Contactless blood perfusion assessment of the free flap in breast reconstruction surgery

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***Abstract*—Remote photoplethysmography proved useful as a non-contact method for estimating physiological data from different parts of the body. Recent studies have mainly focused on the face region for extraction of blood pulsation signal. In this paper, we have demonstrated the feasibility of non-contact remote photoplethysmography in the monitoring of free flap tissue. An experimental study was conducted, where video recordings of free flaps are obtained during breast reconstruction surgery for 8 patients. The hemoglobin absorption rate of the free flap is closely related to signal-to-noise ratio (SNR) values extracted from free flap pulsation signal during surgery. Obtained results show significantly lower SNR values when the free flap is disconnected from the blood supply compared to the SNR values when the flap is intact or after successful blood supply establishment. This method shows potential as a convenient, non-invasive and reliable tool in post-operative microvascular free flap monitoring.**

***Index Terms*—photoplethysmography, remote sensing, free flap, pulse rate**

I. Introduction

Non-contact vital signs sensing has attracted considerable attention in recent years, due to the possibility of convenient and nonrestrictive estimation of individual's health parameters. With contactless analysis of the skin of the individual, such as face and hands, important vital signs including heart rate and respiratory rate can be estimated with satisfying accuracy [1]–[3]. Blood pulsations beneath the skin lead to changes in light that can be detected with the camera image sensor. Video recordings of the patient's skin are used for extraction of the beat-to-beat pulsatile signal, also known as remote photoplethysmogram (rPPG), that is closely related to the delivery of blood volume pulse to peripheral tissues [4].

Direct visual inspection of the skin has always been an important part of the clinical examination of various disease states. Many conditions affecting the skin manifest themselves by modulation of the microcirculation. A potential application for non-contact sensing involves monitoring of the free flap during plastic surgery. A free flap is a piece of tissue that is disconnected from its original blood supply and moved a significant distance to be reconnected to a new blood supply. This type of surgery involves dissection and anastomosis, which are complex and challenging procedures. In addition, it is critical to provide constant monitoring of the flap after the surgery, in order to evaluate microcirculation and thereby the viability of the flap. Any small change in the structure, color or temperature of the flap needs to be reported, in order to avoid the loss of the flap [5] [6]. This is usually obtained with invasive and contact methods, including implantable Doppler probe, surface temperature, near-infrared spectroscopy and microdialysis [7]. However, none of the methods meets the requirements of the non-invasive, accurate, reliable easy-to-use tool with real-time feedback [8].

Remote photoplethysmography has been found applicable for other purposes, such as the recognition of symptoms in peripheral artery disease [9]. In terms of noninvasive monitoring of free flaps in breast reconstruction surgery, periodic noncontact screening of the flap was performed with the smartphone for post-recovery assessment [10]. Smartphone images were evaluated subjectively by surgeons, who reported their opinions based on the color of the flap, observed from the image. However, continuous contactless monitoring of the flap was not explored. In this paper, we have investigated the feasibility of camera-based noncontact sensing method as a monitoring tool of the blood perfusion in the free flap. Video recordings of the free flaps in breast reconstruction surgery procedures were obtained and analyzed for 8 patients. During different stages in the reconstruction surgery, rPPG signal was extracted from the center and peripheral regions of the flap. Simultaneous contact measurements of ECG signal and finger-based photoplethysmography (fPPG) were used for derivation of referent heart rate values of the patient and compared to the blood pulsation rates obtained from the flap. Based on our knowledge, this is the first time that rPPG is used for evaluation of the blood perfusion in the free flap. The power of extracted rPPG signals shows a difference between the center and peripheral regions when the blood supply of the flap is restricted.

II. Materials and methods

A. Experimental study

Eight female patients were selected for free flap breast reconstruction after mastectomy. The surgical procedure was conducted in Oslo University Hospital and the study was approved by Ethics Committee. Informed consent was obtained from all subjects, after a detailed explanation of the nature of the research. The experimental procedure is depicted in Fig. 1.

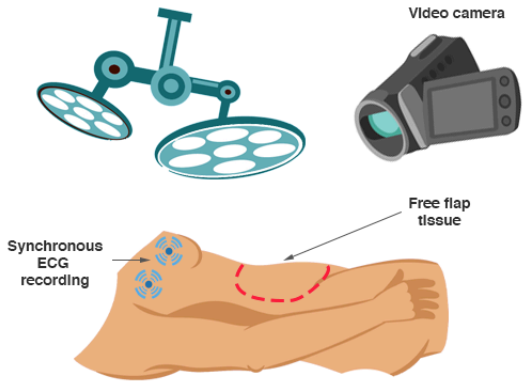

Fig. 1. Experimental setup

Video recordings of the patient's free flap tissue were obtained with a commercial digital camera using 720x576 pixel resolution and a sampling rate of 25 frames per second. Simultaneous acquisition of ECG and finger photoplethysmogram (fPPG) signals with 1000 Hz sampling frequency was conducted as well.

Breast reconstruction was performed by using the abdomen free flap that supplies from deep inferior epigastric perforator (DIEP) artery, also known as DIEP flap. This type of surgery involves cutting the fat, skin and blood vessels from the abdominal wall and using them for reconstruction of the breast tissue. DIEP flap reconstruction has become a golden standard for breast reconstruction with high success rate and faster recovery time compared to the TRAM (transverse rectus abdominis) flap, which involves the cutting of the muscle [11].

TABLE I
DESCRIPTION OF DIFFERENT STAGES DURING SURGERY RECORDED WITH VIDEO CAMERA

Recording	Description
1	The flap is preoperatively marked, but still intact. This is the recording just before the start of surgery
2	A clamp is placed upon artery/vein to prevent blood supply of the flap. The flap relies on the static blood in its blood vessels.
3	The flap is moved to the recipient area and anastomoses performed. The clamps are still on. The flap is without perfusion.
4	The flap is definitely formed and sutured in place, surgery comes to an end. The perfusion is further stabilised. The patient is moved to ICU.

Video recordings of the free flap tissue during surgery were divided into 4 different stages, with a minimum duration of 3 minutes. Description of each stage is listed in Table I. At the beginning of the surgery, abdomen tissue that would be used as a flap is marked on the skin. After the dissection of the flap, blood perfusion of the flap is tested by placing a clamp on the vessels that are providing blood supply to the flap. This test is used for the evaluation of the viability of the flap, before the transplantation. After the removal of the clamp, blood perfusion is established and the division from the donor area is performed. When the reattachment of the blood vessels is finished, the flap is sutured to the breast tissue. After the surgery, constant monitoring of the flap provides information if the breast reconstruction was successful and there are no complications.

B. *Extraction of rPPG signal*

Video recordings of the free flap during surgery were used for the extraction of blood pulsation signal. The extraction of blood pulsation signal consists of several steps, as seen in Fig. 2. rPPG signals are extracted from defined region of interest (ROI). In order to explain the selection of ROIs, it is necessary to understand the blood supply of the flap. External iliac artery provides blood supply to the lower abdominal wall, from where DIEP flap is dissected. DIEP artery is connected to the terminal of the external iliac artery and it runs toward the umbilicus, while laying under the rectus abdominis muscle. It gives off the branches to the muscle, which end up through fascia as perforators in the flap. The points of perforation involve an average of five perforators, that provide the blood supply to the tissue [12]. Before the surgery, the perforators are marked on the flap tissue with computed tomography (CT) scan. Center ROI for extraction of the rPPG signal was selected between marked perforators, while peripheral ROI was chosen near the edge of the flap. Fig. 3 shows a video frame of free flap, with marked ROIs and perforators.

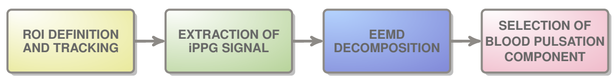

Fig. 2. rPPG extraction methodology

Although the movements of the patient are restricted due to the general anesthesia during surgery, it is necessary to provide the tracking of the ROI. Free flap tissue is inevitably moving due to the patient's breathing. After tracking, spatial averaging of ROI pixels generates three color components, including red, green and blue (RGB). RGB components are used for the extraction of remote PPG signal. In this paper, we have selected POS method for extraction, as proposed in [13]. POS method defines a plane orthogonal to the skin tone in the temporally normalized RGB space for pulse wave extraction. Since the extracted pulsation component exhibited a different type of artifacts including lightning variations, stretching of the skin, movement of the tissue due to the breathing, additional noise removal method is considered. Ensemble empirical mode decomposition (EEMD) is used for separation of the rPPG signal into different intrinsic mode functions (IMF), that correspond to the signal components exhibiting only one mode of oscillation [14]. EEMD incorporates additional white noise data to the rPPG signal, in order to extract only components that correspond to the noise-free pulsation signal.

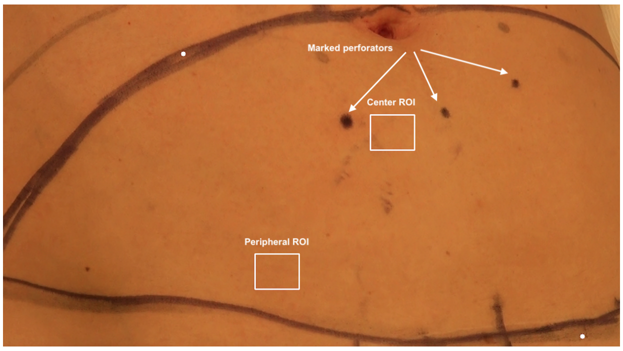

Fig. 3. Frame of free flap video recording at the beginning of surgery with marked tracking points and center and peripheral ROIs

In order to provide the correct assessment of blood perfusion in free flap during surgery, we have calculated the signal-to-noise ratio (SNR) as a parameter of the strength of blood pulsation signal compared to the noise component. This parameter can be directly correlated with haemoglobin absorption rate. Higher SNR values indicate that the pulsation component is stronger compared to the noise. Lower SNR values are expected to appear during surgery in the case when the free flap is disconnected from the artery providing blood supply. In addition, peripheral regions of the flap are getting blood from the center part of the flap, which is closely placed near the DEAP artery.

SNR metrics is defined as suggested in [15]

$$SNR = 10\log_{10}\frac{\sum_{HR=40\ (BPM)}^{HR=140\ (BPM)} S^2(f)U(f)}{\sum_{HR=40\ (BPM)}^{HR=140\ (BPM)} S^2(f)(1-U(f))} \quad (1)$$

where $S(f)$ corresponds to the power of rPPG component while $U(f)$ is the window function defined as

$$U(f) = \begin{cases} 1 & \text{when } |f - f_{HR}| \leq 3\ (BPM) \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where f_{HR} corresponds to the reference value of heart rate frequency obtained from synchronous measurement of the ECG signal. Selected frequency spectrum between 40 and 140 beats per minute (BPM) is adjusted to the values of heart rate that are usually encountered with patients under general anesthesia.

III. Results

A. Blood pulsation rate estimation

For video recordings where blood supply is established (stage 1 and stage 4), the average blood pulsation rate is estimated by calculating the frequency corresponding to the maximal power spectral density obtained with Discrete Fourier Transform (DFT). For contact-based ECG and finger PPG signals, average pulsation rates are calculated as well. In Table II, values of pulsation rate obtained from contact methods (ECG and fPPG), along with values from rPPG are listed for all patients at the beginning of the surgery, when the flap is still intact. It is evident that blood pulsation estimation from the free flap have small deviations compared to the contact methods at the beginning of the surgery.

TABLE II
Estimation values of blood pulsation rate in free flap compared to the heart rate values from contact-based ECG and fPPG signals during stage 1

Patient	**Blood pulsation rate**		
	ECG	**fPPG**	**rPPG**
1	49.02	49.03	49.07
2	50.33	50.35	50.54
3	76.45	76.67	77.09
4	58.23	58.21	58.22
5	57.81	57.81	58.41
6	73.68	74.33	70.5
7	52.21	52.88	52.27
8	56.50	56.52	56.94

B. Blood perfusion assessment

For each stage, SNR values are computed from center ROI and listed in Table III. Obtained results indicate that SNR values are the highest when the flap is still intact, and lowest when the flap is separated and without blood perfusion. SNR values increase after the surgery when blood circulation is established in the flap tissue.

TABLE III
SNR values obtained from the free flap during stages 1-4

Patient	**SNR (dB)**			
	Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
1	6.0012	-3.4195	-7.1304	-2.101
2	1.3253	-2.1797	-8.3749	-4.217
3	3.0838	-7.0009	-4.1843	-0.3527
4	-0.3124	-2.7227	-6.4934	-4.1414
5	5.1401	-6.5617	-9.4232	-3.3259
6	-8.3972	-6.2993	-11.7937	-3.8807
7	0.2361	-0.8034	-4.9131	0.1955
8	3.3231	-2.3995	-2.6157	-5.5525

In addition, we have compared SNR values of the free flap during stage 3, when the flap is without constant blood supply for a certain period of time. This happens during transplantation of the flap from the abdomen to the breast tissue. Two SNR values are extracted from the center and peripheral ROI. Fig. 4 shows resulting SNR values are averaged over all ROIs for each patient separately for stage 3. Lower SNR values are evident in the peripheral ROI. This can be explained by the fact that the highest blood perfusion of the flap is near the perforators, that are located near the center ROI.

Referring to Table III and Fig. 4, we can conclude that changes in SNR correspond to the changes of the blood supply in the free flap during different stages. The power of blood pulsation signal that is extracted from the surface of the skin is closely related to the blood perfusion of the flap. Central part of the flap, which is the closest to the DIEP artery, has

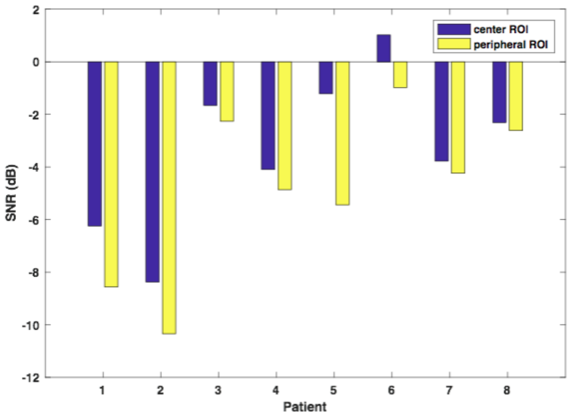

Fig. 4. SNR values for center and peripheral ROI when there is no blood perfusion in the free flap

higher blood perfusion compared to the peripheral parts of the flap. This was demonstrated with differences in SNR values between central and peripheral rPPG signals when the free flap relies on its own blood supply.

IV. Conclusion

In this paper, we have demonstrated the feasibility of non-contact assessment of the free flap blood perfusion during breast reconstruction surgery. Provided experimental results show that changes in SNR values of the blood pulsation signal correspond to the changes of the blood perfusion levels of the flap. Peripheral regions of the flap shown lower SNR values compared to the regions closer to the artery, when the flap is without constant blood supply. Given that video cameras are low-cost tools that can be easily integrated into the surgical environment, the proposed methodology for blood perfusion assessment of the free flap is a promising tool for practical video-based measurement application.

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