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Original Article

Looking beyond conventional indices: Pedal acceleration time in the routine assessment of peripheral arterial disease

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Abstract

Aim: Peripheral arterial disease (PAD) is predisposed by many risk factors, including atherosclerosis, hypertension, diabetes, and smoking. Many clinical classifications, including the Fontaine classification, are used for the assessment of chronic ischemia. Ankle and Toe brachial indices are commonly used in clinical practice for staging of PAD. However, the Ankle Brachial Index (ABI) falls short in the assessment of patients with stiff vessels due to false negative results. Doppler ultrasound (DUS) is a highly sensitive imaging modality for the assessment and classification of lower limb ischemia, within which pedal artery acceleration time (PAT) represents an objective quantitative DUS technique. In this study, we evaluated PAT as a hemodynamic parameter for assessing lower limb ischemia, providing complementary sensitivity to existing clinical scoring classifications. The study aimed to assess the role of PAT in the evaluation of chronic lower limb ischemia.

Material and Methods: A cross-sectional study was conducted on 22 patients (44 limbs) diagnosed with peripheral vascular disease. Patients were classified according to the Fontaine clinical classification. ABI was measured when applicable, and DUS was performed to assess the lower limb arterial tree. PAT was measured in both the anterior circulation (arcuate and dorsalis pedis arteries) and the posterior circulation (medial and lateral plantar arteries). Appropriate statistical analyses were subsequently performed.

Results: Acceleration times of the medial and lateral plantar arteries were significantly prolonged in patients with higher Fontaine classifications, with statistically significant p values. Sensitivity analysis demonstrated that medial and lateral plantar artery acceleration times could reliably predict clinical stage IIB and higher, using a cutoff value of 0.075 s.

Conclusion: PAT is a reliable objective tool for assessing PAD, especially when ABI is not applicable, and can help distinguish mild from moderate-to-severe cases requiring more intensive management.

Keywords: Doppler ultrasound, fontaine classification, pedal acceleration time, peripheral arterial disease, sensitivity

INTRODUCTION

Peripheral arterial disease (PAD) is a circulatory problem that causes reduced blood flow to the extremities due to occlusion or stenosis [1]. The prevalence of peripheral arterial disease increases with age, with more than 10% of individuals in their sixth and seventh decades affected [2].

Many classifications are used for the assessment and hence management of chronic ischemia, including Rutherford and Fontaine classifications that are based on the symptomatology of the patients [3].

In order to identify PAD, a combination of clinical signs and symptoms, together with physiological testing, is commonly used. Commonly performed tests include the Ankle Brachial Index (ABI) and toe–brachial index (TBI) [4].

Doppler ultrasound (DUS) is based on the Doppler shift effect, first described by the Austrian mathematician and physicist Christian Andreas Doppler [5]. While ABI and TBI—both clinical applications of DUS—are widely used to assess lower

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limb ischemia severity, they may yield false-negative results in patients with stiff or noncompressible vessels, limiting their diagnostic accuracy [6] .

Other Doppler waveform characteristics, such as pulsatility index or systolic rise time measured more proximally, may not accurately reflect microvascular or distal perfusion in the foot, particularly in patients with arterial calcification. Doppler ultrasound is a cheap, available, radiation-free modality that is highly sensitive in the assessment of lower limb vasculature [7].

PAT is a novel ultrasound technique that is described in the literature and has demonstrated potential as an adjunctive vascular test. PAT uses readily available vascular ultrasound equipment to measure acceleration time within the foot [4].

PAT was evaluated in patients with chronic lower limb ischemia while considering the potential contribution of collateral circulation in addition to DUS morphological assessment of the lower limb arterial tree. As a hemodynamic parameter reflecting arterial inflow, PAT may provide complementary functional information beyond anatomical imaging. This may be particularly relevant in patients in whom conventional indices, such as ABI or TBI, are unreliable or unobtainable. Accordingly, this study aimed to assess the potential value of PAT as an adjunct hemodynamic parameter in the evaluation and objective assessment of chronic lower limb ischemia.

MATERIAL AND METHODS

A prospective cross-sectional analytical study was conducted between March 2023 and January 2024 on a cohort of patients referred to the radiology department with symptoms of lower limb peripheral arterial disease. All measurements were performed by experienced radiologists and ultrasound specialists/consultants, each with a minimum of seven years of duplex ultrasound experience, ensuring expertise and consistency in the measurements.

We included patients of both genders and a wide range of ages who presented with symptoms of lower limb PAD. Uncooperative patients, had severe systemic illness, refused to participate, or had total occlusion of all pedal arteries—representing a severe disease state in which PAT could not be measured—were excluded from the study.

History Taking and Clinical Examination

The medical history of the participants was carefully taken and comorbid conditions were identified. Cardiac patients were identified as patients with coronary artery disease (CAD) and congestive heart failure (CHF). Hypertensive (HTN) patients were identified as patients with chronically elevated blood pressure who are on regular anti-hypertensive medications. Patients with Behçet's disease of the lower limbs were also identified.

Clinical examination of the patients was done, and based on which initial clinical staging was identified for categorizing the participants according to Fontaine classification [4] into four clinical stages:

- Stage I – Asymptomatic.
- Stage IIa – Intermittent claudication after more than 200 m of walking.
- Stage IIb – Intermittent claudication after less than 200 m of walking.
- Stage III – Rest pain.
- Stage IV – Ischemic ulcers or gangrene.

ABI measurement

Resting ABI measurement was taken from all participants in the supine position after 10 minutes of rest by a digital sphygmomanometer. ABI was calculated as the product of the division of the systolic blood pressure of the examined lower limb by the highest systolic blood pressure of both upper limbs [4]. Measurements were classified as follows:

- Normal between 1-1.3
- Borderline 0.9-1
- Below normal < 0.9
- Noncompressible < 1.3
- Non-obtainable (no reading by the sphygmomanometer or patients with local limb conditions preventing ankle pressure measurement)

Ultrasound Protocol

The General Electric LOGIQ P9 ultrasound system was used. A linear array transducer between 3 and 12 MHz and a curved transducer between 1 and 5 MHz were occasionally used. A lower limb arterial duplex study was performed with the patient lying in the supine position.

Morphological Doppler ultrasound of the lower limb arterial tree was done to assess the degree of atherosclerosis. Any proximal stenoses were classified according to the degree of stenosis as "patent" for absence of stenotic segments, "non-hemodynamically significant stenosis", and "hemodynamically significant stenosis", and according to the morphological distribution along the arterial tree into aorto-iliac, femoro-popliteal, and infrapopliteal (including ATA, PTA, and tibio-peroneal trunk) stenoses. Using Spectral Doppler, peak acceleration time (measured in secs) was measured in the pedal arteries. Measurements were performed with a Doppler angle ≤ 60° and with optimal adjustments of gain, wall filter, and pulse repetition frequency to ensure accuracy.

Acceleration time (AT) was defined as the time slope between the onset of systole and the systolic peak. It is measured as the interval from the onset of systole to the peak of systolic flow. On

the Doppler waveform, this corresponds to the rising slope of the systolic peak. Measurement was obtained by placing the sample volume over the target artery and tracing the slope from the start of systole to the peak using standard spectral Doppler ultrasound, ensuring the gain and scale settings were optimized to clearly visualize the waveform (Figure 1).

The anterior circulation was represented by measuring the AT of the Arcuate and Dorsalis Pedis arteries, whereas the posterior circulation was represented by measuring the AT using the Medial and Lateral Plantar Arteries.

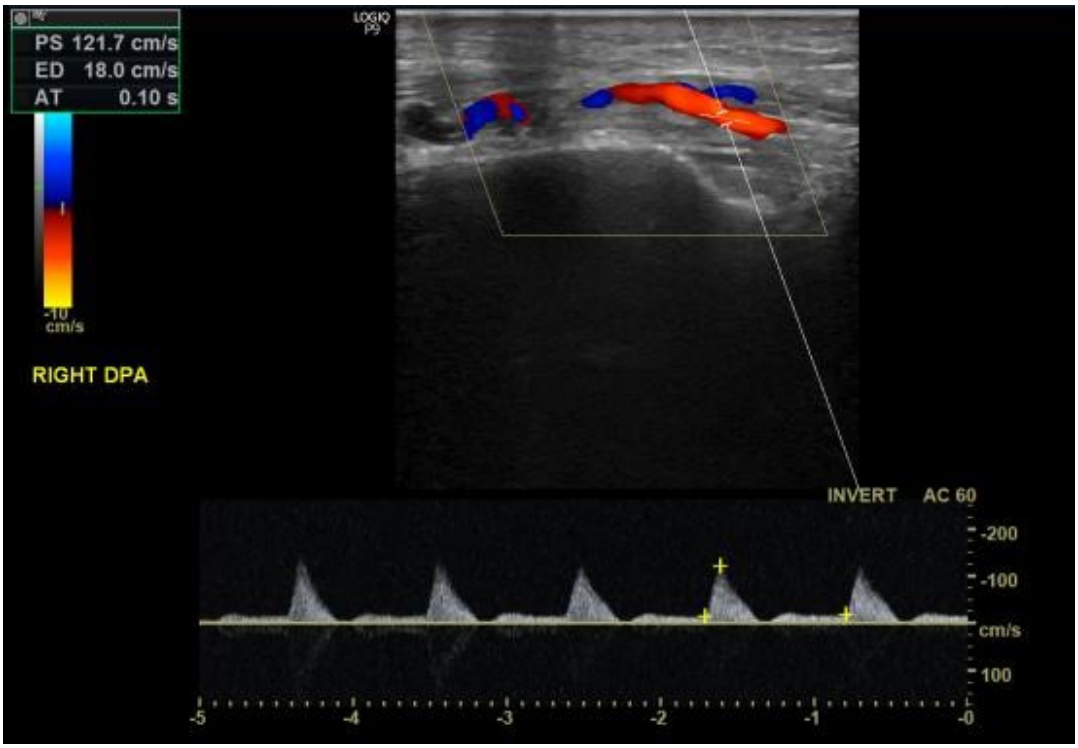

Figure 1. DUS examination of right DPA

Consent

Written and informed consent was obtained from the study participants.

Ethics Committee Approval

The study received ethical approval from the Research Ethics Committee of the Faculty of Medicine, Cairo University (Code: MS-186-2023) (Date: 29.07.2023).

Statistical Analysis

Statistical analysis was conducted using SPSS 27th edition, categorical variables were presented in count and percent, and compared using the Chi2 test. Quantitative variables were presented in mean, standard deviation, min, and max. It was compared using Mann Whiteny U test, and the correlation between two quantitative variables was conducted using spearman correlation test. Receiver operator characteristics (ROC) analysis was conducted to assess the cutoff for diagnosis of clinically significant classes of Fontaine classification along with sensitivity and specificity of this point and area under the curve (AUC). All tests are two-tailed and a p-value <0.05 was considered significant.

RESULTS

We conducted a cross-sectional study to evaluate the role of PAT in the assessment and grading of lower limb peripheral vascular disease.

We enrolled 22 patients (44 limbs) diagnosed with PAD leading to chronic lower limb ischemia. The mean age of the cohort was 60.9 ± 8.7 years (range: 46–82) (Table 1).

Gender distribution showed a male predominance, with 13 patients (60%) having a mean age of 58 years (range: 46–72). Female patients comprised 9 individuals, with a higher mean age of 64 years (range: 54–82) (Table 1).

Hypertension was the most common comorbidity reported among the included patients, accounting for 45.8%, followed by diabetes in 39.6%, Behçet's disease in 8.3%, and cardiac diseases in 4.2% of the included patients. Among the study population, smoking was reported by (56.3%) patients (Table 1).

Table 1. Age and co-morbid conditions distribution of the included patients

Baseline characteristics	Mean ± SD	Min-Max
Age in years	60.9 ± 8.7	46-82
	Count	**%**
Gender distribution		
Male	13	60.4%
Female	9	39.6%
DM		
No	13	60.4%
Yes	9	39.6%
HTN		
No	12	54.2%
Yes	10	45.8%
Smoking		
No	10	43.8%
Yes	12	56.3%
Other		
Behçet's disease	2	8.3%
Cardiac diseases	1	4.2%

Clinical classification of the included limbs is summarized in (Figure 2). Among the 44 limbs (22 patients), Fontaine stage I was observed in 16 limbs (35.4%), followed by stage IIA in 13 limbs (29.2%), stage IIB in 12 limbs (27.1%), stage III in 2 limbs (4.2%), and stage IV in 2 limbs (4.2%) (Figure 2).

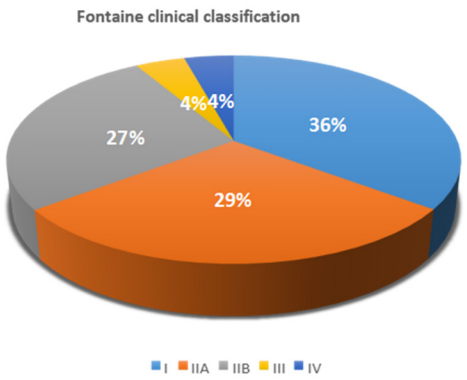

Figure 2. Distribution of Fontaine classification between studied patients

Assessment of the ABI demonstrated a mean value of 1.2 ± 0.2, calculated only for limbs with obtainable ABI measurements. ABI values were normal (1.0–1.3) in 18 limbs (42%), noncompressible (>1.3) in 8 limbs (19%), and ischemic (<0.9) in 2 limbs (4%). ABI measurements were non-obtainable in 16 limbs (35%), and these limbs were excluded from the calculation of the mean ABI (Figure 3).

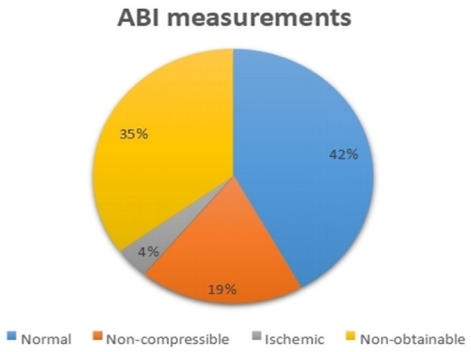

Figure 3. Distribution of ankle–brachial index (ABI) measurements in the examined limbs

The DUS assessment of the lower limb arterial tree showed that aortoiliac stenosis was found in two limbs, while femoropopliteal stenosis was found in six limbs, iliofemoral stenosis was found in eight limbs, ATA stenosis was found in eight limbs, PTA stenosis in three limbs and tibioperoneal trunk stenosis in one limb (Figure 4).

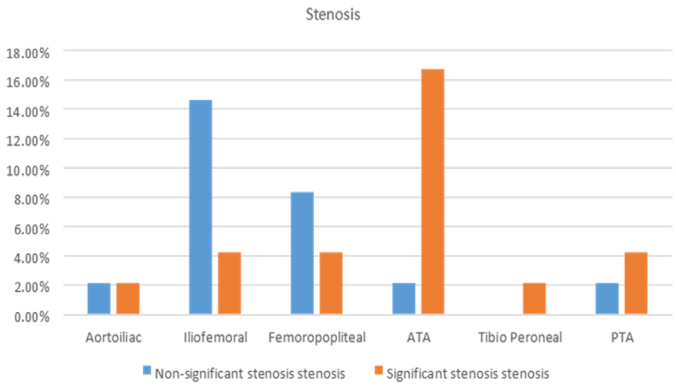

Figure 4. Degree of vessels stenosis among studied patients

Acceleration times were assessed in the pedal arteries. The anterior circulation, represented by arcuate and dorsalis pedis (DPA) arteries, and the posterior circulation, represented by the medial and lateral plantar arteries, showed a mean of 0.1 ± 0.04 sec, 0.08 ± 0.04 sec, 0.09 ± 0.05 sec, and 0.09 ± 0.05 sec in DPA, Arcuate, Medial, and Lateral Plantar arteries, respectively (Table 2).

Table 2. Acceleration times (AT) in assessed pedal arteries

Artery (AT site)	Mean ± SD	Min-Max
DPA-AT	0.1 ± 0.04	0-0.2
Arcuate-AT	0.08 ± 0.04	0-0.23
Medial plantar-AT	0.09 ± 0.05	0-0.21
Lateral Plantar-AT	0.09 ± 0.05	0-0.25

When patients were stratified according to the Fontaine classification into early stages (I–IIA) and advanced stages (IIB–IV), no statistically significant difference was observed in the Ankle–Brachial Index values between the two groups (p = 0.757) (Table 3).

Duplex ultrasound assessment of the arterial segments demonstrated no significant association between disease severity and stenosis at the aortoiliac (p = 0.304), femoropopliteal (p = 0.141), tibio-peroneal trunk (p = 0.454), or posterior tibial artery segments (p = 0.054). A borderline association was observed at the iliofemoral level (p = 0.050). In contrast, stenosis of the Anterior tibial artery was significantly associated with more advanced Fontaine stages (p = 0.003), with a markedly higher prevalence of significant stenosis among patients in stages IIB–IV (Table 3).

Patients with a higher Fontaine class had significantly longer medial and lateral plantar acceleration times (p = 0.005 and 0.012, respectively) (Figure 5, Figure 6, and Table 4).

Table 3. Comparison of the degree of lower extremity arterial stenosis and the ABI between patients with early (I–IIA) and advanced (IIB–IV) stages according to the fontaine classification

Predictor	Fontaine classification				P value
	Stage I, IIA		Stage IIB, III, IV		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	
ABI	1.18 ± 0.17	0.8-1.5	1.22 ± 0.21	1-1.5	0.757
	Count	**%**	**Count**	**%**	**P value**
Aortoiliac					
No stenosis/patent	30	96.8	16	94.1	0.304
Non-significant stenosis	0	0.0	1	5.9	
Significant stenosis	1	3.2	0	0.0	
Iliofemoral					
No stenosis/patent	28	90.3	11	64.7	0.050
Non-significant stenosis	3	9.7	4	23.5	
Significant stenosis	0	0.0	2	11.8	
Femoropopliteal					
No stenosis/patent	28	90.3	14	82.4	0.141
Non-significant stenosis	3	9.7	1	5.9	
Significant stenosis	0	0.0	2	11.8	
ATA					
No stenosis/patent	29	93.5	10	58.8	0.003
Non-significant stenosis	1	3.2	0	0.0	
Significant stenosis	1	3.2	7	41.2	
Tibio peroneal					
No stenosis/patent	30	96.8	17	100.0	0.454
Non-significant stenosis	0	0.0	0	0.0	
Significant stenosis	1	3.2	0	0.0	
PTA					
No stenosis/patent	31	100.0	14	82.4	0.054
Non-significant stenosis	0	0.0	1	5.9	
Significant stenosis	0	0.0	2	11.8	

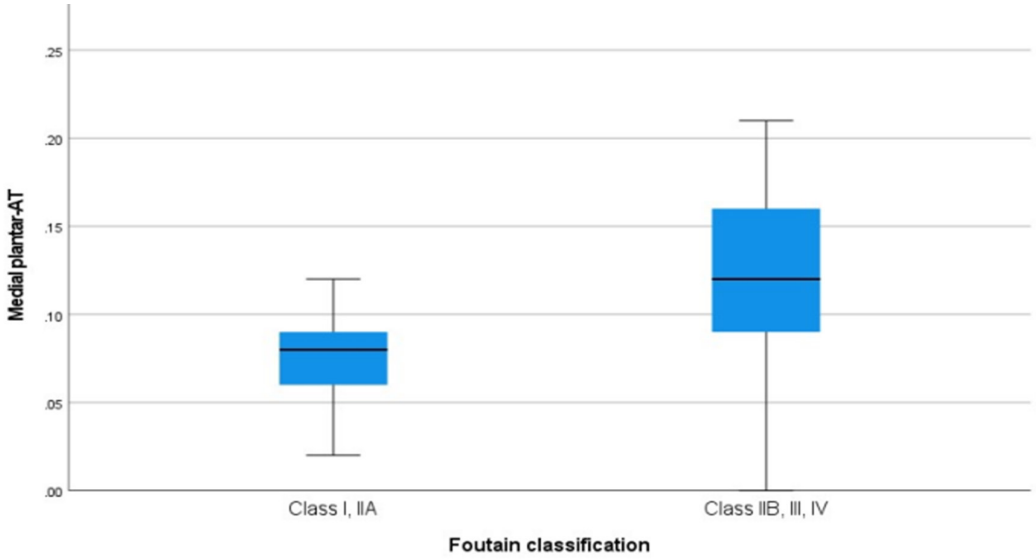

Figure 5. Medial plantar vessels acceleration time according to severity of Fontaine class

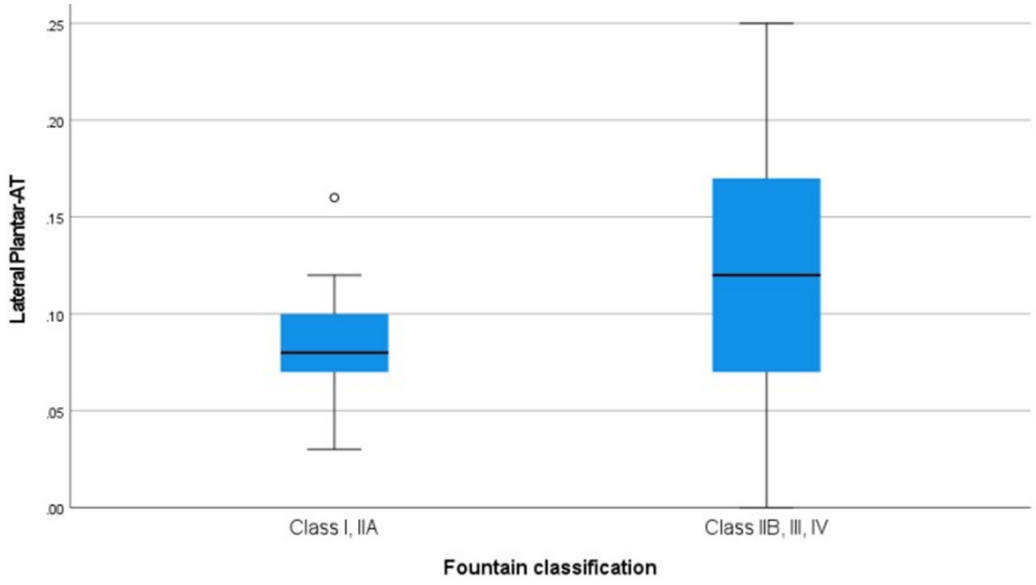

Figure 6. Lateral plantar vessels acceleration time according to severity of Fontaine class

Table 4. Comparison of mean acceleration time (AT) of pedal arteries in patients with Fontaine I–IIA and fontaine IIB–III–IV PAD classes

Mean AT of the pedal arteries	Fontaine classification				P value
	Class I, IIA		Class IIB, III, IV		
	Mean ± SD	Min-Max	Mean ± SD	Min-Max	
Arcuate artery AT	0.08 ± 0.02	0.03-0.14	0.09 ± 0.07	0-0.2	0.052
DPA AT	0.09 ± 0.03	0.05-0.14	0.12 ± 0.06	0-0.23	0.352
Medial plantar AT	0.07 ± 0.02	0.02-0.12	0.11 ± 0.06	0-0.21	0.005
Lateral plantar AT	0.08 ± 0.03	0.03-0.16	0.12 ± 0.07	0-0.25	0.012

The correlation between Fotaine classification, ABI, and acceleration times was not linear and statistically insignificant (Table 5).

Sensitivity analysis showed that acceleration times of medial and lateral plantar vessels can significantly predict clinical stage IIB and higher using a cutoff point of 0.075 sec with sensitivity 76.5%, 70.6%, and specificity 49% and 45% respectively (Figure 7 and Table 6).

Table 5. Correlation between clinical classification, ABI, and acceleration times (AT)

Fontaine clinical classification	Rho	P value
ABI	0.066	0.717
DPA-AT	0.272	0.062
Arcuate-AT	0.052	0.724
Medial plantar-AT	0.277	0.057
Lateral Plantar-AT	0.245	0.093

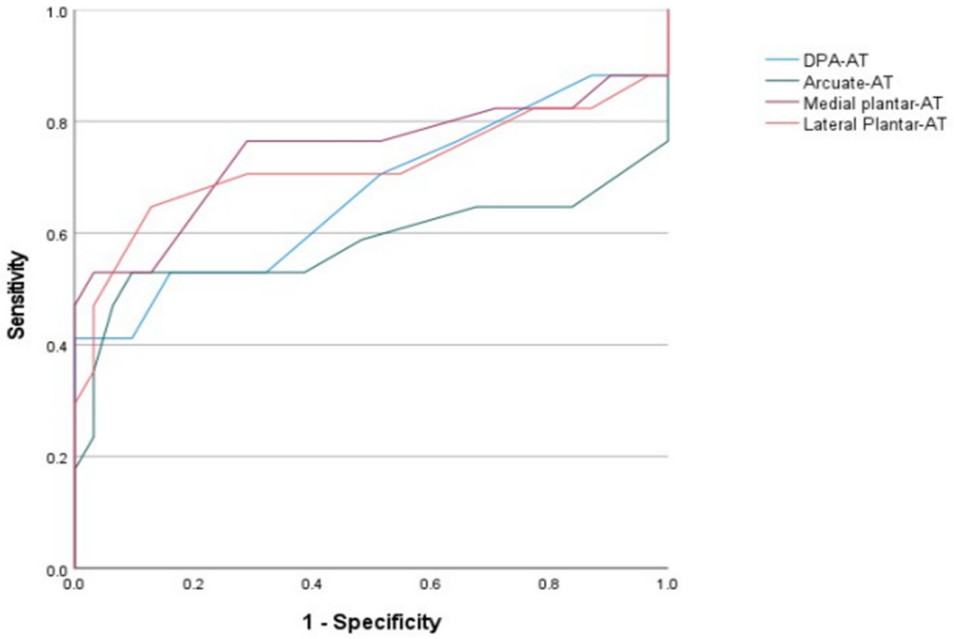

Figure 7. ROC analysis sensitivity and specificity plot of PAT

Table 6. ROC analysis showing the predictability of clinical fontaine classification (class IIB and higher)

Predictor	AUC	P value	95% CI	Cutoff	Sensitivity	Specificity
DPA-AT	0.67	0.054	0.488-0.852	0.085	70.6%	49%
Arcuate-AT	0.582	0.354	0.370-0.794	0.075	58.8%	52%
Medial plantar-AT	0.745	0.005	0.568-0.922	0.075	76.5%	49%
Lateral Plantar-AT	0.719	0.013	0.533-0.905	0.075	70.6%	45%

DISCUSSION

PAT is a novel DUS measurement in patients with PAD, particularly in cases with non-compressible vessels or inaccessible ABI measurements [8].

In the present study, medial and lateral plantar artery acceleration times were significantly prolonged in patients with higher Fontaine classifications. In contrast, no statistically significant linear correlation was observed between Fontaine classification, ABI, and acceleration times. The findings presented in Tables 4 and 5 reflect different statistical approaches addressing distinct research questions and are therefore not contradictory.

According to our results, female patients had a higher mean age of 64 years, whereas male patients had a mean age of 58 years. This difference may be attributed to the higher

prevalence of smoking among males, which accelerates the development of PAD.

Our findings were consistent with Man JJ et al., who previously reported that men tend to develop an earlier and greater burden of atherosclerotic plaques compared with women of the same age [9].

In our cohort, the majority of patients were older, with 63.6% aged above 60 years and 86% above 50 years. This observation aligns with the data reported by Norgren L et al., who stated that the prevalence of PAD increases with age and approximately doubles with each advancing decade, occurring in 3% of individuals younger than 60 years and rising to 15–20% among those older than 70 years [4].

In our study, among patients with PAD, 45.8% had hypertension, which was the most common comorbidity, followed by diabetes in 39.6%, and cardiac diseases in 4.2%. Smoking was reported by 56.3% of the patients. These findings are consistent with previous studies reporting that PAD is associated with multiple modifiable risk factors, including smoking, diabetes mellitus, and hypertension [10-12].

According to our results, the severity of infra-popliteal stenosis, specifically in the anterior tibial artery (ATA), was significantly associated with the severity of clinical symptoms and higher Fontaine classification stages ($p = 0.003$). This finding is consistent with McGinigle et al., who reported that rest pain, non-healing arterial ulcers, and chronic limb-threatening ischemia (CLTI)—the main causes of patient symptoms—are particularly associated with infrapopliteal occlusive PAD, compared with more proximal iliofemoral arterial disease [13].

ABI is the most commonly used method for screening and diagnosing lower-extremity PAD [14]. However, its sensitivity is reduced in patients with medial arterial wall calcifications, which can cause incompressible arteries—particularly at the ankle level—in older adults, individuals with diabetes mellitus (DM), and those with advanced chronic kidney disease (CKD). In these patients, ABI may be falsely elevated or appear normalized despite the presence of symptoms of lower-extremity PAD [15].

In our study, no significant linear correlation was found between ABI, clinical symptom classification, and PAT ($p = 0.757$). Only 4% of the examined population had abnormally low ABI measurements (<0.9, ischemic), despite all patients exhibiting atherosclerosis and the majority being symptomatic.

Consistent with these findings, Maruhashi et al., Chung et al., and Bunte et al. reported that normal or non-compressible ABI measurements are frequently observed in patients with diabetes mellitus, advanced chronic kidney disease, isolated distal lesions, and elderly patients [15-17]. Additionally, false-negative ABI readings have been reported in patients with mild stenoses, which may be attributed to the presence of sufficient collateral circulation [18].

AbuRahma AF et al. also reported that 43% of the symptomatic PAD patients with 50% or greater stenoses (by DUS) had normal/inconclusive resting ABIs (49%were diabetics and 57% had CKD) [19].

Trihan JE et al. reported that PAT correlated strongly with TBI ≤ 30 mmHg, while the correlation between ABI and PAT was weak. This is consistent with our findings, which showed no significant correlation between ABI and PAT [8].

PAT values of the medial and lateral plantar arteries were significantly higher in patients with Fontaine IIB–III–IV PAD compared to those with Fontaine I–IIA (medial: 0.11 ± 0.06 vs. 0.07 ± 0.02 sec; lateral: 0.12 ± 0.07 vs. 0.08 ± 0.03 sec; $p = 0.005$ and 0.012, respectively), indicating a significant correlation between PAT and the severity of clinical symptoms.

We also found high sensitivity of the PAT for the prediction of ischemia in Fontaine IIB–III–IV PAD classes, which is crucial in guiding the management approach of the patient. PAT of medial and lateral arteries can significantly predict clinical stage IIB and higher using a cutoff point of 0.075 sec, with a sensitivity 76.5%, 70.6% respectively.

According to Sommerset et al., PAT strongly correlates with both clinical symptoms and ABI findings ($p > 0.001$) [20]. They reported a significant difference in PAT values according to clinical presentation, which aligns with our findings. They further noted that a plantar acceleration time of less than 120 ms is considered normal, whereas a value greater than 225 ms indicates severe ischemia and correlates with critical limb ischemia (CLI) [20].

In their study, they examined 250 non-diabetic patients (499 limbs) and excluded patients with non-compressible ABI [20], which could be the explanation for why ABI correlated strongly in this study with PAT and clinical presentation, which disagrees with our findings.

Pyun AJ et al. reported that both ABI and TBI showed negative correlations with PATs, with no significant correlation observed between clinical symptoms and PAT. They also noted that PAT increased as ABI, AP, TP, and TBI decreased, suggesting it may serve as an alternative metric for assessing limb ischemia severity, particularly in patients with heavily calcified tibial and pedal arteries [21].

These findings are discordant with our results. This discrepancy can be explained by several factors. First, as previously mentioned, most patients in our study had atherosclerosis and were elderly; advanced age and atherosclerosis contribute to increased arterial wall stiffness, particularly in patients with calcified plaques, which may lead to falsely normal or negative readings. Second, approximately 39% of our study population had diabetes, a condition known to produce false-negative or

non-compressible ABI measurements. Third, about 35% of patients had non-obtainable ABI readings, either due to severe lower limb pain, edema, or critical hypo-perfusion of the ankle vessels, and approximately 19% had non-compressible (above-normal) readings.

In summary, ABI measurement posed a challenge in our study, both due to false-negative readings encountered in many patients and the inability to obtain ABI in others. Consequently, the correlation between ABI, PAT, and clinical symptoms was not significant in our cohort, despite previous studies reporting a strong correlation when the ankle vessels are compressible [21].

In conclusion, the PAT can be used as a surrogate for ABI in assessing the PAD patients, especially in patients with non-obtainable/ non-compressible ABI. PAT can also have multiple clinical applications as diagnosis, screening, and follow-up of PAD, and therefore guiding the clinical intervention [21].

Study Limitations

1. This is a single-center study and the enrolled population could not be representative of all classes of PAD patients.
2. The inability to assess the ABI in a considerable percentage of the examined patients secondary to severe lower limb pain and/or edema.
3. There was no statistically significant linear correlation between the ABI, PAT, and clinical staging; however, this can be attributed to the small sample size.

CONCLUSION

PAT can be added to peripheral artery disease practice for diagnostic approaches, pre-treatment planning, and monitoring of treatment in patients with chronic limb ischemia. Our study showed that pedal acceleration time can be considered a good objective modality for the assessment of lower limb ischemia patients, especially those for whom ABI cannot be applied. We found that PAT can differentiate between mild ischemia and moderate-to-severe ischemia, the latter of which may require more aggressive medical intervention.

Ethics Committee Approval: The study received ethical approval from the Research Ethics Committee of the Faculty of Medicine, Cairo University (Code: MS-186-2023) (Date: 29.07.2023).

Patient Consent for Publication: Written and informed consent was obtained from the study participants.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: All authors contributed equally to the article.

Conflict of Interest: The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

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