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Setting–up of PPG Scaling Factors for SpO_2% Evaluation by Smartphone

D.L.Carnì, D. Grimaldi, P.F. Sciammarella
Dept. of Informatics, Modelling, Electronics and System Engineering, University of Calabria, Rende, Italy

F. Lamonaca
Dept. of Engineering
University of Sannio, Benevento, Italy

V. Spagnuolo
Clinical and Therapeutic Unit of Arterial Hypertension, Unit of Internal Medicine, AO Cosenza, Italy

***Abstract*—The recent literature proposes the smartphone's camera to evaluate the arterial blood oxygenation (SpO_2%) with the characteristic of friendly and ubiquitous measurement instrument. Some issues remain open, making difficult the compensation of artefacts causing error in the estimation of the photoplethysmogram signal (PPG) and not guarantying that the measurement of SpO_2% is correctly executed. In the research, a method is proposed for setting-up the parameters to compensate the effects of the environmental light sources. Initially, the method evaluates the quality of the PPG signals by analysing the light intensity in the red and green colour channels of the video frames of the patient fingertip. Successively, a proper digital procedure sets the scale factor of the PPG to compensate the effects of external light for improving the accurate evaluation of the SpO_2%.**

In order to assess the effectiveness of the proposed method, the experimental results are compared with the gas chromatograph's analysis.

Keywords—Oxygen saturation measurement, signal features extraction, photoplethysmogram signal, smartphone.

I. Introduction

The evaluation of the arterial blood oxygen saturation (SpO_2%) is important task for healthy and sick people [1-3]. In fact, healthy people during hard muscle training exercise can be in state in which the body oxygenation is lacking. For the sick people the SpO_2% can be used to dose the care.

The gold standard of the SpO_2% measurement is the gas chromatograph [4], but it is an invasive technique. A non-invasive technique is the pulse oximeter that evaluates the SpO_2% by the absorption property of the oxy and deoxyhaemoglobin. In fact, the haemoglobin absorbs different wavelength if it is combined with the oxygen (940nm) or not (600nm) [5]. The pulse oximeter [6, 7] provides these two wavelengths at 940nm and 600nm with two specific light sources, and uses light detector to provide the photoplethysmographic (PPG) signals for the oxy and deoxy haemoglobin, respectively. The SpO_2% is evaluated from the parameters of the two PPG signals [8, 9].

In the recent literature, the smartphone is proposed, at least of a specific device, for the evaluation of the PPG signals and the SpO_2%, also [10-14]. The smartphone uses the LED with wide spectrum light emission in the place of specific wavelengths. The SpO_2% is evaluated from the pulse parameters of PPG_{Red} and PPG_{Green} signals evaluated for the red and green colour channels of the smartphone's camera.

The external light affects on different manner the smartphone's camera, depending on the model and manufacture. The estimated PPG_{Red} and PPG_{Green} signals are scaled of a factor depending on the device quantum efficiency. This scale factor introduces systematic error in the estimated SpO_2% because it does not take into consideration the intensity of the external light superimposed to the artificial light used in the estimation.

Moreover, kind of skin, the non-perfect positioning of the finger on the camera, involuntary movements of the patient can influence the acquired signal. The hypothesis that the patient is motionless during the test and that his finger adheres perfectly to the smartphone camera lens does is not real and not guaranty that the measurement is executed correctly, and not influenced by the external light sources. The results are noise and artefact on the reconstructed PPG_{Red} and PPG_{Green} that do not permit accurate evaluation of the SpO_2%.

In order to overcome these difficulties, in the paper is proposed and developed a proper method for setting-up the parameters to compensate the effects of the environmental light sources.

Initially, the signal is pre-processed to verify if it can be used for accurate evaluation of the SpO_2% by analysing in the spectral domain the PPG_{Red} and PPG_{Green}. In this manner, the method is able to recognize automatically if the patient is using correctly the smartphone, making the use suitable for unskilled patient, also.

Once assessed that both PPG_{Red} and PPG_{Green} are suitable for the SpO_2% evaluation:

- the quality of the signal is increased by band pass filtering;
- each pulsation of the PPG_{Red} and PPG_{Green} is extracted, because the SpO_2% is evaluated by using the parameters of a single pulsation;
- the effects of external additional noise sources, due to infrared radiation of the environment, are compensated

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by proper setting-up the scale factors of the PPG_{Red} and PPG_{Green}.

The setting-up method is implemented on android smartphone with low computational capability in order to permits the diffusion of the application on large number of devices.

The paper is organized as follows. In section II the proposed setting-up method is presented. In section III the evaluation of the SpO_2% by PPG_{Red} and PPG_{Green} signals is abstracted for sake of completeness. In section IV the results of the experimental tests are shown and compared with the results obtained by gas chromatograph's analysis. Finally, the conclusions are drawn.

II. PROPOSED SETTING-UP METHOD

The PPG_{Red} and PPG_{Green} signals are evaluated according to the method proposed in [14]. This method analyses the frame of the fingertip video in separate red and green colour channels to monitor the light intensity change that is proportional to the PPG_{Red} and PPG_{Green} signals, respectively. The band of the colour channel influences the PPG_{Red} and PPG_{Green} signals. To evaluate the PPG at a specific wavelength 940nm and 600nm factor equal to the ratio between the quantum efficiency of the camera at the specific wavelength and the summary of the quantum efficiency of the colour channel is used. Each of the resulting signal is proportional to a single wavelength and not to the band of the colour channel. The SpO2% evaluation uses this two signals [14].

In order to make negligible the influences of the environmental light, in [14] black drop to cover the smartphone is used. In the paper, this last shrewdness is not used because the effect of the external light source is compensated.

Initially, the validation test is pointed out to pre-process the PPG_{Red} and PPG_{Green} signals in order to assess if they are suitable for the SpO_2% evaluation. In fact, the not correct use of the smartphone as partial occlusion, excessive pressure of the finger on the smartphone camera, voluntary or involuntary movement can modify the shape of the PPG_{Red} and PPG_{Green} signals. The test is based on the evaluation of parameters in the frequency domain in order to discern if the PPG_{Red} and PPG_{Green} have characteristic compatible with the usual trend.

Successively, the setting up of the scale factors of the PPG_{Red} and PPG_{Green} is pointed out in order to compensate the effects of the environmental light sources on the variation of the quantum of the camera.

Indeed, different environmental conditions can induce slight alterations in amplitude of the PPG_{Red} and PPG_{Green} signals, due to the addition of infrared light. The external light sources directly influence the coloration of the pixels causing error in the estimation of the PPG_{Red} and PPG_{Green} signals and, consequently, in the SpO_2% evaluation. In [14], the flash LED supplied to the smartphone and constant scale factors are used to compensate the influence of external light sources. The experimental results show that the use of constant coefficient does not fit all the conditions of dynamic acquisition. The variation of a few tenths of the quantum efficiency coefficients determine a variation up to 4% of the estimated SpO_2%.

Fig.1 shows the block scheme of the proposed method for the accurate evaluation of the SpO_2%. After the fingertip video acquisition, the PPG_{Red} and PPG_{Green} signals are extracted from the red and green colour channels [14] and are tested to assess if they are suitable. If suitable, the PPG_{Red} and PPG_{Green} signals are processed to (i) improve the quality of the signal, (ii) pulse extraction, and (iii) compensate the effects of the external light radiation by setting up the scale factors of the PPG_{Red} and PPG_{Green} signals.

A. Validation test

Fig.2 shows the block scheme of the validation test. Both the PPG_{Red} and PPG_{Green} signals are analysed in the frequency domain by the Fast Fourier Transform (FFT). In particular, the test verifies the two following conditions for the first and the second tone:

- the frequency f_c of the first tone, representing the heart rate, belongs to the range [0.5-1.7] Hz;
- the frequency of the second tone with maximum amplitude belongs to the range ±10% of f_c.

The first condition guaranties that the heart rate is included in the range [30 – 102] pulse per minute. The second condition is empirically determined.

The two tests assess if the signal is quasi-periodic. In fact, the PPG_{Red} and PPG_{Green} are not periodic, as every biological signal. If these conditions are not satisfied, the signal is discharged. If it is suitable, another condition verifies the pulse shape of PPG_{Red} and PPG_{Green} signals. With this aim, the quality index is defined by the ratio of:

- sum of the power spectrum components in the narrow band of fundamental frequency f_c, and the harmonic at $2f_c$;
- sum of all the components not previously considered.

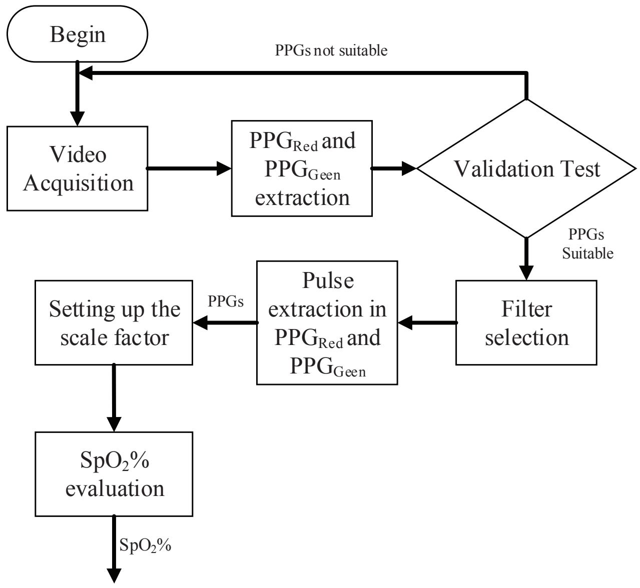

Fig.1 Proposed method for improving the accuracy in the evaluation of the SpO_2%.

Due to the reduced number of samples, the spectrum has low resolution and is affected by spectral leakage.

The threshold value of the quality index is set so as the SpO_2% evaluated by the proposed method and that of the gas chromatograph are comparable. The difference between the smartphone and the gas chromatograph is lower than 1% if the quality index is higher than 2. Therefore, the threshold equal to 2 permits to discharge all the signals that non provide suitable PPG_{Red} and PPG_{Green} signals.

B. *Filter selection*

In order to reduce the influence of noise and artefact, the PPG_{Red} and PPG_{Green} signals are filtered. The criteria to set the filter parameters are:

- the PPG_{Red} and PPG_{Green} signals have limited bandwidth, and the lower frequency component changes with the heart rate. The filter bandwidth must include this frequency and the fundamental components at f_c.
- the sampling frequency of the smartphone changes according to the device and internal decision system. Then the filter parameters, for the same band, must be calculated for each expected sampling frequency.

Therefore, 42 band-pass zero-phase filters are implemented with different band and sampling frequency. The filters are Butterworth IIR with order equal to 9. The band of each filter versus the range of the estimated f_c is shown in Tab.I. Each filter is designed for sampling frequency in the range [15, 33] S/s, and step of 3 S/s.

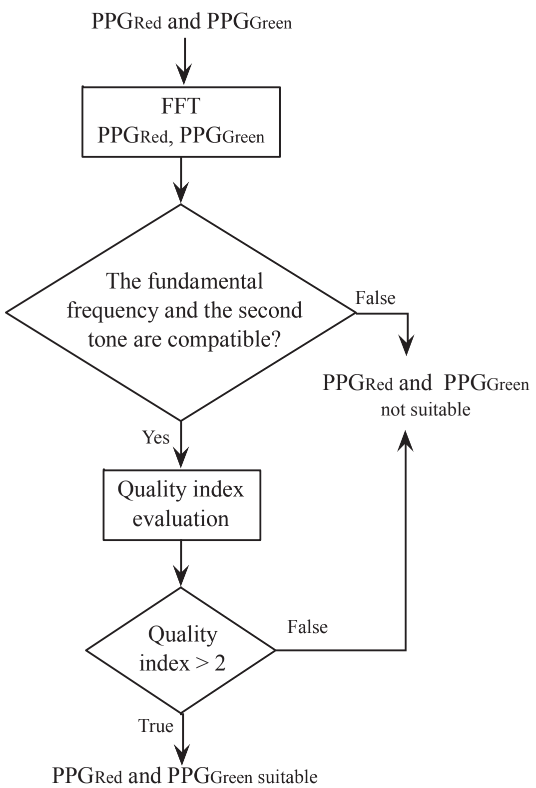

Fig.2 Validation test.

TABLE I. BAND OF THE FILTER VERSUS THE HEART RATE RANGE FOR ALL THE SAMPLING FREQUENCY.

Range of f_c [Hz]	Pass-band [Hz]
[0.5, 0.7)	0.3 – 1.6
[0.7, 0.9)	0.5 – 2.0
[0.9, 1.1)	0.7 – 2.4
1.1, 1.3)	0.9 – 2.8
[1.3, 1.5)	1.1 – 3.2
[1.5, 1.7)	1.3 – 3.6
[1.7, 1.9)	1.5 – 4.0

Fig.3 shows the PPG_{Red} before and after the filtering. The signal has f_c equal to 1.4Hz, the filter has the band in the range [1.1, 3.2] Hz. Before the filtering, the PPG_{Red} signal is affected by artefacts generated by the breathing, and involuntary movements of the patient that introduce fluctuation in the signal and noise. After the filtering, these effects are negligible.

C. *PPG pulse extraction*

The pulses are extracted from the PPG_{Red} and PPG_{Green} signals according to the procedure showed in the block scheme of Fig.4. In particular:

- the period of a single pulse is evaluated by the signal fundamental frequency f_c;
- the local maximum and local minimum values are estimated by peak detection algorithm.

Each maximum value is related to one pulse in the signal and the previous local minimum is assumed as beginning of the pulse. The information about the period is used in the case two consecutive maximum or minimum are found. In this case, the value not compatible with the period is discharged.

Another suitably test is performed on the single pulse. In fact, the evaluation of theSpO_2% is strongly linked to the pulse shape. The test verifies if the pulse has the strict monotonicity between the minimum and the maximum, associated to the systolic movement. If this condition is not satisfied, the pulse is discharged.

D. *Setting-up the scale factors*

Fig.5 shows the Quantum Efficiency (QE) of the colour channels of a smartphone camera. The QE quantifies the

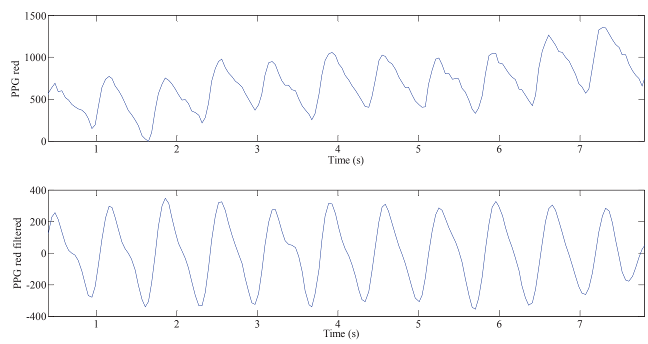

Fig.3 PPG_{Red} before (upper) and after the filtering (down).

sensitivity of the camera to transform light with specific wavelength in an electrical signal. Each colour channel has the trend of band-pass filter. Consequently, all the light in the pass-band of the channel influences the resulting colour of the image. The external light sources have not a flat spectrum and cannot be considered as constant during the measurement procedure, so they can influence the colour channel in different manner. In particular, if there is a combination between the imposed light source (LED) and the external light sources, this last increases the amplitudes of the constant and of the pulsatile parts of the PPG_{Red} and PPG_{Green} signals.

Moreover, the external light sources introduce alteration in the colour of the frame's pixels. The result is offset and gain error on one or both red and green channels, and then on the PPG_{Red} and PPG_{Green} signals.

In order to quantify the effect of the external sources, the analysis considers two parameters depending on the smartphone camera:

- the difference (D) between the maximum values of the PPG_{Red} and PPG_{Green};
- the band width (B) in which the red and green signals fall.

By using these two parameters a two dimensional look-up table *L(D, B)* is pointed out. The elements of the look-up table are the couple of scale factors (C_{Red}, C_{Green}) of the PPG_{Red} and PPG_{Green}, respectively. These factors are determined in experimental phase.

In this phase, the SpO_2% is evaluated, for the same patient and at the same time, by the proposed method and the gas chromatograph. The estimated PPG_{Red} and PPG_{Green} signals are scaled by trial value of (C_{Red}, C_{Green}). The PPG_{Red} has amplitude lower than the PPG_{Green}, so it requires higher value to obtain sensible variation in the SpO_2%. The couple of scale factors that makes compatible SpO_2% of the proposed method with the gas chromatograph is included in *L(D, B)*.

In order to validate the results, tests are repeated on the same patient but in different conditions of external brightness.

Not all the possible couple of *(D, B)* can be defined in the experimental phase. To determine the factor to be used, the couple *(D', B')* is found in the look-up table, with the property that has minimum geometrical distance from the *(D, B)*.

Therefore, the compensated signals PPG'_{Red} and PPG'_{Green} to be used are:

$$\begin{cases} (C'_{Red}, C'_{Green}) = L(D', B') \\ PPG'_{Red} = C'_{Red} * PPG_{Red} \\ PPG'_{Green} = C'_{Green} * PPG_{Green} \end{cases} \quad (1)$$

According to [14], PPG_{Red} is evaluated from the video frame compensating the quantum efficiency with the constant value corresponding to 600 nm. PPG_{Green} is evaluated from the video frame compensating the quantum efficiency with the constant value corresponding to 940 nm.

III. SpO_2% EVALUATION

The modified formula used in [14] for the SpO_2% evaluation is:

$$SpO_2\% = \frac{\varepsilon_{Hb,Red}\sqrt{m_{Green}}\ln(PPG'_{Green})}{\sqrt{m_{Green}}\ln(PPG'_{Green})(\varepsilon_{Hb,Red}-\varepsilon_{HbO,Red})}\cdots$$
$$\cdots\frac{-\varepsilon_{Hb,Green}\sqrt{m_{Red}}\ln(PPG'_{Red})}{-\sqrt{m_{Red}}\ln(PPG'_{Red})(\varepsilon_{Hb,Green}-\varepsilon_{HbO,Green})}\% \quad (2)$$

where $\varepsilon_{HbO,Red}$, $\varepsilon_{Hb,Red}$, $\varepsilon_{HbO,Green}$ and $\varepsilon_{Hb,Green}$ are the absorption coefficients for the deoxy and oxy haemoglobin for the red channel at 600nm and green colour channel at 940nm, m_{Red} and m_{Green} are the slope of the rising edge of each pulse of the PPG'_{Red} and PPG'_{Green}.

IV. EXPERIMENTAL RESULTS

In the experimental tests, the SpO_2% evaluated by the smartphone is compared with the gas chromatograph analysis.

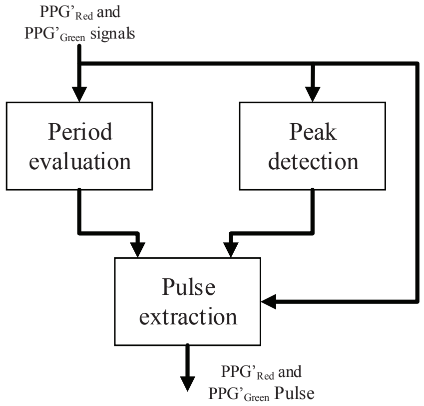

Fig. 4 Pulse extraction procedure.

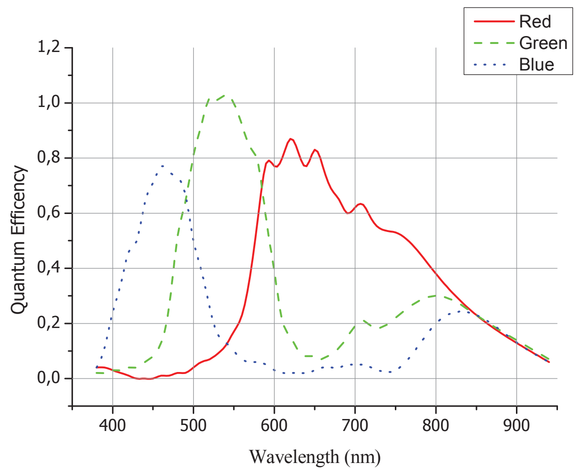

Fig. 5. Quantum efficiency trend for the RGB components of smartphone camera [12].

The smartphone is the HTC One Mini, the gas chromatograph is the ABL800 Flex.

During the tests, the camera is placed on the fingertip of the forefinger of the right arm, and the blood sample extracted by the left arm is analysed by the gas chromatograph.

The subjects are voluntaries of both the gender with age in the range [43-82] years. The values of C_{Red} and C_{Green} are evaluated experimentally. C_{Red} is in the range [0.8, 21.0], C_{Green} is in the range [0.9, 1.5]. The difference between the two ranges is due to the different amplitude of the PPG_{Red} and PPG_{Green}.

Some scale factors for PPG_{Red} and PPG_{Green} are show in Tab.II.

Tab. III shows the values of the SpO_2% evaluated by gas chromatograph and smartphone. The difference is equal to 1% in the worst case. This difference can be justified by the fact that the gas chromatograph analyses blood sample and gives only one value, the smartphone evaluates the SpO_2% related to a time interval by averaging the results of different pulses.

In all the experimental tests the proposed method does not provide a result if the signals are not suitable for the elaboration. This fact ensures that the results are compatible with the value of the gas chromatograph analysis.

The maximum experimental error obtained with the proposed method is equal to 1%. The maximum experimental error in [14], without the proposed method is equal to 2%.

TABLE II. *L(D, B)* USED IN THE EXPERIMENTAL TESTS.

B \ D	425	475	525	525	675
300	(0.90,1.00)	(0.95,1.00)	(1.35,1.00)	-	-
500	-	-	-	(1.80,1.00)	(2.00,1.00)
750	-	-	-	(1.95,1.00)	(3.00,1.00)
800	(0.90,1.00)	(0.95,1.00)	(1.35,1.00)	-	-
1150	-	-	-	(1.80,1.00)	(2.00,1.00)

TABLE III. COMPARISON BETWEEN THE SpO_2% EVALUATED BY GAS CHROMATOGRAPH AND SMARTPHONE.

#Patient	Age	Gender	SpO_2 gas chromatograph [%]	SpO_2 smartphone [%]
1	83	Male	94	93
2	72	Female	98	97
3	43	Male	93	93
4	66	Male	95	95
5	66	Male	96	96
6	64	Female	95	96
7	79	Male	94	94
8	63	Female	96	97

V. CONCLUSIONS

In the paper, the setting-up of the PPG_{Red} and PPG_{Green} scale factors for the blood oxygenation evaluation is proposed.

The setting-up is necessary to compensate the effects of the environmental light sources on the obtained photoplethysmogram signals.

Moreover, intermediate validation test is proposed to validate the signal and establish if it is suitable for the analysis. This test permits to recognize if the patient is not using correctly the smartphone, making the use suitable for unskilled patient, also.

The proposed method is experimentally tested. These tests demonstrate that the proposed method provides results comparable with the gas chromatograph analysis.

References

[1] J.M. Gomes, J.H. Correia, J.P. Carmo, "A Low-Cost Flexible-Platform (LCFP) for characterization of photodetectors", Measurement, Vol. 61, Feb. 2015, pp, 206-215.

[2] M.L. Vold, U. Aaseb, T. Wilsgaard, H. Melbye, "Low oxygen saturation and mortality in an adult cohort: The Troms study", (2015) BMC Pulmonary Medicine, 15 (1), art. no. 9.

[3] M. Penhaker Ph.D., M. Černý, L. Martinák, J. Spišák,A. Válková, "HomeCare – Smart embedded biotelemetry system", World Congress on Medical Physics and Biomedical Engineering 2006.

[4] ABL800 FLEXreferencemanual" Radiometer Medical ApS, 2012,. 995-940.

[5] iWorx, "PO2-100D Pulse Oximeter Technical Note", iWorx Systems, Inc., 2012.

[6] O. Wieben, "Light absorbance in pulse oximetry," in Design of Pulse Oximeters, J.G. Webster, ed., Bristol: Institute of Physics Publishing, 1997, pp. 40–55.

[7] J. G. Webster, Design of Pulse Oximeters. Bristol and Philadelphia: Institute of Physics Publishing, 1997.

[8] M. Nitzan, H. Taitelbaum, "The Measurement of Oxygen Saturation inArterial and Venous Blood", IEEE Instrumentation & Measurement Magazine, June 2008, pp. 9-15

[9] M. Nitzan, A. Babchenko, B. Khanokh, and H. Taitelbaum,"The measurement of oxygen saturation in venous blood by dynamic near IR spectroscopy," J. Biomed. Optics, 2000, vol. 5, pp. 155–162.

[10] F. Lamonaca, K. Barbè, G. Polimeni, D. Grimaldi, "Health parameters monitoring by smartphone for quality of life improvement Measurement", Measurement, Volume 73, Issue 28, May 2015, pp. 82-94.

[11] C.G. Scully, J. Lee, J. Meyer, A. M. Gorbach, D. Granquist-Fraser, Y. Mendelson, K.H. Chon, "Physiological Parameter Monitoring from Optical Recordings with a Mobile Phone", IEEE Trans Biomed Eng. Feb.2012, Vol. 59, n. 2, pp. 303–306.

[12] W. Verkruysse, L.O. Svaasand, J.S. Nelson,"Remote plethysmographic imaging using ambient light", Opt Express. 2008, Vol. 16 n. 26, pp.21434–21445.

[13] J.E. Scharf, "Green light pulse oximeter" patent number US 5830137 A, 1998.

[14] F. Lamonaca, D. L. Carnì, D. Grimaldi, A. Nastro, M. Riccio, V. Spagnuolo, "Blood oxygen saturation measurement by smartphone camera", Proc. of IEEE International Symposium on Medical Measurements and Applications, MeMeA 2015 –May 7-9, Torino, Italy.