Clinical applications of functional optical coherence tomography

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QUANTITATIVE MEASUREMENT OF ATTENUATION COEFFICIENTS OF BLADDER BIOPSIES USING OPTICAL COHERENCE TOMOGRAPHY FOR GRADING UROTHELIAL CARCINOMA OF THE BLADDER

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CHAPTER 7


*BOTH AUTHORS HAVE CONTRIBUTED EQUALLY
Abstract

Real-time grading of bladder urothelial carcinoma (UC) is clinically important, but the current standard for grading (histopathology) cannot provide this information. Based on Optical Coherence Tomography (OCT) measured optical attenuation ($\mu_{\text{oct}}$) the grade of bladder UC could potentially be assessed in real-time. We evaluated ex vivo whether $\mu_{\text{oct}}$ differs between different grades of UC and benign bladder tissue.

Materials & Methods: Human bladder tissue specimens were examined ex vivo by 850 nm OCT using dynamic focusing. Three observers independently determined the $\mu_{\text{oct}}$ from the OCT-images and 3 pathologists independently reviewed the corresponding histology slides. For both methods a consensus diagnosis was made.

Results: We included 76 OCT scans from 54 bladder samples obtained in 20 procedures on 18 patients. The median (interquartile range) $\mu_{\text{oct}}$ of benign tissue was 5.75 mm$^{-1}$ (4.77-6.14) versus 5.52 mm$^{-1}$ (3.47-5.90), 4.85 mm$^{-1}$ (4.25-5.60) and 5.62 mm$^{-1}$ (5.01-6.29) for grade 1, 2 and 3 UC, respectively (p=0.732). Interobserver agreement of histopathology was “substantial” (Kappa 0.62, 95%CI 0.54-0.70) compared to “almost perfect” (ICC 0.87, 95%CI 0.80-0.92) for OCT.

Conclusion: Quantitative OCT analysis (by $\mu_{\text{oct}}$ ) did not detect morphological UC changes. This may be due to factors typical for an ex vivo experimental setting.

Introduction

The current standard for grading and staging of urothelial carcinoma (UC) of the bladder is histopathology: the pathologists’ assessment of the bladder specimen obtained by transurethral resection or biopsies. However, various clinical scenarios would benefit from real-time endoscopic diagnosis, which cannot be provided by histopathology. First, for instance, when a bladder tumour is treated by electric coagulation or laser ablation, no tissue is harvested and thus the urologist has to rely on his/her estimation of the stage and grade of that tumour, without histopathological confirmation. This estimation of grade or stage often is inaccurate [1]. Second, and likewise, in many centers nowadays patients with a history of low grade NMIBC with small recurrent bladder tumours are being followed-up by regular cystoscopy, instead of directly being treated by transurethral resection (i.e. no biopsy) [2,3]. The possibility of determining grade or stage at time of the cystoscopy would be very useful for both patient populations. A third example is a red lesion seen during cystoscopy, which may be either inflammation or CIS. Currently, if the urine cytology is suspicious for bladder cancer, random and targeted biopsies need to be taken for these lesions to exclude CIS. This strategy leads to a significant proportion of unnecessary biopsies, which might be avoided by use of a reliable, real-time diagnostic technique.

Grade is an important prognostic factor in predicting the biological aggressiveness of papillary UC of the bladder. It is the most important factor for progression in the European Organization for Research and Treatment of Cancer risk tables [4]. Therefore, grade has a strong impact on the clinical management of non-muscle invasive bladder cancer (NMIBC) patients [5,6]. Grade is defined based on the degree of morphological changes in the bladder tissue. In normal tissue, the urothelium usually contains less than 7 cell layers, has normal sized nuclei and a well preserved polarity, whereas in papillary UC, the urothelium is broadened, shows higher mitotic activity, cyto-nuclear ratio is changed and in high grade tumours the polarity is also disturbed. The first 3 changes are more pronounced as the grade increases. Besides papillary UC with different grades, carcinoma in situ (CIS) is a high grade flat lesion in which the urothelium is not per se broadened, shows high mitotic activity, severe disturbance in the cyto-nuclear ratio and loss of the polarity.

Optical Coherence Tomography (OCT) is a high-resolution, cross-sectional imaging technique that was studied for real-time endoscopic detection of bladder cancer [7-10]. The reported diagnostic accuracy is relatively high, with a sensitivity of 84-100% and specificity of 78-
89% [9,11,12]. For this, the OCT image is evaluated in a qualitative way (based on differences in gray scale levels and structural appearance) [10], which requires training and thus makes the diagnosis dependent on the skills of the observer. Assessment of the stage (i.e. the depth of tumour invasion into the different bladder tissue layers) of a bladder tumour by means of this method appears to be feasible [9], but grade is difficult to determine from qualitative analysis of OCT images. However, by additional OCT data analysis, the optical properties of tissue can be quantified: from the intensity of detected light versus depth the attenuation coefficient (μ<sub>oct</sub>) can be fitted using Beer’s law [13]. This method has been applied in analyzing atherosclerotic plaque components [14,15] and apoptosis and necrosis in human fibroblasts [16], showing that OCT indeed is sensitive for changes in μ<sub>oct</sub> caused by morphological changes in tissue. Moreover, it has been demonstrated that the measured backscattering differs at various stages of tumour genesis (hyperplasia/dysplasia and neoplasia) in rat bladders [17]. We therefore hypothesize that μ measurement from OCT enables assessment of the grade of a bladder tumour. As a first step towards in vivo diagnostic application, we tested this hypothesis ex vivo by evaluating whether the attenuation coefficient differed between benign bladder tissue and different grades of UC.

In the operation theatre, representative bladder tissue samples from each tumour or suspicious lesion were put into separate numbered containers filled with isotonic saline. Within 1 to 3 hours after surgery, examination with OCT was performed at the department of Biomedical Engineering & Physics. Samples were measured with (what was considered to be) the luminal surface exposed, covered in saline to prevent dehydration. Directly thereafter each sample underwent regular histological processing: formalin fixation was followed by paraffin embedding, cutting sections of 4 µm thickness and haematoxylin and eosin staining at the department of Pathology.

### OCT and histopathology analysis

The employed OCT system was a standard time domain OCT system, operating at 850 nm, using a moving reference arm and dynamic focusing in the sample arm. The axial and lateral resolutions of the system were 14 µm and 6 µm measured in air, respectively. The measured signal to noise ratio (SNR) was 118 dB. We verified that the power coupled back from the reference arm was constant over the scan range. Dynamic focusing was achieved by translating the sample arm lens in depth, during A-scan acquisition resulting in one A-scan per second data acquisition time. From each biopsy, one investigator (DMdB) created 1 to 4 OCT B-scans which were stored on hard disk to be analysed at a later date.

Dynamic focusing allows precise measurements of the μ<sub>oct</sub> of weakly scattering media, as described by Faber et al [13], because during the measurement, the positions of the coherence and confocal gates are matched. Using Beer’s law, the detector current I<sub>det</sub> of the system is described as I<sub>det</sub> = I<sub>0</sub>e<sup>-2μ<sub>oct</sub>Z</sup> where Z is the round trip path length of the light in the sample. The square root accounts for the fact that the detector current is proportional to the field returning from the sample, rather than intensity. The attenuation coefficient μ<sub>oct</sub> is then extracted from the OCT data by fitting Beer’s law to the averaged A-scans from a selected region of interest in the OCT image using the Levenberg-Marquardt least squares minimization algorithm (~100 A-scans of 2048 points, 1.5 mm scan length) (Figure 1). Prior to averaging and fitting, all A-scans in the region of interest are aligned. The standard deviation corresponding to the average A-scan is used for weighting in the fitting procedure in such a way that depths with large standard deviation contribute less to the minimization procedure.

![Figure 1](image_url)

**Figure 1.** Demonstration of the quantitative analysis of OCT data to obtain the μ<sub>oct</sub> of a bladder tumour biopsy (pTa grade 3). 1a is the obtained OCT B-scan of a bladder tumour biopsy (pTa grade 3), 1b shows the aligned image with the region of interest (ROI) indicated in a square, 1c shows the plot of the mean signal intensity versus depth of the selected ROI, the slope is fitted using Beer’s law (μ<sub>oct</sub> indicated in dashed line).

The fit model features three parameters; an amplitude for scaling, the μ<sub>oct</sub> and an offset, which is fixed at the mean noise level. An uncertainty estimate for the fitted μ<sub>oct</sub> is computed from the co-variance matrix returned by the fitting algorithm and is specified as 95% confidence interval (95% CI) of the fitted μ<sub>oct</sub>. The curve fit typically included ~1500 points.

The stored OCT B-scans were analysed by 3 independent observers (ECCC, DMdB, DJF), who were blinded for clinical information and histopathological diagnosis. After the individual review of the B-scans,
the 3 observers together repeated the analysis of the B-scans to obtain a consensus-\(\mu_{\text{oct}}\) of each scan. To this end, the B-scans were projected on a large screen. One observer aligned the image and selected the region of interest for fitting with the other 2 observers commenting to reach consensus.

In case of multiple B-scans from one biopsy, the mean \(\mu_{\text{oct}}\) was calculated for both individual as well as for the consensus-\(\mu_{\text{oct}}\) with the corresponding 95% CI.

The histopathological diagnoses were made by 3 independent pathologists (MV, JvdT, BR) working in the same academic center. They classified each biopsy as normal/benign, UC Grade 1, UC Grade 2 or UC Grade 3, while being blinded for clinical information and OCT results. Samples in which a definitive diagnosis was not possible (e.g. due to cautery, desquamation, insufficient size of the sample), were classified as non-diagnostic. It is well known that histopathological grading is a subjective method with a high interobserver variability reported in literature (13-62%) \cite{18-20}, despite guidelines on the interpretation of slides and consensus on the definition of the different grades \cite{21,22}. Therefore, we used a consensus diagnosis in order to optimize our reference standard. For this, the 3 pathologists reviewed the samples together on a multihhead microscope to reach a consensus diagnosis, after the individual review of the slides.

**Results**

In total, 76 OCT scans from 54 bladder tissue samples obtained in 20 procedures on 18 patients were available for analysis. Demographic and pathological characteristics are summarized in Table 1.

The independent as well as consensus diagnosis of pathological grade of the samples is displayed in Table 2. Overall, 11 samples (20.4%) were classified as non-diagnostic by the pathologists’ consensus review procedure and were excluded for the Kruskal-Wallis analysis whilst the remaining 43 samples (60 OCT scans, 16 patients, 18 procedures) were included. The median 95% CI of the fitted \(\mu_{\text{oct}}\) (consensus review procedure) was 0.06 mm\(^{-1}\) (IQR 0.04-0.10 mm\(^{-1}\)), indicating accurate fitting.

Figure 2. Boxplot of attenuation coefficients for different pathological categories; horizontal lines represent median values, boxes indicate IQR and error bars indicate range.
procedures. The median attenuation coefficient of normal/benign tissue was 5.75 mm$^{-1}$ (IQR 4.77-6.14 mm$^{-1}$) versus 5.52 mm$^{-1}$ (IQR 3.47-5.90 mm$^{-1}$), 4.85 mm$^{-1}$ (IQR 4.25-6.50 mm$^{-1}$) and 5.62 mm$^{-1}$ (IQR 5.01-6.29 mm$^{-1}$) for grade 1, 2 and 3 UC, respectively ($H(3)=1.29$, $p=0.732$) (Figure 2).

The interobserver agreement on the OCT data, evaluated by intra-class correlation, was “almost perfect” (ICC 0.87, 95% CI 0.82-0.92, $p<0.001$). The overall agreement for histopathology, calculated by Fleiss generalised Kappa, was “substantial” (Kappa 0.63, 95% CI 0.54-0.70, $p<0.001$). The Kappa’s and corresponding pathologists’ agreement for the different histopathological categories are summarized in Table 3.

**DISCUSSION**

Although prior research [17] showed a difference in backscattering (e.g. OCT signal amplitude) in an OCT image containing both a normal and hyperplastic region, and another image containing both a normal and neoplastic region, we could not demonstrate such a difference in the attenuation coefficient of bladder cancer tissue, in this human ex vivo study. Xie et al assumed in their theoretical model that nuclei were the main source of scattering, and that nuclear morphological changes occurring in carcinogenesis (increased nuclear-cytoplasm ratio, loss of polarity) could be detected by OCT based on measured backscattering. With a controllable bladder tumour model in Fisher rats they showed that the calculated backscattering increased less than 20% in hyperplastic lesions, but over 60% for neoplastic lesions, compared to normal urothelium. The backscattering change between hyperplastic and dysplastic lesions was insufficient to discriminate these stages [17]. Note that changes in cellular morphology do not necessarily cause similar changes in $\mu_t$ and backscattering because the former depends on the scattering phase function in the backscattering direction which in turn is a strong function of particle size.

Several factors, some inherent to an ex vivo experimental setting, might account for the lack of difference in $\mu_{tot}$ between the different pathological types in the current study. First, bladder cancer is a morphologically heterogeneous disease and different grades may exist within one tumour [18,24]. Though OCT and histopathology both result in cross-sectional images of the sample, it is very difficult to obtain a histological section of 4 µm thickness in a sample of 5x5 mm at the exact same point as where the OCT imaging took place, even if imaged areas would have been marked with ink. This discrepancy in region of interest might therefore account for difficulties in correlation of the $\mu_{tot}$ with pathological grade. Moreover, histopathological grading can be based on just a few altered cells in a specimen, whereas OCT analysis averages morphology over a complete OCT image. Second, the relatively low Kappa value of histopathology indicates that grading of (some of) the samples was not straightforward. Despite the fact that we used consensus histopathological diagnosis to optimize the reference standard, this subjective nature of histopathology might hamper correlation. It must be acknowledged that the OCT-analysis also has a subjective element, i.e. the choice of the region of interest. Third, finding the right orientation of the biopsy (i.e. to identify the mucosal surface) can be difficult, especially in cold cup biopsies, which tend to be rather small (2x2 mm on average). For “warm” biopsies (biopsies obtained by resection), cauteration effects helped with the orientation, and the non-cautered side was regarded as the mucosal site. Nevertheless, this cauteration may induce changes in $\mu_{tot}$ and also account for artefacts in the OCT data. Moreover, the optical properties of excised tissue may change from live tissue. Although we took care to image the biopsies as soon as possible after resection, our present protocol did not allow faster processing than within 1-3 hrs after the procedure. To minimize any changes in optical properties, the biopsies were kept in isotonic saline solution after resection and during OCT imaging. Furthermore, the samples were measured in a relaxed state and not stretched and pinned, which would better mimic the in vivo situation in the human bladder. Hermes et al conducted an ex vivo study on qualitative analysis of OCT for bladder cancer which enabled detailed tissue characterization, and they did measure the specimens under gentle tension by clamping them on cork [11]. Due to the small size of the specimens, this was not possible in the current study. In addition, we measured the samples at room temperature, and since the optical properties of tissue are temperature-dependent [25], this may also have influenced the $\mu_{tot}$ in our study. However, the effect of temperature on $\mu_{tot}$ is most prominent in tissue with high-lipid content [26], thus in bladder tissue this effect most probable will be minimal.

Our current protocol did not allow deliberately taking biopsies of normal tissue. Consequently, a paired comparison of $\mu_{tot}$ of normal versus tumour tissue within individual patients (i.e. patients as their own control) was not possible. Nevertheless, for 4 patients biopsies were taken that were classified as normal/benign and for which a biopsy classified as UC was also available. In a post-hoc test, we did compare the median $\mu_{tot}$ of the normal sample with the median $\mu_{tot}$ of the tumour sample (5 samples in total for each group, data not shown). In 1 patient only, the tumour sample revealed a higher $\mu_{tot}$ (6.70 mm$^{-1}$) than the normal sample (4.31 mm$^{-1}$). In the other 3 patients the $\mu_{tot}$ of the tumour sample...
was either equal to or lower than the $\mu_{\text{oct}}$ of the normal tissue. However, sample size was too small to draw statistically sound conclusions.

In addition, we made a sub-analysis on the 20 biopsies from tumours that were confined to the urothelium without invasion in the lamina propria or muscularis propria (pTa tumours). In these tumours morphological changes occur solely in the most superficial layer of the bladder (i.e. urothelium). We assumed that measuring $\mu_{\text{oct}}$ for the complete depth of the sample would be inaccurate for these tumours. Therefore, we only determined the $\mu_{\text{oct}}$ from the most superficial layer identified in the B-scan. Within these 20 samples (3 samples with grade 1, 13 with grade 2, 4 with grade 3) also no difference in median $\mu_{\text{oct}}$ was found for the different grades (data not shown).

This study did confirm the high interobserver variability of histopathological grading. This was especially noticeable for grade 1 tumours, which is also acknowledged in literature [18]. Because of this well known interobserver variability, an objective assessment of grade would be desirable because of its importance for prognosis and thus management. We could demonstrate that the interobserver variability for OCT-analysis was much lower than of pathology.

Some of the factors that may (at least in part) account for the lack of differences in $\mu_{\text{oct}}$ in our study, like orientation of the biopsies, cauterization effects and the effect of tissue relaxation of the biopsies, are typical for an ex vivo setting. Since these factors may be circumvented in an in vivo approach using a cystoscopically guided fiber based catheter to obtain the OCT data, further in vivo investigation of our hypothesis is warranted.

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Significance of this study
Even though our hypothesis could not be confirmed, this study revealed a number of points that are worth stressing. Most importantly, the correlation of in vivo measured $\mu_{\text{oct}}$ in suspicious lesions with histopathology may be challenging because of the heterogeneity of bladder cancer and the (only) “substantial” agreement of the gold standard. Moreover, our study shows that the translation of theoretical considerations and controlled animal studies [17] to a clinically realistic, heterogeneous patient population is far from straightforward. Finally, if an in vivo study (which is about to start in our center) would show a positive outcome, we can conclude that our present study mostly reflects limitations due to ex vivo circumstances rather than limitations of OCT technology, which could be an important factor in future study designs.

**Conclusion**

We could not confirm our hypothesis that morphological changes occurring in malignant bladder tissue can be assessed in a quantitative way by determining the attenuation coefficient by OCT in this ex vivo study. Because this lack of correlation may (at least in part) be due to environmental factors typical in an ex vivo setting (orientation of the biopsy, cauterization effects and relaxed bladder wall), further in vivo testing is warranted.

**Acknowledgements**

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**Tables**

| Table 1. Demographic and pathological characteristics |
|-----------------|-----------------|
| Patients        | 18              |
| Gender (%)      |                 |
| Male            | 14 (77.8)       |
| Female          | 4 (22.2)        |
| Mean age (range), yrs | 73.0 (53.4-88.0) |
| Procedure (%)   |                 |
| TUR             | 17 (83.3)       |
| Bladder biopsies| 3 (16.7)        |
| Pathology – stage (%) |                 |
| Normal/benign   | 9 (16.7)        |
| Ta              | 20 (37.0)       |
| T1              | 4 (7.4)         |
| T2              | 5 (9.3)         |
| Tis             | 3 (5.6)         |
| Non-diagnostic  | 13 (24.1)       |
Table 2. Kappa and corresponding pathologists’ agreement of the different pathological categories

<table>
<thead>
<tr>
<th>Pathologist A</th>
<th>Pathologist B</th>
<th>Pathologist C</th>
<th>Consensus diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td></td>
</tr>
<tr>
<td>Normal/benign</td>
<td>7 (15.0)</td>
<td>6 (11.1)</td>
<td>11 (20.4)</td>
</tr>
<tr>
<td>Grade 1 UC</td>
<td>10 (18.5)</td>
<td>9 (16.7)</td>
<td>7 (13.0)</td>
</tr>
<tr>
<td>Grade 2 UC</td>
<td>7 (13.0)</td>
<td>12 (22.2)</td>
<td>16 (27.8)</td>
</tr>
<tr>
<td>Grade 3 UC</td>
<td>22 (40.7)</td>
<td>18 (33.3)</td>
<td>15 (27.8)</td>
</tr>
<tr>
<td>Non-diagnostic</td>
<td>8 (14.8)</td>
<td>12 (22.2)</td>
<td>12 (22.2)</td>
</tr>
</tbody>
</table>

UC: urothelial carcinoma

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<table>
<thead>
<tr>
<th>Pathologist A</th>
<th>Pathologist B</th>
<th>Pathologist C</th>
<th>Consensus</th>
</tr>
</thead>
<tbody>
<tr>
<td>N (%)</td>
<td>N (%)</td>
<td>N (%)</td>
<td>Diagnosis</td>
</tr>
<tr>
<td>Normal/benign</td>
<td>0.61 (0.23-0.99)</td>
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<td>Substantial</td>
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<tr>
<td>Grade 1 UC</td>
<td>0.26 (-0.12-0.84)</td>
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<td>Moderate</td>
</tr>
<tr>
<td>Grade 2 UC</td>
<td>0.50 (0.12-0.87)</td>
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<td>Substantial</td>
</tr>
<tr>
<td>Grade 3 UC</td>
<td>0.76 (0.34-1.00)</td>
<td></td>
<td>Substantial</td>
</tr>
<tr>
<td>Non-diagnostic</td>
<td>0.84 (0.47-1.00)</td>
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<td>Almost perfect</td>
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</tbody>
</table>

UC: urothelial carcinoma

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