Three-dimensional optical imaging of microvascular networks within intact lymph node in vivo

Yeongri Jung,* Zhongwei Zhi,* and Ruikang K. Wang
Oregon Health & Science University, Department of Biomedical Engineering 3303 SW Bond Avenue, Portland, Oregon 97239

Abstract. Sentinel lymph nodes (SLNs) are the first lymph nodes to drain wastes originated from cancerous tissue. There is a need for an in vivo imaging method that can image the intact SLN to further our understanding of its normal as well as abnormal functions. We report the use of ultrahigh sensitive optical microangiography (UHS-OMAG) to image functional microvascular and lymphatic vessel networks that innervate the intact lymph node in mice in vivo. The promising results show a potential role of UHS-OMAG in the future understanding and diagnosis of the SLN involvement in cancer development. © 2010 Society of Photo-Optical Instrumentation Engineers. [DOI: 10.1117/1.3496301]

Keywords: lymph node; optical microangiography; lymphangiography; lymphatic morphology; blood flow.

Paper 10375LR received Jul. 3, 2010; revised manuscript received Aug. 31, 2010; accepted for publication Sep. 2, 2010; published online Oct. 6, 2010.

The lymphatic system is one of the key constituents in the human immune system that plays a significant role for metastatic dissemination of malignancies. It consists of multiple lymphoid tissue structures (lymph nodes) interconnected by a network of lymph vessels through lymph circulation. The lymph nodes (LNs) entrap foreign, potentially harmful substances such as bacteria and cancer cells that travel through the human body via blood and lymph carriers. The first lymph nodes receiving drainage from a tumor are called sentinel lymph nodes (SLNs). Currently, SLN biopsy has become the preferred method for axillary lymph node staging of breast cancer patients with clinically negative axillary lymph nodes.1 If the outcome of SLN biopsy is positive, then the breast lesions of concern are most likely metastatic. The procedure of SLN biopsy requires the removal of full axillary lymph nodes, with the help of an invasive use of blue dyes, for histological assessment.2 If pathologic results for SLNs are negative, then it is not necessary to dissect the full axillary lymph nodes, because the outcome from the SLN alone can achieve a firm diagnosis with success rates of 90 to 97%.2 In addition, this invasive SLN biopsy procedure, although clinically effective, would potentially result in postoperative complications, e.g., lymphedema, sensory nerve injury, seroma formation, etc.3 Consequently, a noninvasive or minimally invasive imaging technique that can provide functional information of the SLN would represent a significant advance in the clinical diagnosis of metastatic cancers.

Optical imaging techniques are increasingly being used in the clinical environment, allowing for improved screening and diagnosis while minimizing the number of invasive procedures. Among them, photoacoustic (PA) imaging has recently attracted much attention, with hopes that it may provide a useful alternative to the current SLN biopsy.4 PA relies on transient light absorption and subsequent detection of acoustic emission to achieve imaging. With the help of exogenous contrast agents, PA imaging has been reported to identify rat SLNs in vivo.5 However, its relatively low spatial resolution (> ~ 100 μm) currently limits its imaging capability at the lymph node organ level.

To further improve our understanding of the physiological functions of the LNs, what is needed is an imaging technique capable of visualizing its detailed morphology, as well as the blood and lymph microcirculations that supply the LN. In this regard, optical coherence tomography (OCT) has recently been reported for high resolution 3-D visualization of lymph node morphology.6,7 The reported ex-vivo OCT imaging results were shown morphological structures that corresponded well with histological features of the LNs, suggesting the potential of OCT to visualize LN microstructures on a scale of micrometastases, and to detect metastatic nodal diseases intraoperatively. However, these morphological studies detected no significant differences between the OCT images of LNs from tumor-bearing animals and those from control animals.6 Notwithstanding, there is no imaging technique available to date that can provide the 3-D information of microcirculation that supplies the lymphatic tissue in vivo.

Being a novel extension of OCT, optical microangiography (OMAG)8 is a recently developed imaging technique capable of producing 3-D images of dynamic blood perfusion within microcirculatory tissue beds with an imaging depth of ~2 mm. OMAG is a label-free technique, because it uses the endogenous light scattering from flowing blood cells within patent vessels to produce the imaging contrast. An unprecedented sensitivity to the blood flow down to 4 μm/s was reported with the most recent development of ultrahigh sensitive OMAG (UHS-OMAG).9 With such high sensitivity to the flow, the modality has been successfully employed to image the microcirculations within tissue beds of small animals10 and has also extended to human studies such as skin and eye.11 In this work, we approach the feasibility of UHS-OMAG to image the 3-D blood vessel networks in the LNs of mice in vivo.

The UHS-OMAG system setup used in this study is similar to the one used in our previous work.10 Briefly, the setup was operating at 1310-nm wavelength with a spatial resolution of ~9 μm (x-y-z) in biological tissue. The system has an imaging depth of 2.22 mm in biological tissue and a sensitivity of 105 dB measured at the focal spot (~0.5 mm below the zero delay line). The total loss of system sensitivity was measured to be less than 15 dB at 2.00 mm. The sensitivity of the system to the blood flow ranged from ~4 μm/s to ~22.2 mm/s,9 which we expect is sufficient to image the blood vessel networks within the lymph nodes. When imaging, we rapidly scanned the probe beam over the sample,
while the spectrometer was continuously recording the OMAG signals formed between the reference and the sampling light at an imaging speed of 47,000 depth scans (A-scans) per second. With this imaging speed, we acquired 256 A-scans in the x direction (B-scan) of 1.8 mm to form one cross sectional image (B frame). This configuration determined the system frame rate at 180 frames per second (fps). In the y direction, we captured a high density C-scan (i.e., y direction scan), consisting of 1500 B-scans over 1.8 mm. Accordingly, it required ~8 sec to acquire a complete 3-D data volume of $1.8 \times 1.8 \times 2.22$ mm$^3$. Then, a UHS-OMAG algorithm$^9$ was applied to this 3-D dataset to obtain morphological and microcirculary images of the scanned tissue volume.

To demonstrate the ability of UHS-OMAG imaging of the LN vascular networks in vivo, three-month-old C57 BL/6 mice (26 to 30 g) were used. All experimental animal procedures were performed in conformity with the guidelines of the United States National Institutes of Health. During imaging, the mouse was immobilized in a stereotaxic stage and was anesthetized with vaporized isoflurane (0.2 L/min oxygen and 0.8 L/min air). The body temperature was kept at 37°C with use of a heating pad. For imaging, the axillary lymph nodes were exposed by pulling aside the skin and surrounding tissues. Then, the mouse was positioned under the scanning probe, with the lymph node carefully placed within the depth of focus of the probe beam, as monitored by real-time OMAG/OCT structural images on the fly.

The imaging results for one LN are shown in Fig. 1. A photograph of the sample is given by the insert in the upper left corner of Fig. 1(c) where the white box indicates the region scanned by OMAG. The top images show (a) a typical cross sectional microstructure and (b) the corresponding blood flow images at the location indicated by the dashed line in the photograph. The bottom images show the enface images of (c) the microstructures and (d) the corresponding blood vessels, extracted from the 3-D optical dataset. The results show the morphological features as well as the microvascular network within the lymph node. (scale bar=500 µm).

Fig. 2 UHS-OMAG visualizes 3-D morphology and microvascular network within an axillary lymph node. Shown are (a) the merged view of volumetric microstructures and blood vessels, where a cut-away view of the microstructural volume gives an appreciation of how blood vessels innervate this lymphatic tissue; (b) the volumetric visualization of the blood vessel network alone; and (c) the x-y projection view of the blood vessels shown in (b). The volume size is $2.0 \times 2.0 \times 1.5$ mm$^3$ ($x$-$y$-$z$) in (a) and (b).
tissue volume in vivo.\textsuperscript{13} Being an extension of OCT technology, UHS-OMAG is also able to extract the information about the lymph vessels within axillary LNs, and that can be coregistered perfectly with the lymphatic tissue morphology and vasculature. One such example is shown in Fig. 3, where the enface structure images of an axillary LN are shown at depths of \(\sim 200\) [Fig. 3(a)] and \(400 \mu m\) [Fig. 3(b)], respectively, along with a cross sectional tissue slice across a lymph vessel [Fig. 3(d)]. Dark areas [low scattering region, e.g., in Fig. 3(c)] observed from the OMAG microstructure images were due to the lymph fluid in the patent lymph vessels. According to this feature, an automatic algorithm was developed to segment the lymph vessels from the 3-D OMAG dataset by setting a fixed intensity threshold to transform the 3-D images into binary format. After segmentation, the lymphatic network was merged with the vasculature network, illustrating the relationship between the blood and lymph vessels. The result is shown in Fig. 3(e), where the efferent lymph vessel is seen almost parallel to the large collecting vein, with the LN vasculature appearance similar to that in Figs. 1 and 2. Without the need for exogenous contrast agents, UHS-OMAG may have potential to monitor functional lymphatic and blood vessels within the LNs. Notably, the OMAG lymphangiography can be performed simultaneously with the tissue morphology and vascular microangiography, and these can be done from one single OMAG volumetric scan.

One difficulty with UHS-OMAG when it requires deeper imaging within lymphatic tissue is its poor penetration depth in tissue, which is typically limited to one transport mean-free path length (\(\sim 1.5\) mm). Therefore, the current study required US to surgically expose the axillary lymph nodes for UHS-OMAG imaging. However, reports have shown that an OCT probe can be miniaturized and encased in a medical needle.\textsuperscript{14} Such an imaging probe could be integrated with OMAG to interstitially image the LNs in vivo. In addition, further improvement of the system resolution (currently \(\sim 9 \mu m\)) is also necessary to facilitate the accurate segmentation of detailed lymphatic vessels from the 3-D microstructural images. Furthermore, in the current study, we assume that lymph fluid is transparent, which gives us the opportunity to extract lymph vessel within the scanned tissue volume. This assumption needs further experimental validation through a correlation study of OCT images with histopathological preparation.

In summary, we demonstrate the ability of UHS-OMAG to provide detailed morphology, and microvasculature, as well as lymphatic vessels within intact axillary lymph nodes. The results suggest that, by using OMAG, it could be feasible to visualize the lymphatic tissue morphology and to monitor changes in blood and lymph microcirculations, thus offering potential for assessing LN involvement in diseased conditions, as well as for monitoring the dynamic responses of the microvascular and lymphatic vessels to therapeutic treatment in vivo.

This work was supported in part by research grants from the National Institutes of Health (R01HL093140, R01EB009682, and R01DC010201), and the American Heart Association (0855733G).

References