35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Free flap pulse oximetry utilizing reflectance photoplethysmography

T. Zaman, P. A. Kyriacou, Senior Member, IEEE and S. K. Pal

Abstract—**The successful salvage of a free flap is dependent on the continuous monitoring of perfusion. To date there is no widely accepted and readily available post-operative monitoring technique to reliably assess the viability of free flaps by continuously monitoring free flap blood oxygen saturation. In an attempt to overcome the limitations of the current techniques a reflectance photoplethysmographic (PPG) processing system has been developed with the capability of real-time estimation of arterial oxygen saturation (SpO_2) levels implemented in LabVIEW. This system was evaluated in clinical measurements on five patients undergoing breast reconstruction using Deep Inferior Epigastric Perforator (DIEP) flap. Good quality PPG signals were obtained from the flaps and fingers simultaneously. The estimated free flap SpO_2 values were in broad agreement with the oxygen saturation readings from the commercial pulse oximeter. The results suggest that reflectance free flap photoplethysmography can be used as a continuous monitoring technique to non-invasively monitor the perfusion of free flaps.**

I. Introduction

In some patients diagnosed with breast cancer, partial or complete mastectomy is carried out to remove breast cancer tissue. In most of these patients breast reconstructive surgery is performed where autologous tissue is used to construct a natural looking breast. One of the most common types of these surgeries is Deep Inferior Epigastric Perforator (DIEP) free flap where skin and fat along with their blood supplies are transferred from the lower abdomen to the chest. Continuous monitoring of the perfusion of free flap is vital to flap survivability. Recent studies have reported that circulatory compromise is detected in approximately 5-25% of free flaps where surgical re-exploration is required to salvage flap tissue [1-2]. It has also been suggested that flap failure occurs due to both venous and arterial occlusion with an increased risk of arterial occlusion within the first 24 hours post operatively [3].

Various techniques and technologies have been used for monitoring free flap perfusion [4]. However, during the post-operative period following DIEP free flap surgery most clinical centers rely on qualitative clinical assessment of the flap by evaluating the skin color, skin temperature, capillary refill time and occasionally pin prick time. However, these techniques are mainly qualitative and subjective and can be unreliable, inconsistence and sometimes erroneous. They also depend on the experience and skill of the clinical staff [5].

Photoplethysmography (PPG) has been suggested as a monitoring technique in an attempt to overcome the limitations of the current technologies used for assessing free flap perfusion [6]. PPG is a non invasive, low cost, simple and easy to use optical technique that can be used to detect changes in arterial blood volume in the microvascular bed of tissue. 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 [7]. This variation of blood volume in arteries is detected by illuminating the tissue under observation using LEDs, usually in the range of 600 nm to 940 nm. The transmitted or reflected light is detected using a photo-detector which is sensitive to the emitted wavelengths. Photoplethysmography has widespread clinical applications such as pulse oximetry, where the technology is utilized to determine the oxygen saturation of arterial blood (SpO_2) by measuring the ratio of the red and infrared light which is absorbed by oxygenated and deoxygenated hemoglobin [8].

Earlier preliminary studies on patients undergoing DIEP free flap surgery using a prototype dual wavelengths optical sensor suggest that good quality PPG signals with good signal-to-noise ratio at two wavelengths of red and infrared could be detected during pre-operative, intra-operative and post-operative periods [5].

In the present study the data acquisition system with the PPG processing system used in a previous study [5], has been modified to allow the real-time estimation of SpO_2 levels of the free flap. Another alteration to the system is the addition of an extra PPG processing system to allow the simultaneous monitoring of PPG signals from both the free flap and the finger where both the flap and the finger sensors and the processing system are optically and electrically identical.

The aim of the design and development of this finger PPG sensor was to enable the simultaneous detection and comparison of the PPG signals from both the flap and the finger as well as comparing and validating the estimated arterial oxygen saturation values from both flap and finger channels with the SpO_2 values recorded from a commercial finger pulse oximeter which is routinely used as part of the patients' regular clinical observations.

*This work was supported in full by the Engineering and Physical Sciences Research Council.

T. Zaman is with the School of Engineering and Mathematical Sciences, City University London, London, UK (e-mail: tina.zaman.1@ city.ac.uk).
S. K. Pal is with the St Andrews Plastic and Burns Unit, Broomfield Hospital, UK (email: Sandip.Pal@meht.nhs.uk).
P. A. Kyriacou is with the School of Engineering and Mathematical Sciences, City University London, London, UK (e-mail: p.kyriacou@city.ac.uk).

II. METHODS

A. PPG flap and finger sensor and processing system

A flap reflectance PPG sensor was developed using LEDs with wavelengths at 940 nm and 660 nm (infrared and red) respectively and a photodiode with the appropriate spectral range sensitivity to enable detection of both wavelengths. The distance between the LEDs and the photodiode was 5 mm as such distance has been proven to provide good quality PPGs in reflectance pulse oximetry [9]. The shape of the sensor was circular and designed to be small enough (diameter: 20mm) in order to be accommodated on the exposed part of the DIEP flap during and after the operation. The detected PPG signals consist of two components; a dc component which is an almost constant voltage due to the absorption by venous blood, bone, tissue and skin pigmentation and an ac component which is the pulsatile part of the total light absorption, this is often attributed to the change of blood volume which is in synchronous with the cardiac cycle.

As shown in Figure 1, in addition to the flap PPG sensor (a), a finger PPG sensor (b) was also developed using identical optical components which were placed inside a modified commercial pulse oximeter clip to ensure the probe is secured onto the patient's finger with adequate pressure. The flap and finger sensors will enable comparison of the estimated oxygen saturation and PPG signals from both sites.

As seen in Figure 1(a), the flap probe was attached to a black sensor cover which was specifically designed to shield the probe from ambient light. The cover also facilitated in securing the sensor on the flap.

The optical components of both the flap and finger PPG sensors were driven using two electrically identical PPG processing systems [5]. The detected ac and dc PPG signals at both wavelengths were then preprocessed using these developed systems where the signals were then digitized using a 12-bit data acquisition card (DAQCardTM-6024E) by National Instruments. The ac and dc PPG signals from both red and infrared wavelengths were then acquired, stored, displayed and analyzed using an implemented Virtual Instrument (VI) on the software program LabVIEW.

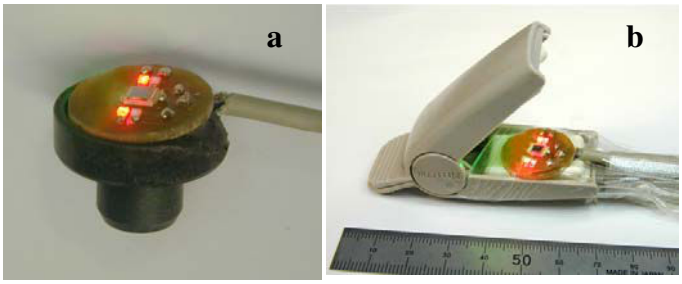

Figure 1: Reflectance photoplethysmographic sensors; (a) flap PPG sensor; (b) modified commercial pulse oximeter finger clip with PPG finger sensor.

As discussed earlier, percentage of arterial oxygen saturation can be estimated by determining the absorption of red and infrared wavelengths by oxygenated and deoxygenated hemoglobin. A VI has been implemented in LabVIEW to estimate the percentage of blood oxygen saturation of both the flap and finger using the ac and dc components from both red and infrared wavelengths. This value is calculated by measuring the amplitude of the ac component and the constant voltage of the dc component of the PPG signal at these two wavelengths, and calculating the ratio (R) value using (1)

$$R\ (ratio) = (ac_{660}/dc_{660}) / (ac_{940}/dc_{940}) \quad (1)$$

where R represents the ratio of absorption of oxygenated and deoxygenated hemoglobin. This value is then compared to a "look-up" table which is based on calibration curves derived from healthy subjects at various SpO_2 levels [8]. Using (2) the percentage of arterial oxygen saturation is then calculated.

$$SpO_2 = 110\text{-}25R \quad (2)$$

Equations (1) and (2) have been implemented in a VI to enable real-time display of flap and finger SpO_2 values as well as displaying the raw and filtered PPG signals as shown in Figure 2.

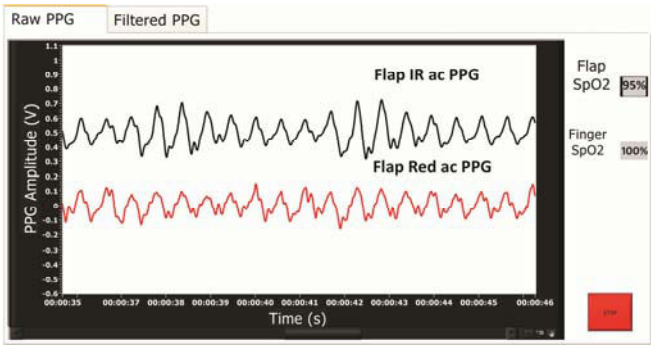

Figure 2: Front panel of the developed VI with real-time display of flap and finger SpO_2.

B. Preliminary Investigation of Flap and Finger Sensor

Local research ethics committee approval, research and development approval of the NHS site and patient consent were acquired prior to commencing the study. The clinical trials were carried out at St. Andrew's Centre for Burns and Plastic Surgery at Broomfield Hospital, UK.

A preliminary clinical study was carried out on five patients (mean age of 61 ± 6.2 years) suffering from breast cancer who underwent mastectomy with immediate elective breast reconstruction using DIEP flap.

Following the surgical procedure of transferring the free flap from the abdominal region to the recipient site (the chest) and the anastomosis of the arterial and venous blood vessels and the successful completion of the surgery the patient was transferred from theaters to the post-anesthesia care unit, where with the surgeons consent post-operative monitoring commenced.

To ensure patient safety the flap PPG sensor was covered with a sterile transparent adhesive film dressing (3M™ Tegaderm™ Film). The sensor was then placed on the flap and secured in place using surgical tape (3M™ Transpore™) to facilitate repeatability of the measurements as shown in

Figure 3. The finger PPG sensor was secured onto the patients' index finger. The sensor was also covered with Tegaderm to ease sanitization of the sensor and to avoid cross-contamination between patients.

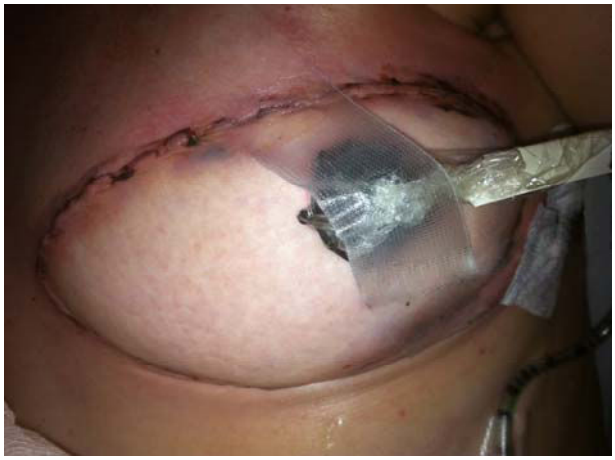

Figure 3: Photograph of the flap PPG sensor secured on the exposed skin of the DIEP free flap in the post-operative period.

PPG measurements were obtained at the same intervals as the routine qualitative assessment of the free flap in the post operative period. This ensures that the PPG study did not add any extra complication in the procedure plus enabled a comparison/correlation of PPGs with the qualitative assessment (temperature, skin color, capillary refill time and flap texture). These observations were recorded at regular intervals of every 15 minutes in the first two hours, every 30 minutes for the following four hours and hourly for the subsequent 12 hours. The initial post-operative measurement was obtained in the post-anesthesia care unit where measurements were obtained at the specified intervals as well as continuing with data acquisition when the patient was discharged to the surgical ward for up to 11 hours post-operatively. In addition to keeping a record of the flap assessment chart, patient vital signs such as blood pressure, temperature, heart rate and SpO_2 levels were also recorded.

III. Results

Photoplethysmographic signals were successfully acquired from both red and infrared wavelengths from the flap and finger using the two identical reflectance PPG sensors and processing systems from all five recruited patients post-operatively.

A. Photoplethysmographic signals from free flap and finger

Figure 4 shows typical red and infrared ac PPG signals acquired at one hour post operatively from the flap and the finger of a patient. Signals from both PPG processing systems appear to be of good signal-to-noise ratio with adequately large amplitudes that enabled the estimation of SpO_2 values for both channels.

Table 1 shows the mean of infrared ac PPGs for each of the five patients independently at all intervals beginning from post-anesthesia care unit for up to 11 hours post operatively.

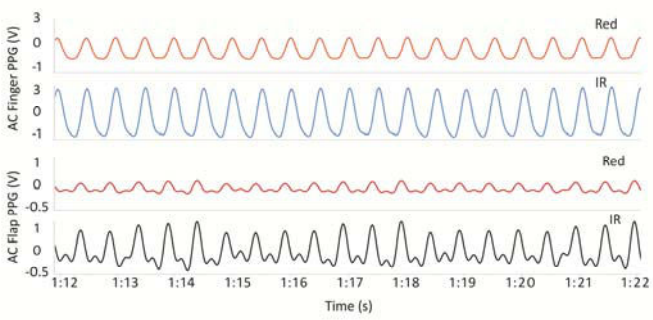

Figure 4: Typical red and infrared PPGs from the finger (top graph) and free flap (bottom graph) sensors.

The table also shows the mean and standard deviations of the amplitudes of the infrared ac PPGs for the flap and the finger for all patients. In one of the patients no infrared measurements were obtained from the finger sensor due to technical problems.

The large standard deviation values are due to the great variations in PPG amplitudes at different intervals post-operatively where it has been noted that the PPG amplitude typically increases over time followed by a sudden decrease at approximately 7 hours in the post-operative period. Also, a diverse range of PPG amplitudes can be observed from each patient which can be due to the thickness, weight and position of the flap in the recipient site. Also, for post-operative monitoring, the main perforators are typically marked by the surgical staff and in order to avoid any interference with the routine flap observations the PPG sensor was placed away from the indicated site. Therefore, as the distance from the perforators were different from patient to patient, this could have affected the variation in PPG amplitudes.

Table 1: Mean and standard deviation of the peak-to-peak amplitudes of the infrared ac PPGs for the flap and the finger.

Patient No.	Mean Flap IR ac PPG amplitude (mV)	Mean Finger IR ac PPG amplitude (mV)
1	102.0	n/a
2	139.7	2856.7
3	154.1	1970.8
4	526.3	2729.0
5	463.4	4299.8
Mean	**277.1**	**2964.0**
Std. Dev.	**200.9**	**972.5**

B. Estimating SpO_2 from flap and finger

Arterial oxygen saturation levels were successfully estimated from both finger and flap from all patients except for one patient where due to technical difficulties no infrared PPGs were acquired.

Figure 5 shows the plot of the mean and standard deviation from all patients at all post-operatively periods. This figure represents the difference between the estimated flap and finger SpO_2 values from both the developed PPG processing systems and the SpO_2 readings recorded from the commercial pulse oximeter which is routinely used by

medical staff for the observational check. All three SpO_2 recordings were obtained simultaneously.

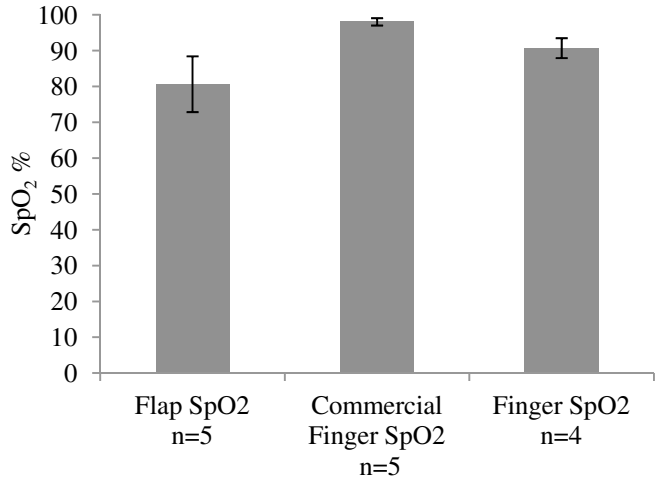

Figure 5: Mean and standard deviation of flap, finger (custom made) and commercial SpO_2 levels from of all patients.

IV. Discussion and Conclusion

The aim of this study was to further develop and evaluate a free flap photoplethysmography processing system which, as well as facilitating in assessing any variation in volume of arterial blood in the post-operative period in the flap it would also allow the estimation of arterial oxygen saturation levels. In order to accurately evaluate the estimated SpO_2 values for the flap, an identical processing system was designed and developed to enable the comparison and assessment of the accuracy of the developed system with the commercial pulse oximeter which is used as part of the routine post-operative observational monitoring.

The flap PPG sensor was designed to be small enough to be easily accommodated on the exposed skin of the DIEP flap and not interfere with the routine flap observational checks performed by the medical staff.

The results show that good quality red and infrared PPG signals can be obtained from both flap and finger. The finger PPG signals generally had considerably larger amplitudes and this was due to the good blood supply and perfusion in the finger compared to the flap.

The SpO_2 results from the finger PPG processing system were in good agreement with the blood oxygen saturation values obtained from the commercial pulse oximeter. The estimated flap SpO_2 values were moderately lower than the finger SpO_2 values which is expected due to anastomosed vessels and general poor perfusion of the flap immediately after free flap surgery. Furthermore, the larger standard deviation of the flap SpO_2 levels compared to the finger oxygen saturation levels are due to change in the health of the anastomosed arterial and venous blood vessels during the post-operative period.

In summary, a non-invasive flap monitoring system has been successfully developed and evaluated which can be used to accurately estimate blood oxygen saturation levels. This system shows promise for the reliable monitoring of SpO_2 and change in volume of arterial blood in free flaps in the post-operative period.

V. References

[1] J. C. Selber, M. Angel Soto-Miranda, J. Liu, and G. Robb, "The survival curve: factors impacting the outcome of free flap take-backs," *Plastic & Reconstructive Surgery,* vol. 130, pp. 105-13, Jul 2012.

[2] T. Kubo, K. Yano, and K. Hosokawa, "Management of flaps with compromised venous outflow in head and neck microsurgical reconstruction," *Microsurgery,* vol. 22, pp. 391-5, 2002.

[3] R. Pudner, *Nursing the surgical patient*, 3rd ed. ed. Edinburgh: Baillie\0300re Tindall, 2010.

[4] H. G. Machens, P. Mailaender, B. Rieck, and A. Berger, "Techniques of postoperative blood flow monitoring after free tissue transfer: an overview," *Microsurgery,* vol. 15, pp. 778-86, 1994.

[5] T. Zaman, P. A. Kyriacou, and S. K. Pal, "Development of a reflectance photoplethysmographic sensor used for the assessment of free flap perfusion," *Conf Proc IEEE Eng Med Biol Soc,* vol. 2011, pp. 4006-9, 2011.

[6] T. Zaman, P. A. Kyriacou, A. Belhaj, R. M. Langford, and H. Patel, D, L., "Development of a reflectance photoplethysmographic sensor used for the assessment of perfusion of free jejunum flaps: A case report," *Bioinformatics & Bioengineering (BIBE), 2012 IEEE 12th International Conference on,* vol. 2012, pp. 315 - 318 13/11/2012 2012.

[7] J. Allen, "Photoplethysmography and its application in clinical physiological measurement," *Physiol Meas,* vol. 28, pp. R1-39, Mar 2007.

[8] J. T. B. Moyle, *Pulse oximetry*, 2nd ed. ed. London: BMJ, 2002.

[9] Y. Mendelson and B. D. Ochs, "Noninvasive pulse oximetry utilizing skin reflectance photoplethysmography," *IEEE Trans Biomed Eng,* vol. 35, pp. 798-805, Oct 1988.