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Motility bar: A new tool for motility analysis of endoluminal videos

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ABSTRACT

Wireless Capsule Endoscopy (WCE) provides a new perspective of the small intestine, since it enables, for the first time, visualization of the entire organ. However, the long visual video analysis time, due to the large number of data in a single WCE study, was an important factor impeding the widespread use of the capsule as a tool for intestinal abnormalities detection. Therefore, the introduction of WCE triggered a new field for the application of computational methods, and in particular, of computer vision. In this paper, we follow the computational approach and come up with a new perspective on the small intestine motility problem. Our approach consists of three steps: first, we review a tool for the visualization of the motility information contained in WCE video; second, we propose algorithms for the characterization of two motility building-blocks: contraction detector and lumen size estimation; finally, we introduce an approach to detect segments of stable motility behavior. Our claims are supported by an evaluation performed with 10 WCE videos, suggesting that our methods ably capture the intestinal motility information.

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1. Introduction

Small intestine is a tubular organ that connects stomach with large intestine. Its main function is the digestion and the absorption of nutrients and minerals found in the food. To do so, the small intestine pushes the ingesta by means of an intestinal activity called motility. In general, motility can be categorized in two different dynamic phenomena [2]: peristalsis, synchronized movement of the intestinal wall responsible for moving the ingesta in one direction and segmentation, unsynchronized movement of the intestinal wall, which has the effect of mixing the contents but not pushing them along the intestinal tract. The movement of the intestinal wall is called *contraction*. When the intestine is not active (neither peristalsis nor segmentation is occurring) then the organ is referred to as *static*.

The peristalsis and the segmentation are regulated by three types of intestinal contractions [3]:

- *Rhythmic phasic contractions* that consist of brief periods of both relaxation and contraction. These contractions cause mixing and slow propulsion of ingesta.
- *Ultrapropulsive contractions* that are used to move rapidly the intestinal content without regard for digestion or absorption. These contractions are two to four times larger in amplitude and four to six times longer in duration than phasic contractions. Moreover, since the goal of these contractions is to clean the intestine rapidly, they propagate uninterruptedly over long distances of the small intestine.
- *Tonic contractions* that are maintained for a longer period of time (from several minutes to several hours). The precise role of these contractions in the digestion process has not yet been established [3].

Currently, the main source of information, which leads to a diagnosis of small intestine motility disorders, is manometry [4,5]. However, this technique has three shortcuts: (1) it is highly invasive, causing patient discomfort; (2) it does not provide the visualization of the intestine; and (3) only a part of the organ can be evaluated. Therefore, the researchers are actively looking at alternative methods for evaluating intestinal motility. These alternatives include techniques such as magnetic resonance imaging (MRI) [6–9], magnet tracking system [10], sonograph [11] or pH and pressure measurements [12]. For a review of tools for monitoring intestinal motility, refer to [13,14].

Recently, it was shown that Wireless Capsule Endoscopy (WCE) can be used as a tool for intestinal motility inspection [15]. The main advantage of the capsule is the fact that it allows inner-visualization of the entire small intestine in a non-invasive manner. There are only two factors that control the capsule movement, velocity and

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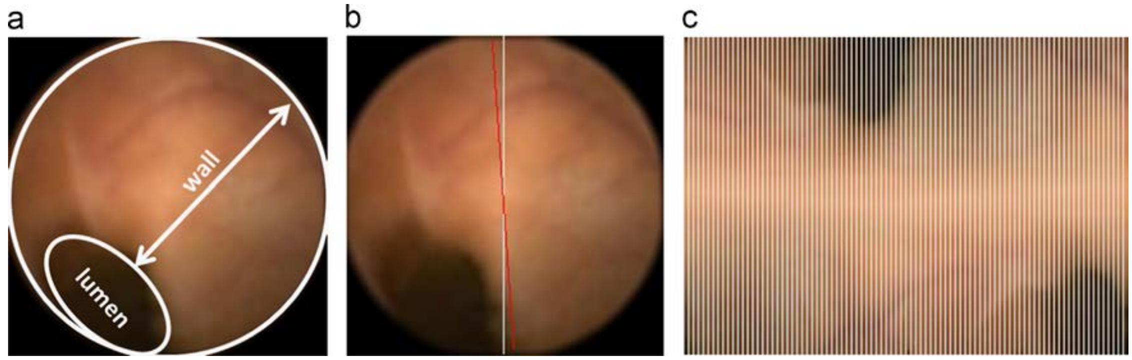

Fig. 1. (a) An image showing intestinal lumen and intestinal wall; (b) an image showing two different diameters of a WCE frame (white and red lines); (c) an image showing all possible diameters obtained from a single WCE frame, each diameter is separated by white space. The motility bar algorithm picks one diameter to represent each frame. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

direction: the small intestine motor activity and the gravity. Thus, the capsule transit time can reach up to more than 8 h, resulting in a video that has up to 60.000 frames. The main limitation of WCE is the time associated with video analysis time.

To overcome a problem of large amount of video frames, a variety of systems for WCE video analysis have been developed (for a review refer to [16]). Only a small amount of works deal with the application of WCE to the small intestine motility analysis, including contraction analysis and static segments detection. Contraction detection is tackled in [17,18], where a three-stage cascade for contraction detection is proposed, or in [19], where a sequential design is developed. In [20], a method for the contraction's central frame detection (referred to as wrinkle frame), based on a mid-level centrality descriptor combined with a structural output SVM classifier, is presented. Whereas, static sequences are characterized by color distribution changes between consecutive frames [21–23]. All methods for static frames detection are used as filters to reduce the video analysis time, they are not considered as modules extracting motility information. In this scenario, the static frames, once detected, are removed or subsampled.

To reduce the motility analysis time, we previously designed a tool for visual analysis of WCE video, called motility bar. An early version of this tool was introduced in [1]·[1] (see Section 2 for a review of the motility bar). The idea of the bar is to map information present in 3D video signal into 2D motility image. This transformation is done by picking a single line of pixels, representing a diameter of the circular image of WCE, in every video frame. The concatenation of all the lines of pixels composes a motility bar. The reduction is framed as an optimization problem that finds the best mapping from a frame to a line of pixels. The best mapping is the one that maintains, where possible, lumen size information and, thus, motility information. In order to solve the optimization problem, Dynamic Programming method is used.

The motility bar has several advantages over the video-based visualization of the gut. First, it introduces a new way for the visual inspection of the small intestine motility since, for the first time, the whole intestinal motility can be evaluated at one glance at an image representing all the motility information. Second, it permits to develop more efficient automatic algorithms for endoluminal image analysis leaving behind classical, inefficient video frame processing methods. Finally, the representation of the whole intestinal motility in a single image permits to focus on holistic aspects of the motility analysis that were not exploited up to now (e.g. sequential nature of intestinal events).

The aim of this paper to introduce automatic methods for characterization of intestinal behavior visible in the motility bar. For the first time, a system for global characterization of the intestinal motility, which combines a motility bar with computational methods, is presented. In detail, the contributions of the paper are the following:

- We introduce automatic methods for the detection of intestinal events using the motility bar image: a method for characterizing the intestinal contractions (Section 3.1) and a lumen perimeter estimator (Section 3.2).
- We propose an unsupervised algorithm for the analysis of multivariate data streams that can capture segments of stable intestinal motility (Section 3.3).
- We perform exhaustive visual evaluation of the proposed methods for sequential motility description. To this end, we present several rankings of motility segments (Section 4).

2. Background

In this section, we review the algorithm for motility bar building, which was firstly introduced in [1] as an optimization problem with two constraints: intestinal lumen visibility and motility bar smoothness.

WCE video can be considered as a stream of m frames. Each frame displays the relation between intestinal lumen and intestinal wall[2] (for an example, see Fig. 1(a)). The evolution of the lumen–wall relationship throughout the video represents the motility viewed by the capsule. Each frame can be represented by a set of diameters (see Fig. 1(b) and (c)). According to [1], if we pick the diameter that best represents intestinal motility information in a single frame and concatenate the diameters from the whole video then, as a result, we obtain an image that represents the WCE video motility information.

The choice of the best diameter can be formalized as follows. Let us parameterize the diameters by an angle (measured counter clockwise and starting with the vertical diameter, see white line in central image in Fig. 1). Let $d(\alpha_i)$ denote the pixels lying on the diameter with an angle α in i-th frame, then the lumen visibility cost D can be defined as

$$D(\alpha_i) = 1/(\sigma(d(\alpha_i))+1)+\mu(d(\alpha_i)) \tag{1}$$

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[1] In [1], the motility bar is referred to as longitudinal view.

[2] In some cases this information might be occluded by the intestinal content or might be out of the field of view of the capsule.

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