Assessment of Blood Flow, Blood Volume and Haemoglobin concentrations by Photoplethysmography during induced hypothermia

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Background: The monitoring and assessment of blood flow, blood volume and oxygenation is of vital importance in clinical settings such as emergency medicine and surgery. Non-invasive techniques such as Photoplethysmography (PPG), Laser Doppler Flowmetry (LDF) and Near Infrared Spectroscopy (NIRS) are generally used to assess these parameters. Since the principle on which these techniques are based is similar, the possibility of measuring all these parameters using a singular technique should be investigated. In the present work, we investigated the feasibility of using PPG to assess blood flow and haemoglobin concentrations during a cold stress. The estimated parameters were then compared with simultaneous standard LDF and NIRS measurements.

Methods: Cold stress study was carried out in 6 healthy subjects after gaining the ethical approval of the Senate Research Ethics Committee at City University London. The investigation started with 2 minutes of baseline measurements at room temperature (24^{o}C), followed by ten-minute period of cold stress (10^{o}C) and additional ten minutes re-warming at ambient temperature. Red and infrared raw PPG signals were acquired from the left index finger. An LDF probe (MoorVMS-LDF2, Moor Instruments) was placed on the dorsal side of the left hand for RBC flow (Flux) and skin temperature measurements. An NIRS probe (NIRO 200NX, Hamamatsu) was positioned above the left brachioradialis for acquisition of haemoglobin concentration changes. All the signals were simultaneously acquired at 1 kHz sampling frequency.

Peak-to-peak amplitudes of IR AC PPG signals were calculated in a three-seconds rolling window and were normalized with respect to the baseline measurements. Oxygenated, reduced and total haemoglobin concentrations (HbO_2, HHb and tHb) were estimated by applying the modified Beer-Lambert law to red and infrared DC PPG signals. The solutions of the modified Beer-Lambert law are expressed in equation 1 and 2.

$$\Delta[HbO_2] = \frac{A_R \cdot \alpha_{IR_{HHb}} - A_{IR} \cdot \alpha_{R_{HHb}}}{\left(\alpha_{R_{HbO_2}} \cdot \alpha_{IR_{HHb}} - \alpha_{IR_{HbO_2}} \cdot \alpha_{R_{HHb}}\right)} \tag{1}$$

$$\Delta[HHb] = \frac{A_{IR} \cdot \alpha_{R_{HbO_2}} - A_R \cdot \alpha_{IR_{HbO_2}}}{\left(\alpha_{R_{HbO_2}} \cdot \alpha_{IR_{HHb}} - \alpha_{IR_{HbO_2}} \cdot \alpha_{R_{HHb}}\right)} \tag{2}$$

Results: Exposure to cold induced a drop of the mean skin temperature across the volunteers from 29.13 ± 1.44 °C in baseline to 18.94 ± 0.97 °C at the end of the cold stress. The decrease in temperature caused the LDF and AC PPG readings to drop to 0.51 ± 0.32 and 0.36 ± 0.24 from respective 1.16 ± 0.27 and 1.19 ± 0.32 baseline measurements. Fig. 1 shows Flux and AC PPG traces from four different volunteers during the stages of the experiment. The changes in normalized AC PPG during both cold exposure and recovery periods strongly correlated with Flux measurements.

Fig. 2 illustrates the haemoglobin concentration changes for the same volunteers presented in fig. 1. HbO_2 and tHb estimated from PPG decreased in all volunteers and followed the same parameters measured by NIRS. The gradual drop in oxygenated and total haemoglobin indicated the vasoconstriction throughout the cold stress. More pronounced increases in HHb measured by NIRS from the forearm were observed in some volunteers and might be related to muscle shivering. Moreover, the different locations from which haemoglobin concentrations were estimated (finger vs. forearm), and consequent light interrogation depth, may explain the quantitative differences between the two techniques.

Conclusion: This work wanted to investigate the feasibility of using PPG signals for the assessment of blood flow, blood volume, and haemoglobin concentration changes during an induced cold stimulus. The preliminary results showed responses to the induced stimulus and comparative analysis with state-of-the-art LDF and NIRS measurements indicated a satisfactory level of agreement between the techniques. These results may demonstrate that PPG signals could be used for the estimation of other useful cardiovascular parameters.

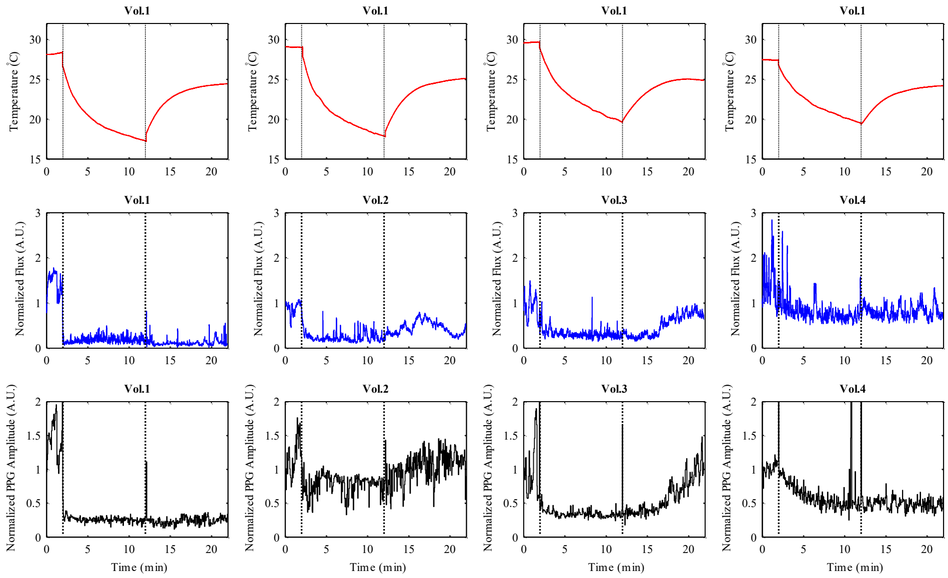

Figure 1: Changes in skin temperature (red traces), Flux (blue traces), and AC PPG amplitudes (black traces) in four volunteers investigated. Vertical dotted lines indicate the start and conclusion of the cold exposure.

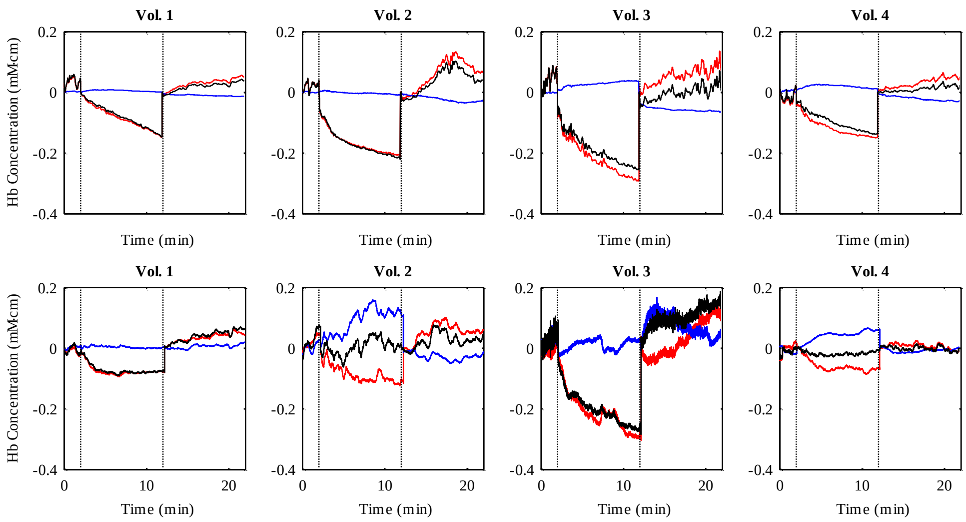

Figure 2: Changes in estimated concentrations of oxygenated (red), reduced (blue), and total haemoglobin (black) from four volunteers investigated. Top traces: haemoglobin concentrations estimated from PPG signals. Bottom traces: haemoglobin concentrations estimated from NIRS. Vertical dotted lines indicate the start and conclusion of the cold exposure.