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Pulse oximetry and photoplethysmographic waveform analysis of the esophagus and bowel

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Purpose of review

This article reviews the development of novel reflectance pulse oximetry sensors for the esophagus and bowel, and presents some of the techniques used to analyze the waveforms acquired with such devices.

Recent findings

There has been much research in recent years to expand the utility of pulse oximetry beyond the simple measurement of arterial oxygen saturation from the finger or earlobe. Experimental sensors based on reflectance pulse oximetry have been developed for use in internal sites such as the esophagus and bowel. Analysis of the photoplethysmographic waveforms produced by these sensors is beginning to shed light on some of the potentially useful information hidden in these signals.

Summary

The use of novel reflectance pulse oximetry sensors has been successfully demonstrated. Such sensors, combined with the application of more advanced signal processing, will hopefully open new avenues of research leading to the development of new types of pulse oximetry-based monitoring techniques.

Keywords

bowel, esophagus, photoplethysmography, pulse oximetry, waveform analysis

Introduction

The development of pulse oximetry is arguably the most important advance in clinical monitoring of the past 30 years. The pulse oximeter provides an indicator of arterial oxygen saturation (SpO₂), a quantity that is extremely simple to interpret, thus providing a rapidly responding indicator of hypoxemic events. Because of its success, there is much current research to improve pulse oximetry and to develop it as a technique for use in a wide variety of novel applications. In particular, there has been recent development of dedicated pulse oximetry probes for use in internal tissue sites, utilizing either miniaturized optoelectronic components or optical fibers. Internal probes are potentially very reliable as they do not depend on the presence of a peripheral pulse and may reveal information about local tissue oxygen saturation and perfusion.

Despite the success of pulse oximetry, the plethysmographic waveform on which it depends is poorly understood. Although it is known that the periodic 'AC' variations of the signal represent changes in blood volume of the peripheral vascular bed, the clinical utility of the signal has been limited to the calculation of oxygen

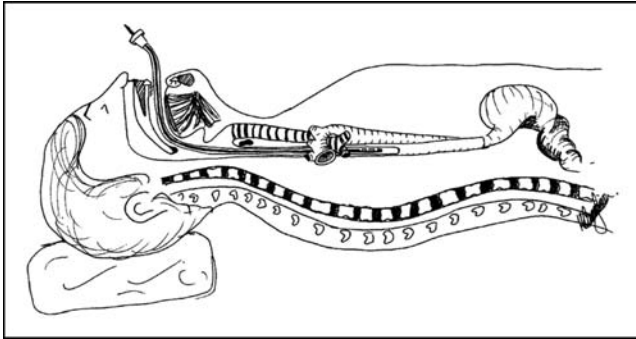
saturation and heart rate (HR) by the pulse oximeter. It has been suggested that there is much information contained within the morphology of the photoplethysmographic (PPG) waveform, which may be interpreted with appropriate signal analysis [1•]. Furthermore, development of more advanced signal-processing techniques might enable some of the limitations of pulse oximetry to be overcome.

Pulse oximetry in the esophagus

Commercial pulse oximeter probes have a serious flaw in that they cease to function in the absence of a peripheral pulse. In cases of peripheral vasoconstriction, when blood flow to the extremities is poor, pulse oximeters are known to give inaccurate readings or even fail altogether [2]. Clinical situations such as these occur in patients with hypothermia, either in the emergency setting or in those in whom hypothermia is induced; for example, intra-operatively in the period following cardiopulmonary bypass [3,4].

To overcome the problems associated with the measurement of SpO₂ in states of poor peripheral perfusion, Kyriacou *et al.* [5] described a 'reflectance' esophageal

Figure 1 The esophageal photoplethysmographic probe contained within the stomach tube is shown placed in the esophagus via the mouth



pulse oximetry system, which allowed detailed investigation of PPG signals and SpO_2 values within the esophagus. The esophagus is a potentially suitable central monitoring site as it is readily accessible in most anesthetized patients, and is perfused directly by main arteries. The esophageal probe was composed of two infrared (IR) and two red light-emitting diodes (LEDs; one of peak emission 880 and the other of peak emission 655 nm) arranged adjacent to a photodetector and was designed to fit into a size 20 French gauge plastic transparent disposable stomach/esophageal tube [6].

An initial clinical study was performed on patients undergoing general anesthesia requiring tracheal intubation. After induction of anesthesia, the probe was placed into the esophagus until the end of the probe was between 25 and 30 cm from the upper incisors (Fig. 1). A finger probe containing an identical arrangement of optoelectronic components was placed on the finger for comparison.

It was found that the amplitudes of the esophageal PPGs were on average approximately three times larger than those obtained simultaneously from a finger for both wavelengths. Follow-on clinical studies [7,8] investigated and compared esophageal and finger PPGs and SpO_2 in 49 patients undergoing hypothermic cardi thoracic bypass surgery. PPG signals were observed at various depths in the esophagus and esophageal SpO_2 values were compared with those measured using a commercial finger pulse oximeter. Measurable PPG traces at red and IR wavelengths were obtained in the esophagus in all 49 patients [7]. SpO_2 values estimated from the esophageal signals compared well with those obtained from the commercial device. The bias (commercial pulse oximeter devoid of esophageal pulse oximeter) was -0.3% and the SD was 1.5% .

Of the 49 patients included in the study, it was found that five patients had one or more periods of at least 10

consecutive minutes during which the commercial finger pulse oximeter failed to display PPG signals and SpO_2 values, despite being correctly positioned on the finger. Conversely, the esophageal pulse oximeter operated successfully throughout these periods. Use of the esophageal pulse oximeter has also been successfully demonstrated in patients with major burns [9]. Another study [10] using a smaller version of the esophageal pulse oximetry probe showed that reliable signals could be obtained from neonatal and pediatric patients.

Use of the esophageal probe to record photoplethysmographic signals from the bowel

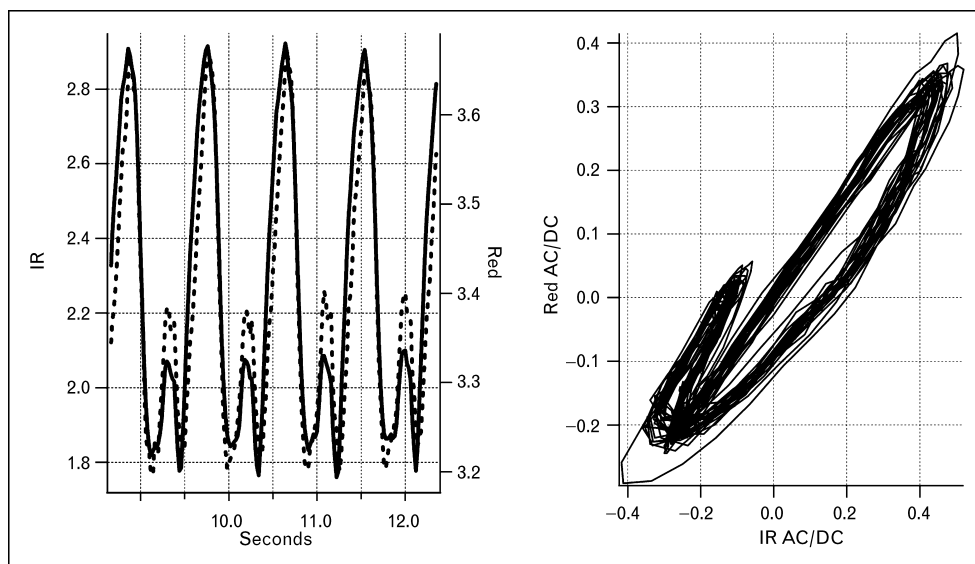
The esophageal pulse oximeter has also been used to investigate PPG signals in the human bowel [11]. In many critically ill patients, poor tissue oxygenation is due to disordered regional distribution of blood flow, despite high global blood flow and oxygen delivery. Ischemia of the gut and other internal organs may ultimately lead to cellular hypoxia and necrosis and may well contribute to the development of multiple organ failure and increased mortality [12].

Twelve adult patients undergoing elective laparotomy under general anesthesia were studied. The esophageal probe was inserted into a sealed and sterilized disposable size 20 French gauge gastric tube. The gastric tube containing the probe was then applied gently to the outer surface of the bowel and an identical reflectance finger probe was placed on the finger of the patient. It was reported that measurable PPG signals were always obtained from the surface of the bowel in all 12 patients. The PPG amplitudes from the bowel were, on average, approximately the same as those obtained simultaneously from a finger for both wavelengths, although there was considerable inter-patient variability.

Effect of venous pulsation on the photoplethysmographic waveform

The PPG waveform is conventionally thought of as an approximation of the arterial pressure wave. The arterial pressure itself is modulated by various physiological phenomena, which influence the PPG waveform. The PPG is also affected by changes in the volume of venous blood in the tissue vasculature. Shelley *et al.* [13] published several case studies that showed small peaks appearing in the diastolic part of the recorded PPG waveforms. These peaks were not present in the arterial pressure waveform but were shown to coincide with peaks in the simultaneously recorded peripheral venous pressure wave. The presence of venous pulsation has been previously reported to cause underestimation of SpO_2 measured by a pulse oximeter [14].

Figure 2 Short sample of the esophageal photoplethysmographic waveform with infrared and red traces superimposed (left)



Plot of the red PPG signal plotted against the infrared PPG signal (right). IR, infrared; PPG, photoplethysmographic. —, IR_AC; ---, red_AC.

Figure 2 shows a sample of the esophageal PPG waveforms. The signals have been normalized so that the peak amplitudes for the red and IR signals are equal. It can be seen that both signals contain small peaks between the main systolic peaks and that the peaks present in the red signal are much greater in amplitude than those in the IR trace. This suggests that the peaks are caused by pulsating venous blood. Figure 2 also shows a plot of the red PPG signal plotted against the IR PPG signal. In both cases, the signals were divided by their respective total or 'DC' intensities averaged over the measuring period. The gradient of a line of best fit would give an estimation of the ratio-of-ratios, used in pulse oximeters for estimating SpO_2 . Two distinct 'loops' are visible. If it is assumed that the larger loop corresponds to arterial pulsation, the smaller steeper loop is consistent with a pulsating venous component within the tissue.

Effect of respiration on the photoplethysmographic waveform

Positive pressure ventilation can have a profound effect on arterial and venous blood pressure [15]. Compression of the alveolar capillaries during a positive pressure breath reduces the volume of blood returning to the left side of the heart, which results in a temporary fall in cardiac output [16]. Vieillard-Baron *et al.* [17] used trans-esophageal echocardiography to show that mechanical ventilation induces a collapse on thoracic vena cava that is closely related to arterial pressure variation. These effects increase with decreasing blood volume, and the arterial and venous pressures in hypovolemic individuals show significant respiratory variation [18].

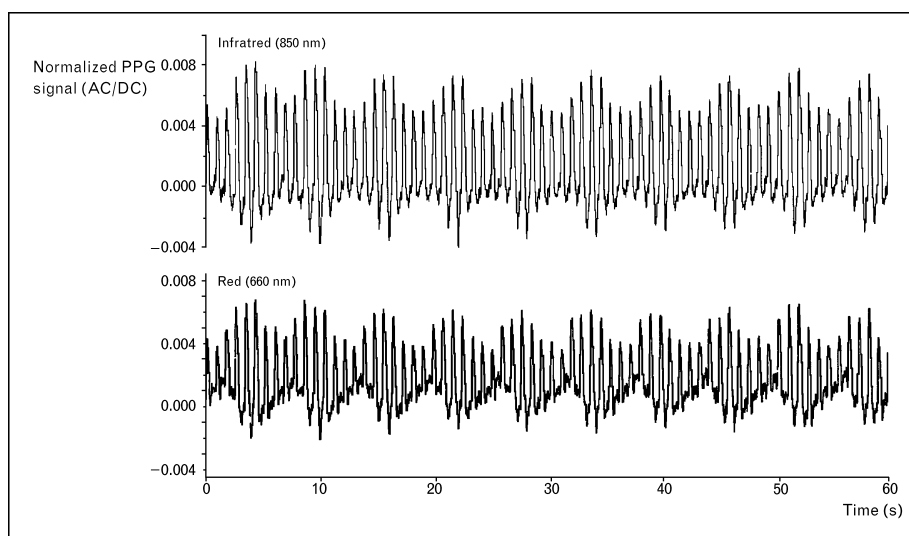
A similar effect has been noted on the PPG waveform [19] but is usually overlooked owing to filtering and auto-scaling of the waveform on clinical monitoring systems. The unfiltered PPG waveform is modulated by a slowly varying wave, synchronous with the respiratory cycle. Figure 3 shows a 1 min sample of a PPG trace obtained from the esophagus.

Both the IR and red PPG traces show considerable low-frequency modulation of the waveform amplitude and baseline, occurring at the respiratory frequency (10/min ≈ 0.17 Hz). Ventilation has been noted to have two distinct effects on the PPG waveform. The most commonly seen is a shift in baseline with each breath, which is recorded as a modulation in the DC component of the waveform. Shifts in the baseline are felt to be associated with changes in the venous (i.e. nonpulsating) volume in the vasculature. The other phenomenon, less commonly seen, is variation in amplitude of the pulse beats. This AC modulation is caused by changes in arterial pressure induced by positive pressure ventilation and is only significant in hypovolemic states [20^{*}]. Several groups have demonstrated that ventilation-induced waveform variability of the PPG signal could be used as an indicator of hypovolemia [21^{*},22].

Frequency domain analysis

The PPG trace may be analyzed in the frequency domain using a fast Fourier transform (FFT) algorithm. The resulting discrete Fourier transform shows the spectrum of frequencies contributing to the AC PPG signal, plotted as amplitude against frequency. In ventilated patients,

Figure 3 A 60 s sample of infrared (top) and red (bottom) photoplethysmographic signals obtained with the probe inserted into the esophagus to a depth of 20 cm

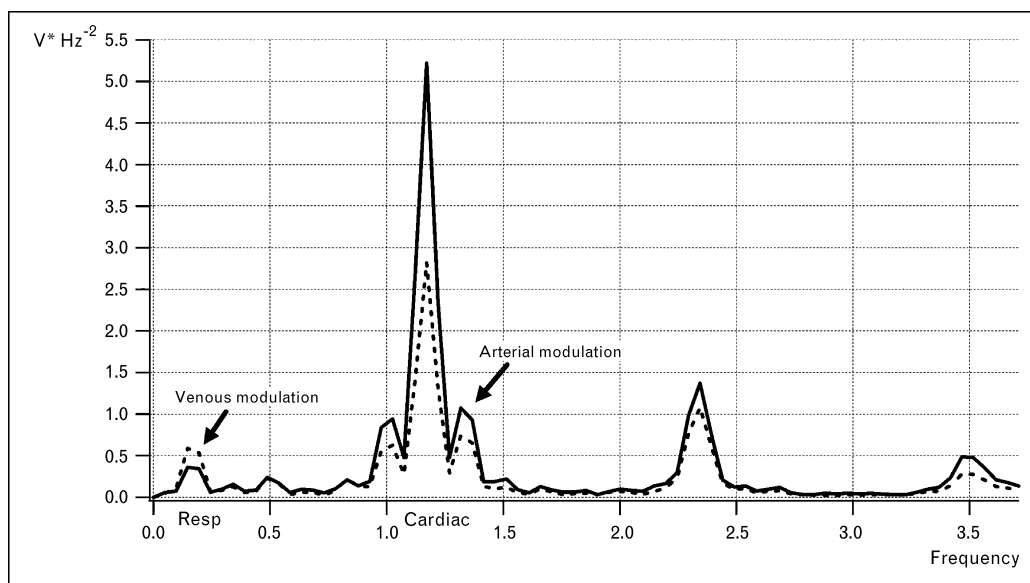


Fourier plots may be used to determine the HR and respiratory rate [23] and to quantify the effect of ventilation on the PPG waveform [24]. Figure 4 shows the Fourier spectrum of a 90 s sample of the normalized IR PPG waveform obtained with the probe inserted into the esophagus to a depth of 20 cm. The amplitude spectrum was produced using a 90 s 8192-point Hamming window and the zero-frequency component was removed.

Both spectra show the dominant peak at the cardiac frequency (approximately 1.16 Hz) with the higher fre-

quency harmonics and a smaller peak at the respiratory frequency (approximately 0.17 Hz). The peaks at 2.32 and 3.48 Hz are harmonics of the cardiac peak. Comparing the size of the respiratory peak with the cardiac peak for each wavelength, it can be seen that the respiratory peak in the spectrum obtained using the red PPG signal has a larger relative amplitude than the corresponding peak in the IR signal. This suggests that the respiratory modulation may occur more strongly in the venous blood volume present in the tissue vasculature than in the arterial blood volume. Two further peaks appear either

Figure 4 Amplitude spectrum of infrared and red AC photoplethysmographic traces obtained from the esophagus with the probe inserted to a depth of 20 cm plotted over the frequency range 0–3.6 Hz



IR, infrared. —, IR AC; ---, red AC.

side of the cardiac peak, which are due to the modulation of the amplitude of the pulsatile component (arterial blood). The difference in frequency between the cardiac peak and each of these modulation peaks is equal to the respiratory frequency.

Frequency-domain analysis may be used for the calculation of SpO₂ from the red and IR PPG waveforms. This has been suggested as providing a more accurate means of determining SpO₂ than by a time averaged beat-to-beat amplitude measurement especially when there is movement artifact [25] or venous pulsation [23] present in the PPG signals. It has also been suggested that a similar method based on a frequency-domain analysis may be useful in estimating the oxygen saturation of the venous blood present in the tissue vasculature noninvasively. The simultaneous measurement of local arterial and venous oxygen saturation would allow calculation of arterio-venous (A – V) difference, a well understood measurement of tissue oxygen consumption. More studies are needed to try to correlate the observed respiratory modulation of venous blood with the local venous oxygen saturation.

Conclusion

The use of reflectance pulse oximetry has been successfully demonstrated in esophageal and bowel sites. The esophagus has been shown to be a suitable alternative site for pulse oximetry in patients in whom measurements using the finger or ear are not possible. Clearly, there are great potential clinical benefits in being able to measure SpO₂ continuously in patients undergoing high-risk surgery or in patients in whom peripheral perfusion is otherwise compromised. Measurement of PPG signals suitable for the calculation of SpO₂ from other internal tissue such as the bowel has also been demonstrated.

We have described the early stages of the development of signal-processing techniques based on the analysis of the photoplethysmographic waveform. One of the aims of future work is to develop time-domain and frequency-domain-based signal-processing algorithms to improve the accuracy of SpO₂ measurements and to derive other clinically useful information from the acquired PPG waveforms.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

- of special interest
- of outstanding interest

Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 815).

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