The Phasor approach: Application to FRET analysis and Tissue autofluorescence

Laboratory for Fluorescence Dynamics
University of California, Irvine
Outline

- Background: Lifetime
- Intro to Fluorescence Lifetime Imaging Microscopy
- Motivation for FLIM
- The Phasor approach
- Rac Activation using FLIM
- Conclusions
Lifetime: Background

$S_1 \rightarrow S_0$

Emission: Fluorescence light

$\text{intensity} = I(t) = A \exp(-t/\tau)$
Time Domain and Frequency Domain FLIM

A sample is flashed many times by a short duration laser source

The histogram of the time intervals between the excitation flash, and 1st emitted photon is measured

A sample is excited by a modulated light source

The fluorescence emission has the same frequency but is modulated and phase-shifted from the excitation source
Why do FLIM?

FLIM is used for:

- FRET
- Intracellular mapping of ion concentration and pH imaging
- Biochemical reactions (oxidation/reduction) processes
  - NAD and NADH
- Long lifetime imaging (phosphorescence).
  - For example $O_2$ concentration in the cell or in tissues
An excited molecule can transfer energy to another molecule even if the other molecule is far away.

**Description of the process:** Consider a molecule (donor D) which absorbs light. After absorption, because of the fast internal conversion, the molecule will be at the bottom (lower vibrational state) of the excited state. If the donor emission energy coincides with the absorption energy of a different molecule (acceptor A), a resonance process can take place. The energy transfer occurs at a rate $k_T$.

\[
D^* + A \xrightleftharpoons[k_{-T}]{k_T} D + A^*
\]

The acceptor rapidly decays to the bottom of the excited state. From this level the acceptor molecule can decay by fluorescence emission or by non-radiative processes.
Because of rapid internal conversion the process $A^*$ to $D^*$ is very unlikely to occur unless the donor is of the same kind of the acceptor (Homotransfer). FRET strongly depends on the distance between the two groups. The theory was developed by Förster in 1949 who calculated the rate of transfer to be

$$k_T = \frac{1}{\tau_D} \left( \frac{R_0}{R} \right)^6$$

$\tau_D$ is the lifetime of the donor in the absence of the acceptor. 
$R$ is the distance between the two groups 
$R_0$ is called the Föster characteristic distance 

$$R_0 = 9.7 \times 10^3 \left( J k^2 n^{-4} \Phi_D \right)^{1/6}$$

$n$ is the refractive index of the medium 
$\Phi_D$ is the quantum yield of the donor 
$k^2$ is a complex geometrical factor which depends on the relative orientation of donor and acceptor.

Energy transfer studies give information

- Distance between groups
- Orientation of two groups

Notice that $D$ and $A$ can be the same kind of molecule provide emission and absorption overlap.
Distance dependence of the energy transfer efficiency ($E$)

\[ R = \left( \frac{1}{E} - 1 \right)^{1/6} R_0 \]

Where $R$ is the distance separating the centers of the donor and acceptor fluorophores, $R_0$ is the Förster distance.

The efficiency of transfer varies with the inverse sixth power of the distance.

$R_0$ in this example was set to 40 Å.
When the $E$ is 50%, $R=R_0$.

Distances can generally be measured between ~0.5 $R_0$ and ~1.5 $R_0$. 

Energy transfer efficiency ($E$)

$$E = \frac{k_T}{k_T + \sum_{i \neq T} k_i}$$

Where $k_T$ is the rate of transfer and $k_i$ are all other deactivation processes.

Experimentally, $E$ can be calculated from the fluorescence lifetimes or intensities of the donor determined in absence and presence of the acceptor.

$$E = 1 - \frac{\tau_{da}}{\tau_d} \quad \text{or} \quad E = 1 - \frac{F_{da}}{F_d}$$
If the acceptor is fluorescent, then it is possible to measure the fluorescence of the acceptor in the absence and presence of the donor.

The sample is excited at $\lambda_1$. The fluorescence at $\lambda_4$ of the acceptor can be observed in the absence of the donor to check if there is any contribution of direct acceptor excitation

$$F_{A_{\lambda_1,\lambda_4}} \simeq \epsilon_{A_{\lambda_1}} C_A \Phi_{A_{\lambda_4}}$$

In presence of the donor the total fluorescence intensity at $\lambda_4$ is

$$F_{A+D_{\lambda_1,\lambda_4}} \simeq \epsilon_{A_{\lambda_1}} C_A \Phi_{A_{\lambda_4}} + \epsilon_{D_{\lambda_1}} C_D E \Phi_{A_{\lambda_4}}$$

measuring $F_A$ and $F_{A+D}$, the energy transfer efficiency $E$ can be obtained

An independent measurement of $E$ can be obtained by comparing the decay time of the donor in the presence and absence of the acceptor.

$$\frac{\tau_{D+A}}{\tau_D} = 1 - E$$
Summary of the FRET detection

• Quenching of the donor (intensity and lifetime)
• Increase of the acceptor fluorescence
• Decrease of the steady-state polarization
• Change of the lifetime of the acceptor (?)
## Conceptual approaches to Spectroscopy

1) **Identification of Molecular Species**

   - Using the Spectra
     - Excitation λ emission
     - Spectral demixing
     - Ratio of acceptor/donor spectral intensity

   - Using the fluorescence decays
     - Lifetime Components
     - Multiexponential analysis
     - Quenching of donor lifetime

2) **Demixing of multiple species in a pixel**

3) **Identification of processes: FRET**
The challenges of FLIM

- At every pixel there are contributions of several fluorescent species, each one could be multi-exponential.

- To make things worse, we can only collect light for a limited amount of time (100-200 microseconds per pixel) which result in about 500-1000 photons per pixel.

- This is barely enough to distinguish a double exponential from a single exponential decay.

- Resolving the decay at each pixel in multiple components involves fitting to a function, and is traditionally a complex computational task “for experts only”.

A major problem is **data analysis and interpretation**
Major issues with FLIM

- Rather difficult technique
- Fitting is slow
- Results depend on initial conditions
- Interpretation requires expertise

Can we avoid all these problems?

- No expertise necessary
- Instantaneous results
- Independent of initial choices
- Quantitative results
- Intuitive simple interface
A new approach: no more fits!

We propose a change in paradigm: Use a different representation of the decay where each molecular species has its own unique representation and where each process (FRET, ion concentration changes) is easily identified.

We need to go to a new “space”
The phasor space and the universal circle
(From Star-Trek)

• Where does this concept come from??
• We need some math.
How to calculate the components $g$ and $s$ of a phasor from the time decay?

A sample is flashed many times by a short duration laser source.

The interval between the excitation flashes, and 1st excited photon is measured.
How to calculate the components $g$ and $s$ of a phasor from the time decay?

$$g_i(\omega) = \frac{\int_0^\infty I(t) \cos(\omega t) dt}{\int_0^\infty I(t) dt}$$

$$s_i(\omega) = \frac{\int_0^\infty I(t) \sin(\omega t) dt}{\int_0^\infty I(t) dt}$$

Time-domain components of a phasor. $I(t)$ is measured.

Note that $I(t)$ can contain raw multiexponential data!!
The algebra of phasors

Simple rules to the Phasor plot:

1) All single exponential lifetimes lie on the “universal circle”
2) Multi-exponential lifetimes are a linear combination of their components
3) The ratio of the linear combination determines the fraction of the components

\[
g = M \cos(\phi) \\
1 = M \sin(\phi) \\
s = M \sin(\phi) \\
m = M \cos(\phi)
\]
Fitting of exponentials

From decay data

Phasor

Fitting of exponentials

Multiexponential analysis

Lifetime distribution

av = 1.309 std = 0.401 n=21263
Separating Single exponential lifetimes using the phasor approach

Fluorescein

Mixture

Rhodamine B1
Pax-eGFP CHO-k1 in collagen

referenced with Fluorescein @ 905nm

P= 47.2 M= 0.343 TP= 2.149 ns TM= 2.751 ns,

P= 38.2 M= 0.344 TP= 1.563 ns TM= 2.748 ns,

P= 2.0 M= 0.706 TP= 0.069 ns TM= 1.283 ns,

Lifetime of EGFP

Combinations of Lifetimes

Lifetime of Collagen
How to identify components?

Phasors for common fluorophores. EGFP (green), autofluorescence (blue) and mRFP1 (red) (at 880 nm -2photon excitation). In any given pixel, mixture of EGFP and autofluorescence must be on the yellow line, mixtures of EGFP and mRFP1 must be on the red line. Mixtures of three of them must be inside the triangle with the corner in the 3 phasors.
How to distinguish two multi-exponential components from FRET?

Simple Rules for FRET:

1) If the experimental point lies on a straight line then it is **NOT** FRET

2) FRET efficiencies follow a “quenching trajectory”

3) Quantitative FRET efficiencies can be obtained from the position on the quenching trajectory
The fractional intensity calculator

1. Click on the phasor plot (or enter the coordinates of the phasor manually) and assign the phasor to species 1.

2. Click to assign the phasor to the phasor 2.

3. The fractional (intensity weighted) contribution of the two phasors is calculated according to the sum rule of the phasor.

Moving this cursor, the circle will move in the phasor plot and automatically display the relative fraction of the two species (of the two phasors), independently on the number of exponential components necessary to describe the decay.
Delay of the excitation of the acceptor due to FRET moves the acceptor phasor to the left (yellow arrow). If the delay is sufficiently long, the phasor could fall outside the semicircle. The donor phasor moves to the right (red arrow) due to quenching (shorter lifetime).
The principle of the calculator

Purpose: to generate trajectories in the phasor’s plot corresponding to different processes

At present there are two functions programmed

The calculator for FRET efficiencies from
\[
\text{FRET efficiency} = \frac{\tau_D - \tau_{\text{FRET}}}{\tau_D}
\]

The calculator for ion concentrations form the relative contribution of the free and bound phasor.
If we have a donor with a single exponential decay that is quenched by the presence of an acceptor. What should we expect?

- The lifetime of the donor is quenched.
- The FRET efficiency can be calculated by the ratio of the two lifetimes.

The trajectory of quenching is an arc rather than a line to the $(1,0)$ point. Why is this the case?
• Can we quench up to zero lifetime?

• Even if we quench all the DONOR, we still are left with the autofluorescence.

• The final point is not at zero but at the autofluorescent phasor!!!
As the lifetime of the Donor is quenched, the phasor of the quenched Donor is added to the phasor of the autofluorescence.

If there is a fraction of Donor that cannot be quenched, the final point will be along the line joining the Donor with the autofluorescence phasor.
The FRET calculator

Information needed to calculate FRET:

- Donor phasor
- Autofluorescence phasor
- Amount of Donor that can’t be quenched
- fractional contribution of autofluorescence and donor lifetimes
Example of FLIM analysis using phasors

Several regions the image can be identified corresponding to a) background (2 exponentials)  b) cell 1 bright (2 exponentials)  c) cell 2 dim, d) cell junctions dim.

Image of cell expressing uPAR-EGFP and uPAR-MRFP receptor. Upon addition of a ligand, the receptor aggregates. FRET should occur at the cell junctions
The pitfall of “conventional” FLIM analysis

Image obtained using B&H 830 in our 2-photon microscope

Shorter lifetime region could be interpreted to be due to FRET

Donor+acceptor+ligand. A) intensity image after background subtraction, B) $\tau_p$ image
Identifying FRET using the phasor plot

Selecting regions of the phasor diagram. Selecting the region in A’ (donor + acceptor) the part in white lights up (A). Selecting the region in B’ (autofluorescence) the part in white in lights up (B). The color scale in B’ has been changed to better show the region of the autofluorescence. Selecting the region in C’ (along the donor quenching line as shown in D) the part in white in at the cell junction lights up in C.
Phasor Fingerprint of pure chemical species: 

- GFP in DMSO
- Porphyrin IX
- Retinol in DMSO
- Collagen
- Retinoic acid in DMSO
- FAD
- NADH
- Bound NADH
Label free FLIM in Living tissues

Intrinsic Fluorophores

✓ Extracellular

✓ Cellular

✓ NADH and FAD: metabolic coenzymes involved in oxidative phosphorylation and glycolysis.

✓ Complex distribution of autofluorescence

✓ Redox ratio (NADH/NAD+ ~ free/bound NADH) reports on metabolic changes associated with cell carcinogenesis and differentiation
C. Elegans germ line: a model for stem cell biology

Mitotic region: stem cell niche

- The distal pool: undifferentiated cells maintained in a “stem cell-like state”
- Proximal pool contains cells that are closer to differentiating

Transition zone: cells that have differentiated and entered meiotic prophase (crescent-shaped DNA)

Meiotic pachytene region: cells that have further progressed through meiosis.

Crittenden et al. Mol Biol Cell, 2006; Cinquin et al. PNAS 2010
Image Segmentation:
from pixel phasor plot to cell phasor plot

- Phasor average value of cells
- Better resolution
- Metabolic state of cells
- Cell phasors can be statistically attributed to the same or different average phasor value
C. Elegans germ line: a model for stem cell biology

**Mitotic region**: stem cells niche

✅ **Distal pool**: undifferentiated cells maintained in a "stem cell-like state"

✅ **Proximal pool**: contains cells that are closer to differentiating

**Transition zone**: cells that have differentiated and entered meiotic prophase (crescent-shaped DNA)

**Meiotic pachytene region**: progression through meiosis.

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**Experimental set-up**

*C. Elegans* histone-GFP fusion in germ line nuclei

\[ \lambda @ 880 \text{ nm and 740 nm} \]

Ti: sapphire laser, 80 MHz, Zeiss 710,

ISS A320 FastFLIM, GaAs PMT, 40 x 1.2 NA,

Power \( \sim 5 \text{ mW, Pixel dwell time=25 } \mu\text{s,} \)

SimFCS software

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Cinquin et al. PNAS 201
Stem cell metabolic “states” in C.elegans

In the large phasor cluster we distinguish statistically different subclusters

N=6

Stringari et al. PNAS 2011
Mapping relative concentration of metabolites

Redox balance and modulation of stem cell self-renewal and differentiation

✓ Growth factors that promote self-renewal cause stem cell to become more reduced.

✓ Signaling molecules that promote differentiation cause progenitor to become more oxidized.

In agreement with in vitro study:
Guo et al 2008 JBO

Stringari et al. PNAS 2011
Single cell phasor plot distinguishes metabolic states of cells

Evolution of the cell phasor fingerprints during differentiation

Gradient of metabolic states of cells.

Phasor fingerprint heterogeneity among mitotic cells could reveal symmetric and asymmetric divisions occurring at the level of the niche.
Conclusions

✓ Image segmentation: Cell phasors

✓ Better resolution

✓ Discrimination of different metabolic states of cells, small differences in redox ratio

✓ We identify and map relative concentration of intrinsic fluorophores

Current work and future directions

✓ Identify asymmetric and symmetric divisions and predict stem cell fate

✓ Metabolic evolution of differentiation pathways to different cell lineages.

✓ Metabolic pathways in colon cancer (Wnt signaling)
The Phasor approach: Application to Biosensor FRET analysis
COS7 cells, CFP only and with KH 449-521 before and after addition of EGF

Images are the average of 10 frames at 2 s each
Images taken on M3, Excitation at 840 nm, 40mW (outside)
Emission filter 460/60nm
P = 49.5 M = 0.279 TP = 2.332 ns TM = 3.202 ns,

P = 44.4 M = 0.329 TP = 1.951 ns TM = 2.842 ns,
KH Rac 449-521 biosensor before addition of EGF (first image) and with increasing time after addition of EGF (about every 30s).
KH Rac 449-521 biosensor with increasing time after addition of EGF (about every 30s).
Features of the new approach

Many of the obstacles in FLIM data analysis can be removed. The accuracy of lifetime determination is improved.

The speed of data analysis is reduced to almost instantaneous for an entire image or several images.

The analysis is “global” over the image and across images.

The interpretation of the FLIM experiment is straightforward. Minimal prior spectroscopy knowledge is needed.

The Phasor analysis method can be applied to all modes of data acquisition (frequency-domain and time-domain).

Ion concentrations can be calculated.
Conclusions

By representing “molecular species” rather than sum exponential decays the phasor approach reduces the problem of fitting exponential components to the exploration of regions of the phasor plot.

The analysis of the trajectories in the phasor plot provides a quantitative resolution of “processes” such as linear combination of two (or more species) and the calculation of FRET efficiencies to simple arithmetic.

You do not need to be an expert spectroscopist to resolve the molecular species present and to calculate ion concentration or FRET efficiencies.

It globally analyze many cells (different experiments) simultaneously.