Research Article

Measurement of Optical Scattering Coefficient of the Individual Layers of the Human Urinary Bladder Using Optical Coherence Tomography

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The author reports measurement of the optical attenuation of the urinary bladder using Optical Coherence Tomography. This method uses the exponential relationship that exists between the intensity of the back-scattered infrared light and the penetration depth. The method is applied to Optical Coherence Tomography images of the human urinary bladder and the scattering coefficients of the top three layers (urothelium, lamina propria, and muscle layers, resp.) are extracted. An optical attenuation ratio of 1 : 6.2 : 4.2 for the three layers is reported.

1. Introduction

Bladder cancer is the fourth most common cancer among men. The current method for bladder cancer detection after the patient has reported symptoms that may be related to cancer is visual inspection of the bladder surface using endoscopic methods followed by biopsy. However, it is possible for cancerous and precancerous lesions to go undetected by urologists using conventional visual inspection. A sensitivity of 78% for bladder lesion detection using white light cystoscopy has been reported by Schmidbauer et al. [1]. Biopsies of these undetected cancer lesions are not taken simply because they are not visible to the urologist. Failure to biopsy these lesions may result in a false negative diagnosis, delaying cancer detection, and increasing mortality risk. High resolution images of the subsurface structures of the bladder will greatly enhance the urologist's ability to diagnose pathological conditions previously undetected by conventional visual inspection. Optical Coherence Tomography (OCT) has shown significant potential in this regard.

Recently, Optical Coherence Tomography (OCT), an imaging modality that measures the intensity of back-scattered infrared light and produces subsurface images with micrometer resolution, has shown significant promise in early detection of bladder cancer [2–4]. The major

disadvantage of OCT is the high level of scattering of near-infrared light in biological tissues, which limits penetration depth to 1–2 mm [4]. However, bladder cancer tends to arise within 600 μm of the tissue surface. This makes endoscopic OCT imaging systems suitable for bladder cancer detection. Several studies using OCT for detection, diagnosis, and staging of bladder cancer have been conducted and shown promising results [3, 4]. It is still unclear how closely the changes in the optical properties of the tissue can be correlated with progression of the disease. de Reijke et al. examined human bladder tissue specimens *ex vivo* by 850 nm OCT using dynamic focusing and presented scattering coefficient data for benign bladder tissue as well as grades 1, 2, and 3 urothelial carcinoma [5].

In this paper, the author presents optical attenuation coefficients of not just the urinary bladder but of the individual layers of the normal urinary bladder.

2. Materials and Methods

OCT images of the normal human urinary bladder were obtained during a study conducted at the George Washington University Medical Center [6]. Images were obtained from 24 patients at high risk of having transitional-cell carcinoma

FIGURE 1: Scattering coefficient extraction algorithm. (a) Original OCT image obtained from OCT system. In (b), the A-lines are averaged and plotted as a function of depth, with intensity normalized to 1. Natural logarithm of the intensity for the urothelium is taken in (c). User is also prompted to select linear region in (c). Linear regression analysis is performed in (d) and algorithm returns scattering coefficient, μ_s , range of fit, r , and correlation coefficient, R^2 .

(TCC) of the urinary bladder. These patients underwent cystoscopic examination with the OCT protocol. Scanning was performed with a 980 nm 10 mW superluminescent diode using a 2.7 mm (OD) optical fiber positioned through a cystoscope sheath [6]. For each urinary bladder image, the mean grayscale intensity for the urothelium, lamina propria, and muscularis layer at each depth was measured and plotted as a function of depth. The scattering coefficient is calculated by

$$I_{(z)} = I_O e^{-2\mu_t z}, \quad (1)$$

$$\mu_t = \mu_a + \mu_s,$$

where $I_{(z)}$ is the intensity as a function of depth, I_O is the incident intensity, μ_t is the total attenuation coefficient, z is the penetration depth, μ_a is the absorption coefficient, and μ_s is the scattering coefficient. For most biological tissues in the near infrared region, the absorption coefficient, μ_a is significantly less than the scattering coefficient, μ_s . Therefore,

$\mu_t = \mu_a + \mu_s \approx \mu_s$. Graphically, μ_s can be obtained as the gradient of the linear region of the graph of $\ln(I/I_O)$ versus z [7].

Figure 1 illustrates the procedure followed to extract the scattering coefficient from the OCT images, adapted from Ugryumova et al. [8]. This procedure was implemented using an algorithm implemented in MATLAB (The Mathworks, Natick, MA, USA). The algorithm has already been successfully used to adequately characterize the optical properties of bladder-wall phantoms [9, 10].

To reduce the effect of speckles in our calculations, we averaged over approximately 200 A-lines [11] and the mean grayscale intensity versus depth in millimeters was plotted, as shown in Figure 1(b). The intensity values were normalized by the maximum intensity value (from the reflection at the surface of the bladder). After taking the natural logarithm of the normalized intensity, the user was prompted to select the linear region on the graph for the urothelium. Linear regression was performed on the selected region by fitting

TABLE 1: Scattering coefficients of the human urinary bladder layers.

Normal bladder image	Urothelium (mm^{-1})	Lamina propria (mm^{-1})	Muscle layer (mm^{-1})
1	—	0.96	2.25
2	—	2.39	2.09
3	0.35	2.69	0.83
4	—	1.68	0.55
5	0.31	2.48	1.19
Average μ_s	0.33	2.04	1.38
μ_s standard deviation	0.03	0.71	0.75
Average correlation coefficient R^2	0.62	0.94	0.97

FIGURE 2: OCT images of the bladder. (a) Normal bladder showing a thin urothelium (U) over a bright lamina propria (LP). The muscularis propria (MP) is below the lamina propria. (b) Invasive cancer of the bladder. The structures of the urothelium, lamina propria, and muscularis are indistinguishable.

the data of the region to a polynomial that best fits the data. After performing a linear regression analysis on the selected region, the equation of the linear fit, the scattering coefficient, μ_s , and the correlation coefficient, R^2 , were extracted. The results from the data calculation as well as the graphs were then exported and stored as text files and bitmap images, respectively. This process was repeated for the lamina propria and the muscularis layer.

3. Results

The first three layers of the urinary bladder are the urothelium, lamina propria, and the muscle layer. The scattering coefficients for each of these layers are shown in Table 1. We were unable to obtain urothelium μ_s for 3 of the 5 images. This layer was less than $100 \mu\text{m}$ and so it did not permit consistent accurate linear regression analysis. The scattering coefficients of the urothelium, lamina propria, and muscle layers were $0.33 \pm 0.03 \text{ mm}^{-1}$, $2.04 \pm 0.71 \text{ mm}^{-1}$, and $1.38 \pm 0.75 \text{ mm}^{-1}$, respectively, giving rise to a ratio of 1:6.2:4.2.

Figures 2(a) and 2(b) show OCT images of a normal human urinary bladder, and a cancerous urinary bladder respectively. Studies that have been performed have shown that the optical properties of the urinary bladder are altered as a result of the presence of cancer [4, 6]. In Figure 2(a), the urothelium, lamina propria, and muscularis layers can be

distinguished optically. However, in Figure 2(b) with invasive cancer, the three layers are indistinguishable optically.

The normal bladder in Figure 2(a) shows a thin urothelium (U) over a bright lamina propria (LP). There is a well-demarcated border, with good contrast, between the urothelium and the lamina propria. The muscularis propria (MP) is below the lamina propria, and once again the border is well demarcated and there is good contrast between the layers. In Figure 2(b), the layers of the cancerous urinary bladder are indistinguishable. This likely represents cancer that has invaded into and possibly through the muscularis [12].

The results presented in this paper characterize only the optical properties of the top three layers of the normal human urinary bladder. However, since the optical properties of the urinary bladder change with the onset and progression of cancer, the results presented in this paper would be useful in forming a standard against which changes in the optical properties of each layer due to cancer can be measured.

4. Conclusion

The optical scattering coefficients of the urothelium, lamina propria, and muscularis layers of the normal human urinary bladder have been measured. The scattering coefficients of the urothelium, lamina propria and muscle layers were $0.33 \pm$

0.03 mm^{-1} , $2.04 \pm 0.71 \text{ mm}^{-1}$, and $1.38 \pm 0.75 \text{ mm}^{-1}$, respectively, giving rise to a ratio of 1:4.2:2.8. Since the presence of cancer alters the optical properties of these layers, future work will include measurements of the optical properties of cancerous bladder images to determine the relationship between the changes in the optical scattering coefficient and the onset and progression of cancer in the human urinary bladder.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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