PPG_ABP_TF

Estimating blood pressure waveforms from the digital photoplethysmogram

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Abstract.

This report presents PPG_ABP_TF, a Matlab ® script for estimating arterial blood pressure waveforms from the digital photoplethysmogram.

1. Summary

Arterial blood pressure (ABP) waveforms contain a wealth of information on the cardiovascular (CV) system, providing potential diagnostic utility [1]. Furthermore, ABP waveforms can be modelled using physical principles [2], allowing one to predict the shape of the ABP pulse under specified CV conditions. However, methods for acquiring ABP signals in vivo either require a skilled operator (*e.g.* applanation tonometry), or are invasive (*e.g.* a pressure catheter). Conversely, the digital photoplethysmogram (PPG) can be easily and non-invasively acquired in a wide range of clinical settings, using a pulse oximetry probe. It is closely related to the BP waveform [3], although the exact physiological mechanisms underlying it remain unclear [4]. A generalised transfer function relating the digital PPG to the ABP waveform has previously been reported [5], which can be used to estimate ABP waveforms from the PPG. This transfer function could allow one to conduct ABP-based analyses on estimated ABP signals, derived from easily acquired PPG waveforms. This would expand the utility of ABP-based analyses to clinical settings where it is not practical to acquire ABP waveforms, and would also allow one to use physical modelling to predict the shape of PPG waveforms.

This report presents PPG_ABP_TF, a Matlab ® script for estimating digital and radial ABP waveforms from the PPG (and vice-versa). It is based on the transfer function reported in [5].

2. Estimating ABP from the PPG

It has been suggested that a transfer function can be used to describe the relationship between PPG and ABP waveforms, which does not differ between normotensive and hypertensive patients, nor during administration of nitroglycerin, a vasodilator which

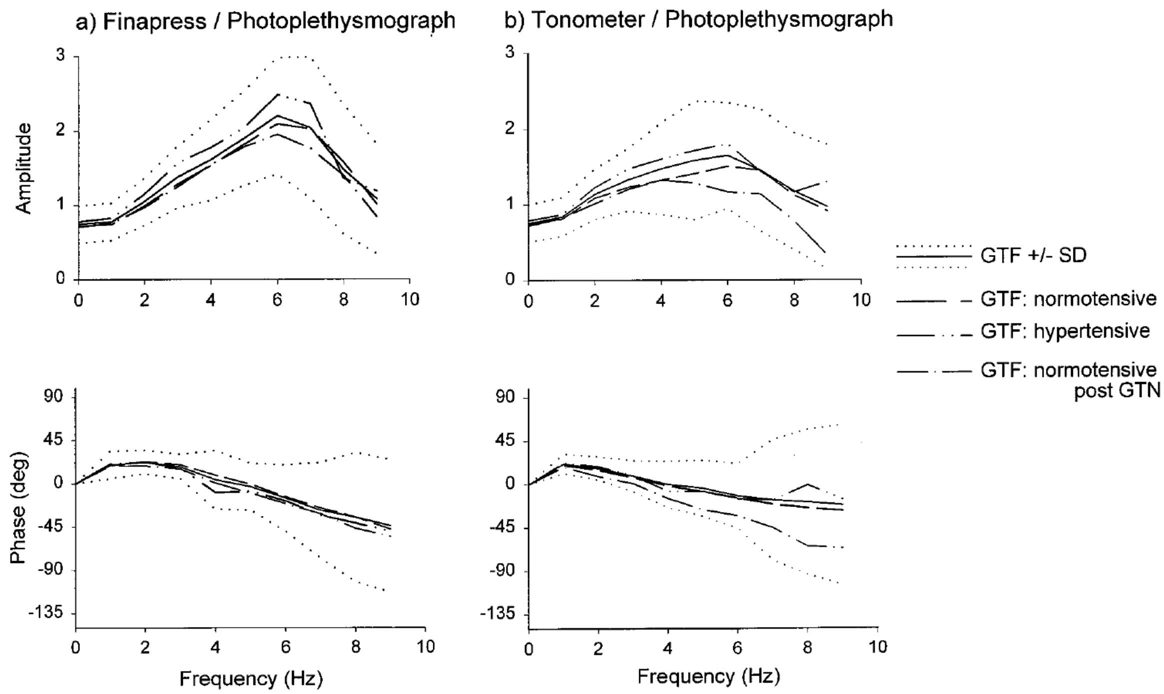

Figure 1. Transfer functions describing the relationship between (a) the digital PPG and digital ABP (left), and (b) the digital PPG and radial ABP. Definitions: GTF - generalised transfer function; GTN - nitroglycerin. Source: [5]

affects the shape of the pulse waveform [5]. The transfer functions calculated using the ratio of the fast Fourier transforms of waveforms: FFT(ABP) / FFT(PPG), and were described using a Bode plot as shown in Figure 1.

To demonstrate how to use the transfer function, it is helpful to firstly show how to recover the PPG signal from its frequency domain representation. The PPG signal is denoted $x(t)$. The FFT of the PPG,

$$X(f) = \mathcal{F}\left(x(t)\right) \tag{1}$$

is calculated, where $X(f)$ is the frequency domain representation of the PPG (a vector of complex numbers). The original PPG signal, $x(t)$, can be recovered from $X(f)$ using the following sum of cosine and sine waves:

$$x[i] = \sum_{k=0}^{N/2} Re\{\overline{X}[k]\} \cos\left(\frac{2\pi ki}{N}\right) + \sum_{k=0}^{N/2} Im\{\overline{X}[k]\} \sin\left(\frac{2\pi ki}{N}\right) \quad , \tag{2}$$

where i is the sample number (varying from 0 to $N-1$), N is the length of the FFT, and

$$Re\{\overline{X}[k]\} = \frac{Re\{X[k]\}}{N/2} \quad \text{and} \quad Im\{\overline{X}[k]\} = -\frac{Im\{X[k]\}}{N/2} \quad , \tag{3}$$

with the exceptions that

$$Re\{\overline{X}[0]\} = \frac{Re\{X[0]\}}{N} \quad \text{and} \quad Re\{\overline{X}[N/2]\} = -\frac{Im\{X[N/2]\}}{N} \quad . \tag{4}$$

A similar approach can be used to estimate an ABP signal ($y(t)$) from the PPG ($x(t)$). Firstly, $X(f)$ is calculated from $x(t)$ using the FFT. Secondly, $y(t)$ is calculated using a sum of cosine and sine waves, where the amplitude and phase offset of each wave are adjusted according to the transfer function. For instance,

$$y[i] = \sum_{k=0}^{N/2} A[k] Re\{\overline{X}[k]\} \cos\left(\frac{2\pi ki}{N} + \phi[k]\right) + \sum_{k=0}^{N/2} A[k] Im\{\overline{X}[k]\} \sin\left(\frac{2\pi ki}{N} + \phi[k]\right) , (5)$$

where the amplitude and phase of the transfer function are denoted by $A(f)$ and $\phi(f)$ respectively, and ϕ is expressed in radians.

The reported transfer functions can also be used to estimate a PPG signal from the ABP. This can be achieved by using the reciprocal of the amplitude, and the negative of the phase, of the reported transfer function.

3. Using `PPG_ABP_TF`

`PPG_ABP_TF` can be used to estimate ABP signals from the PPG, and vice-versa. The input signal can be either a signal containing several pulses, or a single pulse wave. The input data, S, should be prepared as a structure with two fields: $S.v$, a vector of signal amplitudes, and $S.fs$, the sampling frequency of the signal. The type of input signal (digPPG, digBP, or radBP) should also be specified as a string. At its simplest, `PPG_ABP_TF`can be called using

```
transformed_sig = PPG_ABP_TF(S, 'digPPG');
```

where `transformed_sig` is a structure containing individual fields for each of the estimated signals. If the digital PPG is provided as an input, then digital and radial ABP signals will be estimated. Otherwise, if the digital or radial ABP are provided, then the digital PPG will be estimated. Each signal's field is itself a structure, containing the calculated signal amplitudes (*e.g.* `transformed_sig.digABP.v`), and the sampling frequency (*e.g.* `transformed_sig.digABP.fs`). Note that the pre-processed version of the input signal is also provided as one of the output signals.

A plot of the input signal and estimated signals, such as that shown in Figure 2, can be generated by specifying an additional input:

```
transformed_sig = PPG_ABP_TF(_____, options);
```

where `options` is a structure containing a field named `do_plot`, which is a true logical.

4. Methods

`PPG_ABP_TF` consists of three stages: (i) pre-processing the input signal; (ii) estimating additional signals using a transfer function; and (iii) post-processing the output signal. The methods used at each stage are now described in turn.

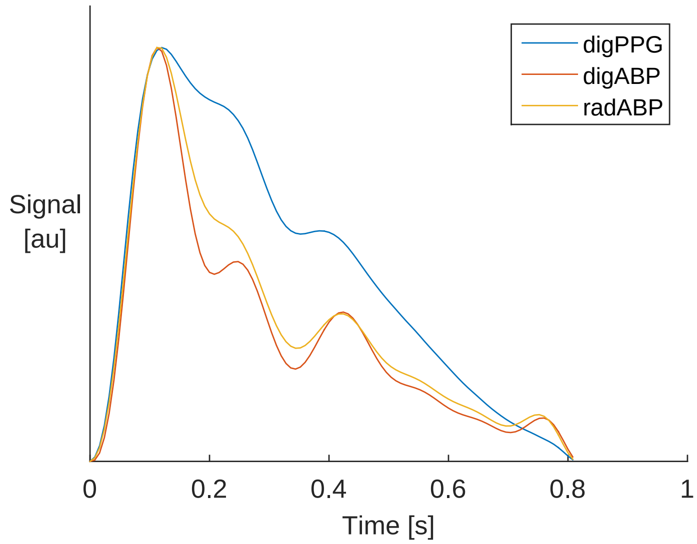

Figure 2. Digital and radial ABP pulses estimated from the digital PPG.

4.1. Pre-processing the input signal

The pre-processing steps applied vary according to whether the input signal contains multiple pulses, or a single pulse. If the signal contains multiple pulses then the signal is filtered to remove irrelevant low (< 0.067 Hz) and high frequency (> 35 Hz) content. If the signal consists of a single pulse, then: (i) low frequency content is removed using linear detrending; (ii) the pulse is aligned to ensure that it commences at the start of the systolic upslope; (iii) the pulse is repeated several times to create a signal consisting of several pulses.

4.2. Estimating additional signals using a transfer function

The methodology described in Section 2 is used to estimate either the ABP or PPG signal (whichever is not supplied as an input). The values of the transfer function at each required frequency are found by linear interpolation of the published plots.

4.3. Post-processing the output signal

In the case of a single pulse being provided as the input signal, two additional post-processing steps are performed. Firstly, the central pulse is extracted from the train of repeated pulses, to avoid any edge effects. Secondly, this pulse is scaled to occupy a range of 0 to 1, since the actual units of the pulse are unknown.

5. Further Work

The transfer function tends to result in a spurious peak during late diastole, as can be seen on the estimated digital and radial ABP pulses in Figure 2 (between 0.7 and

0.8 s). This is thought to be because the transfer functions used are only defined for frequency content of $\leq\ \approx 9$ Hz. This spurious peak should be ignored during analyses, and further work may be required to suppress it.

The methodology and code used in `PPG_ABP_TF`could be adapted to create a script for estimating central BP from peripheral BP signals. For instance, transfer functions are reported in [6, Figure 2] for estimating ascending aortic BP from either the brachial or radial BP.

References

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