Ultrasonic imaging parameters ~Attenuation coefficient

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Methods and Apparatus

- Apparatus
  – Two transducers(one transmitter and one receiver)
- Methods
  – Log Spectral Difference Technique
  – Dispersion correction
  – Diffraction correction

Log Spectral Difference Technique

$$P_s(f) = T^4 e^{-2L\alpha(f)} P_w(f)$$

$P_s(f)$: power spectra recorded with the specimen sample

$P_w(f)$: power spectra recorded without the specimen sample

L: the specimen thickness

$\alpha(f)$: the frequency-dependent attenuation

T: the amplitude transmission coefficient at each specimen/water interface

if transmission losses are negligible

$$\Rightarrow \alpha(f) = \frac{1}{2L}[\ln P_w(f) - \ln P_s(f)]$$

Attenuation and dispersion

- Attenuation obeys $\alpha = \beta \quad f^{n}$
- Use amplitude and phase information of the pulse
- Ultrasound reflection at the water-specimen interface →produce error

$$\alpha(f) = \frac{1}{L}\ln(1 - R^2) + \frac{1}{L}\ln\left[\frac{A_w(f)}{A_s(f)}\right]$$

$A_w(f)$：amplitude spectrum with water path only

$A_s(f)$：amplitude spectrum with the specimen inserted

L : specimen thickness

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Attenuation (amplitude) $P(f) = \alpha(f) - \alpha(f_0) = \frac{1}{L}\ln\left[\frac{A_w(f)A_s(f_0)}{A_s(f)A_w(f_0)}\right]$

$$P^*(f) = \beta(f^n - f_0^n)$$

Dispersion (phase) $Q(f) = \frac{1}{V_p(f_0)} - \frac{1}{V_p(f)} = \frac{\phi_w(f_0) - \phi_s(f_0)}{2\pi f_0 L} - \frac{\phi_w(f) - \phi_s(f)}{2\pi f L}$

Szabo's model

Linear attenuation, n=1 $Q^*(f) = \frac{\beta}{\pi^2}(\ln f - \ln f_0)$

Nonlinear attenuation, n>1 $Q^*(f) = -\frac{\beta}{2\pi}\tan(\frac{n\pi}{2})(f^{n-1} - f_0^{n-1})$

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From the above two equations, they have similar forms.

Then, define a total squared error function:

$$TSE = \lambda_1 \sum_{i=1}^{N} \left[P(f_i) - P^*(f_i) \right]^2 + \lambda_2 \sum_{i=1}^{N} \left[Q(f_i) - Q^*(f_i) \right]^2$$

Minimize TSE, we get

$$\beta = \frac{k \sum_{i=1}^{N} P_i (f_i - f_0) + \frac{1}{\pi^2} \sum_{i=1}^{N} Q_i (\ln f_i - \ln f_0)}{k \sum_{i=1}^{N} (f_i - f_0)^2 + \frac{1}{\pi^4} \sum_{i=1}^{N} (\ln f_i - \ln f_0)^2}$$

$$k = \frac{\lambda_1}{\lambda_2} \cong \frac{\sum_{i=1}^{N} Q_i^2}{\sum_{i=1}^{N} P_i^2}$$ and n=1 $\longrightarrow$

$$\beta = \frac{\sum_{i=1}^{N} Q_i^2 \sum_{i=1}^{N} P_i (f_i - f_0) + \frac{1}{\pi^2} \sum_{i=1}^{N} P_i^2 \sum_{i=1}^{N} Q_i (\ln f_i - \ln f_0)}{\sum_{i=1}^{N} Q_i^2 \sum_{i=1}^{N} (f_i - f_0)^2 + \frac{1}{\pi^4} \sum_{i=1}^{N} P_i^2 \sum_{i=1}^{N} (\ln f_i - \ln f_0)^2}$$

Diffraction Correction

- Diffraction effect on attenuation estimate due to the two media with different ultrasound velocities
- Experimental Diffraction Correction technique
  - Using the spectrum of the reference media, i.e. water

$$\hat{\beta} = \frac{-20\left[\log_{10} A_e(f,z) - \log A_r(f,z)\right]}{|f|d}$$

$$\beta = \frac{-20\left[\log_{10} A_e(f,z) - \log_{10} A_r(f,z) - \log_{10} A_d(f,z)\right]}{|f|d}$$

Ad(f, z)：diffraction magnitude transfer function

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- Fresnel parameter : S=Sa=z λ_a/a^2

$$S_w^* = z_w^* \lambda_w / a^2 = S_a \longrightarrow z_w^* = \frac{\lambda_w (z_a - d) + \lambda_s d}{\lambda_w}$$

z_w^* ensures that the water-specimen-water and water- only paths undergo equivalent diffraction effects

Then, $$\beta_{EDC} = \frac{-20\left[\log_{10} A_e(f, z) - \log_{10} A_r(f, z_w^*)\right]}{|f| d}$$

λ_s : wavelength in water

λ_w : wavelength in specimen

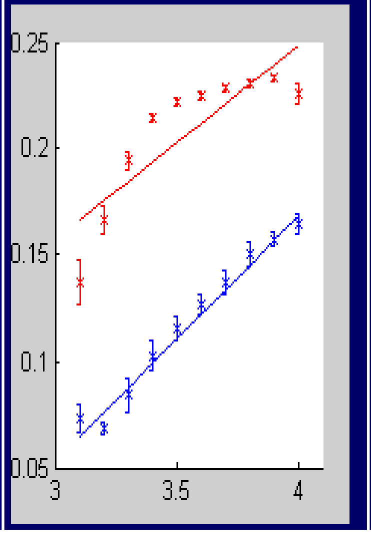
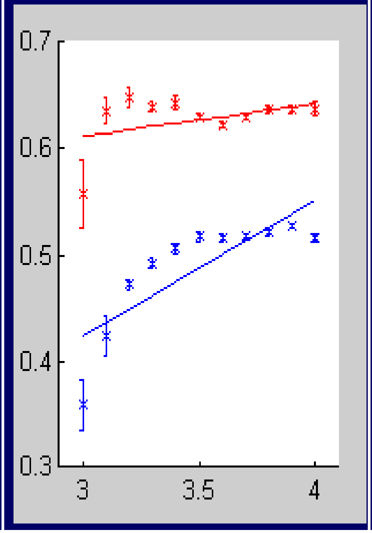
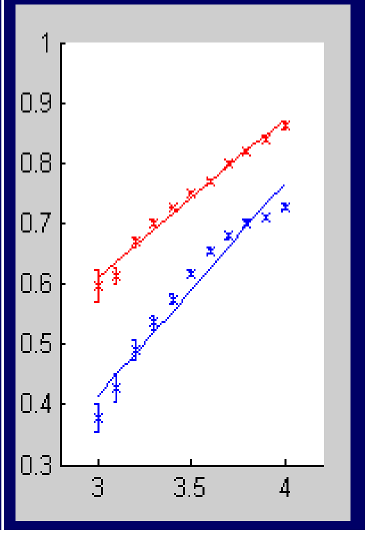
Material

- Phantoms
  - Graphite phantom 1:6:12 (7.6, 6.6, 6.8 cm
  - Breast phantom
- Transducers
  - 3.5, 5, 7.5 MHz
- Pulse receiver
- Oscilloscope
- A/D: GaGe fs=100 MHz
- LabView

Experimental results

Log Spectral Difference Technique

---- concentration & attenuation

	low	middle	high
Fc: 3.5 MHz			

Frequency (MHz)-attenuation (dB/cm)

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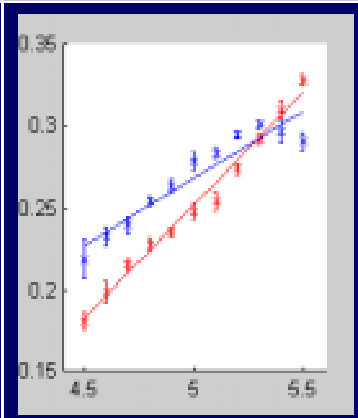
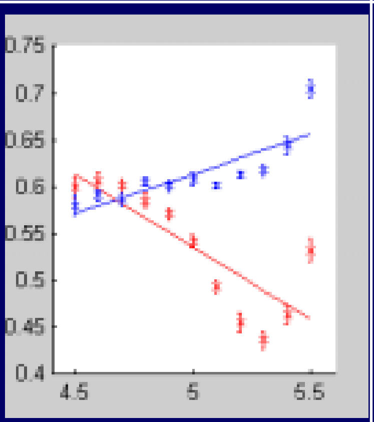
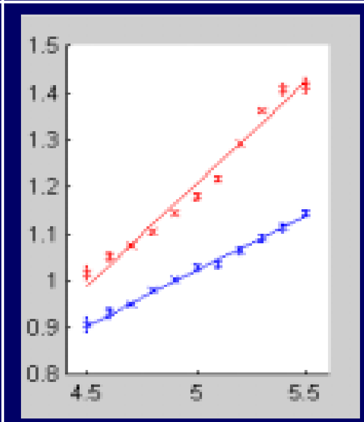
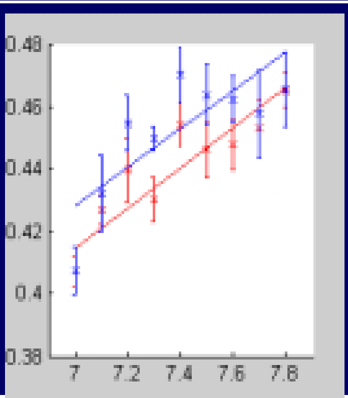
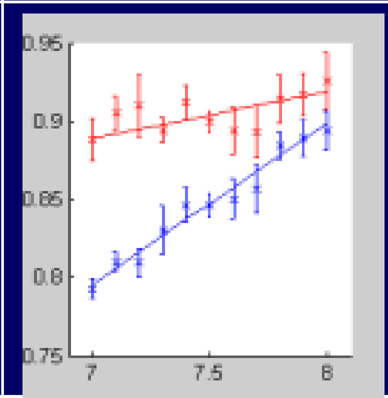
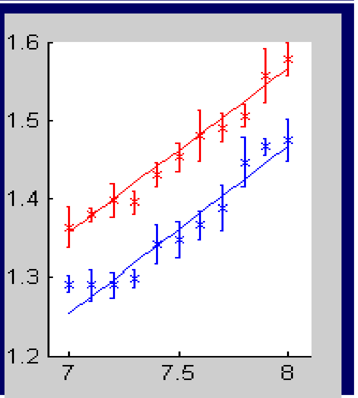
	low	middle	high
Fc: 5 MHz			
7.5 MHz			

Frequency (MHz)-attenuation (dB/cm)

Log Spectral Difference Technique --- frequency & attenuation

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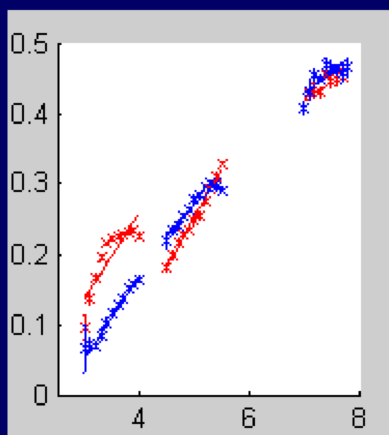
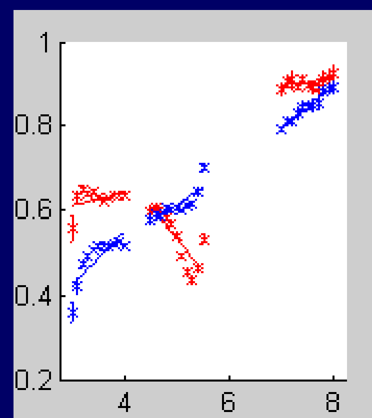
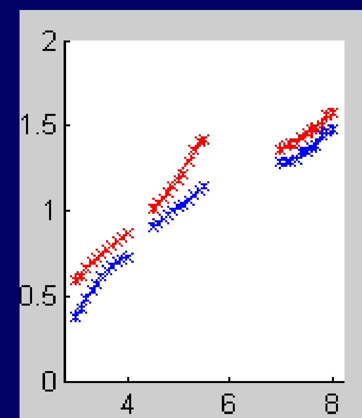
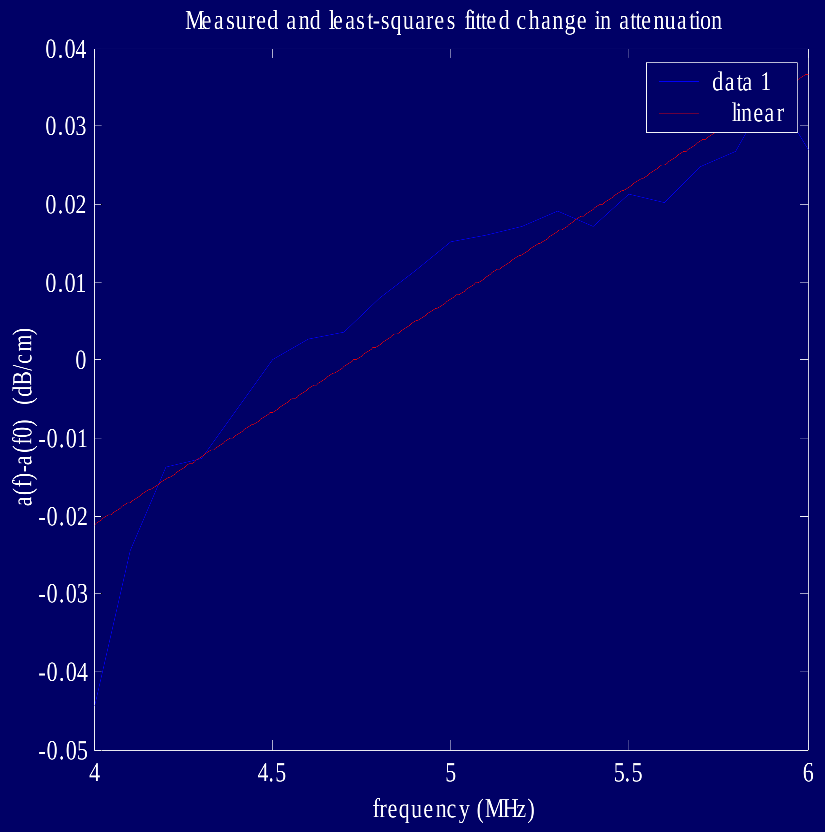
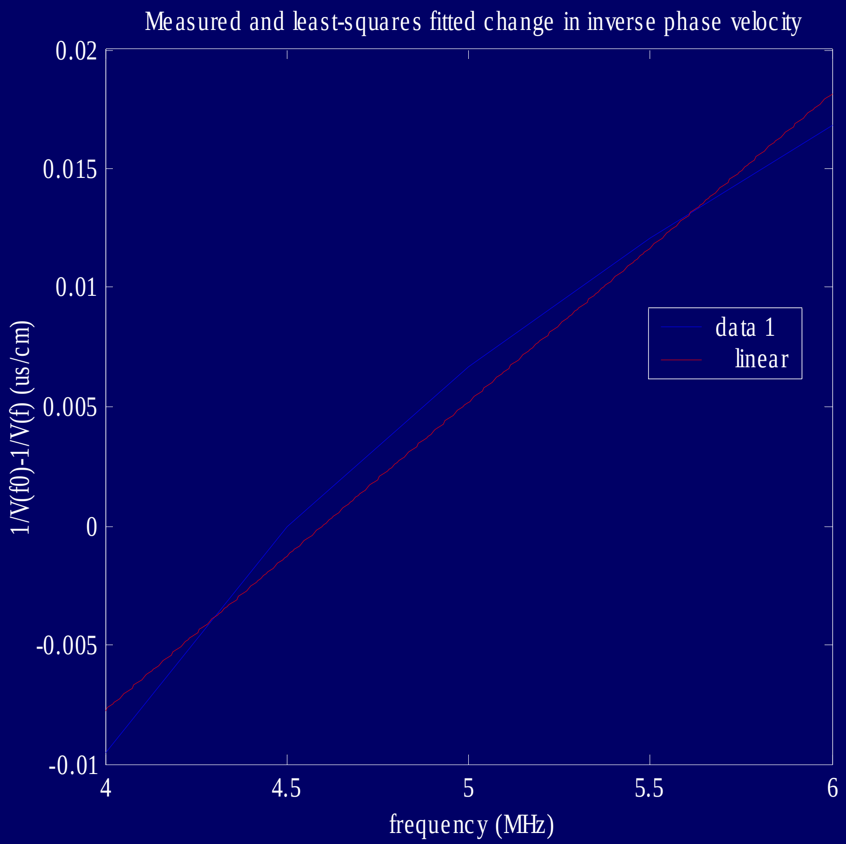
<tr><td>
</td><td>
</td><td>
</td></tr>
<tr><td>Attenuation coefficient
0.0791 ± 0.0137
(dB/cm-MHz)</td><td>Attenuation coefficient
0.1054 ± 0.0225</td><td>Attenuation coefficient
0.2356 ± 0.0257</td></tr>
</table>

Dispersion correction

Linear fitting, n=1





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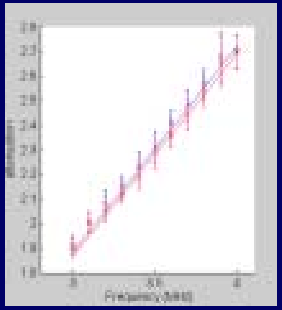
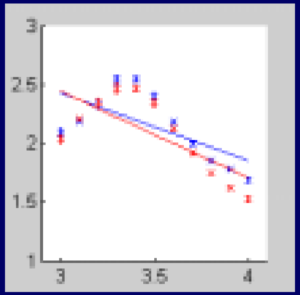
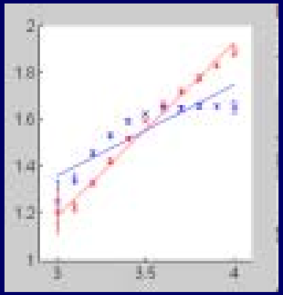
	Low	Median	High
With correction	0.0837±0.0234	0.1274±0.017	0.2455 ±0.0748
Without correction	0.0875±0.0245	0.1101±0.004	0.2605±0.0754

Without correction	Low	Median	High
3.5MHz	0.1077±0.2665	0.1143±0.1012	0.3437±0.6453
5MHz	0.0945±0.2047	0.1106±0.0617	0.2115±0.0511
7.5MHz	0.0602±0.0121	0.1055±0.0534	0.2605±0.0754

With correction	Low	Median	High
3.5MHz	0.1033 ±0.0131	0.1310±0.0085	0.3544±0.0224
5MHz	0.0548±0.0097	0.1417±0.0123	0.2034±0.022
7.5MHz	0.0931±0.0038	0.1094±0.0104	0.1766±0.0147

Diffraction correct

	Distance: 134mm	Distance: 150 mm	Distance: 205 mm
z_w^*	134+ 2.46 mm	150+ 1.5 mm	205+ 2.26 mm
			
Attenuation coefficient (uncorrected)	0.8357	-0.5794	0.3984
Attenuation coefficient (corrected)	0.8225	-0.7393	0.7397

Clinical application

- Heart samples
- Human dermis
- Bone

Heart samples

- Transducer frequency
  - 2.5-40 MHz
- Samples
  - Normal, infarcted, dilated cardiomyopathy
- Results
  - Attenuation of the normal sample was smaller than those of the infarcted and cardiomyopathy samples in all frequency
  - Exponent of power function

$$\alpha_N = \beta_N \cdot f^{1.6} \qquad \alpha_I = \beta_I \cdot f^{1.3} \qquad \alpha_D = \beta_D \cdot f^{1.2}$$

Human dermis

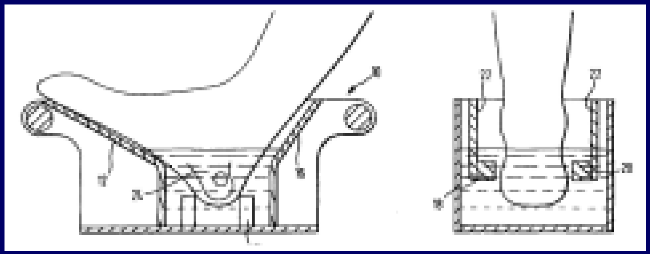
- Transducer frequency
  - 40 MHz
- Volar face of the forearm
  - 150 healthy subjects aged 14-85 yr
- Results
  - the decrease with advancing age of the attenuation coefficient
  - Attenuation coefficient: 0.7-3.6 dB/cm-MHz

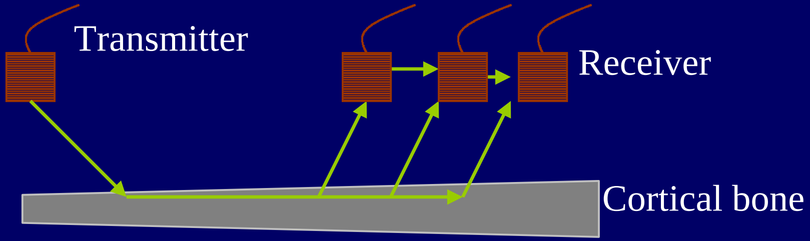
Bone

- Cancellous bone & cortical bone
  - More porous and thinner with advancing age
- Osteoporotic bone
  - Low bone density and deterioration of bone tissue
  - Low attenuation and velocity
- X-ray & ultrasound
  - Bone density, microarchitecture, elasticity

Cont’d

- Measuring techniques (250 kHz-1.25 MHz)
  - Transverse technique
    - Both transducers are placed on each side of the skeletal site
    - The wave passes through bone
  - Axial technique
    - The set of transducers is placed on the skin along the bone
    - Wave propagates along the long axis of bone





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Skeletal site	Type	Technique coupling	Image	Parameter
Calcaneus (cancellous bone)	Transverse transmission	Immersion or contract	Possible	Speed Attenuation
Finger phalanxes (Integral bone)	Transverse transmission	Contract	No	Speed
Radius, Tibia Finger phalanxes (Cortical bone)	Axial transmission	Contract	No	Speed

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