Figure 3-31. Use of the slope, $\Delta d/\Delta t$, of an M-mode trace to estimate reflector velocity. Depth marker dots on the display are generated at fixed time intervals, such as every $\frac{1}{2}$ s shown here, so they provide both depth (cm) and time (s) calibration information for the M-mode trace.
M-mode
Typical Acoustic Outputs

<table>
<thead>
<tr>
<th>Mode</th>
<th>Peak Pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Mode</td>
<td>1.68</td>
</tr>
<tr>
<td>M-Mode</td>
<td>1.68</td>
</tr>
<tr>
<td>Pulsed Doppler</td>
<td>2.48</td>
</tr>
<tr>
<td>Color Flow</td>
<td>2.59</td>
</tr>
</tbody>
</table>

Higher pressures used to get reasonable signal from blood
Mechanically Scanned Hydrophone
1° Measurement Device

- Good for general purpose
- Aperture from .1mm to 1mm
- Tip is extremely fragile, never touch it
- Hydrophone scans are time consuming, very susceptible to vibrations
- Not recommended for high power

FIGURE 2. FEA model
Fiber Optic Hydrophones

- Extremely small tip ~10um
- Immune to Electromagnetic
- Suitable for high temperatures
- Can measure temperature and pressure simultaneously
- Higher acoustic sensitivity for aperture size

http://www.medphys.ucl.ac.uk/research/mle/pdf_files/FO_Hydrophone_dual_sensing1.pdf
Properties of hydrophones

- Small (high spatial resolution)
- Sensitive to low pressures
- Rugged (withstand high pressures)
- Broadband
- Precisely calibrated
Transverse and axial plots

0.5 MHz

mm

0

12

-6

-4

-2

0

2

4

6

8

10

12

mm

-5

0

5

2

4

6

8

10

12

0.5 MHz
Hydrophones: things to keep in mind

- Size of aperture
- Frequency sensitivity
- Continuous vs. pulsed
Derating

- Because the pressures can really only be measured with a hydrophone in water, and water has an attenuation of approximately zero (which is much less than tissue), the FDA mandated “derating” by $a = 0.3 \text{ db/cm}\cdot\text{MHz}$.

- Worst case scenario
Power Measurements

Radiation Force Balances

\[ P = \frac{\text{coeff} \times I}{c} \]

- \( \text{coeff} = 1 \) Perfect Absorber, normal to beam

rate of energy deposition
Power Measurements

- Convert scanning hydrophone pressures into intensity

\[ I = \frac{P^2}{2 \rho c} \]

- Then integrate spatially
Power has increased in recent years for the following reasons:
- interest in increased SNR, lateral resolution, frame rates
- transducers capable of narrower focused beams
- harmonic imaging where tissue is intentionally driven non-linear

Typical Acoustic Outputs

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Mode</td>
<td>18</td>
</tr>
<tr>
<td>M-Mode</td>
<td>3.9</td>
</tr>
<tr>
<td>Pulsed Doppler</td>
<td>30.7</td>
</tr>
<tr>
<td>Color Flow</td>
<td>80.5</td>
</tr>
</tbody>
</table>

Low because low repetition rates are used
Higher power used to get reasonable signal from blood

rate of energy deposition
Intensity

- Peak Compression
- Peak Rarefaction
- Temporal Peak (TP)
- Pulse Average (PA)
- Temporal Average (TA)
- Spatial Peak (SP)
- Spatial Average (SA)

Beam Intensity Profile vs. Distance
Power/area

Power isn’t the whole story - no beam characteristics

\[ I_{\text{SPTA}} = \text{spatial peak temporal average} \]
\[ I_{\text{SPTP}} = \text{spatial peak temporal peak} \]
\[ I_{\text{SPPA}} = \text{spatial peak pulse average} \]
\[ I_{\text{SATA}} = \text{spatial average temporal average} \]
\[ I_{\text{SATP}} = \text{spatial average temporal peak} \]

Duty Cycle = \( \frac{\text{pw}}{\text{PRT}} \)

Typical Acoustic Outputs

<table>
<thead>
<tr>
<th>Mode</th>
<th>( I_{\text{SPPA}} ) (W/cm(^2))</th>
<th>( I_{\text{SPTA}} ) (mW/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Mode</td>
<td>174</td>
<td>18.7</td>
</tr>
<tr>
<td>M-Mode</td>
<td>174</td>
<td>73</td>
</tr>
<tr>
<td>Pulsed Doppler</td>
<td>288</td>
<td>1140</td>
</tr>
<tr>
<td>Color Flow</td>
<td>325</td>
<td>234</td>
</tr>
</tbody>
</table>

\[ I_{\text{SPTA}} = I_{\text{SPPA}} \times \text{DutyCycle} \]

\[ I_{\text{SATA}} = \frac{\text{Power}}{\text{Area}} \]
## Output Comparison

### Typical Acoustic Outputs

<table>
<thead>
<tr>
<th>Mode</th>
<th>Power (mW)</th>
<th>$I_{SPPA}$ (W/cm$^2$)</th>
<th>$I_{SPTA}$ (mW/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Mode</td>
<td>18</td>
<td>174</td>
<td>18.7</td>
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<tr>
<td>Color Flow</td>
<td>80.5</td>
<td>325</td>
<td>234</td>
</tr>
</tbody>
</table>

* $I_{SPTA}$ is low: spread out across the image
* Power is low, but $I_{SPTA}$ is high: same location
* $I_{SPPA}$ is high to get signal, $I_{SPTA}$ is high duty cycle
* $I_{SPPA}$ is even higher to get signal, but spread some
Output Display Standards

MI
TI
Mechanical Index MI

\[ MI = \frac{PNP}{\sqrt{f}} \]

- PNP - peak negative pressure in MPa
- f - frequency in MHz
- likelihood for cavitation
- required to stay under 1.9
- ALARA - use as low as reasonably achievable
Thermal Index TI

1992 Standard

\[ TI = \frac{W_0}{W_{\text{deg}}} \]

- \( W_0 \) = Time average power emitted
- \( W_{\text{deg}} \) = Power needed to raise target tissue by 1°C

- Estimated by system, taking into account the power, the frequency, the beam area, attenuation, etc.
- Need to stay under 2
- Don’t need to report if < 1
- ALARA - use as low as reasonably achievable power levels.
- TIS - TI for soft tissue
- TIB - TI for bone - operator indicated bone may be in field
- TIC - TI for cranium - operator indicates
Exposure

Energy (Joules/cm²) = Intensity (W/cm²) x Time (s)

Threshold at
- 50 Joules/cm²
- 100 mW/cm²

Our FUS treatments:
- Desmoid: 500-1300 Joules/cm²
- Bone: 1500-3000 Joules/cm²
Images
Focal Depth Change

Why do MI and TIs change the way they do?
Safety and Measurement Devices

- In 1985, the FDA was empowered by congress to regulate medical devices.
- Limiting values were selected based on what equipment could do in 1976.
  - In 1976, ultrasound was mainly static B-mode scanners.
  - By 1980’s, dominated by phased arrays.
  - People complained about not enough output power.
- So the FDA revised limits in 1987 and 1992.

FDA limits on Acoustic Output

<table>
<thead>
<tr>
<th>Mode</th>
<th>$I_{SPPA} (W/cm^2)$</th>
<th>$I_{SPTA} (mW/cm^2)$</th>
<th>MI</th>
<th>TI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most imaging</td>
<td>190</td>
<td>720</td>
<td>1.9</td>
<td>2</td>
</tr>
</tbody>
</table>

- Less for fetal and ophthalmic imaging.