Optical Coherence Tomography

Acknowledgements: Joseph Jing
Outline

► Background

► OCT Fundamentals
  ► Coherence
  ► Interferometry
  ► Scattering

► OCT Principles
  ► Axial, Lateral Resolution
  ► Time domain vs Fourier Domain

► Applications
Why Optical Imaging?

- High spatial resolution
- High Contrast with molecular signature
- Noninvasive, non-ionizing (unlike X-rays)

<table>
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<tr>
<th>Imaging Technology</th>
<th>Typical resolution (µm)</th>
<th>Imaging Depth (mm)</th>
<th>System Cost</th>
<th>Speed</th>
<th>Features</th>
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<tr>
<td>Ultrasound</td>
<td>150</td>
<td>150</td>
<td>Low</td>
<td>Video rate</td>
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<tr>
<td>MRI</td>
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<tr>
<td>CT</td>
<td>1000</td>
<td>Unlimited</td>
<td>High</td>
<td>Video rate</td>
<td>Non-Invasive, Radiation</td>
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High Resolution Optical Imaging Modalities

- Fluorescence Imaging
- Confocal Microscopy
- Phase Contrast Imaging
- Two/Multi-Photon Fluorescence Microscopy
- Polarization Imaging

*Surface/Single Layer Imaging*
Tomographic Imaging

Biopsy
Histology

“Optical Biopsy”? Noninvasive cross sectional imaging
What is OCT?

- Interferometer based imaging modality
- Micrometer imaging resolution
- Millimeter penetration depth
- Non-ionizing illumination
Where does OCT fit?
Ultrasound Range Finding

Sound speed = 1,500 m/s,
Light speed = 300,000,000 m/s
Time required to travel forward and bounce back from target at 1 mm
1.3 us for US
6.7 ps for light
Rayleigh Scattering
- Particles < $\lambda$
- Strongly wavelength dependent
- Isotropic

Mie Scattering
- Particles $\geq \lambda$
- Cells, Tissue, Water droplets
- Anisotropic

http://hyperphysics.phy-astr.gsu.edu/hbase/atmos/blusky.html
Challenge: Scattering of photons destroys localization

Mean free scattering path:

Skin tissue: $1/\mu_s \sim 50 \mu m$  
Blood: $1/\mu_s \sim 8 \mu m$
Coherence Gating

\[ |L_P - 2nz| < \frac{L_C}{2} \]
Drawbacks of scattering contrast

- Limited penetration depth
- Deteriorating axial resolution
- Lack of contrast selectivity
How to measure echoes of light?

Interferometry
Coherence

- Two waves are perfectly coherent if they have a constant phase difference and the same frequency.
- For stable interference, two waves must be coherent.

Spatial and Temporal Coherence
- Spatial – correlation between waves at different points in space.
- Temporal – correlation between waves at different periods in time.
Low Coherence Interferometry (LCI)

Periodic interference of single wavelength

\[ I \propto \cos(2k\Delta Z) \]
2 wavelengths

\[ I \propto \cos(2k\Delta Z) \]
3 wavelengths

Wave packets

Wave packet envelope
4 wavelengths

Laser
Beam splitter
Photodetector
Movable mirror 2
Fixed mirror 1

Wave packets
Wave packet envelope
Broadband LCI

\[ L_c = c \cdot \tau_c \]

Coherence Gating
Operating Principle

- Low Coherence Light Source
- Beam splitter
- Reference mirror
- Three scattering surfaces
- Photodetector
OCT Principles

Sample reflectivity profile vs position in sample arm
Axial Resolution in OCT

\[ L_c = \frac{2\sqrt{\ln(2)}}{\Delta k} = \frac{2\ln(2) \lambda_0^2}{\pi \Delta \lambda} \approx 0.44 \frac{\lambda_0^2}{\Delta \lambda} \]
Choosing Wavelength

\[ L_c = \frac{2\sqrt{\ln(2)}}{\Delta k} = \frac{2 \ln(2)}{\pi} \frac{\lambda_0^2}{\Delta \lambda} \approx 0.44 \frac{\lambda_0^2}{\Delta \lambda} \]

http://enacademic.com/dic.nsf/enwiki/11859865
Lateral Resolution in OCT

Lateral Resolution

\[ \Delta x = \frac{2\lambda}{\pi} \frac{1}{NA} = \frac{4\lambda}{\pi} \left( \frac{f}{d} \right) \]

Depth of Focus

\[ 2\Delta z_r = b = \frac{\pi \Delta x^2}{2\lambda} \]

Want high lateral resolution and long depth of focus: *Competing effects*
$I_z \rightarrow^{\text{FT}} I_k$

Split into M channels and sample the entire depth at the same time:
SNR improved by 20 dB, high speed:

$$SNR_{FD} = SNR_{TD} \cdot \frac{M}{2}$$
Fourier Domain OCT

Fourier Domain OCT

Ophthalmology

Eye structure
Anterior Chamber

Axial scan

Reference arm

Light source

Source arm

Sample arm

Detection arm

Transverse scan

Anterior chamber of human eye

CORNEA

AQUEOUS

IRIS

AIR

3.46/n = 2.62 (mm)

CORNEA

AQUEOUS

LENS

AIR

3.84/n = 2.88 (mm)
Doppler OCT

- Utilize the Doppler effect to measure velocity of particles in OCT scans
- Motion induced frequency shift

\[ \Delta f = \frac{\Delta v}{c} f_0 \]
\[ \Delta f = \frac{2V \cdot \cos(\theta)}{c} f_0 = \frac{2V \cdot \cos(\theta)}{\lambda_0} \]

- Phase Resolved Doppler

\[ \frac{\Delta \phi}{2\pi} = \frac{\Delta z}{\lambda_0} \implies \Delta z = \frac{\Delta \phi \cdot \lambda_0}{2\pi} \]

\[ \Delta f = \frac{1}{2\pi} \frac{d\phi}{dt} \]
(A) Full-thickness (internal limiting membrane to Bruch’s membrane) 3 x 3 mm OCT angiogram of retina.

(B) Full-thickness 6 x 6 mm OCT angiogram.

(C) Corresponding OCT b-scan.
Intravascular Imaging

- ~1,100,000 in US will have a new or recurrent heart attack.
- ~70 percent of these heart attacks are due to sudden rupture of unstable arterial plaques that cannot be detected using conventional imaging modalities.
- OCT has the potential to identify arterial plaque and differentiate stable plaque from unstable.
- In addition, OCT can help more precisely direct conventional treatments for stable plaques - balloon angioplasty and stenting.
Heart Disease
Vulnerable Plaque
Cardiac Catheterization

Co-registered Intravascular Ultrasound + OCT (72 fps)

Prof. Zhongping Chen, PhD
Integrated IVUS-OCT Intravascular Imaging

- OCT – High Resolution
  - Measure Fibrous Cap Thickness
- IVUS – Deeper Penetration
  - Visualize Lipid Pool

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