Medical Image Analysis 25 (2015) 103–110

Contents lists available at ScienceDirect

Medical Image Analysis

journal homepage: www.elsevier.com/locate/media

Automatic segmentation of occluded vasculature via pulsatile motion analysis in endoscopic robot-assisted partial nephrectomy video

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ARTICLE INFO

Article history:
Received 17 November 2014
Revised 7 April 2015
Accepted 9 April 2015
Available online 23 April 2015

Keywords:
Motion Analysis
Image-guided Surgery
Robot-Assisted Partial Nephrectomy
Vessel Segmentation
Hilar Dissection

ABSTRACT

Hilar dissection is an important and delicate stage in partial nephrectomy, during which surgeons remove connective tissue surrounding renal vasculature. Serious complications arise when the occluded blood vessels, concealed by fat, are missed in the endoscopic view and as a result are not appropriately clamped. Such complications may include catastrophic blood loss from internal bleeding and associated occlusion of the surgical view during the excision of the cancerous mass (due to heavy bleeding), both of which may compromise the visibility of surgical margins or even result in a conversion from a minimally invasive to an open intervention. To aid in vessel discovery, we propose a novel automatic method to segment occluded vasculature from labeling minute pulsatile motion that is otherwise imperceptible with the naked eye. Our segmentation technique extracts subtle tissue motions using a technique adapted from phase-based video magnification, in which we measure motion from periodic changes in local phase information albeit for labeling rather than magnification. Based on measuring local phase through spatial decomposition of each frame of the endoscopic video using complex wavelet pairs, our approach assigns segmentation labels by detecting regions exhibiting temporal local phase changes matching the heart rate. We demonstrate how our technique is a practical solution for time-critical surgical applications by presenting quantitative and qualitative performance evaluations of our vessel detection algorithms with a retrospective study of fifteen clinical robot-assisted partial nephrectomies.

1. Introduction

Approximately 64,000 new cases of kidney cancer, commonly renal cell carcinoma, are projected to occur in the U.S. in 2014 Siegel et al. (2014). This constitutes double the number of cases reported in 2005. Kidney resection, also known as a nephrectomy, remains the only known effective treatment for this type of localized cancer Drucker (2005). Robot-assisted partial nephrectomy (RAPN) refers to nephron-sparing techniques performed with surgical robots in which only the cancerous cells are excised and the kidney is reconstructed to retain functionality.

The RAPN procedure is organized into five main stages according to Gill et al. (2002): 1) bowel mobilization; 2) hilar dissection and control; 3) identification and demarcation of tumor margins; 4) resection of tumor; and 5) reconstruction of the kidney (renorrhaphy). Hilar dissection stands out as a daunting stage requiring significant expertise since improper clamping due to overlooked accessory renal vessels can cause significant bleeding during resection Singh (2009).

Hilar dissection is a delicate procedure during which the surgeon dissects through Gerota's fascia and removes the connective tissue that surrounds the renal artery (RA) and renal vein (RV). This task is complex due to substantial natural variability in patient vasculature (Fig. 1) and the amount of perinephric fat surrounding the kidney. Access to the hilum grants the surgeon control over the flow of blood in and out of the kidney, which is critical as warm ischemia is required during the excision of the tumor to minimize internal hemorrhaging. In some cases, accessory vessels that branch off from the RA or the abdominal aorta (AA) are accidentally missed as they lie hidden behind a thick layer of perinephric fat. In one study of 200 laparoscopic partial nephrectomy cases by world leading surgeons Ramani et al. (2005), seven incidents of intraoperative bleeding were reported as a result of inadequate hilar control, two of which were directly caused by missed

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http://dx.doi.org/10.1016/j.media.2015.04.010
1361-8415/

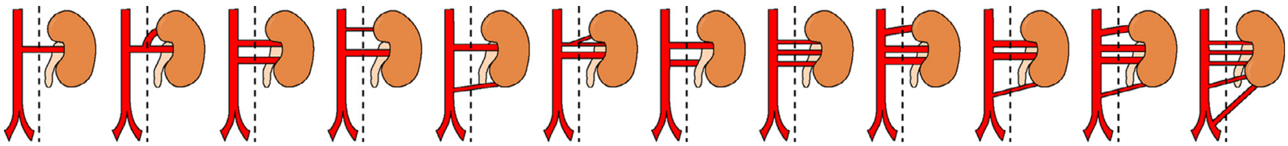

Fig. 1. Variation of renal artery structure and corresponding percentage of occurrence in 266 kidneys adapted from Sampaio and Passos (1992). In each case all vessels that cross the dotted line must be clamped or ligated to minimize intraoperative hemorrhaging. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

accessory vessels. Although the number of incidents is relatively low, other studies by Sampaio and Passos (1992); Urban et al. (2001) observed the existence of accessory vessels in more than 35% of patients. These accessory vessels also prolong the hilar dissection stage as the surgeon must locate them prior to resection. If the surgeon's level of experience is limited, the incidence of bleeding and overall dissection time may be much higher. The implications are many, aside from obvious complications that would arise from internal hemorrhaging, as bleeding may also jeopardize the surgical outcome by occluding the surgeon's view while the tumor is being resected.

Surgeons often make use of preoperative medical images for identifying troublesome accessory vessels Mottrie et al. (2010). Even with high-resolution scans and segmented preoperative plans available to them, surgeons are still burdened with the complex and error-prone task of mentally transferring these abstractions onto the surgical site during the operation. Reducing the difficulty of navigation has been attempted by various approaches that rely on multi-modal registration to align the preoperative surgical map of the vessels onto the surgeon's endoscopic view, e.g. Amir-Khalili et al. (2013); Estépar and Vosburgh (2014); Hamarneh et al. (2014); Nosrati et al. (2014); Pratt et al. (2012); Puerto-Souza et al. (2014); Su et al. (2009); Teber et al. (2009). Registering and augmenting preoperative segmentations into intraoperative video is an excellent idea. However, such techniques have major limitations including selection of sensitive parameters Nosrati et al. (2014), manual alignments Pratt et al. (2012); Su et al. (2009), use of invasive fiducials Teber et al. (2009), and high computational complexity that prohibits practical real-time operation Amir-Khalili et al. (2013); Estépar and Vosburgh (2014); Hamarneh et al. (2014); Puerto-Souza et al. (2014). These limitations stem from the difficulty of registering intraoperative video data with 3D anatomy that deforms and changes due to factors such as cutting, retraction, and breathing. Furthermore, these methods do not specifically focus on augmenting the location of vasculature.

Recent methods that focus more specifically on the detection of vasculature include the use of hardware solutions such as near infrared fluorescence imaging Tobis et al. (2011) or algorithmic methods that only use color intensity information from the endoscope to highlight vasculature based on perfusion models Crane et al. (2010). Solutions that use near infrared fluorescence are not widely accessible as they are cost restrictive, requiring additional equipment and expert clinicians to control the dosage of fluorescent agents. On the other hand, simple algorithmic methods fail to identify vessels that are hidden under a layer of fat.

Intraoperative ultrasound (US) imaging is another hardware solution employed during the tumor demarcation and excision stages of RAPN; mainly to resolve uncertainties in the location of tumor boundary Gill et al. (2002). Recent advancements in the field of US guidance, i.e. 'pick-up' transducers Schneider et al. (2011), motivate the use of US during hilar dissection, but such US based guidance techniques also incur additional costs in terms of an increase in required personnel (as some robotic surgeons are not trained to operate and interpret US), operating time, and equipment upkeep. Even with Doppler US imaging, the localization of complex vascular structures is further ameliorated by the fact that the laparoscopic US probes currently available in the market can only acquire 2D images and, depending on the availability of picture-in-picture visualization, the surgeon may have to look at a separate screen to view the US images.

Our work is motivated by the need for a hardware-free non-invasive automated guidance system that can reduce the complications and the time required to perform hilar dissection by assisting the surgeon in localizing hidden accessory vessels. Our proposed system highlights occluded vessels by analyzing the temporal motion characteristics of the scene captured in the endoscopic video. These pulsatile motion characteristics are novel features for vessel segmentation and may be incorporated alongside other complimentary static visual features such as color, intensity, and texture. Our method is inspired by video magnification techniques applied to natural scenes Wadhwa et al. (2013); Wu et al. (2012), where an Eulerian approach to analyzing flow within a video sequence can be used to magnify periodic motions that are invisible to the human eye. An extension of Wu et al. (2012) was very recently implemented in the context of robot-assisted surgery by McLeod et al. (2014) to enhance the appearance of vasculature by magnifying their pulsatile motions. Replacing the actual surgical scene by a processed unnatural and exaggerated motion may be a nuisance to the surgeons and may cause confusion and confound critical visual information in the edited video regions. Furthermore, analysis in Wu et al. (2012) demonstrated that the linear, first order Taylor series and other variants such as the one adopted by McLeod et al. (2014), approximations of motion is susceptible to error and magnification of noise when the motion is large. Linear Eulerian motion analysis is therefore not a good option as a typical surgical scene, in addition to containing small pulsatile motions, also contains gross motion of organs caused by breathing and peristalsis. Since a first order approximation is not suitable for our application, in our current work,[1] we adapt phased-based video analysis to map detected subtle motion patterns into segmentations rather than magnified motions. To demonstrate the potential utility of our method to surgeons, we evaluated our method with a retrospective study of fifteen challenging RAPN clinical cases (selection criteria is detailed in Section 3.2).

2. Methodology

As motivated earlier, hilar dissection prior to clamping is a critical stage in RAPN that would be greatly simplified if occluded blood vessels near the renal hilum are automatically highlighted to surgeons. Blood vessels at the hilum pulsate due to the large amount of blood flowing in and out of the kidney. These periodic pulsations are within a narrow temporal passband centered around the heart rate of the patient. With a high definition surgical endoscope, one can observe the pulsations of the vessels as faint movements on the surface of the connective tissue that covers them. Our goal is to automatically process every frame in the surgical video and label pixels that exhibit this characteristic motion. We denote our labels as:

$$L(x, y, t) : \mathbb{R}^2 \times \mathbb{R}^+ \rightarrow l \in [0, 1], \quad (1)$$

where l is a normalized fuzzy value that is proportional to the magnitude of pulsatile motion measured at the pixel $(x, y) \in \mathbb{R}^2$ at a given

[1] An earlier version of this appeared in Amir-Khalili et al. (2014)