Unification of laser speckle contrast imaging and laser Doppler perfusion imaging

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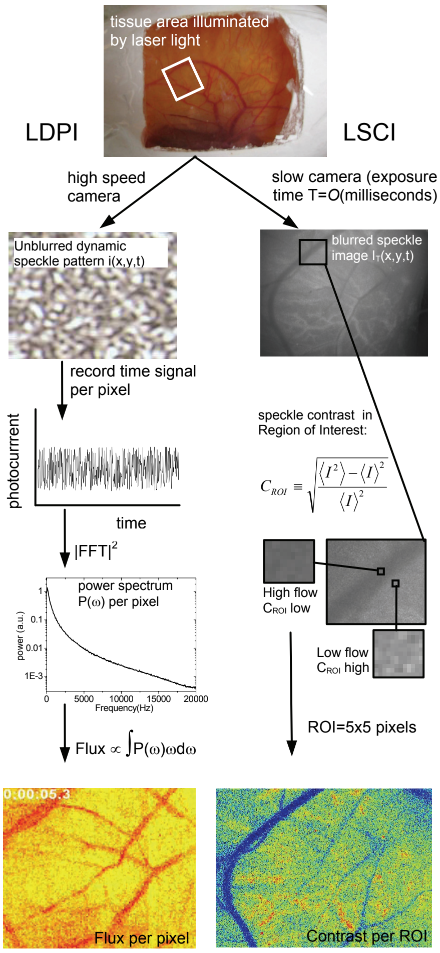
Aims

- Presentation of two principles for wide field perfusion imaging of tissue using coherent light:
  - Laser Doppler perfusion imaging (LDPI)
  - Laser speckle contrast imaging (LSCI)
- Development of a theory linking contrast in long exposure images of static-dynamic speckle patterns (the basis of LSCI) to the power spectrum P(ω) of temporal intensity fluctuations in static-dynamic speckle patterns (the basis of LDPI)
- Use of theory to predict spatial and temporal speckle contrast from the power spectrum P(ω)
- Some speculations on the information provided by LSCI

The two principles



$$C_{ROI} \equiv \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}$$

LDPI

- High speed camera needed (>20000 fps)
- FFT processing of signals through >512 raw images
- High temporal contrast feasible
- General theory available based on the Doppler effect and dynamic light scattering principles

LSCI

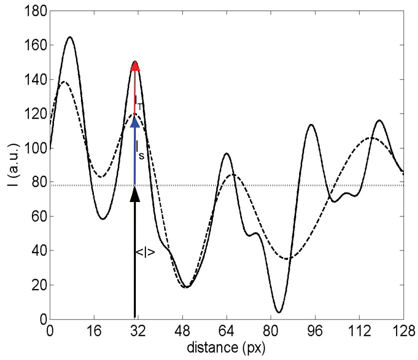
- Low camera frame rate suffices (25-30 fps)
- Simple processing of single raw images
- High temporal contrast feasible
- No general relation between contrast and

Theory

Integrated speckle pattern with blurred intensity I(x,y) is decomposed into:

$$I(x,y) = \langle I\rangle + I_S(x,y) + I_T(x,y,t)$$

⟨I⟩ average intensity in entire pattern
$I_S(x,y)$ local static deviation from ⟨I⟩
$I_T(x,y,t)$ local dynamic deviation from $\langle I\rangle + I_S(x,y)$



The contrast is: $C^2 = \frac{\langle I_s^2\rangle + \langle I_T^2\rangle}{\langle I\rangle^2}$ Only I_T depends on T

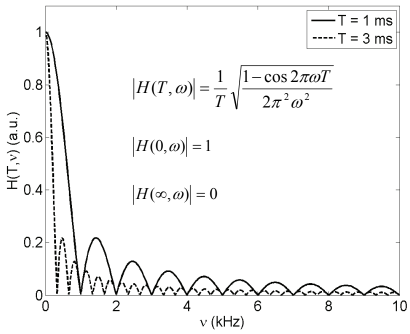
Therefore: $C^2(T) = C^2(0) + \int_0^T \frac{dC^2}{d\tilde{T}} d\tilde{T} = 1 + \frac{1}{\langle I^2\rangle}\int_0^T \frac{d\langle I_T^2\rangle}{d\tilde{T}} d\tilde{T}$

Ideal polarized speckle

$I_T(x,y,t)$ results from averaging static-dynamic speckle pattern i(x,y,t) over time window T

i(x,y,t) → Fourier → F(x,y,ω)
$I_T(x,y,t)$ → Fourier → H(T,ω)F(x,y,ω)

Parseval: $\langle I_T^2\rangle = \int_{-\infty}^{\infty} |H(T,\omega)|^2 |F(\omega)|^2 d\omega = \int_{-\infty}^{\infty} |H(T,\omega)|^2 P(\omega) d\omega$



$$|H(T,\omega)| = \frac{1}{T}\sqrt{\frac{1-\cos 2\pi\omega T}{2\pi^2\omega^2}}$$

$$|H(0,\omega)| = 1$$

$$|H(\infty,\omega)| = 0$$

Back to the contrast:

$$C^2(T) = 1 - \frac{1}{\langle I^2\rangle}\int_{-\infty}^{\infty} P(\omega)d\omega + \frac{1}{\langle I^2\rangle}\int_{-\infty}^{\infty} |H(T,\omega)|^2 P(\omega)d\omega$$

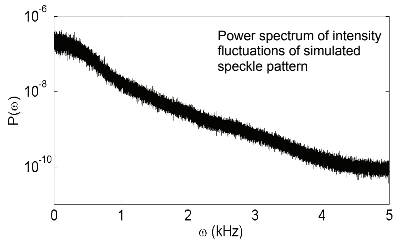
In laser Doppler terms: zero order moment $M_0 \propto$ moving blood cell concentration, for low concentrations

The bottom line:

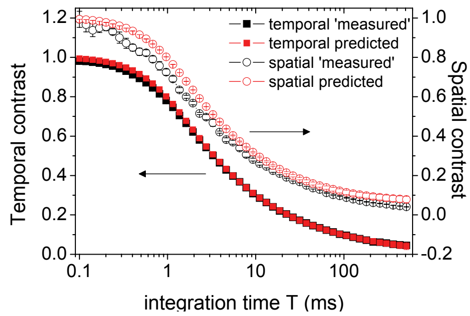
$$C^2(T) = 1 - M_0 + \frac{1}{\langle I^2\rangle}\int_{-\infty}^{\infty} |H(T,\omega)|^2 P(\omega)d\omega$$

Verification: method and results

- Completely dynamic speckle pattern i(x,y,t) simulated with the copula method (Duncan *et al*, JOSA A, 25(9), 2008)
- From i(x,y,t) the power spectrum P(ω) of the photocurrent fluctuations is calculated



- Integrated (blurred) speckle pattern $I_T(x,y,t)$ calculated by moving average procedure, mimicking long exposure time
- From $I_T(x,y,t)$, temporal contrast is calculated in 10 randomly selected independent pixels, for a range of integration times T
- From $I_T(x,y,t)$, spatial contrast is calculated in 10 randomly selected ROIs of 7x7 pixels, for a range of values of T

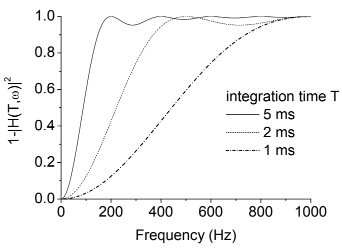


Verification: observations

- Temporal contrast: very good agreement between 'measurement' and prediction
- Spatial contrast: good agreement, in particular for longer integration times
- Slight overprediction by our theory of spatial contrast probably caused by nonideal matching of speckle size and size of Region of Interest.

Discussion, conclusions, speculations

- A theory is developed to predict speckle contrast from power spectra of intensity fluctuations in dynamic speckle patterns
- The theory is designed for mixed static-dynamic speckle patterns
- For blurred versions of simulated fully dynamic speckle patterns, our theory correctly predicts both the spatial and temporal contrast
- The validity for mixed static-dynamic patterns is still to be established
- It can be shown that $1 - C^2 \propto \int_{-\infty}^{\infty}\left(1 - |H(T,\omega)|^2\right)P(\omega)d\omega$



- Compared to linear spectral weighing in LDPI, a nonlinear weighing function $1-|H|^2$ holds if we take $1-C^2$ as flux parameter. For $1/C^2$ a similar conclusion can be drawn.

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