Advancing optical coherence tomography with numerical techniques

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Outline

• Motivation
• Principles of OCT
• Monte Carlo simulations of OCT images
• Speckle statistics for characterization of OCT images
• Study of the role of multiple scattering in OCT signal formation
• OCT image sonification
• OCT image segmentation
• OCT in gynecology: Automated recognition of pathologies of fallopian tubes during OCT-laparoscopy
• OCT in urology: image quantification in CP OCT diagnostics of bladder
• OCT in cosmetology: OCT Monitoring of skin rejuvenation PDT
Motivation

- Requirement for novel high resolution non-invasive imaging modalities in clinical practice and industry
- High potential of OCT providing spatial resolution down to units of microns at depth of units of mm for operational wavelengths in visible and near-IR ranges
- Active introduction of OCT into clinical practice
- Subjectivism in evaluation of diagnostic OCT image by a clinician
- Requirement for account for physical aspects of OCT-image formation, in particular, in case of strong scattering
- Requirement for numerical characterization of OCT-images in biological and medical studies
- Impossibility of analysis by a clinician of OCT-images stream in course of high-speed scanning
Low coherence

1 wave

\[ E_1 = E_0 \cos(\omega t + k_1 x + \phi_1) \]

3 waves

\[ E_1 = E_0 \cos(\omega t + k_1 x + \phi_1) \]
\[ E_2 = E_0 \cos(\omega t + k_2 x + \phi_1) \]
\[ E_3 = E_0 \cos(\omega t + k_3 x + \phi_1) \]

11 waves

\[ E_1 = E_0 \cos(\omega t + k_1 x + \phi_1) \]
\[ E_2 = E_0 \cos(\omega t + k_2 x + \phi_1) \]
\[ \ldots \]
\[ E_{11} = E_0 \cos(\omega t + k_{11} x + \phi_1) \]

Coherence function \( C \)

\( I_c \) – coherence length
Schematics of the OCT setup

Typical OCT signal (A-scan) from a layered scattering medium
OCT scanning: from 1D to 2D and 3D
Numerical techniques in OCT

Numerical simulations of OCT images
- Design and development of OCT systems
- Approbation of image processing techniques
- Study of the role of multiple scattering in OCT signal formation

Parameter extraction from OCT images

OCT image classification

Segmentation of OCT images
Basic idea of Monte Carlo simulation of light propagation in scattering medium

- $R$ – reflected photon
- $A$ – absorbed photon
- $T$ – transmitted photon

Input medium parameters:
- $\mu_s$ – scattering coefficient
- $\mu_a$ – absorption coefficient
- $p(s,s')$ – scattering phase function
- $g$ – anisotropy factor
- $n$ – refractive index

$\mu_s$ – $\mu_a$ – $n$
Application of Monte Carlo method to OCT signal simulation

Monte Carlo simulations

Distribution of photons fitting OCT detection conditions over pathlengths

Convolution with source coherence function

\[ I(z) = \sum_i \sqrt{W_r W_s (\Delta l_i)} \exp \left( - \left( \frac{z - \Delta l_i}{l_{coh}} \right)^2 \right) \]
Application of Monte Carlo method to OCT image simulation
Experimental and simulated OCT images of skin

Structure and compounds of skin

Multilayer skin model

Upper stratum corneum
Lower stratum corneum
Epidermis
Upper dermis
Lower dermis

Photon classification

Diffusive component (DC)

Non-diffusive component (NDC)

Multiple scattering (MSP)

Least scattering (LSP)

\[ N > N_{cr} = \frac{L_{tr}}{L_{fp}} = \frac{\mu_a + \mu_s}{\mu_a + \mu_s'} \]

\[ N < N_{cr} = \frac{L_{tr}}{L_{fp}} = \frac{\mu_a + \mu_s}{\mu_a + \mu_s'} \]

\[ l - 2 z_{max} > l_{coh} \]

\[ l - 2 z_{max} < l_{coh} \]

- \( l \): optical pathlength in medium
- \( z_{max} \): maximal depth reached in medium
- \( l_{coh} \): coherence length
- \( N \): number of experienced scattering events

Contributions of different scattering orders to the OCT image of skin
Contribution of LSP and MSP components to the OCT image of skin.

- Least scattered photons contribution (LSP)
- Multiply scattered photons contribution (MSP)
- Non-diffusive component contribution (NDC)
- Diffusive component contribution (DC)
Extracting attenuation coefficient from OCT signal slope

Analysis of speckle statistics in OCT: tumor differentiation in vivo

Assessment of OCT speckle statistics: Experiment versus Monte Carlo simulation

Assessment of OCT speckle statistics: Experiment versus Monte Carlo simulation

Sonification of OCT images

OCT images segmentation

*Principles*

- Classical segmentation methods: (image partitioning to areas with homogenous property)
- Pixel classification methods
- Pattern recognition methods
- Deformable model methods
- Registration methods (atlas-guided approach)
- Model-fitting methods (fitting a simple geometric shape)

OCT images segmentation

Examples


Advancing clinical optical coherence tomography applications
Diagnostics of fallopian tubes: OCT-laparoscopy

- Prevalence of subclinical forms (up to 60%), which allows to introduce the term of “silent”, atypical or unrecognized inflammations
  
  *(R. L. Sweet and R. S. Gibbs, 2009)*

- Imperfection of diagnostic abilities of traditional techniques: transvaginal ultrasound (TVUS), computed tomography (CT), magnetic resonance imaging (MRI) and laparoscopy.

OCT system “OCT-1300U”

- time-domain OCT
- flexible en-face OCT-probe with angular scanning
- central wavelength @1280 nm,
- in-depth resolution (in air) 15 mm,
- transversal resolution 30 mm,
- frame acquisition rate: 8-10 fps

Typical OCT-images and histology of fallopian tubes tissues in norm and pathology.

- **norm**
- **serous inflammation with edema**
- **chronic inflammation with fibrosis**
Verbal criteria for pathology recognition

norm (unaltered fallopian tube)
• unstructured, with moderate signal level and signal intensity gradually decreasing in-depth
• the rate of signal intensity decrease is uniform

edema (subacute inflammation accompanied by edema)
• inhomogeneous, with dominating transverse striations and alternating areas of low and high signal level
• areas with low signal level are relatively large, of variable size, irregular contours, round or oval in shape
• the rate of OCT signal decrease varies over the image

fibrosis (chronic inflammation with fibrosis)
• the areas with high signal level prevailing

Scoring OCT images

Histogram analysis

In-depth derivative

Application of automated recognition

<table>
<thead>
<tr>
<th>Diagnostic measures</th>
<th>Laparoscopy (open recognition test), %</th>
<th>OCT-laparoscopy (open recognition test), %</th>
<th>blind recognition by 8 respondents, 47 images</th>
<th>Automated recognition, 61 images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity</td>
<td>44%</td>
<td>96%</td>
<td>90%</td>
<td>96%</td>
</tr>
<tr>
<td>Specificity</td>
<td>67%</td>
<td>83%</td>
<td>81%</td>
<td>100%</td>
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<tr>
<td>Diagnostic accuracy</td>
<td>48%</td>
<td>93%</td>
<td>88%</td>
<td>96%</td>
</tr>
</tbody>
</table>
Cross-polarization OCT

[Diagram showing the components of a cross-polarization OCT setup: SLD, Polarizer, PM Splitter, 50/50 beam splitter, Mirror, Lens, and Object with cross-section images.]
The page presents a table titled "State of collagen fibers Diagnosis Group number Number of OCT images," which categorizes different states and diagnoses of bladder conditions.

### State of collagen fibers

<table>
<thead>
<tr>
<th>State of collagen fibers</th>
<th>Diagnosis</th>
<th>Group number</th>
<th>Number of OCT images</th>
</tr>
</thead>
<tbody>
<tr>
<td>norm</td>
<td>Norm</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>excessive accumulation</td>
<td>Chronic inflammation with manifested fibrosis</td>
<td>2</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Post-operative scar</td>
<td>3</td>
<td>18</td>
</tr>
<tr>
<td>degradation</td>
<td>Acute inflammation</td>
<td>4</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Cancer in situ</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Invasive basal cell carcinoma</td>
<td>6</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>Carcinoma relapse at scar</td>
<td>7</td>
<td>14</td>
</tr>
</tbody>
</table>

Integral depolarization factor (IDF)

\[ IDF = \frac{1}{N} \sum_{i=1}^{N} \frac{P_i^\perp - \langle P_{\text{noise}} \rangle}{P_i^\parallel} \]

\[ P_i^\perp > \langle P_{\text{noise}} \rangle + 2\sigma_{\text{noise}} \]
IDF in CP-OCT diagnostics of bladder

Application in differential diagnostics

Revealing of fibrosis

Revealing and characterization of neoplasia

Revealing cancer relapse at scar

<table>
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<tr>
<th>Group</th>
<th>Diagnosis</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>Diagnostic accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Norm</td>
<td>72%</td>
<td>90%</td>
<td>79%</td>
</tr>
<tr>
<td>2</td>
<td>Chronic inflammation with manifested fibrosis</td>
<td>68%</td>
<td>86%</td>
<td>75%</td>
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<tr>
<td>3</td>
<td>Post-operative scar</td>
<td></td>
<td></td>
<td></td>
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IDF in CP-OCT diagnostics of bladder

Characterization of collagen fibres

![Graph showing characterization of collagen fibres with values for different groups.](graph.png)
Conclusion

- Numerical techniques allow to study and interpret OCT images.
- Analysis of speckle statistics demonstrates high potential for differential diagnostics.
- OCT in combination with laparoscopy and image quantification is an alternative to biopsy and morphological verification in diagnostics of PID.
- Development of criteria for automated recognition allowed for increase of diagnostic value of OCT. In future these criteria could be employed for automated recognition when processing video-stream from an OCT-system.
- Employment of integral depolarization factor in evaluation of diagnostic CP-OCT images allows for differential diagnostics of biotissues at different localizations and characterization of the state of collagen fibers.
Thank you for your attention!

Questions?