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Sequential Monte Carlo tracking of the marginal artery by multiple cue fusion and random forest regression

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ABSTRACT

Given the potential importance of marginal artery localization in automated registration in computed tomography colonography (CTC), we have devised a semi-automated method of marginal vessel detection employing sequential Monte Carlo tracking (also known as particle filtering tracking) by multiple cue fusion based on intensity, vesselness, organ detection, and minimum spanning tree information for poorly enhanced vessel segments. We then employed a random forest algorithm for intelligent cue fusion and decision making which achieved high sensitivity and robustness. After applying a vessel pruning procedure to the tracking results, we achieved statistically significantly improved precision compared to a baseline Hessian detection method (2.7% versus 75.2%, $p < 0.001$). This method also showed statistically significantly improved recall rate compared to a 2-cue baseline method using fewer vessel cues (30.7% versus 67.7%, $p < 0.001$). These results demonstrate that marginal artery localization on CTC is feasible by combining a discriminative classifier (i.e., random forest) with a sequential Monte Carlo tracking mechanism. In so doing, we present the effective application of an anatomical probability map to vessel pruning as well as a supplementary spatial coordinate system for colonic segmentation and registration when this task has been confounded by colon lumen collapse.

1. Introduction

Colorectal cancer is the second leading cause of cancer-related death in the United States with over 50,000 deaths reported per annum (Siegel et al., 2013). Key to the reduction in mortality rate is early detection of colorectal polyps. Computed tomography colonography (CTC) is an accurate and safe method of colon cancer screening, and computer-aided diagnosis (CAD) systems implemented in tandem potentially improve a radiologist's detection performance (Dachman et al., 2010; Halligan et al., 2011; Johnson et al., 2008; Pickhardt et al., 2003; Summers et al., 2005). A standard CTC protocol requires patients to be scanned in both supine and prone position, thereby reducing false positive polyp detections and significantly improving sensitivity (Chen et al., 1999; Yee et al., 2003). Registration of supine-prone images relies upon either brute-force mental visualization by the interpreting radiologist or automated methods based on anatomic landmarks such as the hepatic and splenic flexures, haustral folds, or prominent longitudinal bands of smooth muscle known as the teniae coli (Hampshire et al., 2011; Roth et al., 2011; Wang, 2011). Unfortunately, both mental visualization and automated registration based on these aforementioned anatomic landmarks can be confounded by lumen collapse. To address this problem, Wei et al. (2014) have recently proposed the use of the marginal artery (MA) and vein as a supplementary axis to coordinate supine-prone image registration. The marginal artery and vein, which courses along the longitudinal axis of the colon parallel to its mesenteric attachment, lie extrinsic to the colon and are therefore generally unaffected by lumen collapse (Fig. 1). Here we present a semi-automated method of detecting the marginal vessels on CT angiography (CTA) using sequential Monte Carlo (SMC) tracking so that a spatial coordinate system fiducial marker extrinsic to the colon may be attained.

2. Background

Vessel enhancement filtering, region growing, active contours, centerline extraction, and stochastic framework are five major

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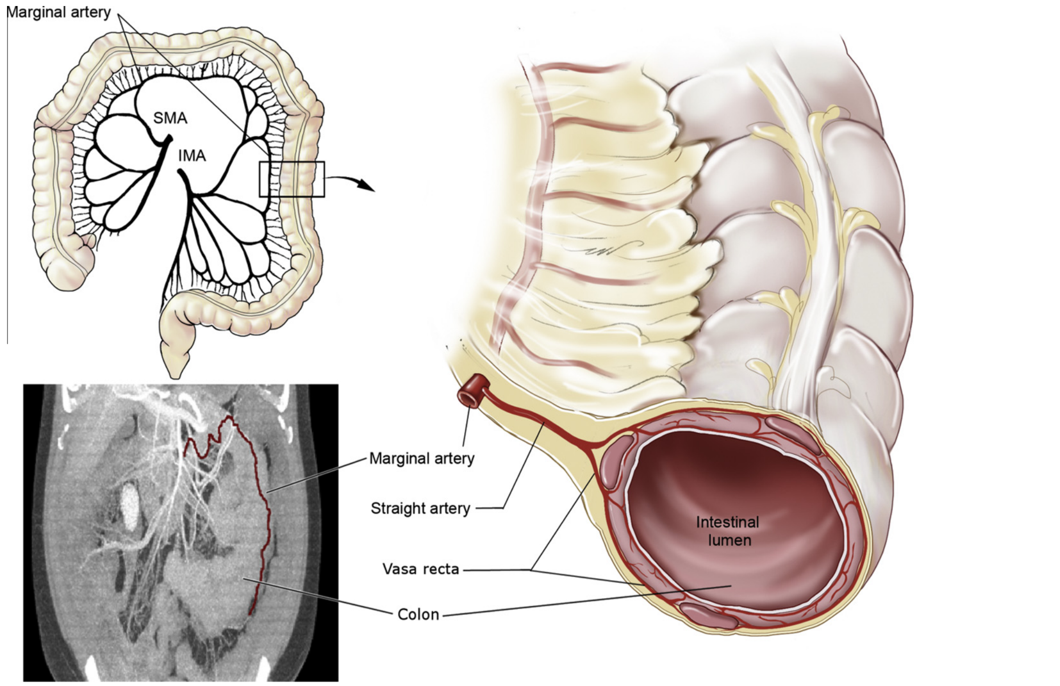

Fig. 1. Illustration of the marginal artery. The marginal artery is an anastomotic channel connecting the superior and inferior mesenteric arteries (SMA and IMA). The marginal artery runs parallel to the colon at a relatively constant distance making this vessel an ideal extrinsic anatomic landmark by which to base a coordinate system of the colon. Segmenting the marginal artery with high fidelity is challenging due to the presence of numerous surrounding straight arteries and vasa recta (bottom left). A ground truth segmentation of the marginal artery is shown in a maximum intensity projection of an abdominal CT examination. [Illustration adapted from (Wei et al., 2014).]

approaches to 3D vessel detection and segmentation (Lesage et al., 2009). Among these methods, sequential Monte Carlo tracking, also known as particle filtering, is a stochastic solution that has been widely used in various tracking problems due to its accuracy, robustness, and computational feasibility. Frangi et al. (1998) first proposed a vessel enhancement filtering algorithm based on local multi-scale second order Hessian structure analysis of an image. The benefit of this technique was demonstrated on aortoiliac and cerebral magnetic resonance angiograms (MRA). While filtering enhancement-based methods (e.g. Frangi and Li's vesselness detectors) demonstrate high sensitivity, they also have a high false positive rate for MA segmentation. Region growing based methods are easy to implement and usually work well on large vessels such as the aorta. However, they demonstrate poorer performance in the detection of small or poorly enhanced vessels like the MA. Additionally, region growing-based methods commonly demonstrate leakage into large organs which further exacerbates its false positive rate. Active contour-based methods are very effective on large vessels on 2D images, but perform less well on smaller, higher order vessels such as the MA due to its small caliber and complex branching pattern, corroborating the inherent difficulty in designing a universal internal, model-based force and external force for segmentation surface evolution.

Many investigators have contributed to the stochastic-based vessel tracking field in recent years. Florin et al. (2005) proposed a particle filtering-based approach for the detection of coronary arteries. In their model, state variables included position, orientation, shape, and vessel appearance. Later, Schaap et al. (2007) presented a Bayesian tracking framework for tubular structures such as carotid arteries in CTA. The key contribution of their work was a novel observation model designed for tube-like objects which consisted of a series of tube segments identified by location, orientation, radius, intensity, and intensity variance. Lacoste et al. (2006) employed Markov marked point processes for the detection of coronary arteries on 2D CTA. Multiple investigators have used SMC-based vessel segmentation methods (Florin et al., 2005; Lacoste et al., 2006; Schaap et al., 2007) to fit the probabilistic model and make it computationally feasible, an approach which worked with large vessels. However, this approach is less successful with MA tracking and segmentation due to insufficient information employed for tracking. More recently, Friman et al. (2010) proposed a multiple hypothesis template tracking scheme for small 3D vessel structures. For other advances in the field of vessel detection and segmentation, readers may wish to refer to the recent review paper on this topic (Lesage et al., 2009).

SMC has also been used in computer vision to handle problems such as athlete or vehicle tracking in video sequences (Kristan et al., 2009; Zhou et al., 2004). For tracking, the collection and utilization of more target and background information typically provide increased accuracy and robustness for a given noise level. In recent years, incorporating multiple cues in the Bayesian tracking framework has been a focus of research for multiple investigators. Wu and Huang (2004) proposed a factorized graphical model to integrate multiple cues for Bayesian tracking. The authors asserted that the inference of a high-dimensional state space could be factorized into many lower-dimensional state spaces to discover their co-inference. The main idea was that the use of several cues with rough models would be more robust and computationally efficient than a complex single cue model. Brasnett et al. (2007) proposed visual cues including color, edge, and texture for object tracking in video sequences. This work also included a multi-component, mixed dynamic model for motion prediction and a robust way to deal with target occlusion. Visual cues were histogram based, weighted adaptively, and represented in likelihood functions employing the Bhattacharyya distance. The work of Moreno-Noguer et al. (2008) focused on integrating multiple dependent cues for robust tracking. Cue dependence was considered and each feature was represented by a separate Bayesian filter. The group used object bounding box, Fisher color space, target and background color distributions, and object contour in a