Measurement of *a-a* Intervals at Rest in the Second Derivative Plethysmogram

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***Abstract*— Analysis of cardiac rhythm is medically and physiological important. A new method to detect the heart rate, using an efficient algorithm for *a* wave detection in the second derivative of the photo plethysmogram (SDPTG), measured at rest, is discussed here. SDPTG is an optical technique that has been developed for experimental use in vascular diseases. It is considered a promising tool that may replace some of the current traditional cardiovascular diagnostic tools. The performance of the proposed algorithm when tested on 27 records measured at rest showed very promising results.**

***Index Terms*—Plethysmogram, *a* wave detection, heart rate**

I. INTRODUCTION

THe analysis of cardiac rhythm has considerable medical and physiological importance. Of particular relevance is the heart rate and the heart rate variability, based on cardiac inter-beat intervals.

The conventional method to detect heart beats is electrocardiogram (ECG). In addition, the distal measurement of arterial pulse has been used by other experts to measure the heart rate. Determining accurate inter-beat intervals from arterial pressure pulses is difficult, however, especially when measured from a distal source like the fingertip photoplethysmogram. Because of the low definition of heart beat peaks in blood pressure pulses compared to the ECG, the length of the cardiac cycle is difficult to determine.

Moreover, ventricular pressure and other parameters of cardiac output can influence the form and timing of the pulse waveform. In addition, peripheral effects, such as changes in vascular tone, may also influence distal pulse peak detection.

These possible weaknesses of the fingertip photoplethysomograph are mentioned by Bernston *et al.* [1]. Hence, they recommend the usage of R-R intervals from ECG signals to determine interbeat intervals.

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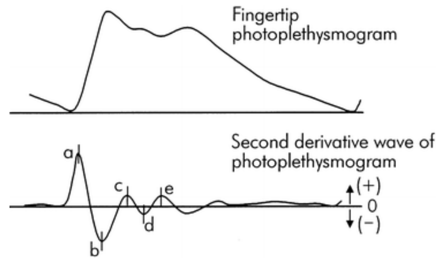

Fig.1. Signal Measurements (a) Original fingertip photoplethysmogram (b) second derivative wave of photoplethysmogram (SDPTG).

They do believe, however, that with a sophisticated peak detection algorithm the use of intra-arterial pressure pulses may be acceptable. According to them indirect measures, such as photoplethymographic signals need further validation.

It has been demonstrated that under resting conditions the distal pulse pressure is sufficient for determining the heart rate [2] Some caution is required in the use of finger plethysmography in experimental studies, where manipulations might change the relationship between cardiac chronotropic control and distal blood pressure changes. Giardino *et al.*[2] recommended extra studies that include test–retest reliability evaluation of different data collection techniques.

To increase accuracy and the detection rate of the inflection points and make interpretation easier, the second derivative of photoplethysmogram (SDPTG) has been introduced. Because the peaks in the SDPTG signal are more clearly defined than the peaks in the photoplethysmogram the heart rate can be more accurately detected using the SDPTG.

The second derivative of photoplethysmogram (SDPTG) has also been called the acceleration plethysmogram (APG). In this paper, the abbreviation SDPTG will be used.

One heart beat cycle in SDPTG consists of four systolic waves and one diastolic wave [3], namely *a*-wave (early systolic positive wave), *b*-wave (early systolic negative wave), *c*-wave (late systolic reincreasing wave), *d*-wave (late systolic redecreasing wave) and *e*-wave (early diastolic positive wave), as shown in Fig.1. The height of each wave was measured from the baseline, with the values above the baseline being positive and those under it negative.

The *a-a* interval in the SDPTG was used by Taniguchi et al[4], instead of the R-R interval in the ECG to determine the heart rate when assessing the stress experienced by surgeons

In order to detect the heart rate using the SDPTG, precise detection of individual *a* waves is a primary critical stage. Automatic detection of *a* waves in SDPTG signals is necessary for real time evaluation of the heart rate. We therefore propose an algorithm that can be used to evaluate the heart rate using the SDPTG. This investigation aimed to develop a fast and robust algorithm to detect *a* waves in SDPTG signals. The SDPTG waveform was measured in a population-based sample of healthy males at rest

II. Data

Twenty seven healthy males volunteers with a mean±SD age of 27±6.9 were measured by a photoplethysmograph (Salus), equipped with a sensor positioned at the cuticle of the second digit of the left hand. The photoplethysmographic measurements were performed while the subject was at rest on a chair. Data were collected at a sampling rate of 200Hz. The duration of each data segment is 20 seconds.

The test was conducted from 20th of April to 5th of May 2006 at Northern Territory Institution of Sport (NTIS).

All procedures were approved by the ethics committee of Charles Darwin University. Informed consent was obtained from all volunteers.

III. Methodology

The proposed *a* wave detection algorithm consists of three main stages: pre-processing, feature extractions and thresholding.

A. Pre-Processing

Pre-processing consists of two steps: bandpass filtering and taking the second derivative of the photoplethysmogram.

1) *Bandpass Filter:* the baseline wander and high frequencies, which do not contribute to *a* wave detection, have been removed by a second order Butterworth filter with passband 0.5-10Hz.

$$s[n] = Butterworth(PTG[n], 0.5 - 10Hz)$$

2) *Second Derivative:* the second derivative, z[n], of the filtered photoplethysmogram s[n] is taken. Inflection points are seen as peaks in the SDPTG.

B. Feature Extraction

Feature extraction consists of two steps: squaring and selection of potential blocks.

1) Squaring: to makes the results positive and emphasizes large differences, the square of the SDPTG signal, is calculated; $y[n] = z[n]^2$.

2) Selection of Potential Blocks: the onset and offset of the potential a waves in the SDPTG signals have been demarcated by using two moving averages, based on the normal duration of the *ab* interval which for a healthy adult is 187±17 ms.

The maximum window size corresponding to the *ab* interval is approximately 40 points (sampling frequency of 200 Hz) and the maximum window size corresponding to complete heart beat interval is approximately 220 points. We will use the maximum window sizes to detect *a* waves. The *a* waves are detected by comparing two moving averages.

First moving-window integration: The fist moving average is., calculated as follows:

$$MA_{Peak}[n] = \frac{1}{W_1}(y[n-(W_1-1)] + y[n-(W_1-2)] + ...+ y[n])$$

where $W_1 = 40$ which is the window width of *ab* segment. The purpose of the first moving average is to emphasize the *a* wave.

Second Moving-window Integration: the second moving average is used as a threshold for the output of the first moving-window integration.

$$MA_{MaxPeak}[n] = \frac{1}{W_2}(y[n-(W_2-1)] + y[n-(W_2-2)] + ...+ y[n])$$

where $W_2 = 220$ is the window width of a complete heart beat.

When the amplitude of the first moving average filter (MA_{Peak}) is greater than the amplitude of the second moving average filter ($MA_{MaxPeak}$), that part of the signal is selected as a block of interest, as follows:

IF $MA_{Peak}[n] > MA_{MaxPeak}[n]$ **THEN**
  $BLOCKS[n] = 1$
ELSE
  $BLOCKS[n] = 0$
END

C. Thresholding

When potential blocks are selected some blocks do not represent potential *a* waves. These blocks are caused by noise and need to be eliminated. Blocks with a small width are considered as blocks caused by noise. Blocks which are smaller than half of the expected size for the *ab* interval are rejected.

The expected size for the *ab* interval is based on the statistics for healthy adults, as described above.

We reject blocks that are smaller than 50% of the width that is expected for the *ab* interval. This corresponds to:

$$width(BLOCKS) < 20$$

The rejected blocks are considered as noisy blocks and the accepted blocks are considered to be containing *a* wave.

The maximum absolute value within each accepted block is considered to be the *a* peak. For this research the algorithm was tested using annotated *a* peaks.

The proposed algorithm was tested on 27 SDPTG records. The photoplethysmogram was recorded at rest. No episodes have been excluded from our analysis

The following statistical parameters were used to evaluate the algorithm:

$$Se = \frac{TP}{TP+FN}$$

$$+P = \frac{TP}{TP+FP}$$

True Positive (TP): *a* wave has been classified as *a* wave.
False Negative (FN): *a* wave has been missed.
False Positive (FP): Non- *a* wave classified as *a* wave.

The sensitivity *Se* is the percentage of true *a* waves that were correctly detected by the algorithm. The positive predictivity *+P* is the percentage of detected *a* waves which are real *a* waves.

Table 1:*a* wave detection performance on SDPTG Data

Record	No of beats	TP	FP	FN
A1	26	26	0	0
A2	24	24	0	0
B1	17	17	0	0
B2	26	26	0	0
C2	20	20	0	0
C3	20	20	0	0
D2	22	22	0	0
D3	19	19	0	0
E1	22	22	0	0
E2	22	22	0	0
E3	19	19	0	0
G2	30	30	0	0
G3	19	19	0	0
H3	23	23	0	0
I1	22	22	0	0
I2	17	17	0	0
J2	23	23	0	0
L2	24	24	0	0
L3	24	24	0	0
N2	18	18	0	0
N3	20	20	0	0
O1	24	24	0	0
O2	17	17	0	0
P1	26	26	0	0
P2	20	20	0	0
Q1	22	22	0	0
Q2	18	18	0	0
27 volunteers	584	584	0	0

Table I shows the result of *a* waves detection in 27 different records of collected SDPTG at rest, containing a total of 584 heart beats.

As shown in Fig. 1, the number of false negatives (FN) and false positives were zero. The overall average sensitivity for *a* waves detection was 100% and the positive predictivity was 100%.

IV. Discussion

The results indicate that the heart rate can be found using the *a-a* interval of the SDPTG signal. Examples of the *a-a* intervals for two different people are shown in Figure 2. This may be used to calculate the heart rate variability, the beat-to-beat variations in heart rate. The heart rate variability is an indicator of the physiological condition of a patient and a significant marker of any cardiovascular diseases.

So far, heart rate calculations have relied on measuring the the R-R interval in the ECG signal, the interval between adjacent normal QRS complexes. Therefore, the recognition of R peak has been the main focus for heart rate detection techniques. There are more than 26 different types of arithmetic manipulations of R-R intervals which have been described in the literature to represent the heart rate variability [5]. These may be applied to *a-a* intervals of the SDPTG signal. A question to be answered still is how suitable the SDPTG signal is for heart rate detection during exercise. This is a topic of further research.

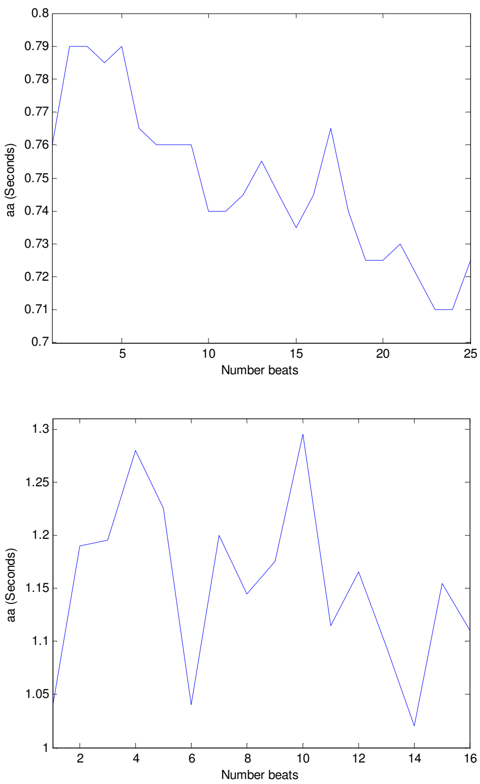

Fig.2. *a-a* intervals in SDPTG (a) fast rhythm (b) slow rhytm

V. CONCLUSION

The heart rate can be calculated using the second derivative of the photoplethysmogram (SDPTG). The length of the *a-a* interval can be accurately determined if the *a* peaks are detected correctly.

The suggested *a* waves detection algorithm for SDPTG signals, measured at rest, performed extremely well with an overall average sensitivity for *a* waves of 100% and a positive predictivity 100% using 27 records, containing a total of 584 heart beats.

The accurate detection of *a* waves in the SDPTG offers a non-invasive method of evaluating cardiac rhythms. The usage of *aa* variability analysis in SDPTG can be useful for the cardiovascular functionality assessment. The method seems promising. Further research is necessary to determine the usefulness during exercise.

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