# Development of a Method for Determining Arterial Pulse Propagation Times and Influence of Arterial Compliance

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## Abstract

*The characteristics of the arterial wall play an important role in cardiovascular physiology and pathophysiology. Arteries are normally elastic or compliant, allowing the artery diameter to expand under pressure. However, very little is known about this important property, as it is difficult to assess in vivo.*

*This study examined this property indirectly from measurements of the time the pulse took to radiate from the heart to peripheral sites on the body. By examining beat-to-beat changes in pulse timing, the effects on arterial compliance were estimated.*

*Subjects with frequent ectopic beats were studied. Electrocardiogram (ECG) and finger and ear photoplethysmograph (PPG) recordings were obtained from all subjects. ECG-pulse times for ear and finger pulses were determined by computer algorithms. The differences in pulse propagation time between sinus beats and ectopic beats with lower pulse pressure were quantified.*

*The ECG-pulse time for ectopic beats was significantly greater than for the sinus beats. The finger ECG-pulse time for ectopic beats was 344±14 ms compared with 228±11 ms for sinus beats (P<0.001), and the ear ECG-pulse time was 288±20 ms compared with 180±13 ms (P<0.001). The differences between the finger and ear ECG-pulse times allowed the pulse propagation time along the arm to be estimated. It was significantly longer for the ectopic beats than for the sinus beats (55.7±8.0 ms compared to 47.7±4.0 ms). This 18% change resulted from the lower pulse pressure of ectopic beats and increased arterial compliance of 42%.*

## 1. Introduction

Arterial wall changes are usually associated with physiological and clinical factors, such as ageing [1], smoking [2], diabetes [3], and hypertension [4]. The structure, properties and function of the arterial wall play an important role in cardiovascular physiology and pathophysiology. The ability to characterize and quantify arterial properties is important, as this could be an early risk marker for arterial disease.

Arterial compliance is used to quantify the mechanical and structural properties of the arterial wall. Currently, a number of methods have been used to estimate arterial compliance non-invasively. These are mainly based on analysis of pulse wave velocity [4], pulse wave contour [5] and direct measurement of arterial geometry and pressure [6]. However, these techniques are not yet used in normal clinical practical.

ECG-pulse time, which is the time taken for the pulse pressure wave to travel from the heart to the peripheral sites, has been used to assess arterial compliance. It includes electrical depolarization time and mechanical contraction time (together now referred to as left ventricular electro-mechanical time) as well as pulse propagation time in the artery. One cardiac event constituting ECG-pulse time is described in figure 1.

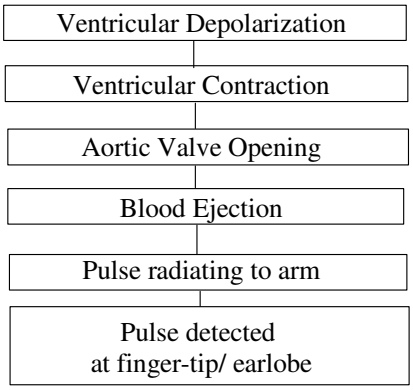


Figure 1. One cardiac event constitutes ECG-pulse time.

The aim of this study was to develop a method for determining the effects of instantaneous arterial pressure changes induced by ectopic beats on the ECG-pulse time and for determining whether the instantaneous arterial pressure changes can lead to measurable differences between finger and ear ECG-pulse times referred to below as the arm pulse propagation time. The changes of arterial compliance with arterial pressure changes were then estimated.

## 2. Methods

### 2.1. Subjects

The data for this study came from a retrospective analysis of multi-site PPG and ECG recordings from normal subjects and from patients under investigation for possible lower limb vascular disease [7]. Subjects were found whose recordings contained 3 or more ectopic beats.

### 2.2. Measurement system

Figure 2 shows the schematic representation of the measurement system. To pick up the changes in infrared reflectance resulting from varying blood volume, two PPG probes were used at the right index finger and the right earlobe. A single channel ECG was recorded to provide a timing reference for the PPG pulses. After the signal conditioning circuits, those signals were sampled at 2500 Hz to a data capture computer for subsequent off-line analysis. The recording time was at least 150 s.

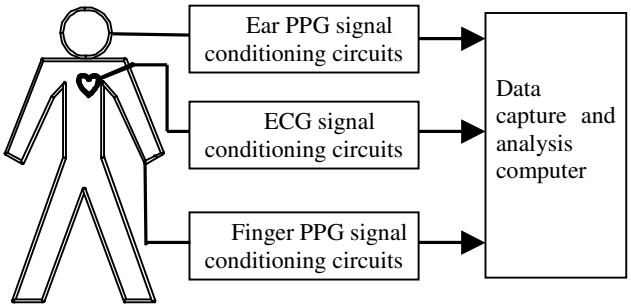


Figure 2. Measurement and analysis system.

### 2.3. Ectopic beat collection

After the ectopic beats were found manually on ECG, the corresponding pulse foot of PPG was observed. Figure 3A shows one example of finger-PPG, ear-PPG and ECG waveforms with an ectopic beat. If the ectopic beat was not followed by an observable pulse on the PPG waveform (Figure 3B), it was excluded from analysis.

### 2.4. Pulse wave analysis

The time interval between each ECG complex and the following PPG pulse was defined as the ECG-pulse time. As shown in figure 3A, the ECG-pulse time (finger and ear) for the ectopic beats and the sinus beats immediately preceding the ectopic beats were measured from the onset of the QRS complex to the corresponding pulse foot of the finger-PPG and ear-PPG using software developed with Matlab 7.0. The ectopic beat coupling interval (CI) was calculated from the Q wave of the sinus beat preceding the ectopic beat to the Q wave of the ectopic beat.

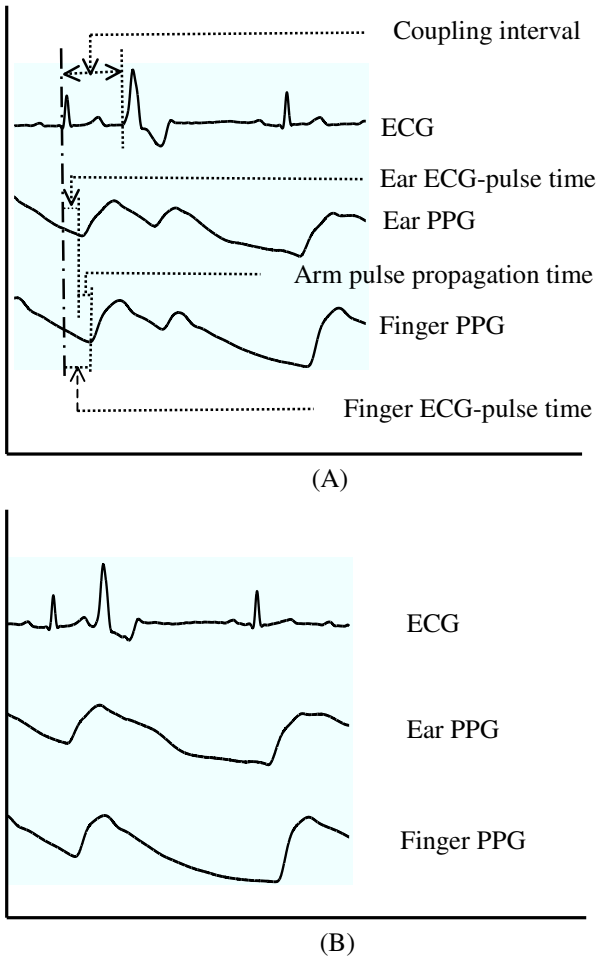


Figure 3. (A) A typical example of PPG and ECG recording with an ectopic beat. (B) No corresponding pulse foot for the ectopic beat.

### 2.5. Statistical analysis

Firstly, the finger and ear ECG-pulse time for all the analyzable ectopic beats and the sinus beats immediately preceding the ectopic beats were obtained. The mean and standard deviation (SD) of the subject finger and ear ECG-pulse times were then calculated.

Next, by subtracting the ear ECG-pulse time from the finger ECG-pulse time, the arm pulse propagation time was obtained. The mean and SD of arm pulse propagation time were separately calculated for the ectopic beats and for the sinus beats immediately preceding the ectopic beats. The change for ectopic beats was also calculated. All differences were for paired values, and all statistical t-tests were performed on paired data.

Finally, the effect of ectopic beat CI on arm pulse propagation time was investigated through regression analysis using software SPSS version 10.0.

## 3. Results

### 3.1. Effect of ectopic beats on ECG-pulse time

Figure 4 shows the mean of finger ECG-pulse time from all the analyzable ectopic beats and the sinus beats in one subject. The finger ECG-pulse time for ectopic beats was 344±14 ms compared with 228±11 ms for sinus beats (P<0.001). The ectopic beats significantly increased the ECG-pulse time by a mean of 116 ms.

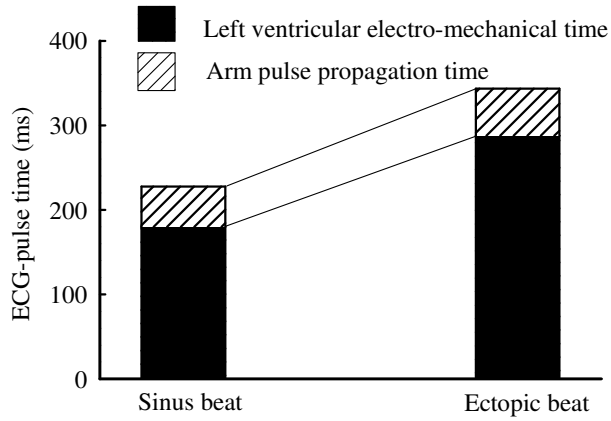


Figure 4. Mean of the finger ECG-pulse time (whole rectangle) in the ectopic beats and the sinus beats.

### 3.2. Effect of ectopic beats on left ventricular electro-mechanical time

Figure 5 shows the mean and SD of left ventricular electro-mechanical time for the subject in figure 4. The left ventricular electro-mechanical time for ectopic beats was 288±20 ms compared with 180±13 ms for sinus beats (P<0.001). The ectopic beats significantly increased the left ventricular electro-mechanical time by a mean of 108 ms.

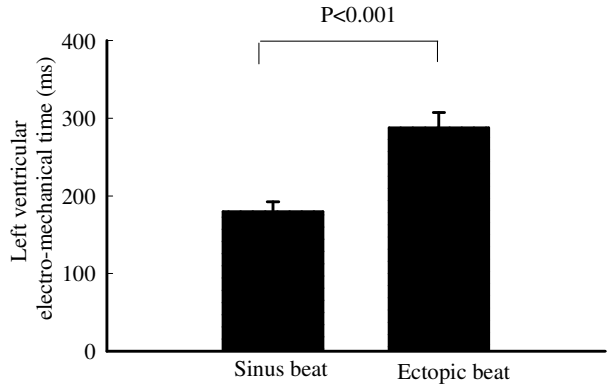


Figure 5. Left ventricular electro-mechanical time in the ectopic beats and the sinus beats.

### 3.3. Effect of ectopic beats on arm pulse propagation time

Since the left ventricular electro-mechanical times were common for both simultaneous finger and ear ECG-pulse times, their differences allowed the left ventricular electro-mechanical time to be eliminated. Figure 6 shows the arm pulse propagation time in the subject shown in figure 4 and 5. The arm pulse propagation time for ectopic beats was significantly greater than sinus beats (55.7±8.0 ms compared to 47.7±4.0 ms, p<0.001). The average 8.0 ms increase of arm pulse propagation time was caused solely by the changes of arterial pressure.

According to the Moens-Korteweg equation [8]: pulse wave velocity PWV= $\sqrt{\frac{E*h}{\rho*D}}$ (Where, E is Young's Modulus, h and D respectively represent the arterial wall thickness and the arterial diameter and ρ is the blood density). Because ρ and h/D may be thought of as a permanent property within the circulatory system, PWV or arterial pulse propagation time is proportional to the square root of Young's modulus or arterial compliance. We would therefore associate the 8.0 ms (18%) increase of arm pulse propagation time, caused by ectopic beats, with an increased arterial compliance of 42%.

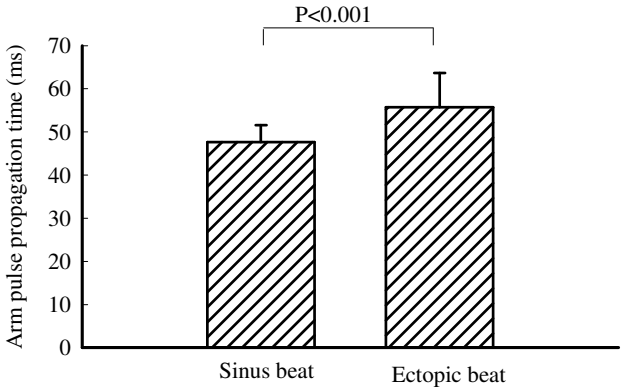


Figure 6. Arm propagation time in the ectopic beats and the sinus beats.

### 3.4. Effect of ectopic beat coupling interval on arm pulse propagation time

Figure 7A shows an example relationship between the ectopic beat CI and ECG-pulse time. The ECG-pulse times were inversely related to the ectopic beat CIs. In addition, the effect of ectopic beat CI on the arm pulse propagation time alone was investigated and the inverse relationship was also noticed. Figure 7B shows an example relationship between the ectopic beat CI and arm pulse propagation time.

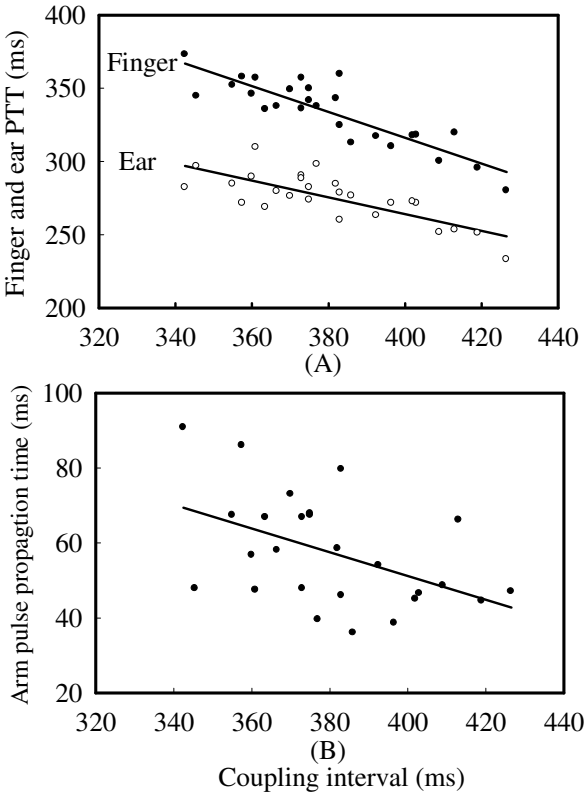


Figure 7. (A) The relationship between the ectopic beat CI and finger and ear ECG-pulse time. (B) The relationship between the ectopic beat CI and arm pulse propagation time.

## 4. Discussion and conclusions

The present study shows a method for detecting ECG-pulse times (finger and ear) in ectopic beats. This confirms that the effect of instantaneous arterial pressure changes induced by etopic beats can be determined at peripheral sites. However, the measured ECG-pulse times in this study include left ventricular electro-mechanical time, which is different for ectopic beats with different lower stroke volumes. In this study, the effect of changes in left ventricular electro-mechanical time on ECG-pulse times was eliminated by the novel method of subtracting the simultaneous ear ECG-pulse time from the finger ECG-pulse time. The time difference, called the arm pulse propagation time, was 47.7 ms in the sinus beat immediately preceding the ectopic beat. In ectopic beats, the mean arm pulse propagation time was 55.7 ms with an average increase of 8.0 ms. From this we estimated a change of arterial wall compliance of around 42% during ectopic beats. Therefore, the detectable arm propagation time change in the major length of the arm provides one new parameter to estimate arterial compliance change.

Furthermore, we have shown an inverse relationship between the ectopic beat CI and the pulse propagation time in the arm. Short intervals, with associated smaller cardiac outputs and lower arterial pressure [9], resulted in significantly longer pulse propagation times.

The limitation of this study is that, by subtracting the ear ECG-pulse time from finger ECG-pulse time to eliminate the left ventricular electro-mechanical time, the equivalent pulse propagation time from the aorta to earlobe is also eliminated. Further development to get the pulse propagation time on different segments of arteries from the aorta to peripheral sites needs to be considered.

## Acknowledgements

We would like to acknowledge the support of an Overseas Research Studentship (Universities UK) and an International Research Studentship (Newcastle University) for this project.

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