Non-invasive blood haemoglobin and plethysmographic variability index during brachial plexus block†

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Editor’s key points

- Plethysmographic techniques have been developed for non-invasive measurement of haemoglobin levels.
- These may have a role in immediate monitoring of the effects of blood loss.
- Regional anaesthesia, using a brachial plexus block, did alter plethysmographic measurements during hand surgery.

Background. Plethysmographic measurement of haemoglobin concentration (SpHb), pleth variability index (PVI), and perfusion index (PI) with the Radical-7 apparatus is growing in popularity. Previous studies have indicated that SpHb has poor precision, particularly when PI is low. We wanted to study the effects of a sympathetic block on these measurements.

Methods. Twenty patients underwent hand surgery under brachial plexus block with one Radical-7 applied to each arm. Measurements were taken up to 20 min after the block had been initiated. Venous blood samples were also drawn from the non-blocked arm.

Results. During the last 10 min of the study, SpHb had increased by 8.6%. The PVI decreased by 54%, and PI increased by 188% in the blocked arm (median values). All these changes were statistically significant. In the non-blocked arm, these parameters did not change significantly.

Conclusions. Brachial plexus block significantly altered SpHb, PVI, and PI, which indicates that regional nervous control of the arm greatly affects plethysmographic measurements obtained by the Radical-7. After the brachial plexus block, SpHb increased and PVI decreased.

Keywords: haemoglobinometry; nerve blockade; perfusion; photoplethysmography; vasodilation

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During the past 5 years, Masimo’s pulse CO-oximeter Radical-7 has received considerable attention for its ability to measure the haemoglobin concentration (SpHb); the device may prove to be an important non-invasive tool to use when monitoring surgical blood loss.1–3 Another interesting variable is the plethysmographic (pleth) variability index (PVI), which could serve as an index of hypovolaemia.4–7 The PVI is an index of the breathing-induced variation in the perfusion index (PI), which is a blood flow parameter displayed along with the heart rate and haemoglobin (Hb) oxygenation. Most studies of PVI have been performed during mechanical ventilation, where it has been used to predict volume responsiveness. Rationally, it should be a more accurate measure when the intrathoracic pressures and the tidal volumes are the same for each breathing cycle. A few studies have examined spontaneous ventilation.8–10 These studies show similar variations in PVI changes, although only one included instructions for the volunteers on how to breathe.

Several studies have suggested that poorly identified physiological mechanisms may interfere with the output from the Radical-7 and therefore confound the data on SpHb and PVI. The SpHb usually shows good accuracy but poor precision when compared with invasive measurements of Hb concentration.11–13 Its accuracy is affected by the simultaneous infusion of fluid; slightly higher SpHb values are obtained when the PI is high.14 The PVI is typically twice as high in the conscious patient as it is in the anaesthetized state,10 which suggests that the nervous system might be involved in the generation of the parameter output.

The purpose of the present study was to investigate the influence of autonomic nervous activity on the three pulse oximeter parameters SpHb, PVI, and PI. The studied situation was the induction and onset of a brachial plexus block (BPB) in patients about to undergo surgery of the hand. The blocked and non-blocked arms were compared at precisely timed intervals using two Radical-7 apparatuses. We expected the PI to rise, because it is a measure of blood flow, and hypothesized that the PVI would decrease as a consequence of what occurs during general anaesthesia.

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Methods

Twenty patients about to undergo hand surgery, where the choice of anaesthesia was in the form of a brachial plexus block (BPB), were asked to take part in this study, which was conducted at Linköping University Hospital between January 2012 and March 2013. They gave written consent to participate in this study after being informed about its purpose orally and in writing. The protocol had been approved by the regional Ethics Committee in Linköping (Dnr 2011/357-31, 2011-10-26, Chairperson Lars Dahlstedt). Patients were recruited when the chief investigator (C.B.) was on duty. Exclusion criteria were abnormal neurological or vascular function of either arm (i.e. stroke, spasticity, arteriovenous fistulae, or extensive burn wounds). Patients unlikely to keep still during the measurements were also excluded from the study. Four patients were excluded because of technical problems with the Radical-7, such as a total loss of signal during the procedure; these participants were replaced with subsequent ones.

After having fasted for at least 6 h, the patients were given paracetamol (1 g) and/or diclofenac (50 mg) as a premedication. An i.v. cannula was inserted in a decubital vein in the arm not scheduled to undergo surgery. The cannula was intended for emergency use and also provided access for blood sampling during the study period. I.V. infusions were postponed until after the study period. All BPBs were performed by C.B. or by a junior colleague under supervision by C.B. Ultrasound guidance (Flex Focus 400; BK Medical, Herlev, Denmark) was used for all BPBs, which were either infraclavicular (n = 11) or supraclavicular (n = 9) depending on where the block seemed to be most easily performed based on a primary ultrasound scanning. Neurostimulation was not used. Seven of the blocks involved the left arm, and 13 were placed in the right arm. The local anaesthetic used was plain 1% mepivacaine (median volume 40 ml; range 33–40 ml).

Two Radical-7 pulse CO-oximeters (Masimo Corporation, Irvine, CA, USA) were used to monitor the SpHb, PVI, and PI in the blocked and the non-blocked arm. Both machines were updated to program V7.8.0.1. A single-use sensor (R2 25-a) was applied to each middle finger. The Radical-7 settings for averaging the parameters were set as follows: PI ‘short’ (few seconds), SpHb ‘medium’ (2–3 min), and PVI ‘short’ (~30 s), which are all in accordance with the recommendations from the manufacturer (Mirea D., personal mail communication). Both arms were covered with a blanket to avoid interference from ambient light sources. Baseline measurements of SpHb, PI, and PVI were taken from both arms. After the BPB had been instituted, the same parameters were recorded every minute for 20 min, beginning when the injection needle was withdrawn. Values for SpHb, PVI, and PI were read from the displays and recorded on paper.

Blood samples were taken for invasive measurement of Hb twice before the BPB was initiated and at 5, 10, 15, and 20 min after the block was performed. The samples were aspirated from the venous cannula and analysed according to the hospital routine on a Cell-Dyn Sapphire Haematology Cell Counter (Abbot Diagnostics, Abbot Park, IL, USA). Duplicate samples drawn at baseline ensured a coefficient of variation of 0.7%.

As some distributions were skewed, the results are presented as the median and 25th–75th percentile range, except where noted. Statistical analysis was made with Statistics version 10 (Stat Soft Inc., Tulsa, OK, USA). Wilcoxon matched-pairs test was used to compare data obtained from each arm, taking the mean of all measurements collected between 10 and 20 min, and to assess changes in the course of the study. The area under the curve (AUC) for each parameter was calculated for the entire study period (0–20 min) using the linear trapezoid method with Excel 2003 (Microsoft Corporation, Redmond, WA, USA). A value of $P < 0.05$ was considered statistically significant.

Results

The 20 participants (six males and 14 females) were aged between 17 and 86 years (median 50 years) and had a body weight of 50–96 kg (median 83 kg).

All BPBs resulted in patient-reported numbness and loss of sensation in the anaesthetized arm sufficient to begin surgery. Two patients required later conversion to general anaesthesia because the block offered insufficient pain relief. Marked changes in SpHb, PVI, and PI occurred during the first 5–10 min after the nerve block had been initiated (Fig. 1 and Table 1).

In the blocked arm, SpHb increased gradually and reached a plateau after 10 min, while there was virtually no change in SpHb or invasive Hb in the non-blocked arm (Fig. 1A). Between 10 and 20 min, the median SpHb in the blocked arm was 8.9% above baseline and 8.6% above SpHb in the non-blocked arm.

For the entire study period, the AUC for SpHb was significantly larger in the blocked arm in comparison to the AUC for SpHb ($P < 0.0015$) and invasive Hb ($P < 0.0001$) in the non-blocked arm. The difference between the mean SpHb and the invasive Hb for the time period between 10 and 20 min was positive for all studied patients in the blocked arm, while they were scattered around zero in the non-blocked arm. Despite this drift, the precision was 21% better in the blocked arm (Fig. 2), which rose to 25% if only the measurements performed at 15 and 20 min, when all patients had reached the plateau, were considered.

The SpHb bias (SpHb minus invasive Hb) showed a weak positive correlation with PI (blocked $r = 0.15$, $P = 0.002$; and non-blocked $r = 0.15$, $P = 0.001$), but scattering was considerable. The drift in SpHb was correlated with PI in the non-blocked arm ($r = 0.35$, $P < 0.001$) but not in the blocked arm ($r = 0.04$, $P = 0.44$; graphs not shown).

The PVI decreased in the blocked arm and reached stable values after 7 min (Fig. 1B). Between 10 and 20 min, the median PVI in the blocked arm was 54% below baseline and 53% lower than the PVI measured in the non-blocked arm. For the entire study period, the AUC for PVI was significantly lower in the blocked than in the non-blocked arm ($P < 0.0004$).

The PI increased in the blocked arm (Fig. 1C). Between 10 and 20 min, the median PI in the blocked arm was 188% above baseline and 106% higher than in the non-blocked arm. For
the entire study period, the AUC for PI was significantly higher in the blocked than in the non-blocked arm ($P < 0.0002$). There was no significant difference in PI between the first and the last measurement in the non-blocked arm.

**Discussion**

The results showed that regional nervous control of the arm greatly affected the plethysmographic measurements performed by the Radical-7. Application of a BPB increased SpHb by about 12 g litre$^{-1}$ in the blocked arm, while in the non-blocked arm the SpHb and the invasively measured Hb did not change. The SpHb is suggested to be a measure of the intravascular Hb concentration. However, interference with the nervous control of the vessels, which is an integral part of many forms of anaesthesia, apparently causes a drift in the signal. This effect is illustrated both in Figure 1A and in Figure 2.

Another finding was that PVI decreased more than 50% in the blocked arm, despite the fact that PVI is considered to reflect intrathoracic variations in blood flow during the respiratory cycle. Hypothetically, a large dose of local anaesthetic could induce vasodilation systemically and contribute to the changes seen in our study. However, this seems unlikely because there was no increase in PI in the non-blocked arm.

The arterioles contribute most to the vascular resistance and, as they are sympathetically innervated, should dilate in response to a BPB. The fact that local nervous control markedly affected SpHb could explain why the 95% confidence interval for the difference between SpHb and invasively measured Hb in some studies has been as wide as 40–50 g litre$^{-1}$. A problem with altering bias has also been described. In those studies, variability in vascular tone is sometimes discussed but not controlled for.

Improved tissue perfusion, as evidenced by the increase in PI, is another possible reason for the drift in SpHb. Previous work has shown that SpHb increases with PI, although scattering is considerable. In the present study, there was only a vague positive correlation between SpHb and PI in both arms and between the SpHb–Hb difference and PI. However, this comparison includes both the drift in SpHb and the baseline difference between SpHb and invasive Hb. When plotting only the drift in SpHb, there was a dependency on PI in the non-blocked arm but not in the blocked arm. Our belief is that the sympathetic tone normally affects both PI and the accuracy of SpHb, while other factors, such as local rheological mechanisms and blood viscosity, play a greater role when the autonomic inflow is blunted.

Fluid infusion experiments suggest that the relationship between PI and the accuracy of SpHb is more complex than indicated here. A volunteer study showed that hydroxyethyl starch causes SpHb to overestimate Hb, while acetated Ringer’s solution produced the opposite result. In fasting healthy volunteers, both fluids cause vasodilation. The difference in SpHb bias could then be attributable to extravasation of crystalloid fluid that could strengthen the background (non-pulsatile) signal of the Radical-7 measurements. The distribution and redistribution of a crystalloid solution in the hand occurs very fast and is completed within 2 min. A bewildering finding is that PI still decreases in response to both colloid and crystalloid fluid.

One possible explanation for the drift in SpHb is that the Hb concentration might genuinely change in the capillary bed.

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**Fig 1** Haemoglobin concentration measured by pulse oximetry and blood sampling (A), plethysmographic variability index (B), and perfusion index (C) during brachial plexus block, which was initiated at time zero. Data represent simultaneous recordings from 20 patients.
of the fingertip as a result of modifications in autonomic inflow. Microcirculatory studies show that the haematocrit changes when blood vessels become very thin. In rabbits, regional differences in haematocrit have been demonstrated in larger vessels. In a study on capillary glucose measurements, a higher capillary haematocrit was found in the forearm than in the finger. Altogether, these trends show that haematocrit is not constant throughout the body. An increase in capillary haematocrit because of the vasodilation caused by the BPB would be in line with these earlier microcirculatory findings. Miller and colleagues published a study about SpHb measurement during general anaesthesia for spinal surgery, and they found an increased number of accurate measurements after a digital nerve block. Our study differs from theirs in that our patients were fully awake with supposedly normal vasomotor tone, while their patients were already under general anaesthesia. Therefore, the difference in the finger perfusion should be more distinct in our study. Furthermore, in the study by Miller and colleagues, much of the normal attenuation of the pulse wave should have been intact, because their nerve block was more distal than our block. In fact, the PI in their study increased by 0.55 units, whereas in ours it increased by 3.8 units.

The PVI is a non-invasive correlate to pulse pressure variation, which is an algorithm implemented in several devices that aims to assess fluid responsiveness in anaesthetized patients. Table 1 shows the baseline values compared with the mean values between the 10th and 20th minute (End), and the difference (Diff). Also shown is the area under the curve (AUC) for the entire study period.

![Bland-Altman plots](image)

Fig 2 Bland–Altman plots comparing the haemoglobin concentration (SpHb) for the blocked (left) and the non-blocked arm (right) with the invasive control (Hb) after initiation of the brachial plexus block. Each circle represents the mean value of SpHb and Hb at 10, 15, and 20 min in a single patient.
patients.\textsuperscript{12} Exactly like pulse pressure variation, the PVI emanates from respiratory influence on the variations in blood flow that occur during cardiac filling.\textsuperscript{4} The PVI is expected to be below 10–12 in euvolaemic anaesthetized patients,\textsuperscript{5} while usually falling between 18 and 25 in conscious subjects.\textsuperscript{10} The present study discloses that a sympathetic block causes a profound decrease in PVI, which means that PVI cannot be a measure of central circulatory factors alone. Brachial plexus block modifies the arterial waveforms recorded in the brachial artery\textsuperscript{16} 19 33 to promote a more steady blood flow in the capillaries, which consequently lowers PVI.

Previous studies have implied (but not demonstrated) that sympathetic tone raises PVI. In surgical patients under general anaesthesia, PVI increased when the first skin incision was made,\textsuperscript{34} which is in concordance with our results. In another study, PI was used to indicate a successful interscalene block. A lower PVI in the blocked arm during subsequent general anaesthesia was a trend, but it did not reach statistical significance.\textsuperscript{20} Differences from our study include the use of sedating drugs for premedication and (later) of general anaesthesia, which probably depressed PVI by reducing the overall sympathetic tone. This view has received support from the thesia, which probably depressed PVI by reducing the overall sedating drugs for premedication and (later) of general anaesthesia and (later) of general anaesthesia.

The sequence of changes in SpHb, PVI, and PI deserves a comment. The Radical-7 averages of raw data are collected over certain time periods, and those time periods differ between the measurements for technical reasons. The fastest change was seen in PI, which is also averaged over the shortest time. The slowest change was in SpHb, which is averaged over the longest time. However, the averaging times differed by only 1–3 min, while PI changed 1–2 min after the block, PVI after about 7 min, and SpHb after ~10 min. Given that these differences are much larger than the changes in averaging times, we believe a physiological factor is involved. We hypothesize that an increase in PI could be elicited only from dilation of the most peripheral arterioles, which is an almost instant effect. The changes in SpHb and PVI probably require changes in the arterial pulse waveform, which requires a better-established blockade. Finally, if SpHb mirrors microvascular Hb, one may accept that displacement of the erythrocytes requires some time.

The present study was performed in conjunction with routine hand surgery, and there was little time for a detailed examination of the analgesia of all the different nerves to the arm. As a result of the ensuing hand surgery, all invasive Hb controls were removed from the non-blocked arm. Another limitation is that the study lasted only 20 min. However, based upon the graphs, it appears that all major changes had taken place at that time.

In conclusion, brachial plexus block increased PI and SpHb but decreased PVI in the blocked arm, while no such changes occurred in the non-blocked arm. The results are interpreted to indicate that sympathetic tone strongly affects readings of these parameters by the Radical-7 pulse CO-oximeter.

Supplementary material
Supplementary Material is available at British Journal of Anaesthesia online.

Authors’ contributions
C.B.: study design, patient recruitment, performing the measurements, data analysis, and writing. J.H.Z.: study design, assistance in performing the measurements, data analysis, and writing. R.G.H.: study design, data analysis, and writing.

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Declaration of interest
None declared.

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