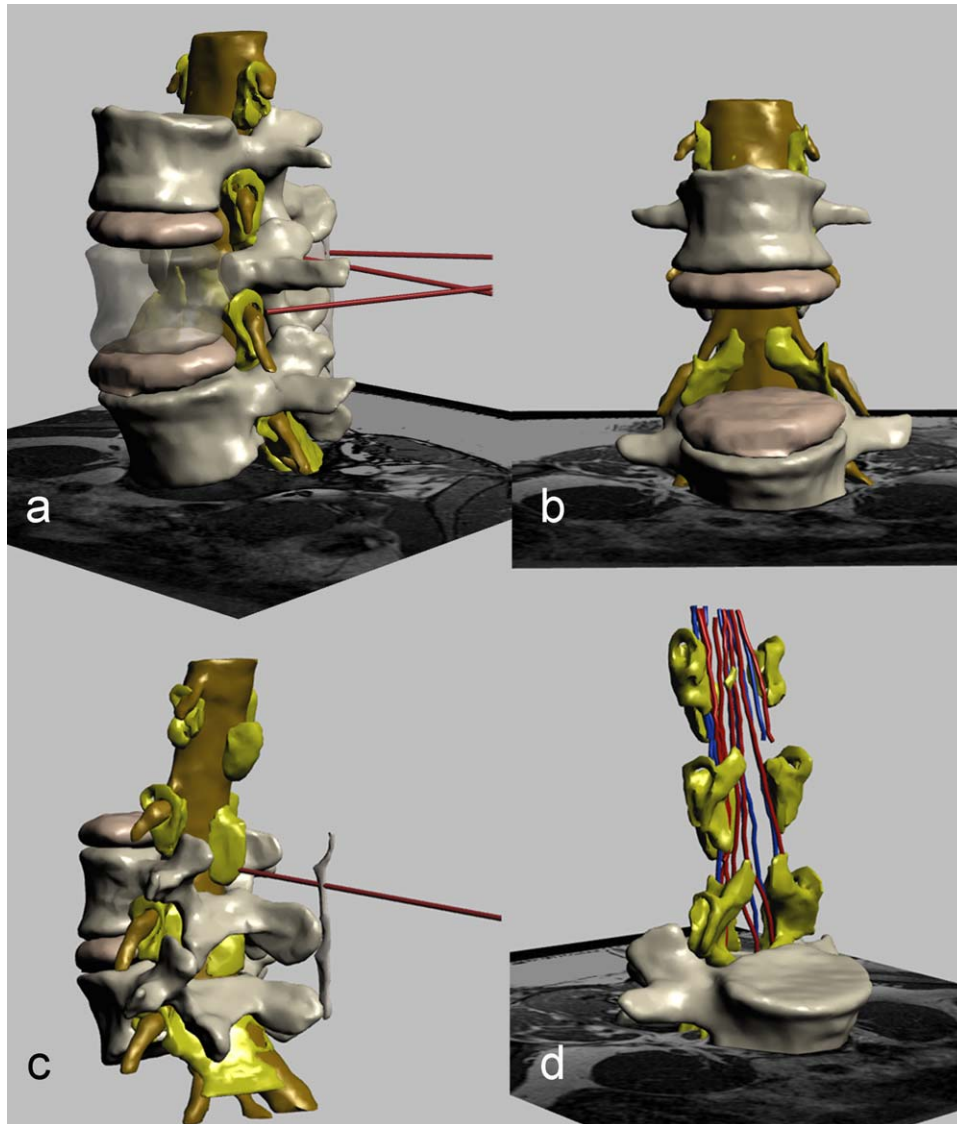


Fig. 4. Partial visualization of the anatomical structures. The user can select which structures are shown. Some examples are provided: **(a)** Transparentiation of L4. **(b)** L4 can be hidden to allow the intervertebral discs, dural sac, and nerve root cuffs to be visualized better. **(c)** L3 is selectively hidden and the model rotated to allow the

epidural medial approach to be visualized. **(d)** The dural sac can be hidden to enhance visualization of the cauda equina sensory (blue) and motor (red) nerve roots. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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 can 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 and photographs of real tissues and atlases is partially available free of

charge (Zygot 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 understanding of the brain for neuroanatomical teaching (Prats-Galino and Juanes, 2003), improving neuroimaging interpretation (Ruisoto et al., 2012), participating in research assessment (Prados et al., 2010; Soria et al., 2011; Prats-Galino et al., 2012b), and enhancing surgical approaches (de Notaris et al., 2010) or surgical training (de Notaris et al., 2013),

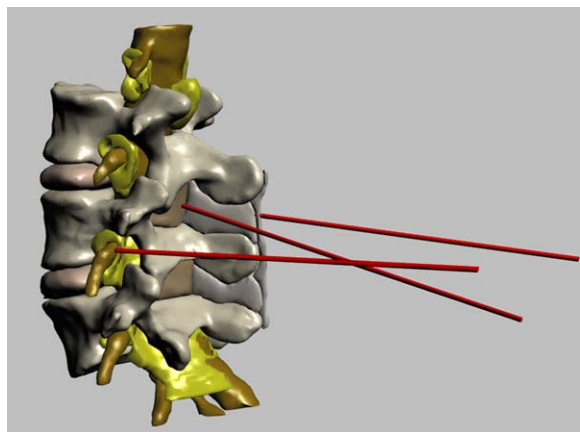


Fig. 5. Needles in the common anesthetic approaches: epidural medial, spinal paramedial, and selective nerve root approach paths. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

our focus has now shifted to 3D reconstruction of lumbosacral structures of anesthetic interest, specifically relevant to neuraxial anesthesia.

The 3D surfaces of most structures enclosed in the spinal canal were reconstructed from MR images using commercial software (Amira[®]), which also allowed the volumes of the reconstructed structures to be measured and enhanced the visualization of relationships between neighboring structures after detailed manual delineation of semiautomatic reconstructions from human 2D MR images. However, the cost and learning curve hinder its widespread use by anesthesiologists seeking to develop interactive 3D models. The final outcome, the 3D PDF model presented here, was later developed to produce accurate and detailed anatomical representations of each of the structures involved in neuraxial blockade.

The advantages of the presented software, in comparison to the commercial anatomical software



Fig. 7. MR planes can be visualized, hidden, or rotated together with the model. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

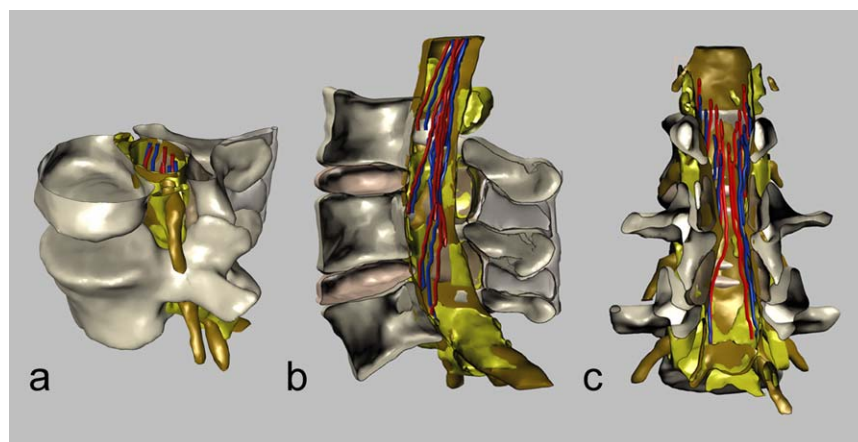


Fig. 6. Clipping in axial (a), sagittal (b), and frontal (c) planes. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

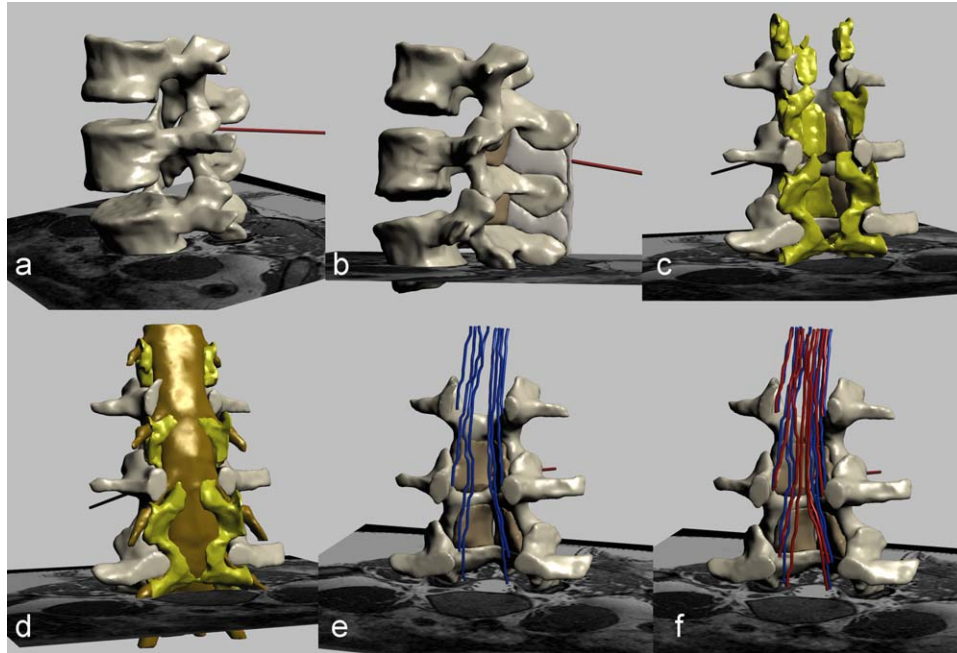


Fig. 8. Predefined models for an educational presentation. The sequence shows progressive appearance of the spine together with the medial spinal approach (a), ligaments (b), fat (c), dural sac (d), and sensory (e) and motor (f) roots. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

mentioned above, are its free availability and the anatomical detail based on human MR images, focused on lumbar anesthetic approaches. The 3D model was embedded in a standard PDF file format that can be opened using freely available programs (Acrobat Reader XI or its successors). The PDF format of the document simplifies its use, portability, and storage as the file can be compressed. At present, 3D PDF documents are not supported on mobile devices (tablets and smartphones).

The document is intuitive and requires no special informatics knowledge by the user, who can be familiarized with the interface in a few minutes. Instructions can be visualized easily 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 the vertebrae, different paths for anesthetic approaches to epidural blocks, progressive appearance of ligaments, epidural fat, dural sac, nerve root cuffs, and sensory and motor nerve roots of the cauda equina. The human MR images from which the 3D model was reconstructed are also visible in three planes.

Altogether, this model could 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 lumbar structures of interest in neuraxial anes-

thesia to be visualized from any perspective, including MR planes. It could be valuable for anatomical and anesthetic teaching programs and patient communication, without the need for previous deep informatics knowledge.

ACKNOWLEDGMENTS

The authors are grateful to Olga Fuentes for her contribution to the image processing. They also thank Dr Julio Castedo and Mr José Manuel Escobar for magnetic resonance acquisitions. The authors have no conflicts of interest to disclose.

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