ASSESSMENT OF LOWER EXTREMITY PERFUSION: WHAT DO THE TEST RESULTS MEAN?

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Objectives

• What are the non-invasive tests for lower extremity PAD and how should we interpret them?
  • What do the results mean for the patient and how should we use them to treat the patient?
Purpose of Noninvasive Arterial Testing

- Objectively confirm presence of PAD/ arterial ischemia
- Provide quantitative and reproducible physiological data concerning its severity
- Document location and hemodynamic significance of individual arterial lesions
- Monitor the progression of disease and impact of revascularization
- Monitor for restenosis after revascularization

- Comprehensive evaluation of PAD requires integration of Clinical (history and physical exam), Physiologic, and Anatomic (Imaging) information
Noninvasive Arterial Testing

• Direct
  • Duplex scanning of arteries (patency and flow in individual vessels)

• Indirect
  • Provide crucial physiologic information about the perfusion of the whole limb
  • Use inference from accessible vessels to estimate degree of stenosis and disease
  • Analysis of velocity waveforms, pressure measurements, plethysmography
Non-Invasive Physiologic Vascular Testing

- “Pencil” Doppler
- Ankle-brachial indices
- Segmental pressures
- Toe-brachial indices
- Pulse volume recordings
- Exercise Stress Testing
- Duplex Imaging
- Transcutaneous Oxygen Tension
- Other
Doppler Ultrasound

- Detect blood flow velocity
- Hand-held continuous wave doppler detect frequency shifts, amplify it, and send it speakers
- Velocity of blood flow is proportional to frequency shifts and is heard a change in pitch of the audio signal

\[
f_D = f_r - f_o = \frac{2f_o v}{c} \cos \theta
\]
Doppler Analysis

• Aural Qualitative Interpretation (Bedside)
  • Absence of flow
  • ↑ pitch = ↑ velocity = luminal narrowing
  • normal triphasic signal vs. dampened monophasic waveform (downstream from a significant stenosis)

• Quantitative Analysis
  • Spectrum analyzers

  • Triphasic: normal artery
  • Biphasic: mild stenosis, mildly increased velocity
  • Monophasic: tight stenosis, greatly increased velocity
  • Dampened monophasic: distal to tight stenosis, reduced velocity
Pressure: Why it measures “perfusion”

- Perfusion = Blood Flow (volume of blood/time/tissue mass)
- Flow is more difficult to measure than pressure
- Pressure differentials drive flow
- Pressures are an acceptable surrogate for flow
Ankle Brachial Index

| Right ABI | Higher right ankle pressure | Higher arm pressure |
| Left ABI | Higher left ankle pressure | Higher arm pressure |

**Interpretation of ABI**

<table>
<thead>
<tr>
<th>Pressure Range</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;1.30</td>
<td>Noncompressible</td>
</tr>
<tr>
<td>1.00–1.29</td>
<td>Normal</td>
</tr>
<tr>
<td>0.91–0.99</td>
<td>Borderline (equivocal)</td>
</tr>
<tr>
<td>0.41–0.80</td>
<td>Mild to moderate peripheral arterial disease</td>
</tr>
<tr>
<td>0.00–0.40</td>
<td>Severe peripheral arterial disease</td>
</tr>
</tbody>
</table>
Ankle–Brachial Index: Rationale

• Rationale:
  • Accounts for normal variation in central pressure throughout the day
    • Normalized value less variable than the central pressure alone
  • SD for ABI = 0.07 → Change of .15 is significant
  • More accurate assessment of the leg: allow ankle pressure could reflect hypotension or PAD
Ankle Brachial Index: Limitations

- The absolute perfusion pressure is an important indicator of critical ischemia at a single point in time

- Significant bilateral subclavian or axillary artery occlusive disease may result in a falsely elevated ABI

- Chronic renal failure or diabetes: medial calcinosis of the popliteal and tibial arteries
  - Falsely elevated ABI
  - TBI/PVR useful

- Improper cuff size

- Although very sensitive (90%) and specific (90%), may not detect subclinical PAD
ABI and Extent of PAD

- ABI > 0.5: Single Vessel Disease
- ABI <0.5: Multilevel disease

**Figure 14-5** Resting ankle-brachial index (ankle systolic/arm systolic) measured in normal limbs and in limbs with arterial obstruction localized to different anatomic levels. SEM, standard error of the mean. (Modified from Strandness DE Jr, Sumner DS. Hemodynamics for Surgeons. New York, NY: Grune & Stratton; 1975; data from Wolf EA Jr, Sumner DS, Strandness DE Jr. Correlation between nutritive blood flow and pressure in limbs of patients with intermittent claudication. Surg Forum. 1972;23:238.)
Ankle-Brachial Indices and Clinical Symptoms

### Functional Impairment

<table>
<thead>
<tr>
<th>Symptom</th>
<th>ABI Range</th>
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<tr>
<td>Noncompressible</td>
<td>&gt;1.2</td>
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<tr>
<td>Normal</td>
<td>0.9-1.2</td>
</tr>
<tr>
<td>Claudication</td>
<td>0.7-0.9</td>
</tr>
<tr>
<td>Rest Pain</td>
<td>0.4-0.7</td>
</tr>
<tr>
<td>Tissue Loss</td>
<td>&lt;0.4</td>
</tr>
</tbody>
</table>

Variability in correlation of ABI to symptoms given other patient comorbidities.
Prognostic Value of the ABI for the Limb

• Limb Outcome in CLI
  Pressure required for healing of tissue loss
  • >60 mmHg in non-diabetics
  • >80 mmHg in diabetics
  • Interpret ABI with caution in patients with tissue loss
    • Index may seem adequate but pedal disease/ inaccurate angiosome perfusion may limit healing

• Limb Outcome in Claudicants
  • ABI > 0.5 infrequently associated with progression to CLI over 6 years
  • ABI < 0.5 and DM most frequently associated with progression from claudication to CLI
Segmental Pressures

- Determining level of disease with serial BP cuffs
- Gradients $>20$mmHg suggest significant obstruction
- Does NOT assess non-axial arteries
  - Normal gradients may be found in pts with disease if collaterals are large.
- Decrease in pressure $\geq 20$mmHg signifies disease
  - $\geq 40$ usually indicates occlusion
- Duplex mapping more commonly used
## Segmental Pressures

<table>
<thead>
<tr>
<th></th>
<th>Normal</th>
<th>Iliac</th>
<th>SFA</th>
<th>Iliac and SFA</th>
<th>Below Knee</th>
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</thead>
<tbody>
<tr>
<td>Arm</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
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<tr>
<td>Upper Thigh</td>
<td>160</td>
<td>110</td>
<td>160</td>
<td>110</td>
<td>160</td>
</tr>
<tr>
<td>Above Knee</td>
<td>150</td>
<td>100</td>
<td>100</td>
<td>70</td>
<td>150</td>
</tr>
<tr>
<td>Below Knee</td>
<td>140</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td>140</td>
</tr>
<tr>
<td>Ankle</td>
<td>130</td>
<td>80</td>
<td>80</td>
<td>50</td>
<td>90</td>
</tr>
</tbody>
</table>
Digital (Toe) pressures

- Useful in patients with pedal artery occlusive disease or highly calcified vessels (incompressible)
- Normal digital waveforms/pressure in patients with calcified proximal vessels -> minimal restriction to blood flow
- Obstructive digital waveform/reduced pressure in presence of normal ankle pulses -> pedal artery occlusive disease or atheroembolism
• Pressures of 30 mmHg and lower associated with ischemic symptoms
• Foot lesions heal when pressure >30-40 mmHg
• TBI
  • Less than 0.7 = abnormal
  • 0.2 to 0.69 = moderate arterial disease
  • Less than 0.2 = severe disease
Plethysmography

• Based on detection of volume changes in the limb in response to arterial inflow
• Can be modified to produce pulse waveforms and determine digital pressures
• 3 types
  • Mercury strain gauge plethysmography
  • Air plethysmography (pulse volume recordings)
  • Photoplethysmography
Air Plethysmography (Pulse Volume Recordings)

- Obtained with partially inflated segmental blood pressure cuffs that detect volume changes sequentially down a limb
- Normal pulse volume waveform:
  1. Sharp systolic upstroke
  2. Peak
  3. Downstroke
  4. Dicrotic notch
Pulse Volume Recordings

- Less affected by Arterial calcification
- More accurate with segmental pressures
- Small changes in limb volume that result from pressure changes with each pulsation are recorded as arterial contours
Air Plethysmography (Pulse Volume Recordings)

• Qualitative evaluation based on shape of curve

• Quantitative interpretive criteria not in widespread clinical use

• Lack of reliable, reproducible, quantitative data limits utility of PVR
Photoplethysmography

- Not a method to record volume change
- Photoelectrode detects changes in cutaneous blood flow
- Combination with pneumatic cuffs detects digital systolic pressures
Exercise Testing

- Patients with mild-moderate disease often have normal flow rates at rest.

- Exercise induces vasodilatation and increases flow, “unmask[s]” flow limiting lesion

- Measurement of Doppler-determined pressures can be combined with treadmill exercise testing

- Useful in a patient with symptoms of claudication who has palpable pedal pulses at rest and a normal or near-normal ABI
Exercise Stress Testing

- Pre and Post exercise ABIs compared
- Criteria for a positive exercise treadmill test
  - Decrease in absolute ankle pressure of 20 mm Hg
  - Decrease in ABI of 0.2 in symptomatic extremity
- Patients with claudication secondary to arterial insufficiency show a significant decrease in the post-exercise ABI
Peripheral Arterial Duplex

- Blood flow and anatomic Information
  - Blood flow=Pulsed Doppler spectral analysis
  - Anatomic=B-mode and color Doppler imaging
- Sensitivity (vs. angio) excellent
  - 90% at the iliac artery to 70% at the popliteal artery
  - 80-90% sensitivity for tibioperoneal arteries
- Sensitivity not influenced by the severity of atherosclerotic disease
Lower Extremity Occlusive Disease

• Maximum velocity at stenosis compared to velocity proximal to stenosis

• PSV ratio 1.5-2 / 1 = 30-49% stenosis
  2-4 / 1 = 50-75 % stenosis
  > 4 / 1 = > 75 % stenosis

• Occlusion characterized by gradual fall in velocity and absence of waveform
Transcutaneous Oxygen Tension (tcPO₂)

- Reflect metabolic state of target tissue
- Quantifies O₂ molecules transferred to skin after heating
- Values > 55 mm Hg are considered normal
- Patients with CLI: tcPO2 20-20 mmHg
- Wound healing requires tcPO2 > 40 mm Hg
- Most helpful in severe ischemia
  - Not impacted by calcification (DM)
- Determining level of amputation
  - Measured dorsum of foot, 10 cm below and 10 cm above knee
- Response to hyperbaric therapy (100% O₂ inhalation)
- Influenced by many factors (age, weight, temp, edema, etc.)
- Time consuming
Other non-invasive tests of microcirculation

- Laser Doppler
- Vasoreactivity
- Capillaroscopy
- Pulp skin flow
- Iontophoresis

- None routinely utilized
# Rutherford Classification of Chronic Limb Ischemia

## Table II. Clinical categories of chronic limb ischemia*

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

*AP: Ankle pressure; PVR, pulse volume recording; TP, toe pressure; TM, transmetatarsal.

*Grades II and III, categories 4, 5, and 6, are embraced by the term chronic critical ischemia.

†Five minutes at 2 mph on a 12% incline.
Corollary:

A broad range of perfusion deficits may be limb-threatening in specific circumstances, depending on severity of tissue loss and concomitant factors.

The utility of a single threshold value for “critical limb ischemia” in the presence of tissue loss is questioned.
The Society for Vascular Surgery Lower Extremity Threatened Limb Classification System: Risk stratification based on Wound, Ischemia, and foot Infection (WIfI)

Joseph L. Mills, Sr, MD, a Michael S. Conte, MD, b David G. Armstrong, DPM, MD, PhD, a Frank B. Pomposelli, MD, c Andres Schanzer, MD, d Anton N. Sidawy, MD, MPH, e and George Andros, MD, f on behalf of the Society for Vascular Surgery Lower Extremity Guidelines Committee, Tucson, Ariz; San Francisco and Van Nuys, Calif; Brighton and Worcester, Mass; and Washington, D.C.

- **Wound**: extent and depth
- **Ischemia**: perfusion/flow
- **Foot Infection**: presence and extent

Excluded: acute limb ischemia, emboli/"trash foot", trauma, vasculitides, pure venous ulcers, neoplastic disease, radiation

*J Vasc Surg 2014; 59(1) 220-34*
## Wound Grade – Clinical Category

<table>
<thead>
<tr>
<th>Grade</th>
<th>Clinical Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Ischemic rest pain; Pre-gangrenous skin change, without frank ulcer or gangrene (Pedis or UT Class 0)</td>
</tr>
<tr>
<td>1</td>
<td>Minor tissue loss: small shallow ulceration) &lt; 5 cm² on foot or distal leg (Pedis or UT Class 1); no exposed bone unless limited to distal phalanx</td>
</tr>
<tr>
<td>2</td>
<td>Major tissue loss: deeper ulceration(s) with exposed bone, joint or tendon, ulcer 5-10 cm² not involving calcaneus – (Pedis or UT Classes 2 and 3); gangrenous changes limited to digits. <em>Salvageable with multiple digital amps or standard TMA ± skin coverage</em></td>
</tr>
<tr>
<td>3</td>
<td>Extensive ulcer/gangrene &gt; 10 cm² involving forefoot or midfoot; full thickness heel ulcer &gt; 5 cm² + calcaneal involvement. <em>Salvageable only with complex foot reconstruction, nontraditional TMA (Chopart/Lisfranc); flap coverage or complex wound management needed</em></td>
</tr>
</tbody>
</table>
### Ischemia Grade – Noninvasive Assessment

<table>
<thead>
<tr>
<th>Grade</th>
<th>ABI</th>
<th>Ankle SP</th>
<th>TP</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>≥ 0.80</td>
<td>≥ 100 mm Hg</td>
<td>≥ 60 mm Hg</td>
</tr>
<tr>
<td>1</td>
<td>0.60-0.79</td>
<td>70-99 mmHg</td>
<td>40-59 mm Hg</td>
</tr>
<tr>
<td>2</td>
<td>0.40-0.59</td>
<td>50-69 mm Hg</td>
<td>30-39 mm Hg</td>
</tr>
<tr>
<td>3</td>
<td>&lt; 0.40</td>
<td>&lt; 50 mm Hg</td>
<td>&lt; 30 mm Hg</td>
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</table>

ABI=ankle brachial index; SP= systolic pressure; TP=toe pressure
<table>
<thead>
<tr>
<th>Grade</th>
<th>Clinical Description</th>
<th>IDSA</th>
<th>IWGDF Class</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>wound without purulence or manifestations of infection</td>
<td>uninfected</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>&gt;2 manifestations of infection (erythema or purulence, pain tenderness, warmth or induration) any cellulitis or erythema extends &lt; 2cm around ulcer; infection is limited to skin or subcutaneous tissues; no local complications or systemic illness</td>
<td>mild</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>Infection in patient who is systemically and metabolically stable but has &gt;1 of the following: cellulitis extending 2cm, lymphangitis; spread beneath fascia; deep tissue abscess; gangrene; muscle, tendon, joint or bone involvement</td>
<td>moderate</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>Infection in patient with systemic or metabolic toxicity</td>
<td>severe</td>
<td>4</td>
</tr>
<tr>
<td>Risk of amputation</td>
<td>Proposed clinical stages</td>
<td>Wijkstra spectrum score</td>
<td></td>
</tr>
<tr>
<td>--------------------</td>
<td>--------------------------</td>
<td>------------------------</td>
<td></td>
</tr>
<tr>
<td>Very low</td>
<td>Stage 1</td>
<td>W0 10 f0,1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>W0 11 f0</td>
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<td></td>
<td>W1 10 f0,1</td>
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<tr>
<td></td>
<td></td>
<td>W1 11 f1</td>
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<tr>
<td>Low</td>
<td>Stage 2</td>
<td>W0 10 f2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>W0 11 f1</td>
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<td></td>
<td></td>
<td>W0 12 f0,1</td>
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<td></td>
<td></td>
<td>W0 13 f0</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>W1 10 f2</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>W1 11 f1</td>
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<td>Stage 3</td>
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<td>W1 11 f2</td>
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<td>W1 12 f1</td>
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<td>W2 10 f2</td>
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<td>W3 10 f0,1</td>
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<td>High</td>
<td>Stage 4</td>
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<td>W1 12,3 f1,2,3</td>
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<td>W2 10 f3</td>
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<td>W2 12 f1,2,3</td>
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<td></td>
<td></td>
<td>W3 11,2,3 f0,1,2,3</td>
<td></td>
</tr>
</tbody>
</table>

Stage 1
- Minimal ischemia; no/minor TL
- Not in strict “CLI” definition

Stage 2
- Stage 1 with more infection
- Rest pain without infection
- Minor tissue loss/ mod infection

Stage 3
- Range of tissue loss/ischemia
- Mild to mod infection

Stage 4
- Advanced in one or more categories
- Stage 5: unsalvageable foot

Estimated 1-Year Amputation Risk by Stage

## Risk of amputation versus WIfI Stage: Compilation of published data

<table>
<thead>
<tr>
<th>Study (year): # Limbs at Risk</th>
<th>Stage 1</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cull (2014):151</td>
<td>37 (3%)</td>
<td>63 (10%)</td>
<td>43 (23%)</td>
<td>8 (40%)</td>
</tr>
<tr>
<td>Zhan (2015): 201</td>
<td>39 (0%)</td>
<td>50 (0%)</td>
<td>53 (8%)</td>
<td>59 (64%)*</td>
</tr>
<tr>
<td>Darling (2015): 551</td>
<td>5 (0%)</td>
<td>111 (10%)</td>
<td>222 (11%)</td>
<td>213 (24%)</td>
</tr>
<tr>
<td>Causey (2016): 160</td>
<td>21 (0%)</td>
<td>48 (8%)</td>
<td>42 (5%)</td>
<td>49 (20%)</td>
</tr>
<tr>
<td>Beropoulis (2016): 126</td>
<td>29 (0%)</td>
<td>42 (2%)</td>
<td>29 (3%)</td>
<td>26 (12%)</td>
</tr>
<tr>
<td>Ward (2016): 98</td>
<td>5 (0%)</td>
<td>21 (14%)</td>
<td>14 (21%)</td>
<td>58 (34%)</td>
</tr>
<tr>
<td>Darling (2017): 992</td>
<td>12 (0%)</td>
<td>293 (4%)</td>
<td>249 (4%)</td>
<td>438 (21%)</td>
</tr>
<tr>
<td>Robinson (2017): 262</td>
<td>48 (4%)</td>
<td>67 (16%)</td>
<td>64 (10%)</td>
<td>83 (22%)</td>
</tr>
<tr>
<td>Mathioudakis (2017): 279</td>
<td>95 (6.5%)</td>
<td>33 (6%)</td>
<td>87 (8%)</td>
<td>64 (6%)***</td>
</tr>
</tbody>
</table>

| **N = 2820 (weighted mean)** | 291 (3.2%) | 728 (6.8%) | 803 (8.5%) | 998 (24%) |

| Median (% 1 year amputation) | 0% | 8% | 8% | 22% |
Benefit of revascularization varies with severity of limb threat and ischemia
Limb staging and appropriateness of revascularization

- CLTI represents a range of limb severity and ischemia as described in WIfI staging.
- Severe ischemia (WIfI ischemia grade 3) mandates revascularization for limb salvage.
- With increased stages of limb threat (WIfI stages 3, 4) moderate degrees of ischemia (grades 1, 2) may be appropriate to address.
- Low risk limbs (WIfI Stage 1) should be treated with wound care; revascularization should be reserved for failure to heal (50% within 4-6 weeks) or clinical signs of deterioration.
- Not indicated for Ischemia grade 0.
Assessment of lower extremity ischemia using smartphone thermographic imaging

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ABSTRACT

Conventional diagnostic modalities for assessing arterial circulation or tissue perfusion include blood pressure measurement, ultrasound evaluation, and contrast-based angiographic assessment. An infrared thermal camera can detect infrared radiation energy from the human body, which generates a thermographic image to allow tissue perfusion analysis. We describe a smartphone-based miniature thermal imaging system that can be used as an adjunctive imaging modality to assess tissue perfusion. This smartphone-based camera device is noninvasive, simple to use, and cost-effective in assessing patients with lower extremity tissue perfusion. Assessment of patients with lower extremity arterial ischemia can be performed by a variety of diagnostic modalities, including ankle-brachial index, absolute systolic ankle or toe pressure, transcutaneous oximetry, arterial Doppler waveform, arterial duplex ultrasound, computed tomography scan, arterial angiography, and thermal imaging. We herein describe a noninvasive imaging modality using smartphone-based infrared thermography. (J Vasc Surg Cases Innov Techniq 2017;3:205-6.)

Fig 2. A, Preoperative infrared thermography in a patient (patient 2) with ischemic rest pain in the left foot and toes. B, Postoperative infrared thermography after femorotibial artery bypass demonstrated significant improvement in tissue perfusion in the toes.
Conclusions

• Noninvasive testing plays a crucial role in evaluation of PAD

• Guides further invasive testing and treatment

• Important to utilize both indirect (physiologic) and direct (duplex) testing to understand the pathophysiology of each patient

• Interpretation of the tests is not necessarily “cookbook” or algorithmic….comprehensive evaluation of PAD requires integration of clinical, non-invasive physiologic, and anatomic information