Modeling Hemodynamics During Venous Occlusion

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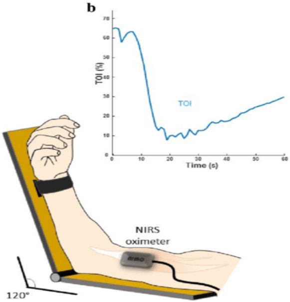
Motivation

Biomedical Relevance:

Understanding hemodynamic responses (such as blood pooling and oxygenation changes) is critical for developing non-invasive diagnostics in vascular health.

Clinical Applications:

- Early detection of vascular insufficiency
- Monitoring microcirculation
- Improving interpretation of near-infrared spectroscopy (NIRS) data



Scientific Challenge:

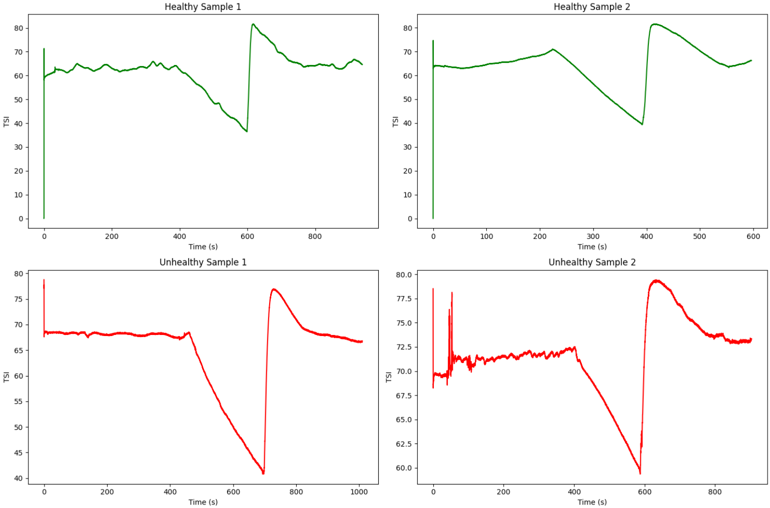
Translating experimental measurements into interpretable physiological parameters requires robust mathematical modeling.

Objectives

- Model Hemodynamic Responses: Capture blood volume increase, flow reduction, and oxygen saturation changes during venous occlusion.
- Identify Physiological Parameters: Extract time constants, slopes, and model parameters that characterize the response.
- Evaluate Modeling Approaches: Compare the Windkessel model and a harmonic oscillator model to assess their ability to reproduce observed dynamics.

Data Visualization & Preprocessing

1. Plot raw NIRS time series (e.g., TSI—Tissue Saturation Index).
2. Identify baseline, occlusion, and recovery phases.



Data Visualization & Preprocessing

1. Smoothing and detrending.
2. Quantify increasing slopes (e.g., blood pooling).
3. Quantify decreasing slopes (e.g., recovery).

Physical Modeling of TSI Dynamics

Initial Model: Windkessel Model

- Simple representation of compliance and resistance
- Captures volume accumulation and outflow resistance

$$dP(t)/dt = \frac{1}{C}\left(Q(t) - \frac{P}{R}\right)$$

rearranging terms for Q(t)

$$Q(t) = CdP(t)/dt + \frac{P}{R}$$

$$dTSI/dt = aQ(t) - b$$

Plugging in Q(t) and solving the ODE,

$$TSI(t) = TSI(0) + a\int_0^t Q(s)\,ds \; - \; bt$$

Physical Modeling of TSI Dynamics

Observation

- While intuitive, the Windkessel model may not fully capture oscillatory features seen in the data.

Extended Approach:Harmonic Oscillator Model

- Incorporates inertia, compliance, and damping.
- Allows modeling of underdamped or overdamped behavior in blood flow and oxygenation recovery.

$$\omega_0^2 x + 2\beta\dot{x} + \ddot{x} - F = 0$$

where

$$\omega_0 \in [0.005, 0.5]$$

and

$$\beta \in [0.0016, 0.16]$$

Parameter Estimation

Optimization Strategy:

- Define a cost function: Mean Squared Error between observed and modeled TSI
- Use optimization algorithms (e.g., Levenberg-Marquardt) to find parameters that minimize discrepancy
- Extract physiologically meaningful quantities: Resistance, Compliance, Damping coefficients, Time constants,etc.

Results & Insights

Model Comparisons:

- Windkessel model captures overall trend but underestimates dynamic features.
- Harmonic oscillator model better reproduces rise and recovery slopes, suggesting complex vascular compliance and inertia.

Parameter Interpretability:

- Time constants correlate with venous compliance.
- Damping terms may reflect microvascular resistance.

Implications for Diagnostics:

- Modeling can enhance interpretation of NIRS signals
- Potential to support personalized assessment of vascular health

Conclusions

Data-Driven Modeling: Combining experimental NIRS data with mathematical models allows deeper insight into blood flow dynamics.

Model Evolution: Starting from the simple Windkessel model and progressing to a harmonic oscillator framework improves fidelity.

Future Directions:

- Explore multi-compartment models
- Integrate additional physiological constraints
- Validate models across larger subject populations

Bibliografía

Questions & Discussion

Thank You!