PulseCam: High-resolution blood perfusion imaging using a camera and a pulse oximeter

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Abstract

Adequate blood perfusion is essential for oxygen delivery to cells, and to maintain metabolic homeostasis. Dynamic changes in local perfusion happen due to changes in body's physiology during tissue repair, circulatory shock, and wound healing. Therefore, measurement of perfusion is important in both medical and surgical care. However, currently available devices for measuring blood perfusion through surface assessment such as laser Doppler imaging are bulky, expensive, and cumbersome to use. An alternative low-cost and portable camera-based blood perfusion monitoring system has recently been proposed, but current known camera-only methods produce noisy low-resolution blood perfusion maps. In this paper, we propose a new multi-sensor modality, named PulseCam, for measuring blood perfusion by combining a traditional pulse oximeter with a video camera in a unique way to provide low noise and high-resolution blood perfusion maps. Our proposed multi-sensor modality improves per pixel signal to noise ratio of the perfusion map by up to 3 *dB and produces perfusion maps with* $2-3$ *times better spatial resolution compared to best known camera-only methods. Blood perfusion measured in the palm using PulseCam during a post-occlusive reactive hyperemia (POHR) test replicates data using existing laser Doppler perfusion monitor but with much lower cost and a portable setup making it suitable for further development as a clinical device.*

1. Introduction

Blood perfusion is the flow of blood to the end organs and tissues through the blood vessels in the body. Blood flow (or perfusion) is vital in ensuring oxygen delivery to the cells and in maintaining metabolic homeostasis. Measuring peripheral perfusion, i.e. perfusion of the blood just underneath the skin surface is important in both medical and surgical fields [1] including assessment of peripheral perfusion in critical care, tissue viability in plastic, reconstructive, and burn surgery as well as for wound assessment.

Blood perfusion generally varies from one tissue site to another, and can also change over time due to varying metabolic demands, and so a spatial map of blood perfusion over time, i.e. a three-dimensional quantity, is usually measured. Laser speckle contrast imaging [2] and laser Doppler imaging [3] devices are commercially available for measuring blood perfusion maps. But, these devices are (i) bulky and require specialized measurement protocols, (ii) are not generally used in operating rooms or at the bedside in the intensive care units (ICUs) as they may cause interference to the ongoing care and discomfort to the patients, and (iii) are too expensive to be routinely used for outpatient care. Recently, an alternative camera-based blood perfusion imaging system has been proposed [4] which has the potential to be a portable, cost effective and non-contact blood perfusion imaging system. However, current camera-only blood perfusion imaging algorithms produce noisy and low-resolution perfusion maps and thus are rarely used in clinical settings.

In this paper, we propose a new multi-sensor modality, named *PulseCam*, for measuring blood perfusion by combining a traditional pulse oximeter and a video camera in a unique way to provide low-noise and high-resolution peripheral blood perfusion maps. Blood flow (or perfusion) is the rate of change of blood volume. Both a pulse oximeter and a camera mea-

sures the blood volume change over time at a peripheral site through optical means. A pulse oximeter is a simple spot measurement device which can measure blood volume waveform reliably from one body location, but cannot simultaneously take spatial measurements from a large region of the skin surface. On the other hand, a camera provides noisy measurements of blood volume waveform, but a camera can simultaneously take spatial measurements from a large region of the imaged skin surface owing to its unique spatial dimension: each pixel on the image sensor can be considered as a pulse oximeter which is virtually (from a distance) attached to the corresponding location on the imaged skin surface and provides an independent but noisy measurement of the blood volume waveform from that location. PulseCam combines these two disparate devices by using the reliable blood volume waveform from a pulse oximeter as a reference, and then correlating this reference waveform with the noisy blood volume waveform obtained from each pixel in the camera to produce low noise and high-resolution perfusion maps of any imaged skin surface.

Several researchers have recently shown the feasibility of camera-only blood perfusion imaging [4, 5, 6]. Most of these works, however, rely on excessive spatial averaging (around 20×20 to 100×100 pixel block) to reduce camera's quantization noise, shot noise and readout noise, and suppress motion artifact before estimating the blood perfusion maps, thereby compromising the achievable spatial resolution. In this paper, our proposed PulseCam requires a minimal spatial averaging over only 4×4 pixel block, and produces blood perfusion maps with $0.5-3$ dB higher signal to noise ratio (SNR) per pixel block compared to the state-of-the-art technique that only relies on camera recordings [4] to measure blood perfusion maps. We also validated PulseCam functionally by conducting a standardized post-occlusive reactive hyperemia (POHR) test on 4 healthy individuals and found the derived blood perfusion measurements to be in agreement with published POHR-test response curve measured using a laser Doppler perfusion monitoring device [7].

Our main contributions in this paper are: (i) a novel multi-sensor modality for measuring blood perfusion maps by combining a camera and a pulse oximeter, (ii) a signal model for blood perfusion imaging taking into account differences in camera operating parameters, and (iii) a maximum likelihood (ML) estimator for estimating three-dimensional blood perfusion maps by combing measurements from a camera and a pulse oximeter.

In Section 2, we propose a signal model for multi-sensor blood perfusion imaging and in Section 3 we develop an ML-estimator for estimating three dimensional blood perfusion maps. In Section 4 we discuss the experimental setup and data collection protocol used for validating PulseCam, in Section 5 we summarize our results, and in Section 6 we discusses our key insights, major challenges, and future direction of research.

2. Blood perfusion signal model

Blood flow (or perfusion) is the rate of change of blood volume at any tissue location over time. The volume of blood in the vessels generally changes in sync with the beating of the heart. As the heart rate remains more or less constant at homeostasis, the rate of change of blood volume is proportional to the amplitude of the blood volume waveform. Thus, to measure spatial blood perfusion map, we estimate the amplitude of the blood volume waveform at different tissue locations over time. In this section, we will develop a blood perfusion signal model based on the optical principle of measuring blood volume waveform using a camera.

When light falls on the skin surface, it is partly absorbed by the skin and the underlying tissue, and is partly reflected back and recorded by the camera sensor imaging the skin surface. Let us assume that the incident light intensity $I(\vec{x})$ does not change over time. Here, $\vec{x}$ denote the location on the skin surface corresponding to pixel $\vec{x} = \{x, y\}$ on the camera. Then, the camera recorded video signal over time can be modeled as

$$V(\vec{x},t) = I(\vec{x})\big(b(\vec{x}) + c(\vec{x},t)\big) + w(\vec{x},t) \qquad (1)$$

where the skin reflectance is separated into two component: first component $b(\vec{x})$ is due to light absorption by skin surface and tissue underneath and is time invariant, and the second component $c(\vec{x},t)$ is due to light absorption by the chromophores in the blood, and is time varying due to pulsatile changes in the blood volume in the microvasculature underneath the skin surface. Finally, $w(\vec{x},t)$ is the noise added during the camera acquisition process [8].

The subsurface light absorption component due to pulsatile changes in blood volume can be decoupled as $c(\vec{x},t) = a(\vec{x},t)p(t-\tau(\vec{x}))$ where $a(\vec{x},t)$ is the amplitude of the blood volume waveform $p(t)$ and is different at different location, The amplitude $a(\vec{x},t)$ can also change over time due to temporal variations in blood perfusion, but at a rate that will be much slower in comparison to the instantaneous variations in $p(t)$ which is in sync with the beating of the heart. The blood volume waveform signal is assumed to be delayed by different time $\tau(\vec{x})$ at different locations $\vec{x}$ on the skin surface. The noise term $w(\vec{x},t)$ is dominated by (i) camera's quantization noise, readout noise and photon shot noise, and

(ii) motion artifact. Taking camera parameters also into account, the camera-recorded video signal can be modeled as

$$V(\vec{x},t) = QI_0\big(b(\vec{x}) + a(\vec{x},t)p(t-\tau(\vec{x}))\big) + w_c(t) + w_m(t) \quad (2)$$

where Q is the multiplication factor due to camera's exposure and aperture settings, $w_c(t)$ is the noise added due to camera's acquisition process, and $w_m(t)$ is the motion artifact. Also, to simplify the model, we have assumed the spatial variation in light intensity to be minimal, and replaced it with mean illumination value I_0 over the imaged skin region.

Based on the proposed signal model, in the next section, we will present an estimator for the blood perfusion map $a(\vec{x},t)$ given that we have noisy camera recording $V(\vec{x},t)$, and the underlying blood volume waveform signal $p(t)$ which is reliably measured using a pulse oximeter.

3. PulseCam blood perfusion estimation

Blood perfusion estimation using PulseCam involves a series of three preprocessing steps to be performed on the raw video recording from the camera. After the preprocessing steps, the processed video from the camera and pulse oximeter recordings are fused together to estimate the blood perfusion map.

As a first pre-processing step, we apply an $M \times M$ spatial mean filter on the raw video recording $V(\vec{x},t)$ from the camera to reduce the contribution of camera sensor noise on the measurement from each pixel. The choice of M will be a trade-off between the spatial resolution of resulting perfusion map and the desired SNR for the perfusion estimate per $M \times M$ pixel block.

Then, as a second preprocessing step, the spatially averaged video is filtered temporally using a bandpass filter having passband between 0.5 Hz - 5 Hz with unity passband gain to obtain $V_{AC}(\vec{x},t)$. This temporal filtering removes the slowly varying surface reflection component in the video recordings, and only allows the subsurface reflection component due to blood volume changes to be retained. The simultaneously recorded blood volume waveform from the pulse oximeter is also filtered temporally using the same bandpass filter with passband between 0.5 Hz - 5 Hz.

In the third preprocessing step, we use a standard Grayscale chart having reflectance b_{std} placed adjacent to the skin surface and then we compute the normalization factor N by averaging the camera recording from the pixels imaging the Grayscale chart. Then, we divide $V_{AC}(\vec{x},t)$ by N to get a normalized video signal $V_N(\vec{x},t)$. The normalization factor N is equal to QI_0b_{std} and it removes the effect of changes in camera exposure and aperture settings Q and intensity of incident light I_0 on the eventual perfusion estimate.

If we assume that the noise in the camera measurement is white and Gaussian, then the maximum likelihood estimator for the perfusion $a(\vec{x},t)$ will be

$$\hat{a}(\vec{x},t)_{ML} = \max_{D(\vec{x})} \langle V_N(\vec{x},t-D(\vec{x})), p(t)\rangle_T \quad (3)$$

where $\langle\cdot,\cdot\rangle$ is the inner product between vectors. The delay $D(\vec{x})$ is used to align the reference blood volume waveform signal $p(t)$ with the blood volume waveform signal at location $\vec{x}$. Based on the proposed blood perfusion imaging model, $\hat{a}(\vec{x},t)_{\mathrm{ML}} = \frac{a(\vec{x},t)}{b_{\mathrm{std}}}$, where b_{std} is the reflectance of the standard grayscale chart used in the normalization step. The inner product in the above equation is defined over the time window T over which the perfusion is assumed to be constant.

Readout or thermal noise generally follows a Gaussian distributed, and under sufficient illumination, camera's shot noise also follows a Gaussian distribution. Quantization noise is uniformly distributed, but if we assume a minimum of $10-20$ pixel in a pixel block over which spatial averaging is done ($M \approx 4$), then due to central limit theorem, quantization noise can also be modeled as Gaussian. Noise due to motion artifact is generally spiky and difficult to model, and is not considered here.

The signal-to-noise ratio of the above ML estimate is same as the SNR of the signal of interest and can be estimated as

$$\mathrm{SNR}(\vec{x},t) = \frac{\hat{a}^2_{ML}(\vec{x},t)}{\widehat{\mathrm{Var}}\left(V_N(\vec{x},t) - \hat{a}_{ML}(\vec{x})p(t-D(\vec{x}))\right)_T}. \quad (4)$$

4. Experiments

We present two sets of experiments. In the first set, we did a controlled experiment to characterize the average SNR per pixel block for blood perfusion imaging using our proposed PulseCam and using camera-only method [4] as a function of ADC quantization level and spatial mean filter size M. In the second set of experiment, we conducted a standard post occlusive reactive hyperemia (POHR) test on 4 healthy individuals to measure the change in their blood perfusion in the palm before, during and after an occlusion event.

The experimental setup consists of a monochromatic CMOS camera (Grasshopper GS3-U3-23S6M-C from Point Grey) on which we put a green optical filter having an optical passband between 520 nm to 560 nm. Using green optical filter improves the SNR of camera-based blood volume waveform as the absorption spectra

of hemoglobin peaks at a wavelength of around 530 nm. The camera is operated at 30 fps, with automatic gain control and gamma correction turned off, and exposure time is set at 12 ms. For all the experiments, the camera records a video of the palm rested on a hand support. Occlusion of blood flowing to the palm is done using a standard pressure cuff put on the arm of the same hand. We simultaneously record a blood volume waveform from the middle finger of the other hand using Biopac system's MP150 data acquisition unit as a reference pulse oximeter.

5. Results

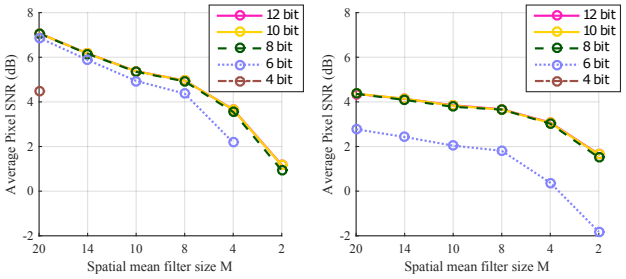
5.1. Perfusion imaging SNR

Figure 1a shows the variation of average SNR (in dB) per pixel block (computed using Equation (4)) of the estimated blood perfusion map using PulseCam as spatial averaging filter size M^2 is varied from 20×20 down to 2×2, and Figure 1b shows the corresponding per pixel block SNR of the estimated blood perfusion map using the camera-only method [4]. The time window T for perfusion estimate is set to 10 sec for both methods. During this controlled experiment, the motion artifact due to hand movement is kept small so that the only source of noise are due to the camera acquisition process. On an average, we see an SNR improvement of $0.5 - 3$ dB per pixel block in the blood perfusion map derived from PulseCam compared to camera-only method. Also, it is interesting to observe that increasing the ADC quantization level in the camera sensor need not necessarily improve the SNR of the blood perfusion map, as at room temperature, and with high exposure settings (12.0 ms), we are limited by the readout noise and the photon shot noise as well, rather than only the quantization noise.

5.2. POHR test

For this experiment, we recorded 2 min video of the palm before the occlusion to get a baseline estimate of perfusion, a total of 1 min video under occlusion, and a 2 min video post occlusion for 4 individuals (3 male and 1 female) having different skin tones (1 Caucasian, 1 Asian, and 2 brown).

Figure 2 shows the temporal variations of the average perfusion in the palm (averaged over all pixel block in the palm region excluding fingers) during the POHR test for 4 healthy individuals before, during and after the occlusion. The time window T for perfusion estimate is set to 5 sec with a 4 sec overlap (sliding window) to track sudden changes in perfusion due to occlusion.



(a) PulseCam (b) Camera only method [4]

Figure 1: Variation of average per pixel SNR (in dB) as a function of the spatial mean filter size M using (a) PulseCam and (b) state-of-the-art camera-only method [4]. PulseCam provides an SNR improvement of around $0.5 - 3$ dB per pixel block.

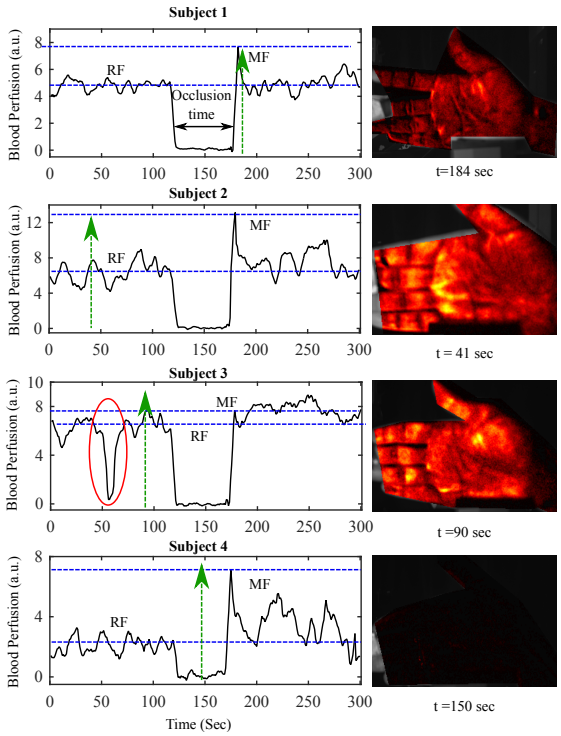


Figure 2: (*Left*): Temporal variation of the average blood perfusion in the palm of 4 subjects before, during and after an occlusion test, RF is the resting flux (perfusion) before occlusion, MF is the maximum flux just after the occlusion; (*Right*): image inlets showing spatial map of blood perfusion computed using PulseCam at specific time instance (marked as green arrows) during the occlusion test. The sudden dip in estimated blood perfusion inside the red marking (Subject 3) is due to recording artifact in the reference pulse oximeter derived blood volume waveform.

These POHR response curve agrees well with POHR curve estimated using laser Doppler perfusion monitoring [7]. The average perfusion before the occlusion (marked as RF) is lower than the average perfusion just after the release of the occlusion (marked as MF), and the ratio MF/RF also has diagnostic value for assessing arterial health. The variations in the average perfusion around the baseline could be due to rhythmic oscillations in the vascular tone caused by changes in smooth muscle constriction and dilation, and are usually $4-10$ cycles per minute (cpm). For subject 3, the sudden dip in estimated blood perfusion at around $t = 50$ sec is due to recording artifact in the reference pulse oximeter derived blood volume waveform.

Adjacent to the POHR response curve of each subject is an image inlet showing the two dimensional spatial map of the blood perfusion at specific times (marked as green arrows) during the occlusion and release cycle. These spatial maps are generated with $M^2 = 4 \times 4$ spatial averaging filter. Darker pixel blocks in the spatial map show lower blood perfusion, whereas brighter pixel blocks show higher blood perfusion. There are significant spatial variations in the recorded blood perfusion e.g. palm regions around the base of the fingers shows higher perfusion, whereas regions around the hand marking in the palm shows lower blood perfusion. Similar conclusions are difficult to draw from noisy blood perfusion maps generated using camera-only methods [4]. Using PulseCam, one can also visualize the dynamics of blood flow using temporal video of blood perfusion maps in the hand before, during and after the occlusion. As this is difficult to show using images, we have uploaded few sample videos at `http://goo.gl/UXxwNg` for the reviewers.

6. Discussion

Since a pulse oximeter is readily available as a low-cost medical device, and CMOS cameras of various form factors, sizes, and specifications are available commercially, therefore our proposed PulseCam can be used as a portable and low cost blood perfusion monitoring system. This could have applications in monitoring wound healing in diabetic patients, in plastic surgery to monitor skin flap perfusion after microvasculaer reconstructive procedure, and to assess the skin's endothelial function. In many scenarios, like in intensive care unit (ICU) and in operating rooms (OR), existing systems like laser Doppler imaging cannot be readily used, whereas PulseCam, by virtue of being passive and operable from a distance, is suited for such scenarios. This may open up the possibility of realtime blood perfusion and micro-circulatory monitoring at the bedside during surgery and in ICU care — the need of which has been identified by several critical care researchers [9].

In this work, we have shown the feasibility of using PulseCam to obtain low noise and high resolution perfusion maps by combining a camera and a pulse oximeter. There are widespread applications of realtime perfusion monitoring, and as a next step, we will extend PulseCam to more challenging scenarios like monitoring patients in ICU and for monitoring wound recovery.

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