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Development of anatomical and radiological digital brain maps

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SUMMARY

The main goal of this study was to develop a tool to manage digital maps of the brain and information related to specific regions in the brain. This tool integrates 3D models of deep brain structures referenced in original Magnetic Resonance and Visible Human Project cross-sections with anatomical, functional, pathological and surgical information for any specific brain region. Digital brain maps and related information were selectively displayed using an intuitive user-friendly interface. The implications of its use as a resource for a wide range of disciplines in neurosciences are discussed.

Key words: Digital map – Human brain – Database – Software

INTRODUCTION

The Visible Human Project (VHP) constitutes one of the most important advances for the anatomical and radiological study of the brain. It comprises the most complete volumetric data of human anatomy, including cryosection photographs, Computerized Tomography (CT) and Magnetic Resonance (MR) images of American male and female samples (Ackerman, 2002; Seifert and Carmichael, 2006; Burke and Patrias, 2007).

Recent advances in information technology, specifically the development of software for medical image processing, have provided digital tools, such as Insight Segmentation and the Registration Toolkit, for the analysis of those original VHP images (Ackerman and Yoo, 2003; Yoo and Metaxas, 2005) or other samples such as the Chinese VHP (Yuan et al., 2003; Zhang et al., 2006; Bao et al., 2007; Chen et al., 2008; Heng et al., 2006) or the Korean VHP (Chung et al., 2002; Park et al., 2005, 2006; Choi et al., 2007).

As a consequence, VHP has become the best digital reference for the anatomical study of the brain (Burke and Patrias, 2007), and numerous devices have been developed and continue to be developed for training and clinical purposes, enriching our knowledge of the morphological and functional aspects of the brain (Juanes et al., 1996; Juanes et al., 2003; Dev and Senger, 2005).

On the one hand, atlases and 3D model reconstructions have drawn most attention, providing powerful training resources for data interaction and navigation, and offering new insight into spatial details and the relation-

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ships among neuroanatomical structures (Shelton et al., 2005; Rizzolo and Stewart, 2006; Temkin et al., 2006; Prats and Juanes, 2007).

On the other hand, the Tailarach atlas is one of the best known in the clinical context of neurosurgery, and it provides an accurate exploration system for localizing any region in the brain (Schaltelrand and Wahren, 1977; Riechert, 1980; Tailarach and Tournoux, 1988; Collins et al., 1994; Toga and Mazziotta, 1996).

Both categories of applications underlie the importance of data visualization, as well as processing and navigation tools, in order to improve our anatomical knowledge with or without clinical purposes. In this context, geographic information systems have been pointed out as key procedures (Antenucci et al., 1991; Maguire et al., 1991; Aronoff, 1989; Croner et al., 1996; Burrough and Donnell, 1998).

This study aims to develop a digital brain map involving a territorial information system that will offer an intuitive and powerful tool for the comprehensive analysis of large volumes of anatomical and radiological information about the brain. This tool will display spatially referenced digital information (georeferenced data).

MATERIALS AND METHODS

Three-dimensional digital models of the brain structures were developed, including soft tissue, cerebrospinal fluid, and bone tissue, from radiological and anatomical images.

Orthogonal images were acquired, first from anatomical sections (1 mm-thick) from the Visible Human Project with a size of 2048 x 1216 pixels per image and a resolution of 24 bits of colour per pixel, and second from magnetic resonance (MR) sections (4 mm thick) with a size of 256 x 256 pixels and a resolution of 12 bits per pixel, and thirdly from computerized tomography (CT) sections (1 mm thick), with a size of 512 x 512 pixels per image and a resolution of 16 bits/pixel.

A total of two hundred and fifty coronal, sagittal and axial sections of the brain were selected for the creation of voxels of 1mm^3 size on a Unix platform, generating between 5 and 10 million entries. Similarly, a relational database was developed in Visual C for this purpose. Open Database Connectivity (ODBC) was used to drive the database, allowing for connections among different applications and types of Structured Query Language (SQL) databases, permitting the organisation, management and retrieval of data stored in those databases. Total brain volume was divided into previously segmented discrete finite brain structures, including structured non-graphic attributes for independent spatial analyses of brain areas.

Then, an exploration system based on universal stereotaxic atlases was developed for accurate localization of any structure within the brain, using coordinates defined by the bicommissural line and orthogonal planes as references: first, the midsagittal plane; second, the plane through the anterior and posterior commissures orthogonal to the midsagittal plane, and third the plane through the anterior commissure orthogonal to the others. The brain images were scaled along each axis according to the dimensions of a standard brain. Thus, each point of a brain section can be accessed by x-y-z coordinates that will place that point in the digital brain map.

Geomedia® Professional software developed by Intergraph® allowed the creation and management of a database for both the geographic and spatial information of segmented brain structures and their attributes. This geographic information system (GIS) was used to model and analyze complex spatial relationships within brain digital maps, using elements such as lines and dots for distance measurements between or within brain structures, and polygons for the representation of brain-structure surfaces (Figs. 1, 2 and 3). Additional GIS tools were used up to guarantee topological consistency and to avoid superimposed polygons.

Finally, a user graphic interface was developed using the Asymetrix ToolBook® version 11 developed by SumTotal®, an excellent tool set for multimedia software development, specifically for creating graphical presentations such as three-dimensional graphics and animations.

RESULTS

A digital brain map was developed using geographic information technology as a tool for the visualization and spatial exploration of a vast number of volumetric medical data. It

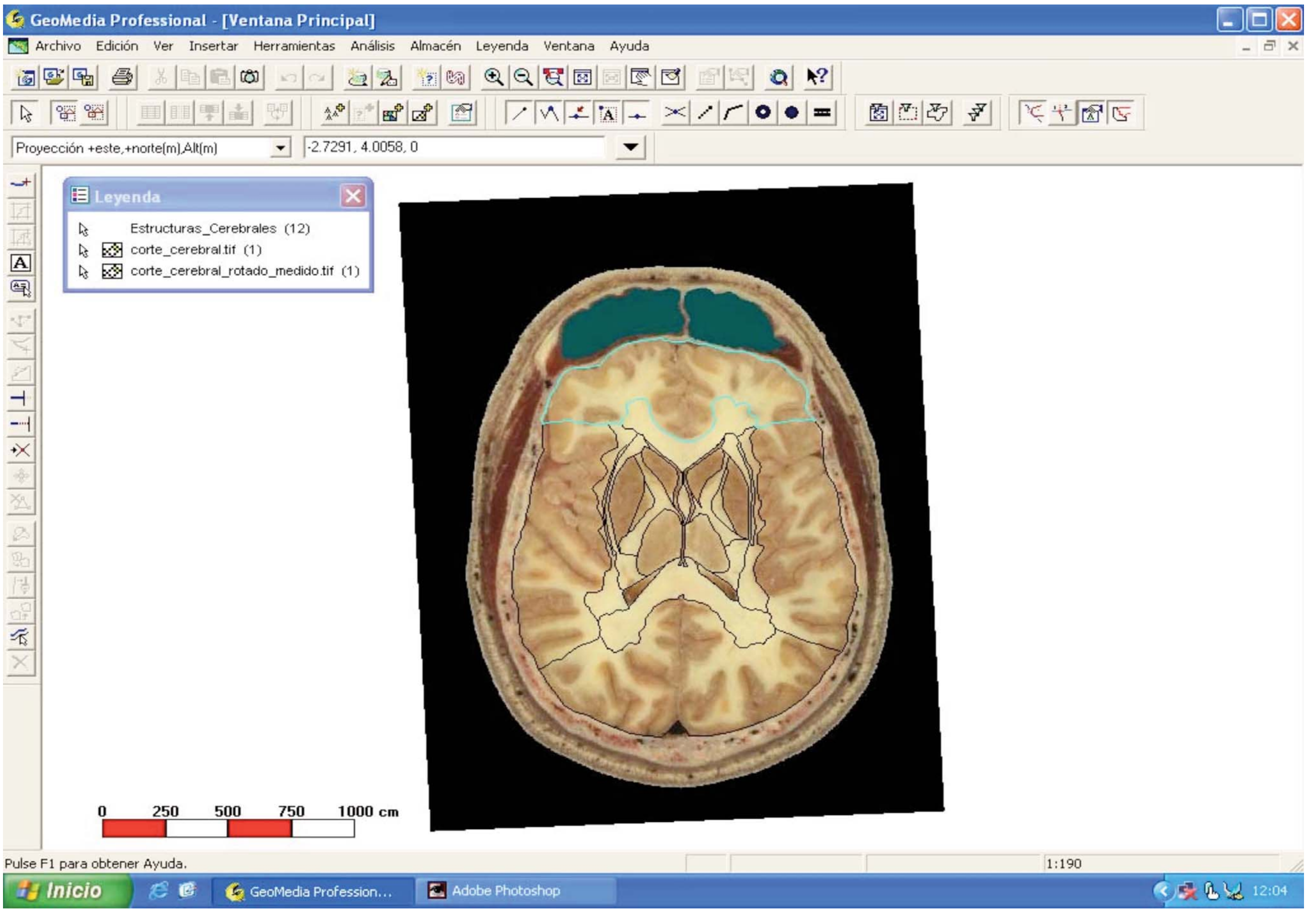

Fig. 1. Geomedia® Professional interface. Note segmented brain structures visualized in a VHP axial section.

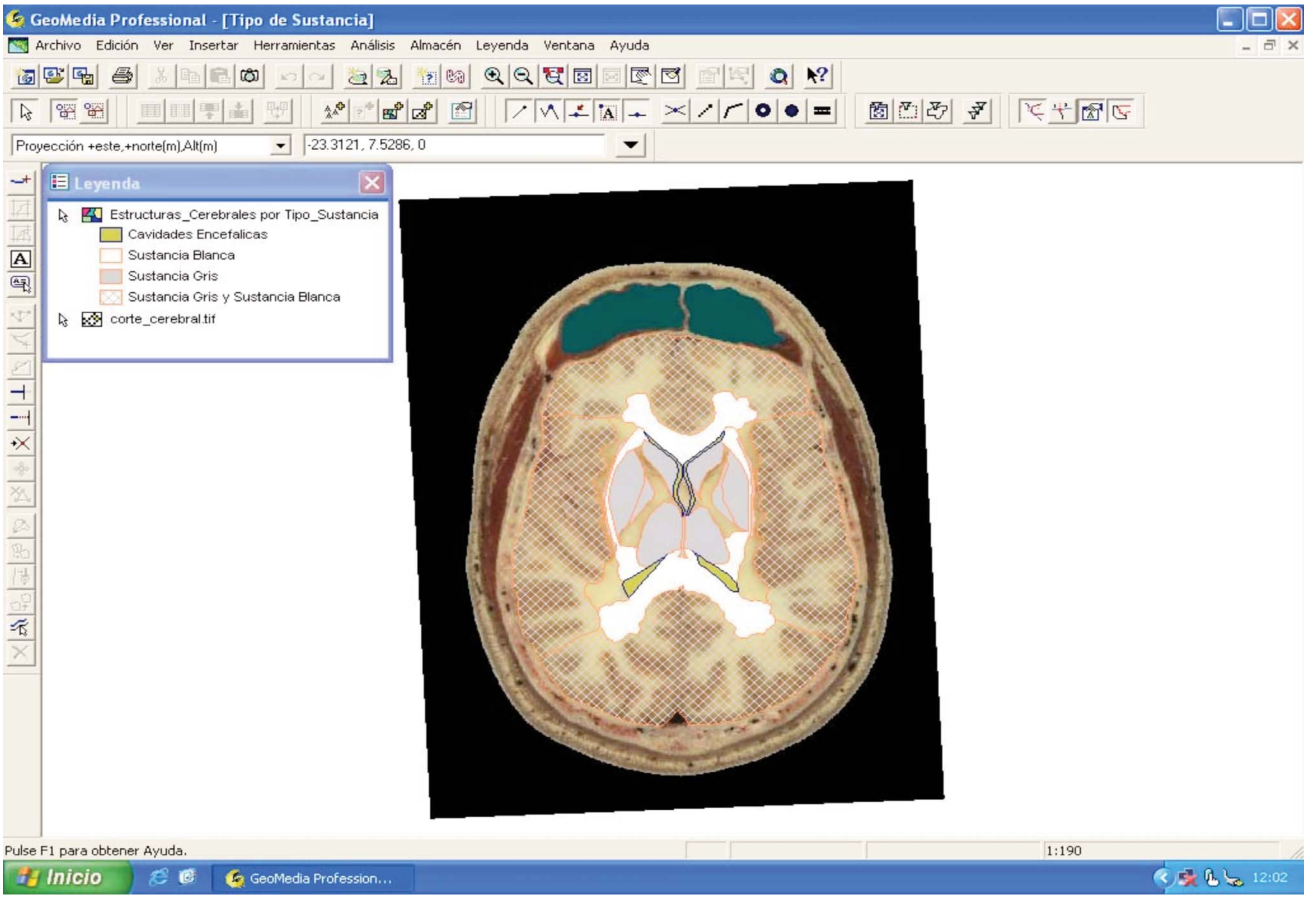

Fig. 2. Neural map layout after deep brain structure segmentation with Geomedia® Professional: basal nuclei and white matter.

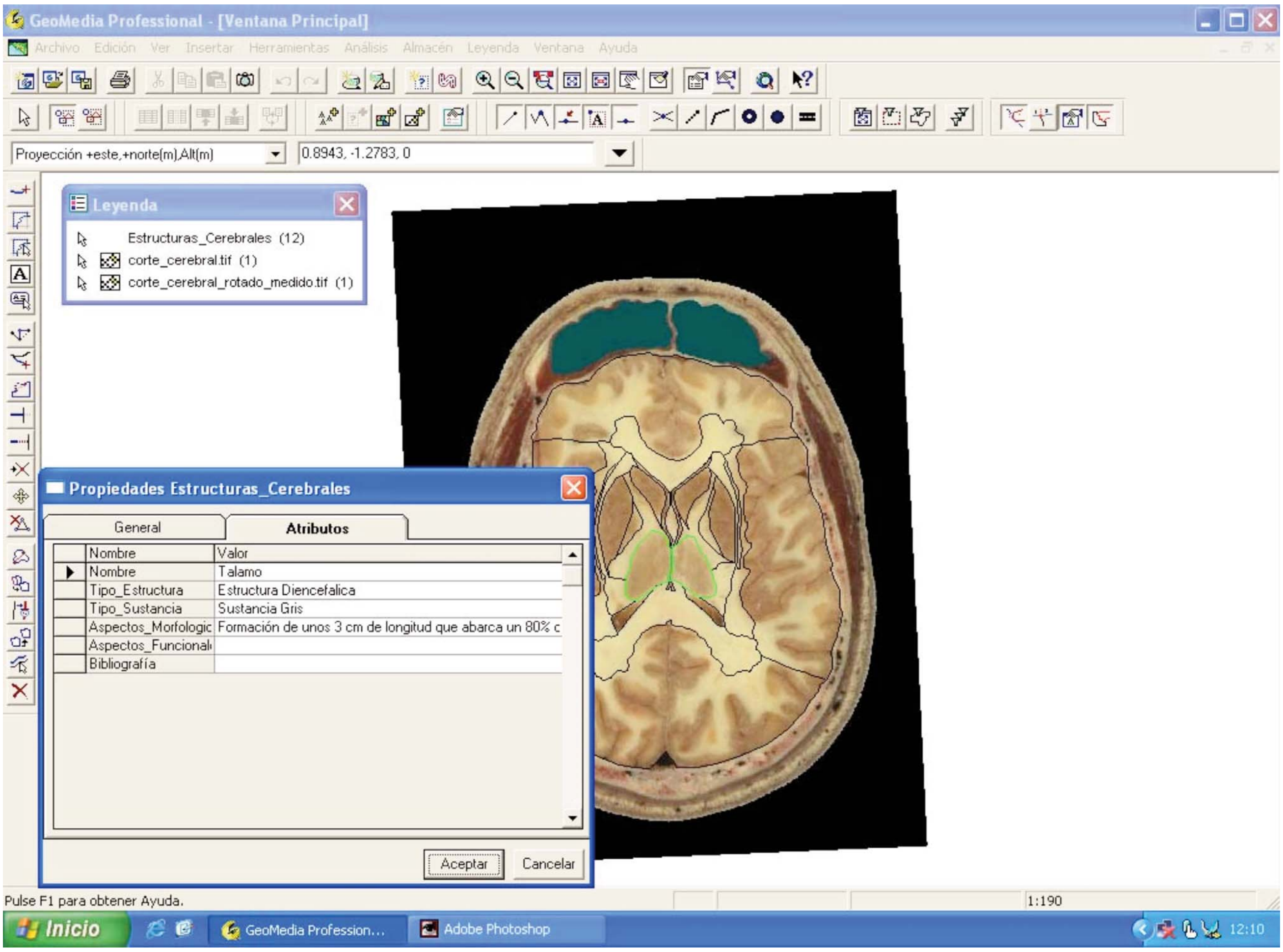

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Fig. 3. Geomedia® professional window for accessing brain structure information included in the database, such as thalamic nuclei.

provides a truly useful system of 3D graphic representations of the brain geo-referenced within a stereotaxic and bi-commissural coordinate system, necessary to locate specific areas within the brain.

First, topological and clinical information was displayed jointly and separately for any spatial territory of the human brain or topological relations within the digital brain map. Second, a user-friendly interface facilitated an interactive access system to the data displayed, depending on user requests, generating new brain maps automatically For example, the menus allow the user to display selective spatial and functional information regarding the brain referenced in VHP (Fig. 4) or MR images (Fig. 5) or data import and export functionalities to interact with other applications.

The 3D models of anatomical structures afford an interactive and independent multiplesviews, which facilitate the evaluation of potential surgical approaches stereotaxic guidance in radiosurgery, and electrode implantation in a virtual or simulated fashion.

The databases, adjoined to the systems of territorial information, provide the visualization of georeferenced data and thematic attributes, signalling different anatomical and clinical information related to that area.

Furthermore, users can zoom the 3D model of any given structure to analyse morphological information in greater detail or perform spatial rotations or translations, removing or adding serial sections, thus supporting a more accurate evaluation of brain structures.

The final application is native for the Windows environment and requires a minimum of 1.8 GHz processor, 256 MB of SDRAM and a graphics card with 64 MB of video memory.

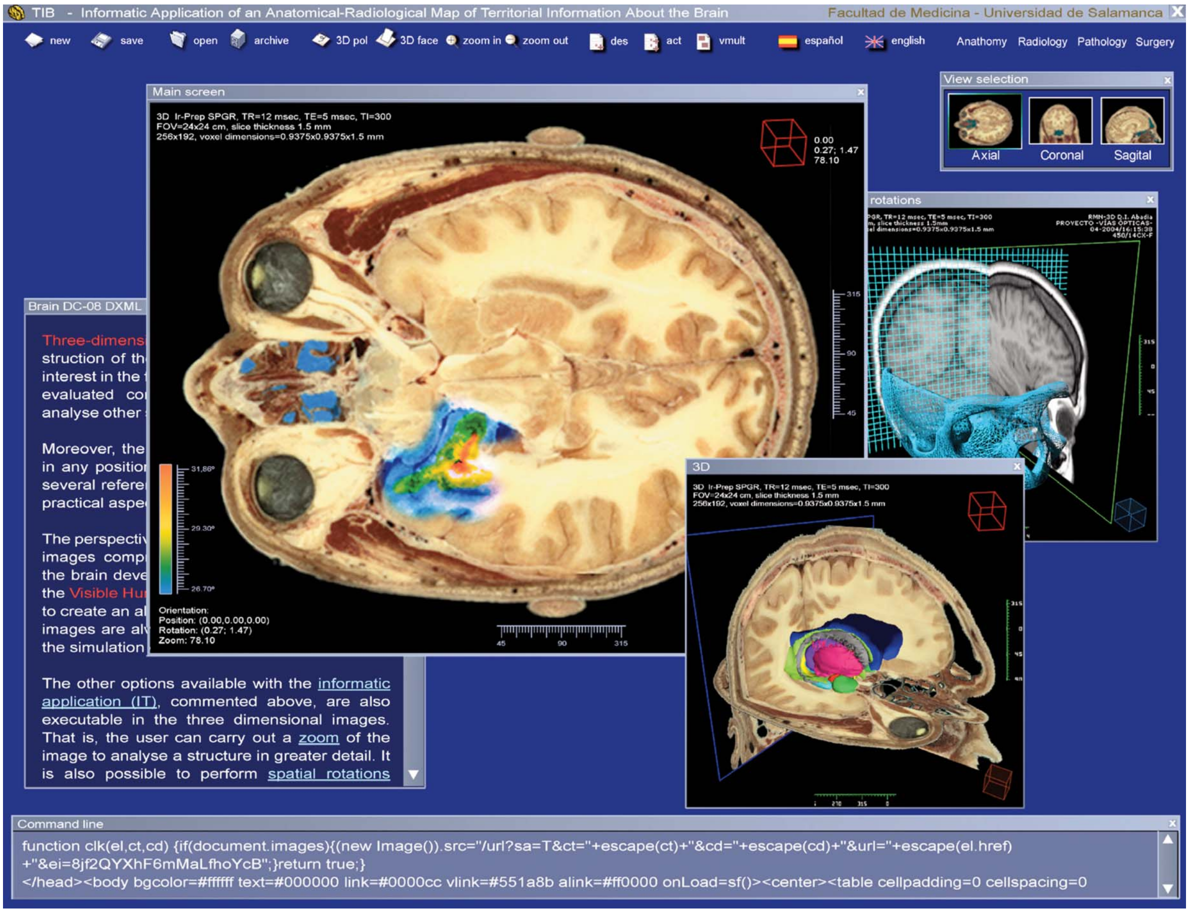

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Fig. 4. Screenshot showing main screen, text information screen (left bottom corner), visualization of 3D models for deep brain structures embedded in orthogonal VHP sections (right bottom corner), volumetric generation for brain tissue and view selection for the main screen (right upper corner).

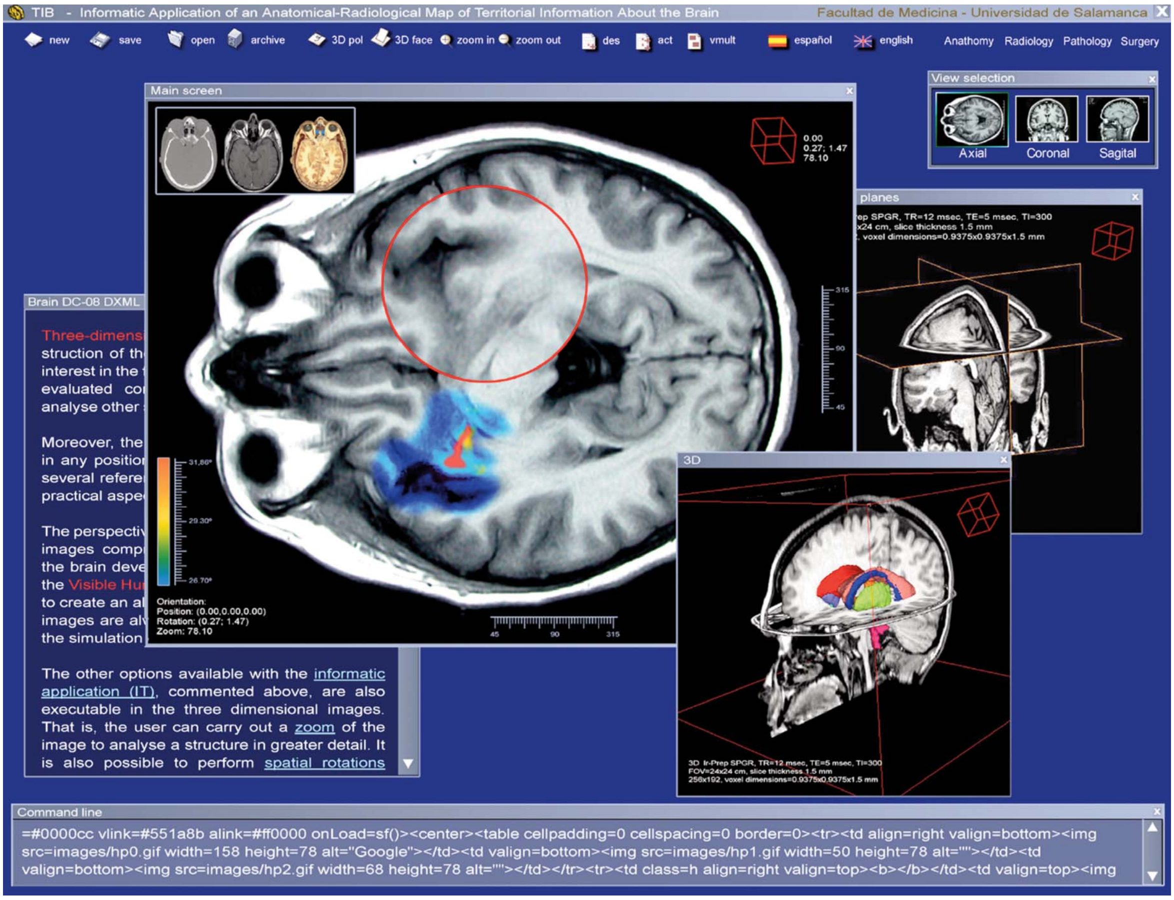

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Fig. 5. Screenshot displaying MR sections, geographically referenced information, and three-dimensional models of deep brain structures.

DISCUSSION

This study discusses a digital geographic information system of the brain that allows handling the spatial features of brain structures such as absolute and relative positions, as well as descriptive functional and pathological information simultaneously.

Geomedia®, as example of geographic information technology, allows bringing data from different databases to be brought into a single geographic information system database environment for viewing, analysis, and the presentation of neuroanatomical information.

Traditionally, medical image processing software was demanding in terms of memory usage (Gatrell and Bailey, 1996). However, this tool stores spatial information in a vector format defined by pairs of coordinates, thereby saving memory storage. For example, 3D models were defined by polygons at the surface, without it being necessary to store each point inside the volume. As a consequence, the time required for processing these models and interacting with them is also reduced, providing a more powerful tool for training and clinical purposes.

Consistent with previous studies that have underlined the importance of geographic information systems in other fields such as epidemiology (Vine et al., 1997) or others (Antenucci et al., 1991; Aronoff, 1989; Yilma and Malone, 1998; English et al., 1999; Moncayo et al., 2000), our study applies this procedure of territorial information system for the handling of spatial brain data to the field of neuroscience.

As expected, this territorial information system offers a powerful tool for understanding the morphological and functional aspects of the human brain. Further studies should extend the application of territorial information systems to the study of other parts of the human body (Juanes et al., 1999).

This digital tool, based on geographic information technology, integrates functional and pathological information about brain anatomy with spatial information about different structures of the brain.

Previous studies have propitiated a large diversity of cartographic data of the brain, ranging from three-dimensional images (Juanes et al., 1996), through histological preparations of brain cytoarchitecture, to regional molecular patterns and patterns of protein distribution and quantization. Most brain atlases are designed for the representation of anatomy following a standard system of stereotaxic coordinates (Ono et al., 1990; Duvernoy, 1991; Collins et al., 1995; Drury and Vanessen, 1997), or are constructed from one or more representations of the brain (Friston et al., 1995; Toga and Mazziotta, 1996).

Several digital neuroanatomical atlases have been developed, using cadaver cryosections including volumetric reconstructions of embedded neuroanatomical structures, which can be used for the planning of surgical procedures or surgical simulations (Juanes et al., 1996).

If neuroscience aims to understand the structure and function of the human brain, one of the most important applications of this tool is the possibility to correlate functional and morphological information (Kretschmann and Weinrich, 1998). In order to achieve this goal, this tool combines a brain atlas and a standard coordinate system, similarly to how geographical information systems or geographical atlases work.

The results of this study complement our previous work, which experimentally analyzed the benefits of 3D volumetric visualization to identify and locate cerebral structures in comparison with classical cross-sectional images (Ruisoto et al., 2012).

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