Electroimpedance method for quantitative assessment of respiratory system activity

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Objectives

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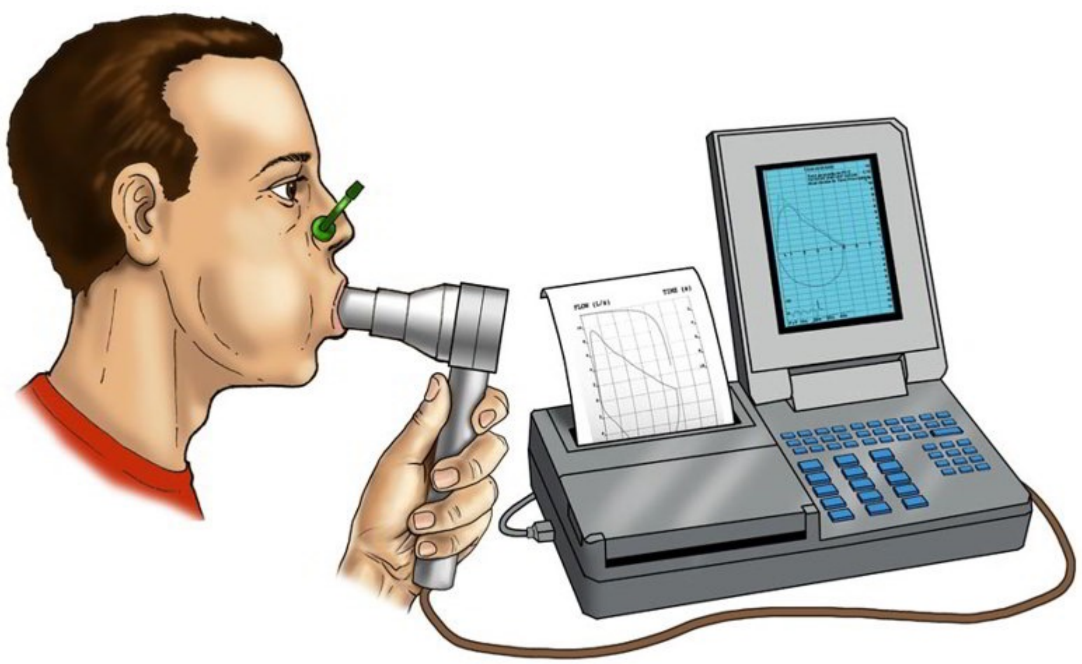
- **Improve accuracy of tidal volume, peak and mean flows** measured by impedance pneumography using several signal processing methods and suitable calibration procedure

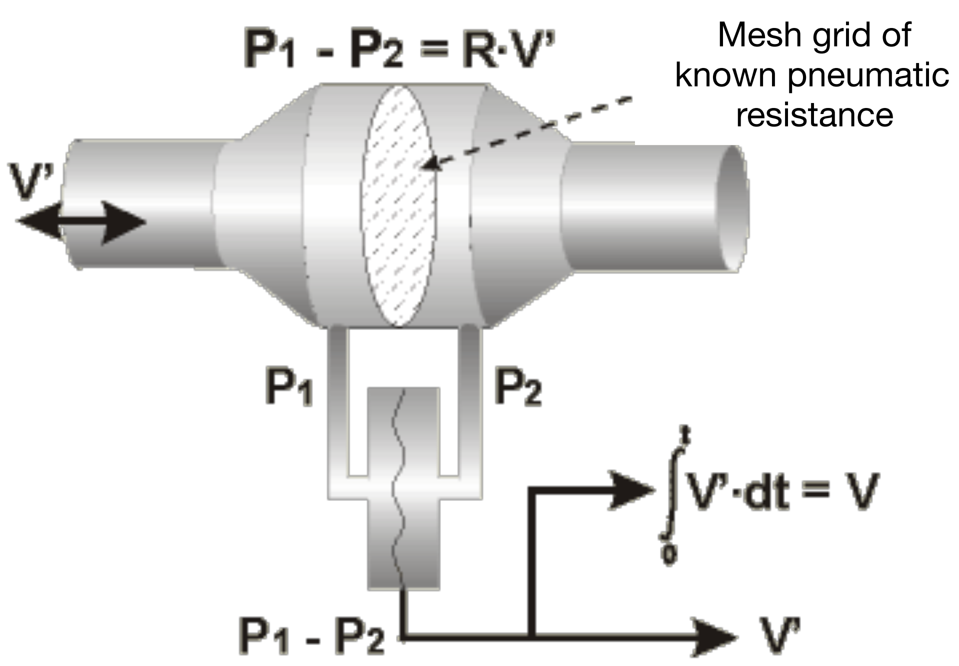
- **Detect motion artefacts** in impedance pneumography signals

- **Optimize sport training control** by adding respiratory data

Gold standard methods

Spirometry and pneumotachometry

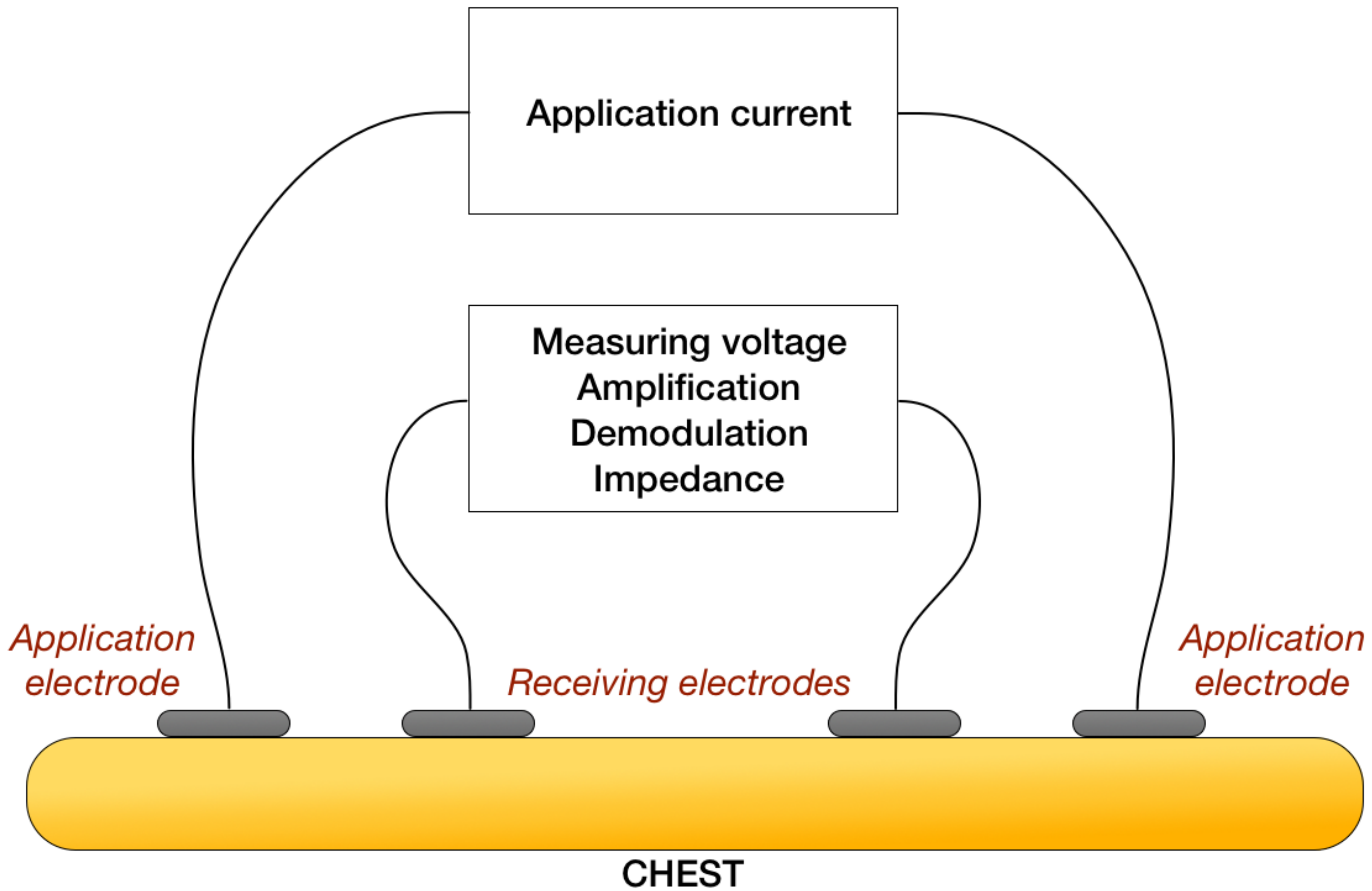




- Direct measurements
- The most reliable results

- Require mouth piece with nose clip, or face mask
- Cannot be performed in an outpatient setting

Impedance pneumography



Changes of thoracic bioimpedance reflect changes of the amount of air in the lungs

Impedance pneumography

Possible ambulatory applications

Sleep

- Breathing disorders monitoring
- Analysis of the effects of pharmacological treatment

Physiology

- Observation of hypo-, normo- and hyperventilation in obese and neuromuscular disorders
- Cardiorespiratory coupling and causal paths analyses

Sport medicine

- Home diagnostics
- Training control
- Determining the level of effort

Raw impedance signal

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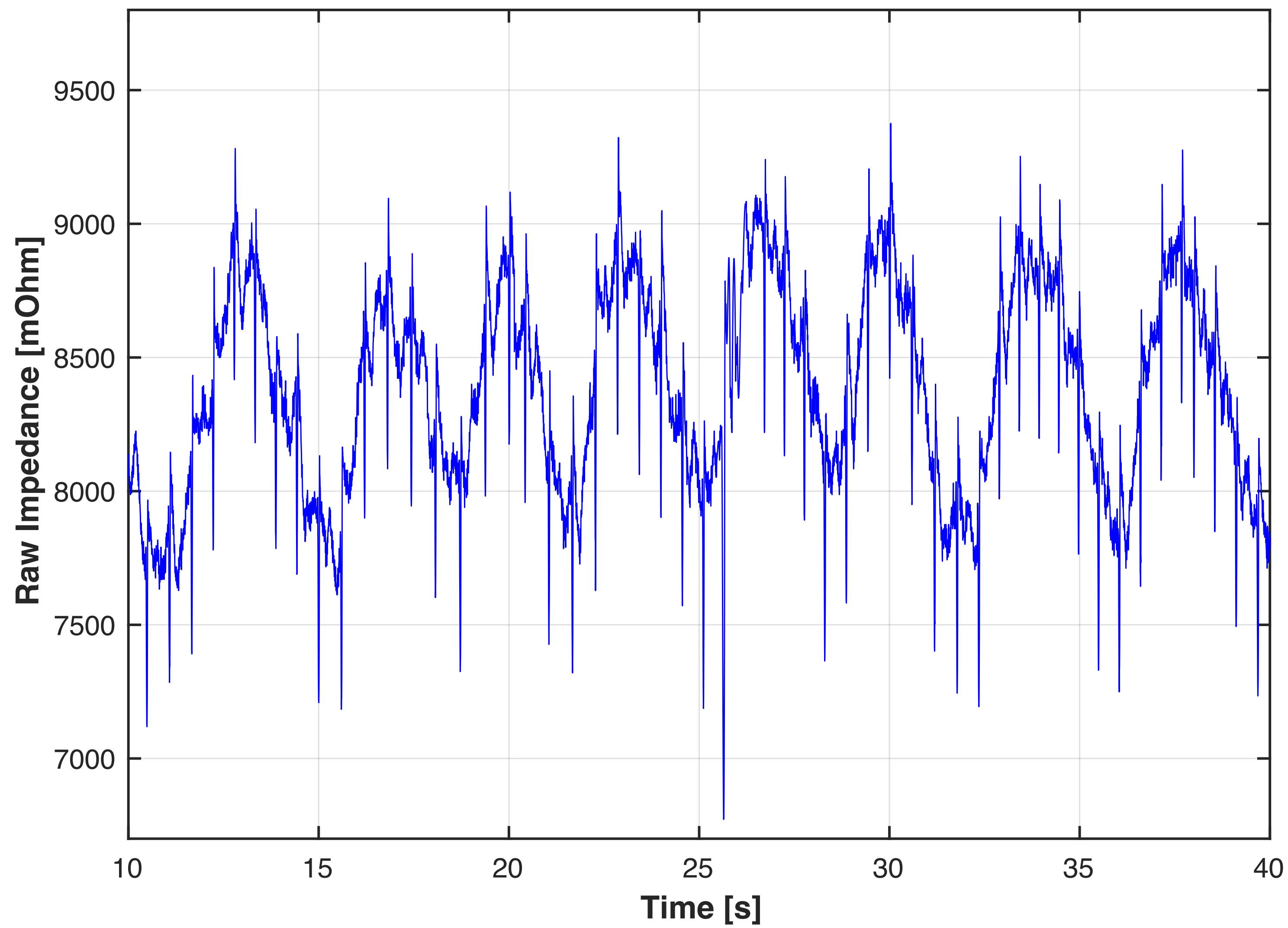
Raw impedance pneumography signal



Could we suppress cardiogenic oscillations *(Seppa et al., 2011)*?
Or even decompose respiratory and cardiac components *(Mlynczak et al., 2017)*?

Signals after preprocessing

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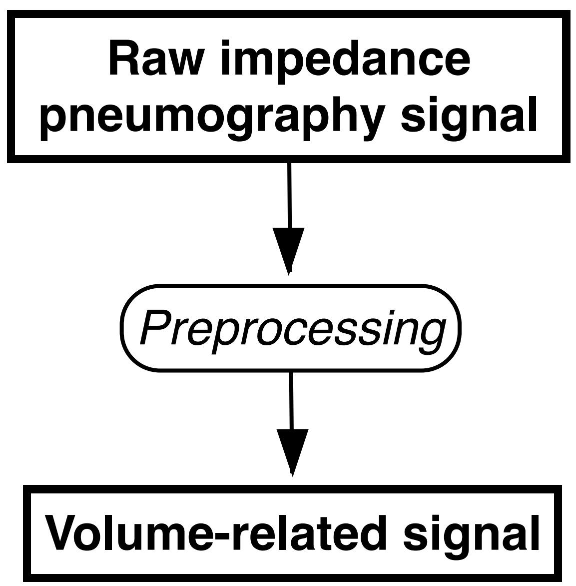
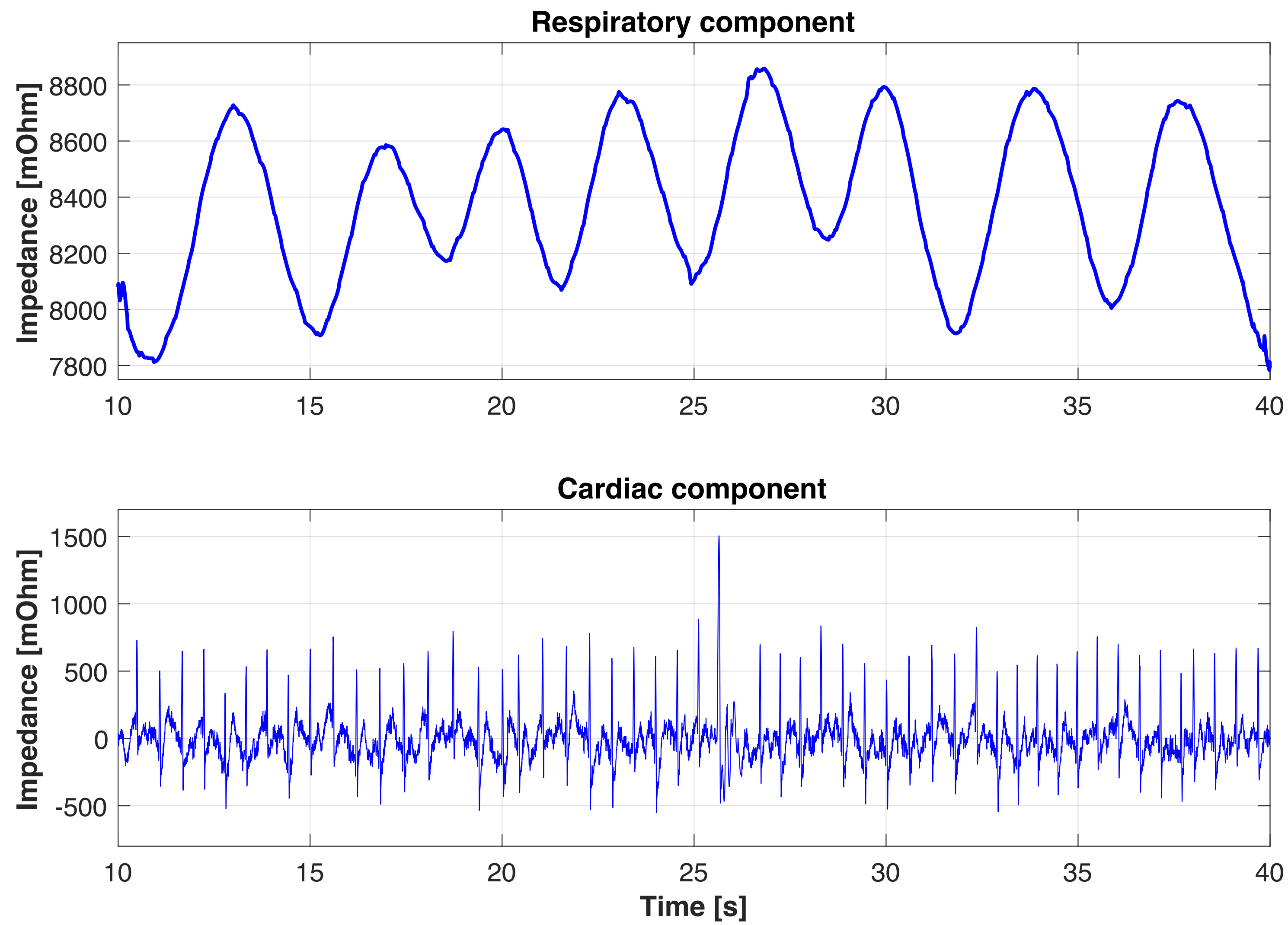
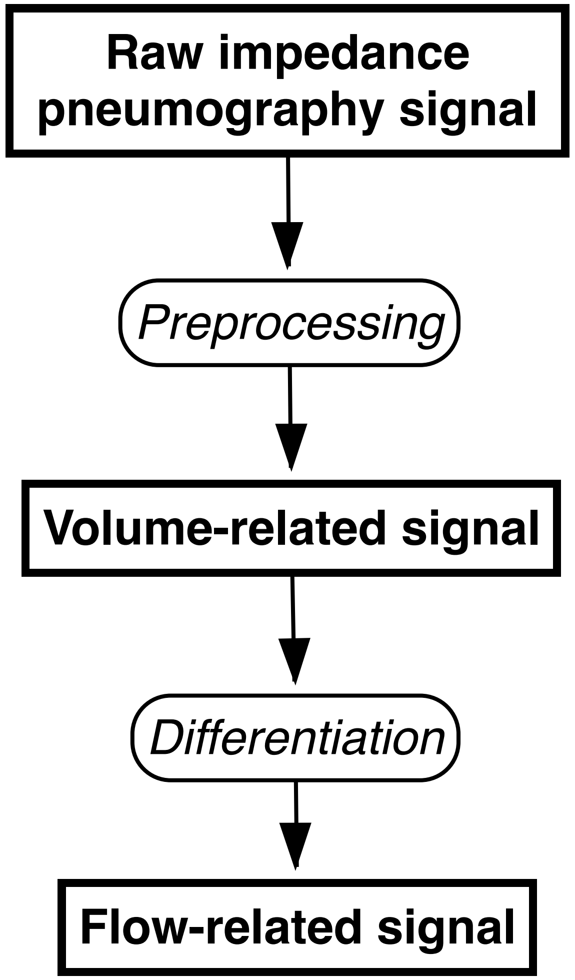
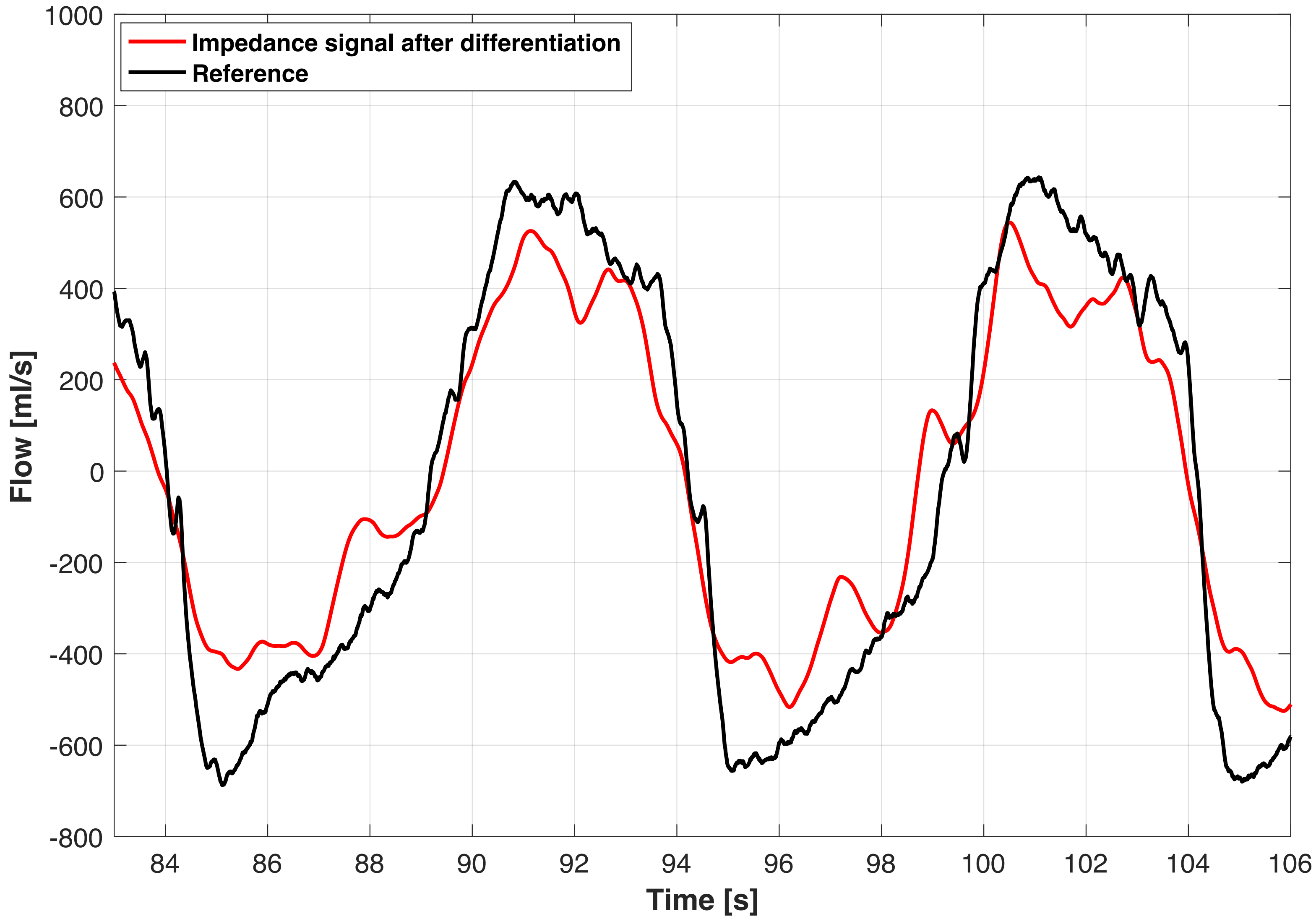




Flow-related signal





Could we improve flow-related signal dynamics *(Mlynczak et al., 2017)*?

Fitting improvement

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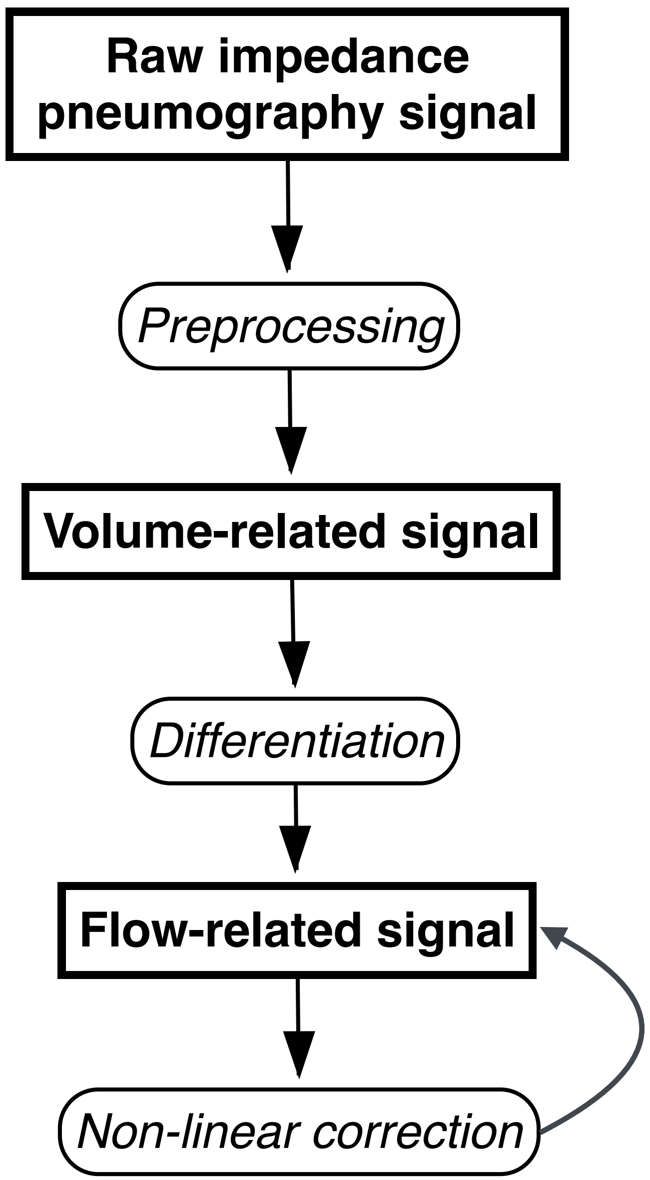

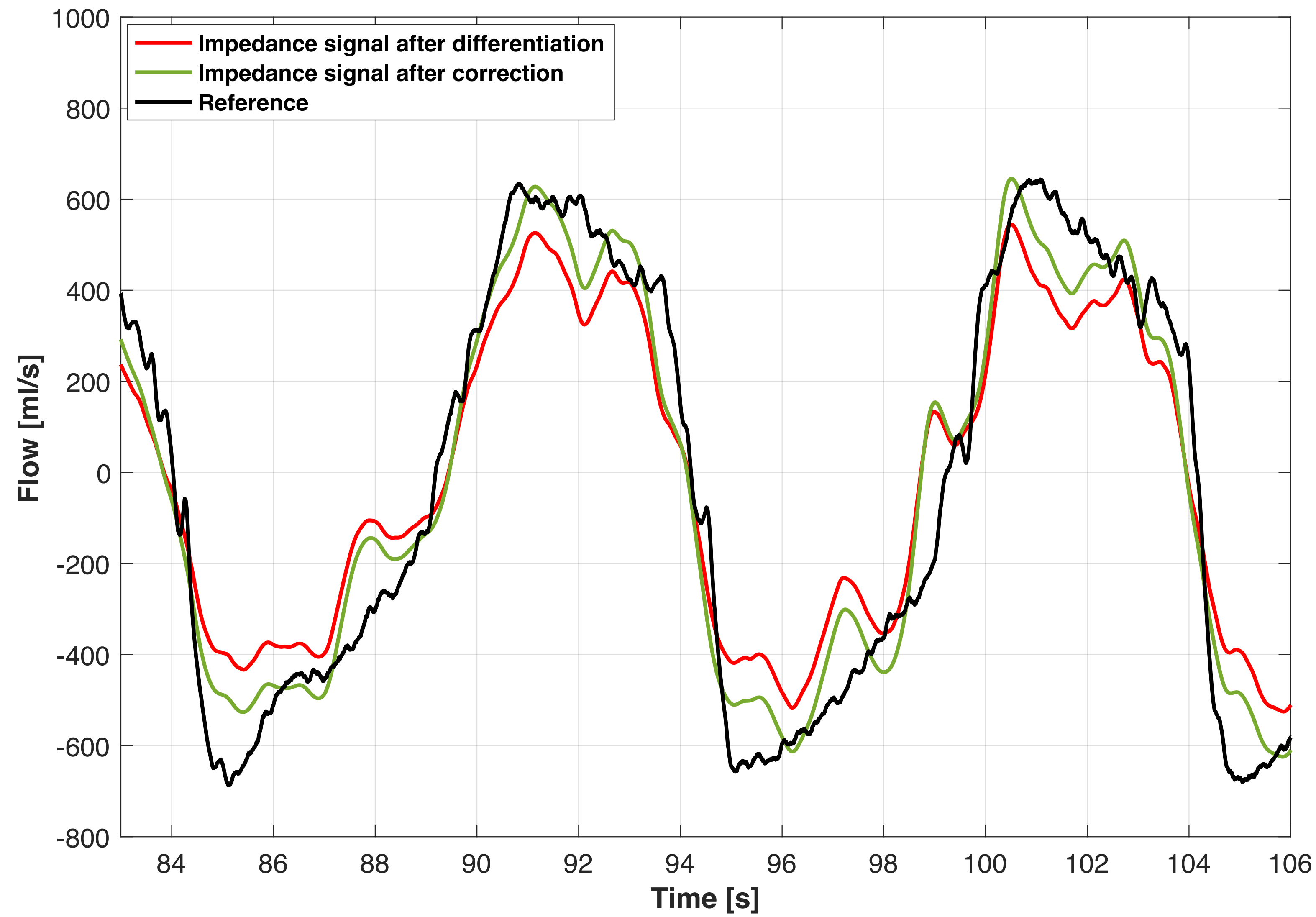

Calibration and reproducibility

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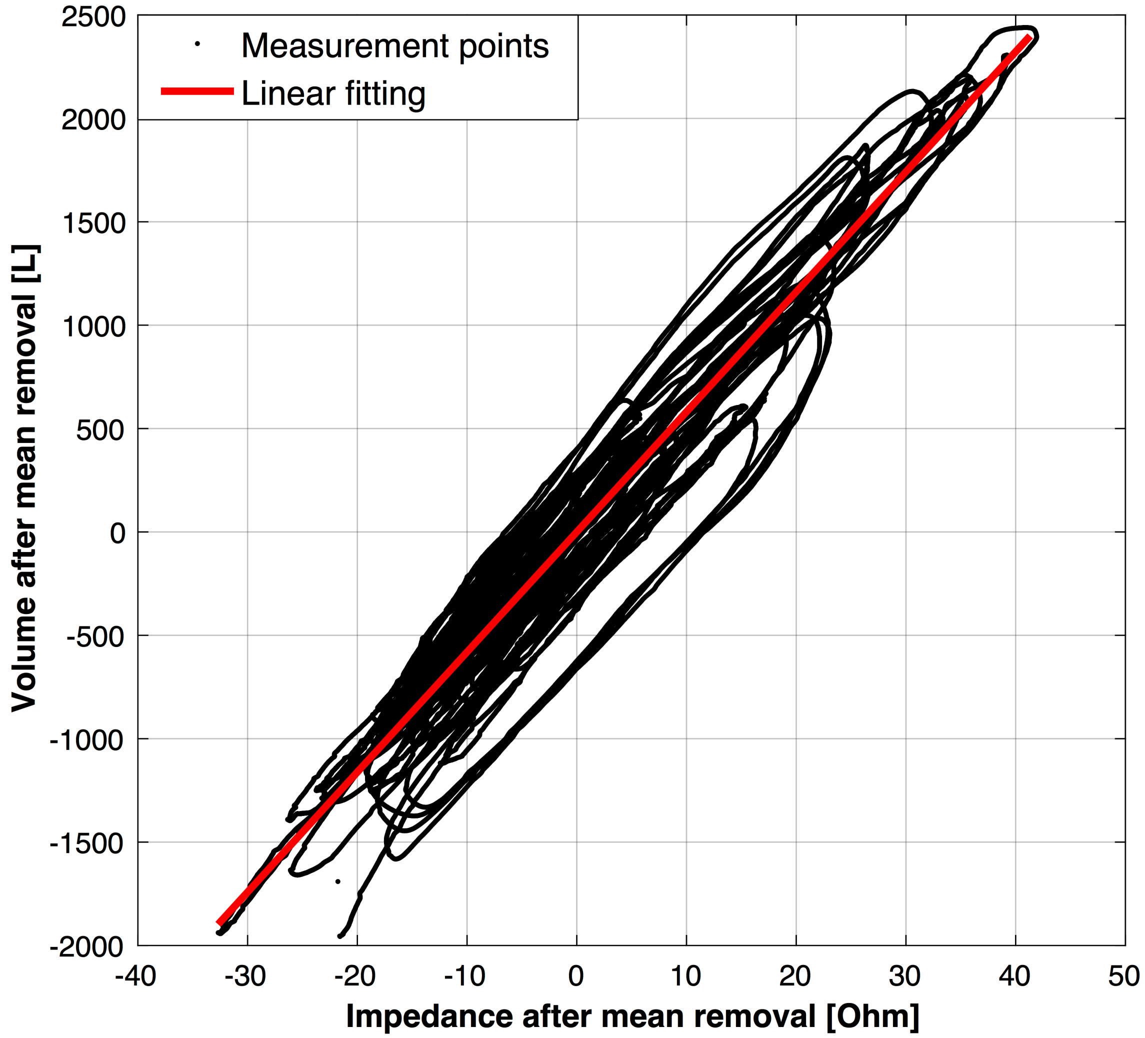


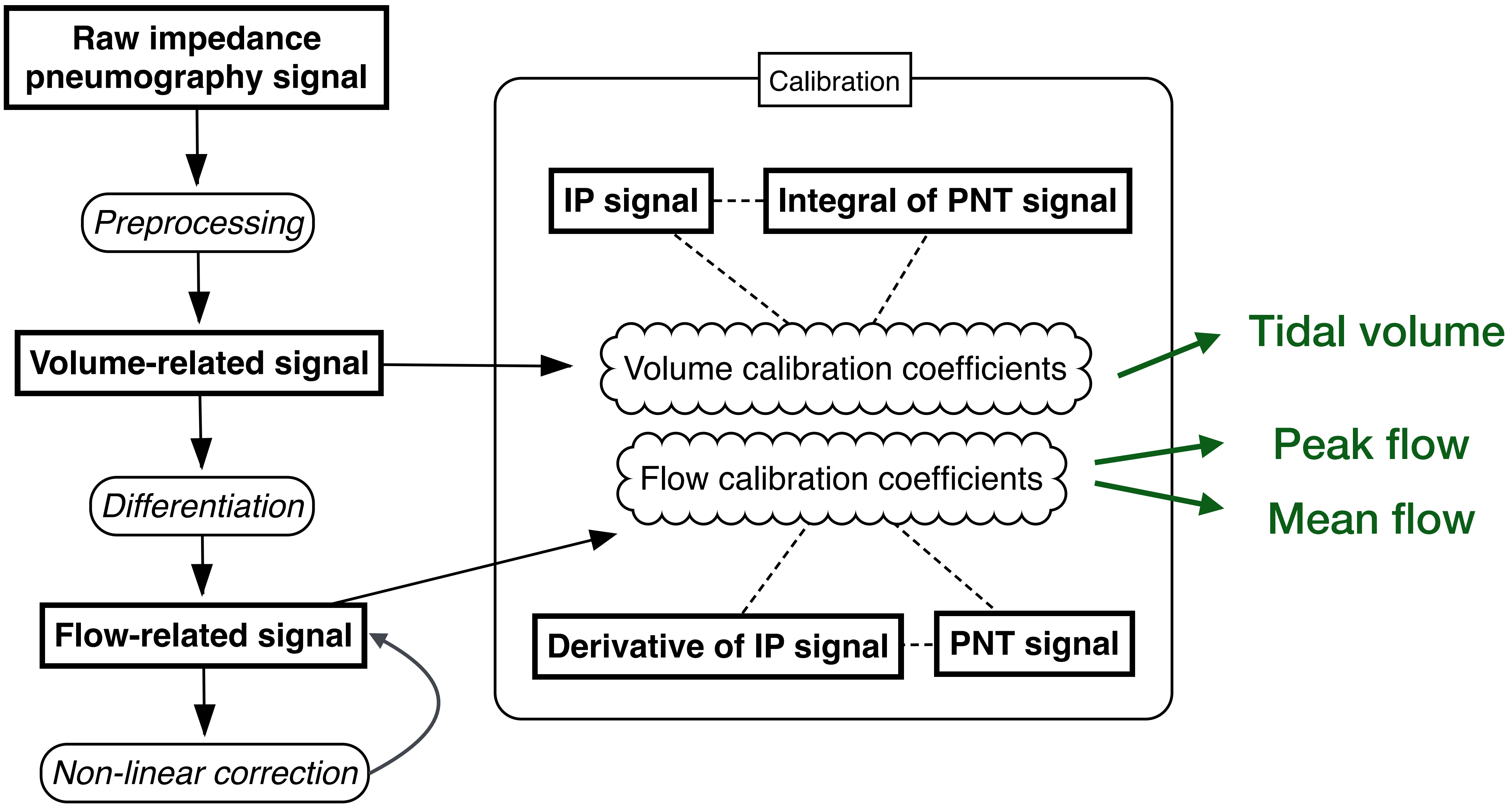
Slopes can change, so we need calibration.

Calibration coefficients are dependent on subject and body position, and not on parameters of breathing *(Mlynczak et al., 2015)*

Calibration coefficients are not permanent in time, they should be recorded just before the measurement *(Mlynczak et al., 2015)*

What is the optimal procedure in terms of volume and flow parameters measurements?

Calibration and parameters



Quantitative parameters determination

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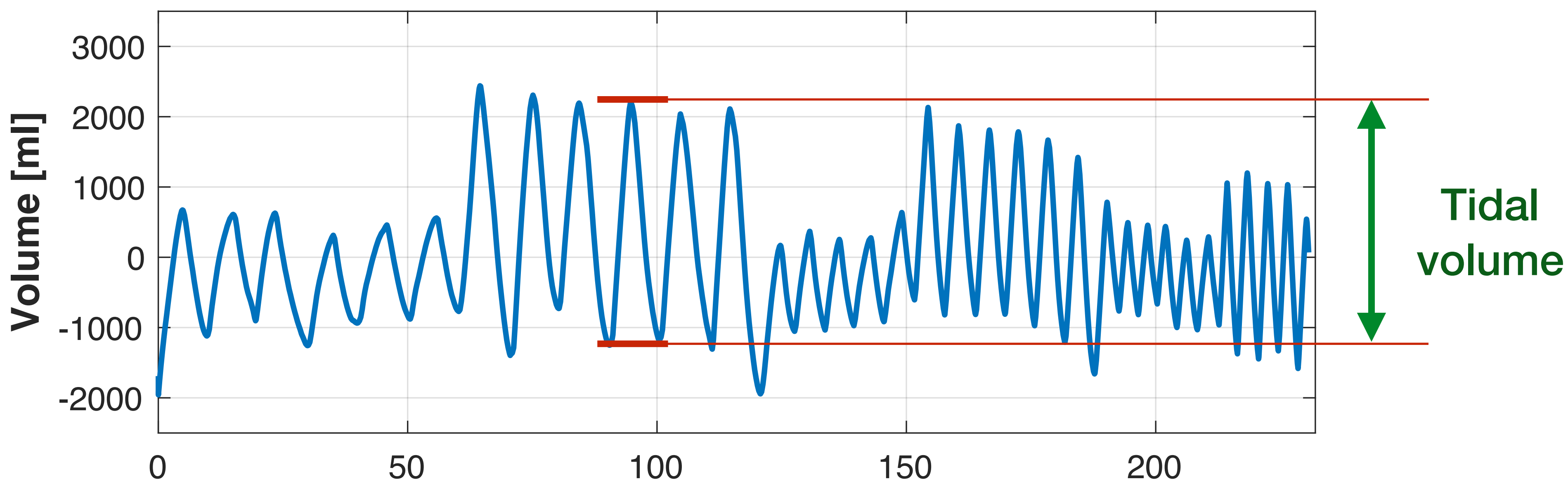

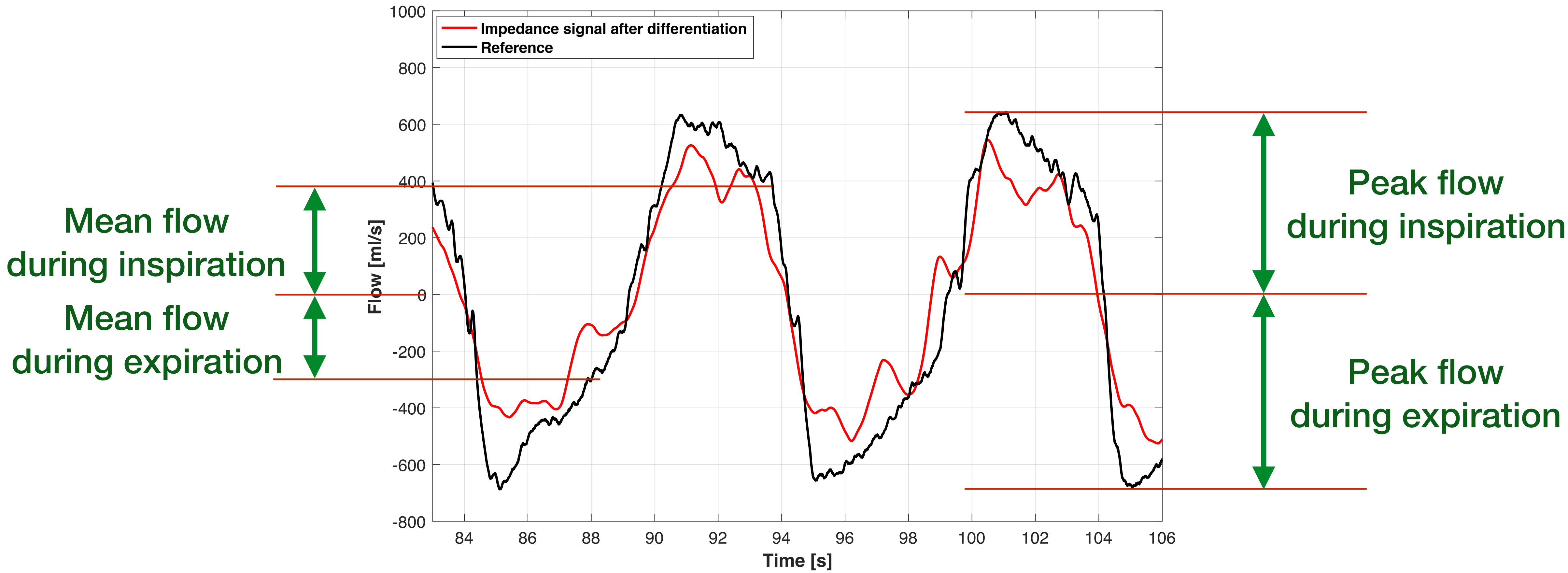

Electrode configuration

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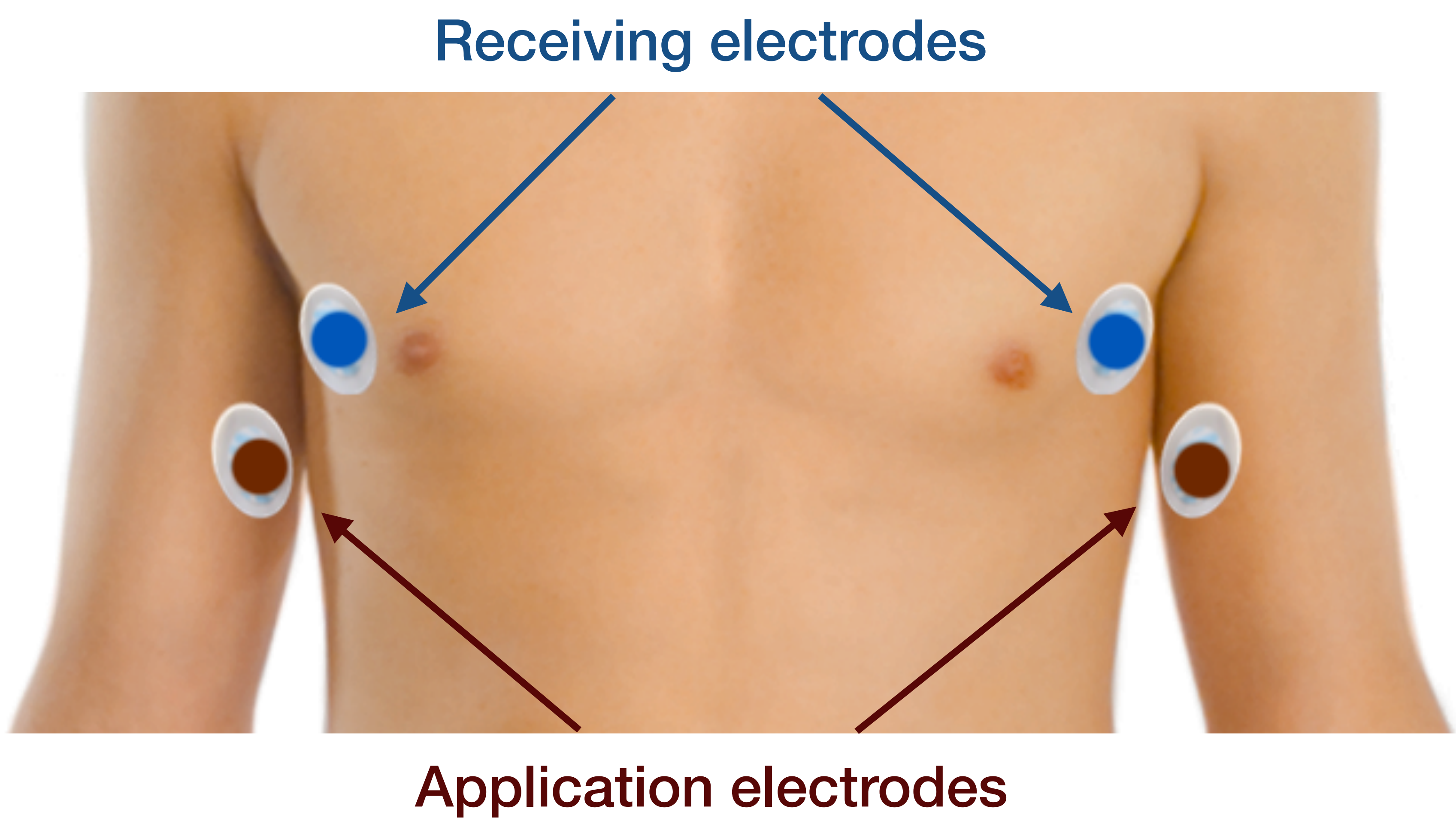
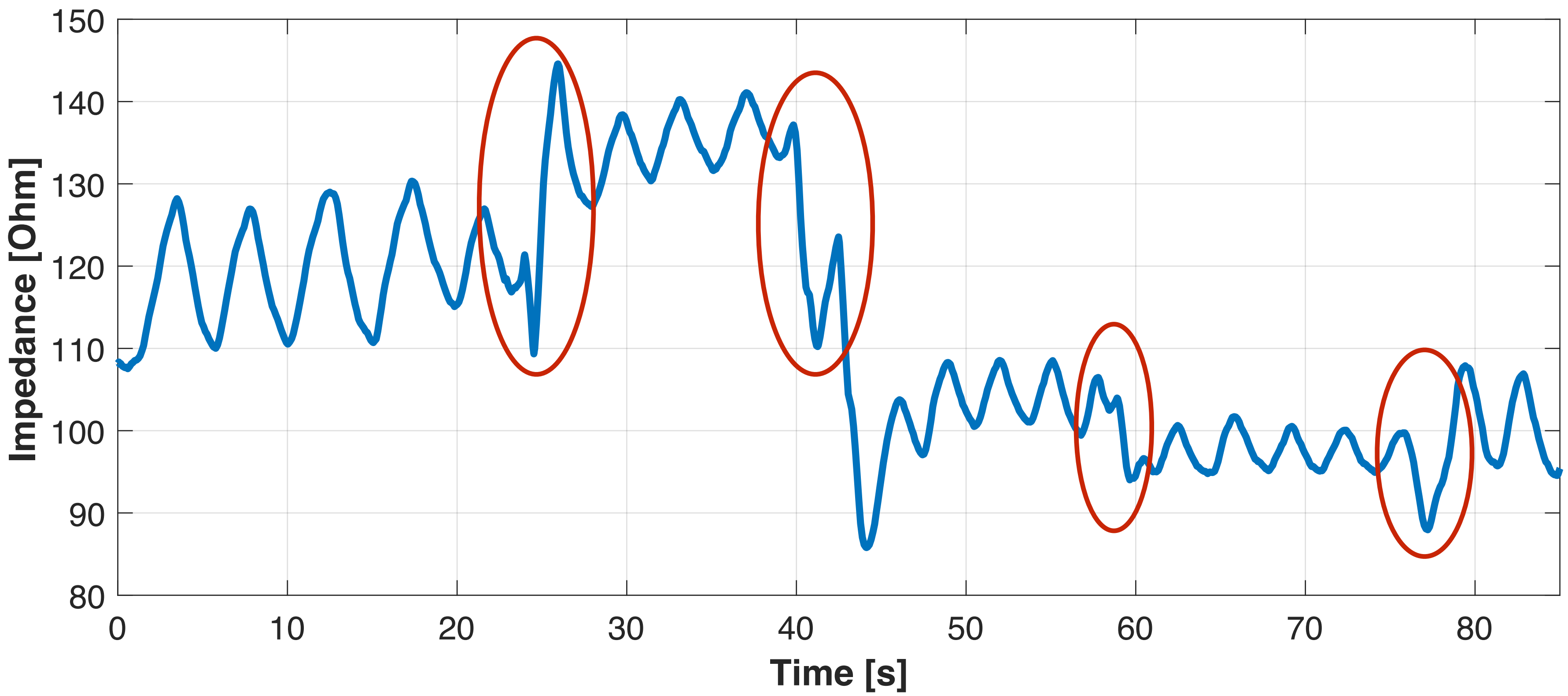
Linear relationship maintained for configuration proposed by *Seppa et al., 2013*, in standing body position.
We proved that linearity is still saved in supine and sitting positions *(Mlynczak et al., 2014)*.



Motion artefacts



Approach with epsilon-tubes based from support vector machine algorithm *(Ansari et al., 2016)*

Could we detect motion artefacts and remove them without changing the shape of the signal *(Mlynczak et al., 2017)*?

Equipment

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Pneumonitor 2 *(Mlynczak et al., 2017)*

- 14.2cm x 6.9cm x 2.3cm; 160g
- Sinusoidal application current amplitude adjustable up to 1mA, with a single, adjustable frequency (100kHz by default)
- Impedance range: 0-250 Ohms
- 250Hz sampling frequency, 100Hz pass frequency, 10-bit resolution
- ECG amplifier has a gain of 100V/V, 10nV/sqrt(Hz) noise
- InvenSense's MPU-6050 (accelerometer and gyroscope unit, available commercially)

- Portable
- Recording on SD card
- Rechargeable battery

- Impedance signal relating to main **breathing activity**

- **ECG signal** to estimate heart rate and tachogram

- **Motion signal** from 3-axis accelerometer to indicate subject's activity and body position

Equipment

Pneumonitor 3 *(Mlynczak et al., 2017)*

- 16.7cm x 10.1cm x 3.5cm; 330g
- Wireless pulse oximetry module - Contec CMS50EW (commercially available)
- 900mAh capacity of rechargeable battery

- **Analog, SD and BT outputs**
- **Improved handling**
- **5 electrodes instead of 7**

- Impedance signal relating to main **breathing activity**

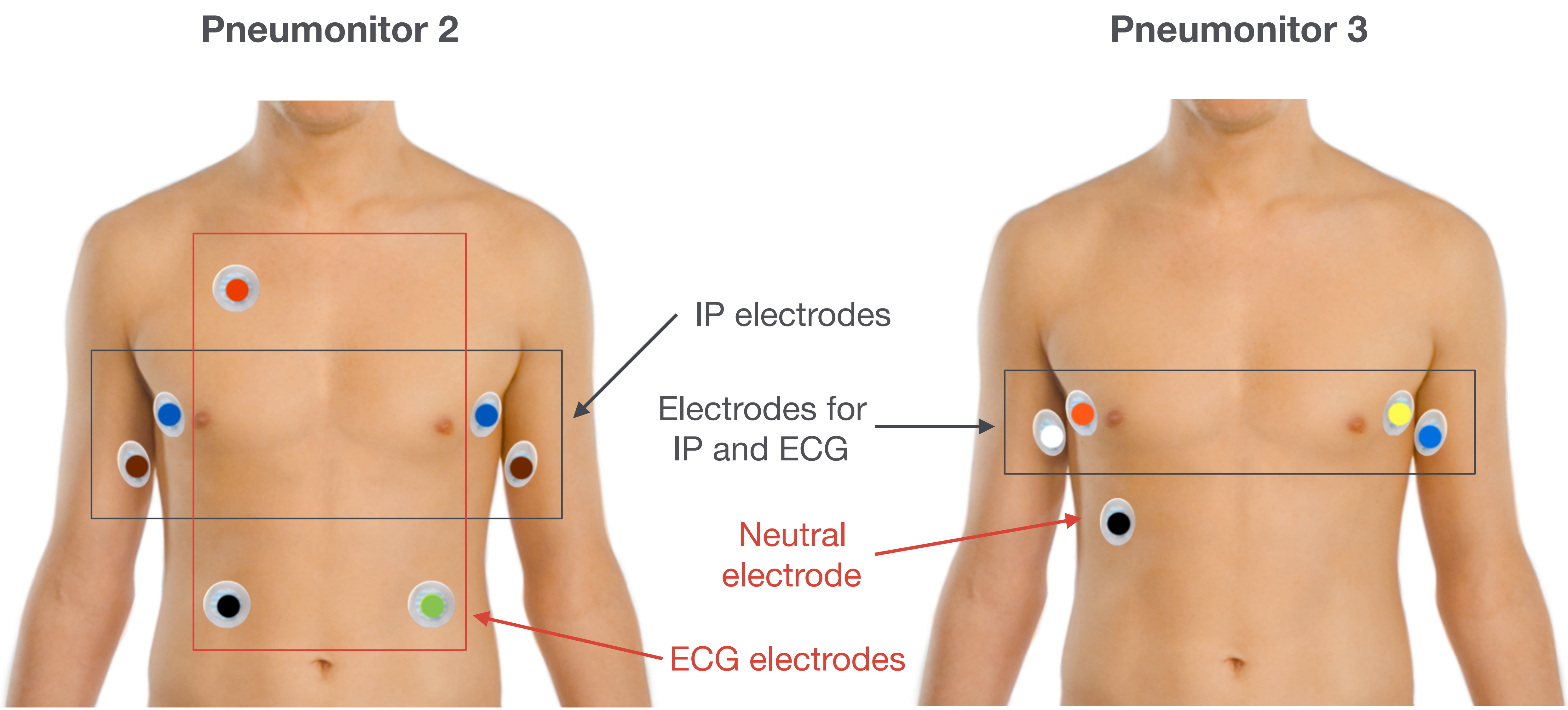
- **ECG signal** to estimate heart rate and tachogram

- **Motion signal** from 3-axis accelerometer to indicate subject’s activity and body position

- Wireless **pulse oximeter** to acquire saturation and pulse wave

Equipment

Electrode configurations *(Seppa et al., 2013; Mlynczak et al., 2017)*



Applicability

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The relation between childhood asthma risk and tidal volume

(Seppa et al., 2016; Malmberg et al., 2016)

Does **adding respiratory signal** to commonly used set of cardiac parameters allows to obtain a **fuller picture of the physiological condition** and **optimize sport training control**?

Objective 1

Improve accuracy of tidal volume, peak and mean flows measured by impedance pneumography using several signal processing methods and suitable calibration procedure

Methodology

Study group - 10 healthy students (all males)

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	Minimum	Mean	Maximum
Weight [kg]	65.0	77.4	100.0
Height [cm]	171.0	179.3	187.0
BMI	20.75	24.14	33.41
Age	19	23	27

Test procedure

6 breaths with different **depths**:

- ➡ normal (approx. 0.5 - 2.0 L)
- ➡ deep (approx. 2.0 - 5.0 L)

for 3 **respiratory rates**:

- ➡ 6 BPM
- ➡ 10 BPM
- ➡ 15 BPM

and for 3 **body positions**:

- ➡ supine
- ➡ sitting
- ➡ standing

<u>Reference</u>:
Flow Measurement System M909
(Medikro Oy, Finland)

<u>Optimization criteria</u>:
absolute and relative error
in comparison to reference

Calibration procedures

Determining optimal in terms of tidal volume and flow parameters

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- The shortest one
  - ➡ **Free breathing** for **30 seconds**
- To check the impact of longer measurement
  - ➡ **Free breathing** for **2 minutes**
- To verify that adding frequency and depth variation can significantly improve accuracy
  - ➡ **Fixed breathing**

Each procedure was repeated for all considered body positions:

- supine
- sitting
- standing

Calibration procedures

Determining optimal in terms of tidal volume and flow parameters

- The shortest one
  ➡ **Free breathing** for **30 seconds**

The best for tidal volume measurements

- To check the impact of longer measurement
  ➡ **Free breathing** for **2 minutes**

- To verify that adding frequency and depth variation can significantly improve accuracy
  ➡ **Fixed breathing**

The best for flow parameters measurements

Each procedure was repeated for all considered body positions:

- supine
- sitting
- standing

Decomposition

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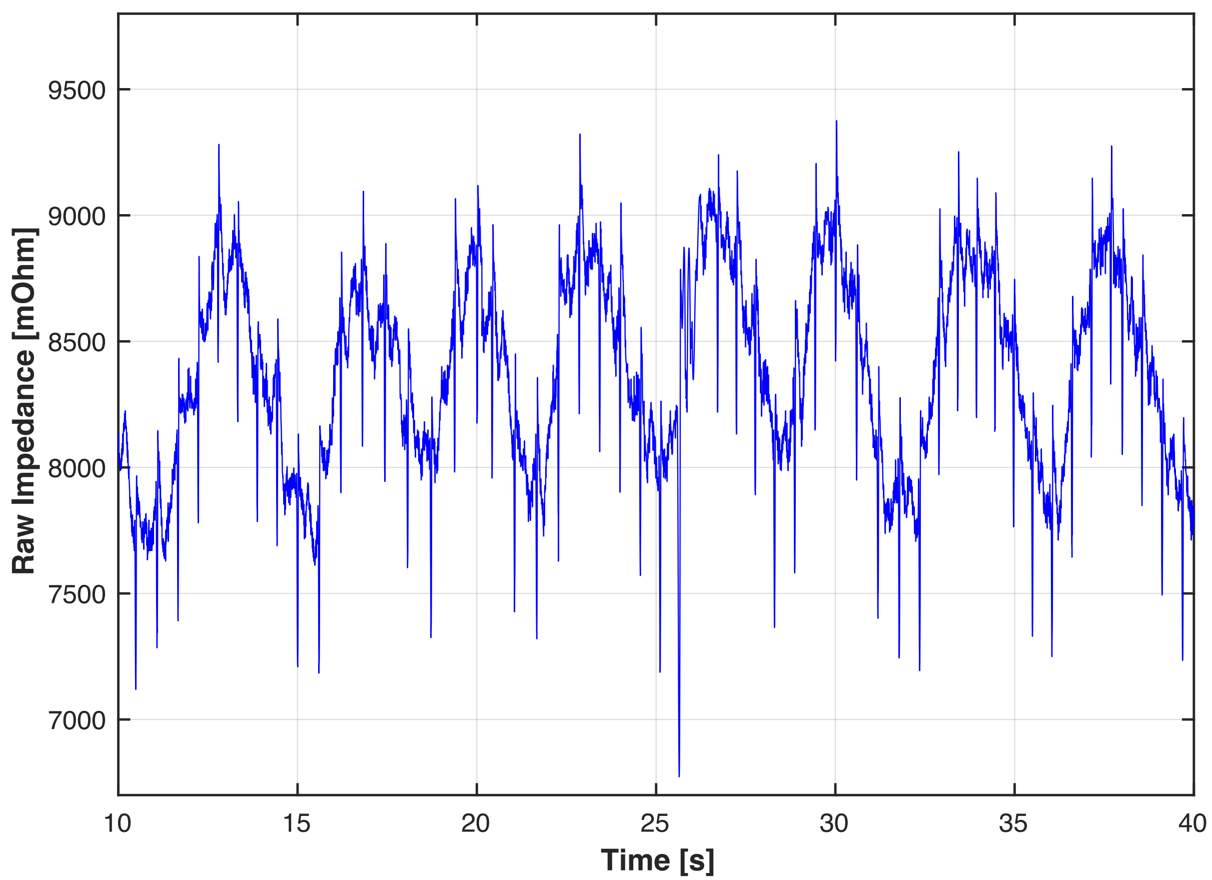
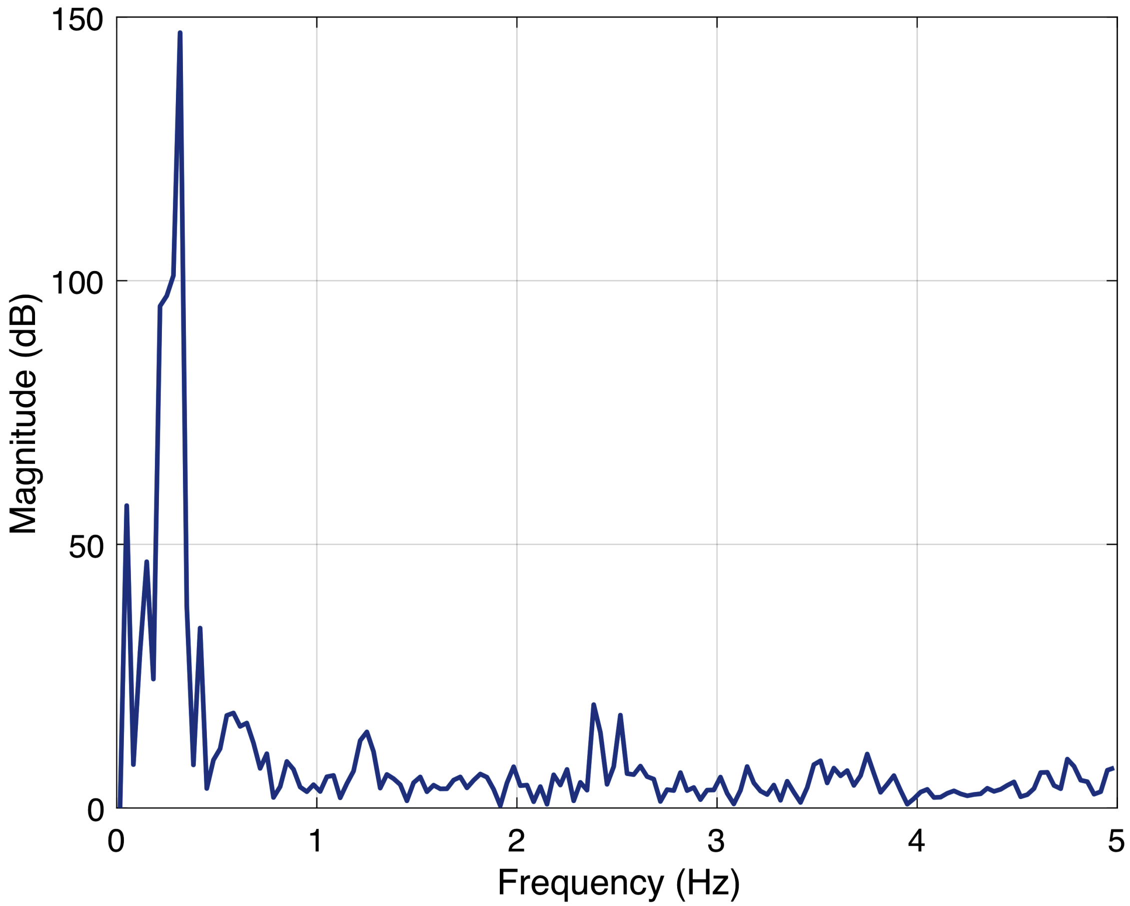
Separating respiratory and cardiac components

Raw signal



Frequency spectrum

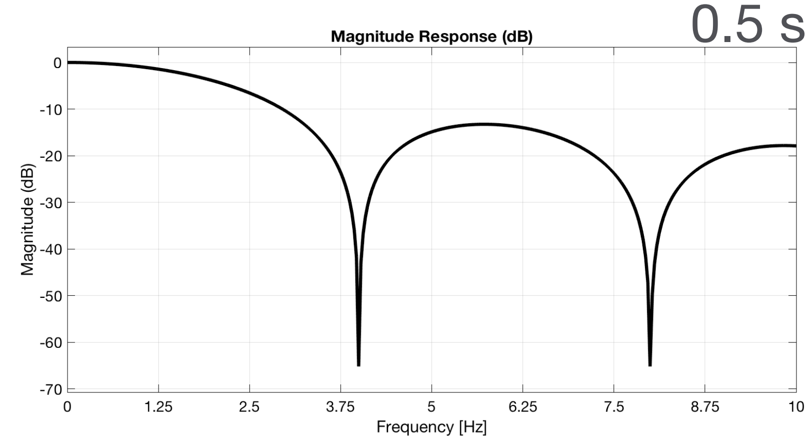


Decomposition

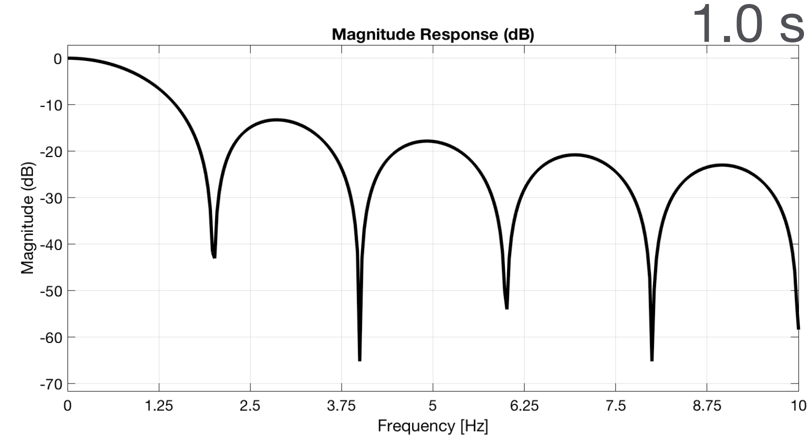
Separating respiratory and cardiac components

- **Moving average smoothing**, with windows:
  - ➡ 0.5 s (mild)
  - ➡ 1.0 s (as proposed by *Koivumaki et al., 2012*)
  - ➡ 1.5 s (strong)
- **Savitzky-Golay filter**
  - ➡ **2nd-order**, with a 25 probes window
  - ➡ **7th-order**, with a 25 probes window
- **Least mean square adaptive filtration**
  - ➡ subtraction of raw IP signal and the noise component, then smoothed with **200 ms** window
  - ➡ subtraction of raw IP signal and the noise component, then smoothed with **400 ms** window

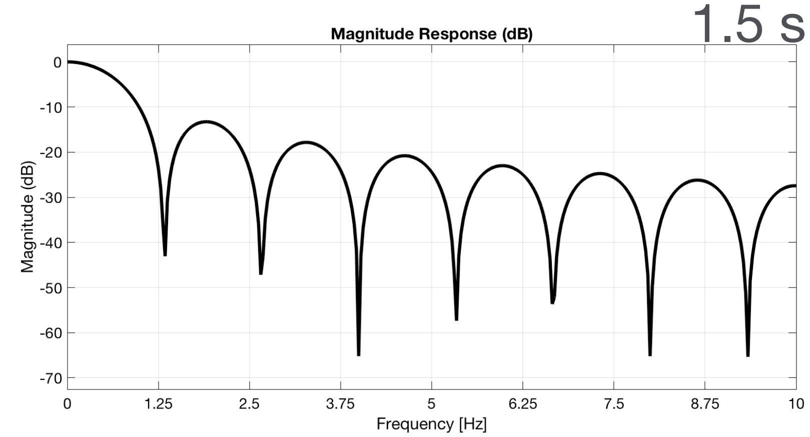
0.5 s



1.0 s

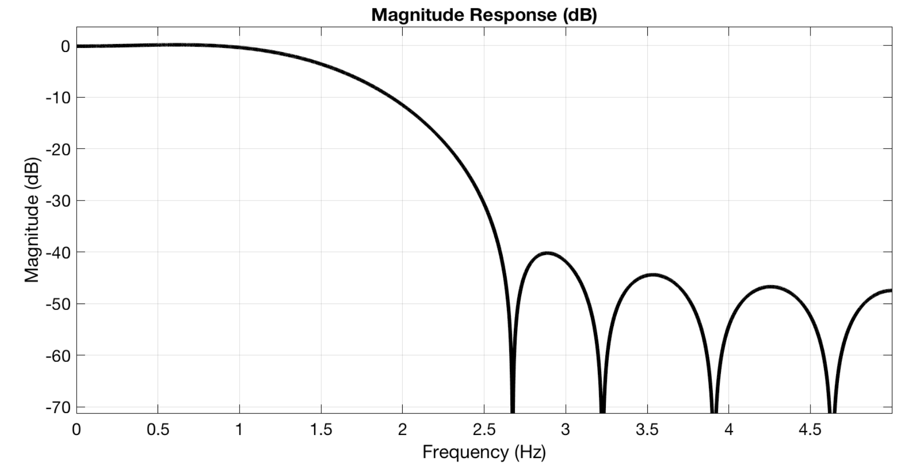


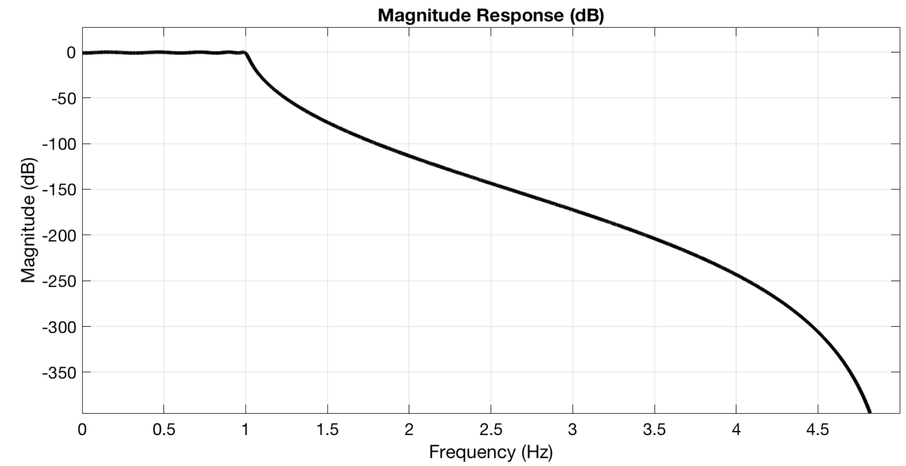
1.5 s



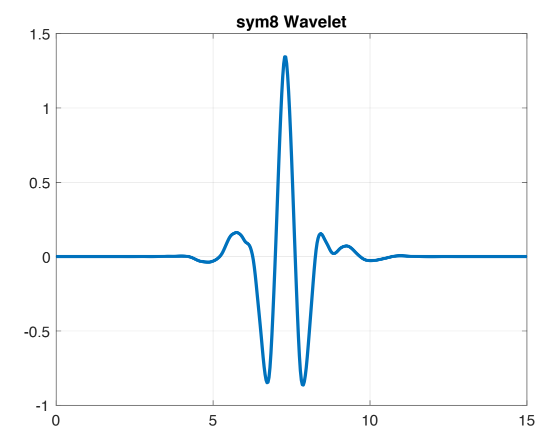
Decomposition

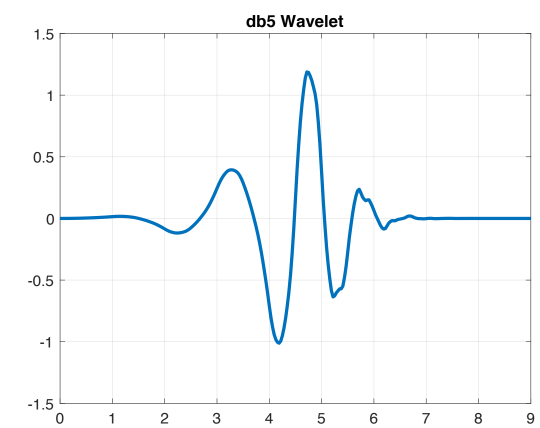
Separating respiratory and cardiac components





- **Impulse response filtration**
  - ➡ 25-fold decimation (performed twice using 5-fold coefficient), then applying **10th order least-square FIR** filter with 1 Hz pass and 2.5 Hz stop frequencies, at the end the spline interpolation to return to original sampling frequency
  - ➡ the same process as above, but with use of **10th order stable Chebyshev IIR** filter with 1 Hz pass frequency
- **Wavelet denoising**
  - ➡ soft heuristic SURE thresholding and scaled noise option, on coefficients obtained at level 5 by **sym8** wavelet
  - ➡ minimax thresholding at level 5 by **db5** wavelet
- **Smoothing Splines**



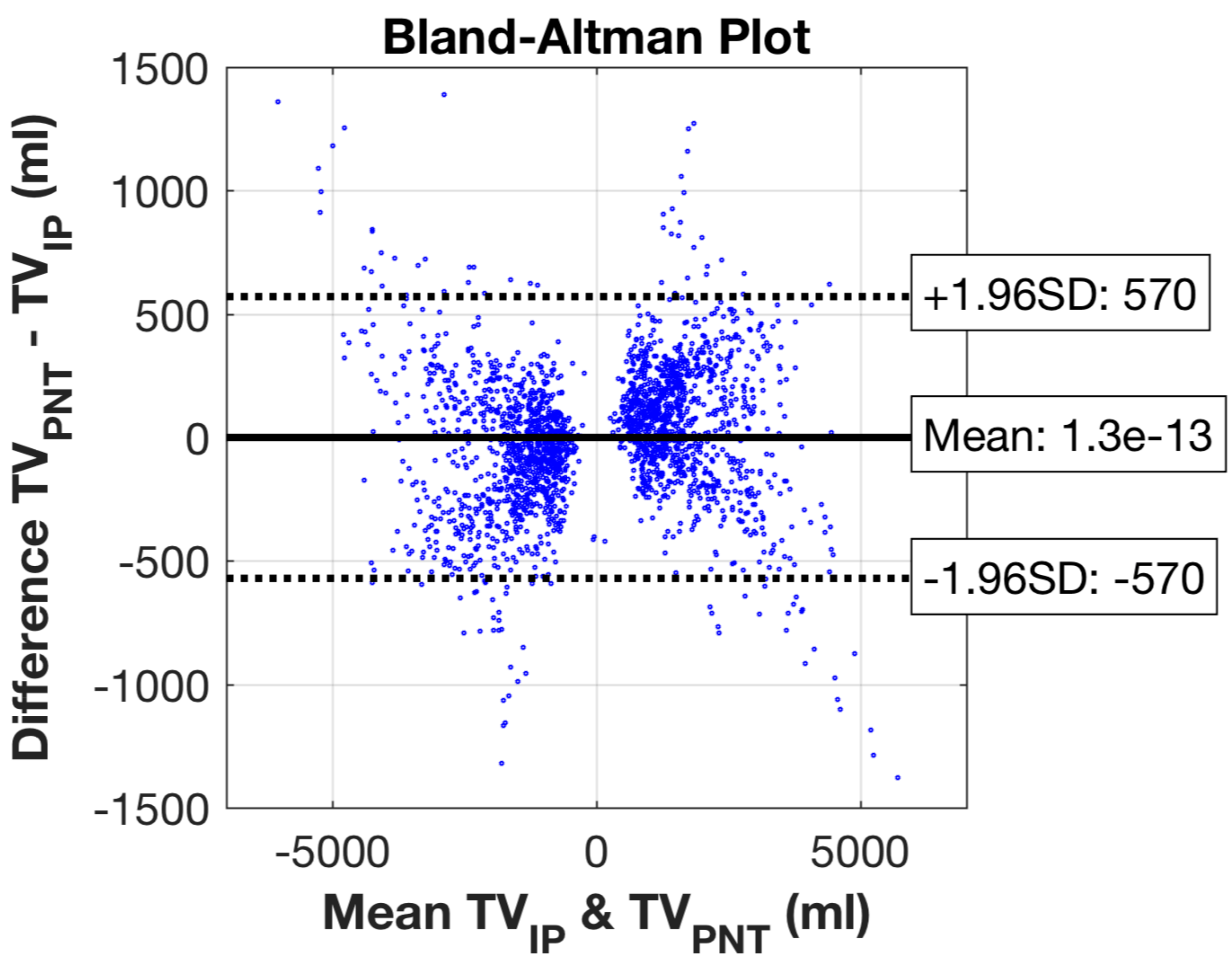


Decomposition

Separating respiratory and cardiac components

Best results obtained for **moving average smoothing (with 1s window)**

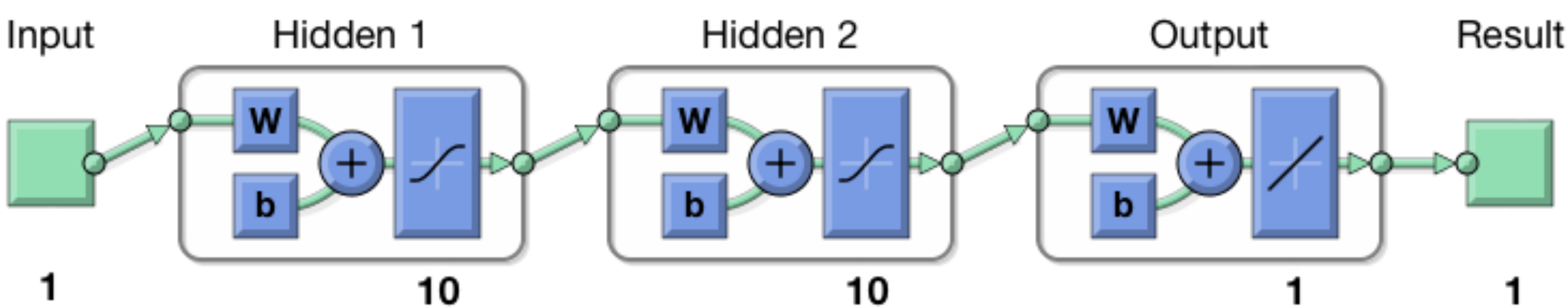
Impedance pneumography seemed to **underestimate tidal volumes** with **206 ml** on average; **average accuracy - 86.5%**; calibrated with 30-second-lasting free breathing



Dynamics correction

Non-linear model for flow-related signals

- **Simple linear modeling** based on flow-related signals (as a reference)
- **Neural network approach, trained individually:**
  - ➡ **single hidden layer** with **10** or **20** neurons
  - ➡ **two hidden layers** of **5** or **10** neurons
- **Simple linear modeling and neural network correction, trained individually:**
  - ➡ **single hidden layer** with **10** or **20** neurons
  - ➡ **two hidden layers** of **5** or **10** neurons
- **Simple linear modeling and neural network correction, trained globally:**
  - ➡ **single hidden layer** with **10** or **20** neurons
  - ➡ **two hidden layers** of **5** or **10** neurons

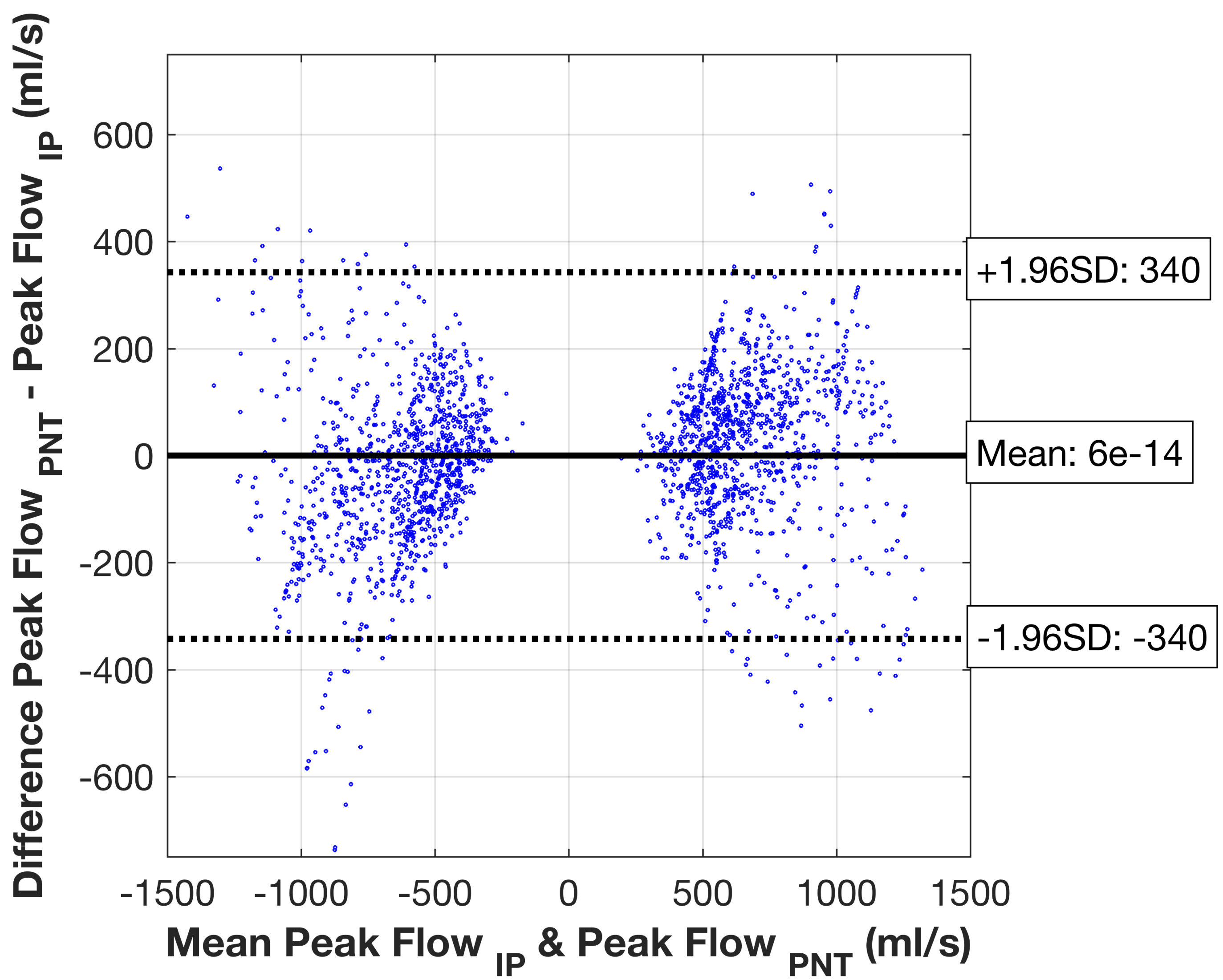


Dynamics correction

Non-linear model for flow-related signals

Best results obtained for **individually trained perceptron with 2 hidden layers (with 10 neurons)**

Average error level of flow parameters estimation - **20%** (in comparison to **27.5%** for linear modeling); using fixed breathing calibration



Objective 2

Detect motion artefacts in impedance pneumography signals

Methodology

Study group - 24 students (12 females and 12 males)

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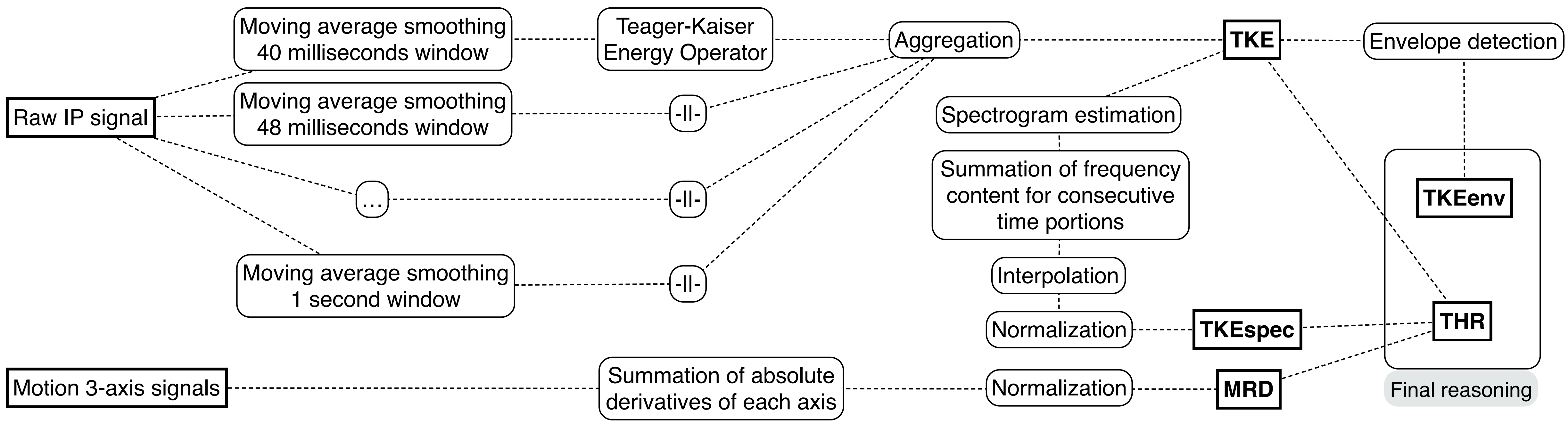
	Females		Males	
	Average	SD	Average	SD
Weight [kg]	58.6	5.6	76.2	9.5
Height [cm]	168.2	6.2	178.8	5.6
BMI	20.7	1.6	23.9	3.3
Age	22.3	5.3	22.9	3.2

Proposed algorithm



$$TKE(x) = \left(\frac{dx}{dt}\right)^2 + x\frac{d^2x}{dt^2}$$

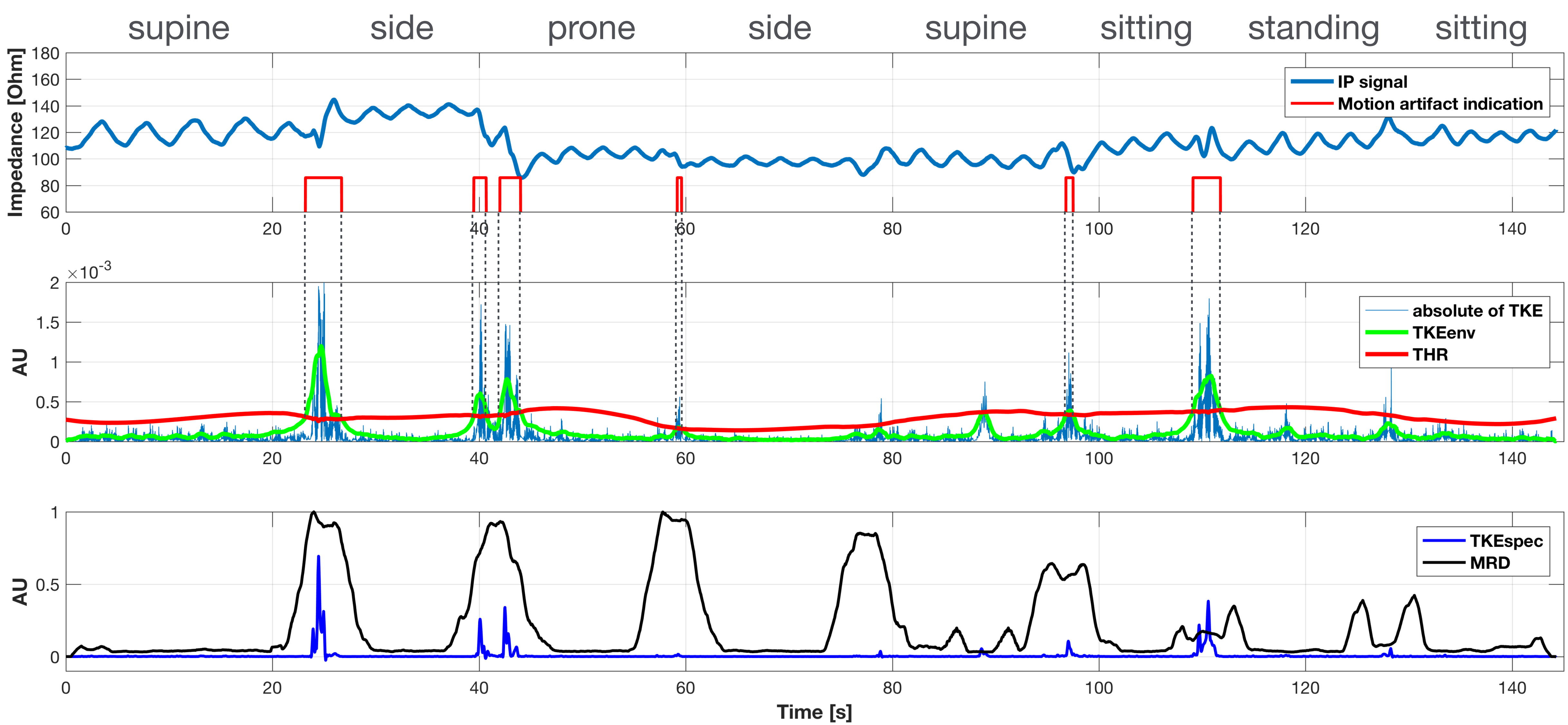
(Kaiser 1990)

$$TKE[n] = x^2[n] + x[n-1] \cdot x[n+1]$$

Abbreviations:

- **TKE** - the sum of all Teager-Kaiser Energy operators
- **TKEspec** - the signal being a processed **TKE** spectrogram
- **TKEenv** - the envelope of the original **TKE** signal
- **MRD** - motion-related signal
- **THR** - adaptive threshold, established from **TKE**, **TKEspec** and **MRD**

Sample signals and results



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Classification results

For the best strategy of threshold level establishing

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Accuracy [%]	**81.3**
Cohen's Kappa coefficient	**0.63**
Sensitivity [%]	**80.9**
Specificity [%]	**81.6**

Objective 3

Optimize sport training control by adding respiratory data

Methodology

Study group - Polish elite athletes

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Study before Olympic Games in Rio de Janeiro 2016: 32 females and 68 males

	Minimum	**Average**	**Maximum**
Weight [kg]	49.1	78.6	151.0
Height[cm]	158.0	183.3	208.0
BMI	17.4	23.2	42.7
Age	16.0	24.6	40.0

Study protocol

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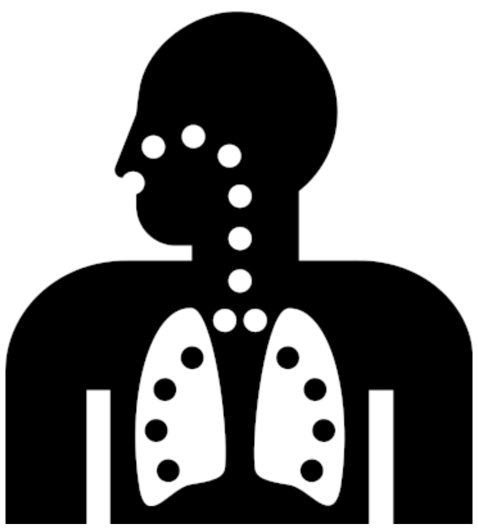
5 minutes



Free breathing

Supine, then standing

Input and output data

- **Parameters based on input data**
  - ➡ Only tidal volume signal
  - ➡ Only tachogram signal
  - ➡ Both, linked
- **Due to the domain**
  - ➡ time
  - ➡ frequency
  - ➡ information

Output labels

- ➡ **I** - moderate dynamic component during performance (wrestling)
- ➡ **II** - high dynamic component during performance (triathlon)

Classification methods

- Recursive Partitioning (CART)
- Random Forests
- Support Vector Machines (SVM)
- adaBoost
- Generalized Boosted Regression Models (GBM)

The best set of parameters

Established by dimensionality reduction algorithms

1. Absolute spectral content in the high-frequency band (0.15 - 0.4 Hz), extracted from the respiration signal
2. Average heart rate
3. Mutual information between signals aligned to mean sample entropy
4. Difference between the slope of the long axis of the fitted ellipse and the slope of the line of equivalence in a standard Poincare Plot
5. Distance from the center of the fitted ellipse to the line of equivalence in the standard Poincare Plot
6. Sample entropy of the cardiac signal
7. Absolute spectral content in the high-frequency band (0.15 - 0.4 Hz), extracted from the cardiac signal
8. Absolute spectral content in the very-low-frequency band (0 - 0.04 Hz), extracted from the respiration signal
9. Absolute cross-spectrum phase between breathing signal and HRV curve in the high-frequency band (0.15 - 0.4 Hz)
10. Relative spectral content in the high-frequency band (0.15 - 0.4 Hz), extracted from the cardiac signal

Classification results

	Accuracy	Cohen's Kappa
Recursive partitioning	0.666	0.333
Random forest	0.817	0.631
SVM	0.733	0.447
adaBoost	0.767	0.533
GBM	**0.833**	**0.669**

Classification results

Comparison of cardiac and cardiorespiratory set using GBM

Standard cardiac parameters utilized in sport medicine applications are:

- root-mean-square difference of successive normal R-R intervals (RMSSD);
- standard deviation of instantaneous R-R interval variability from Poincare plots,
- absolute cardiac spectral content in the high frequency (0.15 - 0.4 Hz)

(Plews et al., 2013; Bellenger et al., 2016)

	Accuracy	Cohen’s Kappa
Cardiac set	0.633	0.267
Novel cardiac + respiratory set	**0.833**	**0.669**

Discussion

Main limitations of the study

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Method verification

- Only 10 and 24 healthy and young participants in two studies
- Conducted in static conditions, without taking into account possible artefacts during natural functioning
- ECG analysis based only from single-lead configuration

Sport medicine application

- No athletes from group of low dynamic component during performance
- No reproducibility and trend analysis
- Lack of taking into account other parameters and psychological questionnaires collected before and after the Olympic Games

Discussion

Innovative contribution to the state-of-the-art

Warsaw University of Technology

- Development of new ambulatory devices for measuring impedance pneumography, ECG, movement, blood saturation and pulse wave data
- **Quantitative assessment of the effects of various factors** (inter-individual variability, body position, depth and frequency of respiration) on the **accuracy of the method**
- Evaluation of **reproducibility of calibration coefficients**
- Checking the configuration of electrodes proposed by *Seppa et al. (2013)* in static conditions in three body positions

Discussion

Innovative contribution to the state-of-the-art

Warsaw University of Technology

- Evaluation of various methods of **IP signal decomposition** for the estimation of tidal volume and cardiac function
- Development of **non-linear correction technique using neural networks** to improve the dynamics of flow-related signals
- Development of **algorithm for detecting motion artefacts** based on Teager-Kaiser energy operator and motion signal
- Evaluation of the ambulatory testing of respiratory activity in sport medicine application
- Proposing a set of known and new cardiorespiratory parameters **to assess the athlete's profiling**

Selected references

Related to thesis

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