A Study on the use of PPG in Quantifying Circulatory Disruptions

Srinivasa Karthik, Jayaraj Joseph and Mohanasankar Sivaprakasam

***Abstract*— We explore the use of photoplethysmography to monitor and detect changes in arterial and venous circulation for potential use in surgical flap monitoring. The typical disruptions in circulation that are seen in a flap are emulated by occlusion tests conducted in controlled settings. Arterial and venous occlusions are performed on a limited number of subjects, and associated changes in the PPG signals captured at the specific region of interest are analysed. A set of parameters that can be used to distinguish between arterial and venous occlusions are identified and quantified. These parameters may be used to detect thrombosis and differentiate between an arterial and a venous thrombosis in free flaps during post-operative monitoring after reconstructive surgery.**

I. Introduction

Reconstruction surgeries in oncology and trauma often require surgical implantation of a tissue, known as a flap. Blood circulation to surgical free flaps is ensured by anastomosis of flap tissue blood vessels with regional blood vessels. Arterial or venous thrombosis at the anastomosis site will affect circulation to the flap and is one of the critical causes of flap failure. Hence, continued monitoring of circulation to the flap in the first 48 hours after surgery is critical [1][2][3]. This is often performed using state of art techniques like Laser Doppler Flowmetry (LDF) and Implantable Doppler ultrasound. LDF can measure blood flow only up to a depth of 1-2mm [2]. Implantable Doppler requires another minor surgery after a few days to remove the implanted sensor, in addition to being expensive.

We investigate the use of an affordable, non-invasive photoplethysmography (PPG) based techniques for detection of changes in arterial and venous circulation that can potentially be used for flap monitoring. The typical circulatory changes that are associated with flap failures are emulated in a controlled laboratory setting, and the ability of the PPG sensors to detect arterial and venous occlusions are studied. A set of parameters that can be used to detect arterial and venous occlusions are identified and evaluated for sensitivity and utility.

The subsequent sections describe the phenomenon of occlusion, the procedure for occlusion, the experimental setup and results of the study.

II. Principle of Measurement

By Beer's law we have, the light transmitted through a medium with an absorbing substance is [4]

$$I = I_0 \, e^{-\varepsilon(\lambda)cd} \quad (1)$$

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When incident light I_0 of a wavelength λ is passed through an absorbing medium of path length d, concentration of absorbing material c, and extinction coefficient $\varepsilon(\lambda)$, the intensity of light exiting the medium 'I' increases with reduced blood volume and vice-versa. With the absorption of light by skin and tissues being constant, the output light intensity is inversely proportional to the blood volume. This principle can be used to find changes in blood volume of a particular region of tissue using photoplethysmography [4]. This is helpful in long term monitoring of flap, where blood volume changes over a long period of time is required to be monitored. If the measurement site is a non-extremity, reflectance photoplethysmography can be used [4].

In an arterial occlusion, the inflow of blood into the region is reduced with the outflow of venous blood remaining unhindered. Hence, this reduction of blood volume increases the light intensity transmitted. Similarly, during venous occlusion, the artery keeps the inflow intact while the outflow through the veins is blocked. The blood volume keeps increasing till it creates a back pressure to stop further inflow. Here, the increase in blood volume reduces the intensity transmitted. This increase and decrease in the light intensity can be used to detect an occlusion and the nature of occlusion. This phenomenon applies to both transmittance and reflectance type photoplethysmography.

The thrombosis occurring in post-operative monitoring of flaps are an 'all or none' phenomenon i.e. the blood vessel when blocked, gets blocked completely, without any presence of partial flow. The study presented here emulates a similar phenomenon and hence results of this experiment have potential to be used in detection of arterial and venous thrombosis in flaps.

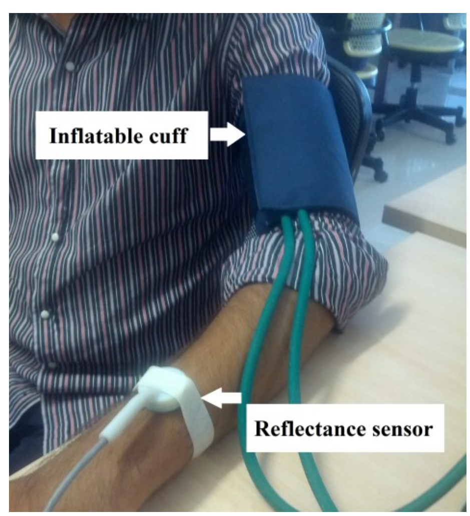

Figure 1. Photograph showing the inflatable cuff and the position of the reflectance sensor on the wrist.

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III. EXPERIMENTAL STUDY

Occlusion tests were performed on five healthy male volunteers between 20-30 years of age. The protocol was in compliance with WMA declaration of Helsinki. The details of occlusion, sensors and data acquisition is presented below.

A. *Venous Occlusion Procedure*

Venous occlusion was created by inflating a blood pressure cuff wrapped around the arm. This prevents the outflow of blood from the lower arm. By placing a PPG sensor on the wrist or finger we can track changes in blood volume during occlusion. The veins can get occluded anywhere between 30 mmHg to systolic pressure. Fig. 1 shows the placement of the reflectance sensor.

B. *Arterial Occlusion Procedure*

Arterial occlusion was created by pressing together the two proper palmar digital arteries feeding the middle finger. The PPG at the fingertip was further recorded and analyzed. Cuff based occlusion is not be possible here since the arteries get occluded at a higher pressure than veins, thus occluding the veins also.

C. *Combined Arterial and Venous Occlusion Procedure*

A third, combined arterial and venous occlusion is also performed by the cuff based method. Inflating the cuff to a pressure higher than the systolic pressure occludes both arteries and veins.

While the above mentioned 3 types of occlusions were analyzed in this study, it may be remembered that only arterial and venous occlusions are significant in the context of flap monitoring.

The above methods are the closest possible means of simulating different occlusions in a laboratory setting. Hence, they may not perfectly occlude the arteries alone without affecting veins and vice versa.

For each type of occlusion, the data is recorded once with a transmittance type sensor and the occlusion is repeated with a reflectance type sensor. Table 1 gives the measurement site for each occlusion and type of PPG.

D. *Sensors*

The reflectance type measurements are taken using a custom designed reflectance sensor shown in Fig. 2, with two LEDs, of wavelengths 660 and 850 nm. The photodiode (PD) is shown in the center, surrounded by an optical isolation in black. The LED and photodiode (PD) have a separation of 8 mm. The diameter of the sensor is 3 cm. Though the photograph indicates a provision for multiple LEDs surrounding the PD, only the LED currently 'ON' in the photograph is used. The IR LED is adjacent to the glowing RED LED. For transmittance measurements, an SPO2 finger clip probe is used with 660/905 nm LEDs.

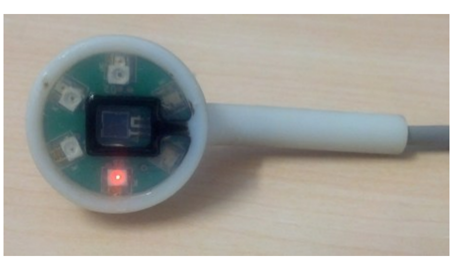

Figure 2. Custom designed reflectance sensor.

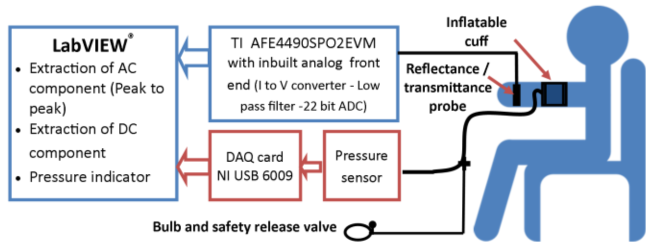

Figure 3. Block diagram of the experimental setup.

TABLE I. SITE OF PPG MEASUREMENT AND METHOD USED TO PERFORM OCCLUSION.

	Transmittance	*Reflectance*	*Method*
Arterial occlusion	Finger tip	Finger tip	Press by hand
Venous occlusion	Finger tip	wrist	cuff
Arterial-venous	Finger tip	wrist	cuff

E. *Data Acquisition and Signal Processing*

Fig. 3 shows the block diagram of the experimental setup. The RED and IR signals are sampled at 500 samples per second each using a 22bit ADC. This is done using - AFE4490SPO2 EVM, an analog front end for SPO2 from Texas Instruments. The signals are further processed by LabVIEW. For cuff inflated occlusions, the cuff pressure is read from the pressure sensor 24PCCFA6D from Honeywell Sensing and Control and digitized using NiDaQ6009.

The light received by PD is analyzed for the following-

- The absolute amount of light received by PD (the DC component)
- The pulsatile component or AC component, which is a very small component of the DC and is extracted using cycle by cycle Fourier series analysis [5].

The AC and DC values from the initial period before occlusion is averaged and used as reference. The AC and DC values measured during the occlusion period are normalized with this pre-occlusion value to see the relative trends. This is done for both RED and IR separately. Hence for plots shown in Fig. 5, Fig. 6, and Fig. 7, the initial values lay around '1'.

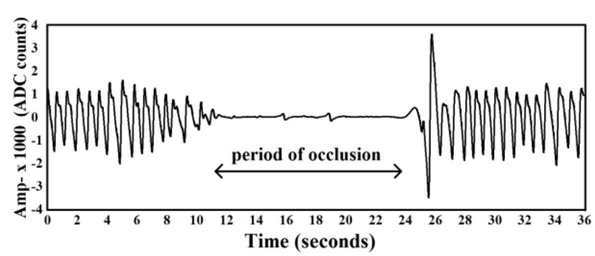

Figure 4. The AC amplitude of the PPG IR signal reaching zero during an arterial occlusion in transmittance type

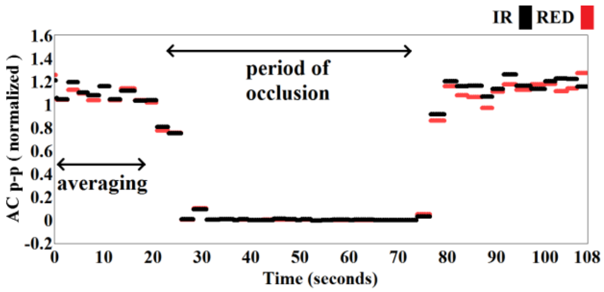

Figure 5. Plot of AC values of volunteer 1, during an arterial occlusion, reflectance type. Values before the occlusion are averaged and used to normalize the AC values during occlusion.

IV. Results

Occlusion tests were performed on 5 volunteers. Three types of occlusions, two types of PPGs resulted in six cases of investigations per volunteer. In each case the following parameters were analyzed.

- AC (peak-peak), normalized to pre-occlusion levels.
- DC, normalized to pre-occlusion level.
- Slope of DC during occlusion period.

$$normalized\ AC, DC = \frac{AC, DC\ during\ occlusion}{avg\ of\ AC, DC\ preocclusion}$$

A. AC (peak-peak) Value of PPG

The AC component of PPG was reduced for all types of occlusions. The amplitude of pulsations instantaneously dropped for arterial occlusions. Fig. 4 shows the PPG signal during an arterial occlusion. The same effect was found for arterial-venous combined occlusion.

Table 2 gives the AC values during occlusion. The values presented are after normalizing with the pre-occlusion levels. The values are shown for all five volunteers, for three types of occlusion and two modes (both transmittance and reflectance). The values in the table are for IR p-p with the RED p-p values given in parentheses below the IR values.

TABLE II. AC Values During Occlusion.

AC p-p values normalized to pre-occlusion						
	arterial occlusion		*venous occlusion*		*arterial and venous*	
	Rx	*Tx*	*Rx*	*Tx*	*Rx*	*Tx*
vol	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*
1	0 (0)	0 (0)	0.2 (0.2)	0.3 (0.4)	0.1 (0.2)	0 (0)
2	0 (0)	0 (0)	0.1 (0.1)	0.2 (0.2)	0.1 (0.2)	0 (0)
3	0 (0)	0 (0)	0.2 (0.2)	0.5 (0.4)	0.1 (0.1)	0 (0.1)
4	0.1 (0.1)	0 (0)	0.2 (0.2)	0.6 (0.6)	0.2 (0.2)	0 (0)
5	0.1 (0.1)	0 (0)	0.1 (0.1)	0.4 (0.4)	0.2 (0.2)	0 (0)
mean	0.04 (0.04)	0 (0)	0.16 (0.16)	0.4 (0.4)	0.14 (0.18)	0 (0.02)
sd	0.05 (0.05)	0 (0)	0.05 (0.05)	0.16 (0.14)	0.05 (0.04)	0 (0.04)

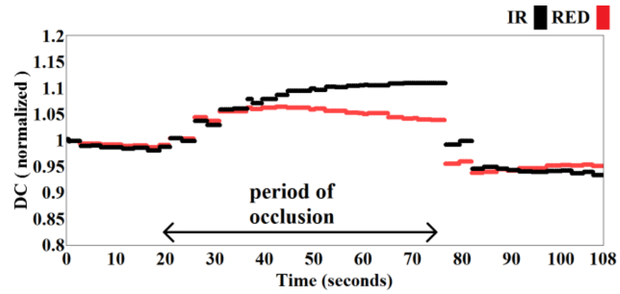

Figure 6. Plot of DC values of volunteer 1, during an arterial occlusion, reflectance type

For arterial occlusions, the final value of AC p-p amplitude of pulsations, at the end of the occlusion period was < 0.2 i.e., less than 20% of pre occlusion level for all volunteers. This is irrespective of the initial amplitude. This was true for both reflectance and transmittance modes of PPG and for both RED as well as IR. Fig. 5 shows the plot of an arterial occlusion. For venous occlusion, the final AC p-p was a little higher, as the artery is not blocked at this pressure. The value during occlusion of AC p-p amplitude of pulsations was < 0.6 i.e. less than 60% of its pre-occlusion level.

B. DC Value of PPG

Fig. 6 shows the DC variation during the arterial occlusion corresponding to the AC values shown in Fig. 5. DC variation during a venous occlusion is shown in Fig. 7. All the three plots in Fig. 5, Fig. 6 and Fig. 7 are for the same volunteer. Table 3 gives the DC values during occlusion.

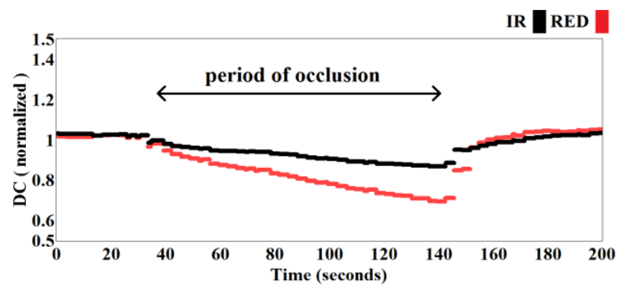

Figure 7. Plot of DC values of volunteer 1, during a venous occlusion, reflectance type.

TABLE III. DC Values During Occlusion.

DC values normalized to pre-occlusion						
	arterial occlusion		*venous occlusion*		*arterial and venous*	
	Rx	*Tx*	*Rx*	*Tx*	*Rx*	*Tx*
vol	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*	*IR (RED)*
1	1.1 (1.05)	1.4 (1.05)	0.85 (0.7)	0.6 (0.65)	0.97 (0.7)	2 (1.1)
2	1.5 (0.8)	1.7 (1.1)	0.8 (0.6)	0.6 (0.6)	0.95 (0.8)	1.6 (1)
3	1.1 (1)	1.2 (1.05)	0.8 (0.7)	0.8 (0.6)	1 (0.95)	1.2 (1)
4	1.15 (0.85)	1.35 (1.1)	0.85 (0.7)	0.75 (0.8)	1 (0.85)	1.6 (1.2)
5	1.1 (1)	1.5 (1.2)	0.7 (0.5)	0.7 (0.7)	1 (0.8)	1.6 (1.2)
mean	1.19 (0.94)	1.43 (1.1)	0.8 (0.64)	0.69 (0.67)	0.98 (0.82)	1.6 (1.1)
sd	0.17 (0.11)	0.19 (0.06)	0.06 (0.09)	0.09 (0.08)	0.02 (0.09)	0.28 (0.1)

TABLE IV. SUMMARY OF NORMALIZED DC SLOPE

Slope of normalized IR and RED during occlusion period					
arterial occlusion		***venous occlusion***		***arterial- venous***	
Rx	Tx	Rx	Tx	Rx	Tx
Both RED, IR +ve but RED DC reduces over time.		Both RED,IR slopes -ve, RED decreasing faster		IR slope=0 Red -ve	Both RED,IR +ve

Arterial occlusions are associated with an increase in the DC of IR. The value of IR DC was found to be >1.1 for all volunteers, showing at least a 10% increase from pre-occlusion levels. DC of RED increases in the initial phase, but it reduces over the duration of occlusion.

Venous occlusions are associated with a decrease in the DC of both RED and IR wavelengths. The value of both RED and IR was found to be < 0.85 for all volunteers, a 15% reduction from pre-occlusion levels.

For arterial cum venous occlusions, the transmittance readings showed an increase in DC for both RED and IR. In reflectance, the IR value remained constant around its pre-occlusion value, but RED DC gradually decreased.

C. Slope of Normalized DC

The distinguishing factor between an arterial occlusion and a venous occlusion is the positive and negative slope of the DC values especially of IR. A qualitative summary of the slopes of RED and IR normalized DC values during the occlusion period is summarized in table 4.

V. DISCUSSION

A. Indicators of an Arterial Occlusion

During occlusion, the pulsatile (AC) component reaches to less than 0.2 for all volunteers, where the normalized pre-occlusion level is '1'.This is true for both RED as well as IR wavelengths.

The IR DC component during occlusion is above 1.1 for all volunteers, showing an increase of at least 10%. The DC component is very stable during non-occluded period. A recording for 30 minutes was performed to see the stability of the DC component without any occlusion. The variation in DC in this duration was found to be minimal (< 2%) without any motion artifact. Hence even a change of 5% during occlusion is very significant. However, the RED DC was first found to increase and then decrease. This may not be a decisive indicator for arterial occlusion.

B. Indicators of a Venous Occlusion

Occluding veins should not affect arterial pulsations. But a reduction in AC values was found, though not as significant as arterial occlusion. This could be the effect of arteries getting occluded to a small degree along with the veins while performing venous occlusion. Hence, DC component alone will have to be observed. The DC value of both RED and IR was < 0.85 during occlusion for all volunteers.

TABLE V. PARAMETERS FOR DISTINGUISHING ARTERIAL AND VENOUS OCCLUSIONS

	Arterial occlusion		***Venous occlusion***	
	IR	RED	IR	RED
AC p-p (normalized)	0	0	-	-
DC (normalized)	+ve	-	-ve	-ve

This shows a reduction of at least 15% from its pre occluded value. Also since the DC value slope goes '-ve', we can use this to differentiate between an arterial and venous occlusion, where in the arterial occlusion, IR has a '+ve' slope.

C. Summary

Table 5 summarizes how an occlusion can be detected and differentiated between arterial and venous occlusion.

Arterial occlusion AC p-p amplitude drops close to zero (or < 0.2). The DC normalized increases with a '+ ve' slope (DC normalized values >1.1). Venous occlusion - DC normalized has '–ve' slope. (DC normalized < 0.85).

Both the DC and the AC values show variations during motion. Techniques to reduce motion artifact will be implemented in future work. Also, perfusion is dependent on the temperature. Lower temperature can lead to low perfusion and incorrect readings.

VI. CONCLUSION

Circulatory disruptions were emulated in laboratory settings in the form of arterial and venous occlusions. Photoplethysmography was used to measure the changes in blood flow in a region of interest. Results indicate a pattern in the presence of an occlusion. Additionally, a pattern exists which can differentiate between the type of occlusion. These results have potential to be used in post-surgical monitoring of tissue flaps, which will be investigated in further studies.

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