Photoplethysmography in post-operative monitoring of Deep Inferior Epigastric Perforator (DIEP) free flaps

P A Kyriacou[1], T Zaman[1], and S K Pal[2]
[1]Research Centre for Biomedical Engineering, City, University of London, UK; [2]St Andrews Centre for Plastic Surgery and Burns, Mid and South Essex NHS Foundation Trust, UK

Email: P.Kyriacou@city.ac.uk

Abstract

Introduction: Deep Inferior Epigastric Perforator (DIEP) free flaps are widely used as a reconstruction option following mastectomy in breast cancer. During such cases partial tissue necrosis can occur due to the insufficient blood supply to the transplanted tissue site. Therefore, monitoring of flap perfusion and early detection of flap failure is a prerequisite to flap survival. There is a need to develop a non-invasive, easy to use, reproducible and inexpensive monitoring device to assess flap perfusion postoperatively.

Method: A three-wavelength reflective optical sensor and processing system based on the principle of photoplethysmography (PPG) has been developed to investigate blood volumetric changes and estimate free flap blood oxygen saturation continuously and non-invasively in Deep Inferior Epigastric Perforator (DIEP) free flaps in the postoperative period. The system was evaluated in fifteen patients undergoing breast reconstructive surgery using DIEP free flap.

Results: Good quality red, infrared and green PPG signals were obtained in the post-operative period. Initial estimation of blood oxygen saturation values estimated from the free flap PPGs seem to be in broad agreement with the commercial finger pulse oximeter used in this study.

Conclusion: This pilot study has demonstrated that Photoplethysmography has the potential to be used as a monitoring technique in assessing free flap viability.

REC Reference number: 10/H0703/39

1. Introduction

Free flap reconstructive surgery is the movement of tissue (e.g. skin, fat, muscle and bone) along with its blood supply from one site of the body to another. Following mastectomy in patients suffering from breast cancer, Deep Inferior Epigastric Perforator (DIEP) free flap is one of the options available for breast reconstruction. However, free flap failure is of a great concern as its been shown that complications such as vessel congestion, fat necrosis, total or partial flap loss, seroma and haematoma occur at a rate of 30% in DIEP free flap reconstructive surgery (Gill et al., 2004). Early detection and re-exploration of the flap is a prerequisite in flap survival therefore, continuous post-operative monitoring is vital for the successful salvage of the flap. Most clinical centres rely on clinical assessment of the flap in the post-operative period following DIEP free flap surgery, as this is considered to be the gold standard for perfusion assessment. Such assessment entails the observation of the flap skin colour, skin temperature, capillary refill time and occasionally pin prick time. Such observations are noted manually and regularly on a paper-based chart. Monitoring of these parameters are mainly qualitative and subjective, depending on the clinician or the nurses' experience. Also, these observations can also be inconsistent as the same person does not always monitor the patient. In addition to the aforementioned free flap monitoring practices, various technologies have also been used for monitoring free flap perfusion and viability such as temperature, Laser Doppler Flowmetry, Doppler Ultrasound and pulse oximetry (Machens et al., 1994). However, some of these techniques such as Doppler Ultrasound, are intermittent and operator dependant and

none of them are widely used routinely for free flap monitoring (van Adrichem, 1992, Rudolf F. Buntic, 2001-2013). An ideal free flap monitoring technique must be objective, continuous, non-invasive, safe, easy to manage and interpret by medical and nursing staff.

In order to overcome the limitations of the current monitoring techniques available and in an attempt to develop a practical device for assessing perfusion of free flaps post-operatively, a three wavelength photoplethysmography (PPG) sensor was designed and underwent preliminary clinical evaluation.

2. Photoplethysmography

Photoplethysmography (PPG) is a non-invasive, low cost, simple and easy to use technique that can be used to detect changes in arterial blood volume in the microvascular bed of tissue (Allen 2007, Kyriacou, 2013, Tamura, 2019). As light interacts with biological tissue it can be transmitted, reflected, refracted, scattered, and/or absorbed. Bone, skin pigmentation, arterial and venous blood are the primary absorbers of light with haemoglobin being one of the main components of blood which absorbs light passing through tissue. The absorbance of haemoglobin depends on its chemical binding and the wavelength of the light it is interacting with. Oxygenated and deoxygenated haemoglobin absorb most of the light at higher wavelengths in the near infrared region of the optical spectrum (Webster, 1997).

As the heart pumps blood to the periphery, the arteries and arterioles change in diameter due to the pulsation of the blood and hence the volume of blood is changing in the vessels. This variation of blood volume in the arteries is detected by illuminating the tissue under observation using LEDs, and detecting the transmitted or reflected light using a photodetector which is sensitive to the emitted wavelengths. The resulting information from the photodetector is a time varying signal which is widely known as the Photoplethysmograph (PPG) signal (Allen 2007, Kyriacou, 2013, Moyle, 2002, Webster, 1997).

The detected PPG signal comprises of two components as shown in Figure 1;

- A DC component, representing absorption by venous blood, bone, tissue and skin pigmentation and non-pulsating arterial blood.
- An AC component which is the pulsatile part of the total absorbance is often attributed to the cardiac cycle and the change of volume in the arteries. The shape of the AC PPG signal can be used as an indicative of vessel compliance and cardiac performance. Usually the amplitude of the AC component usually does not exceed 1-2% of the DC component (Webster, 1997, Kyriacou, 2006).

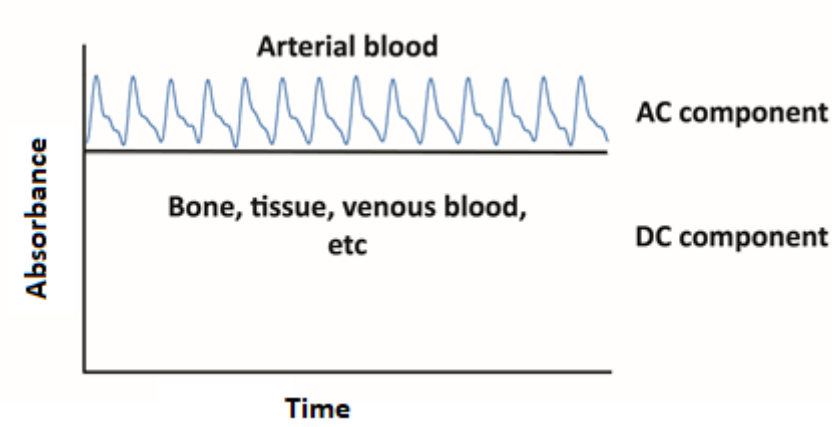


Figure 1: Photoplethysmography waveform with AC (variable absorption due to arterial pulsation) and DC (absorption due to tissue, bone and venous blood) components.

The depth of penetration of light in the skin varies depending on the wavelength. For example, green light (501 nm-543 nm) has a low depth of penetration due to its high absorption by melanin and haemoglobin, therefore it only penetrates approximately 0.2 mm, reaching the epidermal layer providing information from the capillary vessels, however red (620 nm-740 nm) and infrared (750 nm-1000 nm) wavelengths penetrate approximately 2-3 mm into the dermal layer (Mateus and Hargens, 2012, Futran et al., 2000, Asare et al., 2011).

In this study, a three-wavelength PPG sensor and processing system were developed in order to investigate free flap (DIEP) PPG signals in the post-operative period.

3. Materials and Methods

3.1 Free flap PPG sensor

A reflection photoplethysmography flap sensor was constructed using two infrared LEDs with peak emission wavelength at 940 nm and dimensions of 2.0 mm × 1.25 mm (AP2012F3C, Kingbridght), two red LEDs with peak emission wavelength at 660 nm and dimensions of 2.0 mm × 1.25 mm (EM20UR, EUROLED) and two green LEDs with peak emission wavelength of 520 nm and dimensions of 3.0 mm × 1.20 mm (CR60G, CERLED) surface ceramic chip surface mount LEDs. For detecting the reflected light from the tissue, a high speed and high sensitivity surface mount silicon PIN photodiode (VBPW34S) with an active area of 7.5 mm^2 and with dimensions of 6.4 mm × 3.9 mm × 1.2 mm was used. The bandwidth of the photodiode is 430 nm-1100 nm therefore enabling the detection of all three wavelengths used.

Figure 2 shows photographs of the developed three wavelengths reflective PPG flap sensor with the LEDs on and off. In Figure 2b the PPG sensor is covered with a sterile transparent sheath. This transparent medical dressing will be used when monitoring signals during the *in vivo* evaluation in order to avoid cross contamination between patients and ease sterilisation and cleaning of the sensor.

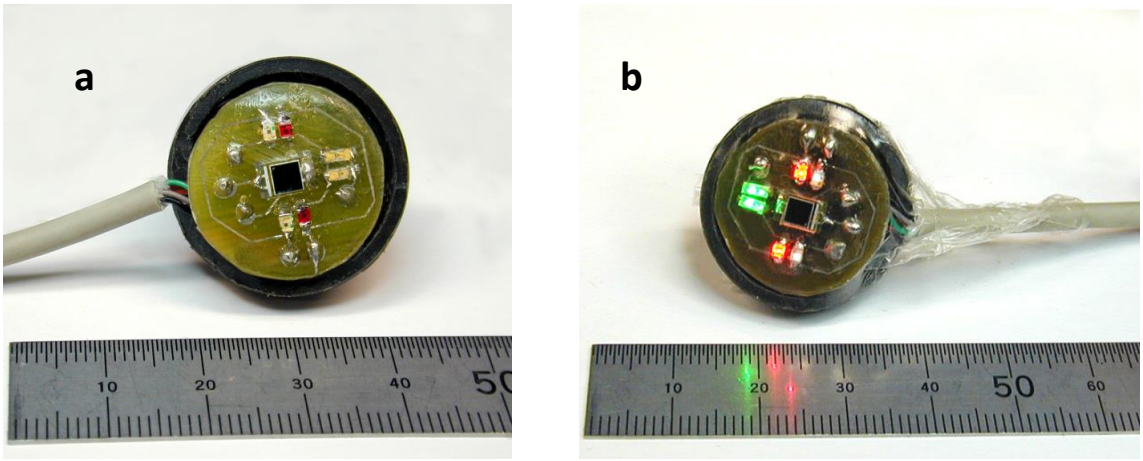


Figure 2: a) Developed three wavelength PPG flap sensor; b) Illuminated PPG flap sensor covered in sterile transparent sheath which will be used during the *in vivo* evaluation.

One of the requirements in designing a reflection photoplethysmography sensor is to determine the optimum separation distance between the light sources and the photodetector. Experimental studies by Mendelson and Ochs have shown that a separation distance of 4-5 mm between the light sources

and the detector is the optimum distance to enable detection of PPG signals with maximum pulsatile components (Mendelson and Ochs, 1988).

The reflection photoplethysmography flap sensor was designed using printed circuit board (PCB) technology utilizing the commercial software package Altium Designer (Altium Limited, Sydney, Australia) which was used for the PCB artwork. The sensor was coated using medically graded light curable clear epoxy (Dymax, OP-29, Ct, USA using a UV light curing system (Electro-lite, ELC-410, Ct, USA) for curing the optical adhesive. Coating the sensor with the epoxy provides adequate shielding and protection of the sensor for any accidental conduct with any fluids within the clinical environment, which can lead to a possible damage of the probe. The OP-29 series adhesive was selected based on its advantages of it being optically clear, resilient, resists yellowing and has high light transmission in the wavelengths of interest (500 nm-1000 nm).

3.2 Free flap PPG processing system

A PPG processing system was constructed in order to drive the optical components on the sensor and to pre-process the detected PPG signals. A detail block diagram of the three wavelength photoplethysmography processing systems is illustrated in Figure 3. The red, infrared and green LEDs on the flap probe were designed to be driven by identical variable current sources (25-151 mA) allowing the user to vary the output light intensity on demand. The current sources were multiplexed using a microcontroller to ensure the LEDs are never on at the same time (each LED was switched on every 10 ms for an interval of 1.66 ms).

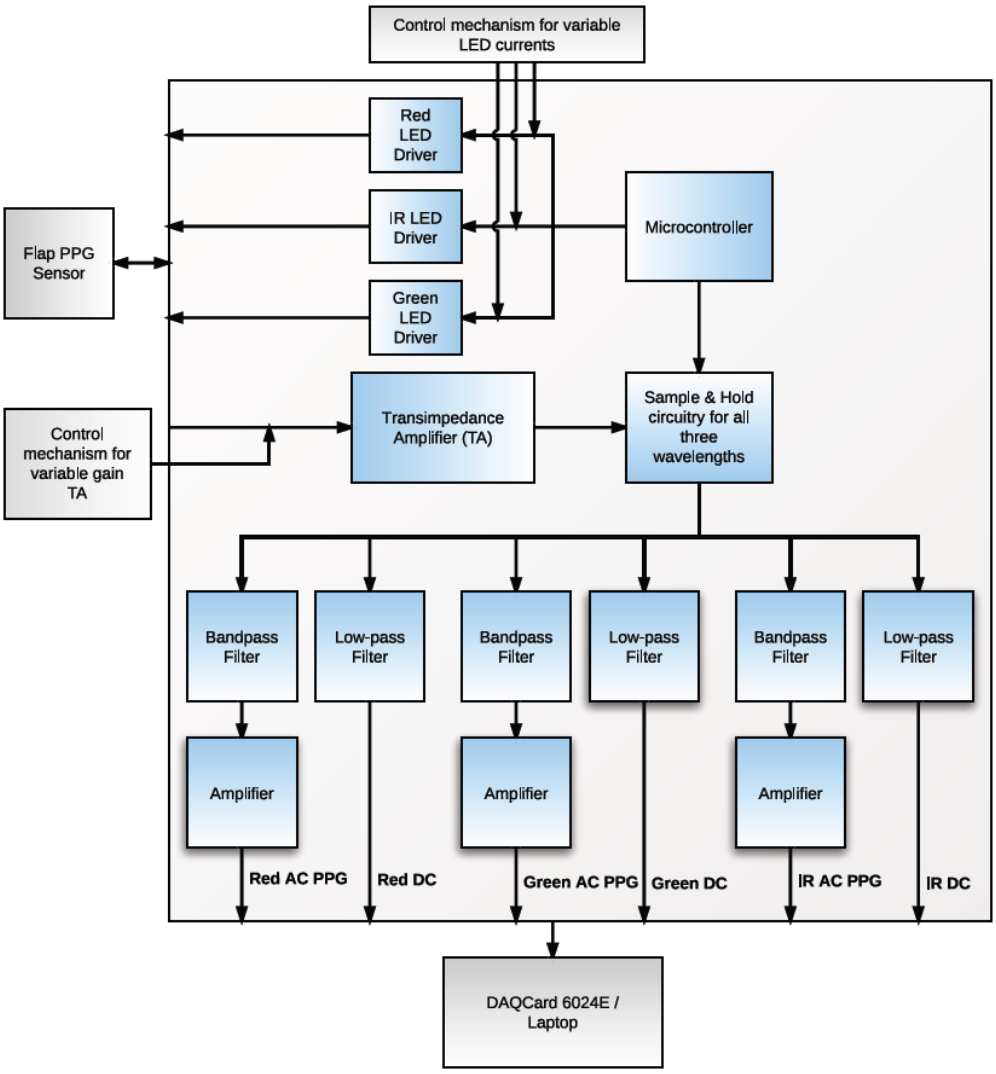


Figure 3: Block diagram of the three wavelength PPG processing system.

The photodiode on the PPG sensor is the main input in the photoplethysmography system where the intensity of the reflected light from the light emitted by the LEDs after their interaction with the tissue under observation is detected. The photodiode produces an output current which is linearly proportional to the intensity of light detected (Webster, 1997). To pre-process and display the detected signal a transimpedance amplifier which works as a current-to-voltage convertor was used. As the photodiode cannot distinguish between the different wavelengths, the signal is a mixed photoplethysmographic signal of red, infrared and green wavelengths. In order to separate the three wavelength PPG signals, the output of the transimpedance amplifier is fed into a demultiplexing circuit consisting of the three sample-and-hold circuits as well as the timing signal generated by the microcontroller. The timing signal is used to trigger the sample-and-hold circuits to sample the output of the transimpedance amplifier signal at appropriate times in order to extract the red, infrared and green PPG signals. Once the demultiplexer separates the photodiode signal into its three components of red, infrared and green signals, the waveforms representing the light levels are reconstructed from the output signal.

The outputs of the sample-and-hold circuits for red, infrared and green wavelengths are signals consisting of both AC and DC PPG components. These components (for all three wavelengths) are separated using filters.

To extract the AC component of the PPG signal band pass filters with cut-off frequencies of 0.4 Hz and 20 Hz were chosen to ensure that the pulsatile component of the PPG signal, which is approximately 1 Hz, is not distorted while the high pass filter was used to eliminate the DC component of the PPG signal and the high frequency switching noise from the demultiplexer was attenuated using the low pass filter. Also, in order to extract the DC component of the detected PPG signal a low pass filter with cut off frequency of 0.15 Hz was used. After the red, infrared and green photoplethysmography signals were separated into their AC and DC components, the AC PPG signals were then amplified, using a non-inverting amplifier.

The processing system provides output signals for AC PPG and DC PPG signals for red, infrared and green wavelengths. These outputs were then digitised (sampling rate at 200 Hz) using a data acquisition card (National Instruments, USA) which was connected to the laptop computer where the signals can then be displayed, analysed and stored using the developed Virtual Instrument (VI). The VI was implemented in LabVIEW (National Instruments, Austin, Texas, USA) on a laptop computer.

The functionality of the developed photoplethysmography processing system, the reflection three wavelength PPG sensor and the VI were successfully evaluated in the laboratory. Since good quality PPG signals were acquired from all three wavelengths from volunteer index fingers, it was deemed ready for preliminary clinical measurements.

3.3 Clinical methods

Following ethical approval from the East London Research Ethics Committees (REC reference number: 10/H0703/39) and patient consent, fifteen adult female patients with average age (±SD) of 54 (±8.9) undergoing elective breast reconstructive surgery using a DIEP flap were recruited to the study.

The post-operative PPG measurements were commenced in the post-anaesthesia care unit following surgery. In Mid Essex hospital where the clinical trials were carried out, the clinical team routinely uses *flap chart* where the flap is examined at 15-minute intervals for the first two hours, at 30 minute intervals for the following four hours and hourly for the next 12 hours. Where there was doubt relating to the viability of the flap, a Doppler Ultrasound was used by the medical staff to confirm flap blood flow.

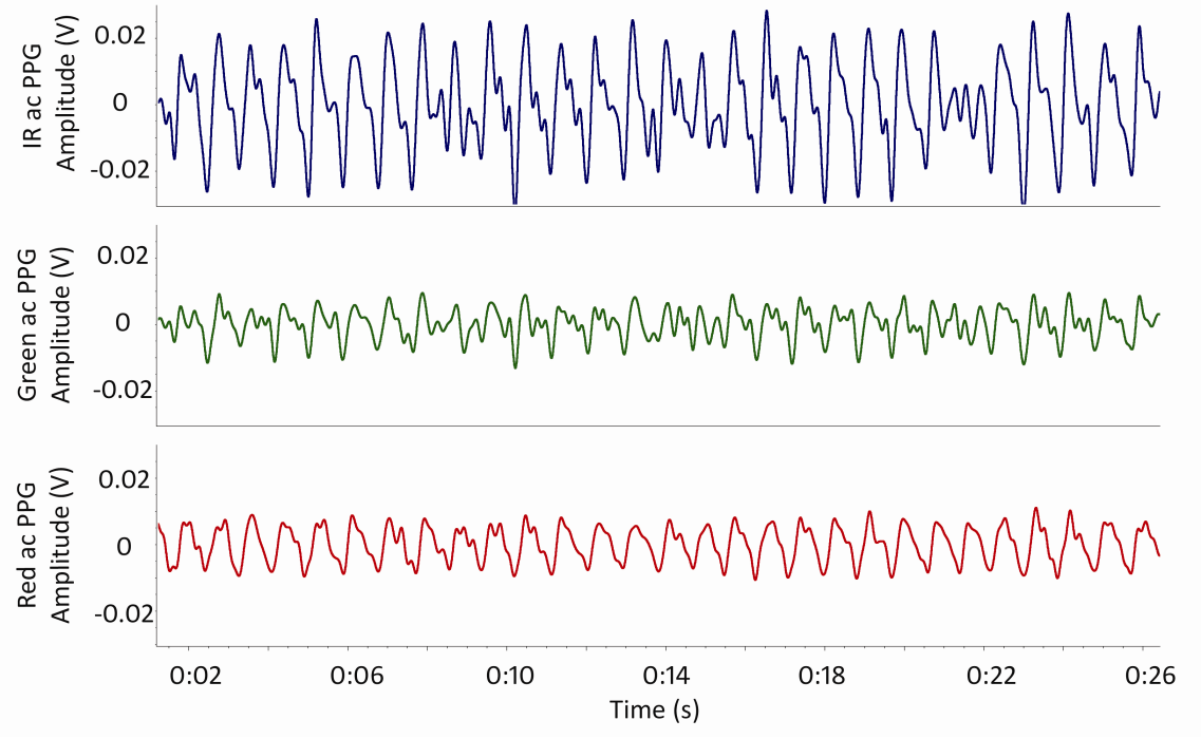
PPG post-operative measurements were performed at the same intervals as the clinical observations, i.e. at 15 minutes in the first two hours, 30 minutes for the following four hours and then hourly for up to 11 hours post-surgery. This monitoring routine ensured that the PPG study did not add any extra complication in the procedure and prevented any further disturbance to the patient. Therefore, the first set of measurements began in the post-anaesthesia care unit and then the latter parts of the measurements were carried out over night by the patients' bed side in the plastic surgery ward.

To avoid any wound contamination the free flap PPG sensor was covered with a sterile transparent adhesive film dressing (3MTM TegadermTM Film). The PPG sensor was placed on the flap and secured using surgical tape (3MTM TransporeTM). The position of the sensor on the flap was away from the area which was marked as having the main perforator supply in the pre-operative period. This was to avoid the PPG sensor being moved by the medical or nursing staff when they use the Doppler to assess

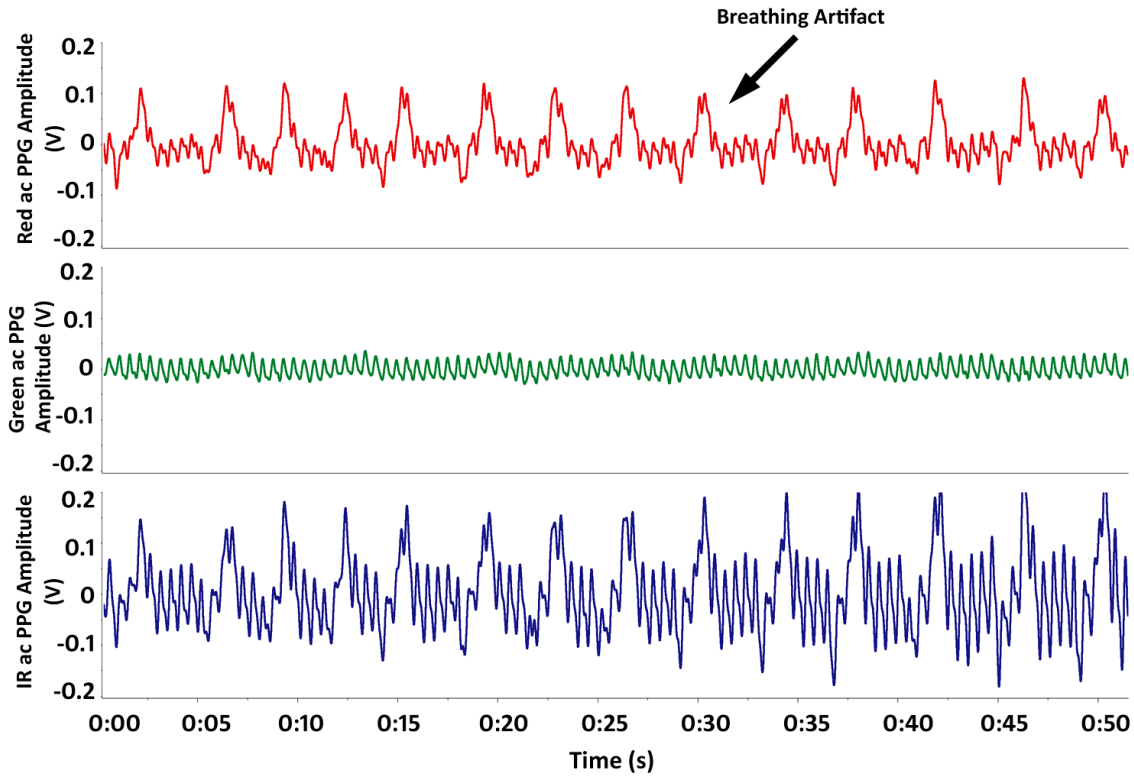
blood flow. To ensure repeatability and consistency of the signals obtained, the position of the sensor did not change throughout the post-operative period.

4. Results

Figure 4 (a and b) depicts typical flap PPGs from two patients in the post-operative period. In this figure (especially 4b) it can be observed that the PPG signals from all wavelengths are modulated by a spontaneous breathing artifact.



(a)



(b)

Figure 4: Typical PPG signals during the post-operatively period from all three wavelengths; (a) PPG monitoring at a time window of 26 s; (b) PPG monitoring at a time window of 50 s in order to capture the respiration modulation.

The acquisition of PPGs at each monitoring period lasted for approximately one minute. Table 1 shows the mean PPG amplitude at all wavelengths for all monitoring periods from one patient. In each patient using the infrared PPG signals the heart rate was also calculated offline and compared with the recorded measurement from the commercial finger pulse oximeter to confirm the capability of the developed system in measuring heart rate.

From the results in Table 1 it is noticed that there is an increase in the PPG amplitude one hour subsequent to the transferring of the patient to the post anaesthesia recovery room, suggesting that this could be an indication of improved blood flow to the flap. At approximately five hours post-operatively a reduction in the amplitude is seen. The reduction could be due to environmental factors such as temperature, since at 8 hours post-operatively the patient warmer blanket was switched on (for this particular patient) as this resulted in the increase of the PPG amplitudes in the red and infrared wavelength but not so in the green wavelength.

Table 1: Mean AC PPG amplitudes from all wavelengths in one DIEP patient.

	AC PPG Amplitude (mV)		
Interval (Hr)	**IR**	**Red**	**Green**
Recovery	120.4	87.3	41.3
1 Hr	229	108.1	29.9
2 Hr	182.1	110.1	23.3
3 Hr	230.7	119.5	29.1
4 Hr	147.3	87.1	31.4
5 Hr	97.6	53	35.6
6 Hr	84.7	45.6	31.1
7 Hr	69.1	44.9	40.8
8 Hr	158.6	70.2	35.8
9 Hr	148	78.3	25.1
10 Hr	149.8	99.4	33.7
11 Hr	108.2	54.5	23.3
12 Hr	139.9	76.5	14.4

In order to analyse and investigate how the PPG amplitude changed during the post-operative period, the mean PPG amplitudes (±SD) from all patients from all monitoring periods is presented in Figure 5. At times, it was found somewhat challenging to monitor good quality PPGs from the DIEP flaps. Patient movement, room temperature, and flap temperature were some of the obvious reasons that compromised both the quality and the amplitude of the PPGs. Since the PPG amplitudes were inconsistent from patient to patient this has resulted in the high amplitude standard deviations seen in Figure 5. This could also be due to the different thickness of the free flap from patient to patient and the diameter and number of the blood vessels used in anastomosing the free flap to the recipient site.

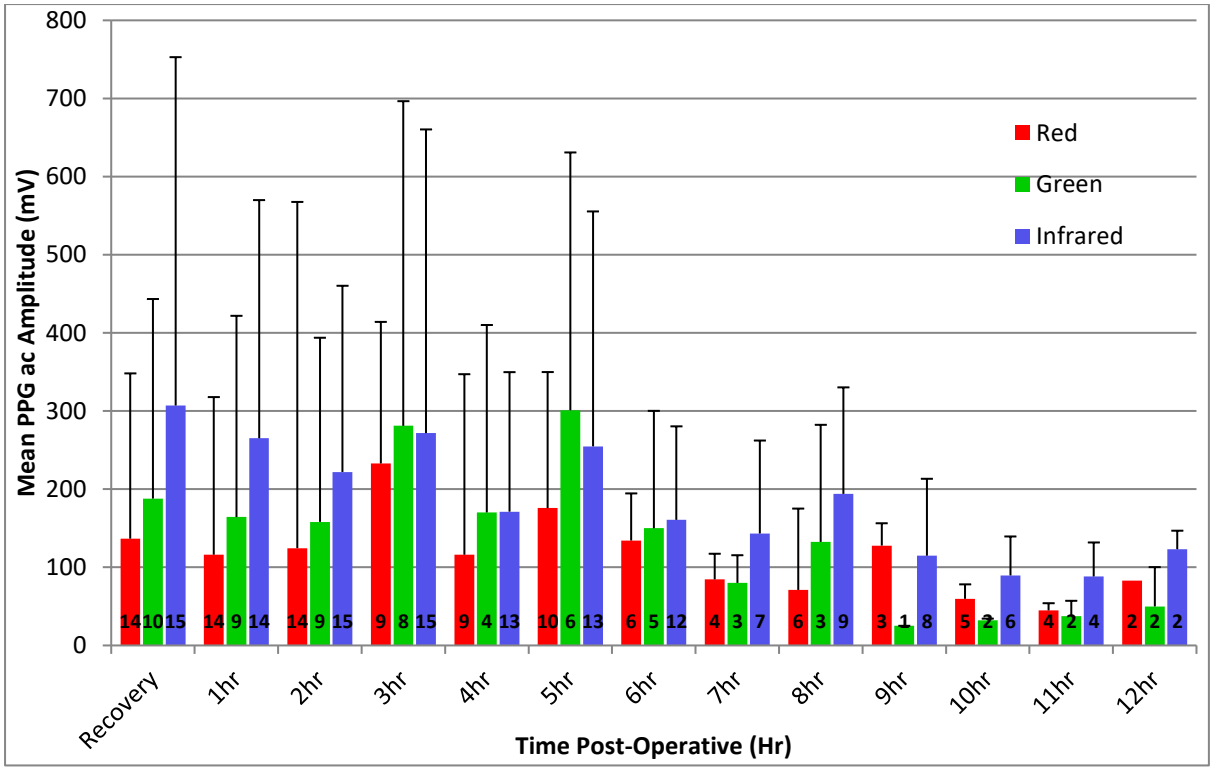


Figure 5: Mean amplitude of red, green and infrared ac PPGs acquired from all patients post-operatively at hourly intervals.

By observing Figure 5, it can be also seen that there is a decrease in the mean PPG amplitude after six hours in the post-operative period in all three wavelengths. Many assumptions have been made regarding this change in blood volume in the flap. Pereira et al. explains that as free flap reconstructive surgery is typically 6-8 hours long, with surgical procedures performed on the abdomen and the chest, this results in considerable blood, heat and fluid loss. If gone unnoticed this can bring about hypovolaemic vasoconstriction and hypothermia, which causes the blood flow through the flap to decrease 50% in the first 6-12 hours following surgery (Pereira et al., 2012). However, the clinical collaborators of the study have explained that hypovolaemia and hypothermia did not occur in these patients as they were looked after in the specialised surgical HDU area with strict monitoring and quick intervention if physiological parameters deviated from a set value. Another explanation offered was that during the ischaemic period, metabolism in the flap occurs without oxygen (anaerobic metabolism) which leads to production of metabolites (or mediators) which causes dilatation of the vessels in the flap. This phenomenon occurs in the body in any anaerobic conditions to allow more blood to flow into the oxygen deprived tissues in order to get more oxygen. When the flap anastomosis is completed and the vessel clamps are removed, oxygenated blood flows through the flap and starts the aerobic metabolism. Simultaneously the blood attempts to flush the metabolites accumulated in the flap. Once the metabolites are flushed out of the flap and oxygenated blood is perfusing the flap, it is unnecessary for the vessels in the flap to remain dilated. It must also be noted that there is no neural autoregulation of blood flow to the flap as the tissue is denervated. It must be considered that no study have yet been carried out on the time taken for the vasoconstriction of the vessels once the metabolites have been flushed out but it can be hypothesised that this could occur within 6-8 hours post-operatively which would explain the reduction in blood flow through the free flap.

Utilising the AC and DC PPGs at both red and infrared wavelengths recorded in the post-operative period, arterial oxygen saturation levels were successfully estimated from the flap sensor. Blood oxygen saturation values were also acquired from a commercial transmission finger pulse oximeter and a custom-made finger reflection pulse oximeter with identical optical and electrical specifications as the flap sensor. Figure 6 shows the plot of the mean and standard deviation from all patients at all post-operatively periods.

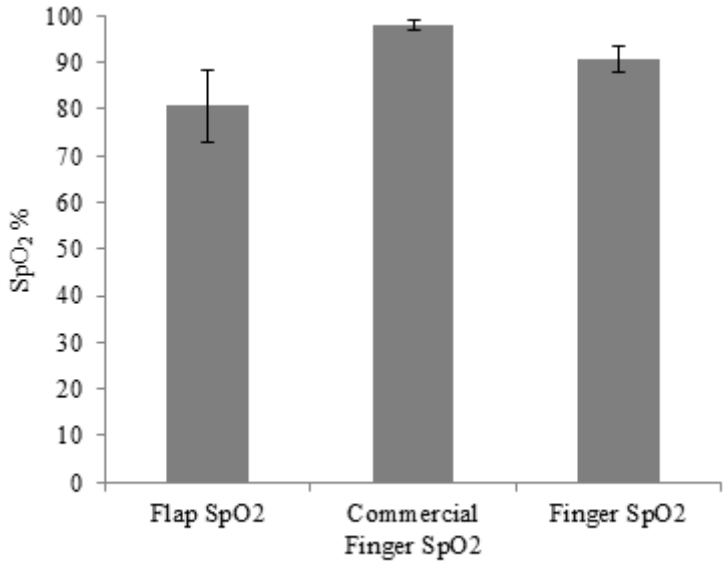


Figure 6: Mean and standard deviation of flap, finger (custom made) and commercial SpO_2 levels from all patient studied in the postoperative period.

4. Conclusion

The developed flap PPG sensor and processing system were successfully evaluated in the fifteen patients post-operatively where the free flap was monitored simultaneously with the routine flap observations carried out at regular intervals over night for up to 12 hours. Investigation of the post-operative PPG measurements show that good quality PPG signals with clear morphologies of a typical PPG waveform can be detected from all three wavelengths. Depending on the surgical time the length of post-operative monitoring period varied between patients as it was only possible to monitor the patient until approximately 5-6 am in the morning after the surgery. In patients where the surgery time was longer, the initial measurement was performed late in the evening following surgery. Therefore, in those cases, 12 hours of post-operative monitoring was not achieved which resulted in fewer patients monitored at 11 or 12 hours following surgery compared to the number of patients where PPG signals were obtained for in the recovery unit in the post-operative period.

Investigation of the PPG signals show that the amplitude of the green AC PPG signals are lower than those from red and infrared, which it might be due to low penetration of green wavelength and its high absorption by blood, therefore it is assumed that the PPG signal from the green wavelength is the reflected light from haemoglobin in dermal capillary (Futran et al., 2000, Mateus and Hargens, 2012).

The developed three wavelength reflection optical sensor was unique as it has used three wavelengths within the visible and the infrared spectrum to simultaneously investigate PPG signals obtained at all

operative periods of the surgical procedure. The motivation for the chosen wavelengths is that it provides the capability to monitor PPGs from vasculature located at different depths. The initial estimation of blood oxygen saturation values estimated from the flap PPG sensor seems to be in broad agreement with the commercial finger pulse oximeter used in this study. Such preliminary results provide the necessary confidence that a PPG based sensor technology can provide both blood volumetric information and blood oxygen saturation of free flaps and hence enhances the justification and motivation that photoplethysmography could be used in the assessment of the viability of free flaps.

In conclusion, the results from the pilot *in vivo* study have demonstrated for the first time that a custom made non-invasive multiwavelength photoplethysmography system has the capability of detecting and monitoring changes in blood volume in free flaps in post-operative patients undergoing breast reconstruction using DIEP flaps.

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