The usefulness of a laser Doppler in the measurement of toe blood pressures

Jurgen C. de Graaff, MD,1 Dirk Th. Ubbink, MD, PhD,1 Dink A. Legemate, PhD, MD,2 Rob J. de Haan, PhD,2 and Michael J. H. M. Jacobs, MD, PhD,1
Amsterdam, The Netherlands

Objective: The purpose of this study was to evaluate the clinical value and reproducibility of laser Doppler (LD) versus photoplethysmography (PPG) in the measurement of the systolic toe blood pressure.

Methods: Toe blood pressure was measured in 60 patients in different stages of peripheral vascular disease with simultaneous digital sampling of PPG and two LD signals, each with a different filter setting (3 second [LD3] and 0.03 second [LD0.03]), and cuff pressure. These measurements were repeated after 1 week. The signals were analyzed with previous results ignored. The agreement of the PPG and LD pressures and reproducibility after 1 week were assessed by calculating the intraclass correlation coefficient (ICC). The agreement variation across the range of pressure values was visually explored by means of difference plots.

Results: In 19 legs with a very low pressure only LD could adequately measure the pressure, whereas PPG did not. The ICCs between PPG and LD3 and LD0.03 were 0.95 or more. The ICCs of the 1-week reproducibility of the PPG, LD3, and LD0.03 pressures were 0.92, 0.88, and 0.86, respectively. The variation was equally distributed across the range of pressures in all three methods.

Conclusion: LD is a reliable alternative to PPG to measure toe blood pressures. Furthermore, LD is able to measure low pressures, which is relevant in the assessment of the presence of critical ischemia. (J Vasc Surg 2000;32:1172-9.)

Toe systolic blood pressure measurements play a prominent role in the diagnosis of critical leg ischemia, especially in diabetic patients, in whom the ankle pressure is not always reliable because of media sclerosis.1,2 The toe pressure is also important in patients with extensive wounds in whom the ankle cuffs or Doppler probes cannot be applied. In patients with severe arterial insufficiency, toe pressure is correlated with the severity of the overall occlusive process,3 the need for vascular intervention,4,5 the healing potential of ulcers,6 and the prediction of the need for amputation.7 The cutoff value used for the diagnosis of critical leg ischemia as defined in the European Consensus8 is low (30 mm Hg). Therefore, the technique must be highly accurate when used in the low-pressure range.

The principle of toe blood pressure is based on the method of arm blood pressure measurements as initially described by Riva-Rocci9; a pneumatic cuff surrounding the limb is inflated to a pressure sufficient to stop blood flow.10 During slow deflation, the onset of resumption of blood flow distal to the cuff is defined as the systolic pressure. Nowadays, toe blood pressure is usually measured by either strain gauge11 or photoplethysmography (PPG).12 Both methods can be used in the alternating current (AC) and direct current (DC) mode. In the AC mode the resumption of blood is detected by the return of the pulsatile signal, which is reduced, or even absent, in patients with multiple occlusions as in patients with critical leg ischemia. In the absence of detectable pulsations, the plethysmograph can be DC coupled. The toe is exsanguinated with a tourniquet before inflation of the occluding cuff. Resumption of arterial inflow is then indicated by an upward shift from

---

From the Departments of Vascular Surgery and Clinical Epidemiology and Biostatistics, Academic Medical Center. Competition of interest: nil. Supported by The Netherlands Heart Foundation, grant number 96-113.

Reprint requests: Dirk Th. Ubbink, Department of Vascular Surgery, Academic Medical Center, Meibergdreef 9, PO Box 22700, 1100 DE Amsterdam, The Netherlands (e-mail: D.Ubbink@amc.uva.nl).

the baseline. However, both methods have their shortcomings. The strain gauge is difficult to position at short digits, and the element might exert some pressure on the toe, which influences measurement accuracy at low pressures, whereas the PPG in the DC mode is very sensitive to movement artifacts and not commonly used.

Many methods, such as clearance of radioisotopes, pink flush reappearance, audio PPG, pulse oximetry, and impedance sphygmmography have been used for the measurement of toe pressures with varying success. More recently, the laser Doppler (LD) technique has been suggested for this purpose. LD has also been used as an alternative technique for PPG in the measurement of skin perfusion pressures. LD has theoretical advantages over PPG, because it is able to detect the minute microcirculatory blood perfusion in the skin. PPG is based on changes in the amount of reflected near infrared light on pulsatile changes in blood filling of the digit, whereas LD is based on the change in frequency shift of the reflected light caused by moving blood particles. Furthermore, LD is readily applied without compression, even to short digits. Andersson et al compared LD with the strain gauge method and concluded that the LD technique is an alternative and is complementary to the strain gauge method in damaged or ulcerating toes and feet. Beinder et al used LD in combination with a specially manufactured transparent plastic capsule for positioning the LD probe and cuff to the digit. The toe pressures obtained were in good agreement with data obtained by means of the strain gauge method measured in another group of patients.

Patients and Methods

Patients. Sixty patients (37 men, 23 women; mean age, 66 years; SD, 10 years) referred to the vascular laboratory for the assessment of the ankle/brachial index (ABI) consented to participate in this study. Patient characteristics are listed in Table I. In eight patients only one toe could be investigated, because in four patients the toe or foot was amputated, while in the remaining four patients it was not

![Fig 1. Scheme of probe application on the big toe and signal analysis. All three signals are plotted in one graph for simplification, although signals were analyzed independently. The arrows represent the points at which the systolic pressures were read.](image-url)

Table I. Patient characteristics (n = 60)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Number (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smoking</td>
<td>52%</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>36%</td>
</tr>
<tr>
<td>History of cerebrovascular accident</td>
<td>17%</td>
</tr>
<tr>
<td>or temporary ischemic attack</td>
<td></td>
</tr>
<tr>
<td>History of cardiac failure</td>
<td>41%</td>
</tr>
<tr>
<td>Hypertension</td>
<td>48%</td>
</tr>
<tr>
<td>Hypercholesterolemia</td>
<td>41%</td>
</tr>
<tr>
<td>Presence of peripheral pulsations (dorsalis pedis or posterior tibial artery)</td>
<td>69% (of 112 legs)</td>
</tr>
</tbody>
</table>

Furthermore, LD tended to be more sensitive than strain gauge at low pressures. However, the LD technique has not yet been compared with PPG, which is mostly used nowadays, in the same population.

In this study we compared two techniques (PPG and LD) for the measurement of toe blood pressure measurements as to their use, reliability, and responsiveness in patients with different stages of peripheral vascular insufficiency. Additionally, we evaluated the 1-week intraobserver reproducibility to evaluate consistency of both methods.
possible to measure the toe blood pressure with both techniques at the same time because of large wounds (n = 3) or the shortness of the toe (n = 1). The remaining 112 legs belonged to different stages of peripheral vascular disease; there were 20 legs without complaints, 54 with intermittent claudication, and 38 with rest pain, ulcers, or gangrene. Patients were acclimatized in a temperature-controlled environment (23 ± 1°C) during a resting period of at least 15 minutes.

**Measurements.** Measurements were performed in the supine position, which implies that, depending on the size and position of the foot, the toe was at or just above heart level during the measurement, which is the usual position for these measurements. The legs were covered with sheets or clothing to prevent cooling. Because of these preparations, we refrained from local heating of the toe, which is sometimes advocated in PPG studies. The toe pressures were simultaneously measured with PPG and LD.

The PPG was AC coupled (filter settings, 0.4-2.3 Hz). A PPG consists of an infrared light-emitting diode and a photosensor mounted adjacent to one another on a small probe. Blood, which is more opaque than surrounding tissue, attenuates light in proportion to its content in the tissue. The speed differences in the flow causing variations in the amount of blood content in the digit result in a pulse contour, which is normally presented on a graph.

LD fluxmetry is a simple, noninvasive sensitive technique used to assess cutaneous blood perfusion. In the LD instrument, light with a wavelength of 780 nm is conducted through optical fibers to an area of the skin of about 0.5 mm² where it penetrates the skin to a depth of 1 to 1.5 mm and is partly reflected. This light, if backscattered by moving objects (principally erythrocytes), undergoes a frequency shift, which is proportional to the
velocity, number, and direction of moving objects (LD flux) and is expressed in volts. Two filter settings of the partly output signal (time constants) of the LD instrument were used: 3 seconds (LD3) for the detection of slow changes in blood flow (which can be compared with the DC mode), and 0.03 seconds (LD0.03), which results in a signal that could trace heartbeats (which can be compared with the AC mode).

**Blood pressure measurements.** The ankle systolic pressures in the dorsal pedal and posterior tibial arteries at the level of the ankle were measured using an 8-MHz Doppler probe and a cuff (12 cm) around the lower leg just above the ankle. The highest pressure was considered to represent the highest perfusion pressure. The ABI was calculated by dividing the ankle pressures by the highest of the left and right brachial blood pressure, measured by means of an automatic blood pressure monitor (Criticon, Dinamap Plus, Tampa, Fla) and expressed as a percentage.

For the toe blood pressure, a cuff with a width depending on the diameter of the hallux (1.5, 2.5, or 3.3 cm disposable cuffs, Hokanson, Bellevue, Wash) was wrapped around the base of the toe. The cuff width closest to 120% of the diameter of the hallux was chosen.26 The PPG and two standard LD probes (PF 408, Perimed, Järflå, Sweden) connected to the LD instrument (Periflux 4001, Perimed) were attached to the apex of the big toe (PPG at the center and LD probes at both sites of the PPG) with double-sided adhesion tape with a notch for the probe (Double-Stick Discs, 3M Health Care, Borken, Germany) and a probe holder (PF 104, Perimed) for the LD probes (Fig 1). The probe holder is a small plastic holder (diameter, 15 mm) in which the LD probe fits exactly and in which the tip of the probe is just above the skin (approximately 0.1 mm Hg). The exact distance from the skin is achieved without compressing the skin by means of the probe holder and adhesive tape.

Our conventional instrument to measure peripheral pressures (PV-lab, Stöpler, EDI, Burbank, Calif) was modified so that the cuff pressure, PPG, and LD signals could be sampled on-line and analyzed off-line by means of a data acquisition system (AcqKnowledge III and MP 100WSW, Biopac System, Inc, Santa Barbara, Calif). The cuff was rapidly inflated up to a pressure at least 30 mm Hg higher than that at which the pulsations in the PPG and LD0.03 signal disappeared. Initially, the LD showed an increase in flux after which the signal declined to the baseline (Fig 1). After the LD signal had reached a stable baseline (after approximately 3 seconds), the cuff was slowly deflated with a speed of approximately 3 mm Hg/s. The systolic pressure was defined as the pressure at which the (pulsatile) signal reappeared or rose gradually from the baseline (Fig 1).

One single measurement of the toe blood pressure (with all three probes at the same time) was performed each session. The measurements were repeated after 1 week to establish the 1-week intraobserver
reproducibility. All measurements and analyses were performed by one investigator (JdG), while previous results were ignored as much as possible.

**Statistical analysis.** The differences between PPG versus LD$_3$ and PPG versus LD$_{0.03}$ pressures were evaluated by the Student $t$ test for paired samples. Because we do not know the true pressure, the average of the LD$_3$ and PPG and the average of LD$_{0.03}$ and PPG were considered to be the best estimates of the true pressures. The differences between LD and PPG were also calculated with limits of agreement and intraclass correlation coefficients (ICCs). The limits of agreement were defined as the mean difference $\pm$ 2 SD of the difference, according to Bland and Altman.$^{27,28}$ These limits reflect the interval in which 95% of the differences in pressures lie. A plot was made of the difference between the two measurements against their mean to check whether the measurement error was independent of the magnitude of pressure. The regression lines (with $\beta$ coefficient, indicating the direction of the deviation and its $P$ value) indicate whether the variability in the pressures is independent of the magnitude of the pressures. The ICC (two-way random effects model) was calculated according to the method as described by Deyo et al.$^{29}$ The ICC not only assesses the strength of linear correlation between two measurements, such as the Pearson correlation, but also detects systematic error.$^{30}$ Thus, if one measurement is systematically higher or lower than the other, the ICC is correspondingly reduced. The same methods were used to assess the 1-week intraobserver reproducibility and the comparison between LD$_3$ and LD$_{0.03}$.

**RESULTS**

The pressure could not be measured with PPG in 19 toes because no pulsatile signal could be detected (taken as 0 mm Hg), whereas all of these toe pressures could be measured with LD$_3$ (mean, 24 ± 14 mm Hg; range, 8–64 mm Hg; number of pressures $\geq$ 30, 5), and 17 of these with LD$_{0.03}$ (mean, 21 ± 12 mm Hg; range, 0–48 mm Hg; number of pressures $\geq$ 30, 5). Of these patients, one presented with intermittent claudication, 11 with rest pain, and 7 with ulcers or gangrene. The mean ankle pressure (AP) and ABI were 64 ± 32 mm Hg (range 0–1 40 mm Hg) and 41% ± 21% (range, 0%-104%), respectively. The incidence of diabetes mellitus among these patients did not differ significantly from the total patient group (39% vs 36%, respectively). Strikingly, in all but one limb, no peripheral pulsations could be palpated. The pressure of 64

![Image of Fig 4](image-url)
mm Hg, undetected by means of PPG but detected by LD, was found in a patient with CREST syndrome with severe microangiopathy without severe arterial occlusions.

Application to the toe of the LD probe using the probe holders was very simple. Except for one very short big toe, the two LD probes could be applied next to the PPG probe on the big toe in all patients investigated. The LD reading was quite stable and less influenced by movement artifacts than the PPG signal. The signal-noise ratio was found to be considerably lower with the LD than with the PPG signals. The blood pressures per patient subgroup are presented in Table II.

**PPG versus LD.** Histograms depicting the differences between PPG and LD pressures showed a normal distribution (graphs not shown). Table III presents the mean difference, the SD of the differences, the limits of agreements, and the ICC between PPG pressure and LD pressure. The mean differences were small and statistically not significant. The ICCs showed almost perfect agreement (≥ 0.95) between the PPG pressure and LD pressure (Table III).

In Fig 2 the differences between PPG and LD pressures are plotted against the mean of both measurements. The regression lines in both figures indicate that the variability in the pressure scores showed a small relation with only the magnitude of the LD3 pressure values (β coefficient Fig 2, A = .15, P = .14; β coefficient Fig 2, B = .28, P < .01). There was no significant difference between LD3 and LD0.03 (Table III; β coefficient Fig 3 = .05, P = .6).

**Reproducibility.** For the analysis of the reproducibility, only 86 legs were eligible because the other patients were treated within that week. There was a small but significantly lower brachial, toe, and ankle pressure measured after 1 week, whereas the ABI remained stable during the 1-week time interval (Table IV). The ICCs indicate a substantial reproducibility for all three methods (≥ 0.85). In Fig 4 the differences between the first and the second PPG and LD pressures are plotted against the mean of the first and second measurement. The error of the measurement was found to be independent of the magnitude of the pressure values (β coefficient Fig 4, A = .1, P = .42; β coefficient Fig 4, B = .15, P = .12; β coefficient Fig 4, C = .05, P = .67).

**DISCUSSION**

This study shows that LD is a reliable and clinically useful technique for the measurement of systolic toe blood pressures. Moreover, LD is more responsive in detecting the reappearance of skin flow at very low perfusion pressures than PPG in the AC mode.

Andersson et al already showed that LD seems to be more sensitive than the strain gauge method in the low-pressure range for measuring blood pressures. Although also critically reduced pressures could be measured with PPG (in our study as low as 15 mm Hg), this study showed that LD was able to measure toe blood pressures in 19 toes, which the PPG in the AC mode could not; these pressures varied between 6 and 64 mm Hg. This pressure range is important, because it is around the cutoff value for critical leg ischemia as proposed by the European Consensus (30 mm Hg). This means that the decision for invasive therapy could be influenced by the method used. A low value (e.g., 0 mm Hg) would suggest that invasive treatment is required, whereas a higher value would advocate initial conservative therapy.

The LD technique appears to be most valuable in the absence of peripheral pulsations, and in patients with low ankle and toe pressures. On theoretical grounds, LD is probably more sensitive than PPG because LD is based on the registration of a frequency shift (Doppler effect) of red light by the moving erythrocytes, whereas PPG is based on a dif-
ference in the amount of reflected light by the absorption of near infrared light by the presence of erythrocytes in the underlying tissue. Thus, LD is able to detect very small blood displacements and is very sensitive in detecting the resumption of microcirculatory blood flow in the toe, as opposed to the more crude detection of blood filling by PPG. Therefore, we believe that LD has an advantage over PPG in establishing critical limb ischemia because the absence of PPG pulsatility, which has even been suggested to predict wound healing, does not have to be concomitant with a critically reduced perfusion pressure. On the other hand, LD has not been compared with the PPG in the DC mode, which is the most accurate method of detecting toe blood pressure using PPG. But the DC mode appears to be commonly used less frequently, probably because this mode is very sensitive to movement artifacts and the toe has to be exsanguinated before inflation of the cuff. Moreover, LD has advantages over the PPG in DC mode, because the LD is hardly influenced by movement artifacts and exsanguination of the toe is not required.

Another advantage of LD is that the LD probe can easily be applied to short digits, especially when much smaller probes (5 mm) or the transparent probe holder as described by Beinder et al are used. Thus, in practice even digit II, III, or IV might be used for toe blood pressure measurements, when the big toe is not available because of ulcerations or after amputation. Furthermore, toe pressures measured with LD are found to be as reproducible as pressures measured with PPG. The coefficients of repeatability are in agreement with other techniques such as strain gauge plethysmography.

On the other hand, the disadvantage of the LD method is that three devices (LD, cuff inflator, and data acquisition system) are needed instead of one, because the LD instrument is not routinely integrated in the peripheral vascular equipment, which increases the costs. A data acquisition system may not be required, but in our experience, the first pulsations are often missed during on-line determination with our conventional laboratory instrument (resulting in a lower pressure), whereas this will not occur when the analysis is performed off-line.

The filter time for the LD signal did not seem to influence the results of the pressure measurement, although the longer time constant (LD3) tends to be more sensitive. Both filter settings methods (LD3 and LD0.03) yield comparative results as to PPG, and the agreement between both methods and PPG is almost perfect (ICC > 0.95). The faster mode (LD0.03) is easier with pulsatile flux at higher pressures, and the more DC (plethysmographic) mode (LD3) is preferred to detect flux increase from baseline at lower pressures not showing any pulsatile flux. A further improvement of the LD and PPG techniques might be the use of heated probes or the application of local heat, because the hyperemia increases the total skin perfusion, which pronounces reappearance of the skin perfusion.

Analysis of the reproducibility indicates that all three methods are comparable and reproducible (ICC > 0.85). Insight in the reproducibility of a technique, especially the limits of agreement, is important when interpreting the results of measurements of the same person within time (eg, in the evaluation of therapy or progress of a disease). The limits of agreement of the ABI are somewhat above 0.2, which is in agreement with the results of Fisher et al but is more than the 0.15, which is generally reported. This somewhat larger variation is mainly caused by the way of calculating the variability. The significantly lower ankle pressure is due to a lower systemic pressure after 1 week, probably because of reassurance of the patient during the second measurement, which is represented by a lower brachial pressure after 1 week.

In conclusion, LD is a responsive and reliable instrument to measure toe blood pressure as compared with routinely used techniques. We recommend the use of LD in situations in which no signal can be detected with PPG and a decision is required as to the presence of critical leg ischemia.

REFERENCES

15. Lassen NA, Tvedegaard E, Jeppesen FI, Nielsen PE, Bell, Gundersen J. Distal blood pressure measurement in occlusive arterial disease, strain gauge compared to Xenon-133. Angiology 1972;23:211-7.

Submitted Dec 17, 1999; accepted Mar 14, 2000.