Photoplethysmography: Beyond the Calculation of Arterial Oxygen Saturation and Heart Rate

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In this article, I examine the source of the photoplethysmograph (PPG), as well as methods of investigation, with an emphasis on amplitude, rhythm, and pulse analysis. The PPG waveform was first described in the 1930s. Although considered an interesting ancillary monitor, the “pulse waveform” never underwent intensive investigation. Its importance in clinical medicine was greatly increased with the introduction of the pulse oximeter into routine clinical care in the 1980s. Its waveform is now commonly displayed in the clinical setting. Active research efforts are beginning to demonstrate a utility beyond oxygen saturation and heart rate determination. Future trends are being heavily influenced by modern digital signal processing, which is allowing a re-examination of this ubiquitous waveform. Key to unlocking the potential of this waveform is an unfettered access to the raw signal, combined with standardization of its presentation, and methods of analysis. In the long run, we need to learn how to consistently quantify the characteristics of the PPG in such a way as to allow the results from research efforts be translated into clinically useful devices.


The photoplethysmograph (PPG) waveform was studied and used clinically long before the discovery of its utility in the calculation of arterial oxygen saturation (1,2). That discovery had such a profound impact on clinical monitoring that the other potential uses of the waveform quickly faded from the attention of clinicians. This neglect of the waveform was accentuated by its absence from the early stand-alone pulse oximeter devices. The pulse was indicated by either a bouncing bar or flashing heart symbol.

My personal introduction to this waveform was during my anesthesiology residency in the late 1980s. Already trained as a critical care provider (internal medicine), I found the opportunity to observe clinical waveforms during surgery fascinating. During my residency, a new clinical monitoring system was purchased and thus I observed for the first time the plethysmographic waveform. One fateful day, I asked one of the senior faculty “What does the waveform mean?” pointing to the plethysmograph displayed below the electrocardiogram. His answer... “That means your pulse oximeter is working.” Undeterred I first looked in a standard anesthesiology textbook, and then in a textbook of monitoring. I could find no mention of this “new” waveform.

The rest of this article will outline what I have found during my investigations, both of the literature and experimentally. I have been fortunate that my interest occurred during a period of remarkable growth in computational power (critical to both waveform analysis and literature searches) and an improved understanding of digital signal processing. My ultimate conclusion is that we have only just begun to tap the potential of this remarkable waveform (3). This article was created as part of the International Symposium on Innovations and Advancements in Monitoring Oxygenation and Ventilation (ISIAMOV) 2007 Supplement to Anesthesia & Analgesia. The topic (Photoplethysmography: Beyond the Calculation of Arterial Oxygen Saturation and Heart Rate) matches the material presented at the symposium that took place at Duke University, Durham, NC during March 2007.

SOURCE OF THE WAVEFORM

Beer’s law of light describes the elements that contribute to the pulse oximeter waveform.

\[ A_{\text{total}} = E_1C_1L_1 + E_2C_2L_2 + \ldots + E_nC_nL_n \]

Where,
- \( A_{\text{total}} \) = absorption at a given wavelength
- \( E_n \) = extinction coefficient (absorbency)
- \( C_n \) = concentration
- \( L_n \) = path length

Conceptually, it is most useful to view the pulse oximeter waveform as measuring the change in blood...
Table 1. Desirable Characteristics for a Pulse Oximeter Used for Waveform Analysis

- Waveform display
  - Ability to change time scales
  - Switch between scroll and “erase bar” display modes
- Ability to turn off auto-gain function
- Ability to turn off auto-center function
- Ability to set the amplitude gain
- Numeric display of amplitude and DC signal
- Ability to use a wide range of probes (finger, ear and reflective)
- Digital and analog outputs of pulse oximeter waveform for capture by data collection equipment

No pulse oximeter commercially available has this combination of characteristics.

Table 2. Factors Affecting Pulse Oximeter Waveform Amplitude

<table>
<thead>
<tr>
<th>Factor</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decreased amplitude due to vasoconstriction</td>
<td>1. Pharmacological—phenylephrine, ephedrine</td>
</tr>
<tr>
<td></td>
<td>2. Physiologic—cold, surgical stress</td>
</tr>
<tr>
<td>Increased amplitude due to vasodilatation</td>
<td>1. Pharmacological—nitroprusside</td>
</tr>
<tr>
<td></td>
<td>2. Physiologic—warming, sedation</td>
</tr>
</tbody>
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in the oxygen saturation. In addition, only the pulsatile component or AC portion is displayed. The static component or DC (created mostly by the absorption of light by surrounding tissue) is eliminated by an auto-centering routine used to ensure the waveform remains on the display screen. With changes in the degree of venous congestion, the waveform can be noted to drift partly off the screen and then return via the auto-centering algorithm.

All clinical pulse oximeters that display a plethysmographic waveform do so with an auto-gain function designed to maximize the size of the waveform displayed. Some manufacturers include an option to turn off this automatic resizing function. Without this option it would be impossible to analyze the amplitude of the pulse oximeter waveform, an important parameter to measure, when analyzing the waveform. When examining the PPG amplitude change over time, the region of the body being measured is important. In the finger, where the walls of the cutaneous vessels are richly innervated by α-adrenoceptors, the sensitivity to changes in the sympathetic system are greater than when compared to other areas of the body such as the earlobe (8).

At this time, no calibration procedure is known to standardize the PPG amplitude for comparing one patient waveform to another. Note, this is an important issue and an excellent research opportunity. The signal is therefore not given a unit designation. Similar to central venous pressure measurement, the value of the plethysmograph comes from an analysis over time, as opposed to any absolute number. The term “plethysmograph” is derived from the Greek root “plethysmos” meaning “to increase.” There is a close correlation (r = 0.9) between the PPG and the more traditional strain gauge plethysmograph (4).

### AMPLITUDE ANALYSIS

One of the more useful plethysmographic features is the waveform amplitude (Table 2). Amplitude changes can be concealed by the auto-gain function found on most pulse oximeters. By turning off the auto-gain, certain observations can be made. For example, over a remarkably wide range of cardiac output, the amplitude of the plethysmograph signal is directly proportional to the vascular distensibility (9). If the vascular compliance is low, for example during episodes of increased sympathetic tone, the pulse...
oximeter waveform amplitude is also low. With vasodilatation, the pulse oximeter waveform amplitude is increased. One should never confuse a large pulse amplitude with the presence of high arterial blood pressure nor vice versa. It is not unusual for the pulse oximeter waveform amplitude to decrease during significant increases in arterial blood pressure that are due to increase sympathetic tone.

Once a baseline measurement has been established, the pulse oximeter amplitude can be followed as a gauge of sympathetic tone (10–12). An intriguing potential use of the plethysmograph may be as an indicator of MAC-BAR (13), the dose of anesthetic required to block adrenergic response in 50% of individuals who have a surgical skin incision. The degree of sympathetic responsiveness a patient retains during an anesthetic might have important clinical implications (Fig. 1). This may be particularly true in patients with a compromised coronary circulation, where dramatic shifts in the hemodynamic status should be avoided. This is an area in which further research efforts would be useful.

RHYTHM ANALYSIS

As can be seen in Figure 2, the pulse oximeter waveform can be a useful tool for detecting and diagnosing cardiac arrhythmias (14). To be used to maximum benefit, the pulse oximeter waveform is used in conjunction with the electrocardiogram. This can greatly help in correctly interpreting artifacts due to patient movement or electrical cautery. As demonstrated in these figures, the pulse oximeter waveform morphology is related to the arterial blood pressure waveform (15). As expected after each premature ventricular beat, there is a compensatory pause, which...
gives more time for the ventricle to fill. The next normal heartbeat is, therefore, associated with an increase in stoke volume. This is reflected in an increase of arterial blood pressure. It is thought that the same mechanism accounts for an increase in the size of the pulse oximeter amplitude after a compensatory pause. A beat-to-beat change of the pulse oximeter amplitude is often the first clue that the patient has developed an irregular heart rhythm. Comparing the pulse oximeter waveform to the electrocardiogram is an excellent way to confirm these changes.

**PULSE ANALYSIS**

A number of unanticipated uses of the pulse oximeter have been developed by clinicians. Most of these uses depend on the ability of the pulse oximeter to detect arterial pulsation. These applications take advantage of the fact that the PPG is remarkably sensitive to pulsatile blood flow.

One clever use of the pulse oximeter has been the determination of systolic blood pressure. This is done by taking advantage of the pulse oximeter’s ability to detect a peripheral pulse. The pressure at which the pulse is detected corresponds closely to the systolic blood pressure (16–18). This technique is helpful in noisy environments, or with neonates in which the use of stethoscope would be difficult. The complex relationship between arterial blood pressure and the volumetric nature of the PPG has complicated the search for the noninvasive beat-to-beat measurements desired by clinicians (15,19). It is hoped that standardization of the equipment, and better understanding of the underlying physiology of the PPG, may allow for obtaining this elusive goal in the future.

A number of studies have been published using the pulse oximeter’s plethysmographic capability to detect tissue perfusion. The advantage the pulse oximeter offers is the ability to do noninvasive, continuous monitoring of peripheral blood flow with readily available technology. Using either transmission or reflective plethysmographic techniques, a number of tissues have been studied. The traditional pulse oximeter depends on transmission plethysmography, with the light taking a direct path through the tissue being studied (i.e., the fingertip or earlobe). Reflective plethysmography takes advantage of the back-scattering of light to the surface (i.e., forehead). Published studies using these techniques to determine tissue perfusion have been performed on small bowel (20), reimplanted fingers (21), and free flaps (22).

Figure 3. The effect of blood loss on the pulse oximeter waveform (Pleth) and arterial pressure waveform (BP). The upper diagram shows the baseline waveforms of the patient under general anesthesia with positive pressure ventilation. The lower diagram is after a 1000 cm³ blood loss. The effect of positive pressure ventilation is apparent.
RESPIRATORY VARIABILITY ANALYSIS

With ventilation (spontaneous and positive pressure) there is fluctuation of both the baseline (D/C) and pulsatile (A/C) components of the plethysmographic waveform. The ability to detect the influence of the respiratory system on the cardiovascular system opens intriguing possibilities. At the minimum, it is believed that the respiratory rate can be reliably determined using the plethysmographic waveform (23–27).

The effect of positive pressure ventilation on the arterial pressure waveform has been well described (28). It is theorized that with each positive pressure breath venous return to the heart is impeded resulting in a temporary reduction in cardiac output. As a patient becomes volume depleted, with a resulting decrease in venous pressure, positive pressure ventilation has an exaggerated impact on the arterial blood pressure. A similar effect on the plethysmograph has been described (29,30). Figure 3 demonstrates this phenomenon. Monitoring the respiratory variability seen in the pulse oximeter waveform may be a useful method of detecting occult hemorrhage, with its resulting hypovolemia (31,32). There are ongoing research efforts designed to find the best site and method of analysis for quantifying the effects of ventilation on the plethysmographic waveform (33,34).

THE PATH FORWARD

The availability of increasingly powerful methods of digital signal processing are allowing for a renaissance in the field of PPG research. Calculations that once required mainframe computers are now performed almost instantaneously with digital signal processing chips. This has allowed for the detailed re-examination of the plethysmograph. Combined with improved understanding of the underlying physiology of the waveform it is easy to predict the emergence of multifunction pulse oximeters.

To uncover the true potential of this waveform, we need standardization and quantification of the plethysmograph as it is presented to the clinician. I believe that the clinician has a vital role to play in the discovery and verification of new uses of the waveform. As was pointed out (7) the clinician attempting to solve clinical questions by innovative means is often faced with highly processed information from their monitoring devices. In their zeal to simplify the clinician’s life, medical device manufacturers strive to present as “clean” a signal as possible, not wanting to distract the care provider with the “messy details.” The downside of this approach is the potential over simplification of complex physiology. It must be remembered that what is viewed as an artifact from one prospective (i.e., respiratory variation of the PPG while determining heart rate) becomes signal in another (i.e., using the same respiratory variation of the PPG to predict fluid responsiveness).

In conclusion, I believe we need: 1) better equipment generating waveforms that can be quantified in a standardized manner, 2) well-designed prospective studies demonstrating that we are measuring clinically relevant information, and 3) outcome studies showing that this information will help the clinician provide better care for their patients.

REFERENCES


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