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FIR FILTER DESIGN FOR REMOVAL OF VENTILATOR ARTEFACT IN OESOPHAGEAL PHOTOPLETHYSMOGRAPHIC SIGNALS

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Abstract: The oesophagus has been found to be a reliable monitoring site for blood oxygen saturation (SpO_2) in anaesthetised patients. Despite it being a very well perfused organ, it was not possible to estimate SpO_2 in the lower to deep oesophagus due to movement artefact caused by the mechanical ventilator. This limitation made the measurements more difficult since the probe had to be placed carefully at a depth where the magnitude of the ventilator artefact was less than 30% of the oesophageal photoplethysmographic (PPG) amplitude. To overcome this limitation, two filters, a 384th order FIR Equiripple linear-phase filter and a 10th order Butterworth bandpass filter, were implemented and compared. The Equiripple filter performed better than the Butterworth filter in terms of attenuation and phase characteristics. This Equiripple filter achieved an attenuation of about 80 dB in the stopbands which significantly reduced the ventilator artefact without changing the morphology of the PPG signal. Such a filter should allow the monitoring of SpO_2 within the whole length of the oesophagus.

Introduction

Pulse oximetry is a valuable non-invasive optical monitoring technique used for the continuous estimation of arterial blood oxygen saturation (SpO_2) and has been used in many clinical applications. Pulse oximetry estimates the arterial blood oxygen saturation by measuring the absorption of light in vascular tissue at two different wavelengths. One of these wavelengths is in the red region of the spectrum being absorbed more by oxyhemoglobin (HbO_2) and the other wavelength is in the infrared region being absorbed more by deoxyhemoglobin (Hb) [1]. The ac component of the photoplethysmographic (PPG) signal is solely due to the pulsatile arterial blood. Pulse oximeters use the ratio of the ac components (red/infrared) along with the corresponding dc components to calculate the SpO_2 value. Therefore, a measurable pulsatile ac component is a necessity for accurate SpO_2 determinations. This dependency leads to pulse oximeter failure in clinical situations where the peripheral perfusion is compromised.

Reich et al. [2] reviewed 9203 computerized anaesthesia records and showed that the overall incidence of cases that had at least one continuous gap of greater or equal to 10 min in pulse oximetry data was 9.18%.

In order to deal with the problem of low perfusion faced at peripheral sites Kyriacou et al. [3] made successful PPG measurements in the middle and lower oesophagus of healthy anaesthetised patients using a reflectance type photoplethysmographic probe. Their hypothesis was that, being supplied by arterial branches directly from the aorta, this central site would be less affected by the conditions that caused low perfusion in peripheral sites. Kyriacou et al. [4, 5] also measured SpO_2 in cardiothoracic patients. The results were in agreement with arterial blood saturation (SaO_2) values obtained from blood gas analysis and CO-oximetry.

Even though the work done by Kyriacou et al. provided convincing evidence for the use of the oesophagus as an alternative site for measuring SpO_2 during surgery, they only managed to measure SpO_2 in the middle to upper oesophagus since the ac PPG signals from the lower oesophagus were frequently corrupted by an artefact, synchronous with the period of the ventilator. The magnitude of this artefact varied from patient to patient and it also depended on the depth of the measurement site. In the middle and lower part of the oesophagus (20 cm and more from the incisors), where the ac PPG signals were of significantly larger amplitude, the magnitude of the artefact was often more than that of the ac PPG signal making the estimate of SpO_2 impossible. The algorithm for estimating the SpO_2 would only process the PPG signals and calculate an accurate value for SpO_2 when the magnitude of the ventilator artefact was less than 30% of that of the ac PPG signal. This made the placement of the probe difficult and time consuming. The use of the Masimo Signal Extraction Technology (SET) was not feasible because of the incompatibility with the system used by Kyriacou et al. [6]. Another important consideration is the signal morphology, as it is essential that during processing the morphology of the PPG signal is not significantly changed, so that it can continue to be used for clinical interpretation.

The aim of the present work is to design a digital filter that will allow reliable, artefact free signals to be measured anywhere in the oesophagus.

Methods

The artefact is expected to be synchronous with the ventilator. It has a fundamental frequency component at about 0.2 Hz whereas, the fundamental frequency component of the ac PPG signal in adults will be between 1 and 2 Hz which corresponds to a cardiac rate of 60 to 120 beats per minute. Therefore, a sharp bandpass digital filter can be used to reduce the artefact and also reject high frequency signals, as the band width of interest in PPG signals is approximately from 0.8 to 10 Hz [1]. The filter was developed in the *Matlab* environment using the available filter design and signal processing toolboxes. The phase characteristics of the filter determine whether it will affect the morphology of the signal or not. Therefore, it is important to have linear phase characteristics in the passband of the filter so that the signal passed by the filter is only delayed. For this reason implementing a FIR filter was preferred over an IIR filter in order to take advantage of the linear phase characteristics of the former. It was decided that the best option would be to implement an Equiripple filter, as these filters are optimal in the sense that they meet the given arbitrary specifications with a minimum filter order. The FIR filter design technique utilised was proposed by Parks and McClellan and uses Remez exchange algorithm [7], which is iterative and can be implemented using a high level computer language efficiently. The PPG signals were originally digitised using a sampling rate of 50 Hz and therefore during filter design the sampling frequency was also taken as 50 Hz. The filter was designed to meet the above specification for the suppression of artefact in the ac PPG signal. The designed filter is a 384th order, type 1 Equiripple filter with the following characteristics:

- First cut-off = 0.5 Hz
- Pass band= 0.83 Hz to 11 Hz
- Second cut-off = 11.2 Hz
- Minimum stopband attenuation= 80 dB (in both stopbands) and
- Maximum passband ripple=1 dB

In order to justify the use of the Equiripple filter, another filter with similar characteristics was designed using the Kaiser Window method. In this case the filter order was 761, which is almost twice that of the

Equiripple filter and would require more processing. A larger filter order would also increase the delay in the signal from 3.84 s (for Equiripple) to 7.61 s (for the Kaiser Window filter). This filter was not considered further. A 10th order bandpass IIR Butterworth filter with cut-off at 0.5 Hz and 11.2 Hz was also designed to compare with the Equiripple filter and to see whether such an IIR filter could perform as well without causing unacceptable phase distortion.

An offline evaluation of the filters was performed using recorded oesophageal PPG signals at both wavelengths from ten adult healthy patients undergoing elective surgery. The statistical significance of the difference between the two proposed filters (Equiripple and Butterworth) was assessed by a paired t-test using *SigmaStat*. A value of $p < 0.05$ was considered statistically significant.

Results

The Equiripple filter response is shown in Figure 1. The phase response is linear in the passband, hence there should be negligible phase distortion and the signal should retain its morphology.

The results of filtering the oesophageal PPG signals obtained using the red and the infrared sources for both the Equiripple and the Butterworth filters are shown in Figure 2 and Figure 3. For both sources, the ventilator artefact is almost 300% of the amplitude of the ac PPG signal; see Figures 2(a) and 3(a). The Equiripple filtered signals (Figure 2(b) and 3(b)) demonstrate clearly that the ventilator artefact has been reduced significantly without distorting the morphology of the PPG signal. The outputs of the 10th order Butterworth filter in Figures 2(c) and 3(c) show that the artefact is not reduced to the same extent, and also that there is some phase distortion as evidenced by the noticeable change in morphology. Increasing the order of the Butterworth filter is of no benefit. When the same data were processed through a 30th order Butterworth filter with the same cut-off frequencies, although better discrimination between signal and artefact was achieved, there were unacceptable changes in the signal morphology because of the non-linear phase characteristics of the filter.

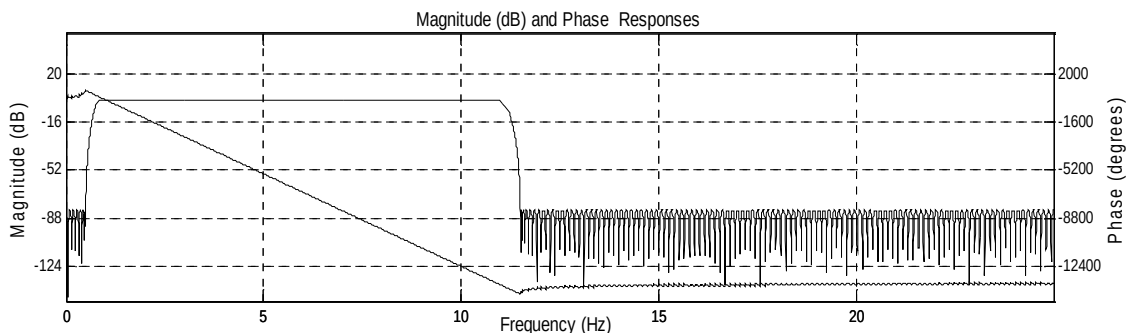


Figure 1: Magnitude and Phase characteristics of the filter

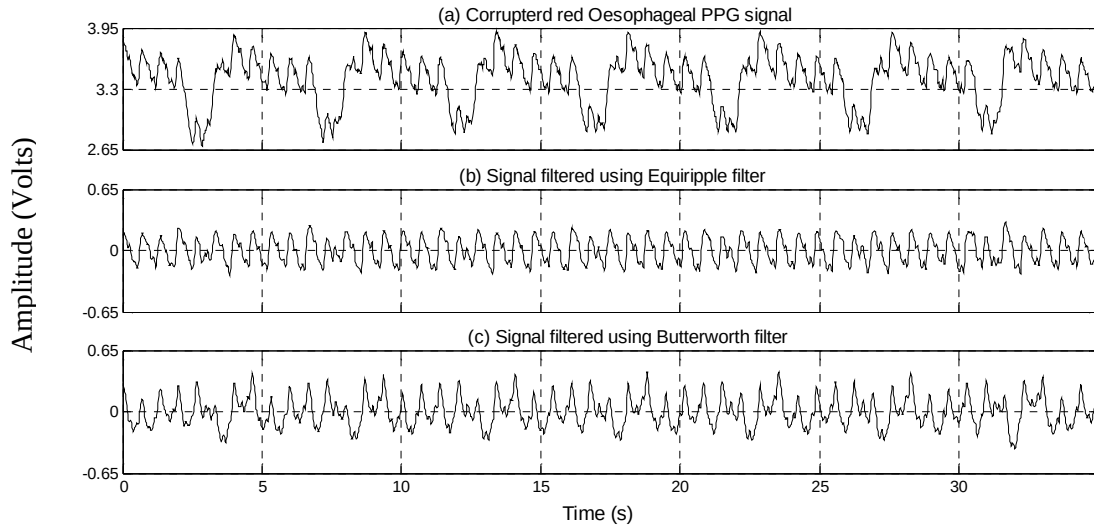


Figure 2: (a) Corrupted red PPG signal, (b) Result from Equiripple filter, (c) Result from Butterworth filter

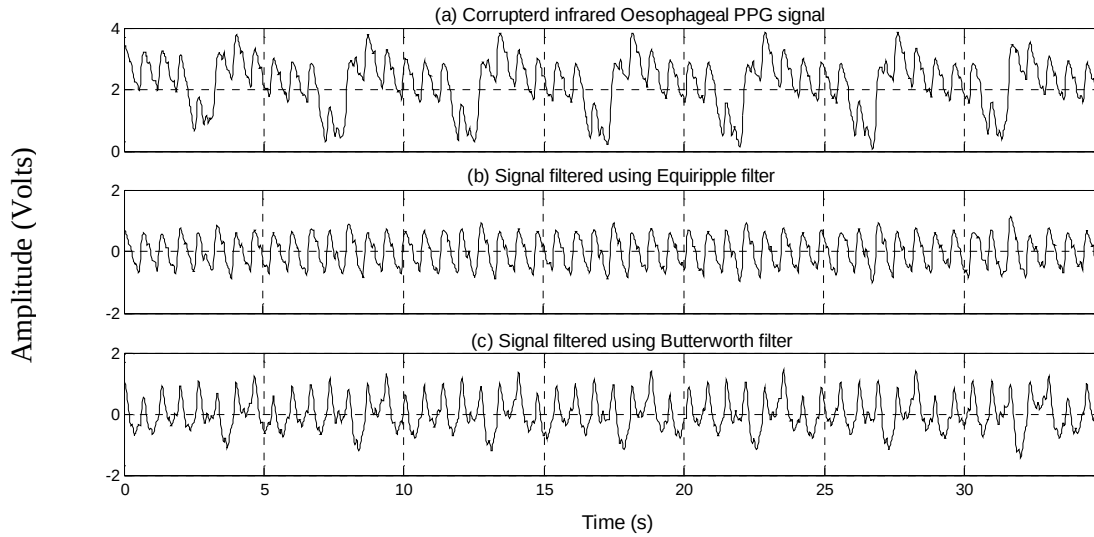


Figure 3: (a) Corrupted infrared PPG signal, (b) Result from Equiripple filter, (c) Result from Butterworth filter

The magnitude spectrum of the corrupted and filtered red PPG signal of Figure 2 is shown in Figure 3. The improvement achieved in the signal-to-noise (artefact) ratio (SNR) for the red source by processing through the Equiripple filter is measured using the magnitude spectrum in Figure 4. The ratios of the amplitude of the fundamental component of the ac PPG to the fundamental and first harmonic components of the artefact are calculated. For the fundamental artefact component (at approximately 0.2 Hz) the SNR increases from -10.59 dB before filtering to 61.13 dB after filtering. Therefore, the total improvement in SNR is 71.72 dB. Similarly, in the case of the first harmonic component (at about 0.4 Hz) the SNR improved from -11.78 dB to 58.63 dB, a total improvement of 70.41 dB. The infrared PPG signal showed similar total improvements in SNR, the ratios for the fundamental

and first harmonic components of the artefact being 72.35 dB and 69.58 dB, respectively.

There were statistically significant differences between the improvements in SNR achieved by the Equiripple and the Butterworth filters. For the fundamental artefact component, the total improvement in SNR for the Equiripple filter was significantly larger than for the Butterworth filter, with the mean difference being 19.02 dB for the red wavelength and 20.79 dB for the infrared wavelength ($p < 0.001$ in both cases). The Equiripple filter also gave larger SNR improvements for the first harmonic component of the artefact, the corresponding mean differences being 36.43 dB and 38.61 dB for the red and infrared wavelengths, respectively ($p < 0.001$ in both cases).

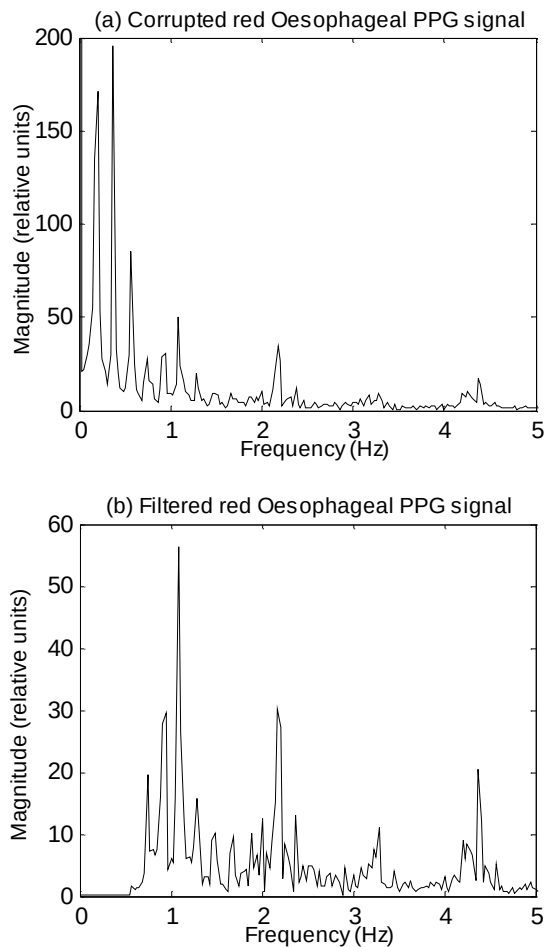


Figure 4: (a) Spectrum of corrupted red oesophageal PPG signal, (b) Spectrum of Equiripple filtered red oesophageal PPG signal

Conclusion

It has been demonstrated that the designed Equiripple filter is capable of reducing the ventilator artefact significantly. For the fundamental components of signal and artefact an improvement in SNR of about 70 dB was achieved for both the red and the infrared PPG signals. Therefore, it should now be feasible to make SpO₂ measurements in those parts of the middle and the lower oesophagus where previously the artefact was more than 30% of the magnitude of the ac PPG signal, thereby making the calculation of SpO₂ impossible. This filter should also reduce the time and effort required for correct placement of the probe in the oesophagus. It has been shown that this filter does not cause major phase distortion, a problem usually faced when dealing with IIR filters. The Equiripple filter performed significantly better than the Butterworth filter. In the case of the fundamental components of the PPG signal and artefact, on average the Equiripple filter gave an approximately 20 dB larger improvement in SNR compared with the 10th order Butterworth filter for both the red and infrared wavelengths. For the first harmonic component of the

artefact the Equiripple filter again gave a significantly larger improvement in SNR than the Butterworth filter, the corresponding mean differences being greater than 36 dB for both the red and infrared wavelengths.

These initial findings are encouraging. However, more clinical studies are needed to test the effectiveness of the filter in allowing SpO₂ readings from all sites in the oesophagus. These SpO₂ readings obtained with the oesophageal pulse oximeter during surgery can then be compared with blood oxygen saturation values from a CO-oximeter.

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