GRAFIP: A FRAMEWORK FOR THE REPRESENTATION OF HEALTHY AND PATHOLOGICAL CEREBRAL INFORMATION

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ABSTRACT

This paper presents a contribution to the large problematic of integrating medical image-based information into a structured framework (such as electronic patient records or anatomo-functional databases). In neuroscience, the complexity of the cerebral anatomy, the wealth of information embedded in imaging data, as well as the difficulty of their interpretation, can benefit from the use of a structural brain model representing prior generic knowledge, which includes information on anatomical structures and their spatial relations. In this paper we describe a novel generic brain model, based on graph representations, and an instantiation procedure for individual patients, based on image segmentation. A complete patient-specific modeling framework is proposed that can be integrated into powerful computational tools to assist image data reviewing, diagnosis and therapeutic patient follow up.

Index terms: knowledge representation, generic brain model, individual model, graphs.

1. INTRODUCTION

Most intelligent medical systems have to deal with large amounts of image-based information, which would greatly benefit from a structured representation. Such structured information must have explicit references to related medical knowledge (canonical knowledge) and must contain numerical information proper to individual patients (instantiated knowledge).

In this paper, we describe an original graph-based modeling framework of the human brain into a Graph of Representation of Anatomical and Functional data for Individual patients including Pathologies (GRAFIP), extending [1]. The proposed framework enables the adaptation of a generic graph model to specific clinical cases including pathological areas. Modification of the generic model is performed via the integration of information extracted from the segmentation of brain MRI exams.

Knowledge-based image interpretation systems, reviewed in [2], have been successfully applied to drive specific recognition procedures, as in [3, 4] for brain imaging, with graph-based representations of the cerebral anatomy. These previous applications only dealt with normal cases and did not discuss the extension of the approach to pathological cases, such as brain tumors. The approach proposed in this paper deals with this aspect.

This paper is organized as follows. In Section 2, we present our generic model of brain knowledge, and we show, in Section 3, how it allows structuring image-based information. The model instantiation procedure using knowledge based segmentation is summarized in Section 4. The impact of pathology on the generic model is presented in Section 5. In Section 6, we present software tools developed for storing, handling and displaying instantiated brain models. Finally we discuss future applications of the proposed framework.

2. KNOWLEDGE MODELING WITH HYPERGRAPHS

An effort towards formalization of the canonical anatomy of the human body has led to an ontology called the Foundational Model of Anatomy (FMA) [5]. Generic anatomical and physiological knowledge on the human brain combines concepts of multiple nature to describe the anatomy, its functional organization, tissue compositions, and pathologies. Moreover, the brain anatomy is usually described as a hierarchical organization, where each level is composed of a set of objects (e.g. cerebral hemispheres, anatomical structures, individual structures subparts). These objects are organized in space in a roughly persistent way, for all individuals. This hierarchical and spatial organization of the brain is an important component of usual linguistic descriptions of anatomical knowledge [6, 7].

Following previous works on structural brain descriptions, we propose a graph-based representation to encode the following elements of knowledge:

- *anatomical knowledge*: hierarchical and spatial organization of the brain,
- *tissue composition knowledge*: description of brain tissue composition, affecting intensity appearance on medical images,
- *functional knowledge*: description of functional areas,

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• *pathological knowledge*: description of pathological structures.

We designed a hypergraph structure, where vertices represent anatomical structures, linked to each other by edges or hyperedges that carry information about their *taxonomical* (i.e. "IS A relation") and *spatial relations*, which include mereotopological (e.g. adjacency) and metric (e.g. relative directions and distances) relations. Matter vertices were also added and linked by a *matter relation* (i.e. "HAS MATTER relation") with all anatomical vertices. Functional vertices were linked by *Anatomo-Functional relations* with anatomical vertices. The choice of a hypergraph structure was motivated by the importance of complex spatial relations between cerebral structures, of cardinality higher than two, such as the spatial relation "in between".

3. STRUCTURING IMAGE-BASED INFORMATION

Patient-specific brain information is extracted from neurological imaging exams and their interpretation. The graph-based brain model, presented in the previous section, is used to structure and represent such image-based information. The resulting GRAFIP data structure, organized according to the generic knowledge, provides links to information encoded as iconic representations (e.g. gray level, labeled or fuzzy images) and stores numerical information extracted from these representations (e.g. structure positions, shapes).

To distinguish the different types of information available on the brain, we separate, as in [8], the anatomical entities from the spatial regions they occupy and the portions of matter they are made up. As illustrated in Figure 1, we propose a structuration according to three different levels [9]. Each GRAFIP node can be represented according to: (1) a *semantic viewpoint*, encoding its semantic medical description in terms of the four knowledge types (anatomical, tissue composition, functional and pathological); (2) a *spatial viewpoint*, encoding its spatial description (e.g. positioning) and spatial relations; (3) a *perceptual viewpoint*, encoding its visual appearance in the images (color, texture, shape, size, location).

A graph vertex can be associated with exactly one spatial region by a "has spatial location" relation specified from an atlas (inserted in the canonical model) or from image segmentation results. The brain segmentation process for MRI exams is described in the next section.

4. PATIENT-SPECIFIC MODEL INSTANTIATION

As illustrated in Figure 2, the generic human brain model is instantiated for a specific clinical case by the integration of information extracted from MRI image data. Anatomical vertices of structures identifiable on the images are updated and fed with image-specific information (e.g. spatial location, average intensity) via a collaborative process between image segmentation and knowledge-based reasoning.

A detailed description of the segmentation procedure can be found in [4, 10]. It uses spatial relations between structures, encoded in the hypergraph and modeled using spatial fuzzy sets (i.e. regions of space where the membership of each point represents the degree of satisfaction of a relation at this point) [11]. Fusion of spatial relations occurs in the spatial domain, in order to define fuzzy regions of interest in which the search for new structures will take place, in a process similar to a focalization of attention. These fuzzy regions enable constraining the evolution of deformable models to provide precise delineations of individual structures. In a sequential procedure, the amount of available spatial relations increases with the number of segmented structures. The order in the recognition sequence is driven by graph-based reasoning: the recognition of the "most difficult" structures is delayed, to benefit from rich focusing constraints accumulated earlier in the sequence. Once segmented structures are available, features of interest (e.g. volumes and shape characteristics) are computed and added to the GRAFIP for further reasoning.

5. PATHOLOGICAL KNOWLEDGE

Specific cases can exhibit significant deviations from the generic model. This is typically the case in medical applications when pathologies (such as brain tumors) may appear as additional objects in the images, which are not represented in the generic model.

In the context of brain tumors, we characterize the pathology with an individual vertex. Generic knowledge on tumors is associated with this vertex, including characteristics from the WHO classification [12] and the Sainte-Anne classification [13].

Introduction of pathological knowledge and patient-specific information in the generic model is performed in several steps. First, the tumor is segmented, using a robust and fully automated approach that combines symmetry analysis and a parametric deformable model [14]. Then the tumor type is analyzed, according to spatial characteristics. These characteristics induce modifications on the normal structures and are used to infer the stability of the spatial relations between these structures based on a learning procedure [15]. For instance, a tumor may modify the relative distances between some gray nuclei. The GRAFIP is updated to incorporate these modifications. The segmentation is then performed based on the updated spatial relations, using the approaches described in [4, 10]. In an iterative process, the GRAFIP is instantiated and updated, incorporating information components from all available segmentation results (cf. Figure 2): a vertex representing the tumor is added, along with attributes describing its characteristics; edges to surrounding structures are created; vertex and edge attributes are updated for all segmented structures to encode their relations to the tumor and to other cerebral structures.

The GRAFIP framework is flexible enough to include timevarying attributes derived from longitudinal MRI studies for patient follow-up. Analyzing the temporal evolution of the pathology and its effect on other structures requires the inclusion of growth indices such as the RECIST [16] criteria, and characterization of shape modification of surrounding structures.

6. DEDICATED SOFTWARE TOOLS

To enable storing, handling and displaying of neurological MRI exams along with GRAFIP information extracted from data segmentation and anatomical models, we developed a Java software application based on the Java Universal Network Graph (JUNG) library [17] and the Visualization ToolKit (VTK) [18] for graph analysis and visualization tools. This application provides dedicated tools including:

• *Model storage in XML Format*: Generic and instantiated GRAFIP structures can be stored in a dedicated file format based on the GraphML [19] file structure. GraphML is a comprehensive and easy-to-use file format for graphs, based on the XML standard. It was extended to store the complex GRAFIP node attributes.

• *Data visualization*: A data visualization tool was developed to provide medical experts with a user-friendly interface, for manipulation and visualization of the GRAFIP content. The physician can interactively select a specific slice within the MRI volume, inside a 3D viewer, which allows simultaneous visualization of the associated 3D segmented structures and the lesions. The GRAFIP components (vertices and edges) can moreover be viewed as single entities or overlayed onto 2D MRI slices. Some functionalities for interacting with the graph are also available, such as visualization of the information associated with a particular vertex, and navigation within graph components using the edge information, as illustrated in Figure 3.

7. CONCLUSION

We presented a novel graph-based brain modeling framework, GRAFIP, which includes original features, combining generic knowledge representation, specific patient's information extracted from medical images, and pathological characteristics. Anatomical structures are characterized by intrinsic attributes and spatial relations with other surrounding structures. Data structures, encoding schemes and coding tools allow efficient updates, manipulation and visualization of the GRAFIP. Preliminary evaluation from medical experts at two hospitals confirmed that the proposed framework is well adapted to provide a quick and structured overview of pathological brain MRI image content, to focus on the region around the pathology and understand its impact on the surrounding structures. Foreseen applications will focus on patient follow up (in particular longitudinal follow up of tumors), surgery planning, as well as medical training and education.

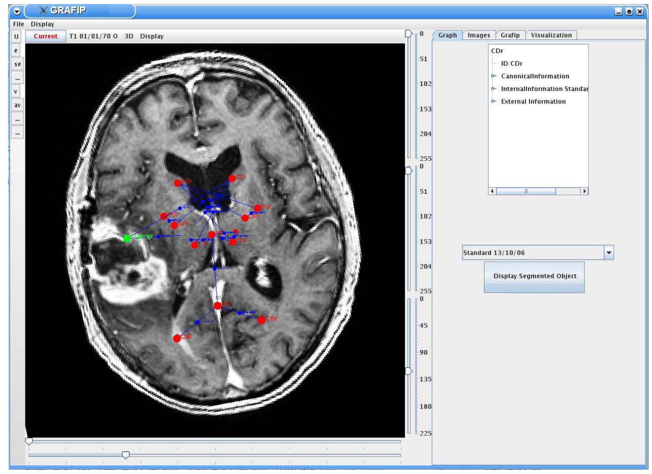

Fig. 3. Visualization of a MRI axial slice with a brain tumor, and its associated GRAFIP.

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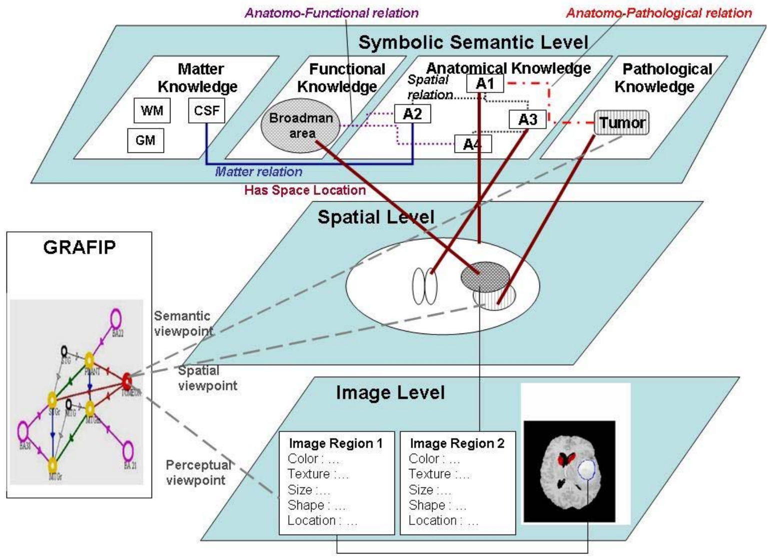

Fig. 1. The generic GRAFIP: organization into three levels combining generic knowledge and patient specific information.

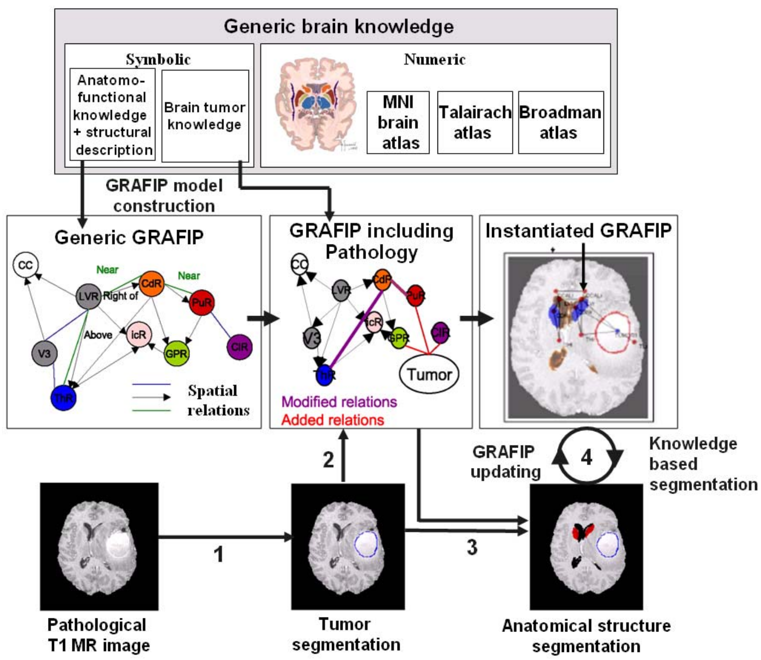

Fig. 2. Global overview of the GRAFIP instantiation framework.

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