Principles of Ultrasound

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Disclosures

• None
Outline

• Introduction
• Benefits and Limitations of US
• Ultrasound (US) Physics
• Terminology
• Equipment
• Normal US appearance of structures
  – Muscle, Tendon, Ligament, Bone, Cartilage, Nerve, Vessels
• Artifacts
• Conclusions
Introduction

• Physiatrists involved in US > 5 decades
  – Founded American Institute for Ultrasound in Medicine (AIUM) in 1951
• Therapeutic US initially
• High frequency, real-time MSK US imaging – 1980’s
• Now used by many physiatrists
  – Diagnostic
  – Interventional
Introduction

• What is MSK US?
  – Use of high frequency sound waves (3-17 MHz) to image soft tissues and bony structures in the body for the purposes of diagnosing pathology or guiding interventional procedures
  – Detailed images of MSK system
    • Sub-millimeter images
    • Higher resolution than MRI for superficial structures
Introduction - Indications

• Diagnostic
  – Tendon (tendinopathy, tears)
  – Muscle (strains, contusions)
  – Nerve (entrapment)
  – Ligament (sprains)
  – Joint (effusions)

• Interventional
  – Injections
  – Tenotomy
  – Aspiration/lavage
  – Biopsy
Benefits of MSK US

• Ability to image in real-time = hands-on, dynamic, fast
• Interactive – allows feedback from patient
• Generally unaffected by metal artifacts
• No radiation to patient or provider
• Exam of contralateral limb for comparison
• High resolution
• Real-time guidance for interventional procedures
• Portable
• Relatively inexpensive
Limitations of MSK US

• Limited field of view
  – Detailed picture of relatively small area
• Limited penetration
  – Lower resolution at greater depths
  – Unable to penetrate bone
• Operator dependent
  – Education (anatomy), scanning skills and interpretation
• Lack of current individual certification
• Equipment – cost, quality variable
Ultrasound Physics

• Transducer (probe)
  – Contains linear array of thin crystals (lead zirconate titanate) linked to the electrical system of the machine

• Machine
  – Applies a rapidly alternating electrical current to the crystals → vibration → generate sinusoidal sound wave (mechanical energy) = Piezoelectricity
Ultrasound Physics

- The frequency and amplitude of the sound waves are determined by those of the electrical current used to stimulate the crystals and the material properties and thickness of the crystals.
- A range of frequencies are produced (Bandwidth).
- There is a preferential frequency.
- Higher frequency ~ higher resolution but increased scatter (reduced penetration).
Ultrasound Physics

• Sound requires a medium
  – Pass through the coupling gel into the body
  – Waves travel into body until they encounter an acoustic interface
    (change in the density of adjacent tissues)
  – Part of the sound wave’s energy is reflected → back to the
    transducer (now a receiver) → Sound energy transformed into
    electrical signal (Piezoelectricity)
  – US machine records the amplitude of the beam and the depth of
    the reflecting structure → computer software generates a 2-D
    black/white B-mode image of the body
Ultrasound Physics

• Echoes
  – Perpendicular incidence
    • Sound wave traveling perpendicular to the boundary of 2 media
    • Reflected pulse - reflected directly back
    • Transmitted pulse – passes straight through
  – Oblique incidence
    • Sound wave NOT traveling perpendicular to the boundary of 2 media
    • Some reflected back at an angle
    • Some passes through refracted (transmission angle)
Ultrasound Physics

• Reflection
  – Specular Reflection
    • Reflection from a smooth surface
  – Scattering
    • Redirection of sound in several directions due to rough edges (torn tissue) or heterogeneous media
    • Some of the sound is reflected back to the transducer (= backscatter)
      → visualization of the media
Ultrasound Physics

• Attenuation
  – Weakening of sound amplitude and intensity as the wave propagates through a medium
  – Absorption, Reflection, Scattering
  – Decibels (dB)

• Attenuation coefficient
  – Reduction (in dB) per centimeter (cm) traveled
  – Dependent on the tissue
  – Soft tissue attenuation / cm = 0.5 x freq (MHz)

• Higher frequency → More attenuation
Ultrasound Physics

• Acoustic interface
  – US waves are reflected at the interface of two different tissues, dependent on the properties of each tissue (impedance)
  – Echogenicity = Ability to reflect sound waves back to transducer
  – If reflects large amount of sound → brighter
    • Interface composed of very different tissues
    • e.g. interface between bone and muscle (bone = bright)
  – Less reflection → darker
    • More similar tissues

• Important point
  – Images are based on the relative material properties of the tissue compared with adjacent regions
Acoustic Impedance

- Impedance = (density of medium) x (propagation speed)
- Important in determination of acoustic transmission and reflection at the interface of two materials with different impedances (impedance mismatch) – the greater the mismatch the greater the reflection at the interface

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>Velocity (m/s)</th>
<th>Acoustic Impedence (kg/m²s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.3</td>
<td>330</td>
<td>429</td>
</tr>
<tr>
<td>Water</td>
<td>1000</td>
<td>1500</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>Fat</td>
<td>925</td>
<td>1450</td>
<td>$1.38 \times 10^6$</td>
</tr>
<tr>
<td>Blood</td>
<td>1060</td>
<td>1570</td>
<td>$1.59 \times 10^6$</td>
</tr>
<tr>
<td>Muscle</td>
<td>1075</td>
<td>1590</td>
<td>$1.70 \times 10^6$</td>
</tr>
<tr>
<td>Bone</td>
<td>1908</td>
<td>4080</td>
<td>$7.78 \times 10^6$</td>
</tr>
</tbody>
</table>
Focusing

• US beam is filled with sound waves
• Beam narrows to ½ width and then widens
  – Narrowest region of beam has most concentrated sound waves → best resolution
• Near zone = proximal to narrowest region
• Far zone = distal to narrowest region
• Multiple focal zones reduce temporal resolution
Terminology - Echotexture

• Refers to the internal pattern of echoes
  – Coarseness
  – Homogeneity and heterogeneity
Terminology - Echogenicity

• It’s all relative
  – Take into context the surrounding tissues, not simply the individual properties of the structure

• Hyperechoic
  – More sound waves reflected back

• Isoechoic
  – Same amount of sound waves reflected back

• Hypoechoic
  – Fewer sound waves reflected back

• Anechoic
  – No sound waves reflected back
Terminology

- Longitudinal
  - Parallel to the long axis of the structure

- Transverse
  - Perpendicular to the long axis of the structure
Terminology
Equipment

• Optimize the image!
• Proper transducer selection
• Depth
  – Structure of interest visible at bottom of screen
• Adjust the focal zones
  – Should be at depth of structure being imaged
  – Reduce # of focal zones to span the area of interest
• Gain
  – Overall brightness of the echoes
• Time-gain Compensation
  – Use if need to focus gain on structure being imaged
Doppler

• **Power doppler**
  – Single color
  – Not angle dependent
  – Detects any movement
  – More sensitive but less specific than Color doppler
  – Good for:
    • Slow flow, small vessels (i.e.: neovessels), deep vessels

• **Color doppler**
  – 2-colors
  – Angle dependent
  – Detects directional movement
  – More specific but less sensitive than Power doppler
  – Good for:
    • Detect flow characteristics (direction, speed)
Extended Field of View

- Panoramic/Extended Field of View
  - Transducer is glided parallel to the scan plane along the structure of interest
  - New echoes added to original image
  - Allows production of pictures wider than the transducer face
Transducers

• Frequency
  – Expressed in megahertz (MHz)
  – High frequency
    • Greater resolution, lower penetration (attenuation)
    • Best for more superficial structures
  – Low frequency
    • Lower resolution, greater penetration
    • For deeper structures
Transducers

• Linear array
  – End of transducer flat
  – Sound waves exit perpendicular
  – Less anisotropy
  – Limited field of view
  – Good for superficial structures

• Curvilinear array
  – End of transducer curved
  – Sound waves emitted in a fan
  – Increased anisotropy
  – Large field of view
  – Good for deep structures
Transducer positioning

- Stabilize transducer with simultaneous contact with the transducer, skin surface, and examiner’s hand
  - maintains proper pressure of transducer on the skin
  - avoids involuntary movement of the transducer
  - allows fine adjustments in transducer positioning
- “Full contact sport” – Jay Smith
Normal US Characteristics

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Echogenicity</th>
<th>Echotexture Appearance</th>
<th>Susceptibility to Anisotropy</th>
<th>Compressibility</th>
<th>Doppler Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Transverse</td>
<td>Longitudinal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tendon</td>
<td>Hyperechoic</td>
<td>Broom end</td>
<td>Fibrillar</td>
<td>+++</td>
<td>--</td>
</tr>
<tr>
<td>Ligament</td>
<td>Hyperechoic</td>
<td>Broom end</td>
<td>Fibrillar</td>
<td>++</td>
<td>--</td>
</tr>
<tr>
<td>Nerve</td>
<td>Mixed echogenicity</td>
<td>Honeycomb</td>
<td>Fascicular</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>Muscle</td>
<td>Mixed echogenicity</td>
<td>Starry night</td>
<td>Pennate or “feather like”</td>
<td>+</td>
<td>--</td>
</tr>
<tr>
<td>Vessel</td>
<td>Hypoechoic or anechoic</td>
<td>--</td>
<td>--</td>
<td>++^a - +++^v</td>
<td>^v - +++a</td>
</tr>
</tbody>
</table>

--- = absent; + = mildly present; ++ = moderately present; +++ = significantly present; ^a = arteries; ^v = veins.
Normal Appearance - Muscle

Longitudinal
Feather or veins
on a leaf pattern

Transverse
Starry night
pattern
Normal Appearance - Tendon

Longitudinal
Fibrillar appearance

Transverse
Broom end pattern
Normal Appearance - Ligament

MCL Longitudinal
Fibrillar

MCL Transverse
Broom end
Normal Appearance - Bone
Normal Appearance – Hyaline Cartilage
Normal Appearance - Nerve

Longitudinal
Fascicular

Transverse – Honeycomb pattern
Normal Appearance – Vasculature

Transverse - CPA

Transverse

Longitudinal - CPA
Artifacts - Anisotropy

• Anisotropy
  – US beam did not encounter the structure perpendicular to the plane of that structure but rather an oblique angle → normal structure will appear artificially hypoechogenic (dark) → easily mistaken as pathology
  – Can be avoided by continually manipulating the transducer to direct the US beam perpendicular to the structure (tilting, heel-toe)
  – Always look for pathology in multiple planes
Artifacts - Anisotropy

(a) Normal

(b) CARPAL TUNNEL TRANSVERSE

(c) CARPAL TUNNEL TRANSVERSE
Artifacts – Posterior reverberation
Artifacts – Posterior Acoustic Shadowing
Artifacts – Posterior acoustic enhancement (increased through-transmission)
Artifacts

• Beam-width artifact
  – If a structure is smaller than the ultrasound beam, artifact may be eliminated (e.g. small calcification with no posterior acoustic shadowing)
Conclusions

• Ultrasound has many uses for physiatrists
• There are many benefits and limitations of US
• Basic understanding of US physics is important
• Various tissues can be identified due to their anatomic location, echotexture, and echogenicity
• Always optimize your image
• Recognize common artifacts
References