Electrocardiograph and photoplethysmograph superimposition as an investigative tool for circulatory function

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Abstract

This paper set out to examine the usefulness of the electrocardiograph (ECG) and photoplethysmograph (PPG) superimposition as an investigative tool for circulatory function. Further, a system was constructed and an experimental protocol established to examine this proposition. The three main components of circulatory function are pulse rate, arterial compliance and blood pressure. These components are each interrelated, and these relationships are the subject of much research. It was decided, focusing on blood pressure, to examine the superimposition information with regard to systolic, diastolic and mean blood pressure. Data was collected, conclusions were drawn and interesting possibilities for further work emerged.

Introduction

The ECG and the PPG are essential medical diagnostic tools. The ECG is based on the amplification and display of electrical potentials over the body. The PPG concerns the detection of changes in the optical properties of blood under conditions of systole and diastole. The PPG forms the basis of pulse oximetry but is seldom used in isolation as a diagnostic tool. When viewed together, ECG and PPG permit us to see the contraction of the heart muscle followed by the consequent pulse at the PPG site. If the chosen site is the finger, the delay between these detected phenomena may result from the mechanical resistance and capacitance presented by the brachial archery. Examination of the phase difference between the two characteristics may form the basis of a measure for blood pressure change. It is particularly useful that this method is non-invasive and non-occlusive to blood flow. Changes in blood pressure will yield information on the state of circulatory function.

Physiological background

Arteries supply oxygenated blood to all parts of the body (except the pulmonary archery, which supplies deoxygenated blood to the lungs)[3]. Atherosclerosis is the combination of arterial hardening and the deposit of fats that impede blood supply. Atherosclerosis adversely affects the circulation, raising blood pressure and damaging bodily organs over time. Existing means of measuring poor circulation include:

- Angiogram
- Biopsy
- Continuous blood pressure monitoring
- Combined PPG and ECG [4].

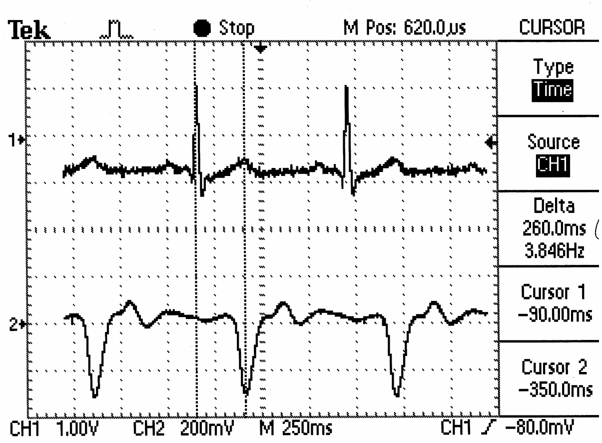

Figure 1; Superimposition of the ECG and PPG

With reference to *figure 1* the time interval between the R wave and the min point of the PPG, representing maximum light absorbance during systole, is known as the pulse transit time (PTT). PTT has been found to have a quasi-linear relationship with blood pressure [5].

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Experimental apparatus

A PCB was designed and constructed, containing an ECG amplifier and a PPG detector. The ECG amp' was designed around a circuit presented in a Burr-Brown application bulletin [1]. The amplifier is configured to measure the potential difference between an electrode on the right arm and an electrode on the left arm whilst driving the right leg with a small current. This is known as Lead I configuration. The amplifier's bandwidth is 0.05Hz to 100Hz. The gain of the amplifier is G=1000. The circuit is powered through a DC-DC converter, providing isolated +/- 15V rails. Modifications to the Burr-Brown circuit were necessary due to component obsolescence.

The PPG circuit and probe were designed by the team. This circuit comprises a current source driving an infrared LED. This was implemented with a linear regulator and rheostat arrangement, as a PWM source would have potentially introduced noise into the system. The trade off here is that the source may need to be adjusted manually if the signal, detected by the photodiode, is not strong enough. The IR detector comprises a photodiode and an initial FET gain stage detecting the transmitted light through the finger. The signal from the photodiode contains a large DC component or offset. Superimposed on this is an AC characteristic reflecting the pulsatile component of the circulation. This component can vary between 0.01% and 1% of the DC level. The signal from the IR detector is filtered and then amplified on the circuit board. A band pass filter is used, where the lower cut-off frequency is 0.05Hz. The upper cut-off frequency is 10Hz. The gain of the filter is G=522. To ensure the 'cleanest' possible signal, the ECG / PPG system is implemented with high quality active and passive components on a double sided PCB. A system diagram is shown in *figure 2*.

The experimental approach outlined in this paper involves a number of subjects altering their blood pressure through bursts of strenuous exercise and relaxation. The changes in blood pressure are monitored by a clinical blood pressure monitor whilst the phase delay can be measured each time the BP is taken.

Experimental Procedure

The subject was seated in a comfortable position with their arms resting on their lap. ECG Electrodes were connected to their right and left arms and to their right leg. The PPG probe was placed on the forefinger of the left hand. The system was connected to its battery power supply and to a digital oscilloscope. The oscilloscope has a printer port. The system was allowed to stabilise for a few moments and then the ECG and PPG waveforms were displayed simultaneously on the oscilloscope.

There may be wide variation in the PPG signal

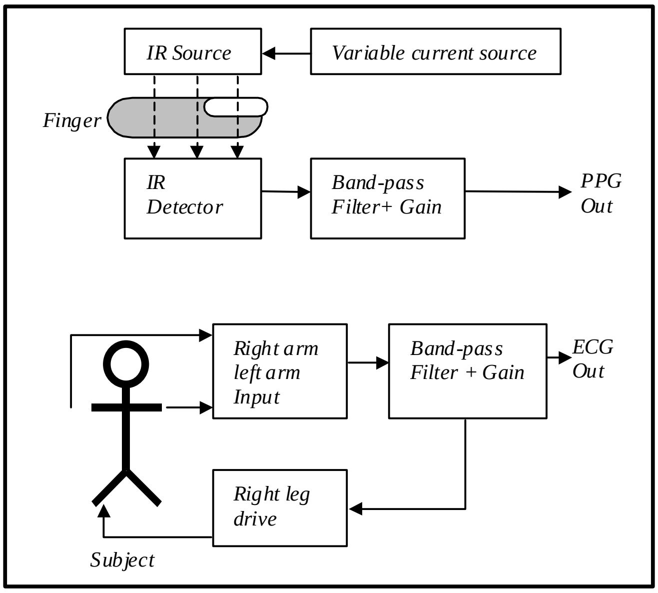


Figure 2; Block diagram of ECG / PPG monitor

amplitude due to skin pigmentation, digit size and the subject's perfusion level. The oscilloscope gain is used to roughly match the ECG and PPG signal amplitudes. A typical trace can be seen in *figure 1.* Markers are used to determine time difference between the 'R' wave in the ECG and the lowest point of the PPG, corresponding to systole.

An initial set of readings was taken with six male subjects and readings were taken for PPT and heart rate

- At rest
- With the left arm raised to the front, at an angle of 45° to the horizontal, after 1 minute.
- With the left arm raised to the front, at an angle of 90° to the horizontal, after 1 minute.

The motivation for this set of experiments was the fact that blood pressure in the arm will fall as the arm is raised however the cardio vascular system will attempt to regulate the blood pressure back to a set point.

A second set of experiments was performed, this time using bursts of exercise and relaxation to increase and decrease blood pressure. As each PTT measurement was taken the blood pressure was measured using an automatic oscillometric blood pressure monitor. PTT values were in this instance plotted against blood pressure to examine their relationship. These tests were done in the presence of an anaesthesiologist.

Results

Referring to *figure 3*, during the first set of experiments six subjects were tested and marked differences were found to exist between the PTT at rest and that with the arm raised. Additionally the body demonstrated an ability to recover, regulating the PTT back towards its 'at rest' value. The system performed well from a noise perspective giving waveforms with a high level of definition. The results also demonstrated an increase in muscular electrical noise as the arm tired.

Subject	At Rest		At 45°		At 90°	
	PL	HR	PL	HR	PL	HR
MM	260	76	280	81	300	72
TK	270	69	290	78	260	80
DM	290	62	300	67	320	65
OK	290	48	390	50	350	54
JM	290	68	320	72	360	75
TW	270	52	310	52	310	51

Figure 3

PTT (pulse transit time) is measured in ms

HR (heart rate) is measured in BPM

Referring to *figure 4* and *figure 5*, during the second set of experiments, two subjects were tested. On this occasion a blood pressure cuff was added to the right arm (whilst the PPG probe was on a finger on the right hand). It can be clearly seen that only three data points could be taken for each subject. This was due to the time taken for the blood pressure monitor to calculate blood pressure and in no small part to the relative discomfort of repeated cuff inflations.

The results of both sets of experiments highlighted another phenomenon, as the time base on the oscilloscope was stretched to achieve greater time definition it became increasingly difficult to determine exact reference points on the traces. It was finally noted that the range of blood pressures, over which measurement was possible, was limited as the body continued to regulate blood pressure towards a metabolic set point.

Figure 4; Subject MM

ms	Systolic	Diastolic	Mean	HR
260	125	86	97	73
249	113	81	99	91
260	125	86	97	73
253	126	73	86	88

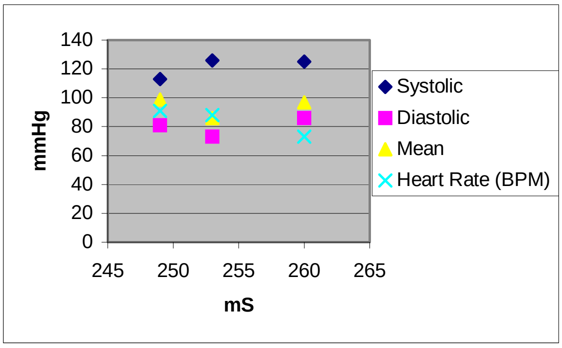
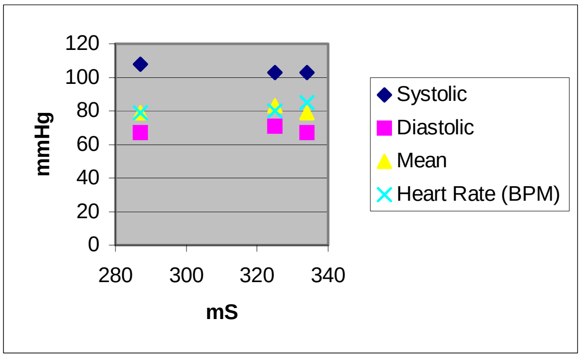


Figure 5; Subject LK

ms	Systolic	Diastolic	Mean	HR
325	103	71	83	80
334	103	67	79	85
287	108	67	79	79



Conclusions

In drawing conclusions on the experimental results, it is important to ask what results were expected. A body of work points to the fact that there is a linear relationship between BP and PTT [8]. Other relationships exist between BP and vascular compliance [6] and BP and Heart

rate [7]. In the case of blood pressure three parallel lines with negative slopes would confirm an inverse linear relationship between PTT and three blood pressure measurements; systolic, diastolic and mean. These lines have not been plotted to date and not been directly compared, to the knowledge of the investigators.
Conclusions that we can draw are, in every case in the first experiment, the subject's arm was raised to 45°, lowering BP, the PTT increased. Conclusions based on the results, beyond this become circumspect as we are examining, in effect, the transient behaviour of a control system. The use of the R wave of the ECG, as a reference point, has been questioned [8]. This is due to the fact that the R wave is an electrical signal occurring prior to the aortic pulse. The time difference between these may vary from one person to another. Finding a method of detecting the physical pulse would remove this variable.
It is clear that improvements need to be made in the method of data collection and reference point identification and definition. These needs have given rise to a variety of innovative solutions that will form the core of new work in this area.

Discussion

It was proposed over 100 years ago by Moens and Korteweg that blood pressure is proportional to pulse wave velocity. Subsequent years of research have brought the prize of non-invasive, non-occlusive beat to beat blood pressure tantalisingly close. This research has been invaluable, to the investigators, in identifying the factors that make non-invasive blood pressure measurement and circulatory function assessment a nebulous pursuit. It has also spurred the development of a 'reflective brachial PPG' as a replacement for the ECG R wave, as a time reference. This device will be assessed in further work, however initial results show great promise.
Interest in non-invasive medical diagnostic techniques has never been keener. As the main factors in circulatory function are inter-related, work done in one area invariably has applications in another. The techniques of blood pressure determination through pulse transit time, will be an invaluable investigative tool for assessing circulatory function.

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