Normalization of the Photoplethysmographic Signal Using the Post-Extrasystolic Potentiation

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Abstract

The widespread use of wearable devices such as smartwatches has made continuous heart activity monitoring using photoplethysmography (PPG) more accessible and commonplace. However, PPG suffers from a lack of an absolute, interpretable unit for the signal amplitude, limiting its full diagnostic potential. We present a method to normalize PPG signals by leveraging the post-extrasystolic potentiation (PESP), a physiological phenomenon in which the contractility of the heart increases following a premature ventricular contraction (PVC). PVCs occur naturally in the human heart and have a well-studied resulting potentiation which behaves independent of many otherwise confounding factors. This allows the normalization to be relative to a consistent behaviour, giving meaning to the recorded signal amplitude. Preliminary findings indicate that PESP-based normalization provides insights into PPG signal interpretation, correcting for amplitude variations caused by the measurement modality, ensuring remaining variations are reflections of physiological changes. While promising, the method remains local to PVC-induced disturbances in normal heart rhythm, necessitating further research for broader applicability.

1. Introduction

Due to the prevalence of wearable devices such as smartwatches, an abundance of continuous data on heart activity is available in the form of photoplethysmography (PPG) signals. PPG is an optical measurement of changes in blood volume in the tissue underneath the sensor location and reflects heart activity [1, 2]. From PPG, several vital signals can be determined, such as heart rate and heart rate variability [3, 4]. PPG acquisition is low-cost, requiring only an LED and a photo diode, non-invasive as it is placed against the skin, and non-intrusive as it is easily placed in commonly used devices such as a smartwatch, a ring or a finger cap (in the case of transmissive PPG).

However, PPG as a measurement modality suffers from some downsides [5, 6]. For one, the measurement is very sensitive to noise from outside sources, such as ambient light, skin tone, skin contact. Combined with the most common sensor location, on the wrist, the recording will often be irreversibly contaminated with motion artifacts caused by the wearer. Secondly, PPG lacks an interpretable unit. The received amount of light depends on many factors, such as skin pigmentation, level of skin contact, angle, as well as cardiac changes. Because of this, the absolute amount of light received is often considered arbitrary. This downside is often overcome by using ratios, as those are still proportional. However, there is a loss of information by not being able to have absolute values. For example, certain vital signs such as blood pressure would be able to be recorded continuously while remaining non-invasive.

Post-extrasystolic potentiation (PESP) is a concept in which the contractility of the heart increases for the beat following the compensatory pause after an extrasystolic beat [7]. This extrasystolic beat can occur in the heart after a premature ventricular contraction (PVC). The PVC has only a short filling time and expels little blood out of the heart. After the compensatory pause introduced by the PVC, the following beat has an increased filling time and is enhanced because of it. PVCs are fairly common with a high prevalence in the general population, increasing with age, presence of underlying heart disease or other comorbidities such as hypertension or coronary artery disease [8]. The actual number of occurrences might be higher than reported, as PVCs are only commonly detected during routine cardiac evaluations and remain asymptomatic for most. In subjects without underlying cardiopulmonary disease, PVCs are often benign.

Sprenkeler *et al.* [9] measured that, depending on the interval of the preceding extrasystole, the potentiation is enhanced. This enhancement is consistent, depending on the time after the occurrence of the extrasystole in the PVC, and potentiation created by the PESP degrades ac-

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cording to a negative exponential [10]. The time constant of this is measured to be around 765 milliseconds for the human heart [11, 12]. It is important to note this enhancement does not follow the Bowditch effect, also known as the force-frequency relationship (FFR), which dictates that for a higher heart rate, more force is generated per heartbeat such that the stroke volume increases as well, which is caused by the Frank-Starling mechanism [13].

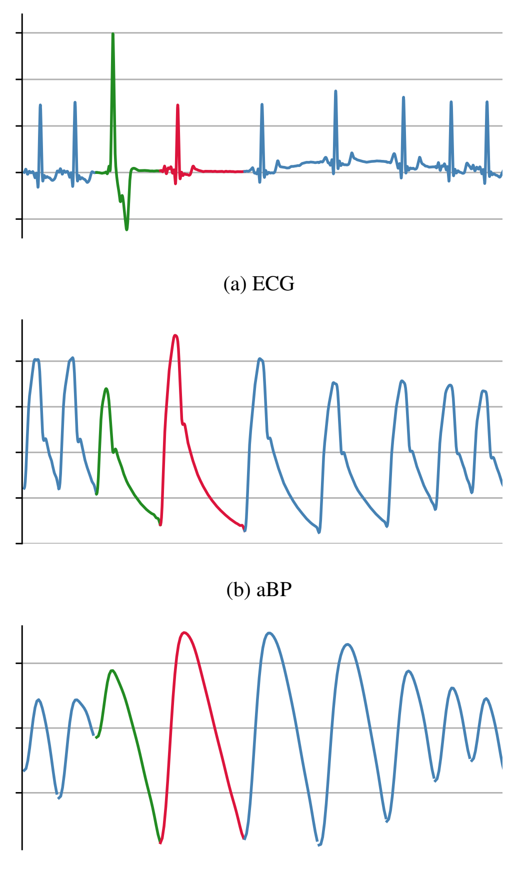
This paper describes a developed method to determine a normalization factor for a PPG recording, local around the normal and sudden occurrence of PVCs and the resulting pulses potentiated by the corresponding PESP, using the consistent response of the heart. This normalization factor is based in a consistent physiological phenomenon, and can therefore attach meaning to the absolute amplitude of the recorded PPG signal around the occurrence of a PVC.

2. Methods

The normalization algorithm was developed on an internal dataset acquired at the Catharina Hospital in Eindhoven, the Netherlands. Patients were recruited who underwent for heart surgery. During this surgery, the heart is paced in regular intervals, upon which the regular rhythm is purposefully disrupted to cause a premature contraction. This was repeated for 30 times per patient with varying extra-systolic intervals, varying between 60 and 240 milliseconds. Because the heart is already paced during the surgery and invasive measurements like the arterial blood pressure (aBP) are already measured during the surgery, the additional measurement time did not significantly increase patient risk. At the time of writing, 7 patients have been included, which were recorded for a total of 47 minutes in which ECG, aBP and wristwatch PPG were recorded. In these patients, the protocol was performed, as well as natural PVCs occurring while measuring, resulting in a total of 2328 detected pulses, in which there are 286 combinations of PVC and a following pulse potentiated by the PESP. The normalization algorithm is constructed as follows. First, the PPG signal is preprocessed. This includes removing segments where the signal quality was too low to obtain reliable cardiac information. The PPG signal was preprocessed by applying a second order Butterworth band-pass filter between 0.07 and 8 Hz to remove noise. Additionally, artifacts caused by movement of the patient or sensor were detected and left out of consideration using the approach detailed by Armañac *et al.* [14]. In their work, they use the energy of the filtered signal, as well as the Hjorth parameters of the signal to detect occurrences of artifacts.

Next, pulses are separated and classified whether they are PVC, potentiated by the PESP, normal or rejected based on additional filtering checks such as presence of a local maximum. Because of the large electrical response of the heart during a PVC, the ECG and aBP signals were used to label the data. An example of a PVC and the following PESP can be seen in Figure 1. Pulses are detected using common peak finder methods based on detecting local maxima. However, the limitation of removing peaks that happen more frequent than the (commonly used) physical limit of 240 beats per minute is lessened; 240 beats per minute would mean a beat every 250 milliseconds, and PVCs can occur in less time than that. Specifically in the acquired dataset, PVCs can occur within 60 milliseconds after the previous beat.

Because the PVC has a lower amount of blood expelled from the heart, the change in pressure and volume is lower. This reduction in the change of volume makes it harder to detect the occurrence of a PVC in the PPG signal. As an



(a) ECG

(b) aBP

(c) PPG

Figure 1: Example of the recorded signal around a PVC and the corresponding response in the following beats. For clearness, the PVC has been indicated in green, while the following beat enhanced by the PESP has been highlighted in red. It should be noted the exponential decay of force can be seen in the blood pressure signal (b) and the PPG (c) by way of their amplitude reducing each beat.

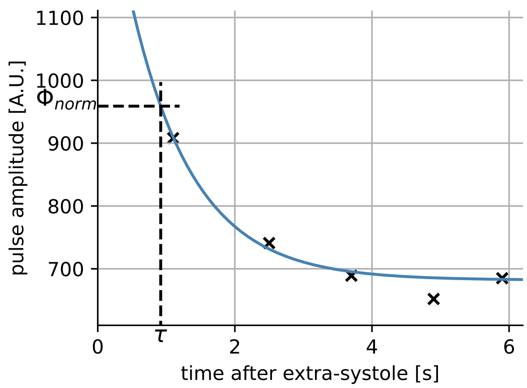


Figure 2: Example of a constructed exponential curve on five amplitudes taken from the blood pressure signal.

additional step in an attempt to include the PVC pulses in the PPG signal, a peak was set on the local maximum between the two surrounding peaks in case there was an additional peak detected in the aBP signal that could not be matched to a nearby PPG peak, and the interbeat interval between the two surrounding found PPG peaks exceeded more than 1.5 times the average interbeat interval of the surrounding 11 pulses.

Next, to determine a normalization factor, a function is set up to characterize the degradation of the PESP. To construct the monotonically decreasing function to determine the decay of the PESP, the following function is used:

$$F_n = \alpha_n + \beta_n e^{-\frac{t}{\tau}}, \tag{1}$$

where F_n is the level of potentiation, t is the time since the start of the PVC, and α_n, β_n and τ are the parameters to be determined. The level of potentiation is characterized as the difference between the peak and the starting value of the pulse, and the parameters α and β are different for each PESP n, depending on the previous interbeat interval and heart rate, while τ is assumed to be constant for one patient. τ is assumed to be constant because it is a parameter describing a physiological mechanism of the heart muscle, which does not vary over the recording time. It can however change over a longer period of time.

To determine the parameters of Eq. 1, the curve is fitted on the amplitudes of the potentiated pulses. That is to say, the difference between the value at the peak and the value at the onset of the first five pulses following the PVC. The least squares algorithm was used to determine optimal values for the parameters in Equation 1. Lastly, the final normalization factor is calculated based on the model fitted in the previous step. This was chosen to be the value of the level of potentiation after one decay according to the exponential function determined with the least squares fit of Eq. 1. Because $t = \tau$, the equation simplifies to

$$\Phi_{norm,n} = \alpha_{n,opt} + \frac{1}{e}\beta_{n,opt}, \tag{2}$$

where $\Phi_{norm,n}$ is the normalization factor for the n-th PESP and $\alpha_{n,opt}$ and $\beta_{n,opt}$ are the solutions of α_n and β_n from the least squares fit. The value of $t = \tau$ was chosen over the value of $t = 0$, as the now chosen moment in time is closer to one of the data points acquired from the data, unlike the value at $t = 0$, which has a larger variance and is further removed from empirical data.

Lastly, the signal is normalized by the linearly interpolated value of Φ_{norm}. This is done because the value of Φ_{norm} varies slowly over time, and there is no consistent amplitude information present between the pulses potentiated by the PESP. Thus, the slowly varying normalization value is approximated as the linearly interpolated value of the two nearest values.

3. Results

The normalization factor is patient-specific, and can change over time. An example of the normalization factor over time for a patient having regular PVCs is shown in Figure 3. The factor displays how the amplitude of the PPG changes over time.

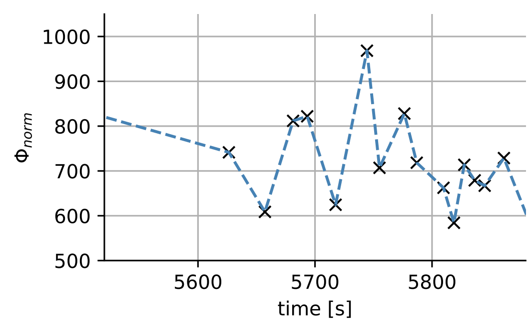


Figure 3: Example of the normalization factor over time for a specific patient. Factors calculated from the exponential curve are marked in black and the blue line indicates the interpolated values.

4. Discussion

Multiple avenues can be explored to extend this method. For the current implementation, a dataset with provoked PVCs was used, and labeling was then performed manually. While there is no limit to making this implementation work in real time, automatic detection of the PVCs and the following PESP pulses would be required. However, such a task is less arbitrary than it might seem. For one, the PVC might be hard to detect in the PPG signal. The electrical response of a PVC is large, and thus easily detectable in an ECG recording, yet the amount of blood expelled is minimal. Combined with the sensor location and other factors such as age, the final pulse might become hard to detect by pulse detectors designed for common use. Furthermore, the frequency of a PVC happening is low, and automatic detection might run into issues of assigning false positives, a common problem in classification algorithms when the class imbalance is in the order of magnitudes [15].

It should be noted that the response of the PESP is reported to slightly vary in cases of severe heart failure (HF) [7, 16]. The occurrence of PVCs and the resulting PESP does increase, lending additional credence to the clinical relevancy of detection and interpretation of the PPG signal around such moments. However, due to the change in response, part of the described method might generalize too broadly to apply the same method. More research needs to be done to investigate the feasibility of applying the described method to such occasions, and the applicability and reliability in determining cases of heart failure.

Results indicate that PESP-based normalization provides meaningful insight into PPG amplitude interpretation, despite inherent noise challenges. While promising, the method remains local to PVC-induced variations, necessitating further research for broader applicability, especially in detecting heart failure-related changes. As stated before, the actual number of occurrences of PVCs might be higher than reported [8], but to what extent is as of yet unknown.

5. Conclusion

This paper proposes a way to attach meaning to the absolute value of recorded PPG signals. Using the manifestation of the force-interval relationship in the the PVC and the following potentiated pulse, the amplitude becomes related to a consistent physiological phenomenon. Because of this, other research avenues relying on the absolute unit of the PPG measurement could be explored in data located around the PVC. More research needs to be done to investigate the reach of such an interpretation and the validity of its conclusions.

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