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Survey Paper

Three-dimensional solid texture analysis in biomedical imaging: Review and opportunities

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ABSTRACT

Three-dimensional computerized characterization of biomedical solid textures is key to large-scale and high-throughput screening of imaging data. Such data increasingly become available in the clinical and research environments with an ever increasing spatial resolution. In this text we exhaustively analyze the state-of-the-art in 3-D biomedical texture analysis to identify the specific needs of the application domains and extract promising trends in image processing algorithms. The geometrical properties of biomedical textures are studied both in their natural space and on digitized lattices. It is found that most of the tissue types have strong multi-scale directional properties, that are well captured by imaging protocols with high resolutions and spherical spatial transfer functions. The information modeled by the various image processing techniques is analyzed and visualized by displaying their 3-D texture primitives. We demonstrate that non-convolutional approaches are expected to provide best results when the size of structures are inferior to five voxels. For larger structures, it is shown that only multi-scale directional convolutional approaches that are non-separable allow for an unbiased modeling of 3-D biomedical textures. With the increase of high-resolution isotropic imaging protocols in clinical routine and research, these models are expected to best leverage the wealth of 3-D biomedical texture analysis in the future. Future research directions and opportunities are proposed to efficiently model personalized image-based phenotypes of normal biomedical tissue and its alterations. The integration of the clinical and genomic context is expected to better explain the intra class variation of healthy biomedical textures. Using texture synthesis, this provides the exciting opportunity to simulate and visualize texture atlases of normal ageing process and disease progression for enhanced treatment planning and clinical care management.

1. Introduction

The mature field of imaging physics brought a large variety of irreplaceable diagnosis and research tools to the clinicians and biologists. These tools are perfectly aligned with evidence-based medicine aiming to take decisions based on proven facts (Simel and Drummond, 2008). Since the 1970s, tomographic imaging devices such as X-ray computed tomography (CT) and magnetic resonance imaging (MRI), 3-D ultrasound (US) since the late 1980s have allowed observing the human body in 3-D with sub-millimetric voxel dimensions. These tools are widely used in clinical routine and research. Research in biology has also been relying extensively on confocal microscopy providing 3-D images with sub-micrometric resolution and specific contrast thanks to fluorescent markers (Pawley, 2006). When compared to bi-dimensional images, 3-D volumetric image series cannot be visualized comprehensively and MPR (Multi-Planar Rendering) or semi-transparent rendering is needed to navigate through the various parts of the observed organ. The image interpretation process is time-consuming and error-prone since the radiologists or researchers in biology have to exhaustively browse image series having sometimes several thousand slices (Andriole et al., 2011). As a consequence, computerized analysis of 3-D data has become one of the major research subjects in medical imaging and diagnostic radiology, known as computer-aided diagnosis (CAD) (Duncan and Ayache, 2000; Doi, 2007). The goal of CAD is to use computer vision to assist radiologists in focusing their attention on diagnostically relevant events and to provide quantitative measures for suspicious biomedical tissue, as well as automatic segmentation of anomalies and retrieval of similar cases (Müller et al., 2004; Nishikawa, 2007). Recent imaging devices have been reaching increasingly high spatial

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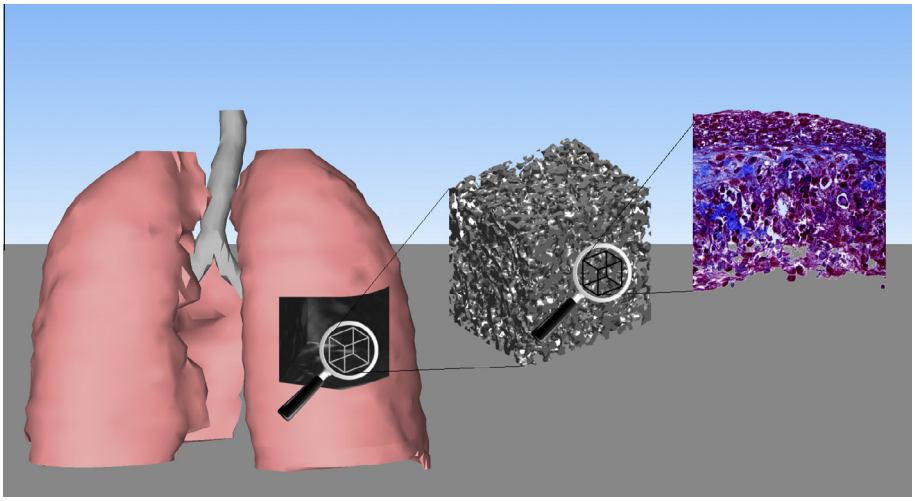

Fig. 1. 3-D biomedical tissue defines solid texture at multiple scales.

resolution, allowing to characterize structural properties of biomedical tissue.[1] Tissue anomalies are well characterized by localized texture properties in most imaging modalities (Tourassi, 1999; Kovalev and Petrou, 2000; Castellano et al., 2004; Depeursinge and Müller, 2011). This calls for scientific contributions on computerized analysis of 3-D texture in biomedical images, which engendered major scientific breakthroughs in 3-D solid texture analysis during the past 20 years (Blot and Zwiggelaar, 2002; Kovalev and Petrou, 2009; Foncubierta-Rodríguez et al., 2013a).

1.1. Biomedical volumetric solid texture

A uniform textured volume in a 3-D biomedical image is considered to be composed of homogeneous tissue properties. The concept of organs or organelles was invented by human observers for efficient understanding of anatomy. The latter can be defined as an organized cluster of one or several tissue types (i.e., defining solid textures). Fig. 1 illustrates that, at various scales, everything is texture in biomedical images starting from the cell level to the organ level. The scaling parameter of textures is thus fundamental and it is often used in computerized texture analysis approaches (Yeshurun and Carrasco, 2000).

According to the Oxford Dictionaries,[2] texture is defined as "the feel, appearance, or consistency of a surface or a substance", which relates to the surface structure or the internal structure of the considered matter in the context of 2-D or 3-D textures, respectively. The definition of 3-D texture is not equivalent to 2-D surface texture since opaque 3-D textures cannot be described in terms of reflectivity or albedo of a matter, which are often used to characterize textured surfaces (Dana et al., 1999). Haralick et al. (1973) also define texture as being "an innate property of virtually all surfaces" and stipulates that texture "contains important information about the structural arrangement of surfaces and their relationship to the surrounding environment", which is also formally limited to textured surfaces.

Textured surfaces are central to human vision, because they are important visual cues about surface property, scenic depth, surface orientation, and texture information is used in pre-attentive vision for identifying objects and understanding scenes (Julesz, 1962). The human visual cortex is sensitive to the orientation and spatial frequencies (i.e., repetitiveness) of patterns (Blakemore and Campbell, 1969; Maffei and Fiorentini, 1973), which relates to texture properties. It is only in a second step that regions of homogeneous textures are aggregated to constitute objects (e.g., organs) at a higher level of scene interpretation. However, the human comprehension of the three-dimensional environment relies on objects. The concept of three-dimensional texture is little used, because texture existing in more than two dimensions cannot be fully visualized by humans (Toriwaki and Yoshida, 2009). Only virtual navigation in MPR or semi-transparent visualizations are made available by computer graphics and allow observing 2-D projections of opaque textures.

In a concern of sparsity and synthesis, 3-D computer graphics have been focusing on objects. Shape-based methods allow encapsulating essential properties of objects and thus provide approximations of the real world that are corresponding to human understanding and abstraction level. Recently, data acquisition techniques in medical imaging (e.g., tomographic, confocal, echographic) as well as recent computing and storage infrastructures allow computer vision and graphics to go beyond shape-based methods and towards three-dimensional solid texture-based description of the visual information. 3-D solid textures encompass rich information of the internal structures of objects because they are defined for each coordinate $x, y, z \in V_{x,y,z} \subset \mathbb{R}^3$, whereas shape-based descriptions are defined on surfaces $x, y, z \in \Gamma_{u,v} \subset \mathbb{R}^3$. $|V| \gg |\Gamma|$ because every point of Γ can be uniquely indexed by only two coordinates (u, v). Texture- and shape-based approaches are complementary and their success depends on the application needs. While several papers on shape-based methods for classification and retrieval of organs and biomedical structures have been published during the past 15 years (McInerney and Terzopoulos, 1996; Metaxas, 1996; Beichel et al., 2001; Heimann and Meinzer, 2009), 3-D biomedical solid texture analysis is still an emerging research field (Blot and Zwiggelaar, 2002). The most common approach to 3-D solid texture analysis is to use 2-D texture in slices (Castellano et al., 2004; Depeursinge et al., 2007; Sørensen et al., 2010) or by projecting volumetric data on a plane (Chan et al., 2008), which does not allow exploiting the wealth of 3-D texture information. Based on the success and attention that 2-D texture analysis obtained in the biomedical computer vision community as well as the observed improved performance of 3-D techniques over 2-D approaches in several application domains (Ranguelova and Quinn, 1999; Mahmoud-Ghoneim et al., 2003; Xu et al., 2006b; Chen et al., 2007), 3-D biomedical solid texture analysis is expected to be a major research field in computer vision in the coming years. The extension of 2-D approaches to $\mathbb{R}^3$ (or $\mathbb{Z}^3$ for

[1] Biomedical tissue is considered in a broad meaning including connective, muscle, and nervous tissue.

[2] http://oxforddictionaries.com/definition/texture, as of 9 October 2013.