Received: 29 August 2023 | Revised: 19 September 2023 | Accepted: 21 September 2023

DOI: 10.1111/iwj.14431

ORIGINAL ARTICLE

IWJ WILEY

The correlation between transcutaneous oxygen pressure ($TcPO_2$) and forward-looking infrared (FLIR) thermography in the evaluation of lower extremity perfusion according to angiosome

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Funding information

National Research Foundation of Korea, Grant/Award Number: 2020R1A2C1100891; Soonchunhyang University research fund

Abstract

The increased peripheral arterial disease (PAD) incidence associated with aging and increased incidence of cardiovascular conditions underscores the significance of assessing lower limb perfusion. This study aims to report on the correlation and utility of two novel non-invasive instruments: transcutaneous oxygen pressure ($TcPO_2$) and forward-looking infrared (FLIR) thermography. A total of 68 patients diagnosed with diabetic foot ulcer and PAD who underwent vascular studies at a single institution between March 2022 and March 2023 were included. Cases with revascularization indications were treated by a cardiologist. Following the procedure, ambient $TcPO_2$ and FLIR thermography were recorded on postoperative days 1, 7, 14, 21 and 28. In impaired limbs, $TcPO_2$ was 12.3 ± 2 mmHg and FLIR thermography was 28.7 ± 0.9°C. $TcPO_2$ ($p = 0.002$), FLIR thermography ($p = 0.015$) and ankle–brachial index ($p = 0.047$) values significantly reduced with greater vascular obstruction severity. Revascularization ($n = 39$) significantly improved $TcPO_2$ (12.5 ± 1.7 to 19.1 ± 2.2 mmHg, $p = 0.011$) and FLIR (28.8 ± 1.8 to 32.6 ± 1.6°C; $p = 0.018$), especially in severe impaired angiosomes. $TcPO_2$ significantly increased immediately post-procedure, then gradually, whereas the FLIR thermography values plateaued from day 1 to 28 post-procedure. In conclusion, FLIR thermography is a viable non-invasive tool for evaluating lower limb perfusion based on angiosomes, comparable with $TcPO_2$.

KEYWORDS

diabetic foot, peripheral vascular diseases, reperfusion, thermography, transcutaneous oximetry

Key Messages

This study aims to report on the correlation and utility of two novel non-invasive instruments: $TcPO_2$ and FLIR thermography.A total of 68 patients diagnosed with diabetic foot ulcer and PAD were included. For the impaired limbs, both $TcPO_2$ and FLIR thermography values significantly increased after the procedure in the more impaired angiosomes ($TcPO_2 = 12.5 \pm 1.7$ to 19.1 ± 2.2 mmHg, $p = 0.011$; FLIR thermography $= 28.8 \pm 1.8$ to $32.6 \pm 1.6°C$, $p = 0.018$). In conclusion, FLIR thermography serves as a diagnostic tool with statistically significant diagnostic relevance for evaluating lower limb perfusion based on angiosomes, comparable to $TcPO_2$.

1 | INTRODUCTION

The prevalence of peripheral artery disease (PAD) is increasing owing to the aging population and rising incidence of cardiovascular conditions, such as diabetes and chronic kidney disease.[1] Particularly, in patients with diabetic foot ulcers (DFUs), the progression of PAD elevates the risk of neuropathic, infectious and ischemic complications that result in major infections and limb amputations.[2] These complications significantly increase patient mortality rates, with an increase of up to 39%–80% mortality rate within 5 years.[3] Assessment of lower limb perfusion is essential for formulating appropriate treatment plans for patients with diabetes and PAD, and its significance is continuously increasing.

Various non-invasive methods have been employed to assess lower limb perfusion. Currently, clinically utilized techniques include the ankle–brachial index (ABI), duplex ultrasonography, skin perfusion pressure (SPP), contrast-enhanced lower extremity angio-computed tomography (CT) and transcutaneous oxygen pressure ($TcPO_2$). More recently, due to the coronavirus disease of 2019 (COVID-19) crisis, forward-looking infrared (FLIR) thermography has been utilized to evaluate lower limb perfusion.[4] Among these options, we focused on two novel non-invasive instruments: $TcPO_2$ and FLIR thermography.

$TcPO_2$ is a non-invasive tool that measures oxygen pressure at the microvascular level. It is calculated by attaching a heated electrode to the skin to detect percutaneous light. It has a sustained clinical utility, as it is currently used clinically to predict wound healing potential and identify viable tissue in patients with chronically ischemic limbs.[5] In numerous cases, surgeons utilize $TcPO_2$ to determine the amputation level for patients with lower limb ischemia.[6]

FLIR thermography detects heat emitted from the skin tissue, representing the temperature through displayed colourization and numerical values. Recently, thermography has gained popularity for its practical application in hospitals due to its ability to detect various infectious diseases. Research regarding FLIR use in

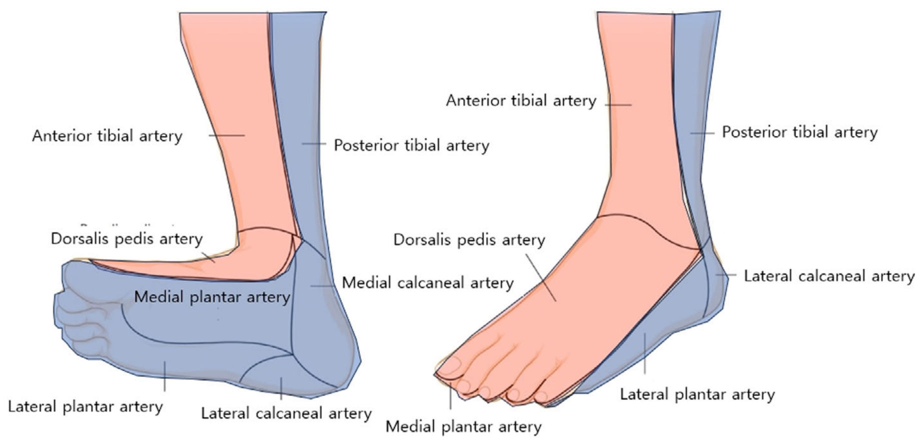

FIGURE 1 Angiosomes of the foot and ankle.[20] Three main arteries supply blood to the six angiosomes of the foot and ankle. The anterior tibial artery (ATA) and the dorsalis pedis artery supply the dorsal side of the foot and toes (red image). The posterior tibial artery (PTA) supplies the plantar aspect of the foot that comprises of three angiosomes: a calcaneal branch to the heel, the medial and lateral foot are supplied by the medial and lateral plantar artery, respectively (blue image). The heel and lateral border of the ankle are supplied by the peroneal artery (PA).

various fields is actively underway. However, to the best of our knowledge, no study has investigated the relationship between oxygen supply and lower limb perfusion status using the two novel non-invasive tools, FLIR and $TcPO_2$. We noted the potential of employing FLIR to track changes in perfusion patterns.

Nutrient supply to the lower limbs below the knee is primarily provided by three major below-knee arteries: the anterior tibial artery (ATA), posterior tibial artery (PTA) and peroneal artery (PA). These arteries branch and supply blood to six angiosomes at the ankle and foot levels (Figure 1).[7,8] An angiosome refers to a three-dimensional zone supplied by arteries, and this concept is crucial to accurately evaluate the blood flow in specific regions. Angiosomes must be considered for successful wound healing as they can predict vasculopathy in affected vessels.[9] Consequently, assessment of perfusion based on angiosomes has been emphasized.

The objective of this study was to elucidate the correlation and relevance of $TcPO_2$ and FLIR thermography when evaluating lower limb perfusion according to angiosomes in the presence of impaired blood flow. Additionally, this study aimed to report the utility of both methods in situations where lower limb perfusion changes due to revascularization. Furthermore, this study highlights the utility of FLIR thermography for assessing lower limb perfusion.

2 | PATIENTS AND METHODS

2.1 | Patients

This retrospective study included 120 patients diagnosed with DFU or PAD at a single institution between March 2022 and March 2023. The study protocol was approved by the Institutional Review Board approval (IRB number: 2023-04-028) and adheres to the Declaration of Helsinki. Written informed consent was obtained from all patients.

The inclusion criteria were: ≥18 years, both sexes, Rutherford classification stages 3–6 and grade 1 (superficial wound and no penetration) and stage B (with infection) of The University of Texas Diabetic Wound Classification system (UT classification). The Rutherford classification system, established in 1986, is based on common risk factors and has been widely adopted for patient management and research purposes[10–12] (Table 1). The UT classification, introduced in 1996 for diabetic foot classification and treatment, categorizes ulcers into grades 0–3 and stages A–D for infections or ischemia[13] (Table 2). All patients exhibited mild or greater stenosis in at least one angiosome during vascular evaluation. Exclusion criteria were: history of critical life-threatening illness or major amputation, major amputation above the below-knee level during hospitalization, underwent open or hybrid surgery due to a critical event or having a body temperature exceeding 37.3°C during hospitalization. Patients with allergic reactions to contrast during enhancement, those who declined vascular evaluation, those with missing records or those who were lost to follow-up for more than 1 month were excluded (Table 3).

Vascular studies were conducted using lower extremity angio-CT, lower extremity magnetic resonance angiography and lower extremity angiography. The location, pattern and severity of obstruction were documented. Within the framework of lower extremity angiography, we categorized the patients' blood vessels into three

TABLE 1 Rutherford classification for chronic limb ischemia.[11]

Grade	Category	Clinical description	Objective criteria
0	0	Asymptomatic—no hemodynamically significant occlusive disease	Normal treadmill or reactive hyperemia test
	1	Mild claudication	Completes treadmill exercise; AP after exercise > 50 mmHg but at least 20 mmHg lower than resting value
I	2	Moderate claudication	Between categories 1 and 3
	3	Severe claudication	Cannot complete standard treadmill exercise, and AP after exercise < 50 mmHg
II	4	Ischemic rest pain	Resting AP < 40 mmHg, flat or barely pulsatile ankle or metatarsal PVR; TP < 30 mmHg
III	5	Minor tissue loss—nonhealing ulcer, focal gangrene with diffuse pedal ischemia	Resting AP < 60 mmHg, ankle or metatarsal PVR flat or barely pulsatile; TP < 40 mmHg
	6	Major tissue loss—extending above TM level, functional foot no longer salvageable	Same as category 5

Abbreviations: AP, ankle pressure; PVR, pulse volume recording; TM, transmetatarsal; TP, toe pressure.

TABLE 2 The University of Texas Staging System for diabetic foot ulcers with associated interventions.[13]

Stage	Grade 0	Grade I	Grade II	Grade III
A	Pre- or post-ulcerative lesion completely epithelialized	Superficial ulcer, not involving tendon capsule or bone	Ulcer penetrating to tendon or capsule	Ulcer penetrating to bone or joint
B	Infection	Infection	Infection	Infection
C	Ischemia	Ischemia	Ischemia	Ischemia
D	Infection and Ischemia	Infection and Ischemia	Infection and Ischemia	Infection and Ischemia

TABLE 3 Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Males and females over the age of 18 presenting with wounds and symptoms of peripheral arterial disease (PAD) and diabetic foot ulcers (DFU)	Patients who have undergone major amputation equal to or above–below knee amputation (excluding toe amputation)
Classified as Rutherford classification three to six	Undergone open or hybrid surgery as a critical event
Classified as UT classification grade 1 (superficial wound and no penetration) and stage B (with infection) or higher	Experienced traumatic vessel injury or bypass surgery
In cases of vascular evaluation, when mild or greater stenosis is identified in a single angiosome	Confirmed body temperature above 37.3°C
Patients without a history of major amputation	Documented allergic reaction to contrast solution
Patients without a history of critical illness	Refuse vascular evaluation
	Follow-up loss for more than 1 month or miss the record

Abbreviations: DFU, diabetic foot ulcer; PAD, peripheral artery disease; UT classification, University of Texas classification.

groups based on the degree of blockage: mild, moderate-to-severe and totally occluded. Additionally, within each group, we categorized the patients based on the location of vascular damage in their blood vessels, dividing them into impaired and normal contralateral limbs. $TcPO_2$, FLIR thermography and ABI values were recorded for both subgroups.

Patients who met the revascularization indication criteria underwent a procedure performed by a cardiologist, and the outcome of the procedure was recorded. Various demographic factors including age, sex, mortality, heart disease, end-stage renal disease, smoking, body mass index, haemoglobin A1c, C-reactive protein level and ABI were measured.

2.2 | Methods

Following admission, all patients underwent $TcPO_2$ and FLIR thermography measurements according to the protocol. For patients who underwent revascularization, measurements were taken at the initial time point as well as on postoperative days (POD) 1, 7, 14, 21 and 28. Clinical photographs of the patients' feet were captured using a Canon EOS R6 Mark II camera (Canon®, Tokyo, Japan), maintaining a consistent distance of 40 cm from the foot. All measurements and photography were performed in a standardized surgical room to ensure a relatively consistent measurement environment. The temperature and humidity were maintained between 18°C and 24°C and at 50%–55%, respectively.

2.2.1 | $TcPO_2$ assessment

$TcPO_2$ was measured using a TCM400® device (Radiometer Medical ApS; Copenhagen, Denmark) (Figure 2A). The temperature of the sensor was set between 37°C and 45°C and adjusted in increments of 0.5°C. The measurement range for $TcPO_2$ was set from 0 to 2000 mmHg. Probe E5250, a transcutaneous Clark-type O_2 electrode, was used. The sensor consisted of an O_2 sensor cathode (25 m platinum) and an O_2 anode (silver) with a fixed 30 mm diameter ring attached. The electrolyte solution on the sensor surface comprised 1.2-propanediol, potassium chloride and sodium hydrogen carbonate. The calibration gas consisted of 5.0% CO_2, 20.9% O_2 and balance N_2, with a gas flow of 8 ± 2 mL/min. Shut-off occurred automatically after 5, 10, 15, 20 and 50 min. The calculated regional perfusion indices ranged from 0 to 3 (Figure 2B).

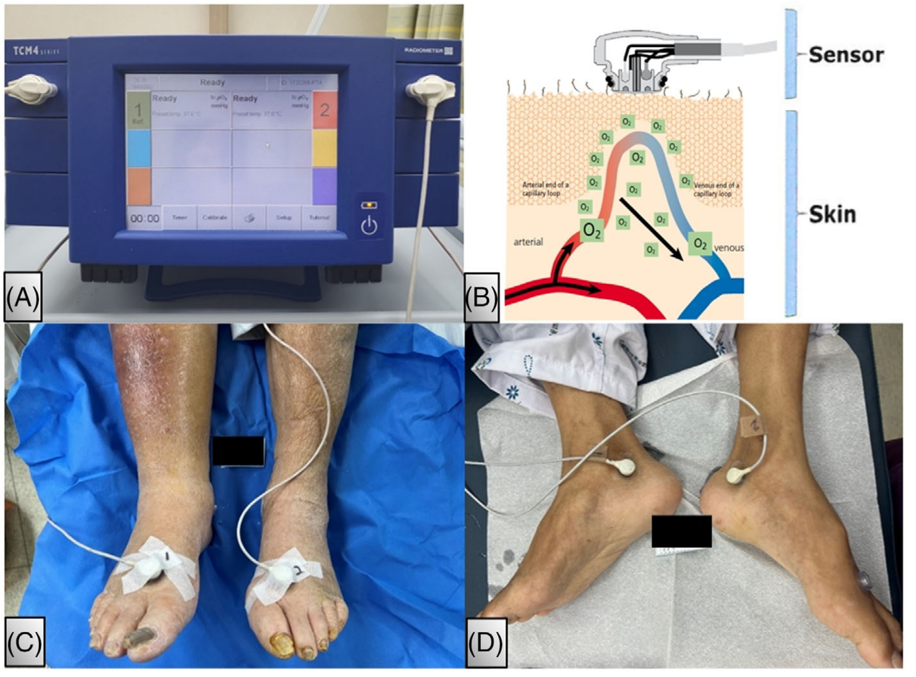

FIGURE 2 Measurement of transcutaneous oxygen pressure ($TcPO_2$). (A) $TcpO_2$ measuring instrument (TCM400®, Radiometer Medical ApS, Copenhagen, Denmark). (B) Schematic illustration of $TcPO_2$ measurement: The heated sensor increases blood flow in the capillaries beneath it, and the oxygen diluted in the blood or within the skin cells passes through the skin. Oxygen then passes through the sensor membrane and is solved in the electrolyte where the amount of blood is measured. (C) Measurement according to anterior tibial artery angiosome and (D) posterior tibial artery angiosome.

The patients were maintained in supine and covered with a warm blanket during the measurements. The probes were attached to each angiosome of the feet: the dorsum of the second metatarsal area for the angiosome corresponding to the ATA and the medial side of the heel for the angiosome corresponding to the PTA. To prevent low-temperature burns, the electrode was heated to 41°C and maintained for 10 min (Figure 2C, D).

2.2.2 | FLIR thermography assessment

FLIR thermography was performed using an FLIR C5 camera (Teledyne FLIR LLC, US). The FLIR C5 is a handheld camera that includes a thermal imager (160 × 120 pixels), a 5-megapixel visual camera (640 × 480 pixels) and an LED flashlight. The images from both cameras were merged using multispectral dynamic imaging technology (Teledyne FLIR LLC, US) to generate a single thermal image with a resolution of 640 × 480 pixels.[14] Although not used in this study, smartphone-compatible thermography tools, such as the FLIR ONE-Pro (Teledyne FLIR LLC, US), have emerged and are researched in addition to the handheld camera format[15] (Figure 3A, B).

Patients with a whole-body temperature exceeding 37.3°C were excluded from measurements. All measurements and photography were conducted in a standardized surgical room to maintain a relatively consistent measurement environment. The temperature and humidity were maintained between 18°C and 24°C and at 50%–55%, respectively. A 15-min, rest time was provided before the measurements. Patients were photographed in supine with body areas other than the foot covered with a warm blanket. Foot angiosomes were divided into dorsal view (ATA angiosomes) and medial and plantar views (PTA angiosomes) for photography. A distance of 40 cm was maintained for photography, and all shots were taken twice (Figure 3C, D).

2.2.3 | Thermography analysis

The captured images were analysed using FLIR Thermal Studio software (Teledyne FLIR LLC, US; Figure 4). This software allows the analysis, visualization and manipulation of stored thermal imaging data based on predefined regions. We set territories for each angiosome using this software and measured the average temperature of each defined angiosome. This process was performed twice, and the average of the two measurements was recorded.

2.2.4 | Ankle–brachial index

The ABI was measured using a Vascular Profiler 1000 (VP-1000 Plus; Omron Co., Kyoto, Japan). ABI is easily measurable and a useful test for evaluating the degree of lower extremity arterial sclerosis. In this test, the patient was placed in supine for approximately 5 min to achieve stability. Blood pressure was then measured and recorded using either the anterior dorsalis artery or the PTA for ankle pressure and the brachial artery for arm pressure. The ankle systolic blood pressure was divided by the

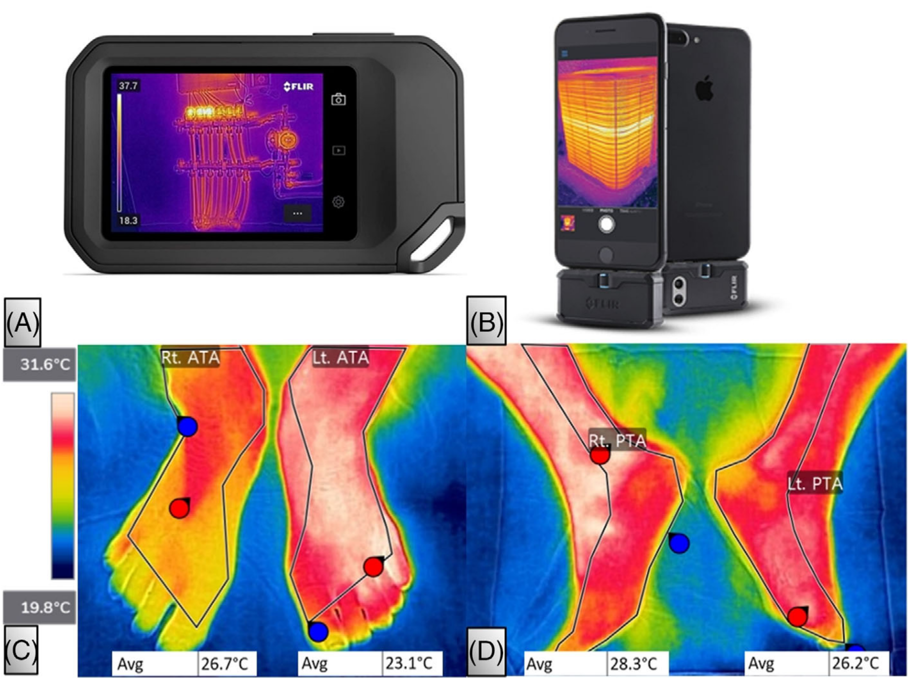

FIGURE 3 Measurement of forward-looking infrared (FLIR; Teledyne FLIR LLC, US) thermography according to angiosomes. (A) A handheld camera type device. (B) Smartphone connected type device. (C, D) Application of FLIR thermography according to angiosomes. (C) Anterior tibial artery angiosome in dorsal view. (D) Posterior tibial artery angiosome in medial view.

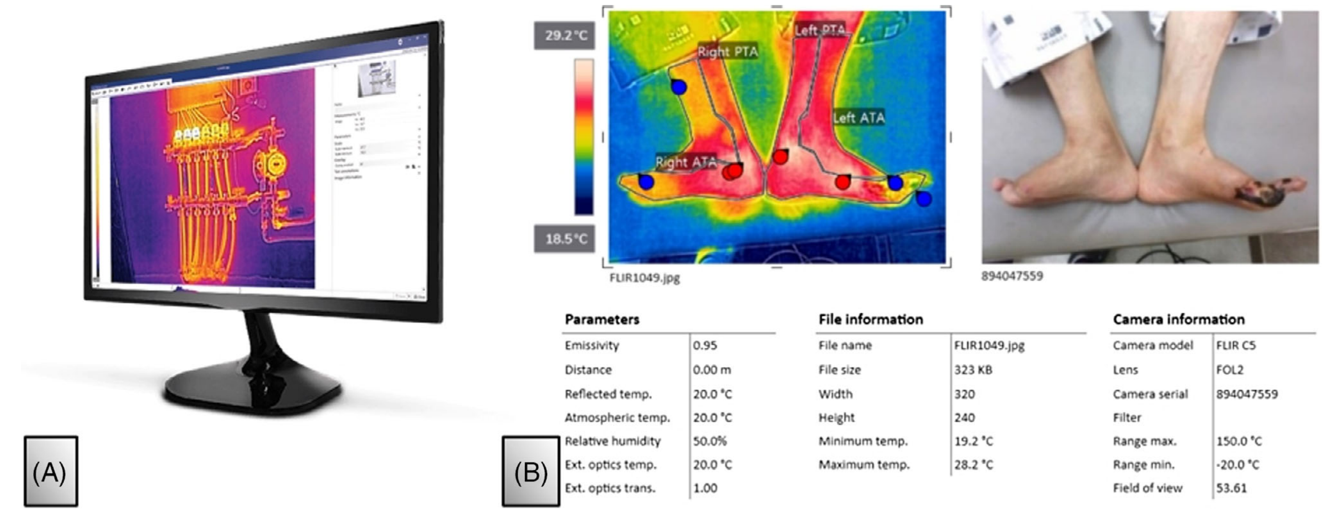

FIGURE 4 System set-up of forward-looking infrared (FLIR) thermography and the analysis program. FLIR Thermal Studio software (Teledyne FLIR LLC, US) was used to identify the temperature at a specific point on a thermal image and calculate the temperature difference. (A) FLIR Thermal Studio software. (B) Measurement of FLIR thermography using the Thermal Studio software.

brachial systolic blood pressure to determine the ABI. Normal values were set between 1.1 and 1.3; values below 0.9 and 0.7 indicate arterial stenosis and arterial occlusion in the lower extremities, respectively.[16]

2.2.5 | Percutaneous transluminal angioplasty

Angioplasty was performed under local anaesthesia by a skilled cardiologist when the diameter stenosis of an iliac or femoropopliteal artery lesion was ≥70% or when the diameter stenosis was between 50% and 70% with a systolic pressure gradient of ≥20 mmHg. Angioplasty was performed using the Seldinger technique; a guiding sheath was inserted through the femoral artery, and a guidewire was threaded into the vessel.[17] The position of the guiding sheath was verified using a contrast dye, and a balloon was inflated within the vessel using inflator at pressures ranging from 6 to 20 atm. Depending on the operator's judgement, a stent insertion or dilatation might be performed. Once an improvement in blood flow was confirmed, the procedure was concluded. Subsequently, the guiding sheath was removed, puncture site was compressed and haemostasis was achieved. As per established protocol, ambulation was restricted for approximately 6 h after the procedure. The location of the stenosis or occlusion and success of the procedure were recorded.

2.3 | Statistical methods

Statistical analyses were conducted using SPSS (version 27.0; IBM Corp., Armonk, NY, USA). Comparisons among the three groups were performed using one-way analysis of variance (ANOVA), Welch's ANOVA and the Kruskal–Wallis test for continuous variables, along with post hoc tests. Categorical variables were analysed using Pearson's chi-square test and Fisher's exact test. Additionally, paired *t*-tests were used to compare changes before and after the procedure. Pearson's correlation analysis was used to assess the correlations between changes. A significance level of $p < 0.05$ was considered statistically significant for all analyses.

3 | RESULTS

3.1 | Patient demographics

A total of 68 patients (68 limbs) out of 120 were included. Among them, 49 were male patients and 19 female patients, with an average age of 64.9 years (range: 32–86, mean SD: ±9.65). For the impaired limb group, $TcPO_2$ and FLIR thermography values calculated based on the average ATA and PTA angiosome values were 12.3 ± 2 mmHg and 28.7 ± 0.9°C, respectively. The ABI value was 0.77 ± 0.08. The $TcPO_2$, FLIR thermography and ABI values significantly decreased with respect to the severity of vascular obstruction ($TcPO_2$, $p = 0.002$; FLIR thermography, $p = 0.015$; ABI, $p = 0.047$).

In the contralateral limb group, no statistically significant associations were observed for $TcPO_2$, FLIR thermography and ABI values ($TcPO_2$, $p = 0.223$; FLIR thermography, $p = 0.273$; ABI, $p = 0.718$).

There was no statistically significant association between affected ATA and PTA angiosomes ($p = 0.499$). Revascularization was performed by a cardiologist and was categorized as successful, failed or not performed. Notably, the proportion of patients who underwent revascularization was significantly higher in the totally occluded and moderate-to-severe obstruction groups ($p = 0.002$).

In terms of Rutherford classification, category 5 had the highest frequency (26 cases): category 3 was the most common in the mild group and category 5 was the most frequent in moderate-to-severe and totally occluded groups. According to the UT classification, grade 2D was the most common in the totally occluded group, whereas grades 1C and ID were common in the mild group and moderate-to-severe group, respectively. Demographic characteristics and laboratory findings did not show statistically significant differences (Table 4).

3.2 | Oxygen pressure and temperature changes after revascularization

3.2.1 | Immediate postoperative results

Among the 39 impaired limbs subjected to revascularization, the successfully recanalized vessels were categorized as more impaired angiosomes, whereas the patent vessels were classified as less impaired angiosomes. $TcPO_2$ and FLIR values were measured and recorded according to the pre- and post-procedural protocols for each angiosome territory.

For the impaired limbs, both $TcPO_2$ and FLIR thermography values significantly increased after the procedure in the more impaired angiosomes ($TcPO_2 = 12.5 \pm 1.7$ to 19.1 ± 2.2 mmHg, $p = 0.011$; FLIR thermography $= 28.8 \pm 1.8$ to 32.6 ± 1.6°C, $p = 0.018$). In the less impaired angiosomes, $TcPO_2$ values significantly increased from 22 ± 1.8 to 24 ± 1.1 mmHg ($p = 0.031$). However, FLIR thermography values did not significantly increase (32.1 ± 1.9 to 33.1 ± 2.5 mmHg, $p = 0.103$). Graphically, a significant positive correlation was observed between the differences in $TcPO_2$ and FLIR thermography values in the impaired angiosomes before and after the procedure ($p = 0.047$), whereas no distinct trend was evident in the less impaired angiosomes ($p = 0.751$; Figure 5).

Additionally, no significant changes were observed in the contralateral limbs before and after the procedure. The ABI demonstrated a significant increase in the impaired limb (0.72–1.1, $p = 0.0049$), whereas no significant change was observed in the contralateral limb ($p = 0.42$; Table 5).

3.2.2 | One-month follow-up results

The average $TcPO_2$ and FLIR thermography values were recorded for the more impaired angiosomes before and from days 1 to 28 after the procedure. These values are graphically represented (Figure 6). $TcPO_2$ significantly increased immediately after the procedure and continued to rise gradually until day 28, ultimately reaching a value of 29.3 ± 1.4 mmHg, whereas FLIR thermography

TABLE 4 Demographics of all groups.

Variable	Mild (n = 12)	Moderate to severe (n = 30)	Totally occluded (n = 26)	p
Age, yr (range: 32–86)	64.75 (16.17)	61.27 (14.02)	69.35 (10.22)	0.079
Gender				0.339
Male	7 (58.3)	21 (70.0)	21 (80.8)	
Female	5 (41.7)	9 (30.0)	5 (19.2)	
$TcPO_2$ (mmHg, range: 6.5–55.1)				
Impaired limb	18.38 (3.15)	15.29 (1.60)	9.00 (0.54)	**0.002***
Contralateral limb	29.40 (28.18–30.93)	29.25 (28.15–31.00)	31.00 (28.18–38.08)	0.223
FLIR (°C, range: 22.0–35.3)				
Impaired limb	30.37 (1.43)	29.48 (1.74)	24.82 (1.98)	**0.015***
Contralateral limb	32.16 (1.29)	32.17 (1.16)	32.65 (1.12)	0.273
ABI (range: 0.47–1.36)				
Impaired limb	1.06 (0.69)	0.79 (0.57)	0.66 (0.12)	**0.047***
Contralateral limb	1.05 (0.97–1.13)	1.04 (1.00–1.09)	1.02 (0.90–1.09)	0.718
BMI, kg/m^2				
(range: 17.65–34.45)	24.25 (4.44)	23.84 (3.39)	23.1 (3.34)	0.623
HbA1c, % (range: 5.4–11.8)	7.1 (6.85)	7.18 (6.31)	7.89 (7.09)	0.466
CRP (range: 1–99.2)	10.2 (1.7)	12.2 (4.6)	12.9 (7.0)	0.734
Smoking	1 (9.2)	10 (29)	2 (9.4)	0.172
IHD	1 (9.2)	5 (16.67)	7 (28.9)	0.823
ESRD	5 (37.1)	9 (27.5)	9 (33.4)	0.539
Dominant affected angiosomes				0.499
ATA	8 (66.7)	14 (46.7)	14 (53.8)	
PTA	4 (33.3)	16 (53.3)	12 (46.2)	
Revascularization, n				**0.002***
Success	1 (8.3)	12 (40.0)	18 (69.2)	
Fail	0 (0.0)	1 (3.3)	7 (26.9)	
None	11 (91.7)	17 (56.7)	1 (3.8)	
Rutherford Classification				0.108
Category 3	5 (41.7)	5 (16.7)	3 (11.5)	
4	3 (25.0)	10 (33.3)	6 (23.1)	
5	4 (33.3)	12 (40.0)	10 (38.5)	
6	1 (8.3)	3 (10.0)	7 (26.92)	
UT Classification				0.344
Grade 1 B	1 (8.3)			
C	5 (41.7)	3 (10.0)	2 (7.7)	
D	3 (25.0)	8 (26.7)	2 (7.7)	
Grade 2 B	1 (8.3)	2 (6.7)	1 (3.8)	
C	2 (16.7)	3 (10.0)	5 (19.2)	
D		7 (23.3)	6 (23.1)	
Grade 3 B		1 (3.3)	1 (3.8)	
C		4 (13.3)	5 (19.2)	
D		2 (6.7)	4 (11.5)	

Note: Values are expressed as mean (SD), n (%) or median (interquartile range). p-values were calculated by one-way analysis of variance (ANOVA) with Scheffe's multiple comparison, Welch's ANOVA with Game–Howell test or Kruskal–Wallis test with Bonferroni corrected pairwise comparison for continuous variable, and Pearson chi-square test or Fisher's exact test for categorical variable.
Abbreviations: ABI, ankle–brachial index; BMI, body mass index; CRP, C-reactive protein; ESRD, end-stage renal disease; FLIR, forward-looking infrared; IHD, ischemic heart disease; $TcPO_2$, transcutaneous oxygen pressure; UT classification, University of Texas classification.
*p-value <0.05.

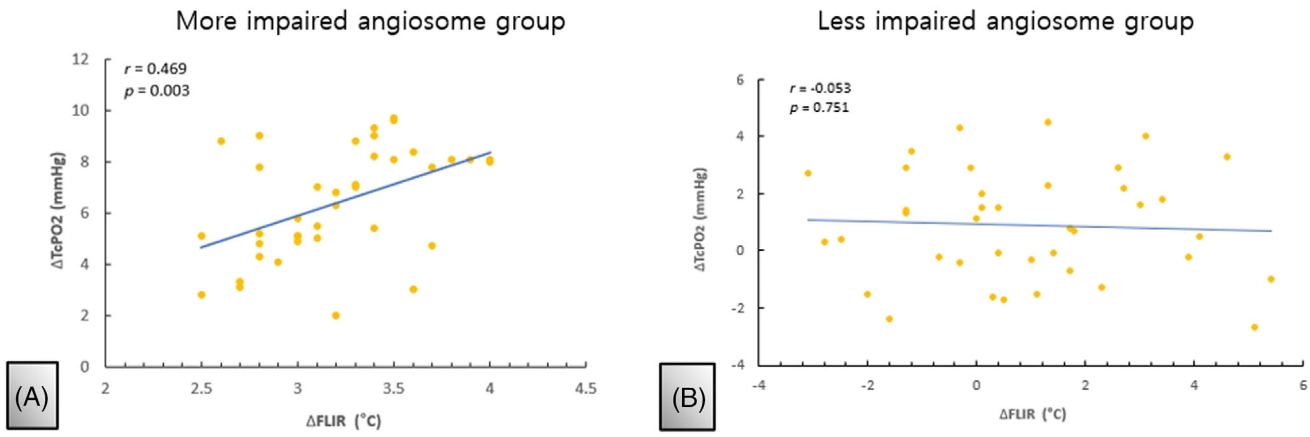

FIGURE 5 Graph showing correlation between transcutaneous oxygen pressure ($TcPO_2$) and temperature. (A) The more impaired angiosomes show a positive correlation between $TcPO_2$ and temperature ($p = 0.047$). (B) The less impaired angiosomes show no specific correlation between the values ($p = 0.751$). Δ: Difference between post and preoperative values. FLIR, forward-looking infrared.

TABLE 5 Ankle–brachial index (ABI), transcutaneous oxygen pressure ($TcPO_2$) and forward-looking infrared (FLIR) thermography values according to angiosomes in the revascularized group.

	Impaired limb			Contralateral limb		
Variable	**Before**	**After**	***p***	**Before**	**After**	***p***
$TcPO_2$ (mmHg, range: 6.5–55.1)						
More impaired angiosome	12.5 ± 1.7	19.1 ± 2.2	**0.011***	24.1 ± 2.5	24.9 ± 1.9	0.36
Less impaired angiosome	22 ± 1.8	24 ± 1.1	**0.031***	25.7 ± 1.8	25.1 ± 1.7	0.29
FLIR (°C, range: 22.0–35.3)						
More impaired angiosome	28.8 ± 1.8	32.6 ± 1.6	**0.018***	32.8 ± 1.3	31.8 ± 1.9	0.25
Less impaired angiosome	32.1 ± 1.9	33.1 ± 2.5	0.103	31.9 ± 2.3	32.0 ± 2.8	0.17
ABI (range: 0.47–1.36)	0.72	1.1	**0.049***	1.01	1.02	0.42

Abbreviations: ABI, ankle–brachial index; FLIR, forward-looking infrared; $TcPO_2$, transcutaneous oxygen pressure.
**p*-value <0.05.

initially increased right after vascularization and gradually plateaued, and the final value recorded on day 28 was 33 ± 0.9°C.

3.2.3 | Case 1

A 60-year-old male patient with a history of diabetes and ischemic necrosis of the right third toe presented to our clinic. He was classified as Rutherford classification 4 and UT classification 1D. At admission, the ABI value of his right foot was 0.8, and $TcPO_2$ and temperature of the ATA angiosome were 8 mmHg and 23.1°C, respectively. One week later, angiography revealed severe occlusion of the right ATA, leading to revascularization. Improved blood flow was confirmed after the procedure. Immediately after the procedure, the $TcPO_2$ value of the right ATA angiosome increased to 26 mmHg, and the temperature rose to 28.9°C. In the initial FLIR thermography, colour changes in the right ATA angiosome indicated temperature recovery after blood flow improvement, with similar changes on both sides. After 3 weeks of dressing treatment, the patient was discharged upon confirmation of total wound healing (Figure 7).

3.2.4 | Case 2

A 73-year-old male patient with a history of diabetes, cerebrovascular disease and ischemic necrosis of the right second toe presented to our clinic. He was classified as Rutherford classification 4 and UT classification 2D. At admission, the ABI of his right foot was 0.6, $TcPO_2$ was 18 mmHg and PTA angiosome temperature was 27.0°C. The patient with total occlusion of the right PTA underwent revascularization on the third day of admission, resulting in improved blood flow. Following the procedure, the immediate postoperative $TcPO_2$ value of the

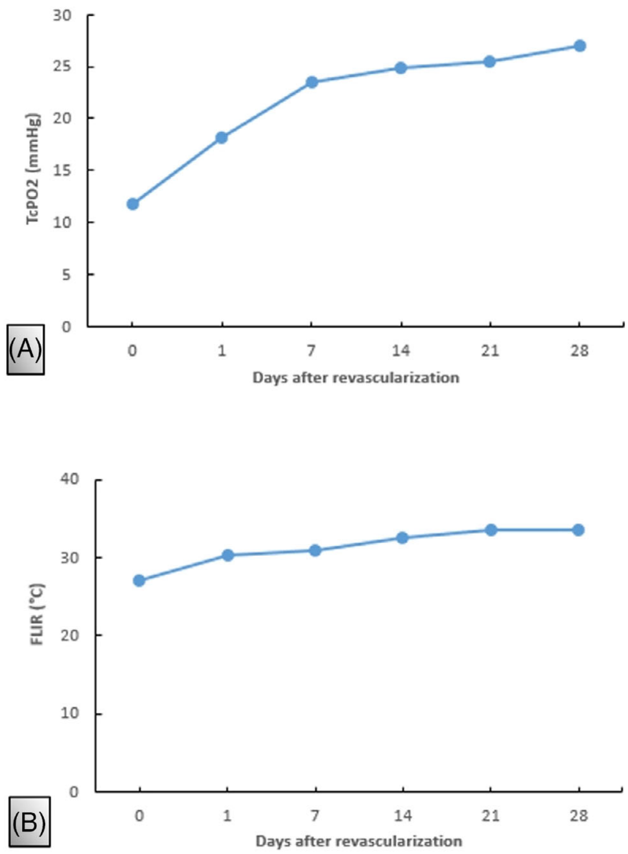

FIGURE 6 Graph showing courses in patients with revascularization pre- and post-percutaneous transluminal angioplasty in the more impaired angiosomes. (A) Course of transcutaneous oxygen pressure ($TcPO_2$) of the more impaired angiosomes. A steep curve immediately post-procedure and on the 7th day is seen, followed by a gradual increase until the 28th day. (B) The forward-looking infrared (FLIR) thermography graph of the more impaired angiosomes shows a gradual increase immediately post-procedure on 28th day.

right PTA angiosome was 19 mmHg, and the PTA angiosome temperature was 28.4°C. The patient underwent minor amputation and was discharged 1 month after confirming total healing (Figure 8).

4 | DISCUSSION

The treatment for patients with PAD, especially those with DFU, begins with perfusion assessment. The likelihood of PAD in patients with diabetes is reportedly two to four times higher than that in non-diabetic individuals.[18] According to the current literature, the probability of lower extremity amputation in patients with diabetes ranges from 40% to 70%.[3] However, appropriate perfusion assessment and vascular interventions are known to improve the success rate of free tissue transfer and significantly reduce amputation rates in diabetic limbs.[19]

To objectively correlate the assessment of blood flow with the symptoms and clinical presentation of diabetic feet, we used the Rutherford classification[11] (Table 1). Claudication was divided into three levels, whereas gangrene was divided into two levels. To address the limitation of the wound classification comprising only two categories, we employed the UT classification. Rutherford classification is widely used to classify ischemic diseases of the extremities. Similarly, previous studies used the Rutherford classification to assess the risk factors for the patency of the descending branch of the lateral circumflex femoral artery[12] and to evaluate wound healing and symptom relief based on the patency of the communicating arteries.[20]

This study assessed lower limb perfusion assessments based on angiosomes. The concept of angiosomes has been discussed in various studies, emphasizing its importance. Accurate evaluation of pulsatile flow based on angiosomes is crucial for wound healing,[9,21] and the three-dimensional concept of tissue territory has been demonstrated to be significant in the field of endovascular surgery.[7,8,22] As previously mentioned, six angiosomes of the foot are supplied blood via three main arteries (Figure 1). The PTA has three main branches: the calcaneal branch to the heel, medial plantar artery to the instep and lateral plantar artery to the lateral mid and forefoot, and supplies blood to the plantar aspect of the toes, web spaces, sole and inner heel. The ATA becomes the dorsalis pedis artery and provides blood to the dorsum of the foot. The PA supplies blood to the ankle and heel.[9] In this study, which focused on the dorsal, forefoot and plantar aspect angiosomes, we utilized measurements of PTA and ATA angiosomes, excluding stenosis and obstruction of the PA.

Currently, various non-invasive methods are used for the swift and appropriate assessment of blood flow. ABI is a ratio obtained by measuring the systolic blood pressure in the arm and ankle, whereas the toe–brachial index (TBI) is a ratio measured based on the toe instead of the ankle. They serve as indicators of atherosclerosis and prognostic markers of cardiovascular events and functional impairment.[23] Despite their ease of use and high utility, a study indicated that their utilization in isolation results in approximately 43% false positives, underscoring the need for complementary tests.[24]

SPP measures the microcirculation in the skin using laser Doppler. Unlike ABI and TBI, arterial calcification does not affect SPP; thus, enabling a relatively accurate arterial function assessment.[25]

Colour Doppler ultrasonography is non-invasive, reproducible and cost-effective, making it the preferred

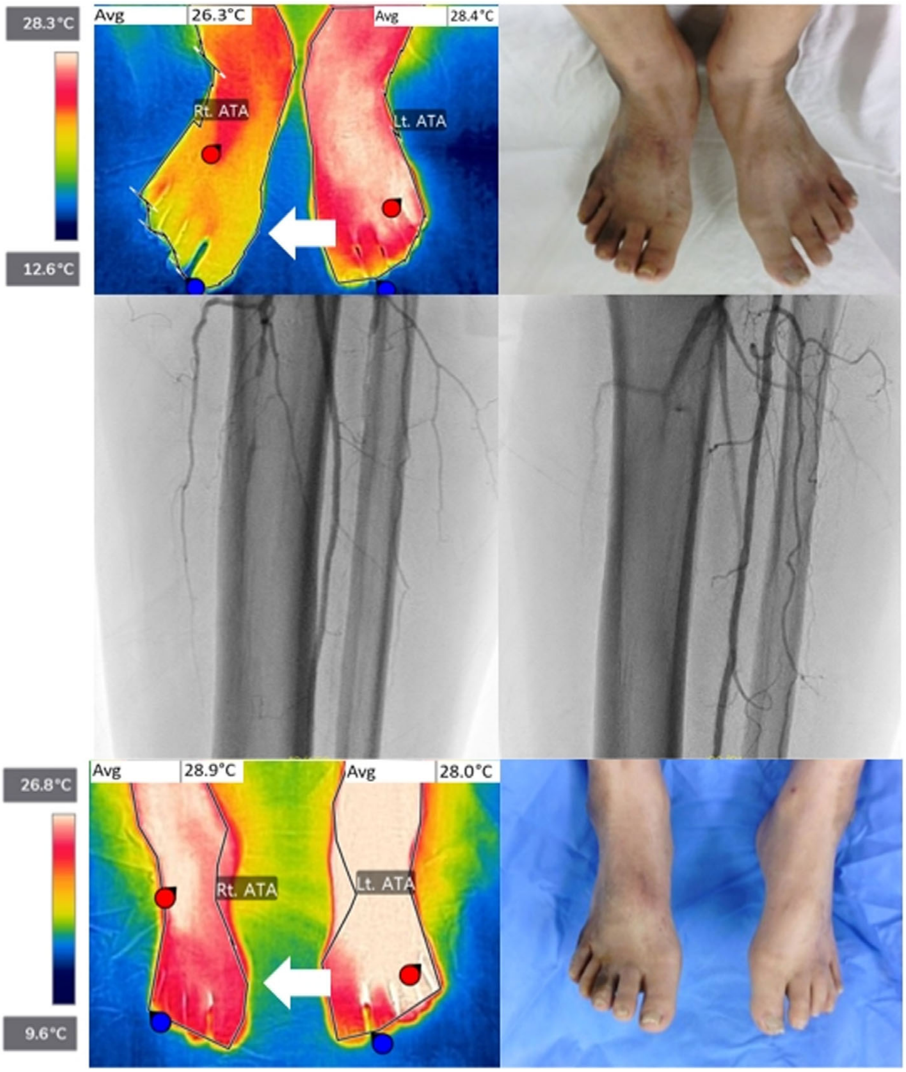

FIGURE 7 Top panel: A 60-year-old male patient with ischemic necrosis of the right third toe. At admission, the transcutaneous oxygen pressure ($TcPO_2$) in the right anterior tibial artery (ATA) angiosome was 8 mmHg and temperature was 23.1°C. Centre panel: Angiography revealed severe occlusion of the right ATA, leading to revascularization and subsequent improved blood flow. Bottom panel: Following treatment, the immediate postoperative $TcPO_2$ value within the right ATA angiosome increased to 26 mmHg, while the temperature rose to 28.9°C. Postoperative forward-looking infrared (FLIR) thermography of the right ATA angiosome showed restored temperature after improved blood flow through colour changes, with similar temperatures observed on both sides (White arrow).

choice in clinical practice. However, it has limitations regarding panoramic view, potential subjectivity and physical constraints owing to the use of ultrasound.[26]

ABI, TBI and Doppler ultrasonography are hemodynamic indices, whereas $TcPO_2$ and FLIR thermography are metabolic tests.[27] $TcPO_2$ measures the oxygen tension at the microvascular level using a heated electrode, which detects light, attached to the skin. This method non-invasively determines local perfusion pressures. $TcPO_2$ has gained clinical utility and has been used in various fields. It is utilized to predict wound healing potential, detect viable tissue in patients with chronic limb ischemia[5] and determine the amputation level in patients with lower limb ischemia.[6] Additionally, a recent study has demonstrated the use of $TcPO_2$ to monitor free-flap viability.[28]

FLIR thermography detects the infrared portion (wavelength 7–13 μm) of the electromagnetic spectrum. Based on this property, FLIR thermography colourizes and quantifies the heat emitted from the skin tissue and displays it on a screen. Thermography use is widespread owing to the rise in various infectious diseases, including COVID-19, and research utilizing FLIR thermography is underway (Table 6). Studies have demonstrated its application in assessing burn depth and predicting prognosis,[15] locating perforator vessels during preoperative planning of perforator flap procedures[29] and detecting Grade I pressure sores.[30] Additionally, recent research has assessed the utilization of FLIR thermography to evaluate and track changes in blood perfusion.[31–33] FLIR thermography allows contact-free evaluation of lower limb perfusion and is not influenced by operator experience.[34,35] Temperature is proportional to the degree of tissue blood perfusion, and reduced tissue blood perfusion due to arterial occlusion can diminish cellular metabolism, leading to decreased heat generation. Consequently, changes in temperature can vary according to the severity of PAD.[15] In a previous study, Zenunaj et al. evaluated changes in lower limb perfusion before and after revascularization using FLIR thermography and found statistically significant correlations between these changes and variations in the ABI.[4]

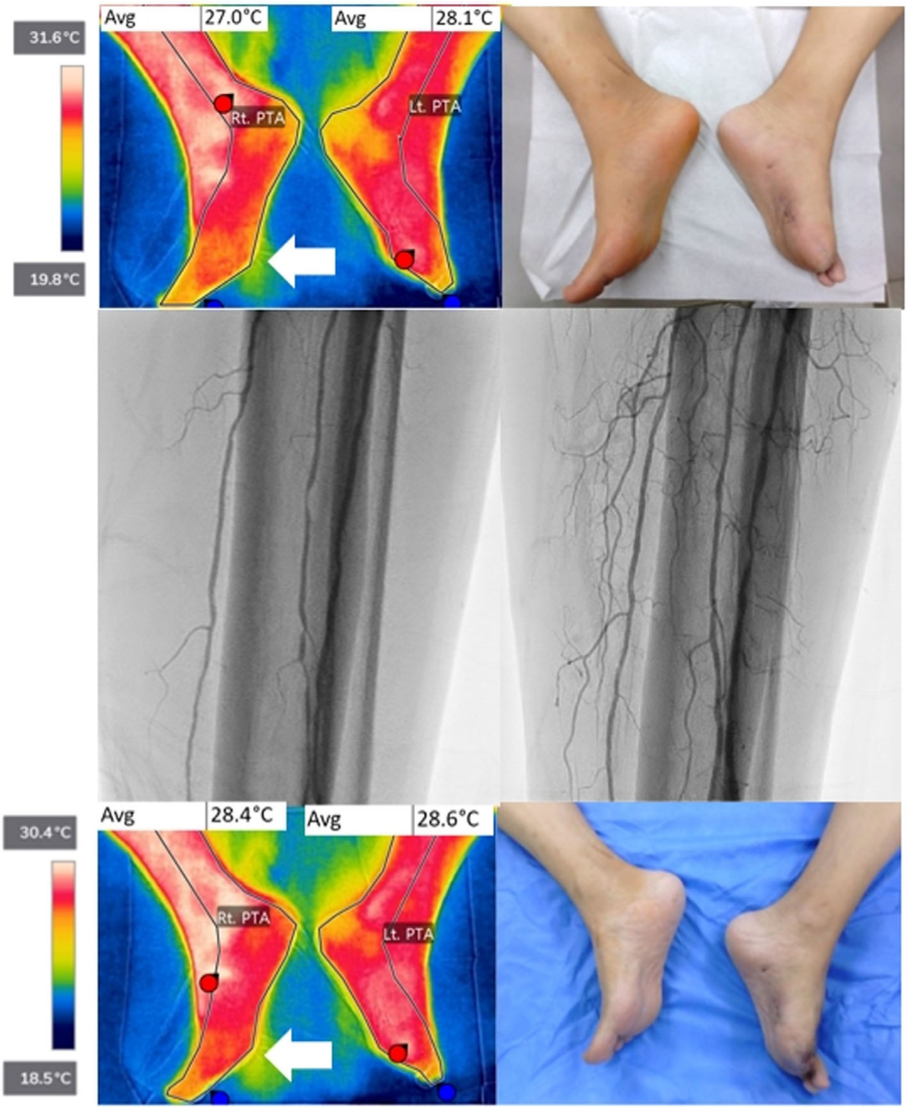

FIGURE 8 Top panel: A 73-year-old male patient presented with ischemic necrosis of the right second toe. The transcutaneous oxygen pressure ($TcPO_2$) in the right posterior tibial artery (PTA) angiosome is 18 mmHg and temperature is 27.0°C. Centre panel: Revascularization is performed due to total occlusion of the right PTA, resulting in improved perfusion. Bottom panel: Immediately after the procedure, the $TcPO_2$ value for the right PTA angiosome is 19 mmHg and the temperature is 28.4°C. Postoperative forward-looking infrared (FLIR) thermography of the right ATA angiosome shows restored temperature after improved blood flow through colour changes, with similar temperatures observed on both sides (White arrow).

However, this study was limited to capturing thermographic images of the dorsal view of the foot and had the constraint of a univariate analysis.

In this study, to compare $TcPO_2$ and FLIR thermography values with lower limb perfusion based on angiosomes, we divided existing imaging examinations and the location and severity of blocked vessels during angioplasty into three groups. According to the results, as the degree of vessel obstruction worsened, both $TcPO_2$ and FLIR thermography values of the impaired limb decreased in a statistically significant manner. $TcPO_2$ was found to be more sensitive to the extent of obstruction ($TcPO_2$, $p = 0.002$; FLIR thermography, $p = 0.015$; Table 4).

This study focused on the patient group that underwent revascularization, and limbs with altered perfusion were distinguished separately. These were further divided into the more impaired and less impaired angiosomes, allowing us to investigate the patterns of change in $TcPO_2$ and FLIR thermography based on the angiosomes. In terms of $TcPO_2$, a significant increase was observed in both the more impaired and less impaired angiosomes ($p = 0.011$ and 0.031, respectively). Similarly, FLIR thermography values increased in both types of angiosomes, but no statistical significance was observed in the less impaired angiosomes ($p = 0.103$). This could be attributed to the influence of indirect revascularization or communication arteries, as suggested in a previous study.[20] The ABI values were statistically significant ($p = 0.002$); however, evaluation based on angiosomes was not feasible.

Conversely, both $TcPO_2$ and FLIR thermography allowed for the specific evaluation of perfusion based on angiosomes, and a positive correlation between the two changes was identified ($p = 0.047$; Figure 5). In the less impaired angiosomes, an increase in $TcPO_2$ corresponded to an increase in FLIR thermography values; although, the difference was not statistically significant ($p = 0.751$). Therefore, FLIR thermography can potentially be used for perfusion evaluation similar to $TcPO_2$. Although it

TABLE 6 Articles using handheld forward-looking infrared (FLIR) camera for diagnosis and evaluation.

Article number	Author	Year	Diagnosis	Purpose	Location	Number of subject
1	Miccio et al.	2016	Burn	Burn depth analysis	Back (Porcine)	40
2	Jaspers et al.	2017	Burn	Burn depth analysis	Whole body	50
3	Xue et al.	2018	Burn	Burn depth analysis	Lower extremity	5
4	Goel et al.	2020	Burn	Burn depth analysis	Whole body	45
5	Ganon et al.	2020	Burn	Burn depth analysis	Whole body	40
6	Dhatt et al.	2021	Complex regional pain syndrome	Monitoring the response to treatment	Upper extremity	4
7	Fuman et al.	2021	Pressure sore	Prediction of pressure sore	Trunk	349
9	Illg C et al.	2022	Skin and soft tissue defect	Free flap perforator mapping	Lower extremity	50

Abbreviation: FLIR, forward-looking infrared.

can be concluded that $TcPO_2$ provides higher specificity and accuracy in assessing limb perfusion due to its statistically significant results, FLIR thermography offers the advantage of simultaneously evaluating multiple angiosomes, and the visual assessment based on colour is intuitive and convenient (Figure 3).

In the follow-up assessments spanning from 1 week to a total of 4 weeks after revascularization, $TcPO_2$ demonstrated its steepest increase on the first and seventh days after the procedure, followed by a gradual increase. In contrast, FLIR thermography exhibited a consistent and gradual increase immediately after the procedure, with values remaining relatively stable from the 14th day post-procedure (Figure 6).

In a study by Caselli et al., successful revascularization resulted in a peak increase in $TcPO_2$ by the third day, followed by gradual recovery over 28 days, leading to a reported optimal timing for wound healing at 3–4 weeks after the procedure, rather than immediately after.[36,37] This trend aligns with the observations of the present study. Interestingly, FLIR thermography showed an increase in post-procedure values that were sustained over time, a trend which is different from that of $TcPO_2$. A plausible hypothesis for this discrepancy is that the temperature increase due to post-procedure vasodilation, edema or increased perfusion caused by induration might result in overestimation using FLIR thermography compared with $TcPO_2$. Furthermore, the effects of revascularization become more evident during wound stabilization. Additionally, the gradual recovery of the subdermal plexus, which may have been compromised by revascularization, could have contributed to the gradual increase in skin temperature. Based on these findings, $TcPO_2$ appears to be advantageous than FLIR thermography for the long-term follow-up of perfusion.

Compared with $TcPO_2$, FLIR thermography has several advantages. While $TcPO_2$ is non-invasive, it has the potential for thermal injury because of the heating and attachment of the probe.[38] By contrast, FLIR thermography is completely contact free and safe. It allows for faster assessment, is considerably easier and more convenient to perform. Although $TcPO_2$ requires approximately 10–15 min for probe attachment and detachment, FLIR thermography enables immediate evaluation. Moreover, easy temperature analysis through smartphone applications is possible (Figure 3B), and it is less influenced by operator experience. Finally, it is more cost-effective than $TcPO_2$. Based on our institution's financial analysis, it demonstrates a notable cost–benefit advantage, with prices being approximately 1/60th lower than those of $TcPO_2$. Moreover, considering a relatively lower level of procedural complexity, we anticipate a significant reduction in the estimated patient-borne cost. We are actively implementing the medical application of FLIR thermography and introducing a concise algorithm that encompasses various non-invasive instruments (Figure 9).

However, one of the drawbacks of FLIR thermography is that it measures surface temperature, which can be influenced by the surrounding environment, and internal factors affecting temperature other than perfusion, such as infection and inflammation, must be considered. To mitigate these issues, all procedures were performed in the same operating room with consistent temperature and humidity levels and implemented a 10-min preparation time before measurements to minimize the impact of external temperature. Additionally, patients with an abnormal fever as a vital sign during hospitalization were excluded based on the inclusion criteria, further minimizing these drawbacks. Another

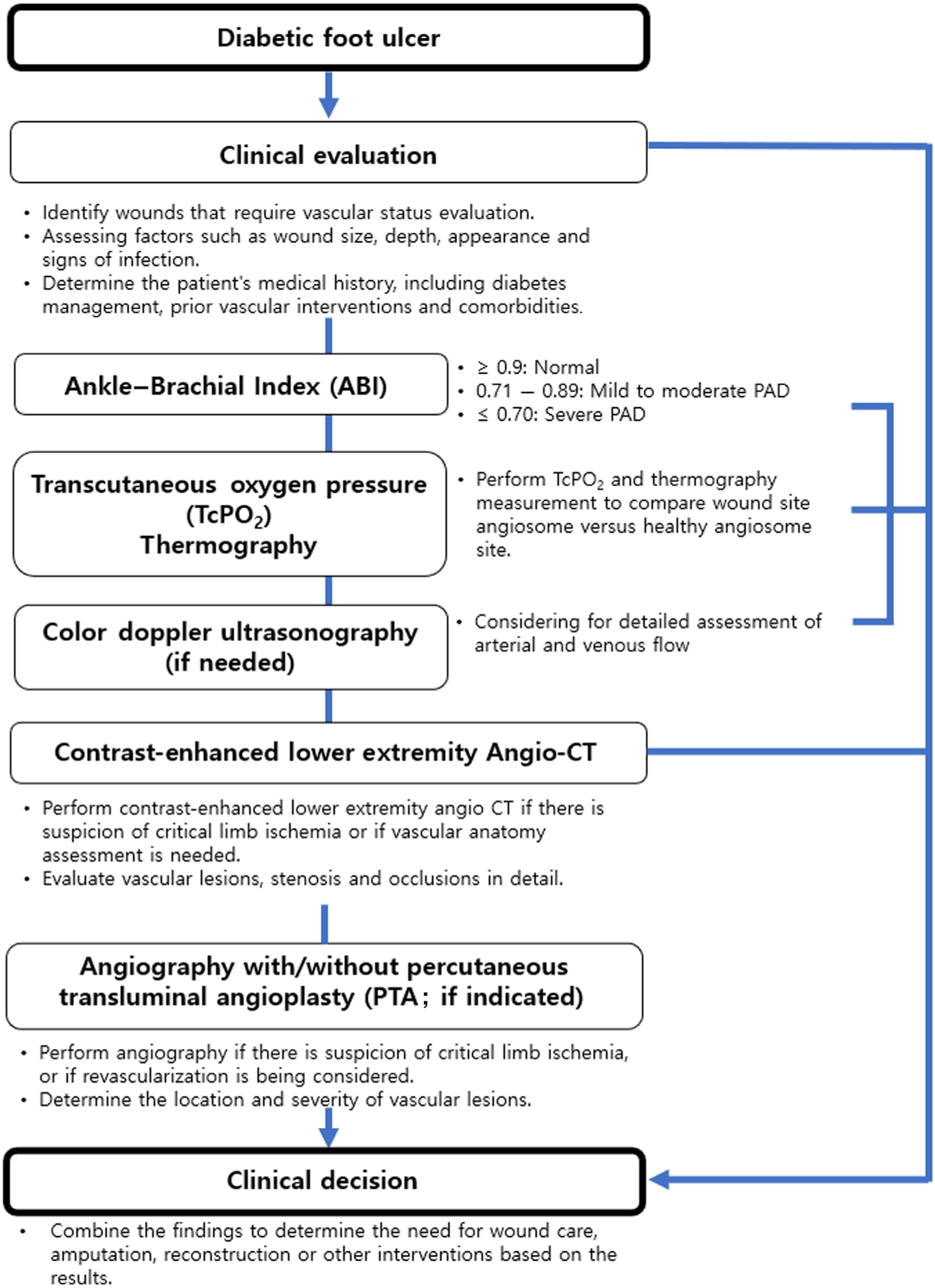

FIGURE 9 An algorithm for the vascular status evaluation of diabetic foot wounds. CT, computed tomography; FLIR, forward-looking infrared; PAD, peripheral artery disease; $TcPO_2$, transcutaneous oxygen pressure.

limitation is that the range of the parameter was relatively lower than that of $TcPO_2$, resulting in a lower sensitivity. Additionally, there is a challenge in distinguishing between the ischemic and non-ischemic zones due to the presence of subdermal plexus. Temperature measurements displayed a continuous spectrum, making this differentiation less precise. To address this issue, we established angiosome regions based on existing literature and calculated their average temperatures to determine the ischemic zones.

This study had several limitations. First, it was a retrospective study. Second, the relatively small number of participants and lack of consideration of the effects of other medications that can influence the vascular state, such as beta-blockers, are notable points. Additionally, the exclusion of the influence of PA, even though it is a foot angiosome, can be considered a limitation. However, the majority of blood supply to the foot corresponds to the via ATA and PTA angiosomes,[7] and the results obtained from the correlation analysis between $TcPO_2$ and FLIR thermography values within these areas are statistically significant. Therefore, in the context of angiosome-based evaluation, this study's value lies in confirming FLIR as a convenient and useful tool that, alongside $TcPO_2$, exhibits a correlation, as well as the added advantages of rapid image capture, ease of use and cost-effectiveness. Moreover, the significance of this study extends to identifying the potential for the future use of these non-invasive tools in the advancement of home care systems.

In conclusion, this study confirmed that FLIR thermography serves as a viable diagnostic tool with a statistical significance comparable to that of $TcPO_2$ when assessing lower limb perfusion based on angiosomes. Although an indirect method, FLIR thermography is versatile in clinical applications and is useful for evaluating lower limb perfusion because of its intuitive and non-contact nature.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT; Grant number 2020R1A2C1100891) and was supported by Soonchunhyang research fund.

FUNDING INFORMATION

National Research Foundation of Korea, Grant/Award Number: 2020R1A2C1100891; Soonchunhyang University Research Fund.

CONFLICT OF INTEREST STATEMENT

No potential conflict of interest relevant to this article was reported.

DATA AVAILABILITY STATEMENT

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

ETHICS STATEMENT

Institutional Review Board Statement: The study was approved for exemption by the Institutional Review Board of Soonchunhyang University Hospital (IRB exemption No. 2023-03-017).

Informed Consent: The patients provided written informed consent for the publication and use of his or her images.

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How to cite this article: Nam HJ, Wee SY, Kim SY, et al. The correlation between transcutaneous oxygen pressure ($TcPO_2$) and forward-looking infrared (FLIR) thermography in the evaluation of lower extremity perfusion according to angiosome. *Int Wound J*. 2024;21(2): e14431. doi:10.1111/iwj.14431