Increasing the Dynamic Range of a Pulse Oximeter using Heart Rate Characteristics

Chris J Brouse[1], Ron Gatzke[2], Dan Freeman[1], Yu Chen[1]

[1]Draeger Medical Systems, Inc., Andover, MA, USA
[2]Gatzke Technologies, Lexington, MA, USA

Abstract

Aims: This theoretical investigation aimed to increase the dynamic range of a pulse oximeter by reducing electronic noise in the photoplethysmogram (PPG) using characteristics of the heart rate (HR) signal. The PPG is used to measure blood oxygen saturation (SpO$_2$).

Methods: We developed a novel algorithm for dynamically tuning a band-pass filter in real-time to pass the SpO$_2$ information while maximally rejecting the electronic noise. The algorithm tunes the filter based on characteristics of the HR signal recorded from a separate source (e.g. an electrocardiogram, or ECG). We derived a theoretical model of the signal and noise levels in a physiological monitor, and calculated the expected increase in dynamic range resulting from the new filter.

Results: The dynamically tuned band-pass filter achieved a narrow bandwidth of just 0.1 – 0.2 Hz, increasing the PPG SNR by 14 dB (5x). If the filter is applied to the PPG signal from the physiological monitor's SpO$_2$ AFE, the device could theoretically measure signal levels 5x lower than without the filter.

Conclusions: A band-pass filter, tuned based on characteristics of the HR signal, can be used to reduce the electronic noise in the PPG signal, increasing SNR and thus increasing the dynamic range of a pulse oximeter.

1. Introduction

SpO$_2$ is measured from a signal called the photoplethysmogram (PPG). Red and infrared light emitting diodes (LEDs) illuminate a patient's tissue, and the reflected or transmitted light is measured. Each recorded PPG channel (red and infrared) contains a constant (DC) component representative of static tissue (e.g. muscle, bone) and a pulsatile (AC) component representative of arterial blood. The SpO$_2$ is encoded in the relative amplitudes of the red and infrared channels.

Dynamic range is a key feature that separates a clinical grade pulse oximeter from an off-the-shelf consumer grade pulse oximeter. Clinical oximeters are expected to operate across a wide range of patient conditions. The oximeter sensor may be attached to a patient finger that is thick and dark, or thin and light (producing a small or large DC component, respectively). The patient may have a strong pulse, or a very weak pulse (producing a large or small AC component, respectively). These conditions translate into dynamic range; that is, the range of input signal strengths over which the oximeter can accurately measure SpO$_2$.

Electronic noise is introduced into the PPG signal by the analog front end (AFE) circuitry, limiting the oximeter's dynamic range. Most analog electronic components introduce noise into the measured PPG signal. The LED current driver introduces some noise into the emitted light signal. The patient's appendage (e.g. a finger) scatters much of the light. Some of the light impinges upon a photodiode, which converts the signal into a very weak electrical current. A receiver circuit amplifies and filters the received current; however, the signal and noise are amplified together. To make matters worse, the act of amplifying and filtering the signal introduces additional noise, as these features are implemented with analog components. Every time noise is added, the signal-to-noise ratio (SNR) decreases. The PPG AC component is typically a very small fraction of the overall measured signal (often on the order of 1% or less), and it may easily be obscured or overcome with noise. This makes it more difficult for digital signal processing to estimate the SpO$_2$. At any given (fixed) signal level, the noise dictates the SNR. At a given noise level, we can calculate the smallest possible AC/DC signal that can be measured accurately. This smallest signal defines the lower side of the oximeter's dynamic range (i.e. its ability to measure weak signals).

In this paper, we propose a novel algorithm for rejecting electronic noise from the PPG signal using characteristics of the heart rate (HR). In decreasing the noise level, we can increase the SNR and thus the dynamic range of the pulse oximeter.

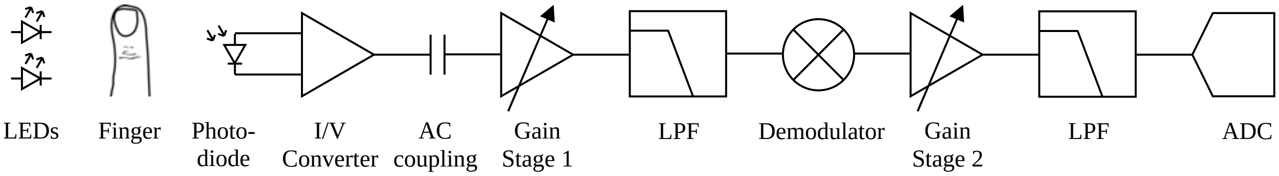

Figure 1. Pulse oximeter analog front end (AFE) signal path. I/V = current to voltage; LPF = low-pass filter; ADC = analog to digital converter. Each stage of the path introduces additional noise into the signal.

2. Method

2.1. Modeling signal and noise levels

Each stage of the SpO_2 AFE (see Fig. 1) contributes some electronic noise. Resistors and active circuit elements (such as operational amplifiers, or op amps) are the greatest noise contributors. Resistors inject thermal noise proportional to the square root of the temperature, resistance value, and frequency bandwidth. The thermal noise is white; that is, it is the same at all frequencies. Op amps inject 1/f noise; that is, it decreases with increasing frequency. Amplifiers (like in Gain Stages 1 and 2, shown in Fig. 1) indiscriminately amplify both signal and noise together. The analog-to-digital converter (ADC) that samples the signal also contributes some noise of its own. The combined noise from all these components dictates the AFE's noise floor and detracts from the SNR.

We can derive SNR requirements from knowledge of the SpO_2 encoding in the PPG. The SpO_2 is encoded in the relative amplitudes of the red and infrared signals. In order to achieve 1% accuracy in SpO2 measurements on the range from 70 – 100% (the standard clinical range), using Nellcor-compatible sensors, the algorithm requires an SNR of up to 38 dB. This value is derived from the worst-case calibration curve (RCAL, representative of the sensor's physical characteristics) at the worst-case slope (in the region of 70% SpO_2). The calculation is not difficult, but is too lengthy for treatment in this paper. An additional ~10 dB of SNR is recommended for the algorithm to accurately separate the signal from the noise and to measure the SpO_2. An overall SNR of ~48 dB is thus needed in the measured PPG signal.

2.2. Tunable multi-parametric filtering to reject noise

The noise amplitude decreases with the square root of the signal bandwidth. While most electronic noise in the PPG signal is a combination of white and 1/f noise, the typical PPG signal bandwidth is so narrow (< 5 Hz) that the noise can all be approximated as white. We can improve the SNR by further narrowing the bandwidth of the measured signal.

All of the relevant SpO_2 information exists at the pulse rate (PR). There are other features in the PPG that exist at different frequencies. For example, the dicrotic notch exists at higher frequencies and respiratory-driven cycles are manifested at lower frequencies. However, these features do not contain any information about the SpO_2. Indeed, these features can all be interpreted as noise from the standpoint of SpO_2 measurements. If we knew the PR *a priori*, we could isolate the frequency of interest for SpO_2 and reject all others, improving the SNR.

Some characteristics of the HR have already been used to estimate the PR and thus the frequency band of interest. The HR and PR are approximately equivalent. Most modern oximeters low-pass filter the PPG signal up to approximately 5 Hz, as this represents the entire physiologically-reasonable range of possible HR values (i.e. 300 beats/min). However, this is a very wide range of HR values, and a typical patient will only occupy a small percentage of this range (say, between 60 – 100 beats/min). Draeger Medical Systems, Inc. has previously invented an algorithm for further narrowing the bandwidth [1]. It uses an HR value recorded from a different signal source (e.g. an electrocardiogram, or ECG) to estimate the time-varying PR and calculate the expected information frequency in the PPG. The algorithm tracks the HR as it changes over time, and applies a band-pass filter to the PPG around this center frequency to extract the relevant signal information. However, the algorithm uses the standard HR trend value reported on the physiological monitor, which is typically heavily filtered and averaged over a 10 s moving window. The HR can change significantly over this time period, but the algorithm cannot know the full HR range in any given window. The algorithm thus applies a filter with a bandwidth fixed at 1 Hz. This value was chosen as a compromise between rejecting noise and risking missing the SpO_2 information. If a very narrow filter were applied, there would be significant risk that the HR may have drifted to a value outside of the passband, and the filter would then reject the relevant SpO_2 information. If a very wide filter were applied, it would not be very effective at rejecting the electronic noise. In most cases, the bandwidth of 1 Hz is likely too wide, but the algorithm cannot know with certainty.

Higher order HR characteristics, such as heart rate variability (HRV), may be used to more precisely tailor the filter bandwidth to changing requirements. HRV refers to fluctuations in the instantaneous HR over time. The HR is not constant; it varies with changing conditions in the subject's body. For a good introduction to HRV, see [2]. The HRV is often considered to fluctuate in different frequency bands. A high frequency band (HF, 0.15 – 0.4 Hz) is driven primarily by the respiratory cycle, in a phenomenon called respiratory sinus arrhythmia (RSA). A low frequency band (LF, 0.04 – 0.15 Hz) is driven primarily by the blood pressure regulation cycle, called baroreflex. A very low frequency band (VLF, < 0.04 Hz) is driven primarily by the cycle of the circadian rhythm. Multiple HRV cycles can occur within a single 10 s averaging window used to measure the standard HR. This is particularly true of RSA cycles. As a result, the standard HR captures only the mean, but not the full range of HR in the cycles. The HRV, based on the instantaneous HR, would support measurement of this full range. An algorithm could then precisely tailor the filter bandwidth to pass the SpO_2 information at all relevant HR frequencies across the full range.

The proposed algorithm dynamically tunes the parameters of a band-pass filter based on information obtained from a secondary HR source. The goal of the tuning is to track the HR to maximally pass the relevant SpO_2 information at the PR, while maximally rejecting the noise at all other frequencies.

The simplest approach involves fitting the filter's passband as an envelope over the recent instantaneous HR series. The min and max HR values can be measured over a short-term sliding window, and set as the filter's lower and upper cutoff frequencies, respectively. The length of the sliding window may be tuned to compromise between rapid adaptation to changing conditions and risk of rejecting valid SpO_2 information. A longer window will have reduced risk of missing the SpO_2 information but will often be unnecessarily wide, allowing more electronic noise into the passband. A shorter window will more aggressively reject noise but will have greater risk of missing the SpO_2 information, as the PR may stray outside the filter passband. The shape of the passband, stopband, and transition bands may be set independently of the cutoff frequencies.

A guard band may be added to the filter to help mitigate the risk of rejecting relevant SpO_2 information. The HR may stray outside the min/max limits of its recent history, in which case the relevant SpO_2 information would be rejected. A guard band can widen the filter's passband, providing a hedge against uncertainty in the HRV. The guard band may be static or dynamic.

2.3. Filter testing

The filter was tested on example HR series derived from the MIMIC II database [3]. ECG segments were extracted from 10 different subjects, each of length 10 minutes. The instantaneous HR series was manually derived from each segment by measuring the distance between successive ECG R-peaks. The min/max HR values over a moving window were calculated and set as the lower/upper cutoff frequencies of a hypothetical band-pass filter. The moving window length was tuned between 1 – 30 s. A guard band tuned from 0 – 10 beats/min was applied to each side of the filter passband.

The best settings were chosen as those that always passed all relevant SpO_2 information, but had the smallest average bandwidth across all HR series.

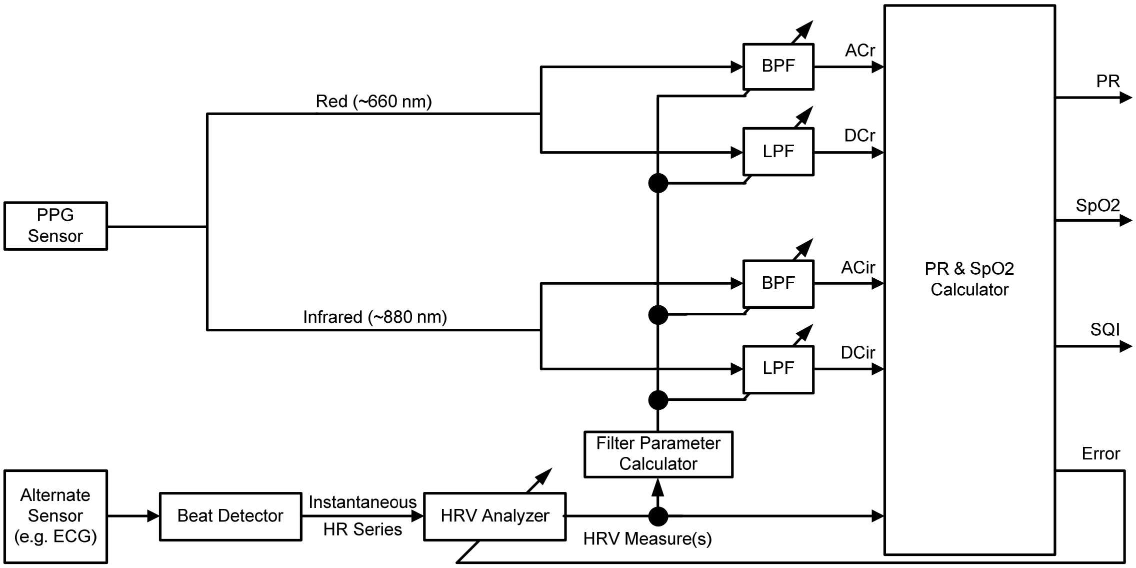

Figure 2. Block diagram of the algorithm. HRV measures, calculated from instantaneous HR series originating from an alternate signal source, are used to tune the characteristics of band-pass (and possibly low-pass) filters applied to the PPG channels. The resulting filtered signals are used to calculate PR and SpO_2, and estimate the signal quality. An error signal feeds back into the HRV Analyzer, to tune its calculations based on its historical performance.

3. Results

A moving window length of 5 s with a guard band of 2.5 beats/min was found to produce the minimum required bandwidth to pass all the relevant SpO_2 information. Using these settings, the dynamically tuned multi-parameter filter achieved an average bandwidth ranging from 0.1 – 0.2 Hz. The bandwidth depended on the recent HR history. Periods with greater HRV required wider bandwidths than those with less.

The new filter's narrower bandwidth can theoretically improve the PPG SNR by approximately 14 dB (5x) as compared to the full physiological bandwidth of 5 Hz. This should allow the oximeter to measure SpO_2 in more challenging clinical conditions.

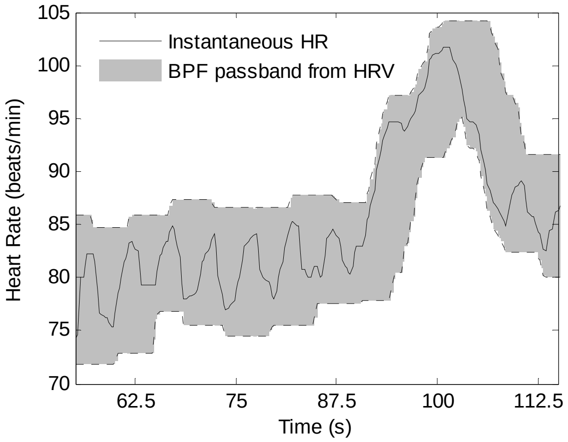

Figure 3. Dynamic filter passband derived from HRV, using the min/max HR values in a sliding 5 s window.

4. Discussion & conclusion

This theoretical investigation suggests that heart rate characteristics may be used to improve the dynamic range of a pulse oximeter. HRV measurements, calculated from an alternate signal source such as an ECG, can be used to dynamically tune a band-pass filter. The filter can then maximally reject electronic noise while still passing the relevant SpO_2 information. The proposed algorithm can theoretically improve the SNR by 14 dB (5x) as compared to the full physiological bandwidth of 5 Hz.

The improved SNR from the new algorithm translates directly into improved dynamic range. A greater dynamic range allows a pulse oximeter to measure SpO_2 in more challenging clinical conditions, such as on thick fingers, dark skin, or in patients with a weak pulse (low perfusion). The proposed algorithm, when running on a physiological monitor's AFE hardware, should be able to measure SpO_2 accurately down to a perfusion level of ~0.02%. Clinicians using an oximeter with this algorithm should be more satisfied with its performance.

This investigation was largely theoretical, and did not consider the design of the band-pass filter, its adaptation time to the changing HRV, or its roll-off. Further work will be needed to demonstrate the proposed algorithm's real-world performance in an end-to-end implementation.

More advanced algorithms are possible using further features of the HRV. The sinusoidal fluctuations (e.g. the RSA in the HF band [2]) could be modeled and predicted into the near future. The band-pass filter could then be tuned to the expected future HR values. This method would work well when the HR is exhibiting a stationary pattern like that shown in the first half of Fig. 3. However, it would fail when the HR changes state and becomes nonstationary (like at ~90 s in Fig. 3). Another advanced algorithm option could involve tuning the band-pass filter's guard band by using estimates of the HR's unpredictability. For example, an algorithm called Approximate Entropy can estimate the information content of the HR series, analogous to its unpredictability or surprisal [2]. During periods of greater entropy, we can then expect unpredictable swings in HR and we can widen the guard band accordingly to hedge against them.

Future research will involve collecting ECG and PPG data simultaneously from patients in clinical environments, and testing the new algorithm on these data. The algorithm's performance can be assessed even in average (non-challenging) patients. The PPG signals filtered with the new algorithm can be compared to their unfiltered counterparts to ensure no relevant SpO_2 information is being rejected. The dynamic filter bandwidth can be measured in practice and compared to expectations. Comparisons can be used to refine and tune the algorithm's parameters to optimize performance.

A band-pass filter, tuned based on characteristics of the HR signal, can be used to reduce the electronic noise in the PPG signal while still passing all relevant SpO_2 information, increasing SNR and thus increasing the dynamic range of a pulse oximeter.

References

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Address for correspondence.

Chris J Brouse
Draeger Medical Systems, Inc.
6 Tech Dr., Andover, MA, 01810, USA
chris.brouse@draeger.com