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Probing Complex Systems with Light:
From Photon Transport to Functional Imaging

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Politecnico di Milano
Physics Engineering

Scientific Motivation and Content Overview

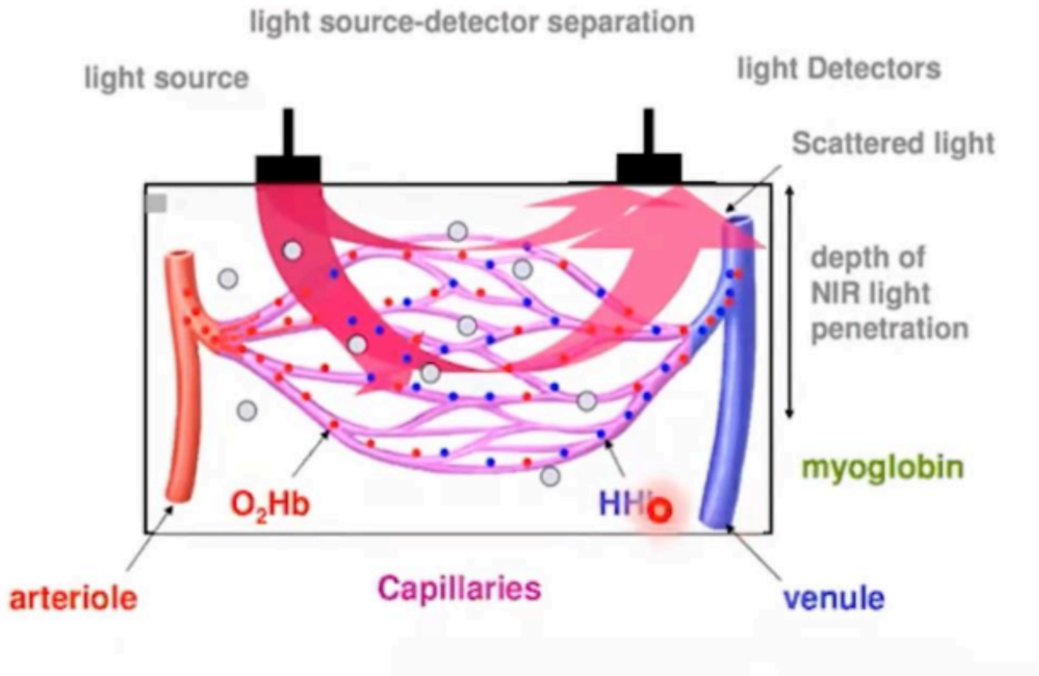
Aim of the project:

Non-invasive monitoring of tissue metabolism, quantifying oxygenation, perfusion, oxidative metabolism.

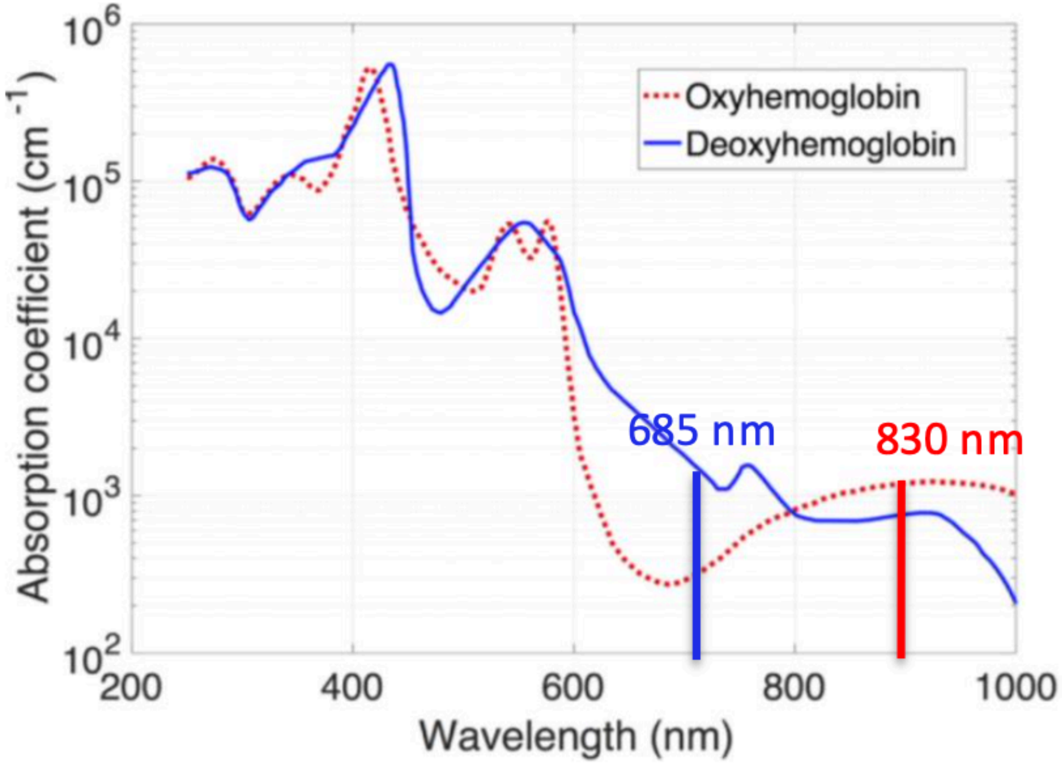
Content Overview:

- Light as a Physical Probe: Near Infrared Spectroscopy
- TRS combined with DCS
- Instrumentation Overview
- Phantom Measurements
- In Vivo Measurements
- Frequency Analysis
- Conclusions and Future Developments

Light as a Physical Probe: Near Infrared Spectroscopy



NIRS

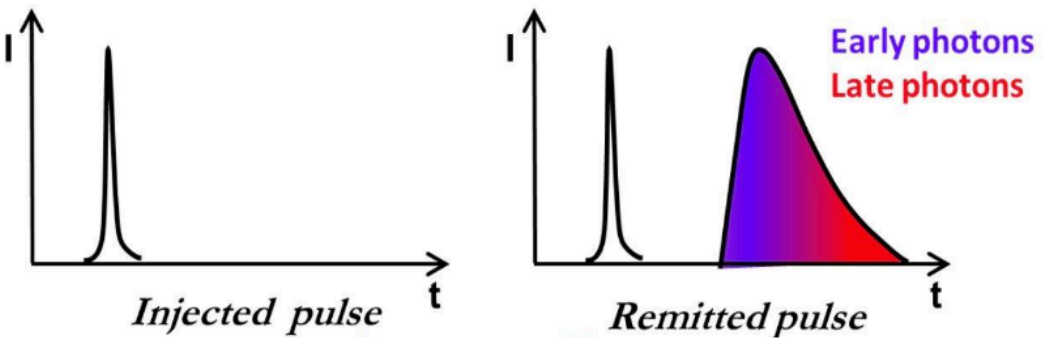


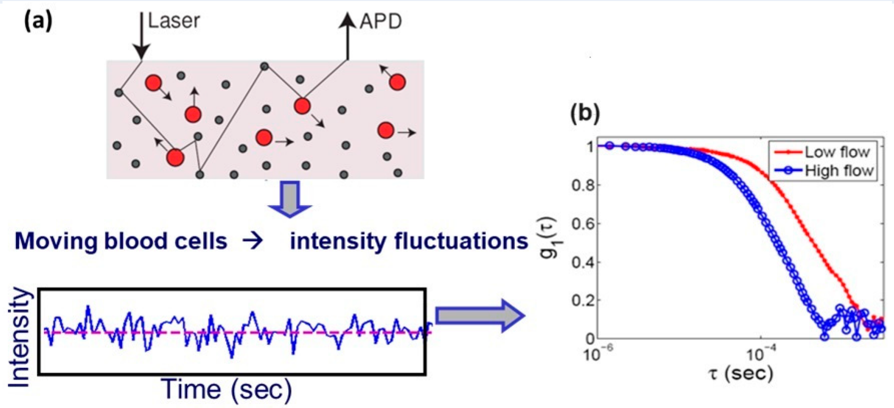
Light in diffusive media can be:
Reflected, Absorbed, Scattered, Transmitted

Different chromophores exhibit distinct absorption spectra

TRS combined with DCS

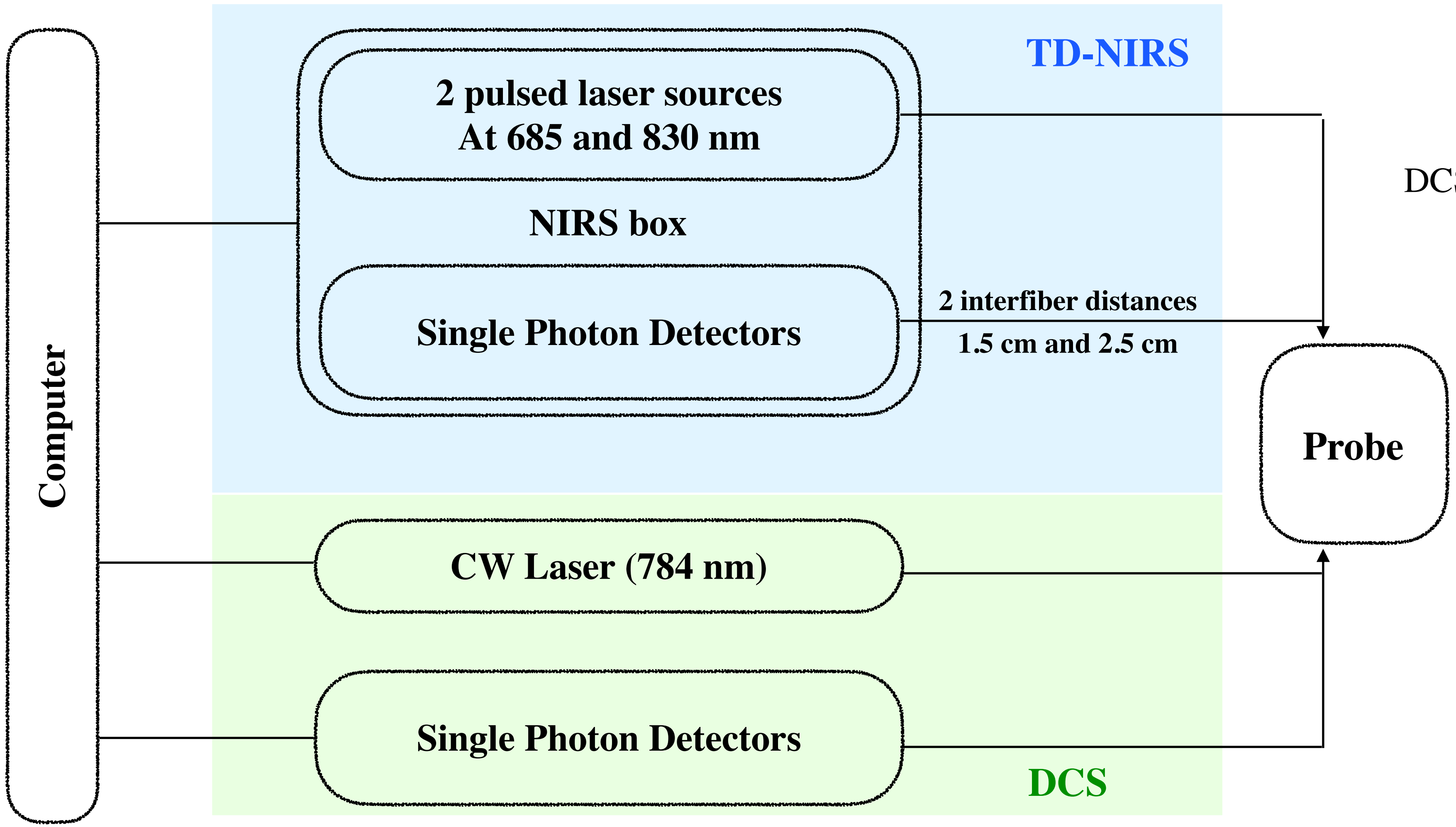
TRS	DCS
Time-Resolved near-infrared Spectroscopy	Diffuse Correlation Spectroscopy
Pulsed Laser	Continuous Laser
Radiative Transport Equation	Autocorrelation Intensity Functions
Measures: Dispersion and Absorption Coefficient	*Measures*: Movement of Scattering Particles

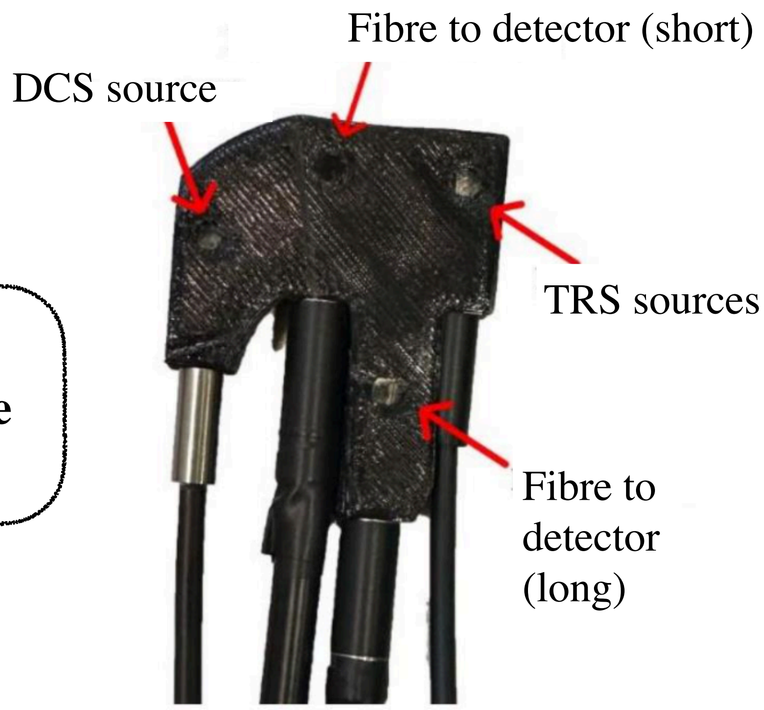




TRS quantifies optical properties; DCS quantifies dynamics. Their combination yields absolute, time-resolved metabolic information

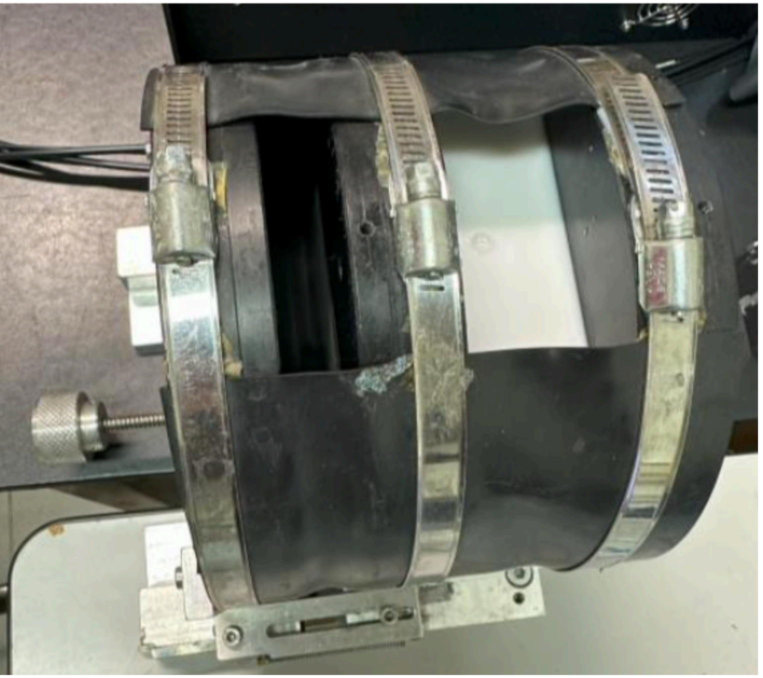
Instrumentation Overview





Phantom Measurements

To assess the performance of the instrument, in vivo measurements were preceded by preliminary tests on tissue-mimicking phantoms (solid and liquid, with variable viscosity)



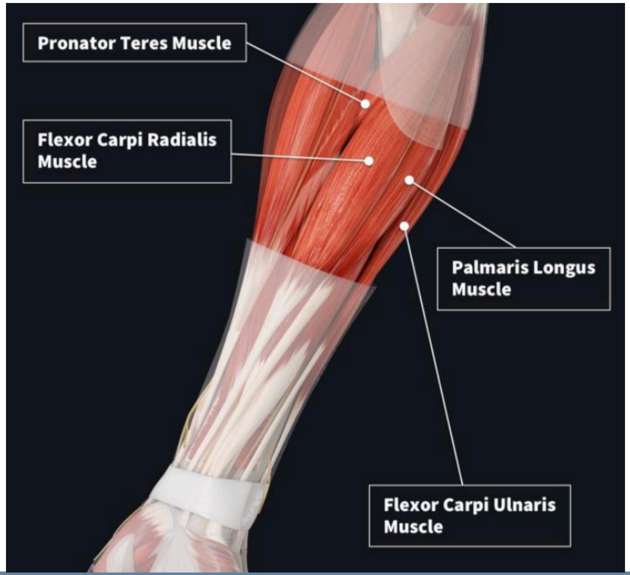
PROPERTIES OF THE INSTRUMENT:

- *Measurement stability*: relative variation < 1%
- *Reproducibility*: standard deviation ≈ 1% across repeated trials
- *Linearity*: confirmed (for both modules)
- *Depth sensitivity*: ~11 mm (effective photon penetration depth)
- *Acceptable noise level*: signal > 10^4 counts

DCS module shows higher intrinsic noise than TRS due to correlation statistics

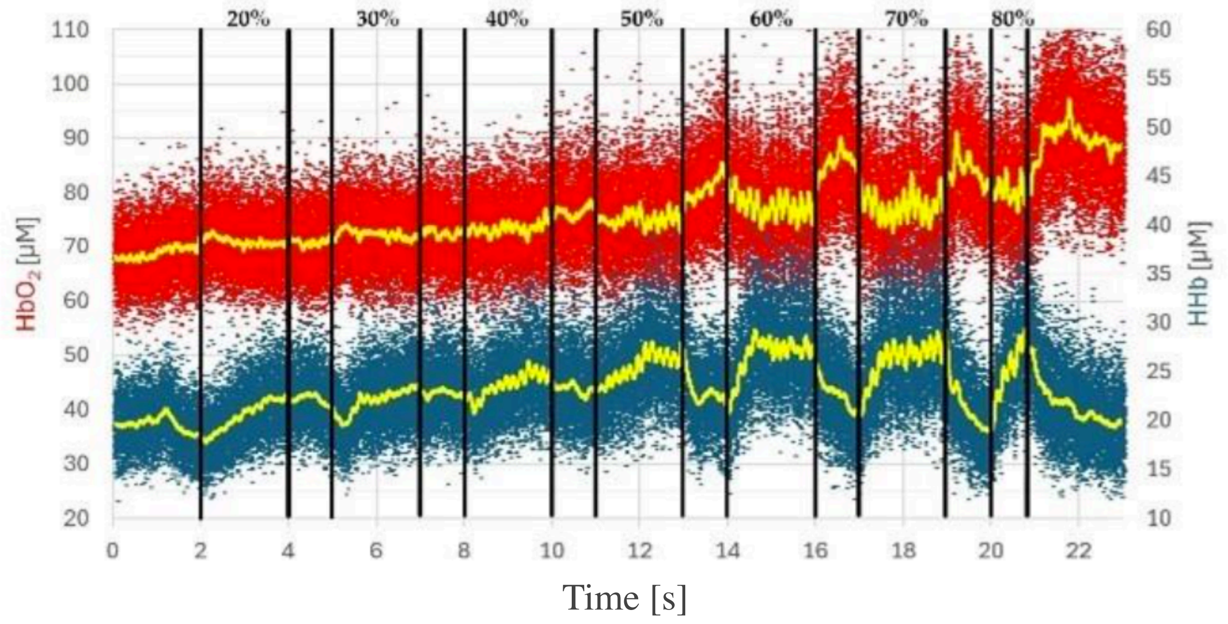
In Vivo Measurements: Handgrip Protocol

Scheme of the Protocol (Incremental Exercise task)		
Baseline 2 minutes	**Work** 2 minutes	**Recovery** 1 minute
Before measurement	5-second contractions and releases for each serie (at increasing effort level from 20% of baseline).	After each serie of contractions

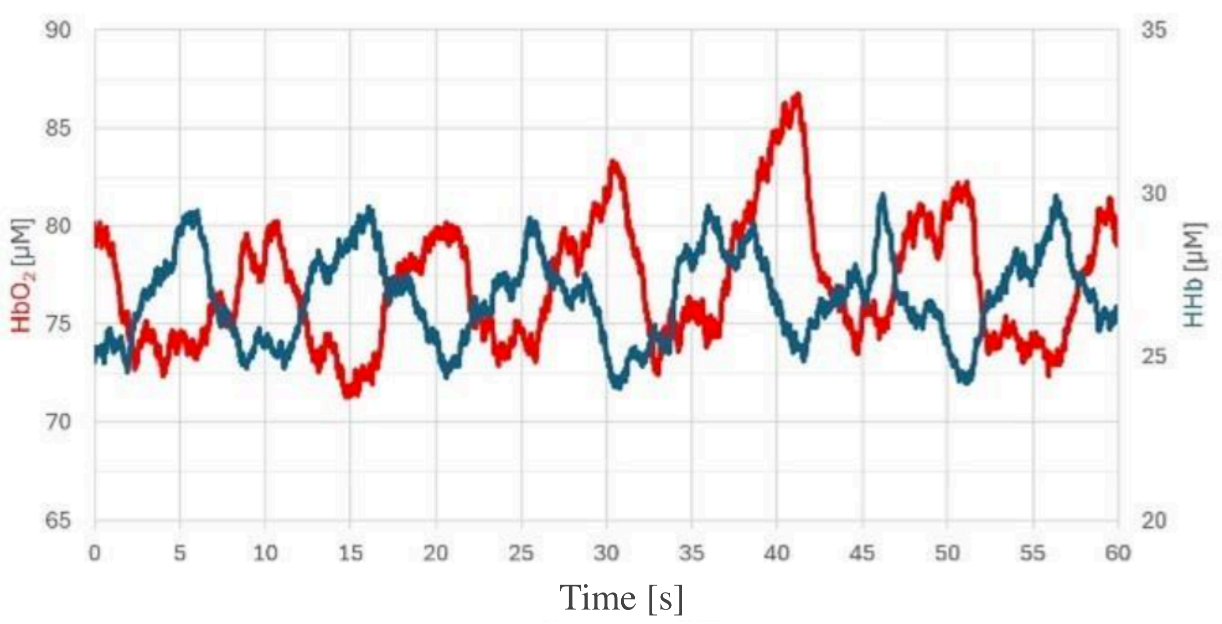


Results of the Handgrip Protocol

HbO_2 and HHb signals during the baseline and handgrip phases (5 s cycles)



Hemoglobin detail during strain (70%)



Low Intensity

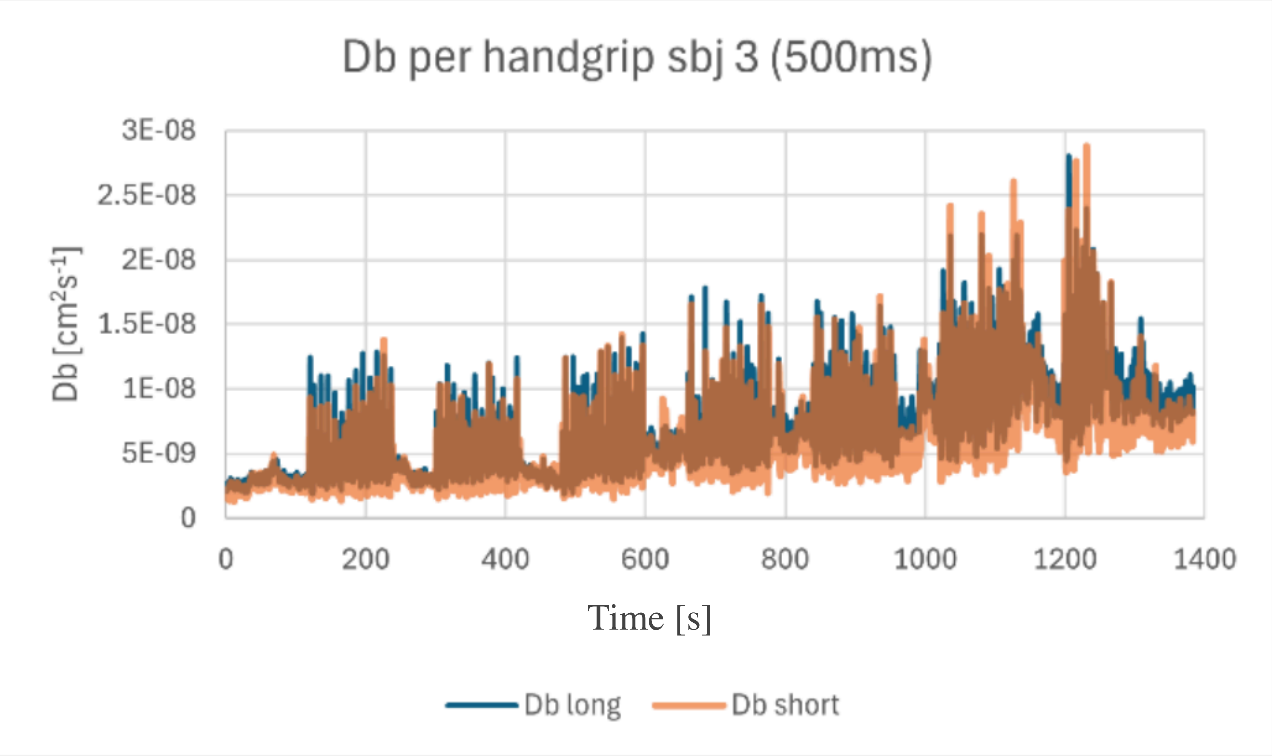
High Intensity

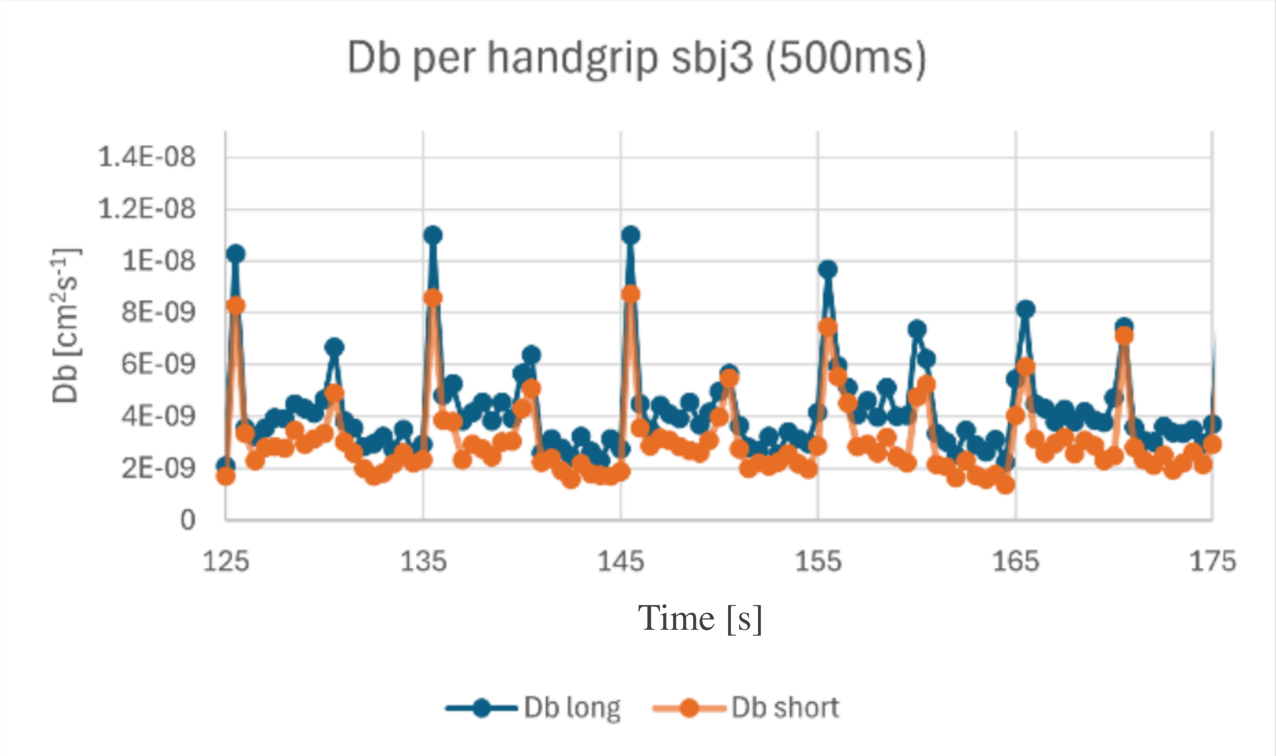
At higher effort levels: oxygenated and deoxygenated hemoglobin show an oscillatory pattern (cyclic exercise)

Contractions and relaxations clearly distinguishable

The two hemoglobin curves show opposite trends with precision

Results of the Handgrip Protocol

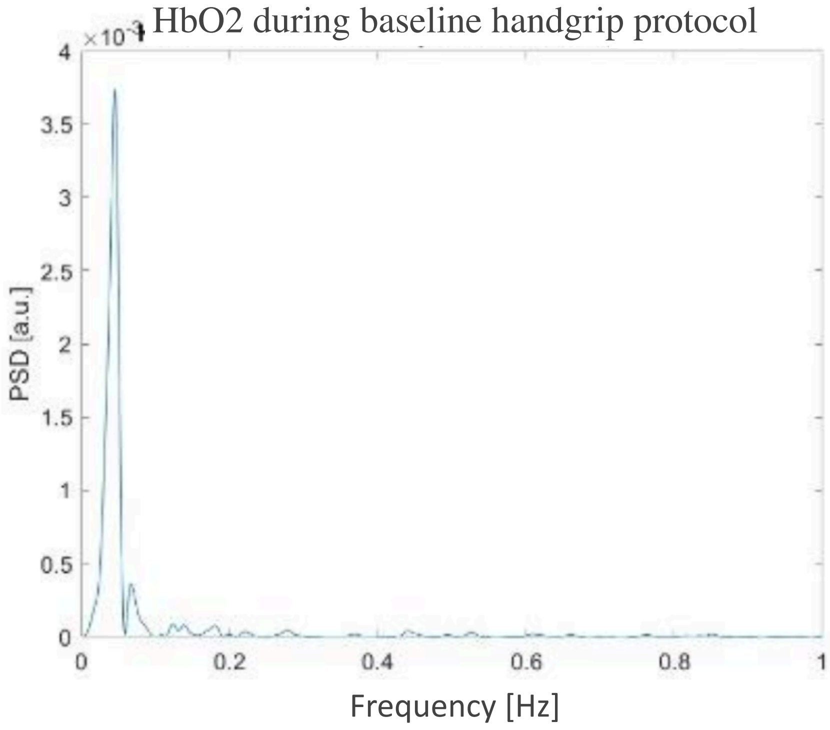


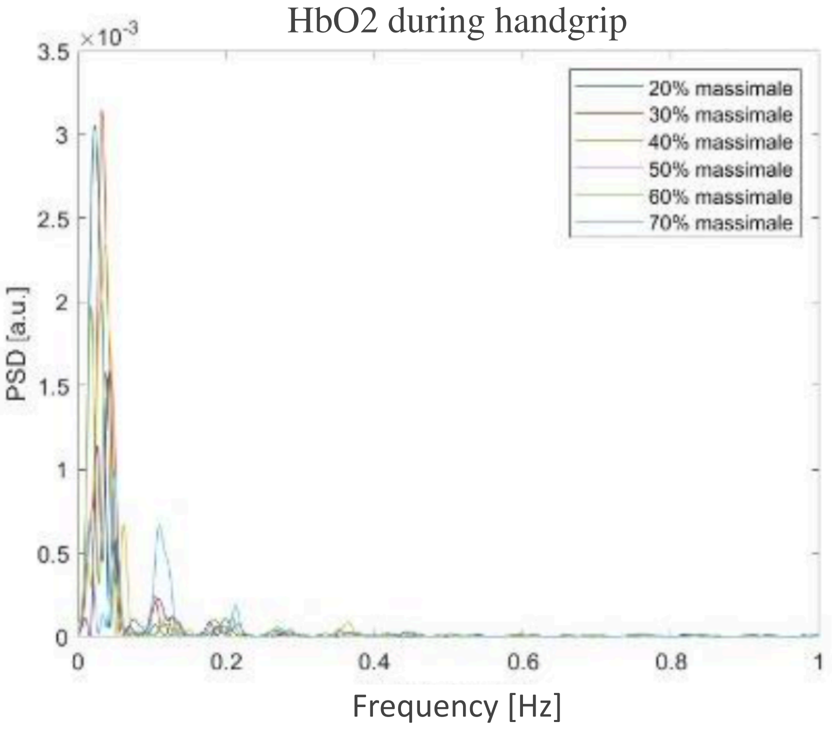


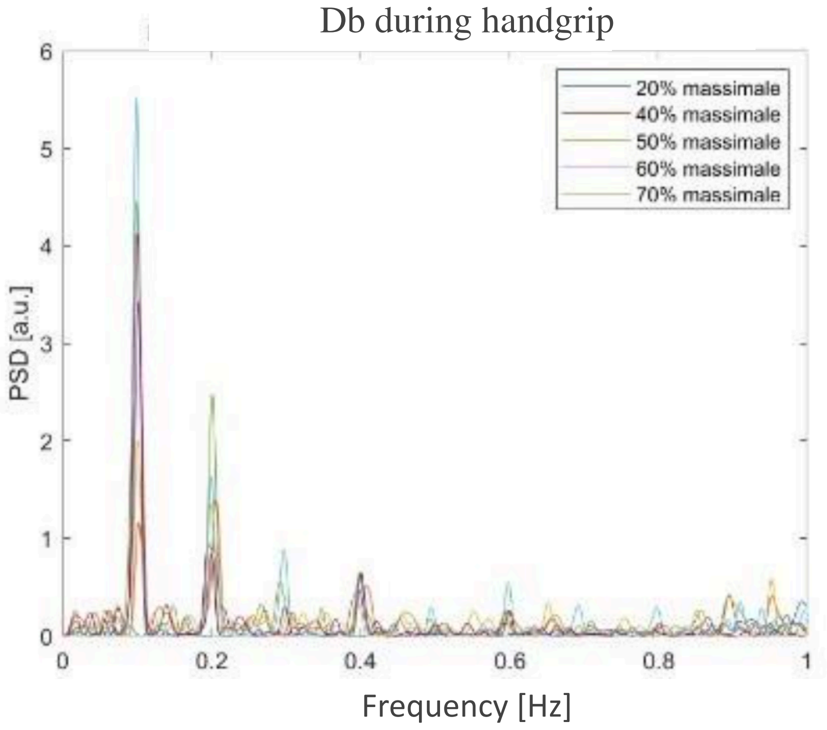
Blood flow increases during exercise

Two narrow peaks within each 10-second period, corresponding to contraction and relaxation

Frequency Analysis







Baseline: only very low frequencies

↓

endothelial activity (spontaneous vasoconstrictions and vasodilations)

→

Exercise phases: additional peaks,

↓

time-varying behavior of the hemoglobins associated with muscular activity.

→

Direct correlation between variations in the muscle's hemodynamic parameters and its mechanical activity.

Conclusions and Future Developments

By combining TRS and DCS modules it is possible to continuously monitor blood flow, muscular responsiveness and overall physiological condition during physical training or clinical rehabilitation.

Applications of TD-NIRS:	**Possible future applications of DCS:**
• neonatal brain imaging,	• measurement of cerebral blood flow,
• stroke or traumatic brain injury assessment,	• tumor diagnosis and monitoring,
• psychiatric and neurological disorder evaluation.	• analysis of ischemic consequences.