Introduction

- Prior to 1960’s → No tool to quantify blood flow
- Vascular surgeons pioneered field of vascular ultrasound
- Duplex imaging developed at U Washington through 1960-70’s¹
- Living field of continued development

Outline

- **Vascular Ultrasound Instrumentation/Physics**
  - **Arterial testing**
    - Carotid
    - Lower extremity arterial/physiologic testing
    - Mesenteric/Renal
  - **Venous testing**
    - Acute/chronic DVT
    - Venous insufficiency
**Ultrasound Instrumentation**

- **System components**
  - Transducer/Probe
    - Continuous Wave vs. Pulsed Wave
    - Linear vs. curved array
  - Image/signal processor
  - Display
    - Speaker vs. screen
Vascular Ultrasound Physics

- Doppler effect
- Continuous vs. Pulsed Wave Doppler
- Spectral analysis
- Color Flow Imaging
The Doppler Effect (Doppler Shift)

Change in frequency of a sound wave produced by relative motion between a sound source and a listener

- **Moving toward each other:**
  - Frequency change is positive (increased)

- **Moving away from each other**
  - Frequency change is negative (decreased)
Doppler Equation

Frequency change proportional to Velocity

$$\Delta f = 2f V \cos \theta \frac{C}{C}$$

$\Delta f$ = Doppler shifted frequency

$f$ = Frequency of transmitted Ultrasound

$V$ = Velocity of blood cells

$\theta$ = Doppler Angle

$C$ = Speed of sound in tissue (1540 m/sec)
Transmitting Frequency and Depth

- Decreased energy as sound passes through tissue
- Depth of imaging inversely proportional to transmitting frequency
- Low freq (≤ 5MHz) penetrate more deeply than high freq (≥7 MHz)
**Continuous Wave Doppler**
- Transmitting and receiving transducers operated simultaneously & continuously
- Cannot identify flow at specific site/depth
- Qualitative assessment of flow
- Bedside dopplers

**Pulsed Wave Doppler**
- Signal transducer alternated between transmitting and receiving
- Able to determine flow at specific site/depth
- Burst of US (pulse) is transmitted and after specific time interval, receiver...
Spectral Analysis: Waveform

- **Doppler Signal Processing**

- **Fast Fourier Transform (FFT)**
  - Generates amplitude vs. frequency profile thru analysis of the detected signals

- Displays **frequency** and amplitude content over time

- *Frequency* = proportional to velocity
- *Density* = proportional to number of reflectors (blood cells/proteins) moving through sample volume
- Complementary to waveform analysis for displaying pulsed Doppler information

- **Duplex**: Color coded Doppler information superimposed on B-mode image

- Color flow: color based on flow direction and a single (mean) freq. estimate for each site
Aliasing occurs when sampling is not frequent enough to capture actual movement.

A similar effect is seen in film:
- Car wheels/spokes going reverse due to lower frame rate of film.
Aliasing occurs when the Nyquist limit (frequency) is exceeded.

Nyquist limit = 1/2 PRF

Aliasing in spectral waveforms:
- Decrease by increasing pulse repetition frequency (PRF)
- Waveform wraps around and appears as flow in the opposite direction
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Arterial testing: Carotid Artery Duplex
Carotid Duplex Ultrasound

- First vascular duplex developed and validated vs. angiography
- Acquire data
  - % Stenosis, plaque character, anatomy
  - Standardized protocol
- Few (No) Contraindications
- Limitations
  - Recent neck surgery – discomfort
  - Marked tortuosity – difficult probe angle
  - Distal ICA disease – difficult access
Carotid Duplex: Goals of full exam

- Identify, distinguish and compare CCA, ICA, ECA, vertebral, (SC)
- Normal flow patterns and flow characteristics
- Evaluate, profile, and grade stenoses
- Distinguish vessel tortuosity vs. stenosis
- Assess plaque and surface characteristics
Carotid Artery Duplex: Vessel Identification

- Identify, distinguish and compare all vessels
- Bilateral exam:
  - CCA
    - Prox: near origin
    - Mid: 2 cm prox to bifur (ratio)
    - Dist: prox to bifur
  - ECA origin for disease
  - ICA
    - Prox: 1-2 cm (bulb)
    - Mid: dist to dilation, 2-3 cm
    - Dist: ≥ 3 cm distal
  - Vertebral
    - mid neck for direction
    - origin for disease
- Transverse and longitudinal scan
- Distinguish ICA from ECA
  - Hemodynamics, branches, size, location
Carotid Artery Duplex: Normal Waveform Characteristics

- Representative flow pattern for each location
  - **CCA** – combination of ICA & ECA flow patterns; sharp upstroke, diastolic flow \( > 0 \)
  - **ICA** – low resistance, flow above 0 throughout diastole
  - **ECA** – higher resistance, may have forward diastolic flow or reversal with flow to 0

- Distinguish ICA from ECA
- Identify and distinguish normal flow disturbances
  - Flow separation
Normal Carotid Bulb: Flow Separation

- Unidirectional flow along the flow divider throughout systole
- Reversal of flow at posterolateral region at peak systole (center stream)
- No flow along outer wall at end diastole
Vertebral Artery

- Normal vertebral artery, low resistance similar to ICA
- Normal flow direction is cephalad (antegrade)
- Retrograde flow may be noted with subclavian stenosis or occlusions
Carotid Duplex: Evaluate and Profile Stenosis

- **Pre-stenotic region**
  - Disturbance reflects the geometry of stenosis
  - Spectral waveform may be normal

- **Stenosis/maximum velocity**
  - Focal or complicated
  - Requires careful survey with Doppler sample volume
  - May be distal to the site of visual narrowing

- **Post-stenotic turbulence**
  - Random, chaotic activity
  - Verifies the presence of true stenosis
Carotid Artery Duplex: Tortuosity

- Clarify tortuosity from stenosis
- Doppler angle difficult to determine/keep constant
- Increased velocity
- No post-stenotic turbulence
- Normal flow disturbances present downstream
- Caution: misinterpret as stenosis
Carotid Artery Duplex: Plaque Characteristics

- Qualitative description, brightness, texture
  - **Homogeneous** – uniform texture & echogenicity
  - **Heterogeneous** – mixed density echogenicity
  - **Calcific** – bright echogenicity with shadowing
  - **Anechoic** – without echoes
  - **Hypoechoic** – low echogenicity
  - **Hyperechoic** – increased echogenicity
Carotid Artery Duplex: Data Collection

- Sample Volume
- Position center of vessel or flow channel
- Site of max velocity increase
- Document / Measure PSV & EDV
## Carotid Duplex Ultrasound: UW Velocity-Stenosis Criteria

<table>
<thead>
<tr>
<th>ICA stenosis</th>
<th>ICA/bulb Velocity</th>
<th>Spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>PSV&lt;125cm/s, no plaque (flow separation)</td>
<td>No broadening</td>
</tr>
<tr>
<td>1-15%</td>
<td>PSV&lt;125cm/s, minimal plaque (loss of flow separation)</td>
<td>Limited broadening (late systole)</td>
</tr>
<tr>
<td>16-49%</td>
<td>PSV&lt;125cm/s, moderate plaque</td>
<td>Broadening throughout systole</td>
</tr>
<tr>
<td>50-79%</td>
<td><strong>PSV&gt;125cm/s</strong>, EDV&lt;140cm/s, heavy plaque</td>
<td>Broadening throughout systole</td>
</tr>
<tr>
<td>80-99%</td>
<td>PSV&gt;125cm/s, <strong>EDV&gt;140cm/s</strong>, severe plaque</td>
<td>Broadening throughout systole</td>
</tr>
<tr>
<td>Occlusion</td>
<td>No ICA doppler signal, ED flow to zero in CCA</td>
<td></td>
</tr>
</tbody>
</table>
## Carotid Duplex Ultrasound: Bluth Criteria

<table>
<thead>
<tr>
<th>ICA stenosis</th>
<th>ICA/bulb Velocity</th>
<th>ICA/CCA ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>PSV&lt;110cm/s, EDV&lt;40cm/s</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>1-39%</td>
<td>PSV&lt;115cm/s, EDV&lt;40cm/s</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>40-59%</td>
<td>PSV&lt;130cm/s, EDV&gt;40cm/s</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>60-79%</td>
<td>PSV&gt;130cm/s, EDV&gt;40cm/s</td>
<td>&gt;1.8</td>
</tr>
<tr>
<td>80-99%</td>
<td>PSV&gt;250cm/s, EDV&gt;100cm/s</td>
<td>&gt;3.7</td>
</tr>
<tr>
<td>Occlusion</td>
<td>No ICA doppler signal</td>
<td></td>
</tr>
</tbody>
</table>
Post-intervention Criteria

- Criteria for surveillance after Carotid stenting:
  - In general, PSV more reliable and higher than native disease due to flow changes in stent
  - Carotid in-stent restenosis:
    - >50%: PSV > 220 cm/s, ICA/CCA: 2.7
    - >80%: PSV > 340 cm/s, ICA/CCA: 4.15

1. Lal et al. JVS 2008
Arterial testing:

Extremity Arterial/Physiologic Testing
Physiologic Testing—Why?

- Designed to define **physiologic** rather than **anatomic** deficits

**Address:**
- Is significant arterial occlusive disease present?
- How severe is the physiologic impairment?
- Where are the responsible lesions located?
- In multilevel disease, which arterial segments are most severely involved?
- In tissue loss, what is the potential for primary healing?
Extremity Arterial Physiologic Testing: Overview

- Pressure measurements-
  - Ankle pressure, ABI
  - Segmental LE pressures
  - Toe pressures
- Stress testing
  - Exercise
- Doppler Ultrasound
  - Waveform analysis
  - Audible signals
- Plethysmography/PVR
  - Pulse volume recording
Pressure measurements

- Based on basic equation:
  - \( \Delta P \) (pressure) = \( Q \) (flow) \times R (resistance)
  - For constant flow \( \Rightarrow \)
    - \( \uparrow R \) (stenosis) \( \sim \) \( \uparrow \Delta P \) (pressure gradient)
Ankle-Brachial Index

- Normal $\geq 1.0$, Abnormal $< 0.9$
  - Ankle pressure higher than arm pressure due to distal pressure wave augmentation
  - Provides normalization of ankle pressure
  - Reflects degree of occlusive disease over entire lower extremity system

- Technique:
  - Place pneumatic cuff around ankle just above malleolus
  - Inflate cuff and measure pressure when signal return over DP and PT
  - $\text{ABI} =$ Higher of two pressures/highest brachial pressure

Adapted from Yao JST. Hemodynamic studies in peripheral arterial disease. Br J Surg. 1970; 57: 761.
- Provides pressure measurements at 3 or 4 anatomic points across LE to identify degree and location of occlusive disease.

- Gradients > 30mmHg between any two indicates presence of significant occlusive disease.
Toe pressures

- Normal toe pressures 20-40mmHg less than ankle pressure
- Toe-brachial index ~ 0.75 normal, 0.5 claudication, 0.2 CLI
- Can be used when calcific ankle vessels preclude pressure measurement
- Predictor of primary healing
  - **toe pressures <30mmHg** predict poor healing
Some arterial stenoses only become significant when flow is increased → WHY?

Back to: $\Delta P = Q \times R$ where for fixed resistance (stenosis) →

$\uparrow Q$ (flow) $\sim \uparrow \Delta P$ (pressure gradient)

Pts have normal distal pressures and/or pulse exam at rest with claudication symptoms

Not indicated in pts with CLI
Exercise ABI testing

- Walking on treadmill or heel raises for ~5 min. or symptoms
- Measure ankle pressures before, immediately after, and at 2min increments until pre-exercise levels or 10min have elapsed
- Expect increase in ankle pressures after exercise in disease-free individuals
Doppler waveform analysis

- **Visual velocity waveforms of directional blood flow and corresponding audible signals**

- **Triphasic velocity waveform**—systolic forward flow, diastolic flow reversal, and end-diastole forward flow
  - Normal in arteries feeding high resistance vascular beds

- **Monophasic velocity waveform**—amplitude dampening and loss of phasicity from proximal stenosis

- **Absence of phasic components with arteries feeding low resistance vascular beds** (e.g. ICA, renal, hepatic) but forward end diastolic flow
Doppler waveform analysis

Iliac Artery at Rest

Iliac Artery post Vigorous Exercise
Audible Signal analysis

Triphasic Doppler Signal

Monophasic Doppler Signal—distal to stenosis/occlusion

Doppler Signal—proximal to occlusion
Plethysmography/Pulse volume recording (PVR)

- Plethysmography = measurement of volume change
- Has been applied through several mediums—air, strain-gauge
- Can be measured as segmental plethysmography or digital plethysmography
- Can be used to localize and assess severity of occlusive disease
Arterial testing:
Mesenteric/Renal Artery Evaluation
Objectives

- Anatomy
- Duplex technique for mesenteric/renal imaging
- Diagnostic criteria for mesenteric and renal stenosis
Visceral Aorta Anatomy

- Celiac trunk
- Common hepatic a.
- Proper hepatic a.
- Gastroepiploic a.
- Middle colic a.
- Inferior pancreaticoduodenal a.
- Left gastric a.
- Splenic a.
- Superior mesenteric a.
- Inferior mesenteric a.
Mesenteric Duplex: Technique

- Developed at University of Washington
- Low frequency probe
- Overnight fasted patient
- Find vessels with B-mode/color flow
- Delineate anatomy
- Sample Doppler signals
- Careful Doppler angle adjustment
Mesenteric Duplex: Technique
Normal Celiac Artery

- Sharp systolic upstroke
- Typically PSV < 125 cm/sec
- Low resistance pattern
  - Antegrade diastolic flow
  - Hepatic flow
Normal Fasting SMA

- Sharp systolic upstroke
- Typically PSV < 125 cm/sec
- Triphasic morphology
- Minimal to no forward diastolic flow
- Post-prandial signal is **low resistance** → dilation of mesenteric bed
Mesenteric Duplex Diagnostic Criteria

- **Oregon Criteria (PSV)**
  - Based on angiographic correlation
  - Correspond to 70% angiographic stenosis

- **Dartmouth Criteria (EDV)**
  - Correspond to 50% angiographic stenosis

# Celiac/SMA Diagnostic Criteria for Stenosis

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Stenosis</th>
<th>Velocity criteria</th>
<th>Sens./Spec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Celiac</td>
<td>&gt;70%</td>
<td>&gt;200cm/s¹ PSV (Oregon)</td>
<td>87/80</td>
</tr>
<tr>
<td></td>
<td>&gt;50%</td>
<td>&gt;55cm/s² EDV (Dartmouth)</td>
<td>93/100</td>
</tr>
<tr>
<td>SMA</td>
<td>&gt;70%</td>
<td>&gt;275cm/s¹ PSV (Oregon)</td>
<td>92/96</td>
</tr>
<tr>
<td></td>
<td>&gt;50%</td>
<td>&gt;45cm/s² EDV (Dartmouth)</td>
<td>90/91</td>
</tr>
</tbody>
</table>

Post-intervention Criteria

Criteria for surveillance after SMA or Celiac stenting:

- In general, PSV more reliable and higher than native disease due to flow changes in stent

Mesenteric in-stent restenosis:\(^1\)

- SMA >70%: PSV>412 cm/s
  - Sens 100%, spec 95%, Accuracy 97%

- CA >70%: PSV>363 cm/s
  - Sens 88%, spec 92%, Accuracy 90%

1. AbuRahma et al., JVS 2012
Renal Artery Duplex Technique

- Obtain aortic PSV proximal to visceral segment
- Locate main renal landmarks
- Examine main renal artery from origin to renal parenchyma with recording of waveforms
- Examine intraparenchymal renal arteriole flow
- Document kidney length
# Renal Artery Duplex Criteria

<table>
<thead>
<tr>
<th>Stenosis</th>
<th>PSV</th>
<th>Renal/Aortic PSV Ratio</th>
<th>Post-stenotic turbulence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal-Mild</td>
<td>&lt;180cm/s</td>
<td>&lt;3.5</td>
<td>None</td>
</tr>
<tr>
<td>Mild-&lt;60%</td>
<td>&gt;180cm/s</td>
<td>&lt;3.5</td>
<td>None</td>
</tr>
<tr>
<td>&gt;60%</td>
<td>&gt;180cm/s</td>
<td>&gt;3.5</td>
<td>Present</td>
</tr>
</tbody>
</table>
Mesenteric/Renal Conclusions

- Normal celiac, renal—low resistance waveform
- Normal fasting SMA—high resistance waveform, post-prandial low resistance waveform
- Mesenteric/renal duplex excellent screening test with criteria for native disease
- Intervention increases PSV threshold for restenosis
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Venous testing:
Acute and Chronic Deep Venous Thrombosis
Duplex for Acute/Chronic DVT: Overview

- Techniques & Protocol of peripheral venous scanning
- Diagnostic findings for acute/chronic DVT
- Limitations of duplex for acute/chronic DVT
Instrumentation

- **Transducers**
  - 5-7.5 MHz – Proximal LE & Central UE veins
  - 10 MHz – Distal LE & UE superficial veins

- **Gray scale gain**
  - Minimize intraluminal artifacts
  - Maximize venous wall definition

- **Color velocity**
  - Maximize detection of low velocities
  - Confine color to lumen

- **Prograde flow displayed below baseline**
Lower Extremity Venous Duplex Scan

- Detect the presence, location, and extent of venous thrombus
- Functional evaluation of venous hemodynamics
- Flow information (Absence of femoral respiratory variation → iliofemoral venous occlusion)
- Moderate dependency of the legs to provide full dilation of the veins
- Transverse (compression) and longitudinal views
- Watch for duplicated systems/unusual anatomy
Lower Extremity Venous Duplex Data

- **Spontaneous flow** - calf veins may not have spontaneous flow and must be examined with augmentation.
- **Phasicity** - cyclic variation with respiration.
- **Augmentation** - produced by distal compression or release of proximal compression.
- **Valvular competence** - presence or absence of reverse flow in response to proximal compression or Valsalva maneuver.
  - Short period of reverse flow may be seen during valve closure.
  - Flow reversal > 0.5 sec abnormal.
## Duplex Findings: Acute vs. Chronic DVT

<table>
<thead>
<tr>
<th>CRITERIA</th>
<th>ACUTE DVT</th>
<th>CHRONIC DVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Echogenicity</td>
<td>Echolucent</td>
<td>Echogenic</td>
</tr>
<tr>
<td>Incompressibility</td>
<td>Spongy</td>
<td>Firm</td>
</tr>
<tr>
<td>Vein Diameter</td>
<td>Dilated</td>
<td>Contracted</td>
</tr>
<tr>
<td>Heterogeneity</td>
<td>Homogeneous</td>
<td>Heterogeneous</td>
</tr>
<tr>
<td>Luminal Surface</td>
<td>Smooth</td>
<td>Irregular</td>
</tr>
<tr>
<td>Collaterals</td>
<td>Absent</td>
<td>Present</td>
</tr>
<tr>
<td>Flow Channel</td>
<td>Confluent</td>
<td>Multiple</td>
</tr>
<tr>
<td>Free floating tail</td>
<td>+/- Present</td>
<td>Absent</td>
</tr>
</tbody>
</table>
Venous Compressibility: Normal
Venous Compressibility: Partial Occlusion
Venous Compressibility: Complete Occlusion
Spontaneous Respiratory Phasic Flow
Continuous Femoral Venous Flow: Proximal Obstruction

- Marker of iliocaval venous occlusion
- Continuous flow even with Valsalva
- No augmentation
Venous testing:
Venous Insufficiency
Venous Insufficiency Exam: Goals

- Anatomic location(s) of disease
- Hemodynamic information regarding reflux time
Supine & Standing Positions
Standing reflux scan

- **Goal**
  - Assess abnormal venous reflux (>0.5sec)

- **Position**
  - Standing with leg offloaded

- **Equipment**
  - Duplex scanner and rapid inflation/deflation pressure cuff
Reflux
Supine position

- **Goals:**
  - Evaluate for obstruction/thickening
  - Incompetent perforators

- **Position**
  - 30 degrees reverse Trendelenberg
  - Knee partially bent/relaxed
Perforator localization

- Commonly found penetrating fascia
- Evaluation for reflux using hand compression and release
  - Flow should be seen inward but not outward
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