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Clinical Research

Plantar Acceleration Time: A Novel Technique to Evaluate Arterial Flow to the Foot

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Background: Arterial duplex ultrasound (DUS) and ankle-brachial indices (ABIs) are accepted methods for assessing lower limb arterial perfusion. However, in a significant number of diabetic patients, medial wall calcification often precludes an ABI measurement. Direct, noninvasive duplex imaging of the pedal arch in the setting of peripheral arterial disease (PAD) has not been well evaluated. Although plantar arch interrogation is new to vascular ultrasound, imaging the plantar arteries appears to be a reliable angiographic technique for critical limb ischemia. We sought to define the utility of Plantar Acceleration Time as a surrogate for ABIs.
Methods: Patients undergoing DUS including Plantar Acceleration Time for suspicion of PAD were retrospectively reviewed in a prospective database over a 1-year period. Two hundred fifty nondiabetic patients (499 limbs) with documented ABI were studied. Plantar Acceleration Time was calculated (milliseconds [msec]) in each limb in the lateral plantar artery. Statistical analyses were performed using linear regression and analysis of variance testing using Microsoft Excel database (version 2016; Microsoft Corp, Redmond, WA). Patients were then grouped into 4 classes based on their clinical symptoms and ABI. Plantar Acceleration Time was similarly grouped into 4 distinct classes and correlated with the clinical and ABI classes.
Results: Plantar Acceleration Time correlated significantly with ABI ($P < 0.001$). There were significant differences in Plantar Acceleration Times between each class based on ABI and clinical presentation ($P < 0.001$ for each): Class 1 Plantar Acceleration Times 89.9 ± 15.5 msec; Class 2, 152.3 ± 28.4 msec; Class 3, 209.8 ± 25.5 msec, and Class 4, 270.2 ± 35.3 msec.
Conclusions: Plantar Acceleration Time demonstrates a high correlation with ABI in patients with compressible arteries. Based on our results we propose the following categories of Plantar Acceleration Time, which appear to correlate with both clinical and ABI findings. ABI of 0.90−1.3 correlates with a Plantar Acceleration Time of 0−120 msec, ABI of 0.69−0.89 correlates with a Plantar Acceleration Time of 121−180 msec, ABI of 0.40−0.68 correlates with a Plantar Acceleration Time of 181−224 msec, and an ABI of 0.00−0.39 correlates with a Plantar Acceleration Time of greater than 225 msec. Further studies are ongoing to confirm whether Plantar Acceleration Time may be a suitable substitute to ABIs in patients with noncompressible arteries that preclude meaningful ABIs and gives more information regarding targeted angiosome perfusion to the foot.

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INTRODUCTION

Currently, arterial duplex ultrasound (DUS) and ankle-brachial indices (ABIs) are accepted methods for assessing lower extremity perfusion. DUS has good correlation with conventional angiography, although the correlation is more precise in the suprageniculate region.[1] ABI is the most common initial screening test but does not assess perfusion

in the foot, and in noncompressible arteries, cannot be calculated or reliable.[2] This has led investigators to search for more physiologic, reliable measurements of lower extremity perfusion and flow to the foot.[3,4] Based on the angiosome concept, the importance of regional flow in the foot, rather than simply perfusion to the ankle level, has implications with respect to interventions.[5–7] It has been argued that methods which can clearly define perfusion and direction of flow in the angiosomes of the foot may help plan and improve limb salvage in critical limb ischemia (CLI) patients.[5] The importance of understanding angiosome foot perfusion to plan interventions has led our group to closely study plantar arterial flow to the foot.

We wished to first determine if we could correlate ABI with Plantar Acceleration Time in patients across the spectrum of clinical categories. We chose to use the lateral plantar artery because in our experience, this artery is typically dominant and easily visualized using duplex imaging. Our hope is that Plantar Acceleration Time may be a useful tool to measure perfusion in patients with noncompressible ABI. In addition, Plantar Acceleration Time may be a more precise measurement of regional foot perfusion which could provide useful information for interventions and follow-up. Furthermore, in patients with CLI, Plantar Acceleration Time may serve as prognostic indicator for wound healing similar to angiosome concept previously described in tibial anatomy.[7]

METHODS

A 1-year retrospective chart review of a prospectively maintained database was queried. All studies were performed at PeaceHealth Thoracic and Vascular Surgery in our Intersocietal Accredited Commission Vascular Laboratory by Registered Vascular Technologists. Each technologist had performed 20 supervised examinations prior to performing the studies independently, which based on our experience is the training volume which allows for reproducible and reliable plantar artery duplex imaging and proper measurement of Plantar Acceleration Time.

Nondiabetic patients with documented ABI and Plantar Acceleration Time were evaluated. Patients with prior revascularization procedures were excluded. Each limb was considered unique for the purpose of analysis.

To obtain ABIs, a Hokanson 10-cm blood pressure cuff was used for the ankle pressures and a 12-cm blood pressure cuff was used for the arm pressures. A Philips 5 MHz continuous wave Doppler probe was used to obtain bilateral ankle and arm pressures. The highest calculated ABI was used to correlate with Plantar Acceleration Time. Although there are variations in the arterial anatomy of the foot, in general the distal posterior tibial artery bifurcates below the medial malleolus and gives rise to the medial plantar artery and the lateral plantar artery.[8–10] The lateral plantar artery gives rise to the deep plantar and plantar metatarsal artery. The anterior tibial artery becomes the dorsalis pedis artery on the dorsal aspect of the foot and gives rise to the arcuate artery and dorsal metatarsal artery (Figs. 1 and 2).

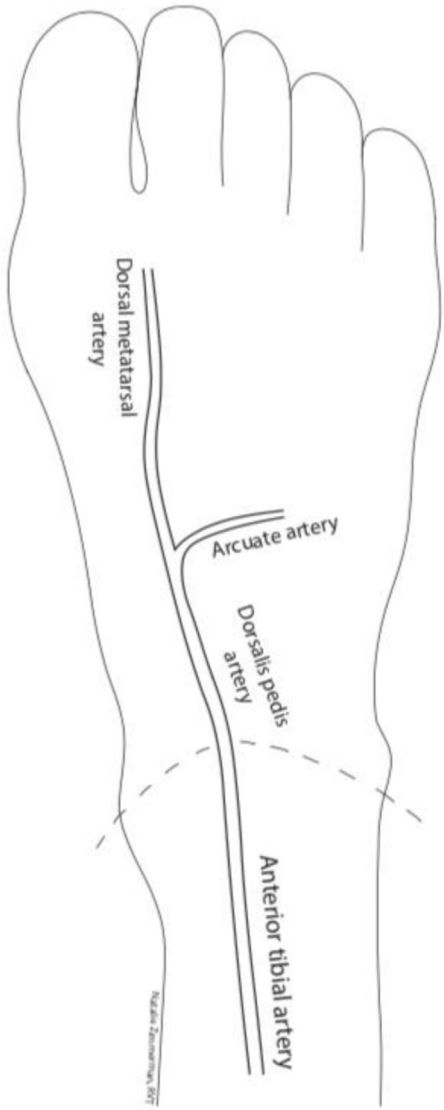

Fig. 1. Dorsal ultrasound anatomy of pedal arteries.

Duplex imaging of the plantar arteries was performed using a Philips EPIQ 5 DUS system

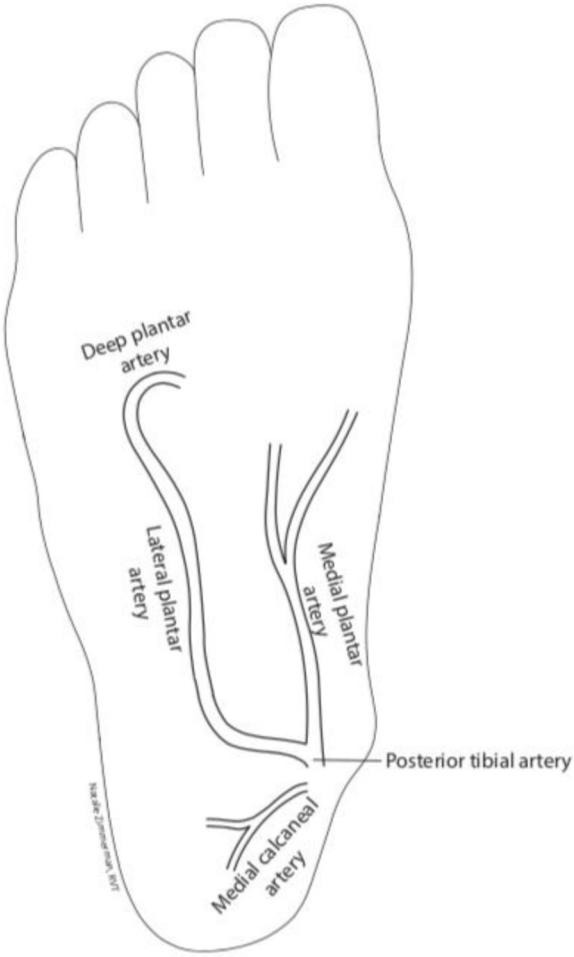

Fig. 2. Plantar ultrasound anatomy of pedal arteries.

Fig. 3. Plantar artery probe position.

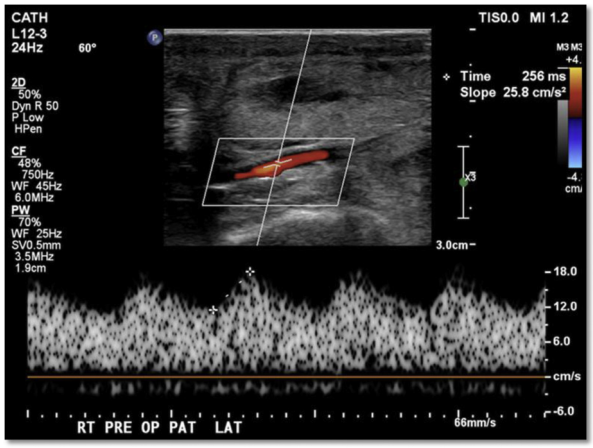

Fig. 4. Plantar Acceleration Time measurement.

(Philips Healthcare, Andover, MA). A linear array transducer with pulsed Doppler frequencies between 3 and 12 MHz was used to measure Plantar Acceleration Time. In long axis (indicator on the probe to the patient's heel), the lateral plantar artery (Figs. 3 and 4) is followed from the posterior tibial artery bifurcation of the medial and lateral planter arteries to the mid plantar aspect of the foot. Color Doppler is applied to the mid lateral plantar artery with a decrease in the color scale. An increase in color gain is applied to fill the artery appropriately. The color box is adjusted in the proper direction. The Doppler sample volume is applied at the center of the artery and can be obtained at 60° or less. Once the spectral waveform is live, the Doppler waveform must fill three-fourth of the spectral window with the sweep speed set at medium. The spectral gain should be appropriate to adequately visualize the waveform contour. Once the waveform is frozen, Plantar Acceleration Time is precisely measured, as time in milliseconds (msec), from the start of the systolic up-rise to the peak of systole (Fig. 5). A useful landmark for the measurement of the lateral plantar artery is to visualize the lateral plantar veins (Fig. 6).

Limbs were then categorized by clinical presentation into 4 classes: normal, mild claudication, severe claudication, and CLI. CLI was defined as ischemic rest pain, gangrene, or nonhealing ischemic ulcers.[11] The clinical presentation was then correlated with ABI (Table I).

Linear regression was used to correlate Plantar Acceleration Time and ABI. Based on these results, the data were separated into 4 classes. A one-way analysis of variance (ANOVA) test and Tukey's post hoc test were conducted to determine if and

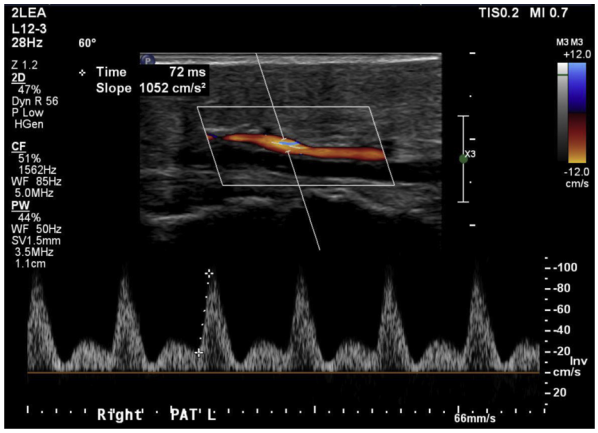

Fig. 5. The start of the systolic up-rise to the peak of the systole was measured by tracing the waveform contour to obtain an acceleration time.

where significant differences in the mean between the 4 groups existed. Ninety-five percent confidence intervals of the means of the 4 groups were also calculated. Significance was determined using $P = 0.05$. Statistical analysis was conducted in R version 3.5.0 with plots created in Excel.

Demographic data were obtained by review of our vascular registry and electronic medical record (EPIC 2015), and included tobacco use, coronary artery disease, hypertension, and renal disease. Consent of the patient was waived, and the study was approved by the Institutional Review Board of PeaceHealth.

RESULTS

Two hundred fifty patients (499 limbs) were studied. We were able to visualize the lateral plantar arteries of all limbs studied. Patients had typical comorbid conditions, without documented diabetes (Table II). Indications are listed in Table III. Patients with venous wounds did not have evidence of arterial insufficiency, but the studies were requested by the wound center, and this population served as clinical Class 1.

The lateral plantar artery acceleration time showed significant linear correlation with ABI (Fig. 7) ($P < 0.001$). Subset analysis showed significant difference in Plantar Acceleration Time among clinical and ABI classes, both within groups and as a continuum ($P < 0.001$ by ANOVA and between each group) (Fig. 8, Table IV). The one-way ANOVA test was significant ($P < 0.001$) indicating that there exists a difference in the mean Plantar Acceleration Time of the 4 classes. Tukey's post hoc test was significant between all

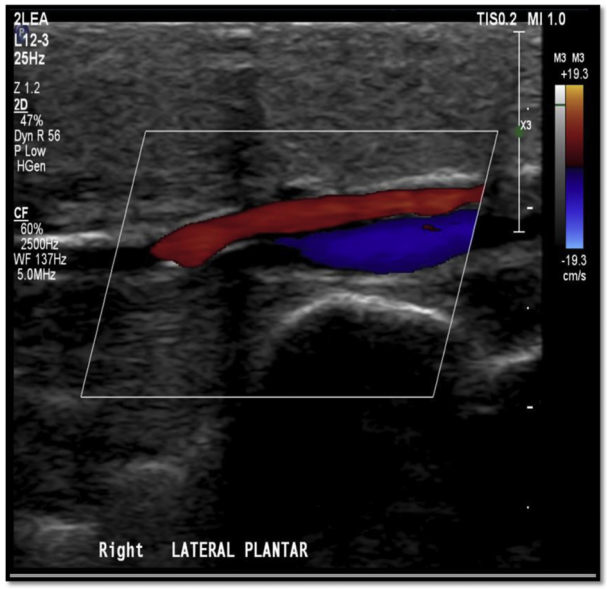

Fig. 6. Lateral plantar artery visualized by the plantar vein.

subsets tested ($P < 0.001$ for all comparisons). The measured Plantar Acceleration Times fit well with our presumptive classification (Table IV).

DISCUSSION

ABI is an accepted initial screening test to assess lower extremity vascular perfusion, and DUS provides complementary information, which in most cases is equivalent to angiograms. However, in patients with noncompressible tibial vessels and/or difficult to visualize infrageniculate arteries, these tests are not a reliable indicator of perfusion in the foot.[1–4]

The angiosome concept was introduced by Taylor and Palmer[12] as a way of understanding the shared and collateral perfusion to different regions of the body. Attinger et al. applied this concept to the foot, describing 6 distinct regions fed by the 3 infrageniculate arteries. They proposed that understanding the perfusion and direction of flow, based on direct arterial supply to the region of interest, would have significant impact in predicting wound healing, the target for intervention, and/or the success of any interventions.[5]

However, other studies have shown that collateral flow to the foot may be adequate for wound healing in the absence of directed angiosome revascularization.[13,14]

This has led to debate about whether direct or indirect revascularization is equally effective.[7,8,15] Not taken into account in these published reports

Table I. ABI and clinical classification

Value	Class I	Class II	Class III	Class IV
ABI	1.3−0.90	0.89−0.69	0.68−0.40	0.39-0.00
Clinical presentation	Normal	Mild claudication	Severe claudication	CLI: rest pain, tissue loss

Ankle-brachial index	Value
Normal	1.2 and 0.9 Greater than 1.3 suggests noncompressibility
Moderate arterial insufficiency	0.89−0.50
Severe arterial insufficiency	0.49−0.30

Table II. Incidence of comorbid conditions in 250 patients

Variable	Percent
Mean age	71.2 ± 8.4
Male	62%
Female	38%
Tobacco use	47%
Coronary artery disease	16%
Hypertension	54%
Hyperlipidemia	54%
Renal disease	1%

Table III. Clinical presentation

Presentation	Percent
Venous wound	40%
Claudication	44%
Rest pain	6%
Nonhealing ischemic ulcers	8%

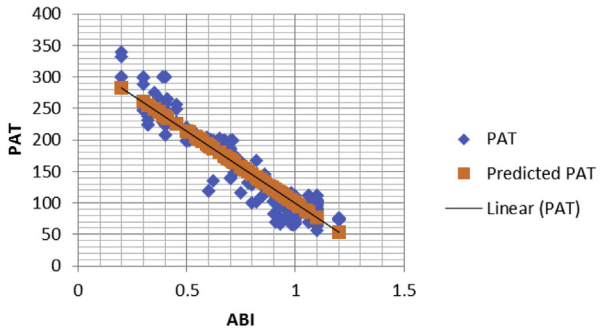

Fig. 7. Correlation of lateral plantar artery PAT with ABI ($P < 0.001$). PAT, Plantar Acceleration Time.

may be variations in anatomy, as well as numerous collaterals. In addition, particularly in patients with diabetes, these collaterals may or may not be sufficiently patent to provide adequate perfusion.[6,7,11,13−15]

Numerous methods have been described to accurately assess angiosome perfusion of the foot, both before and after intervention. These are relatively complicated and involve various forms of angiographic or nuclear studies.[4,8,15,16] Computed tomography angiography has also been felt to have limited accuracy with calcified infrageniculate arteries.[4]

DUS techniques offer a simple, noninvasive approach which can be done rapidly, at the bedside, and other locations such as operative theater or angiography suites. It also allows direct real-time visualization of the arteries and perfusion characteristics in the foot.

In theory, acceleration time can quantify the severity of disease based on how fast or slow the red blood cells are traveling. Acceleration Time has been used in other anatomic beds such as carotid arteries.[17]

This study showed that Plantar Acceleration Time is highly correlated with ABI in patients with measurable tibial pressures.

Anecdotally, we have recorded patients with single vessel runoff via the peroneal artery with intact anterior and posterior communicating arteries filling the hibernating distal Anterior Tibial Artery. Thereby, preserving perfusion to the foot base on Plantar Acceleration Time. Thus, may explain the works reported by Rico et al.[14] Plantar Acceleration Time may give more information to the angiosome concept. Direct visualization and mapping of the lateral plantar artery, medial plantar artery, deep plantar artery, and arcuate artery may

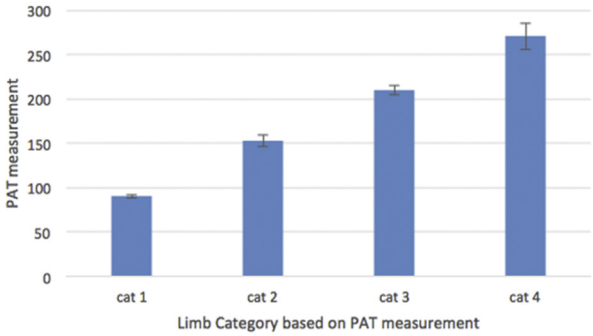

Fig. 8. Comparison of Plantar Acceleration Time with clinical and ABI classification. One-way analysis of variance test was significant ($P < 0.001$) indicating that there exists a difference in the mean Plantar Acceleration Time of the 4 classes. PAT, Plantar Acceleration Time.

Table IV. Plantar Acceleration Time classification

	Class 1	Class 2	Class 3	Class 4
PAT	89.9 ± 15.5 msec	152.3 ± 28.4 msec	209.8 ± 28.4 msec	270.2 ± 35.3 msec

PAT, Plantar Acceleration Time.

potentially aid in the prediction of wound healing based on the location of the wound.

There is paucity of literature about direct duplex imaging of the pedal arteries. This study is limited in that it is retrospective and there were a much smaller number of limbs in the category 4 patients. In addition, DUS is operator dependent and the quality and experience may vary. As such, there are potential for various results across centers. Plantar Acceleration Time may also be erroneous in patients with isolated aortoiliac disease with blunted distal flow.

Although this study reported visualization of the lateral plantar arteries, there are anatomic variations that may preclude visualization of all pedal arteries such as those with CLI and minimal flow. With experience, other pedal arteries can be easily identified using anatomical landmarks. Obtaining the Pedal Acceleration Time in the arcuate artery, medial plantar artery, and deep plantar arteries can be useful when the lateral plantar artery is not identified.

This is the first series to compare Plantar Acceleration Time to ABI across the spectrum of peripheral arterial disease (PAD) limbs. We have demonstrated that Plantar Acceleration Time correlates with ABI. Furthermore, there are significant differences between clinical categories based on Plantar Acceleration Time. We recommend that Plantar Acceleration Time categories be established as an additional data point to ABIs. Plantar Acceleration Time may be an appropriate test to use in patients with noncompressible ABIs.

CONCLUSION

It is widely understood and agreed upon in the vascular community that a better, more reliable initial technique is needed in evaluating patients with PAD and more so with the diabetic limbs. This is the first of many studies to evaluate and quantify flow in the plantar arteries in patients with PAD. In this study, we have established that Plantar Acceleration Time is reliable in patients with compressible arteries when compared to ABI. We have also established that Plantar Acceleration Time is a reliable, unique, and a novel technique that could potentially be applied to the diabetic patients when ABI and/or TBI is not obtainable. We can quantify and breakdown the time (milliseconds) to establish the significance of arterial disease. A Plantar Acceleration Time less than 120 msec is considered normal. A Plantar Acceleration Time of greater than 225 is considered severe and correlates with CLI. Currently, we are collecting data to correlate Plantar Acceleration Time in patients with diabetes and noncompressible tibial vessels with angiographic studies. More study is needed on this exciting new use of Plantar Acceleration Time.

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