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Research Article

Relationship between the Photoplethysmographic Parameters and Derivation from the Windkessel Model in Hemodynamics in Critically Ill Patients

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Abstract

Background: The non-invasive hemodynamic monitoring by photoplethysmography (PPG) stands out as it is easy to use and it can provide information on hemodynamic parameters at the bedside.

Objective: To compare the main PPG parameters with the age and hemodynamic variables in patients hospitalized in Intensive Care Units (ICUs).

Methods: A cross-sectional study was conducted in the ICU of Hospital Nossa Senhora da Conceição, located in south of Brazil. The following data was collected in the 1st 24h of hospitalization: age, Heart Rate (HR), Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), Mean Arterial Pressure (MAP), Pulse Pressure (PP), Hematocrit (Hct), and variables obtained with PPG: Perfusion Index (PI), Pleth Variability Index (PVI), Crest Time (CT), time between the systolic and diastolic peaks (ΔT), Augmented Index (AI), τparameter, and arterial aging (b/a). For comparison of the variables, a bivariate linear regression was performed.

Results: 190 individuals were evaluated. Most of them were male (6:5), median age 67.0 (54.0-75.0) years, main reasons for hospitalization: cardiovascular and neurological causes. With regard to PI, we observed a correlation with age (r=-0.163; p= 0.025), DBP (r=0.167; p= 0.021), MAP (r=0.171; p=0.019), and Htc (r=0.205; p=0.005). The PVI showed an association only with HR (r=0.150; p=0.038). The CT was correlated with SBP (r=0.185; p=0.011), PP (r=0.256; p<0.001), and HR (r=-0.651; p<0.001). The ΔT interval showed an association only with HR (r=0.187; p=0.010). The AI was correlated with SBP (r=0.173; p=0.017), PP (r=0.195; p=0.007), and HR (r=-0.620; p<0.001). The τ parameter showed an association with SBP (r= 0.147;p= 0.043), PP (r=0.169; p=0.020), and HR (r=-0.649; p<0.001). The b/a index was correlated to age (r=0.254; p<0.001), SBP (r=0.257; p<0.001), MAP (r=0.200; p=0.006), PP (r=0.233; p=0.001), and HR (r=-0.312; p<0.001).

Conclusion: Associations were found, with plausibility in cardiovascular physiology, which allow a general view of the variables implied in the PPG. Such data can provide complementary information for hemodynamic monitoring and clinical judgment of the intensivist.

Introduction

The hemodynamic monitoring is one of the bases of intensive care, being essential to evaluate the cardiovascular function and tissue perfusion. Among the techniques used, we can describe invasive methods, such as pulmonary artery catheter, central venous catheter, catheters with thermistors and lithium sensors, and non-invasive methods, such as electrical bioimpedance, finger pressure cuff, radial tonometry, echocardiography, and photoplethysmography (PPG) [1].

In the perspective of a non-invasive monitoring, which can reduce the number of infections and complications [2], PPG stands out as it is easy to use and it can provide information on hemodynamic parameters at the bedside.

PPG generally uses two monochromatic light beams in the red and infrared range, which are transmitted or reflected on the finger and captured by photodetectors. By means of this signal, the variation of light absorbed by the pulsatile blood flowing through the arterioles is obtained. In addition to the parameters routinely obtained, such as Heart Rate (HR) and Peripheral Oxygen Saturation (SpO2), other indexes have been incorporated to this technology, such as the perfusion index, arterial stiffness indicators, hypovolemia, and parameters related to the wave form and its derivatives [3-5].

It is importantto point out that the PPG parameters are related to physiological changes, such as distensibility and vascular resistance, cardiac output, blood pressure, and peripheral perfusion that many times are difficult to interpret [6].

Therefore, many forms of analysis were proposed to better understand the cardiovascular dynamics extracted from PPG. In addition to identifying the parameters of wave form, one of the most used models to simulate this system is based on the Wind kessel effect. Such model represents the elastic reservoir of the large arteries associated to peripheral bed resistance [7,8].

In this sense, the objectiveof this study was to compare the main PPG parameters, including a derivation from the Wind kessel model, with the age and hemodynamic variables in patients hospitalized in Intensive Care Units (ICUs). This interpretation of the PPG indexes can facilitate the cardiocirculatory evaluation and provide more information to the clinical practice of intensivists in the care of severely ill individuals.

Materials and methods

A cross-sectional study was conducted in the adult Intensive Care Center (ICC) of Hospital Nossa Senhora da Conceição (HNSC), located in Tubarão, Santa Catarina, Brazil. This ICC has three ICUs, each one with 10 beds, serving an area of 18 municipalities. One of the ICUs isintended to treat patients with cardiovascular diseases and the other two has a general service profile.

Individuals hospitalized from July 2016 to July 2017 were selected; whose relatives have signed the voluntary informed consent form. The cases with poor quality of PPG signal and with errors in the medical record identification were excluded. This study was submitted to the research ethics committee of the University of Southern Santa Catarina (UNISUL), in Palhoça, Santa Catarina, Brazil,andwas approved by CAAE 50687515.6.0000.5369.

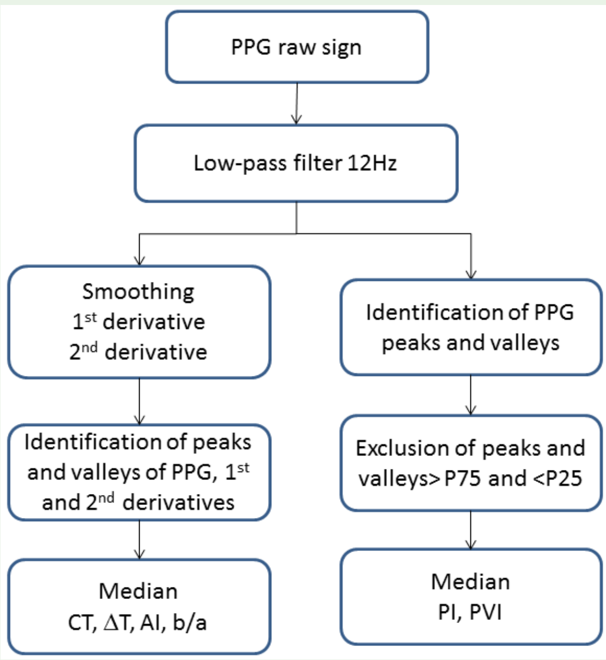

Figure 1: PPG processing.

PPG: Photoplethysmography; CT: crest time; AI: augmented index; PI: Perfusion Index; PVI: pleth variability index; P25: 25th percentile; P75: 75th percentile.

The sample size was estimated in n≥124, based on an error α=0.05, error β=0.20 and correlation level r=0.25, according to the expression [9]:

$$n \geq \{(Z_{1-a/2} + Z_{1-b}) / \left[1/2 * ln\left(1+r\right)/\left(1-r\right)\right]\}^2 + 3$$

In the data collection we included age, PPG pulse curve signal, Systolic Blood Pressure (SBP), Diastolic Blood Pressure (DBP), and Hematocrit (Htc) in the first 24 hours. The pulse pressure (PP=SBP-DBP) and mean arterial pressure (MAP = (SBP+2DBP)/3) were derived.

For acquisition of the PPG signal, a Reflex Aqwave TM oximeter was used. It can store the pulse curve values in a sampling frequency of 60 Hz and duration of one minute. The device can export the text file data for computational analysis. The data from the PPG pulse curve was manipulated in the MATLAB software. Initially, the PPG raw signal processing was performed by filters, derivatives and statistical tools (Figure 1).

The variables related to cardiovascular function, arterial stiffness and peripheral resistance were: Crest Time (CT), time between the systolic and diastolic peaks (ΔT), augmented index (AI=100%. DP/SP) resulting from the division of the Diastolic Peak (DP) and Systolic Peak (SP), and arterial aging (100%.b/a), obtained with the 2nd derivative of the PPG signal [6]. For analysis of the peripheral perfusion and volemia, I used the expressions: perfusion index (PI=100%AC/DC) and Pleth Variability Index (PVI=[(SPmax-SPmin)/SPmax].100%) [10]. The identification of the PPG parameters is described in Figure 2.

In addition to these variables, the parameter τ was derived, obtained from the Windkessel model. "τ" is an indicator of the dynamic functioning of the cardiovascular system. It controls the blood pressure curve form. The Wind kessel model considers the damping effect by the compliance of the large arteries during cardiac contraction. This interaction allows the systolic volume to have a small increase in blood pressure and maintain the organic perfusion during the diastole. Figure 3 shows the derivation from the Windkessel model of 2 elements applied to PPG, in which is the blood flow, is the blood pressure in the aorta, is the aorta arterial compliance, and is the peripheral resistance of the systemic circulation [7,8].

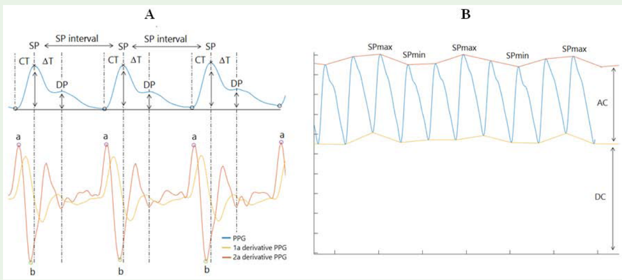

Figure 2: Identification of PPG parameters.

SP: Systolic Peak; DP: Diastolic Peak; CT: Crest Time; SPmax: Maximum Systolic Peak, SPmin: Minimum Systolic Peak; AC: Pulsatile Component; DC: Nonpulsatile Component.

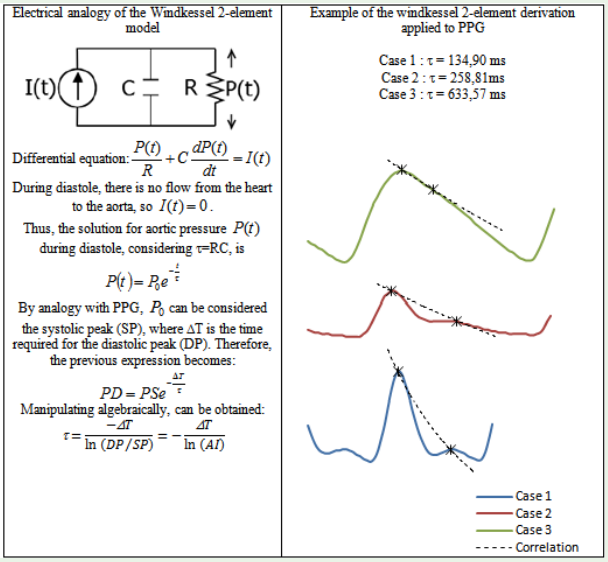

Figure 3: Derivation of the Windkessel 2-element model applied to PPG.

AI: augmented index; PPG: photoplethysmography; P(t): pressure; I(t): flow; C: compliance; R: resistance.

The data was stored in a database created with the assistance of the Excell® software, and then exported to the SPSS 20.0® software. The data was presented in absolute numbers and percentages, measures of central tendency and of dispersion. Bivariate linear regression was performedin the PPG parameters, age and hemodynamic indicators. Error α was considered to be 5%.

Results

We evaluated 230 individuals participating in this research. 14 of them were excluded for poor quality of signal and 26 for errors in the medical record identification, totaling 190 subjects, with a median age (IQL) of 67 (54 - 75), whose characteristics are described in Table 1.

Table 1: Characteristics of the ICC sample of HNSC in Tubarão, SC, Brazil.

	n(%)
Age	
<60 years	68 (35,8)
≥ 60 years	122 (64,2)
Gender	
Male	106 (55,8)
Female	84 (44,2)
Surgical	
No	95 (50,0)
Yes	95 (50,0)
Diagnosis	
Cardiovascular	68 (35,8%)
Neurological	39 (20,5%)
Gastrointestinal	19 (10,0%)
Neoplasm	18 (9,5%)
Respiratory	14 (7,4%)
Infection	13 (6,8%)
Polytrauma	11 (5,8%)
Others*	8 (4,3%)

*Others: genito-urinary, orthopedic, endocrine. ICC: Intensive Care Center

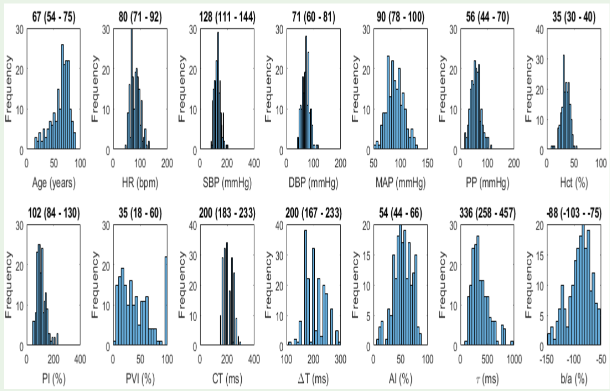

Figure 4: Variables related to PPG and hemodynamic parameters.

HR: Heart Rate; SBP: systolic blood pressure; DBP: diastolic blood pressure; MAP: mean arterial pressure; PP: Pulse pressure; Hct: Hematocrit; PI: Perfusion Index; PVI: pleth variability index; CT: crest time; AI: augmented index.

Figure 4 shows the histogram of the variables obtained with the PPG signal and hemodynamic parameters, identifying the median (P25-P75).

Chart 1 shows three cases as examples with the PPG signal, 1st and 2nd derivatives and the parameters of each curve. Case 1 presented Htc=49.5%, HR 112.0 bpm, SBP=121.0 mmHg, DBP=83.0 mmHg, MAP=95.7 mmHg, and PP=38.0 mmHg. In this case, the individual is young, presenting higher values of ΔT and more negatives of b/a. Demonstrates tachycardia, with reduced CT, AI and τ. It has adequate pressure and Htc values, presenting high PI and intermediate PVI.

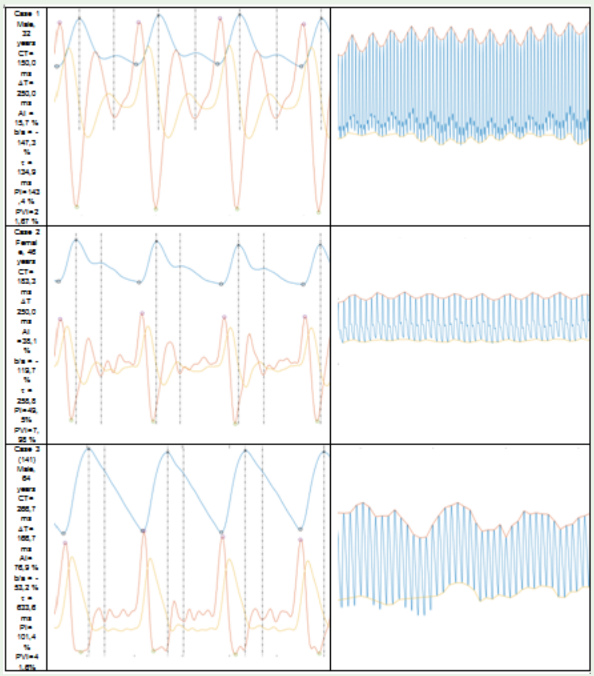

Chart: Example of the PPG signal and derived parameters.

PI: Perfusion Index; PVI: pleth variability index; CT: crest time; AI: augmented index.

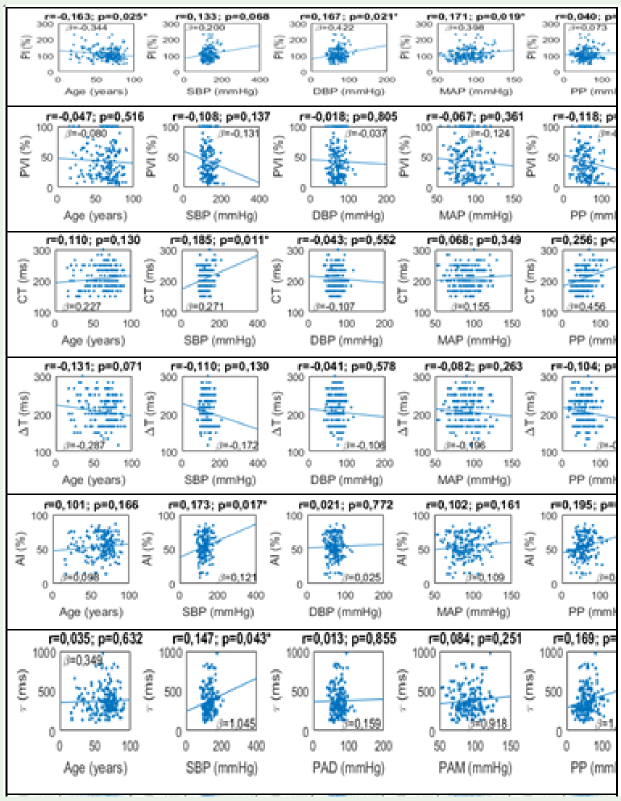

Figure 5: Bivariate linear regression between PPG parameters and hemodynamic indicators.

HR: Heart Rate; SBP: Systolic Blood Pressure; DBP: Diastolic Blood Pressure; MAP: Mean Arterial Pressure; PP: Pulse Pressure; Hct: Hematocrit; PI: Perfusion Index; PVI: Pleth Variability Index; CT: Crest Time; AI: Augmented Index.

Case 2 presented Htc=31.4%, HR 70.0 bpm, SBP=121.0 mmHg, DBP=50.0 mmHg, MAP=73.7 mmHg, and PP=71.0 mmHg. This patient is middle-aged with higher values of ΔT and intermediates of b/a. It has normal HR, presenting median CT, AI and τ. Demonstrates low Htc and DBP, with low PI and PVI.

And in case 3 we observed Htc=43.1%,HR 69.0 bpm, SBP=167.0 mmHg, DBP=81.0 mmHg, MAP=109.7 mmHg, and PP=86.0 mmHg. In this case, the individual is elderly, demonstrating reduced ΔT, high b/a, higher CT, AI and τ. He has normal HR, normal Htc and hypertensive. It has high PVI and suitable PI.

Figure 5 demonstrate the bivariate linear regression between PPG parameters and hemodynamic indicators.

Discussion

The results obtained with the hemodynamic and PPG parameters of ICU patients in the first 24 hours of hospitalization showed associations that can allow a better understanding of the cardiovascular variables implied in the PPG pulse curve. Although it is a cross-sectional study, comparing profiles of different patients, it can show a generalization of the variables found in the main PPG parameters and their hemodynamic relation, providing the intensivist with more information for clinical judgment.

Most of the patients hospitalized in the ICC in this study were male (6:5), old, and the main reasons for hospitalization were cardiovascular and neurological causes. Half of the cases were from the surgical center. Such data is similar to the study carried out in the ICU of Hospital das Clínicas of the Medical School of Marília, Brazil [11]. Moreover, it is similar to the study conducted by Siddiqui [12] in Singapore; the only difference was the main reason for hospitalization, which was septic shock, followed by neurological and cardiovascular causes. Furthermore, a study carried out in an ICU in Nigeria [13] identified the same proportion of men and women; however, most patients were in the age group from 15 to 40 years of age, and the neurological cases were the main basic diagnoses. Such data shows that the epidemiological profile of ICUs can change according to the area and structure of services.

One of the parameters that has been widely used and incorporated in the PPG technology nowadays is the PI. It is an important tool to monitor non-invasive peripheral perfusion and it is based on the vasoconstrictor response resulting from circulatory failure and redistribution of the blood flow. In the evaluation of the extremities, the PI identifies the percentage of pulsatile blood flow (AC component) in all the adjacent tissues (DC component), by the absorption of the light beam passing through the finger. A reduction in the peripheral blood flow, such as a shock, hypothermia and hypotension, can present low PI values [14-17]. In this study, we observed a significant positive correlationamong DBP, MAP and Htc, and a significant negative correlation with age. Such results show that old patients have a lower PI and individuals with a higher DBP and MAP have higher levels of PI, according to the literature [15]. And although the study conducted by Kanmaz et al [18] has not found a relation between Htc and PIin premature babies before and after blood transfusion, Njoumand Kyriacou [19] discussed, for the first time, that PPG can identify the Htc and other hemorheological measurements.

PVIisa parameter that is correlated with respiratory rate variability and, as a result, causes alterations of pulse pressure (ΔPP). This measure has a good correlation with PVI, monitored by the PI variability, and both have indication for evaluation of depletion and volume in critically ill patients. The higher the PVI, the greater the influence of breathing on the signal that indicates decrease in vascular volume [20,21]. In this study, we noticed a positive correlation between PVI and HR. These findings are based on cardiovascular physiology, in which the response in the HR increase is common in hypovolemia, as adaptation and maintenance of cardiac output [22].

With regard to CT, we noticed a significant positive correlation between SBP and PP, and a significant negative correlation to HR. The CT results from blood ejection, beginning after the cardiac isovolumetric contraction and the systolic peak, almost at the end of the systole. The increase in the HR causes a decrease in the CT for the increase of cardiac contractility and the increase of SBP and PP results in the increase of cardiac work, resulting in an increase of the CT. These findings were described by Haiden et al., [23] who, by adjusted linear regression among the ventricular ejection time, HR and gender, have also shown that this time presents a U-curve for all causes of death in an 8-year average segment, in which the reduced and extended ejection time is a risk factor for prognosis.

With regard to ΔT, we found a positive correlation only with HR. The time (ΔT) between the systolic peak and diastolic peak can be considered the interval between the back and forth path of the large arteries to the arterioles. It is known that the higher the stiffness, the shorter the time of this path, serving as an indicator of arterial elasticity. Such parameter, when normalized by the individual's height (h), can be compared to the pulse wave velocity (PWV= h/ΔT) [5,24]. The height-based correction was not performed in this research, but we expected to see a decrease in the ΔTin higher values of blood pressure and age, which did not happen, resulting only in a tendency in the association [25]. The relation between PWV and HR show uncertain results, in which HR seems to be a confusing factor in data adjustments. However, it is known that higher PWV values are related to a higher mortality rate [26].

The AI represents the height proportion between the diastolic peak and systolic peak. The systolic peak is formed by the ejection of blood into the left ventricle, which is transmitted to the finger. The diastolic peak results from the pulse reflected by the peripheral vascular network to the aorta [5,24]. In this research, we observed a positive correlation between SBP and PP, and a negative correlation with HR. The effect of hypertension on the AI increase is a finding that is usually seen [27], but this parameter is subject to change with vasoactive drugs, such as decrease with nitroglycerin and increase with angiotensin II [28]. Moreover, more studies about its implication on the HR are necessary, for although it is reduced with tachycardia, it can be related to other characteristics of arterial stiffness [29].

In a similar manner, the parameter τ, derived from the Windkessel model, showed thesame associations of AI, i.e., a positive correlation between SBP and PP and a negative correlation with HR. The Windkessel model of two elements helps to understand the effect of compliance (C) and resistance (R) of the cardiovascular system, showing that not only peripheral resistance is increased in hypertension, but also the decrease in compliance, which has an important effect on the PP increase, identified as a marker of cardiovascular mortality. After the initial proposal of the model, other elements were incorporated, such as inheritance and impedance to the system, to motivate new analyses and allow a more realistic view of the hemodynamic characteristics [30]. The use of PPG has been proposed with different purposes, such as estimation of blood pressure [7], characterization of the wave form according to the age and parameters of the Windkessel model [31], and also the incorporation of 13 elements to the system for identification of the constants and classification of the PPG wave form according to the age and cardiovascular diseases [8]. In this study, the parameter τ represents another stiffness index, very similar to AIthat, although it does not differentiate between R or C, it allows an analysis of the combined effect of these indicators on the vascular network.

With regard to the results of the variable b/a, positive correlations were found among age, SBP, MAP, PP and a negative correlation with HR. This variable is obtained by the second derivative of the PPG signal and, physically, the wave "a" corresponds to acceleration and wave "b" to deceleration of the initial phase of systole. The parameter b/a is known to be related to arterial aging, associated to age and marker of cardiovascular diseases, such as hypertension, dyslipidemia and diabetes [32,33]. Although the study carried out by Takazawa et al., [34] has not found any changes in the b/a index after the infusion of vasoactive agents, such as nitroglycerine and angiotensin, Kohjitani et al., [35] showed an association of such index with SBP in post-intubation. With regard to HR, Kohjitani et al., [36] have not found any association with the b/a parameter in the investigation of the variables obtained with the second derivative of the PPG signal and autonomic nervous system, different from this study, which obtained an inverse relation between these variables.

It is important to mention, as a limitation to this research, that the results obtained resulted from a variety of profiles of patients hospitalized in ICUs, in a cross-sectional study. In this perspective, the findings show general associations of the PPG pulse curve and hemodynamic variables, and therefore it is not possible to specify the respective effects in a longitudinal study.

This study compared the main PPG parameters to age and hemodynamic indicators in patient are hospitalized in ICUs. Associations were found, with plausibility in cardiovascular physiology, which give a general view of the variables implied in the PPG pulse curve. Such data can provide complementary information for hemodynamic monitoring and clinical judgment of the intensivist.

However, longitudinal studies are necessary to better understand the dynamicity of the patient's clinical evolution and its consequences in the PPG wave.

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