Automatic Ankle Pressure Measurements Using PPG in Ankle-brachial Pressure Index Determination


Departments of 1 Cardiovascular Surgery and Anaesthesia, and 2 Biomedical Engineering, University Hospital, Linköping, Sweden

Objective. To evaluate a new technique using a photoplethysmographic (PPG) probe for automatic ankle pressure measurements.

Design. Comparative study on two techniques for ankle pressure measurement.

Setting. University hospital.

Material. Thirty-five patients with leg arterial disease and eight healthy volunteers. Ankle-brachial indices (ABPI) were measured using conventional CW Doppler technique and PPG-based prototype equipment for the ankle pressure recordings.

Chief outcome measures. ABPIs calculated from CW Doppler and PPG ankle pressure measurements. The PPG signals were analysed both by visual judgement and by a software based, automatic algorithm.

Main results. The mean difference between ABPIs calculated from CW Doppler recordings and PPG (visual analysis) was $0.01$ (limits of agreement ($\pm$ two standard deviations) $0.16$ to $0.19$). The correlation coefficient was $0.93$.

Conclusion. When the algorithm was used, the mean difference (CW Doppler – PPG) was $0.05$ (limits of agreement $0.28$ to $0.18$, $r = 0.89$).

Conclusions. The PPG method is a promising technique with an inherent potential for automatisation of the ankle pressure measurements, thereby reducing the observer-dependency in ABPI recordings.

Keywords: Photoplethysmography; Ankle; Blood pressure determination; Ultrasonography; Doppler.

Introduction

The ankle-brachial pressure index (ABPI, systolic ankle pressure divided by systolic brachial pressure) is a marker for clinical and subclinical atherosclerosis. Besides being diagnostic in symptomatic leg arterial disease, a lowered ABPI is highly associated with future cardiovascular events like myocardial infarction and stroke, and with an increased mortality, irrespective of leg symptoms. The ABPI is usually recorded using a hand-held continuous wave (CW) Doppler pen for detection of the flow signals in the ankle arteries, and a pneumatic cuff. This technique is reliable in well-trained hands, e.g. in the laboratory setting. In everyday clinical practice, the validity decreases substantially due to multiple sources of error associated with the ABI measurement. A less operator-dependent, automated technique would be of great value. Automatic oscillometric blood pressure

recorders, originally designed for arm blood pressure measurement, have been advocated for this purpose,

but their validity in arterial occlusive disease has been put under question. In this paper, we evaluated ABPIs calculated from ankle pressure measurements using an alternate technique with an inherent possibility of automatisation. A photoplethysmographic (PPG) probe, integrated with the cuff was validated against the conventional CW Doppler pen for blood flow detection in patients and healthy volunteers.

Methods

Material

Recordings were performed on 35 consecutive patients, who had intermittent claudication ($n = 33$) or chronic critical ischaemia presenting to the outpatient clinic at the Department of Cardiovascular Surgery and Anaesthesia, University Hospital,
Linköping. Their median age was 77 years (range 27–88), 25 men. Eight were diabetics. None of them had been subjected to a leg arterial reconstructive procedure prior to the study. In addition, eight healthy volunteers (median age 24 years (range 22–29), four men) were examined using the same protocol. Legs with unrecordable CW Doppler ankle systolic pressures, stiff ankle arteries (manifested as an ABPI > 1.4) or painful wounds at the ankle were excluded. In total, 82 legs in 43 subjects were evaluated in the study.

The PPG instrument

PPG measurements were performed using a custom-designed photoplethysmographic probe that was attached to the inside of a standard 12-cm pneumatic cuff. The two-channel probe, using light emitting diodes of 880 nm, was designed to record blood flow related signals from the anterior and posterior tibial arteries separately while, based on previous anatomical studies, the peroneal artery was considered to be too deeply situated to be reached by the emitted light. The cuff-probe unit was connected to an instrument that enclosed a pressure regulator unit for rapid inflation and smooth deflation of the cuff (about 3 mmHg/s), and a digital microprocessor controlled system for signal processing. Fig. 1 shows the measurement set-up consisting of the cuff-probe unit, the PPG instrument and a laptop.

Measurement procedure

The subjects were put to rest on a bed in a warm room for at least 5 min. Systolic pressures in both arms were measured using a standard 12-cm pneumatic cuff and a stethoscope. The arm with the highest pressure was used for further measurements. CW Doppler ankle pressures were recorded in the posterior tibial and the dorsalis pedis arteries of both legs using hand-held CW Dopplers (9.3 MHz, Model 909, Parks Medical Electronics Inc., USA, or 8 MHz, MD-8, Sonotechnik GMBH, Germany) and a 12-cm standard cuff attached just above the ankle. Two sets of measurements were made in each leg. PPG ankle pressure signals were recorded before or after CW Doppler ankle pressures in a random fashion. Two measurements were performed in each leg. Brachial systolic pressures were measured before and after ankle pressure measurements with each method. The ankle-brachial index (ABPI) was calculated as the higher of the ankle pressures (mean of two measurements) in each leg divided by the mean of the systolic arm pressures prior to and after the ankle pressure measurements. During the measurement procedure, the PPG signals were stored on a PC for later analysis. Two specially trained vascular technicians or one of the authors (BJ) performed all the measurements.

Visual and automatic analysis of PPG signals

The PPG signals were analysed in two ways. First, the signals were visually analysed on the PC screen. After low-pass filtering, the first systolic peak in a consecutive series of peaks was identified, and the corresponding cuff pressure was read automatically by the custom-made software. Secondly, an automatic algorithm was used. Peak specific signal data were extracted through a narrow band pass filter and subsequently analysed for peak content. In a first step all signal areas exhibiting peak characteristics specific to a PPG pulse signal were automatically marked, forming a consecutive series of peak indicators. In the next step, stray and singular peaks were removed from the series, as well as peaks occurring in a too irregular manner. The first of the remaining peaks in the series was used to read the corresponding cuff pressure (Fig. 2). Mean pressures from both
channels, presumably corresponding to the anterior and posterior tibial arteries, were calculated. The ABPI was calculated from the higher of these pressures.

**Statistics**

Data are presented as means and standard deviations (SD), unless otherwise stated. Agreement between methods was examined using the Pearson correlation coefficient ($r$) and Bland–Altman plots. All calculations were performed using SPSS for Windows version 12.0 (SPSS Inc., USA).

**Ethics**

The study was approved by the Local Ethics Committee of the University Hospital, Linköping. All subjects gave informed consent.
Results

Visual analysis

Four legs in three subjects were excluded from the calculations due to lack of visible PPG amplitudes. In the remaining 78 legs, there was a good correlation between CW Doppler and visually analysed PPG ABPIs, with a correlation coefficient ($r$) of 0.93 (Fig. 3). The mean difference between CW Doppler-derived and PPG-derived ABPIs was $-0.01$ (limits of agreement (mean difference $\pm 2SD$) $0.16$ to $-0.19$) (Fig. 4). The Bland–Altman plot for analysis of agreement showed no obvious relation between the difference and the mean of ABPIs by the two methods.

In the four legs with no visible PPG amplitudes (5% of all examined legs), three had CW Doppler ABPIs in the very low range (Table 1). The fourth recording was from a 79-year-old diabetic with a high pulse pressure in her arms, indicating falsely elevated systolic pressures. The CW Doppler ABPI in her contralateral leg was 0.36.

Table 1. Legs with no detectable PPG signals at visual analysis

<table>
<thead>
<tr>
<th>Subject</th>
<th>Diagnosis</th>
<th>Leg</th>
<th>Age, years</th>
<th>Diabetes</th>
<th>CW Doppler pressure in ATA/PTA, mmHg</th>
<th>PPG pressure in ATA/PTA, mmHg</th>
<th>CW Doppler ABPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Claudication</td>
<td>Right</td>
<td>79</td>
<td>Yes</td>
<td>49/0</td>
<td>0/0</td>
<td>0.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Left</td>
<td></td>
<td></td>
<td>121/0</td>
<td>0/0</td>
<td>0.90</td>
</tr>
<tr>
<td>2</td>
<td>Claudication</td>
<td>Right</td>
<td>84</td>
<td>Yes</td>
<td>0/65</td>
<td>0/0</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
<td>Claudication</td>
<td>Left</td>
<td>82</td>
<td>Yes</td>
<td>0/61</td>
<td>0/0</td>
<td>0.40</td>
</tr>
</tbody>
</table>

ATA, anterior tibial artery; PTA, posterior tibial artery.

Automatic algorithm

Four legs were excluded due to lack of visible PPG amplitudes, the same as in the visual analysis. Additionally, one leg was excluded because of interpretation difficulties due to irregular cardiac rhythm during the measurement. Thereby, 77 legs could be analysed (94%). The correlation between algorithm- and CW Doppler based ABPIs was almost as good as when visual analysis was performed ($r = 0.89$). The algorithm slightly underestimated the ankle pressures (mean difference between CW Doppler-derived and PPG-derived ABPIs 0.05, limits of agreement $+0.28$ to $-0.18$ (Fig. 5)). The algorithm encountered problems when the signal quality was poor (unfavourable signal/noise ratio) and when artefacts due to muscle movements appeared. However, erroneous readings occurred independent of the actual pressure level (Fig. 5).

The ability of the algorithm-based PPG ABPIs to
identify subjects with a doctor’s diagnosis of leg arterial disease as compared to the CW Doppler technique is shown in Fig. 6. The predictive values of both positive and negative tests were 100%, assuming an ABPI cut-off for a positive test at \( 0.9 \).

Discussion

With a growing interest in using the ABPI for screening subjects for increased cardiovascular risk, utilisation of the test by less experienced personnel is expected. The major advantage of the PPG method studied in this paper is the possibility to automate the measurement procedure, and thereby decrease observer dependency. The correlation between PPG and CW Doppler derived ABPIs was good both when visual analysis and the automatic algorithm were used for signal analysis (0.93 and 0.89, respectively). The sensitivity and specificity for identification of vascular disease were identical even when the algorithm derived PPG data were utilised. These findings are encouraging and motivate continued development of the PPG technique.

Despite a good correlation, the limits of agreement achieved with PPG and CW Doppler ABPIs imply that on visual analysis, a PPG-recorded ABPI of, say, 0.9 may in fact vary from 0.71 to 1.06, if CW Doppler ABPI is used as reference (Fig. 4). Using the algorithm, this span would be 0.72 to 1.18 (Fig. 5). The CW Doppler method is, however, not a true Gold Standard for ankle pressure measurements, showing a considerable variability in itself, especially in the hands of inexperienced personnel. Both the CW Doppler and the PPG techniques aim at detecting the onset of blood flow as the cuff pressure is released beneath the supra-systolic level. This phenomenon is, however, recorded at different anatomical levels. Variation in recorded pressures between subjects with lesions in their lower leg arteries could therefore be expected. CW Doppler based and PPG determined ABPI are based on two different physical principles, therefore, a perfect agreement would not be expected. In a previous study on subjects without vascular disease, a good correlation between PPG ankle pressures and intra-arterial measurements was found (0.89 in 10 subjects).

In the legs where no PPG signals were detected, CW Doppler pressures were in the very low range in all but one. It thereby seems that absent PPG signals indicate severe vascular disease, which is the most relevant clinical information. Both the CW Doppler and the PPG methods suffer the limitations associated with the use of a pneumatic cuff, which might produce invalid blood pressures in subjects with stiff ankle arteries. As the new technique offers no advantage in this respect, the same caution is called for in the interpretation of ABPIs achieved from diabetics.

Light penetration depths in human tissue reported in previous studies using PPG or NIRS (near-infrared spectroscopy) techniques gave reason to presume...
that the peroneal artery is too far from the probe to be detectable in most cases. The PPG probe was originally designed to record signals from the anterior and posterior tibial arteries, accordingly. There is, however, a considerable overlap between the distances from the skin surface to the three individual ankle arteries. Fig. 7 shows this circumstance by depicting X-ray angiographies from two patients in the present series, where contradictory measurement results were achieved. The PPG probe does not solely record signals from the anterior and posterior arteries, therefore, it seems reasonable to use the highest of the two recorded pressures in the numerator in the ABPI calculation, as is usually recommended.

Improved signal quality through reduction of background noise and decreased sensitivity for movement artefacts should further enhance the performance of the PPG equipment. By using the same technique for arm pressure measurements, a complete automatic ABPI recorder could be designed. Visual analysis is unpractical for clinical use, and a reliable algorithm is a prerequisite for automation of the measurements. The algorithm used in the present study is under development, and the results represent the present state of the methodology. However, the ability of the algorithm-based ABPI to identify leg arterial disease motivates further elaboration of this technique.

Acknowledgements

Thanks to Mrs Elisabeth Kindberg and Mrs Pia Bjällander-Stenmark for excellent assistance in clinical measurements. Thanks also to Bengt Ragnemalm and Per Sveider for technical assistance. This work was supported by grants from the Linköping Heart Centre and from The Physicians’ Society of Linköping.
References


Accepted 16 May 2005
Available online 17 June 2005