Time-resolved NIRS and non-destructive assessment of food quality

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Dipartimento di Fisica – Politecnico di Milano

Winter College on Applications of Optics and Photonics in Food Science

20 February 2019
Outline

• Lecture 1 (Alessandro Torricelli) 9-10 am
  • Basics of TD NIRS

• Lecture 2 (Lorenzo Spinelli) 10-11 am
  • Application of TD NIRS to food quality assessment

• Coffee break 11:00-11:30 am

• Discussion 11:30-12:30
  • What does affect TD NIRS?
  • Questions & Answers
Outline

• Lecture 1 (Alessandro Torricelli) 9-10 am
  • Basics of TD NIRS
    • Introducing the PHOOD lab @ PoliMi
    • Modelling light propagation in food
    • CW and TD NIRS
    • Instrumentation for TD NIRS
Politecnico di Milano (PoliMi)
Teaching & Research University

PoliMi since 1863
1863 – 2019
156 years

Engineering
Architecture
Design
Photonics for Health, Food, and Cultural Heritage
Dipartimento di Fisica – Politecnico di Milano

Professor Emeritus: Rinaldo Cubeddu

Full professors: Antonio Pifferi
Paola Taroni
Alessandro Torricelli
Gianluca Valentini

Associate Professors: Andrea Bassi
Daniela Comelli
Davide Contini
Cosimo D’Andrea
Alberto Dalla Mora

Assistant Professors: Rebecca Re
Laura Di Sieno

CNR IFN
Lorenzo Spinelli (CNR)
Andrea Farina (CNR)
Austin Nevin (CNR)

Post-Docs: Lina Qiu
Alessia Artesani

+ PhD Students (11)
+ Facilities (mechanic and electronic workshop)
Photonics for Health, Food, and Cultural Heritage
Dipartimento di Fisica – Politecnico di Milano

Health
- In vivo Tissue Spectroscopy
- Optical Mammography
- Tissue Oximetry and Functional Imaging of the Brain
- Fluorescence Lifetime Imaging in biology and medicine

Food
- nondestructive assessment of internal defects by pulsed NIR
- nondestructive maturity assessment at harvest

Cultural Heritage
- Photoablation and Material Processing
- fluorescence Spectroscopy and Imaging
- Multispectral Imaging and Colorimetry
Photonics for Health, Food and Cultural Heritage Laboratories

**Time-resolved systems**
- mode-locking of dye, gas and solid state lasers
- time-correlated single-photon counting (TCSPC)
- time-gated imaging

**Spectral-domain**
- tunable laser sources
- broadband detectors

**Spatial-domain**
- scanning systems or camera
- multi-channel systems

**Temporal-domain**
- fast acquisition rate

Functional near infrared spectroscopy - fNIRS Lab
Diffuse spectroscopy - DiffS Lab
Optical mammography - Mammot Lab
Molecular imaging - Molim Lab
Near infrared spectroscopy for food - NIRf Lab
Imaging spectroscopy for cultural heritage - ARTIS Lab
Ultras for biomedicine - UB Lab
Can light penetrate biological tissues?

Georges de La Tour (1593 – 1652)

St Joseph (1642)
Louvre, Paris

Thanks to Marco Ferrari (UnivAQ)
Light absorption in the near infra-red (NIR): biological tissue

The therapeutic and diagnostic window
Light absorption in the near infra-red (NIR): fruit
Visible (VIS) and near infrared spectroscopy (NIRS): continuous wave (CW) approach

VIS: 400-700 nm (nondestructive assessment of EXTERNAL properties)
NIR: 700-3000 nm (nondestructive assessment of INTERNAL properties)

Rich Ozanich, Berkeley Instruments Inc., Richland, WA

Figure 1. Overview of NIR spectroscopy.
Visible (VIS) and near infrared spectroscopy (NIRS) : continuous wave (CW) approach

HL200 Ocean Optics \( \approx 1000 \) €

USB4000 Ocean Optics \( \approx 2000 \) €

Notebook \( \approx 1000 \) €

DA-meter, courtesy of P. Rozzi, Sinteleia (Italy)

Spider, courtesy of Manuela Zude ATB Potsdam (Germany)
Light propagation in diffusive media: absorption and scattering

Absorption: related to tissue components

Absorption coefficient:

\[ \mu_a = \frac{1}{\ell_a} \text{ (cm}^{-1}\text{)} \]

Scattering: related to tissue structure

Scattering coefficient:

\[ \mu_s = \frac{1}{\ell_s} \text{ (cm}^{-1}\text{)} \]

→ interplay between light absorption and light scattering
Lambert-Beer law
Light attenuation in a THIN diffusive medium

Clear medium

\[ I_{\text{IN}} \rightarrow I_{\text{OUT}} = I_{\text{IN}} \exp(-\mu_a L) \]

\[ A = \ln \left( \frac{I_{\text{out}}}{I_{\text{in}}} \right) = \mu_a L \]

\[ \mu_a = \varepsilon C \]

Diffusive medium

\[ I_{\text{IN}} \rightarrow I_{\text{OUT}} = I_{\text{IN}} \exp(-\mu_t L) \]

\[ A = \ln \left( \frac{I_{\text{out}}}{I_{\text{in}}} \right) = (\mu_a + \mu_s) L \]

- Valid only if \( \mu_t L < 1 \) (Single scattering regime)
- Scattering coefficient is unknown
- Pathlength is unknown
Modelling photon migration in diffusive media

Radiative Transport Equation (RTE)

Conservation of energy in a small volume $dV$ in a given direction $s$

\[
\frac{\partial n}{\partial t} = -v \hat{s} \cdot \nabla n - v \mu_a n + v \mu_s n + v \mu_s \int p(\hat{s}' \cdot \hat{s}) n \, d\Omega + \varepsilon
\]

1. Photons out
2. Photons absorbed
3. Photons scattered to another direction
4. Photons scattered from another direction ($s'$) to direction of interest ($s$)
5. Light source

$n = \text{photon (angular) density}$

\[n \, dV \, dv\] is the expected number of photons in the volume $dV$ about $r$, with velocity in $dv$ about $v$, at time $t$
The RTE for the Radiance

\[
\frac{1}{v} \frac{\partial L(\mathbf{r}, \hat{s}, t)}{\partial t} = -\hat{s} \cdot \nabla L(\mathbf{r}, \hat{s}, t) - (\mu_a + \mu_s) L(\mathbf{r}, \hat{s}, t) + \mu_s \int_{\Omega} p(\hat{s}' \cdot \hat{s}) L(\mathbf{r}, \hat{s}', t) \, d\Omega + q(\mathbf{r}, \hat{s}, t)
\]

\[
L(\mathbf{r}, \hat{s}, t) = h \nu \nu n(\mathbf{r}, \hat{s}, t) \quad [W \ m^{-2} \ sr^{-1}]
\]

\[
q(\mathbf{r}, \hat{s}, t) = h \nu \varepsilon(\mathbf{r}, \hat{s}, t) \quad [W \ m^{-3} \ sr^{-1}]
\]
Solutions of the RTE

Expansion methods
- $P_N$ approximation:
  - $P_0 = \text{Diffusion (1989)}$
  - $P_1 = \text{Diffusing Wave}$
  - $P_3 = \ldots$

Stochastic methods
- Monte Carlo (1987)

Discretisation methods
- Discrete ordinates
- 2-flux or Kubelka-Munk
- Adding-double method
- Finite Element Method (1993)

Hybrid methods
- Paasschens (1997)

Note: The year represents the first use of the method in the field of Biomedical Optics.
PN Approximation

- Expansion of the RTE terms into *spherical harmonics* to separate the position and directional variables

\[
L(\mathbf{r}, \hat{s}, t) = \sum_{l=0}^{+l} \sum_{m=-l}^{+l} \sqrt{\frac{2l + 1}{4\pi}} \phi_{l,m}(\mathbf{r}, t) Y_{l,m}(\hat{s})
\]

- \(P_N\) approximation truncates the expansion to the \(N\)-th term obtaining a set of \(N+1\) independent equations

- \(P_1\) approximation is typically used in Photon Migration studies
\[ L(r, \hat{s}, t) \approx \frac{1}{4\pi} \Phi(r, t) + \frac{3}{4\pi} \mathbf{J}(r, t) \cdot \hat{s} \]

\[ \Phi(r, t) = \int L(r, \hat{s}, t) d\Omega \quad \text{Fluence} \]

\[ q(r, \hat{s}, t) \approx \frac{1}{4\pi} S_0(r, t) \]

\[ \mathbf{J}(r, t) = \int \hat{s} L(r, \hat{s}, t) d\Omega \quad \text{Flux} \]

\[ p(\hat{s}' \cdot \hat{s}) \approx \frac{1}{4\pi} + \frac{3}{4\pi} g\mu \]

Inserting in the RTE and integrating over \( \Omega \) we get

\[ \frac{1}{v} \frac{\partial \Phi(r, t)}{\partial t} = -\nabla \cdot \mathbf{J}(r, t) - v \mu_a \Phi(r, t) + S_0(r, t) \quad (1) \]

Inserting in the RTE, multiplying by \( \hat{s} \) and integrating over \( \Omega \) we get

\[ \frac{1}{v} \frac{\partial \mathbf{J}(r, t)}{\partial t} = -\frac{1}{3} \nabla \Phi(r, t) - (\mu_a + \mu_s') \mathbf{J}(r, t) \quad (2) \]

\[ \mu_s' = (1 - g) \mu_s \quad \text{Reduced scattering coefficient} \ [\text{m}^{-1}] \]
Diffusion Equation

\[
\frac{1}{v} \frac{\partial J(r, t)}{\partial t} = -\frac{1}{3} \nabla \Phi(r, t) - \left( \mu_a + \mu_s' \right) J(r, t)
\]

Under the assumptions

\[
\frac{1}{J(r, t)} \frac{\partial J(r, t)}{\partial t} \ll v \mu'_s
\]

The relative variation of the flux is smaller than the scattering rate!

\[v = 0.03 \, \text{cm/ps}, \, \mu'_s = 10 \, \text{cm}^{-1}, \, v \mu'_s = 0.3 \, \text{ps}^{-1}\]

We obtain the Fick’s Law

\[J(r, t) = -D \nabla \Phi(r, t)\]

\[D = 1 / \left( 3 \mu'_s \right)\]

Diffusion coefficient [m]

Substituting into (1) we obtain the Diffusion Equation

\[-D \nabla^2 \Phi(r, t) + \mu_a \Phi(r, t) + \frac{1}{v} \frac{\partial \Phi(r, t)}{\partial t} = S_0(r, t)\]
Steady state (or continuous wave, CW) Diffusion Equation

Neglect time dependence

$$- D \nabla^2 \Phi(r) + \mu_a \Phi(r) = S_0(r)$$

Point source solution for infinite medium

$$S_0(r) = \delta(r_0) \quad \Phi(r) = \frac{1}{4\pi D |r - r_0|} \exp \left( - \sqrt{\frac{\mu_a}{D}} |r - r_0| \right)$$
Collimated source

Cylindrical coordinate system with radial symmetry

\[ \Phi(r) = \Phi(r, \varphi, z) = \Phi(r, z) \]

\[ \Phi(r) = \frac{1}{4\pi D} \exp \left( -\sqrt{\frac{\mu_a}{D}} \sqrt{r^2 + (z - z_0)^2} \right) - \frac{1}{4\pi D} \exp \left( -\sqrt{\frac{\mu_a}{D}} \sqrt{r^2 + (z + z_0)^2} \right) \]

Point source solution

\[ S_0(r) = \delta(z_0) - \delta(-z_0) \]

\[ z_0 = (\mu_s')^{-1} = l_s \]
Fluence

\[ \Phi(r) = \frac{1}{4\pi D} \exp \left( - \sqrt[2]{\frac{\mu_a}{D}} \sqrt{r^2 + (z - z_0)^2} \right) - \frac{1}{4\pi D} \exp \left( - \sqrt[2]{\frac{\mu_a}{D}} \sqrt{r^2 + (z + z_0)^2} \right) \]

Reflectance

\[ R(r) = \left| -D\nabla \Phi(r) \right|_{z=0} = \frac{1}{2\pi} z_0 \left( \sqrt[2]{\frac{\mu_a}{D}} + \frac{1}{\sqrt{r^2 + z_0^2}} \right) \exp \left( -\sqrt[2]{\frac{\mu_a}{D}} \sqrt{r^2 + z_0^2} \right) \]

\[ r^2 + z_0^2 \approx r^2 \]

\[ R(r) \approx \frac{1}{2\pi} z_0 \left( \sqrt[2]{\frac{\mu_a}{D}} + \frac{1}{r} \right) \exp \left( -\sqrt[2]{\frac{\mu_a}{D}} \frac{r}{r^2} \right) \]

Number of photons per unit area exiting from the tissue at a distance \( r \) from the source
Things to know about CW NIRS

1) Coupling of absorption and scattering

In a homogeneous medium it is not possible to estimate both $\mu_a$ and $\mu_s'$ with a single distance CW measurement.
Things to know about CW NIRS

2) Penetration depth depends on $\mu_s', \rho$, and $\mu_a$

F. Martelli et al. Scientific Reports 6:27057 (2016)
Things to know about CW NIRS

3) no difference between superficial and deep layers

Reflectance

Contrast = \( \frac{R_{\text{PERT}} - R_{\text{HOM}}}{R_{\text{HOM}}} \)

Single distance
Things to know about CW NIRS
4) multi distance CW might be a solution

SRS = space resolved spectroscopy

Short is short enough, long is long enough
Scalp signal clearly separated from cortex

r

<table>
<thead>
<tr>
<th>Distance</th>
<th>Description</th>
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<tbody>
<tr>
<td>5 mm</td>
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</tr>
<tr>
<td>3.5 mm</td>
<td></td>
</tr>
<tr>
<td>10 mm</td>
<td></td>
</tr>
<tr>
<td>35 mm</td>
<td></td>
</tr>
<tr>
<td>15 mm</td>
<td></td>
</tr>
</tbody>
</table>
Things to know about CW NIRS
4bis) «strange» multi distance CW approaches

Hamamatsu SRS (NIRO 300) and others: multi distance with LONG distances ONLY

Still unable to uncouple superficial from deep signal!

\[
R(r) \approx \frac{1}{2\pi} z_0 \left( \sqrt{\frac{\mu_a}{D}} \right) \exp \left( \frac{-\sqrt{\frac{\mu_a}{D}} r}{r^2} \right)
\]

\[
A(r) = -\ln R(r)\]

\[
\frac{\partial A(r)}{\partial r} \approx \frac{2}{r} + \sqrt{3} \mu_s' \mu_a
\]

Approximation on spectral dependence of scattering coefficient

\[
\mu_s'(\lambda) \approx k(1-h\lambda)
\]

\[
k\mu_a(\lambda_1) \approx k \left( \epsilon_{HHb}^{\lambda_1} HHb + \epsilon_{O2Hb}^{\lambda_1} O2Hb \right)
\]

\[
k\mu_a(\lambda_2) \approx k \left( \epsilon_{HHb}^{\lambda_2} HHb + \epsilon_{O2Hb}^{\lambda_2} O2Hb \right)
\]

Measure of Tissue Oxygenation Index (TOI)

\[
TOI = \frac{kO_2Hb}{kHHb + kO_2Hb} = \frac{O_2Hb}{HHb + O_2Hb} = SO_2
\]
Things to know about CW NIRS

4ter) «strange» multi distance CW approaches

KUL SRS: multi distance with SHORT distances ONLY

Signal only from superficial layers!!
Time Domain Diffusion Equation

\[-D \nabla^2 \Phi(r, t) + \mu_a \Phi(r, t) + \frac{1}{v} \frac{\partial \Phi(r, t)}{\partial t} = S_0(r, t)\]

Point source solution for infinite medium

\[S_0(r, t) = \delta(r_0, 0) \quad \Phi(r, t) = v(4\pi D v t)^{-3/2} \exp\left(-\frac{|r - r_0|^2}{4Dvt} - \mu_a vt\right)\]
Collimated source

Point source solution

$S_0(r,t) = \delta(z_0,0) - \delta(-z_0,0)$

$z_0 = (\mu_s')^{-1} = l_s$

Cylindrical coordinate system with radial symmetry

$\Phi(r,t) = \Phi(r,\varphi,z,t) = \Phi(r,z,t)$

$$\Phi(r,t) = v(4\pi Dvt)^{-3/2} \exp\left(-\frac{r^2 + (z-z_0)^2}{4Dvt} - \mu_a vt\right) - v(4\pi Dvt)^{-3/2} \exp\left(-\frac{r^2 + (z+z_0)^2}{4Dvt} - \mu_a vt\right)$$
\[ \Phi(r, t) = v(4\pi Dv_t)^{-3/2} \exp\left( -\frac{r^2 + (z - z_0)^2}{4 Dv_t} - \mu_a v t \right) - v(4\pi Dv_t)^{-3/2} \exp\left( -\frac{r^2 + (z + z_0)^2}{4 Dv_t} - \mu_a v t \right) \]

\[ R(r, t) = |J(r, t)|_{(r, z) = (\rho, 0)} = -D \nabla \Phi(r, t)|_{(r, z) = (\rho, 0)} \]

\[ R(\rho, t) = z_0 (4\pi Dv_t)^{-3/2} t^{-5/2} \exp\left( -\frac{\rho^2 + z_0^2}{4 Dv_t} - \mu_a v t \right) \]
Photon Diffusion
TD solutions for other geometries

- Infinite
- Semi-infinite
- 2 layer
- Slab
- Parallelepiped
- N layers
- Sphere
- Cylinder
- inhomogeneity

Time domain NIRS

(a) Laser pulse with 10-100 ps duration and Remitted pulse.

(b) Reflectance (mm^2 ps^-1) vs. Time (ps) for different concentrations.

(c) Reflectance (mm^2 ps^-1) vs. Time (ps) for different concentrations.

(d) Reflectance (mm^2 ps^-1) vs. Time (ps) for different concentrations.
Things to know about TD NIRS

1) Uncoupling of absorption and scattering

In a homogeneous medium it is possible to estimate both $\mu_a$ and $\mu_s'$ with a single distance TD measurement.
Things to know about TD NIRS

2) Penetration depth depends on $\mu_s'$ and $t$ (NOT on $\mu_a$ or $\rho$)

Null distance approach feasible in the TD!

F. Martelli et al. Scientific Reports 6:27057 (2016)

Things to know about TD NIRS
3) difference between superficial and deep layers

Depth resolution is related to photon time-of-flight

\[ I \text{ vs. time (s)} \]

\[ \rho \]

\[ \mu_a \text{ and } \rho \]

\[ \mu_s' \text{ and } t \]

- mean penetration depth does NOT depend on \( \mu_a \) and \( \rho \)
- mean penetration depth does depend on \( \mu_s' \) and \( t \)

Things to know about TD NIRS

4) multi distance TD ensures better accuracy

Heterogeneous sample

\[ \rho = 2, 3, 4, 5, 6 \text{ cm} \]

Obviously the multi distance approach introduces further requirements on the setup (e.g. Multi detector, optical switch, ...)
### Evolution of TD NIRS systems

<table>
<thead>
<tr>
<th>Generation</th>
<th>Light sources</th>
<th>Photo-detectors</th>
<th>Acquisition system</th>
</tr>
</thead>
</table>
| 1\textsuperscript{st} (1990-2000) | gas lasers
dye laser
solid state laser | microchannel plate photomultiplier (PMT) | electronic chain for TCSPC with NIM module |
|              | > 500,000 €                               |                                          |                                             |
| 2\textsuperscript{nd} (2000-2010) | semiconductor laser heads with external RF driver | compact metal channel dynode PMT | TCSPC electronic board |
|              | > 100,000 €                               |                                          |                                             |
| 3\textsuperscript{rd} (2010-2015)  | supercontinuum fiber laser                | hybrid PMT                               | TDC module with USB controller              |
|              | > 50,000 €                                |                                          |                                             |
TD NIRS systems
Time correlated single photon counting (TCSPC)

Becker-Hickl GmbH
http://www.becker-hickl.com/literature.htm#handb

++ temporal resolution
+++ sensitivity
- cost
1st generation TD NIRS
Broadband laboratory set-up

Fully automated system

spectral range: 540 - 1100 nm

2nd generation TD NIRS
Time resolved optical mammograph

- Laser driver: “Sepia” (PicoQuant)
- Repetition rate: 20 MHz
- Pulse duration: 180-400 ps
- Average incident power: 1-1.5 mW

- Continuous movement: stepping motors & Counter/Timer PC board
- Maximum scan area: 180 mm x 240 mm
- Step interval: 1 mm
- Measurement time: 25 ms per point

- Photomultipliers (Hamamatsu, KK):
  VIS: R5900U-01-L16, 150 ps TTS, \( \lambda < 850 \text{ nm} \)
  NIR: H7422P-60, 450 ps TTS, \( \lambda < 1100 \text{ nm} \)

- TCSPC board (SPC-134, Becker & Hickl):
  4 independent channels
  16 MHz max count rate
2nd generation TD NIRS
Time resolved optical mammograph

Patient #47, oblique view
age: 36 y
thickness = 5.7 cm
Lesion size = 3.0 cm
Lesion type = tumor

Clinical study (225 lesion)

<table>
<thead>
<tr>
<th>Type</th>
<th>View</th>
<th>Cases</th>
<th>Detection rate</th>
<th>Failures</th>
<th>Corrected detection rate</th>
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<tbody>
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<td>Cancer</td>
<td>2</td>
<td>41</td>
<td>73%</td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>9</td>
<td>89%</td>
<td>4</td>
<td>96%</td>
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<tr>
<td></td>
<td>0</td>
<td>6</td>
<td>11%</td>
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<tr>
<td>Cyst</td>
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<td>8</td>
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<td>22%</td>
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<tr>
<td>Fibroadenoma</td>
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<tr>
<td></td>
<td>1</td>
<td>5</td>
<td>43%</td>
<td>5</td>
<td>50%</td>
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<tr>
<td></td>
<td>0</td>
<td>29</td>
<td>57%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2nd generation TD NIRS
Multichannel dual wavelength system

2 wavelengths
16 channels
50 ms acquisition time

“Medical device” approved for clinical investigations

2nd generation TD NIRS
Multichannel dual wavelength system

In collaboration with: I.Gilioli, S.Franceschetti, F. Panzica, E.Visani @ IRCCS Besta Milan, Italy

A, D: O$_2$Hb and HHb time-courses in the most reactive channel and the corresponding GLM activation maps.

B, E: BOLD signal extracted from the active cluster and fMRI maps.
2nd generation TD NIRS
The BabyLux device for blood oxygenation and blood flow

- The BabyLux project aims to provide a precise, non-invasive and robust integrated system to continuously monitor cerebral oxygen metabolism and blood flow in extremely preterm newborns.

- It will enable neonatologists to prevent the neurological damage due to lack of oxygenation in the brain that not infrequently is accompanied at premature birth.

- Started on 1st January 2014, 40 months 9 partners

Microvascular, local, cerebral blood oxygen saturation blood flow

GA no. 620996 CIP ICT-PSP

http://www.babylux-project.eu
The majority of foods and vegetables produce are diffusive media, like human tissues.
1st generation TD NIRS
Broadband laboratory set-up

Fully automated system
spectral range: 540 - 1100 nm

2nd generation TD NIRS
Dual-wavelength transportable system

Cubeddu et al., Appl Spectroscopy 55:1368-1374 (2001)
3rd generation TD NIRS
Time resolved multi wavelength spectrometer

**Laser source:**
Supercontinuum fiber laser
- spectral range: 450-1600 nm
- power: 6 W
- frequency: 40 MHz

**Wavelength selection:**
Filter wheel
- spectral range: 540-900 nm

**Detector:**
Hybrid PMT
- no afterpulse
- time response: 250 ps

**Time resolution:**
Time-Correlated Single-Photon Counting:
- high dynamic range
- suitable for faint signal
- time resolution: up to 1 ps
Non destructive optical characterisation of internal optical properties and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, tomatoes, ...
- Changes in optical properties during growth in Elstar apples and Tophit plums
- Texture in Jonagored apples, Braeburn apples and Pink Lady apples during storage

Non destructive detection of internal disorders and defects

- Browning in Granny Smith apples, Braeburn apples and Conference pears
- Watercore in Fuji apples
- Mealiness in Braeburn apples and Jonagored apples
- Chilling injuries in Jubileum plums and Morsiani nectarines

Non destructive assessment of fruit maturity at harvest and correlation with quality parameters

- Basic studies in apples, kiwifruits, nectarines, peaches, mangoes, ...
- Sensory attributes, aroma composition, ethylene production Ambra nectarines
- Softening prediction (based on biological age) in Spring Bright nectarines and in Tommy Atkins mangoes
The End
• Discussion 11:30-12:30
  • What does affect TD NIRS?
  • Questions & Answers
What does affect TD NIRS?

- Instrument response function
- Signal to noise ratio
- Temporal stability
- Range of optical and geometrical parameters
- Availability of systems
Linear causal systems: the output $y(t)$ is the convolution of the input $x(t)$ with the impulse response $h(t)$

\[ y(t) = x(t) * h(t) \]

\[ TRS(t) = \delta(t) * \left[ h_1(t) * h_2(t) * R(t) * h_3(t) * h_4(t) * h_5(t) \right] = \delta(t) * \left[ h_1(t) * h_2(t) * h_3(t) * h_4(t) * h_5(t) \right] * R(t) \]

\[ TRS(t) = IRF(t) * R(t) \]

\[ TRS(t) = R(t) * IRF(t) \]
Instrument response function 2/4

\[ TRS(t) = R(t) \times IRF(t) \]

Examples of IRF

- Pulsed laser diode
  - Hybrid PMT
  - 1mm $\varnothing$ GIGA POF, 2m length

- Pulsed laser diode
  - Metal Channel Dynode PMT
  - 3mm $\varnothing$ step index fiber bundle, 1.5m length

- Supercontinuum fiber laser
  - SiPM
  - 1mm $\varnothing$ GIGA POF, 2m length
Effect of IRF

- **Limiting the maximum $\mu_a$ and the minimum $\mu_s'$ that can be fitted**
  - Increase in absorption or decrease in scattering results in narrowing of the TRS curve
  - If IRF is broad we cannot resolve those changes
Effect of IRF

- **Reducing depth discrimination**
  - IRF introduces uncertainty in the time of arrival of photons (i.e. photons detected at time $\tau$ can be originated at time $\tau \pm \Delta T$, with $\Delta T$ depending on the IRF width)
  - Coupling superficial and deep contributions

*Early photons and Late photons well separated*  
*Early photons and Late photons might overlap!*
Signal to noise ratio

Effect of SNR

- Limiting the dynamics of the TRS curve
  - Effect on fitting results and contrast

- Limiting the penetration depth
  - Effect on contrast
Temporal stability

- Time drift (in the range of 10-100 ps!) introduces errors in the fitted $\mu_a$ and $\mu_s'$
  - $\downarrow \tau_0 \rightarrow \uparrow \mu_s' \rightarrow \uparrow \mu_a$
  - $\uparrow \tau_0 \rightarrow \downarrow \mu_s' \rightarrow \downarrow \mu_a$

How to reduce the effect of temporal instability?
Acquire several IRF curves and/or measure calibrated phantoms during the experiment.
Range of optical and geometrical parameters

TD NIRS measure the broadening of a light pulse while traveling in a medium

Broadening is affected by
- distance between source and detector > 1 cm
- value of the reduced scattering coefficient > 5 cm\(^{-1}\)
- value of the absorption coefficient < 0.5 cm\(^{-1}\)
- temporal width of the IRF << 500 ps

If possible the TD NIRS system should be tailored to the application
Optical properties can change with wavelength!

Range of optical and geometrical parameters

Cubeddu et al., Applied Optics 40:538-543 (2001)
Availability of TD NIRS system

Where to buy a TD NIRS system?

Nowhere !!!

How much for a TD NIRS system?

A lot !!!
Evolution of TD NIRS systems

Next generation TD NIRS
Compact two wavelengths system

size 200 x 160 x 50 mm$^3$

total power consumption lower than 10 W (ready for battery operation)

TD NIRS expectations

Access to TD NIRS systems at PHOOD lab @PoliMi

LaserLab-EUROPE project

Center for Ultrafast Science and Biomedical Optics
Politecnico di Milano - Dipartimento di Fisica
Milan, Italy

European Large Scale Facility since 2002

http://www.laserlab-europe.net/
alessandro.torricelli@polimi.it

Access to infrastructure (limited to European researchers)
Full reimbursement of travel and accommodation expenses
Summary

Single channel CW NIRS
- Coupling of absorption and scattering parameters
- Coupling of superficial and deep signals
- Need of photon pathlength from literature for quantitative analysis
- Strongly influenced by contact, movement artefact, signal changes
  → NOT USEFUL

Multi-channel CW NIRS
- Discrimination of absorption and scattering parameters
- Uncoupling of superficial and deep signals (if short and long channels are used!)
- Somewhat influenced by contact, movement artefact, signal changes
  → POTENTIALLY USEFUL

Single channel TD NIRS
- No need to use data from literature (estimate of $\mu'_s$ is equivalent to pathlength)
- Absolute value for absorption coefficient: $\mu_a$, not just $\Delta\mu_a$
- Discrimination of superficial and deep signals by means of early and late photons
- Less influenced by contact, movement artefact, signal changes
  → NOT YET COMMERCIALLY AVAILABLE (just wait ...)
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