Oscillatory behaviour of skin blood flow in response to local temperature change

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Outline

• Background/Motivation
  ➢ Thermoregulation and oscillations in skin blood flow
  ➢ Experiment with local skin cooling (Bandrivskyy et al.)

• The approach
  ➢ Experiments with local skin cooling and heating
  ➢ Wavelet transform
    ✓ Time-varying fluctuations in cardiovascular time series.
  ➢ Wavelet based phase coherence
    ✓ Mutual dependence between oscillations in skin temperature and blood flow.

• Results

• Summary
Thermoregulation and skin blood flow

- Thermal homeostasis in humans is primarily achieved by regulation of the level of blood flow in the skin.

- Spontaneous fluctuations around 0.1 Hz in digit blood flow are attributed to thermoregulation (Burton & Taylor, *Am J Physiol*, 1940)

Simultaneous records of skin temperature of a finger and of the pulse volume of an adjacent finger.
Thermoregulation and skin blood flow oscillations

- Time-scales of the oscillations involved in thermal regulation:
  
  - Spontaneous oscillations in blood flow and skin temperature - Kitney (1980), Shusterman et al., (1997) < 0.1 Hz. Specific frequency intervals not resolved.

  - Local skin **heating** affects variations in blood flow in two frequency intervals - around 0.1 Hz and 10 mHz. (Geyer et al., (2004), del Pozzi (2016)).

  - Local skin **cooling** affects variations in blood flow around 0.1 Hz and below 10 mHz (Bandrivskyy et al., 2004).

- The results vary dependent on **the temperature, duration of exposure and the rate of cooling/heating** (Johnson et al., 2014).
Motivation

Group median, and box-plots of the coherence ($C_\phi$) between skin temperature and blood flow signals before, during and after skin cooling with an ice pack, calculated within six characteristic frequency intervals.

Experiments with local skin cooling/heating

• Home-made module with temperature controller.

Experimental setup:
• Blood flow and skin temperature sensors placed on the volar side of the lower arm.
• Blood flow, skin temperature, ECG, respiration and blood pressure were recorded.
• 10 participants (3 females); mean age 30.8 ± 2.0 years
• Room temperature: (20.5 – 22)°C

• Copper plate (≈10 cm²) with laser-Doppler probe.
Time series of the perturbed site

basal condition (30 min)/24°C (30 min)  
basal condition (30 min)/42°C (30 min)
Time-averaged values

Blood Flow (AU)

Temperature (°C)

NP – non-perturbed (control) site; WP – perturbed site; gray – before; white – after cooling/heating
Questions

i. Which **oscillatory processes** are involved in vascular constriction/dilation resulting from local change in skin temperature?

ii. What we can tell about **physiological origin** of these oscillations?

iii. What is the role of **vascular endothelium** in temperature induced dilation/constriction?
Wavelet transform

- Extracts **time-frequency** information from time series
  - Detects how frequency and amplitude of oscillations **vary in time**

\[
WT(s, t) = \frac{1}{\sqrt{s}} \int_{-\infty}^{+\infty} x(u) \Psi(\frac{u-t}{s}) \, du
\]

- \( \Psi \) is rescaled in time by a factor \( s \) to give a range of frequencies
  - Slow events are analysed with long windows, while for faster events shorter windows are used

- This produces an amplitude and relative phase for each frequency of interest
Wavelet transform of blood flow

- 30 min long blood flow signal
- WT coefficients in the time-frequency plane
- Six peaks in the interval from 0.005 Hz to 2 Hz
- Logarithmic frequency resolution
## Time scales in humans

<table>
<thead>
<tr>
<th>No</th>
<th>Frequency interval (Hz)</th>
<th>Physiological origin</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.6 – 2</td>
<td>Heart rate</td>
</tr>
<tr>
<td>II</td>
<td>0.145 – 0.6</td>
<td>Respiration</td>
</tr>
<tr>
<td>III</td>
<td>0.052 – 0.145</td>
<td>Myogenic</td>
</tr>
<tr>
<td>IV</td>
<td>0.021 – 0.052</td>
<td>Neurogenic (sympathetic)</td>
</tr>
<tr>
<td>V</td>
<td>0.0095 – 0.021</td>
<td>Endothelial (NO-dependent)</td>
</tr>
<tr>
<td>VI</td>
<td><strong>0.005 – 0.0095</strong></td>
<td>Endothelial (NO-independent)</td>
</tr>
</tbody>
</table>

- 30 min long blood flow signal
Wavelet transform

Blood flow

Temperature
Wavelet time-localised phase coherence

• What about the interaction between blood flow and skin temperature?

• From wavelet transform of two time series one gets two phases \( \phi_{k,n} \) and then their relative phase difference \( \Delta \phi_{k,n} \) can be computed.

• Phase coherence can be calculated from time-averaged phase differences as:

\[
C_\phi(\omega_k) = \sqrt{\left\langle \cos \Delta \phi_{k,n} \right\rangle^2 + \left\langle \sin \Delta \phi_{k,n} \right\rangle^2}
\]

• Function \( C_\phi(\omega_k) \) takes values between 0 and 1 and gives values for phase coherence between two signals at the given frequency.
Wavelet phase coherence

Cooling

Heating

Wavelet phase coherence

a) before cooling during cooling

b) before heating during heating

p = 0.019

p = 0.0098

p = 0.013
Surrogate testing

• How do we determine if the phase of the oscillations is physiologically meaningful?

• Phase coherence of all pair of signals tends to 1 at low frequencies.
  ➢ Because the intrinsic frequencies of the time series are slowly varying.
  ➢ Because there are too few cycles of oscillations in the time series.

• Distribution of phase coherence for the real data is compared with the phase coherence values for mismatched signals to estimate significance.
Surrogate testing

- Phase coherence of skin temperature and blood flow (mean of the group) compared with the distribution of phase coherence values for mismatched surrogates (surrogate mean and 1 and 2 standard deviations above the mean).

![Graph showing phase coherence vs frequency with different lines for before cooling data, mean of surrogates, one sigma above mean, and two sigma above mean.](image)
Future directions

• Using this approach to develop a tool for non-invasive monitoring of an impaired thermal regulation as a result of healthy aging.

➢ Aging stiffens blood vessel wall, which results in the development of endothelial dysfunction.

➢ A decrease in endothelial related vascular dilation impairs thermoregulatory peripheral constriction.
Summary

i. Which oscillatory processes are involved in vascular constriction/dilation resulting from local change in skin temperature?

• During cooling, there was a significant decrease in the average frequency of myogenic blood flow oscillations and the myogenic spectral peak became more prominent.

• During heating, there was a significant general increase in spectral energy of blood flow signal, associated with vasodilation, except in the neurogenic interval.
Summary

- Weak **phase coherence** between temperature and blood flow was observed for **unperturbed** skin, but it **increased** in all frequency intervals as a result of **heating**. It was not significantly affected by cooling.

(ii) What we can tell about **physiological origin** of these oscillations?

- The mechanisms of vascular dilation and constriction, in response to temperature change, are oscillatory in nature and are independent of central sources of variability.

Collaborations with

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