Effects of Filtering on Multi-site Photoplethysmography Pulse Waveform Characteristics

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Abstract

Multi-site photoplethysmography (PPG) allows pulse waveforms collected simultaneously from different peripheral body sites to be investigated. PPG waveforms are site-dependent, comprising a pulsatile ('AC') component synchronized to each heart beat, superimposed on a slowly varying ('DC') baseline. Careful high pass filtering of the pulses is needed to reduce the dominant lower frequencies but without distorting pulse shape, and sufficient computer quantization levels to reliably reproduce the pulse. In this study pulses were measured from the right ear, thumb and great toe of 10 healthy adult subjects. Pulses were then filtered offline at cut-off frequencies between 0.05 to 1 Hz using a digital single pole high pass filter. The relationship between filter cut-off frequency on lower to higher frequency amplitudes, AC pulse amplitude relative to system noise, and visible pulse shape distortion were investigated. The ratio of low to high frequency amplitudes decreased with increasing cut-off frequency (highest at toe, lowest at ear). The AC pulse amplitude relative to system noise increased with increasing cut-off frequency (highest at thumb, lowest at toe). A qualitative visual inspection of the waveforms showed that pulse shape distortion was likely at cut-off frequencies greater than 0.2 Hz. A single pole high pass filter cut-off frequency of 0.15 Hz for multi-site PPG measurements enables faithful pulse shape reproduction for subsequent cardiovascular modelling.

1. Introduction

Multi-site photoplethysmography (PPG) is a useful vascular assessment technique as it has the capability for simultaneous comparisons of pulses from different peripheral body sites [1-3]. These waveforms are site dependent and usually comprise a pulsatile ('AC') component synchronised to each heart beat, and superimposed on a slowly varying ('DC') baseline [4-10]. The lower frequency components are attributed to respiration [11], sympathetic nerve activity [12], and thermoregulation [13]. Careful high pass filtering is needed to reduce the dominance of the lower frequencies, and also without distorting (e.g. differentiating) pulse shape features [14]. The aim of this study was to consider suitable single high pass filter cut-off frequencies for multi-site PPG measurements, thereby allowing their inter-relationships to be studied with confidence.

2. Methods

2.1. Subjects

Ten healthy adult subjects were studied. Their mean (standard deviation) age was 37 (12) years, and eight were male.

2.2. Pulse system and measurements

Figure 1 shows the multi-site PPG measurement system. Here, PPG pulses were measured simultaneously from the right ear lobe, thumb and toe pads whilst subjects lay supine, and breathing slowly and gently. Pulses were captured at a sample rate of 500 Hz for 2 minutes using 16 bit resolution analog to digital conversion. The PPG amplifiers were electronically matched with filter bandwidth of 0.005 to 20 Hz. Figure 2 shows example pulse waveforms from a healthy subject.

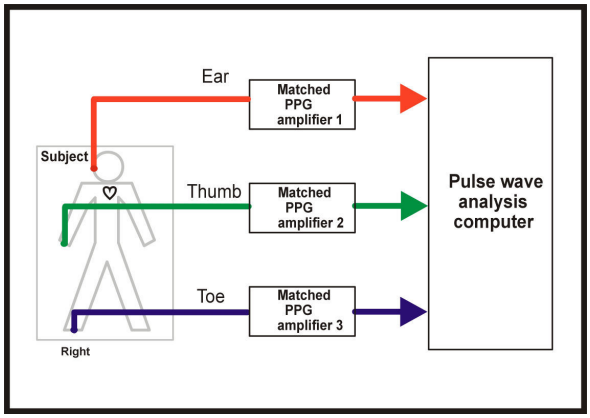

Figure 1. Multi-site PPG measurement system. Pulses are collected simultaneously from 3 different peripheral sites to computer for subsequent pulse wave analysis.

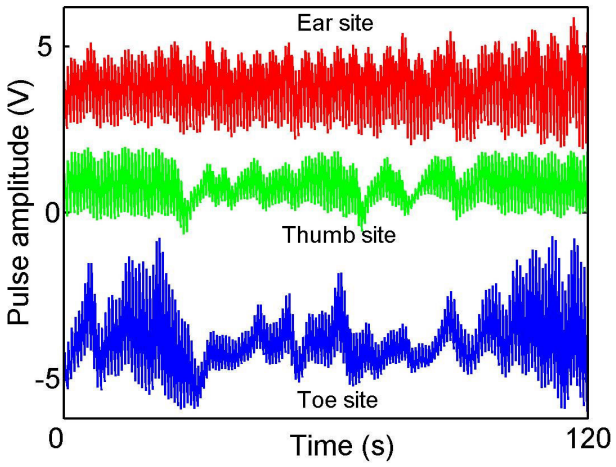

Figure 2. Example multi-site PPG pulse waveforms from a healthy adult subject collected over 2 minutes. There are differences in 'DC' low frequency and 'AC' pulse characteristics between ear, thumb and toe sites.

2.3. Digital high pass filtering

Pulses were high pass filtered offline at cut-off frequencies of 0.05, 0.1, 0.2, 0.5 and 1.0 Hz using a Matlab (MathWorks Inc.) based approximation to an analogue single pole high pass filter [15].

2.4. Analysis

Relationships were investigated between digital high pass filter cut-off frequency and 1) lower to higher frequency amplitudes (DC envelope / minimum AC pulse amplitude, DC:AC) within a 2 minute recording, 2) minimum AC pulse amplitude relative to system noise after scaling the DC envelope to 8 V peak to peak, and 3) a qualitative visual assessment by a single operator (JA) of shape distortion. Pulse amplifier system noise was measured at 1 mV pp at the thumb and toe sites, and 2 mV pp at the ear site.

3. Results

Median DC:AC decreased with an increasing cut-off frequency at all sites, as shown in figure 3. This was highest at the toe (9.3 at 0.05 Hz to 2.8 at 1.0 Hz) and lowest at the ear (3.7 at 0.05 Hz to 1.5 at 1.0 Hz). The AC pulse signal relative to system noise increased with increasing cut-off frequency at all sites, as shown in figure 4. These were highest at the thumb (2450 at cut-off frequency of 0.05 Hz to 5410 at 1.0 Hz) and lowest at the toe (640 at cut-off frequency of 0.05 Hz to 2420 at 1.0 Hz). The figures also show the inter-quartile ranges.

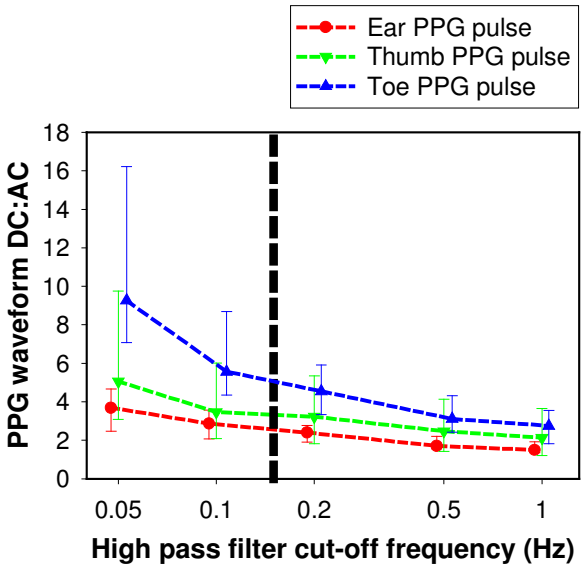

Figure 3. Median (inter-quartile range) DC:AC ratio varies with high pass filter cut-off frequency. There are differences between the 3 sites, with the toe site having the greatest ratios and the ear site having the lowest ratios overall. For comparison the filter cut-off frequency of 0.15 Hz is identified by the vertical dashed line.

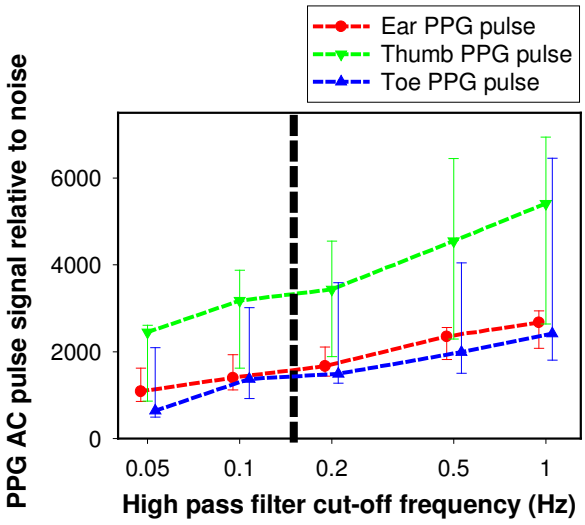

Figure 4. Median (inter-quartile range) AC pulse amplitude relative to noise varies with high pass filter cut-off frequency as lower frequencies are filtered out. There are differences between the 3 sites, with the thumb site having the greatest levels and the toe site having the least levels overall. For comparison the filter cut-off frequency of 0.15 Hz is identified by the vertical dashed line.

Visual inspection of the pulse waveforms showed that shape distortion was seen at cut-off frequencies above 0.2 Hz, particularly with changes to the pulse peaks. An example of typical changes in the shape with high pass filtering can be seen in figure 5 below.

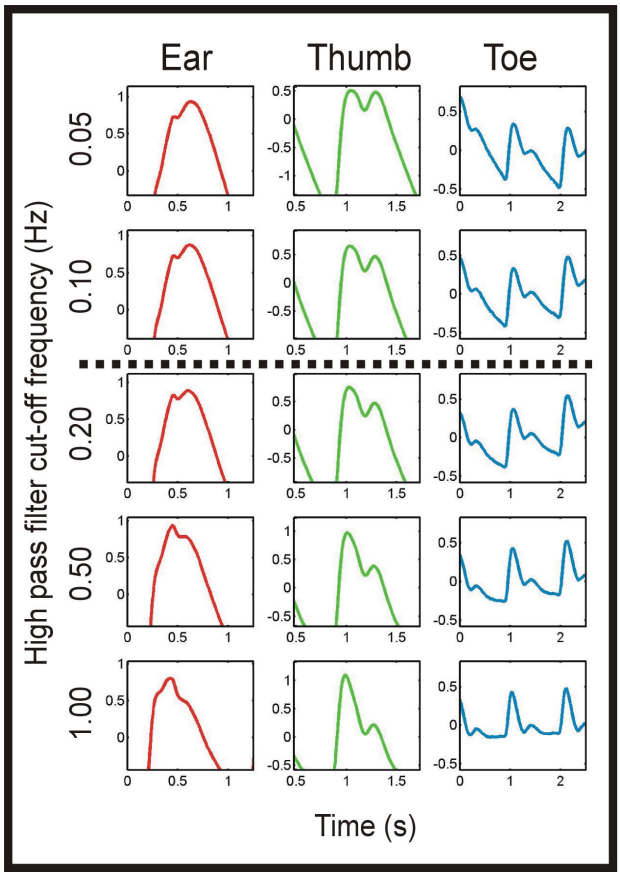

Figure 5. Subtle changes in pulse shape at the ear, thumb and toe sites with high pass filtering. Pulse peaks appear distorted above a cut-off frequency of 0.2 Hz.

4. Discussion and conclusions

The differences in pulse between peripheral body sites in healthy subjects have been demonstrated, as well as the need for careful filtering so that pulse characteristics can be faithfully reproduced and compared between sites. If the high pass filter is set too low then the low frequency components dominate, reducing the capability to reproduce the shape at all sites. If set too high then the pulse shape can be distorted by 'differentiation' and the lower frequency content lost. In this study an appropriate single pole high pass filter frequency was found to be 0.15 Hz as this did not significantly distort (AC) pulse shape, retained a reasonable ratio of low frequency to high frequency PPG components, and achieved an AC pulse signal amplitude to noise level of greater than 1000 in describing a PPG waveform of 8 V peak to peak. The order of the filter was chosen to be one for practical implementation with analogue electronics since this requires the matching of a minimum number of resistor and capacitor components. Duplication and matching of PPG amplifier channels to achieve multi-site capability, especially for right–left body side difference comparisons, is therefore made much easier.

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