Ultrasound Nakagami imaging and its medical applications

超音波Nakagami影像的發展與醫學應用

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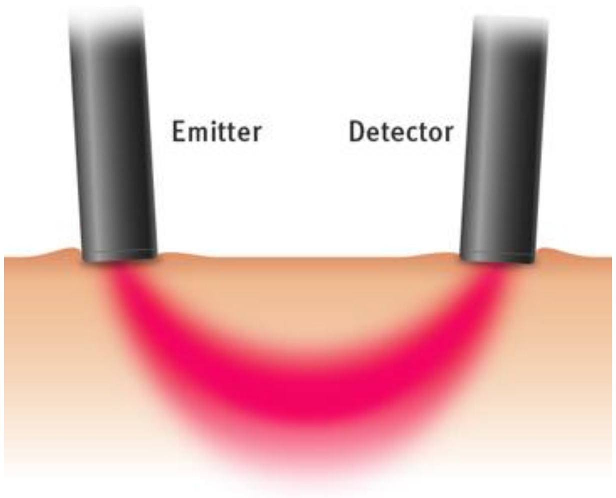
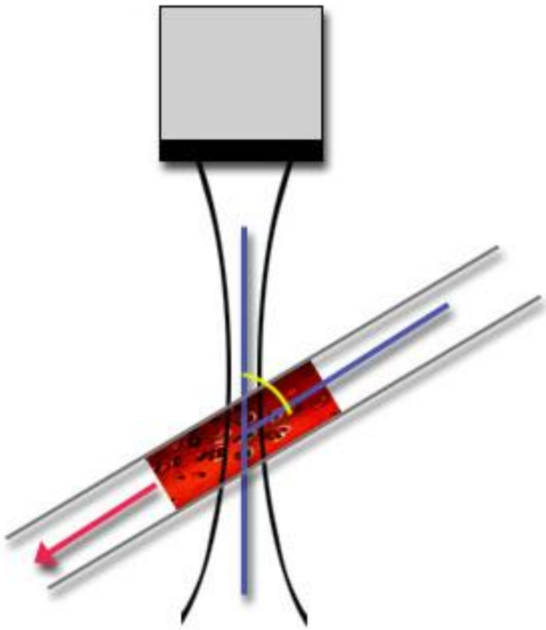
Medical imaging

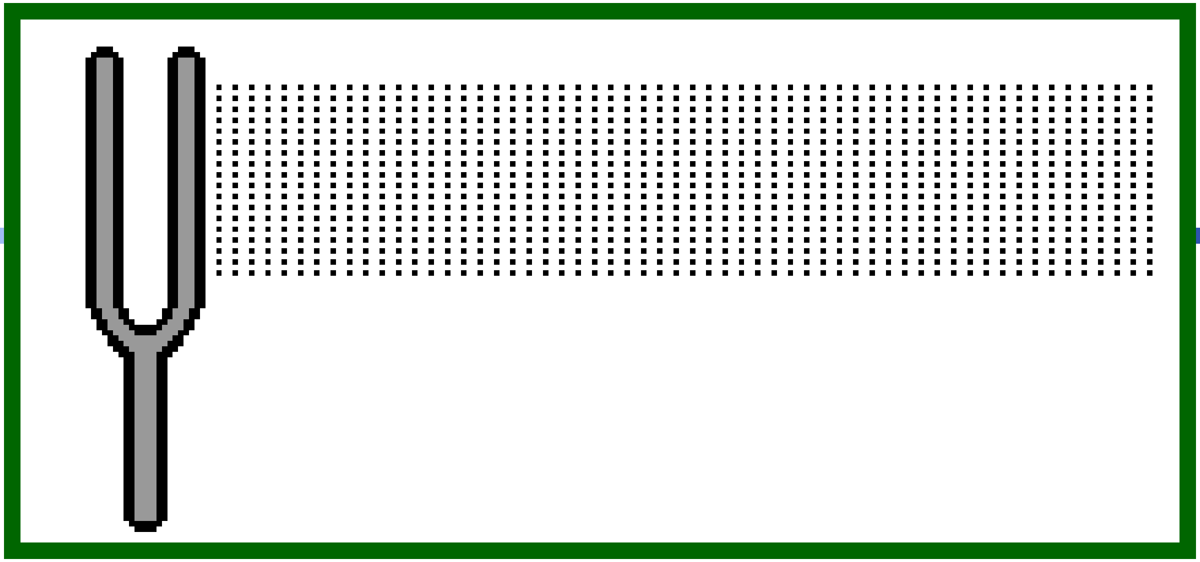
X-ray imaging



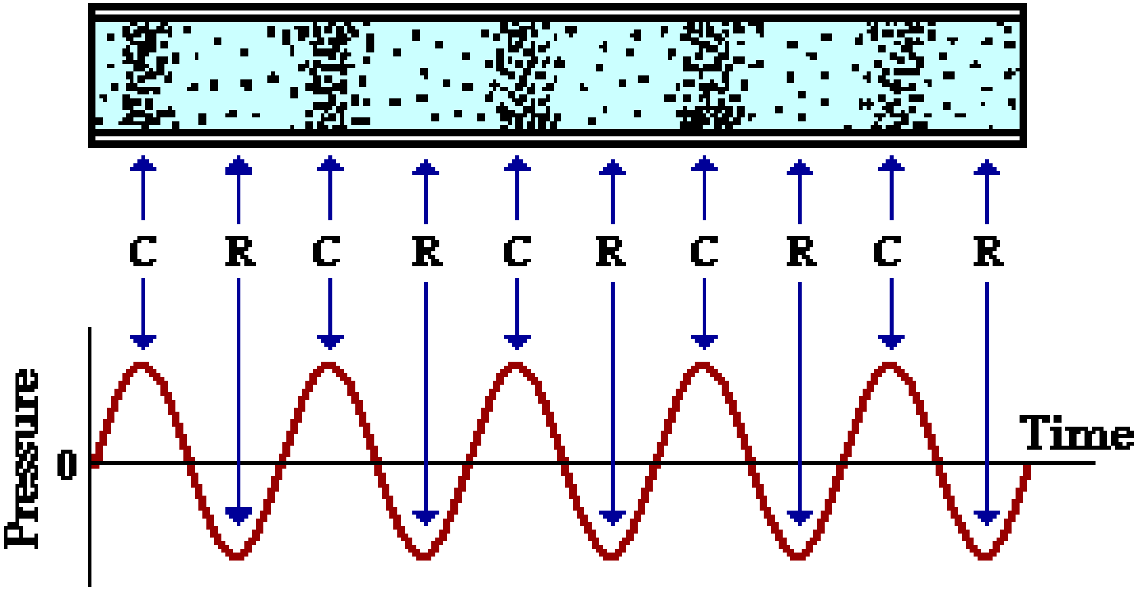
Optical imaging



Ultrasound image



Sound is a Pressure Wave

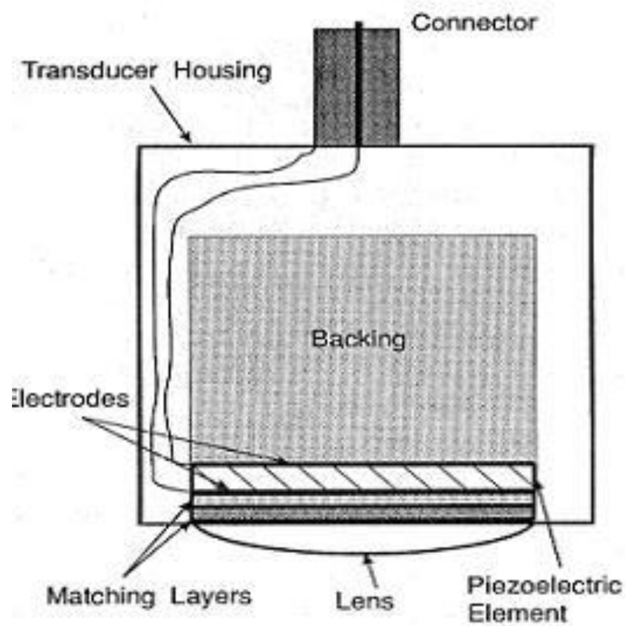


NOTE: "C" stands for compression and "R" stands for rarefaction

Ultrasound

- Acoustic waves with frequencies higher than 20 kHz
- Need a medium to propagate
- Longitudinal wave
- Non-ionizing radiation

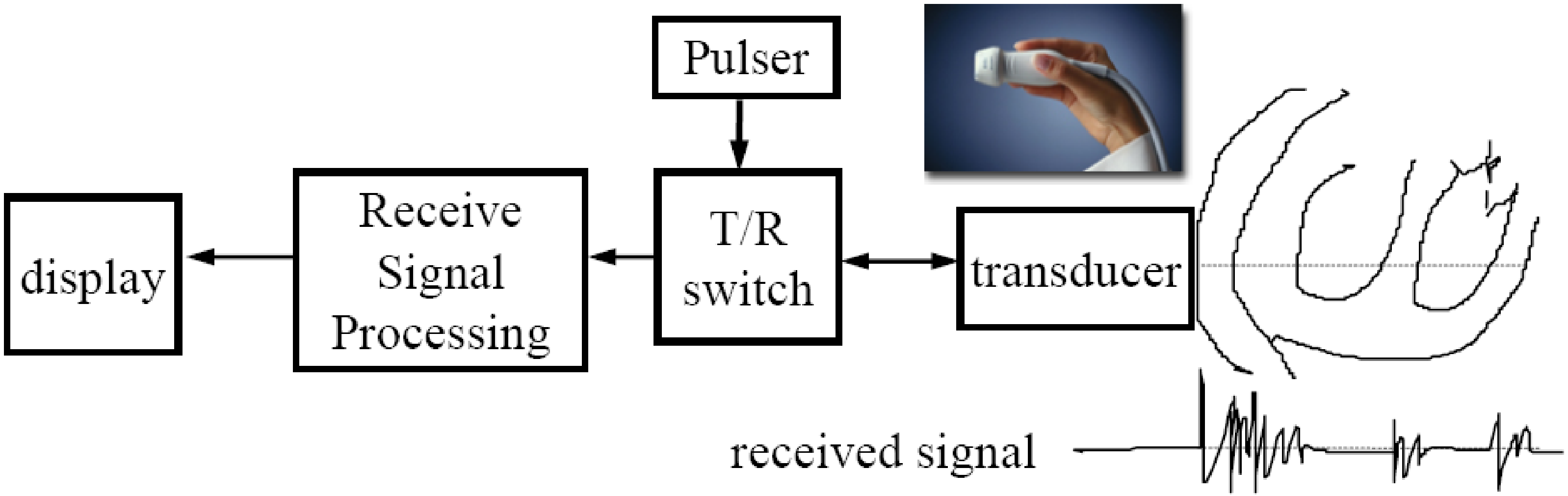
How to generate ultrasound?



5.8 Construction of a single-element ultrasonic trans-

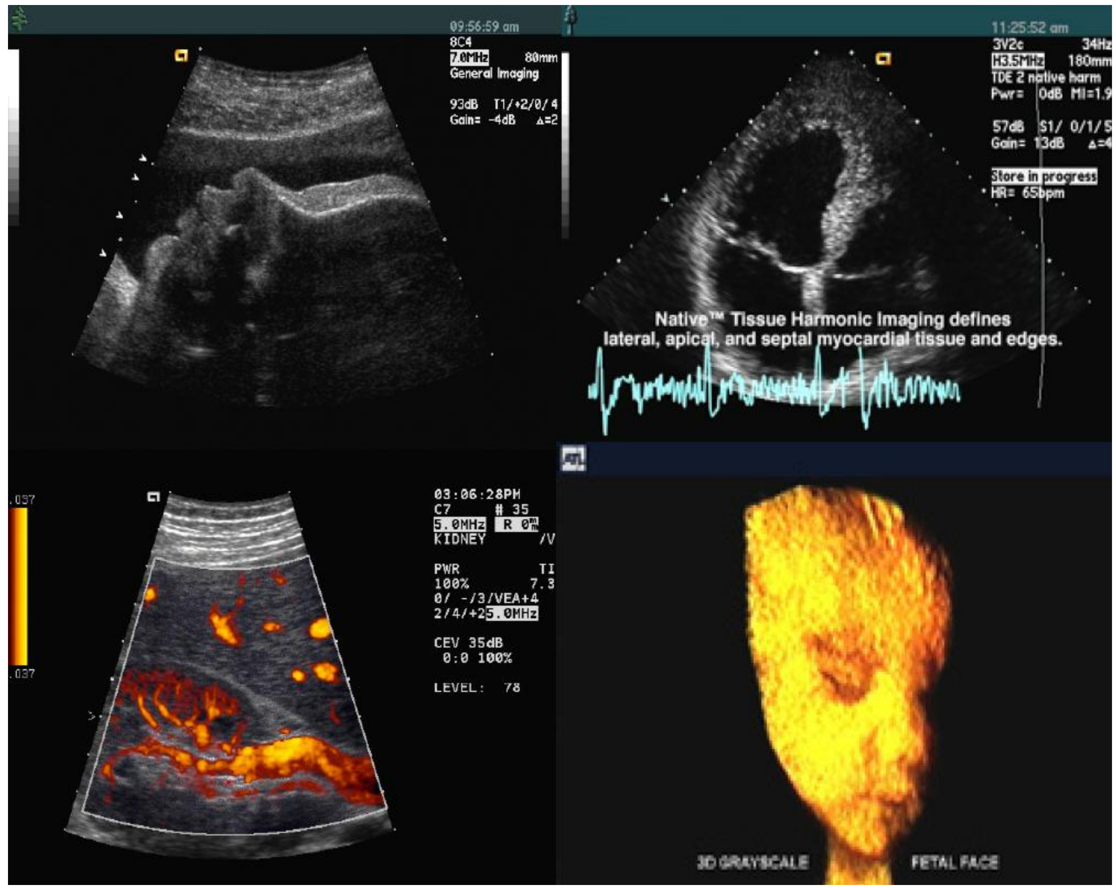
Ultrasound transducer

Medical ultrasound system



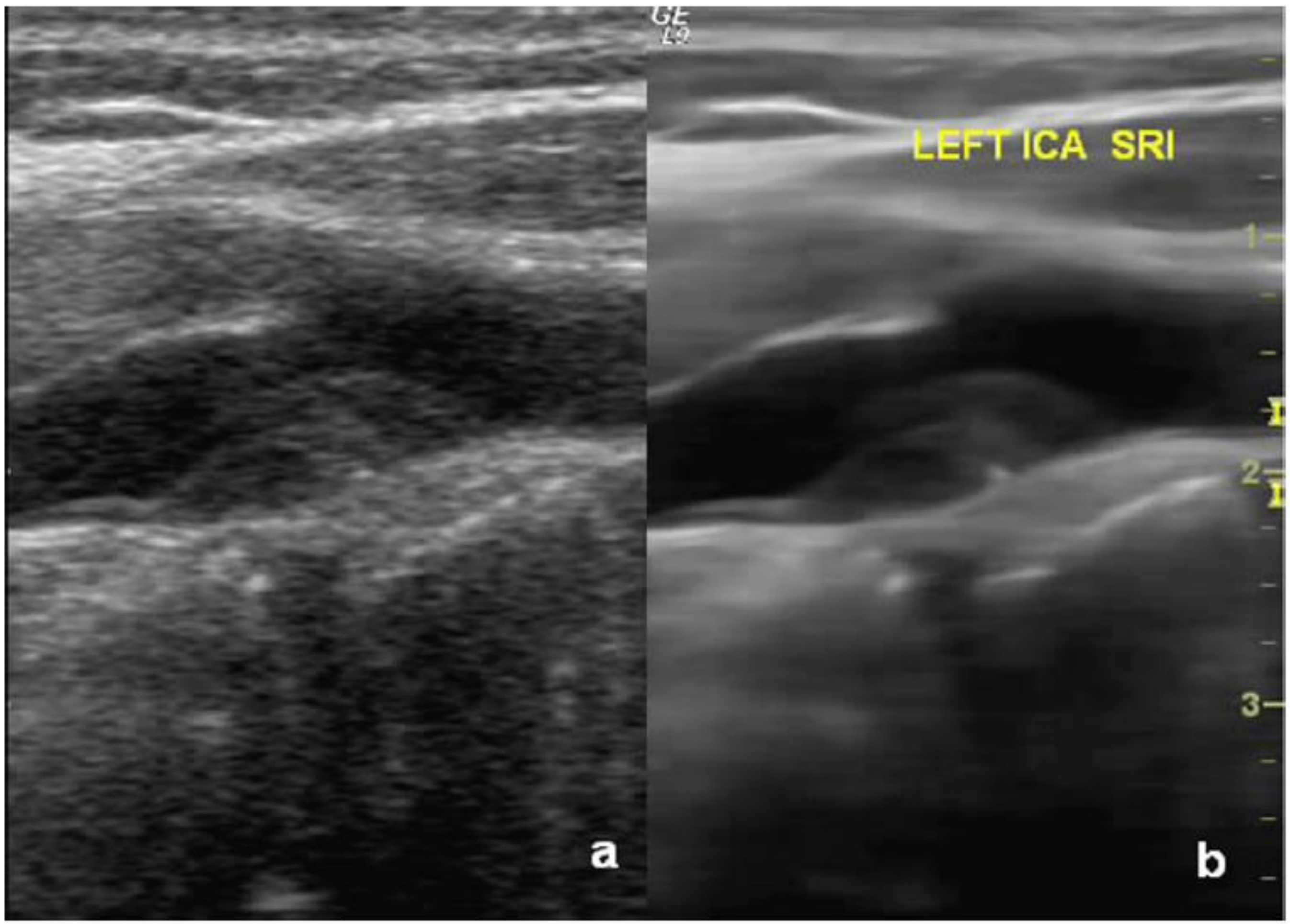
Ultrasonic imaging

- Noninvasive
- Soft tissues
- Real time
- Portable
- Non-ionizing
- Good resolution

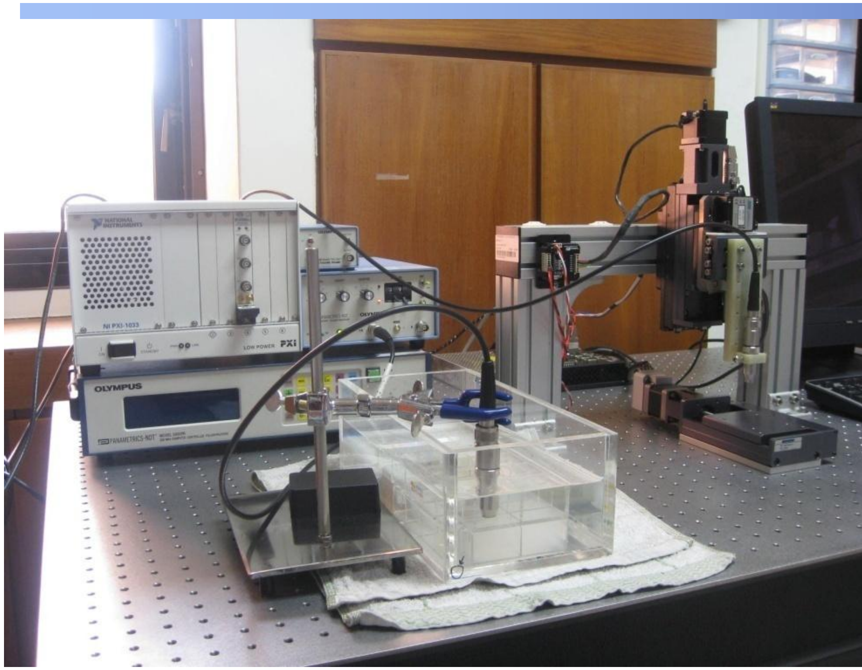


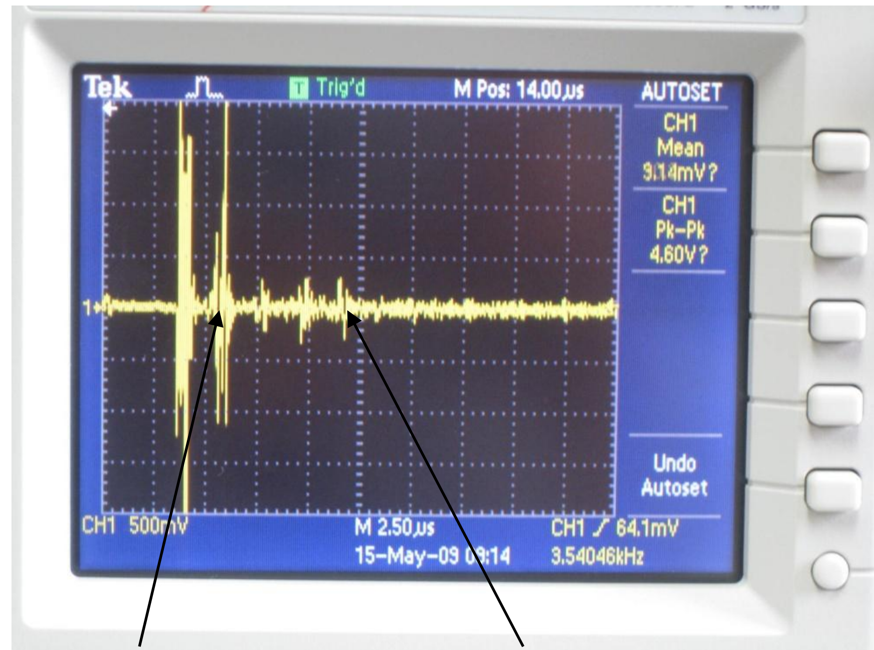
Speckle due to scattering

N. Liasis et al. / European Journal of Radiology 65 (2008) 427–433



Demo: reflection and scattering





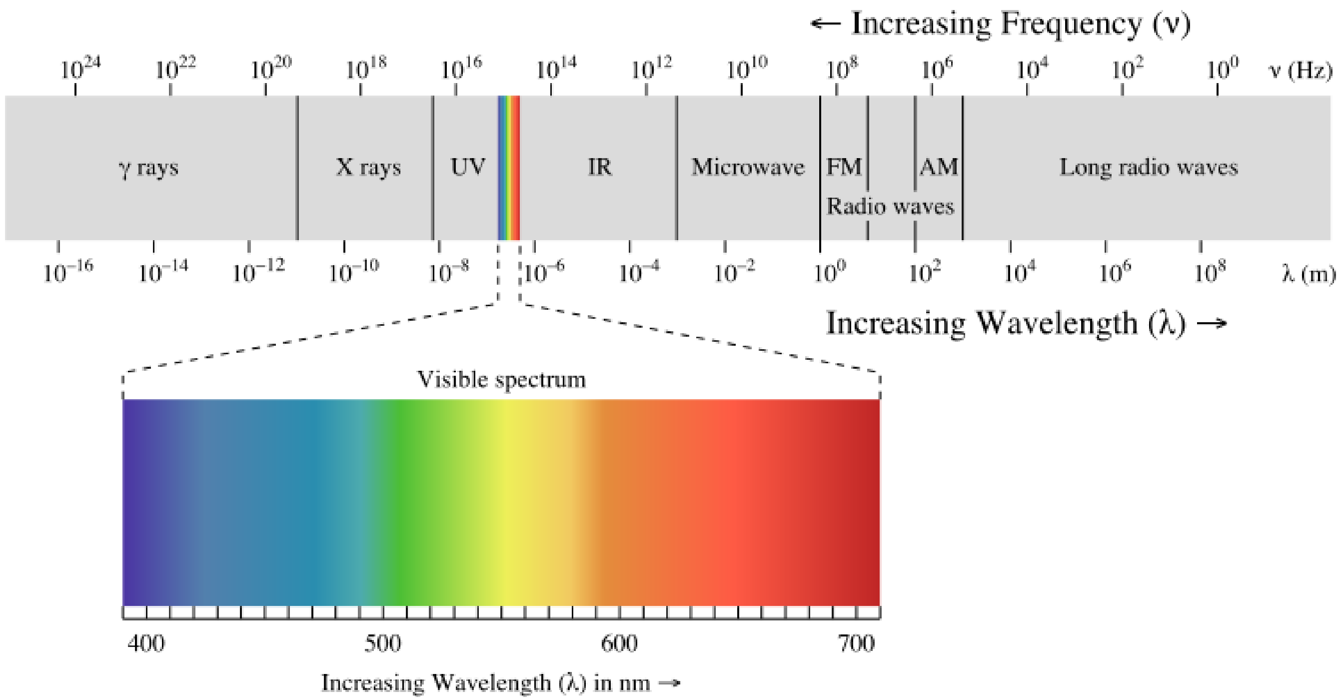
Reflection signal **Scattering signal**

Why is the sky blue?

Rayleigh scattering

Rayleigh scattering intensity for a single particle

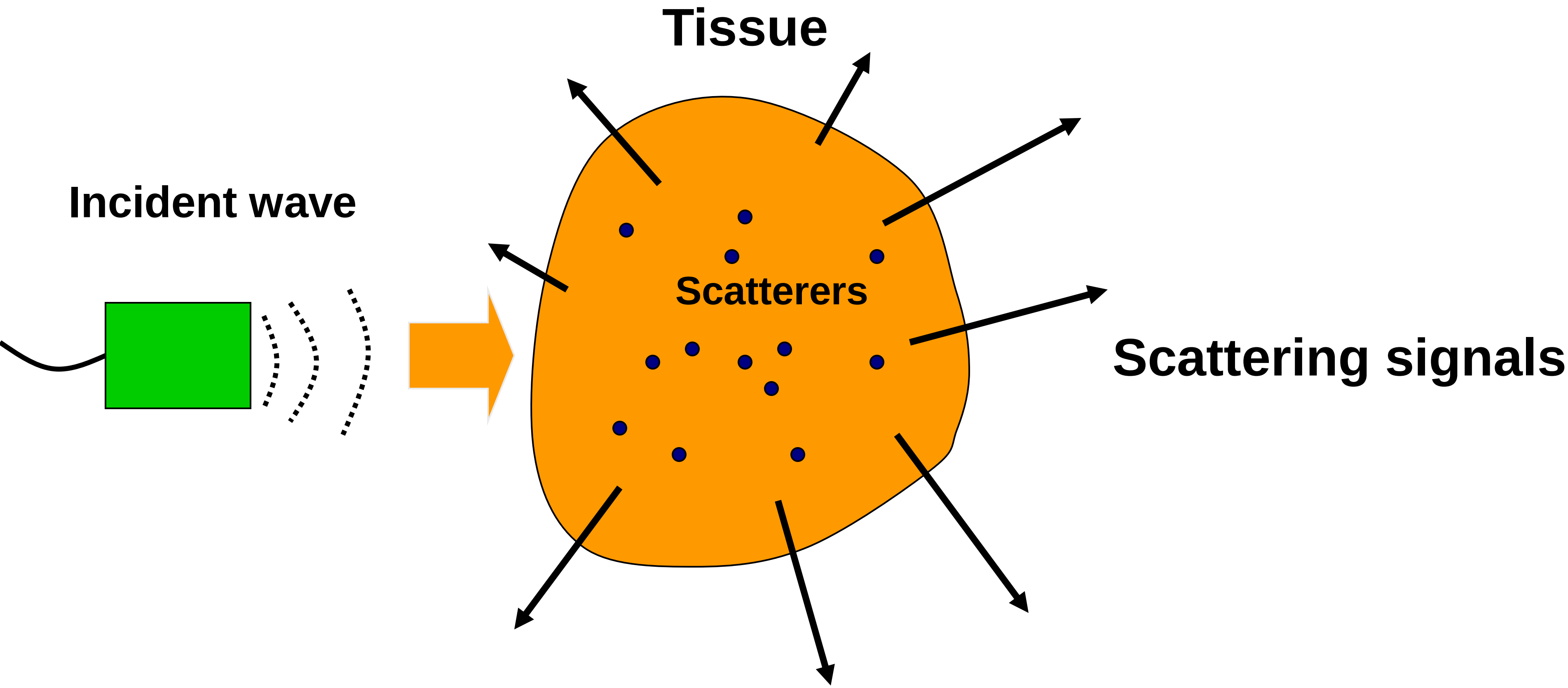
$$I = I_0 \frac{8\pi^4\alpha^2}{\lambda^4 R^2}(1+\cos^2\theta)$$



Clouds are white

Scattering behavior of light depends on particles properties in the air

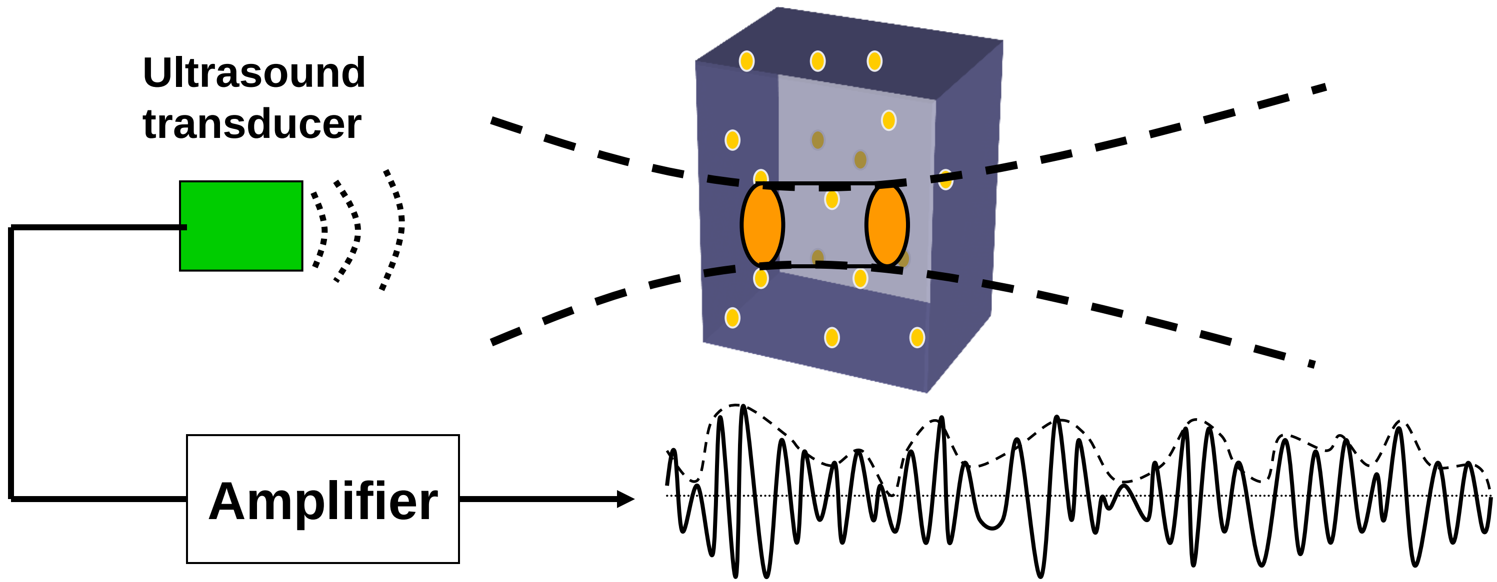
Ultrasonic scattering



Scattering behavior should depend on scatterer structures

What is the scattering behavior of ultrasound in tissues?

Ultrasonic echo model



The resolution cell has N scatterers, and then the complex ultrasonic echoes can be modeled as

$$\mathbf{A} = Ae^{j\theta} = \sum_{n=1}^{N} a_i e^{j\theta_i} = A_r + A_i$$

If N is large, according to central limit theorem, A_r and A_i are Gaussian distributed random variables, and the joint distribution of A_r and A_i is

$$p_{A_r A_i}(A_r, A_i) = \frac{1}{2\pi\sigma^2} e^{-\left(\frac{A_r{}^2 + A_i{}^2}{2\sigma^2}\right)}$$

Change from rectilinear to polar coordinate,

$$A = \sqrt{A_r{}^2 + A_i{}^2}, \qquad p_{A\phi}(A,\phi) = \frac{A}{2\pi\sigma^2} e^{-\left(\frac{A^2}{2\sigma^2}\right)} \quad A > 0$$

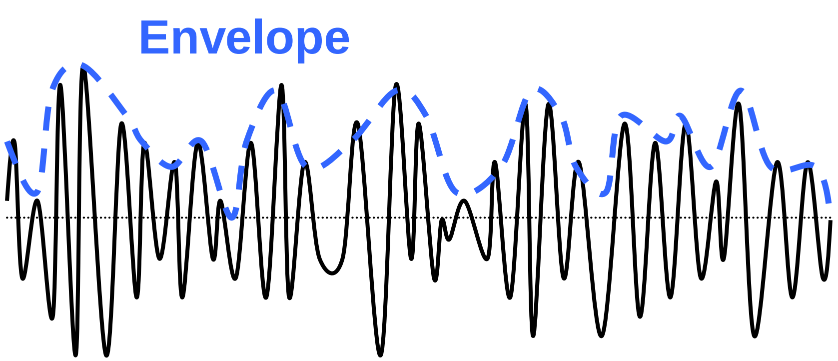
So the pdf of envelope *A* is the marginal density

$$p_A(A) = \int_{-\pi}^{\pi} p_{A\phi}(A,\phi)\, d\phi = \frac{A}{\sigma^2} e^{-\left(\frac{A^2}{2\sigma^2}\right)}$$

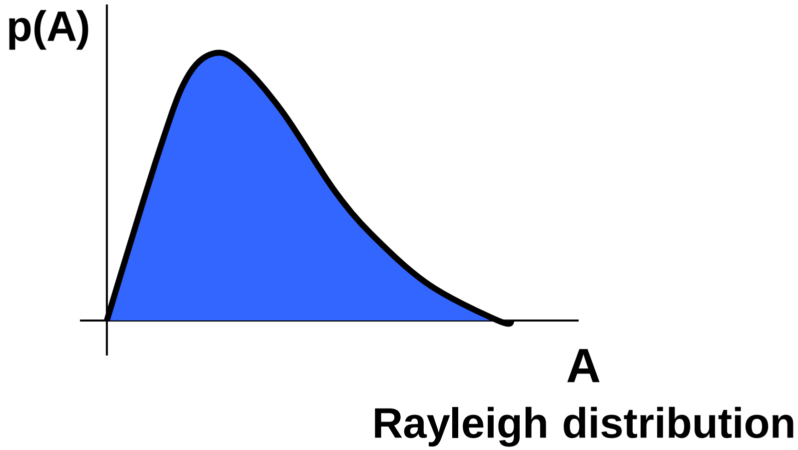
Rayleigh distribution

When the resolution cell has a large number of scatterers, the envelope statistics of echo would follow Rayleigh distribution

$$p_A(A) = \frac{A}{\sigma^2} e^{-\left(\frac{A^2}{2\sigma^2}\right)}$$

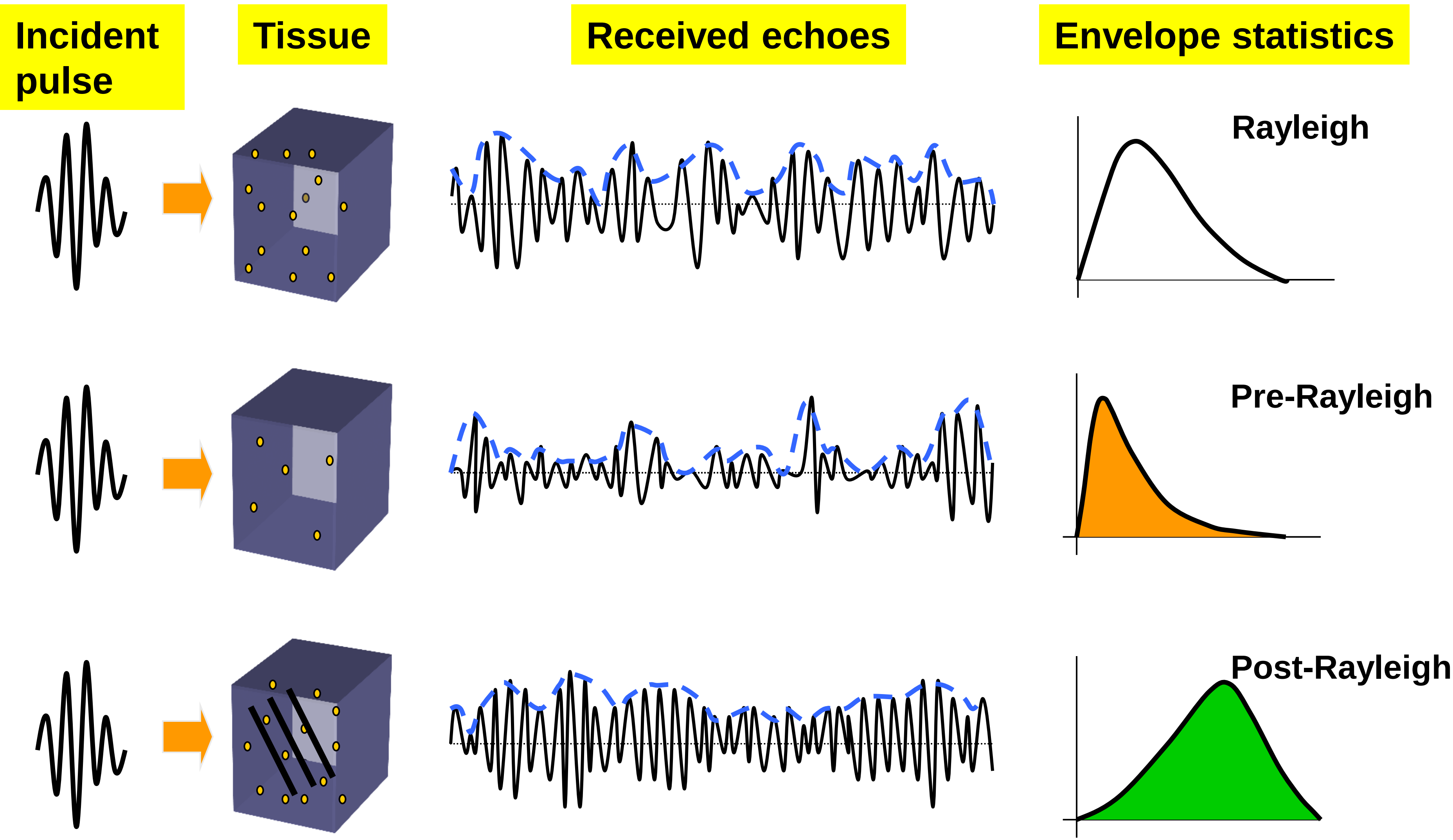


Time-domain ultrasound signal



Envelope histogram

Rayleigh distribution is inadequate



History of developing general models

- **Rayleigh distribution** ***(Burckhardt 1978)***
  - **for Rayleigh**
- **Rician and generalized Rician distributions** ***(Joynt 1979; Wagner et al. 1987)***
  - **for Rayleigh and post-Rayleigh**
- **K-distribution** ***(Weng et al. 1991; Shankar et al. 1993)***
  - **for pre-Rayleigh and Rayleigh**
- **Generalized K- and homodyned K-distributions** ***(Shankar 1995; Dutt and Greenleaf 1994)***
  - **for pre-Rayleigh, Rayleigh, and post-Rayleigh**
  - **the complex nature of these models limited their practical applications**

Nakagami distribution *(Shankar 2000)*

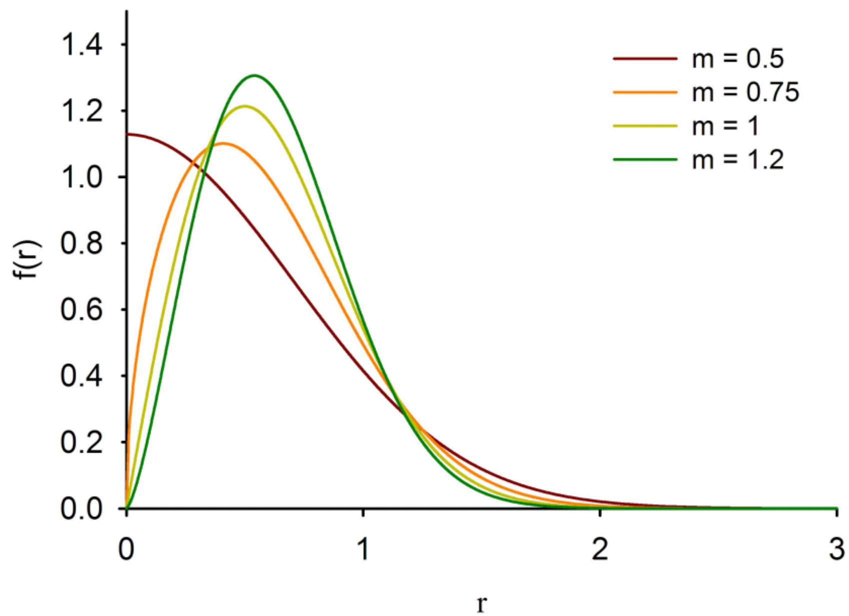
Γ(.) is the Gamma function, U(.) is the step function, and *r* means envelope

$$f(r) = \frac{2m^m r^{2m-1}}{\Gamma(m)\Omega^m} \exp(-\frac{m}{\Omega} r^2) U(r)$$

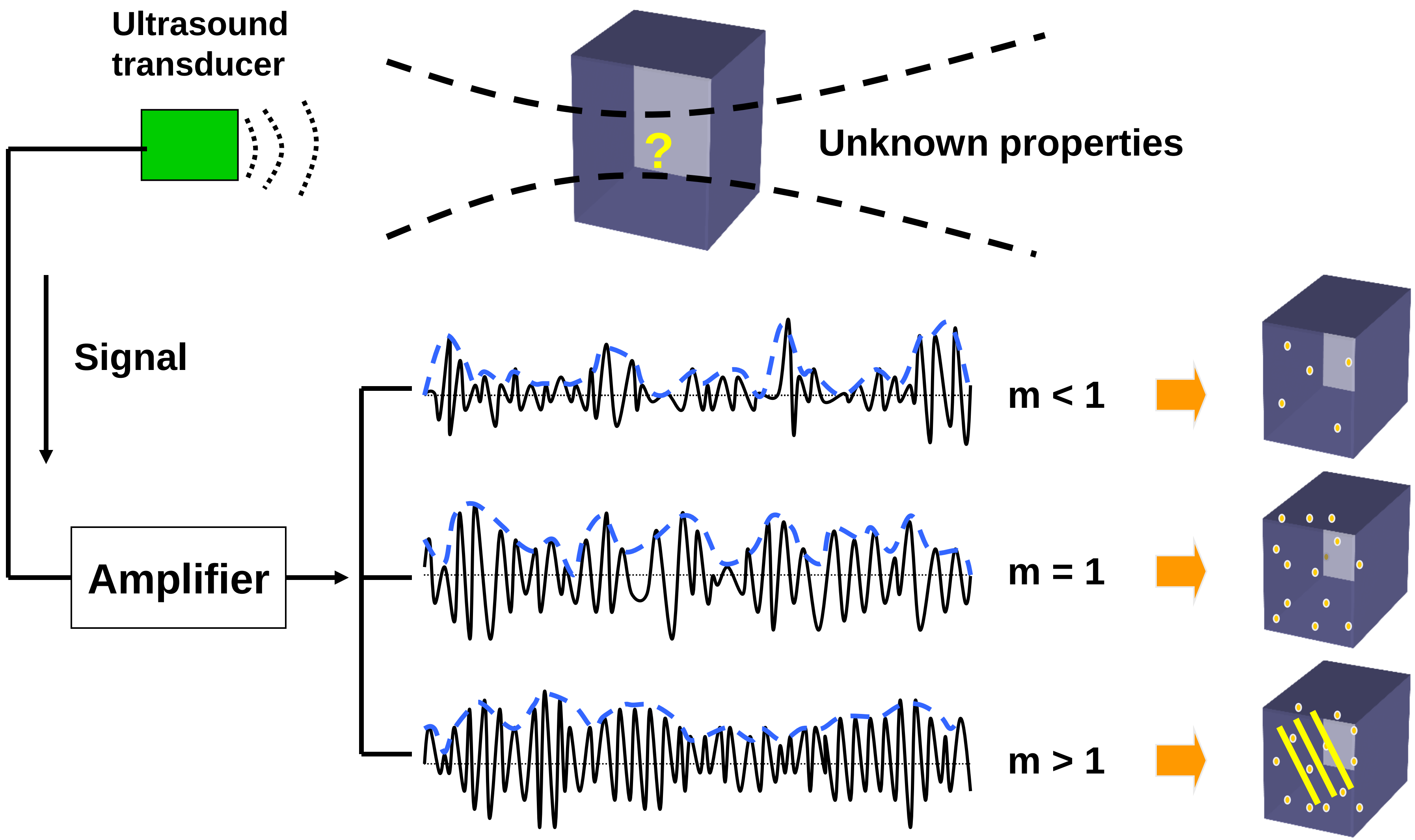
The Nakagami parameter *m* and the scaling parameter Ω can be estimated by

$$m = \frac{[E(R^2)]^2}{E[R^2 - E(R^2)]^2}$$

$$\Omega = E(R^2)$$

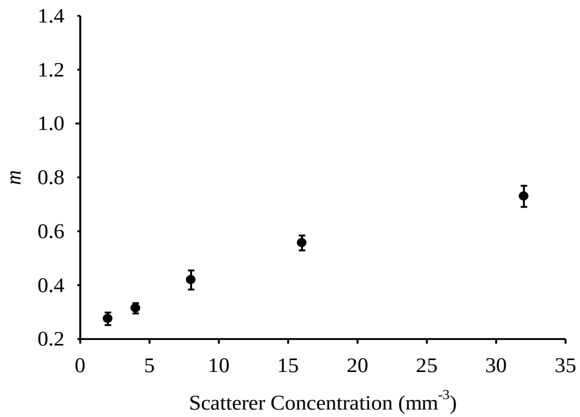


Nakagami parameter
- a predictor for tissue characterization

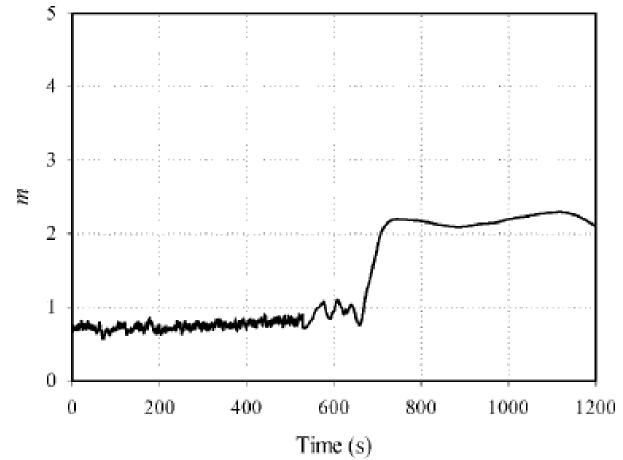


Previous studies

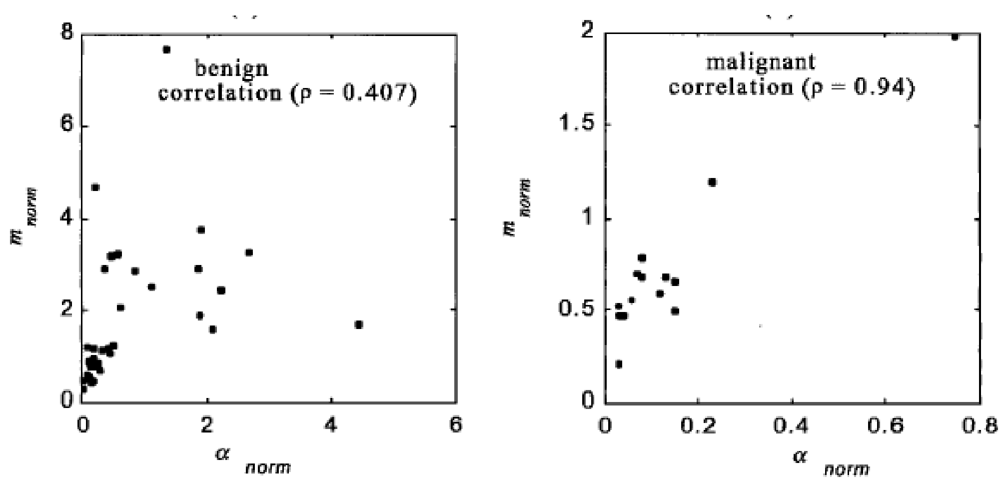
Phantom *(Tsui and Wang 2004)*



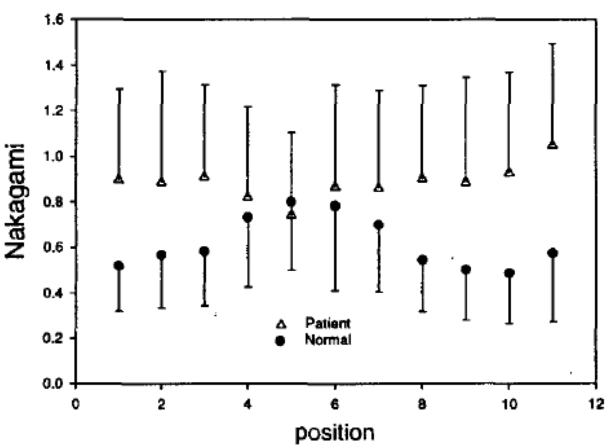
Blood *(Huang et al. 2007)*



Breast mass *(Shankar et al. 2001)*



Bone *(Wang and Tsai 2001)*

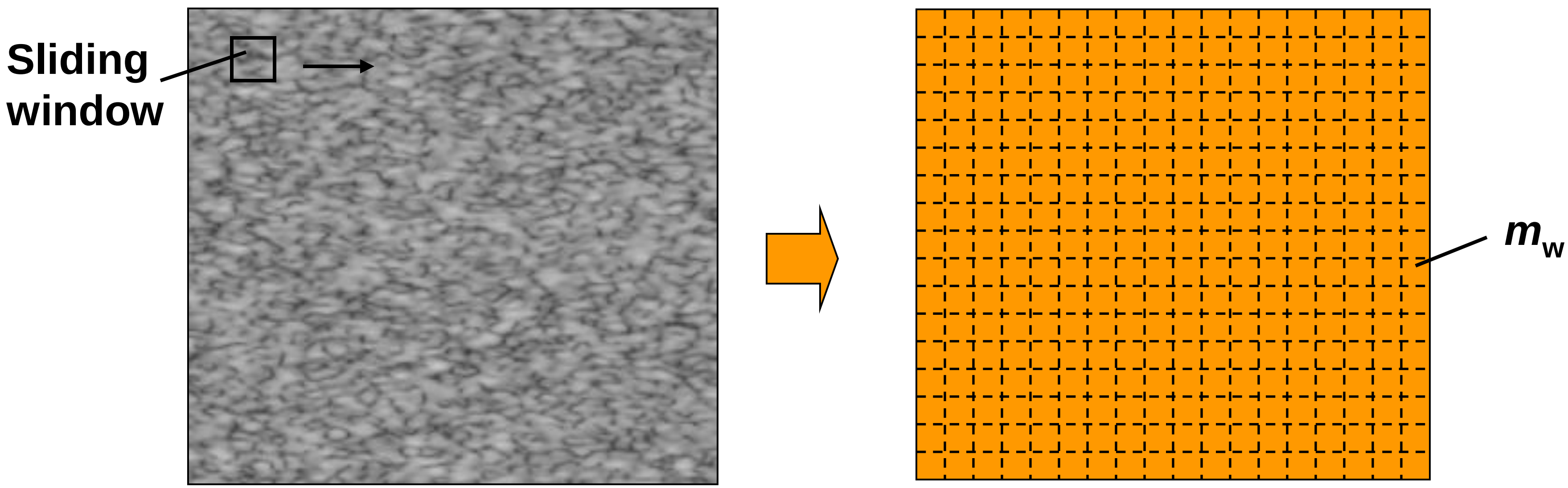


Problems for clinical purpose

- Not an image mode. Not convenient and friendly for clinical physicians.
- Hard to locally characterize biological tissues

Our strategy: Nakagami imaging

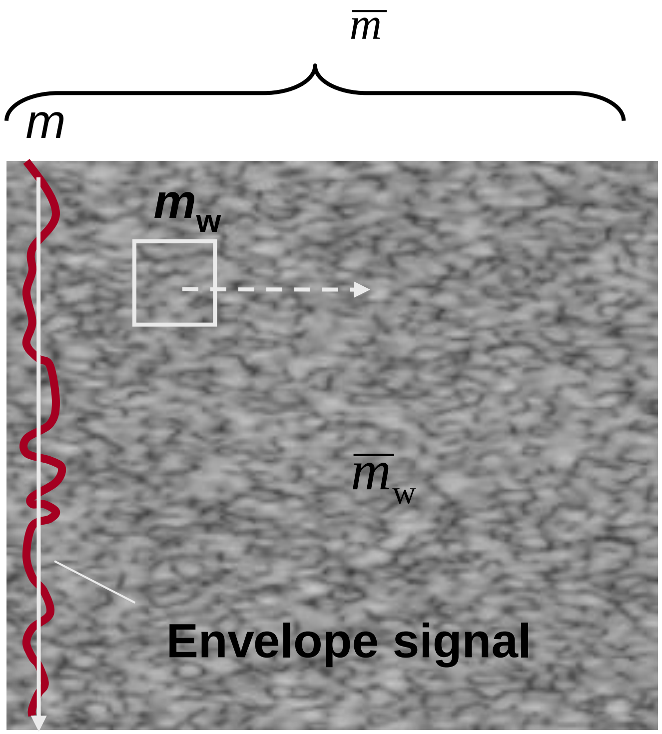
Using a sliding window to construct a parameter map

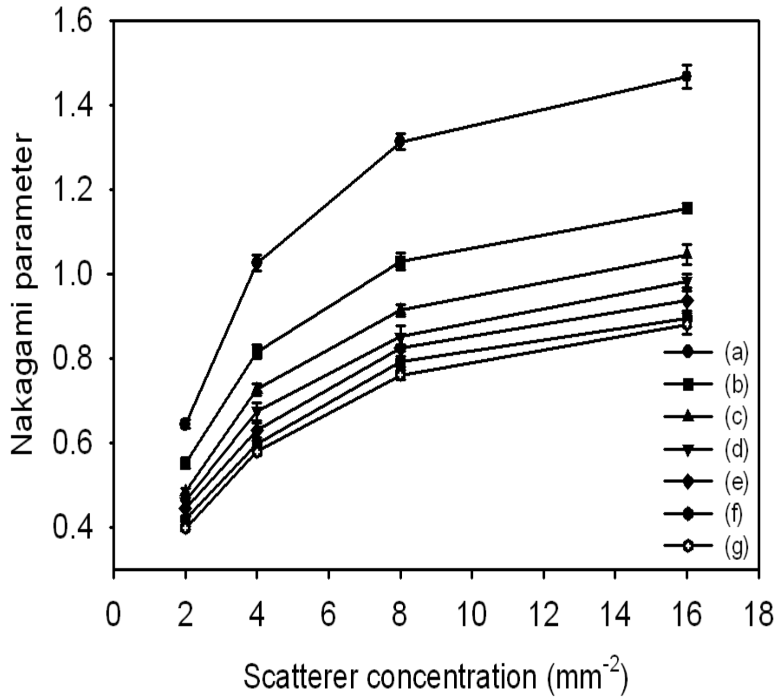


Envelope image

Nakagami image

How to determine the window size?





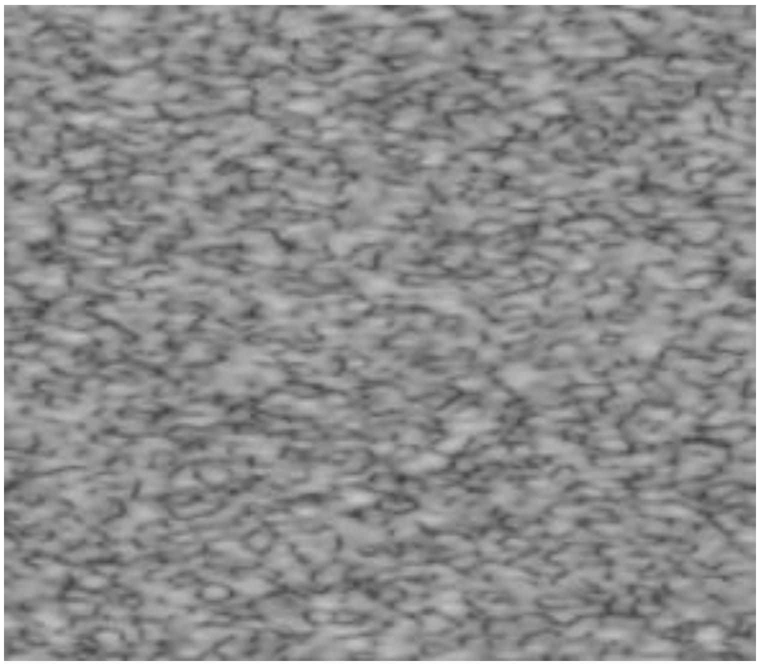
The appropriate size is determined when $\overline{m}_w = \overline{m}$

(sidelength = 3 times pulselength)

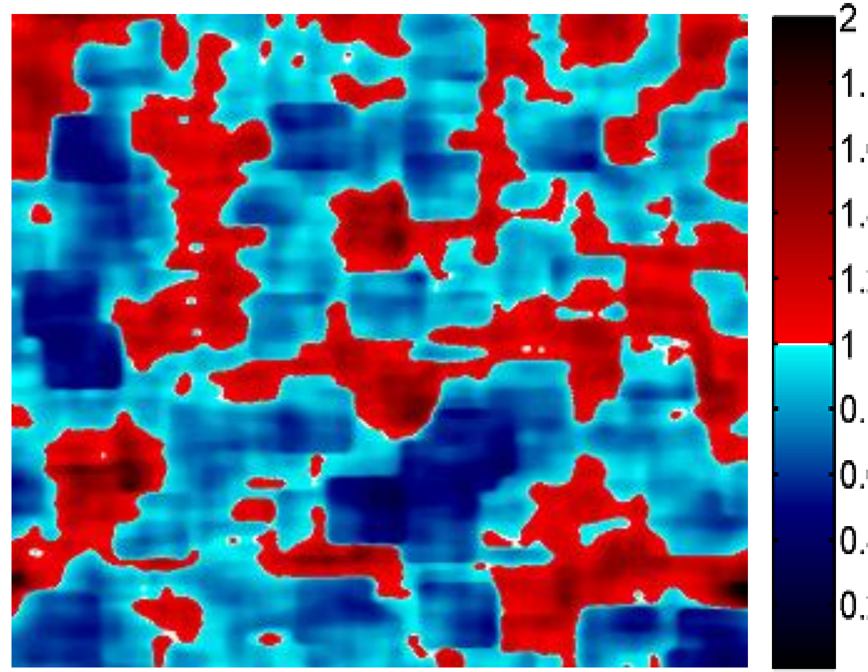
How to display the Nakagami image?

- Grayscale is not suitable for Nakagami image, because Nakagami parameter has physical meanings associated with envelope distribution and scatterer properties.
- We used blue for pre-Rayleigh, white for Rayleigh, and red for post-Rayleigh.

B-scan and Nakagami images



B-mode image



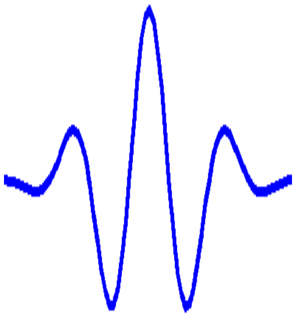
Nakagami image

Simulations and experiments

Simulation model

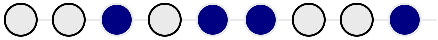
Model of ultrasonic backscattered signals $RF\ signals = H \otimes Z$

For 1-D consideration



$\otimes$

1 1 0 1 0 0 1 1 0



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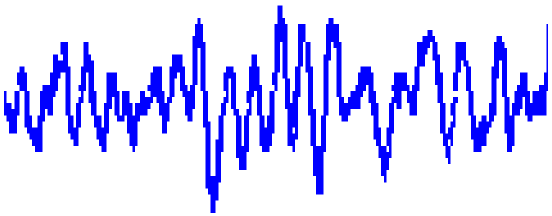
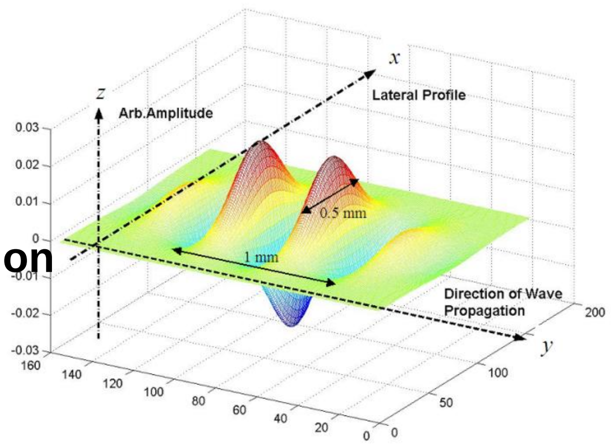
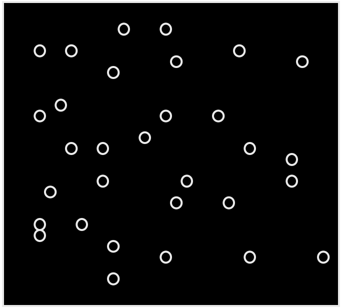


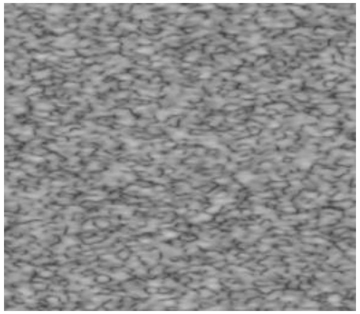
Ultrasonic echo is obtained from the convolution of Gaussian pulse with 1-D scatterers

For 2-D consideration



$\otimes$

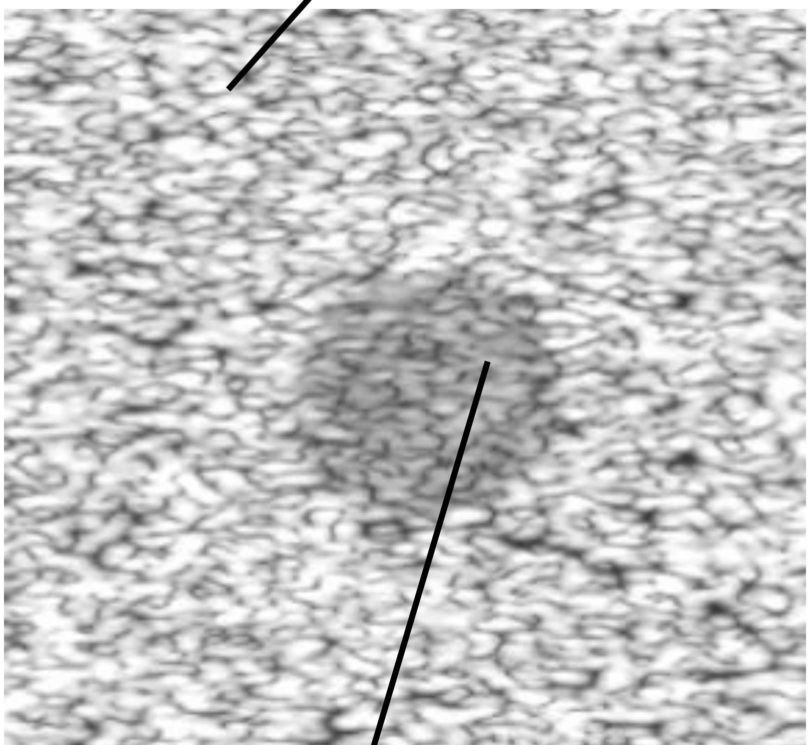


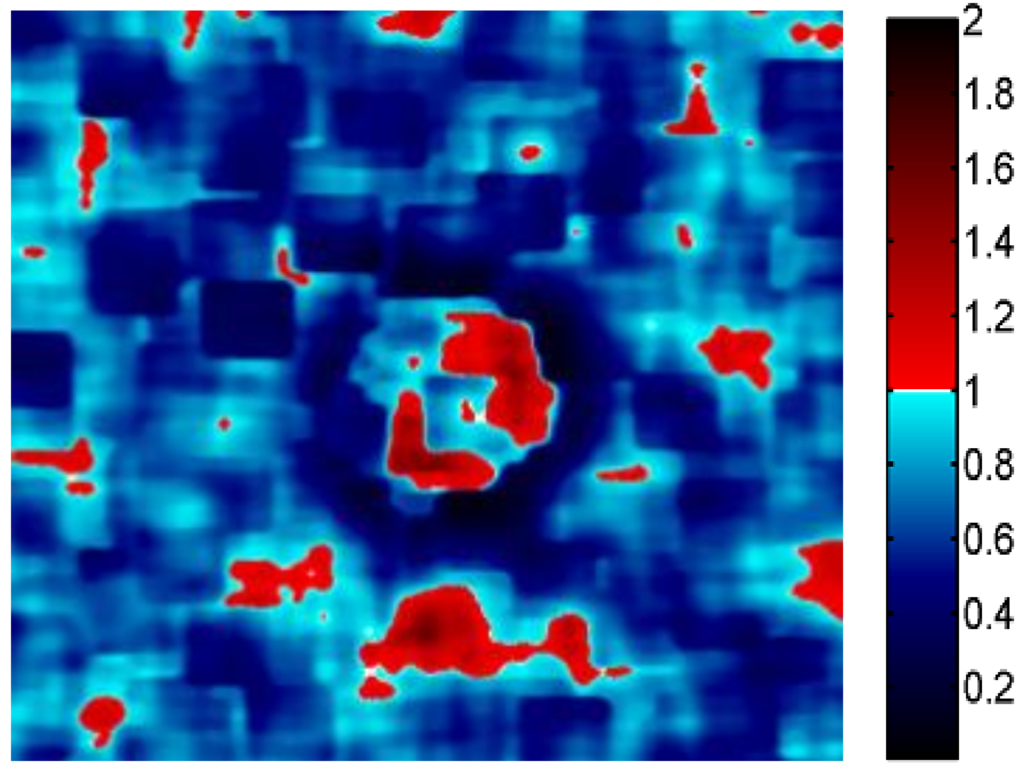


B-mode image is obtained from the convolution of Gaussian pulse with a cross-sectional scatterer distribution

Nakagami imaging

Low scatterer concentration (4/mm^2)
Relative backscattering coefficient: 4

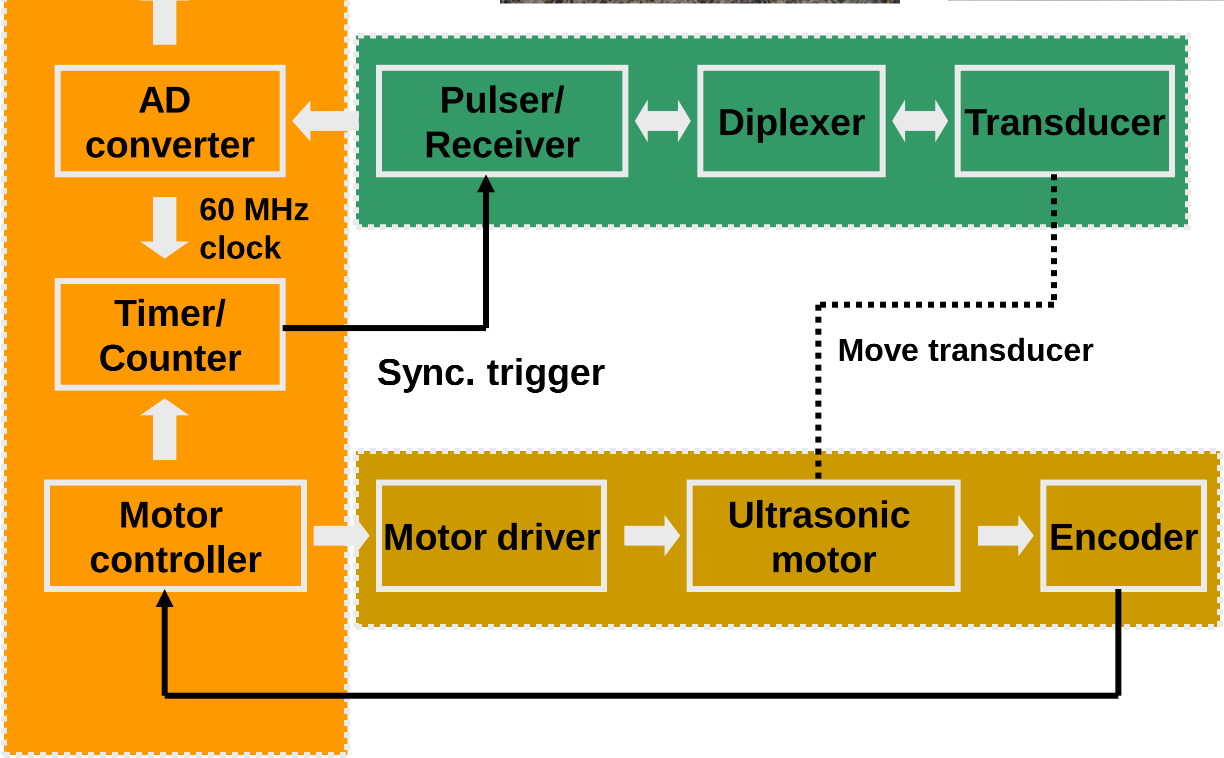




High scatterer concentration (32/mm^2)
Relative backscattering coefficient: 1

Cataract study





35 MHz transducer

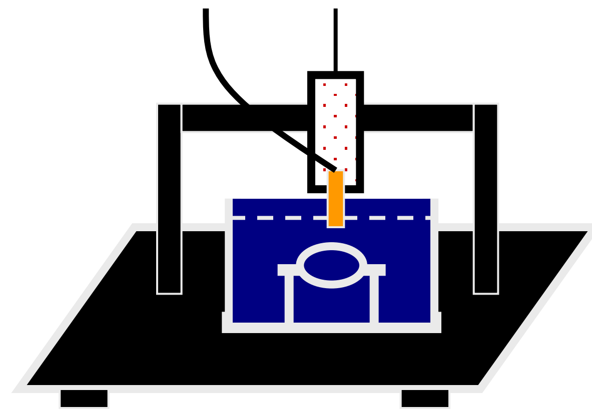
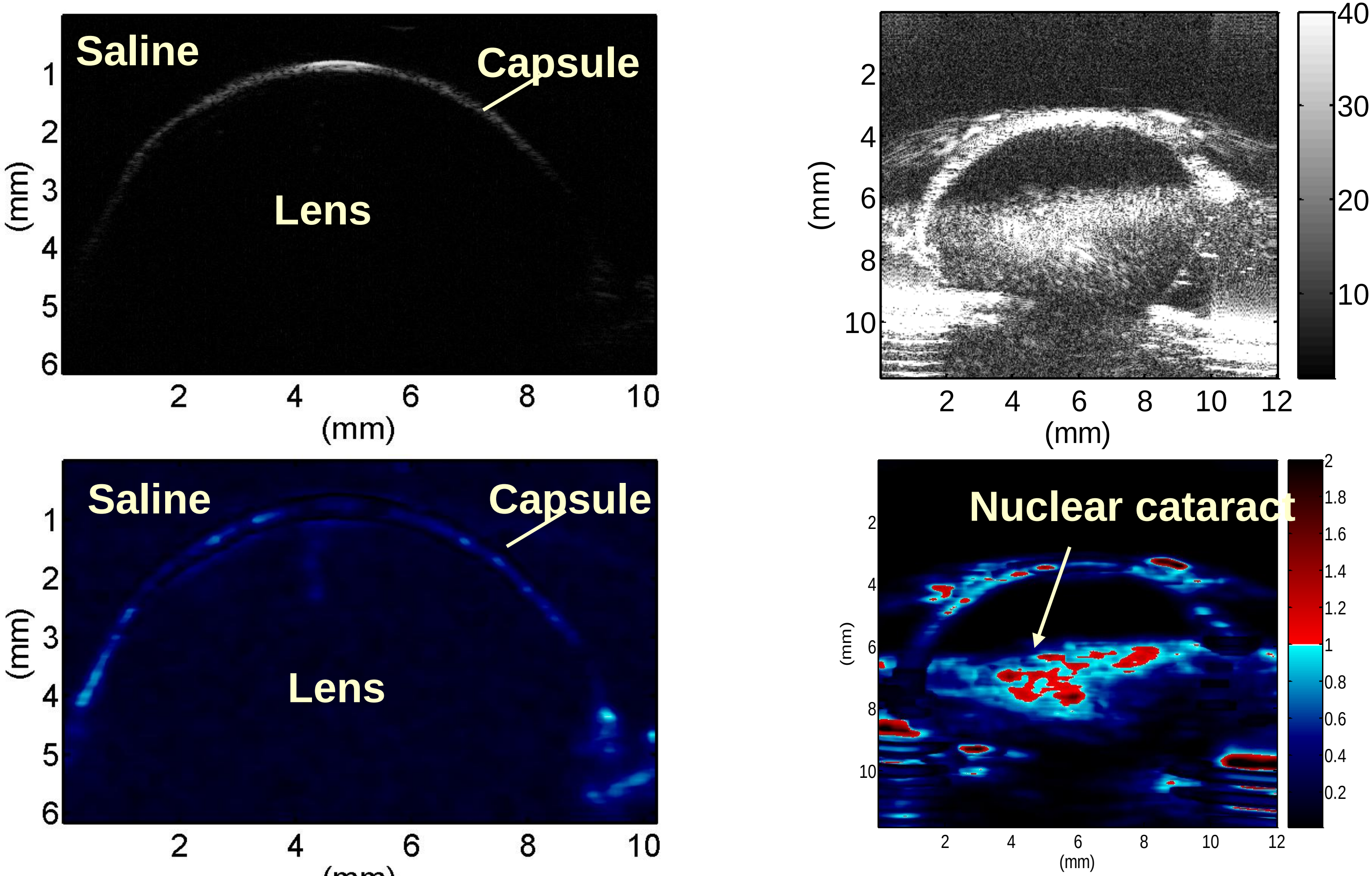
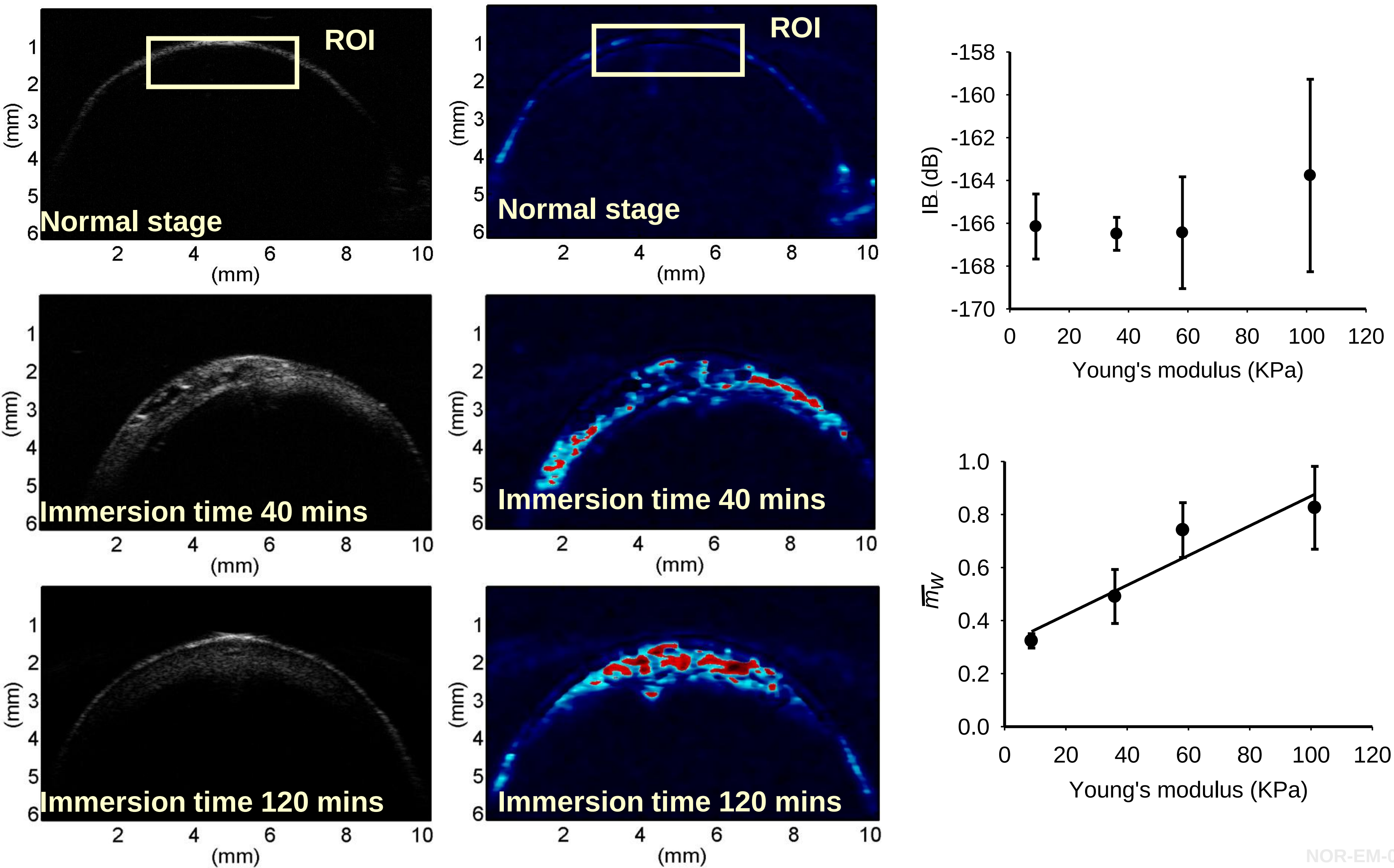


Image scanning stage

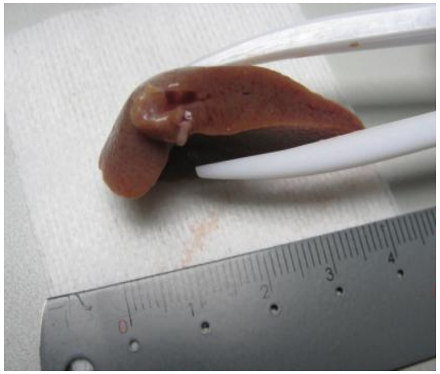
Nuclear cataract

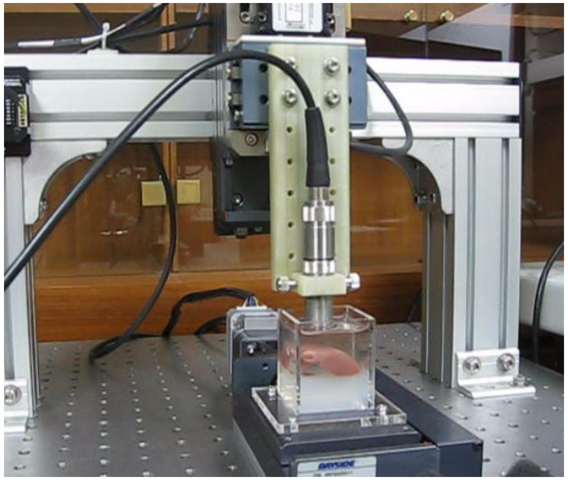


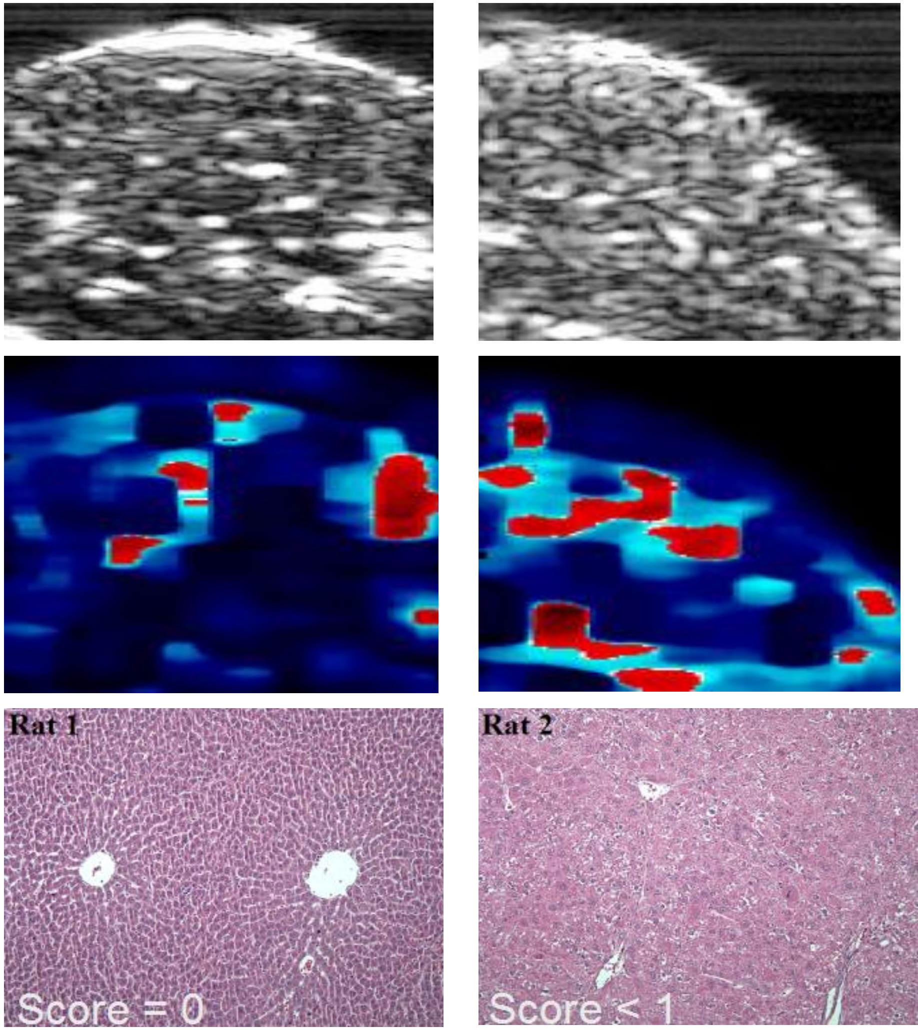
Cortical cataract



Liver fibrosis in rats



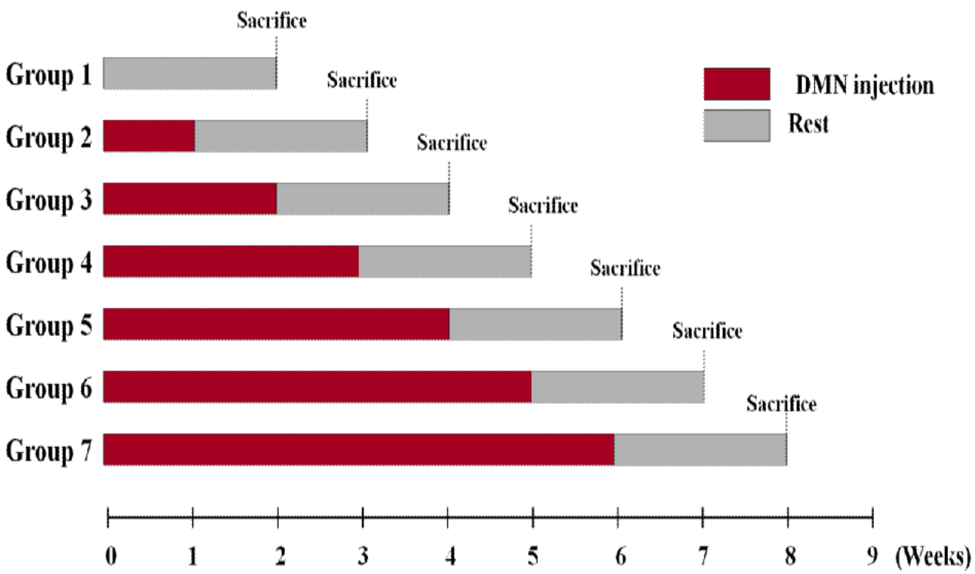


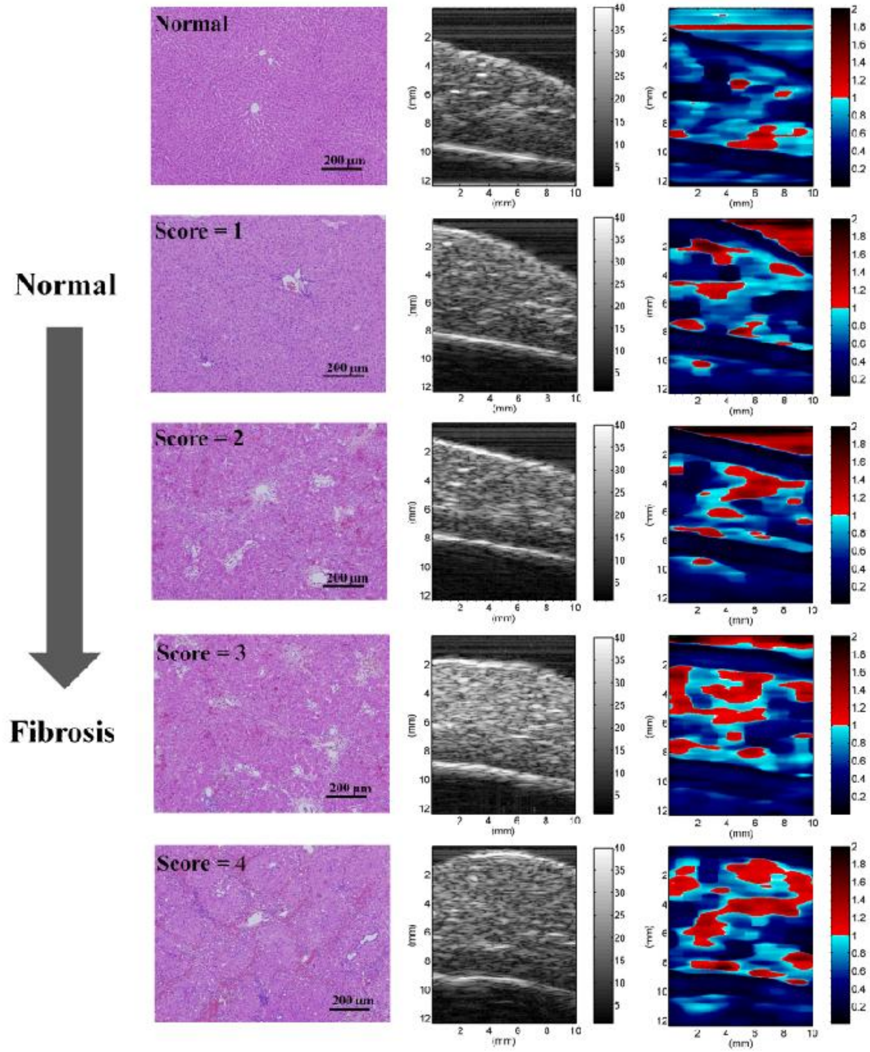


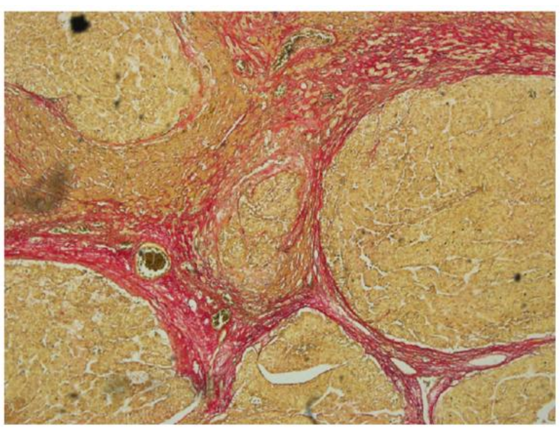
Normal case

Fibrosis (score<1)

Liver fibrosis assessment

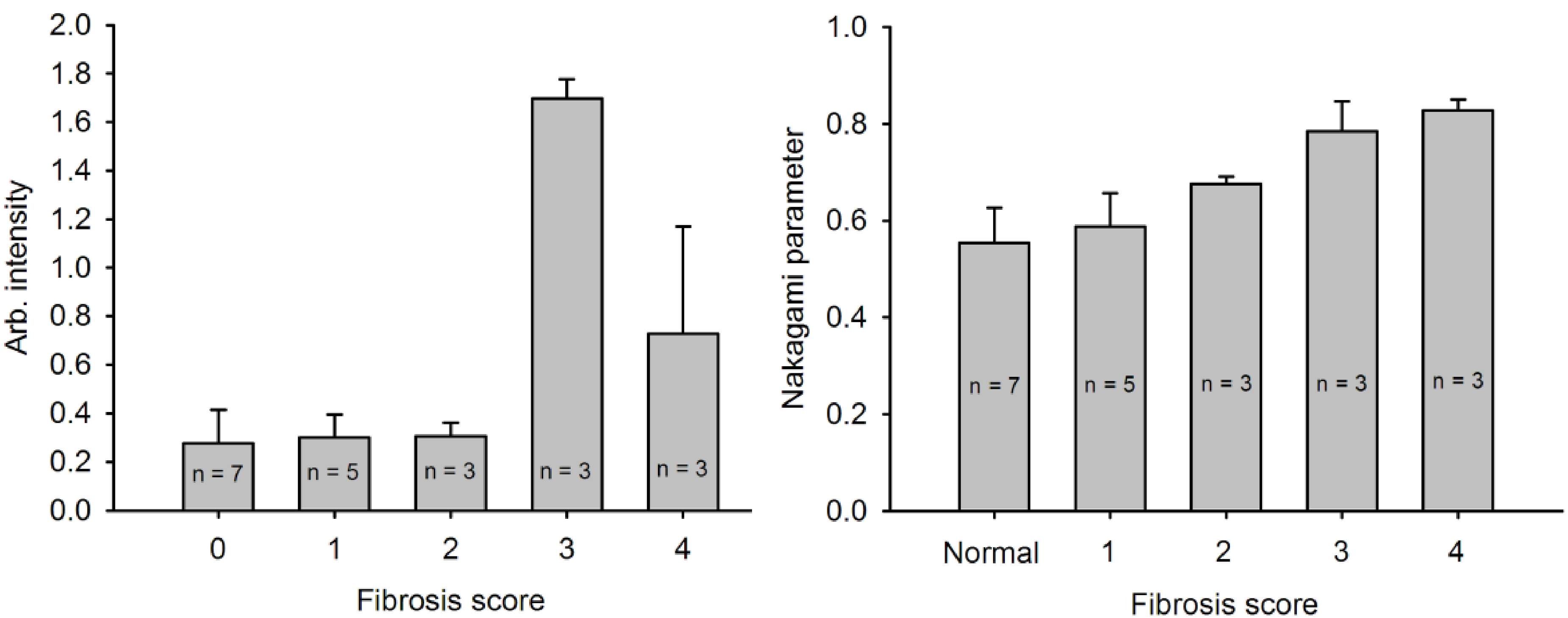




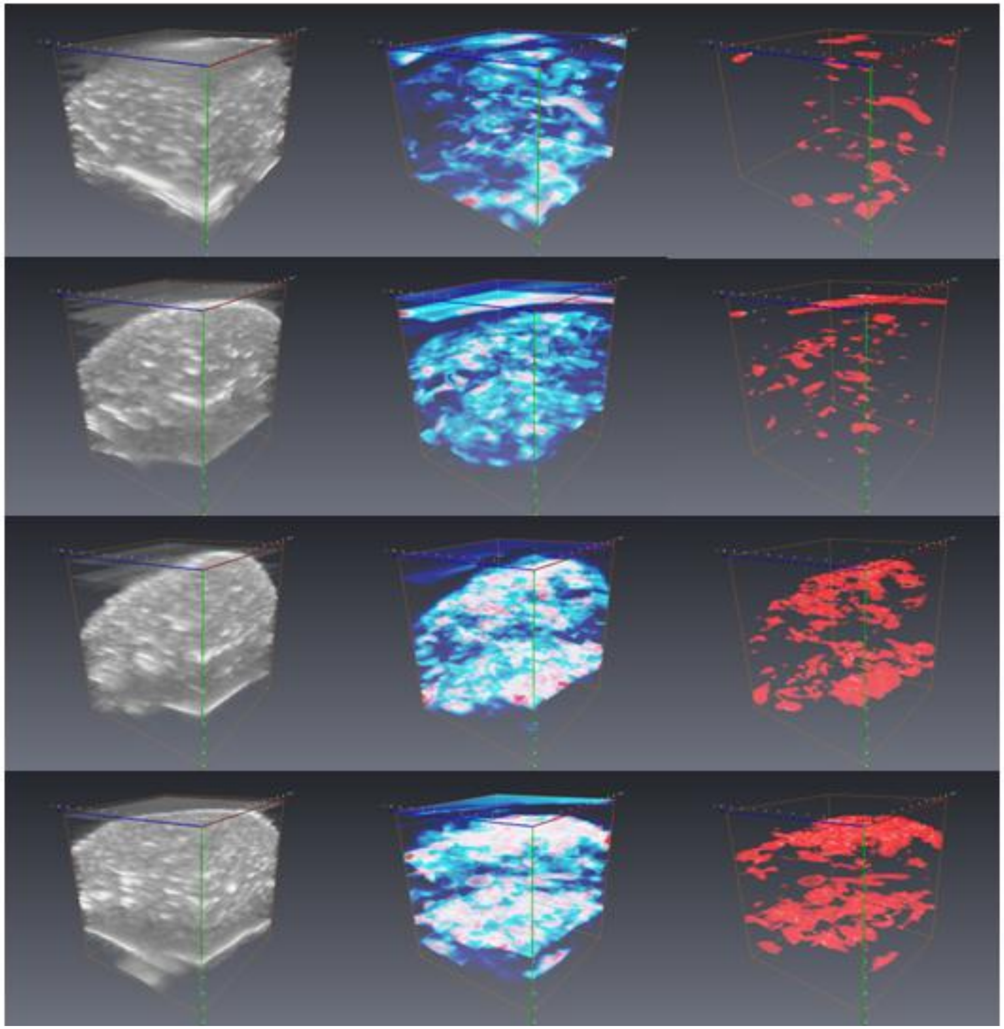


Fibrosis in human

Results as a function of fibrosis stage

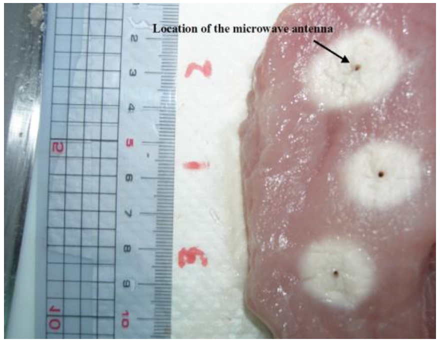


3-D Nakagami imaging for fibrosis detection

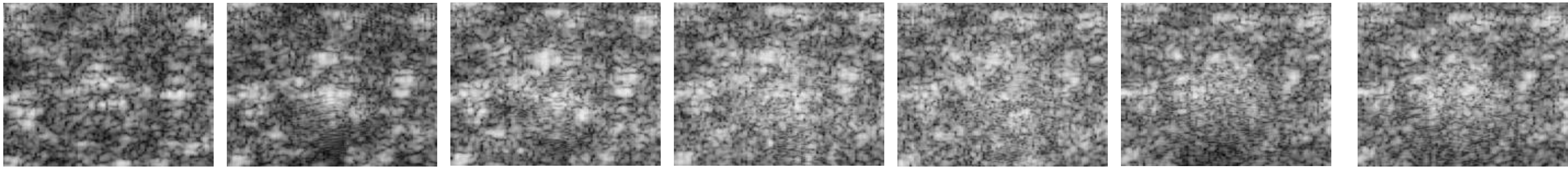


Tissue ablation

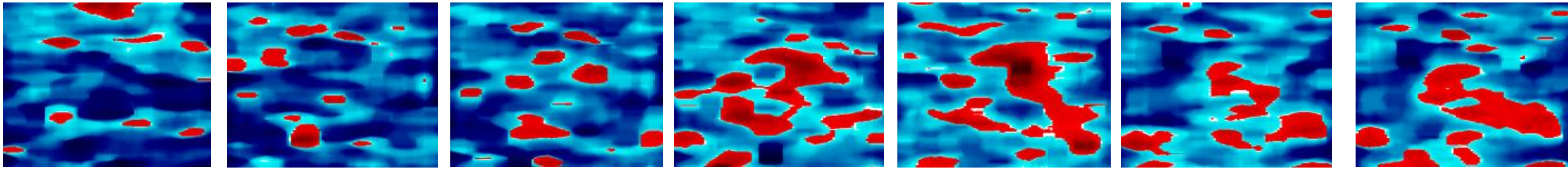
- Sample: pork tenderloin
- Microwave ablation (2.45GHz, 60 W)
- Imaging by portable system (7.5 MHz)
  (Terason 2000)



B-scan



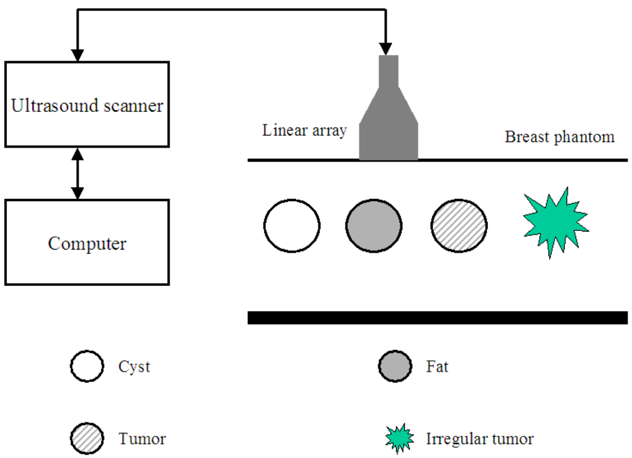
Nakagami image

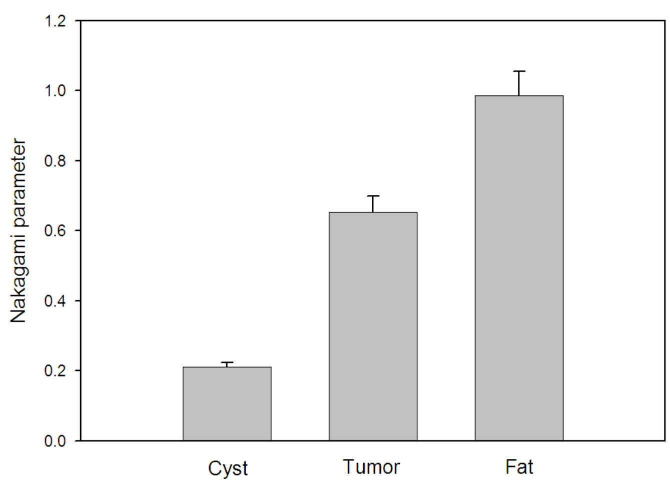


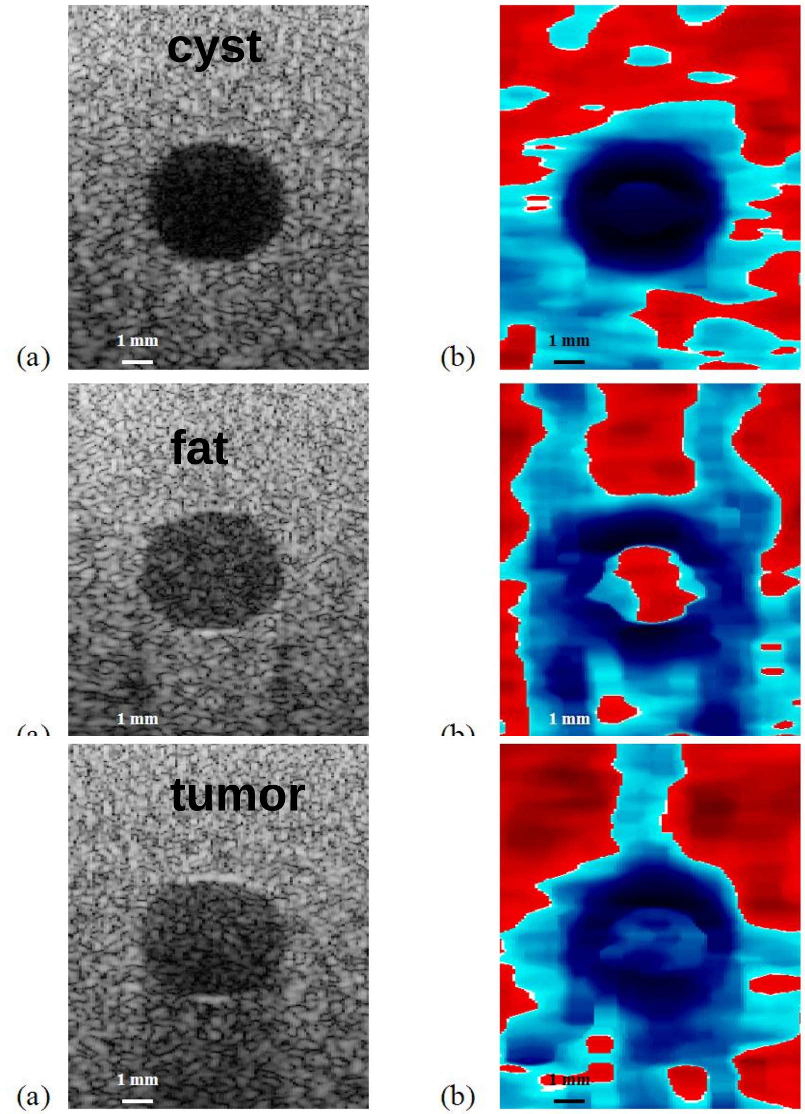
Before t	before (antenna) t= 0	heating 40 sec	heating 70 sec	heating and stop 100 sec	stop (antenna) 280 sec	stop 300 sec

Breast mass classification

Results from breast phantom



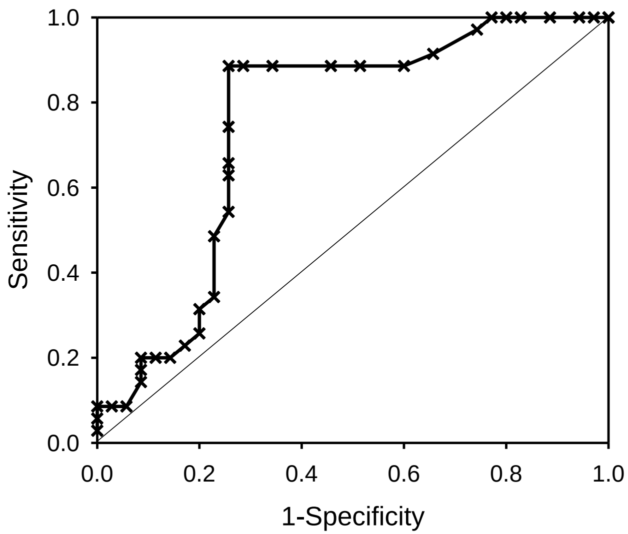




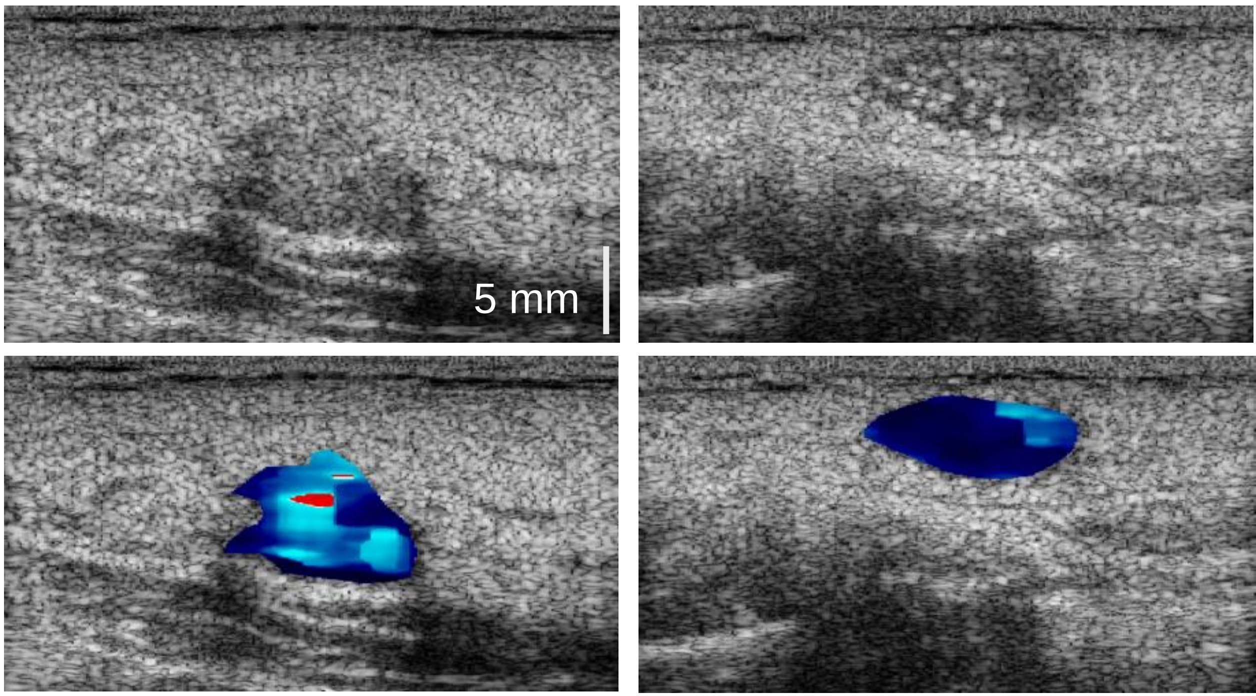
Breast tumor classification

✓Patients come from Taiwan University Hospital
✓In vivo scan by Terason 2000

Nakagami image	Pathology		Total
	Malignant	Benign	
0.64	31 (TP)	9 (FP)	40
0.64	4 (FN)	26 (TN)	30
Total	35	35	70

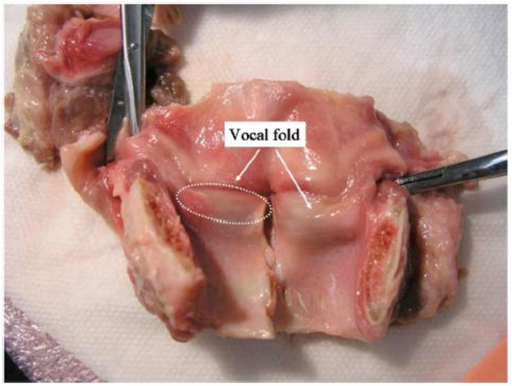


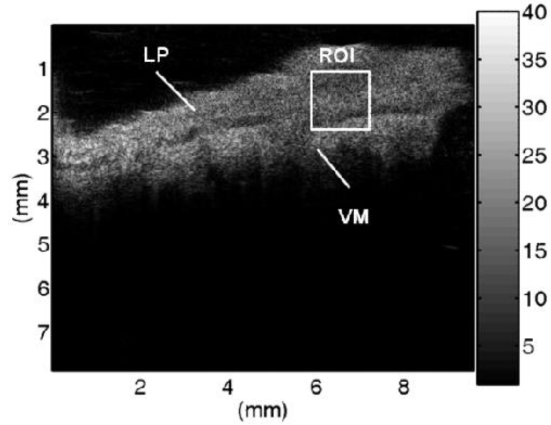
At threshold = 0.64,
Sensitivity: 88.6%
Specificity: 74.3%
Accuracy: 81.4%



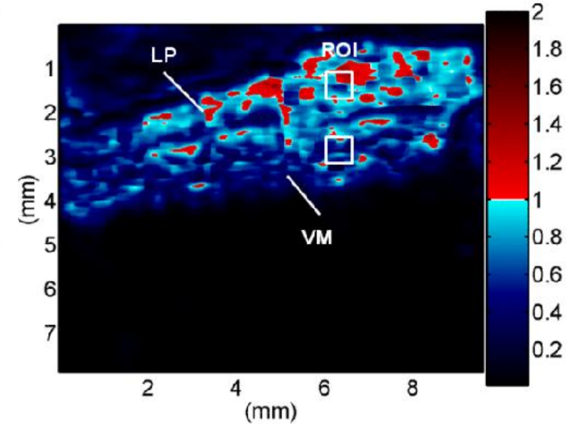
Fibroadenomas
Invasive ductal carcinoma

Vocal fold characterization

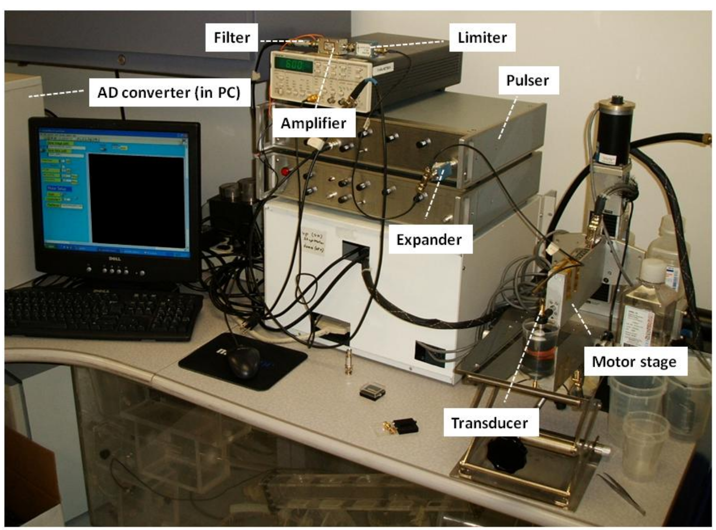


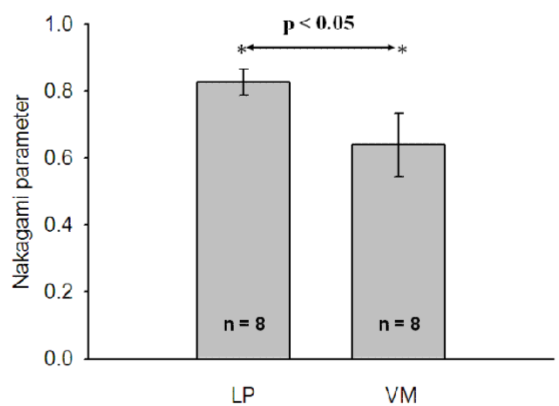


50 MHz B-mode image

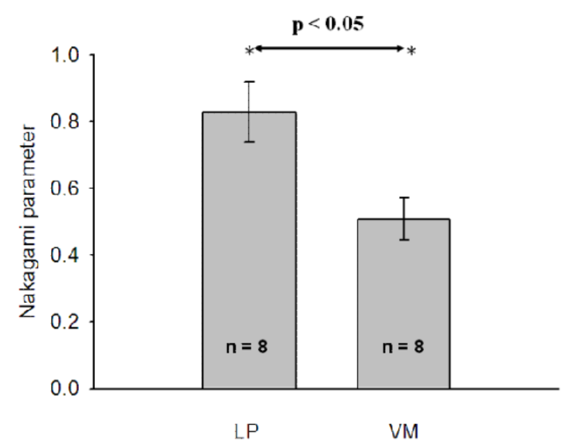


50 MHz Nakagami image



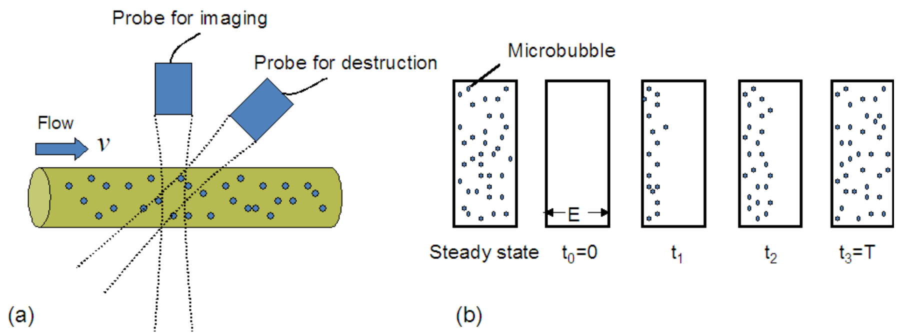


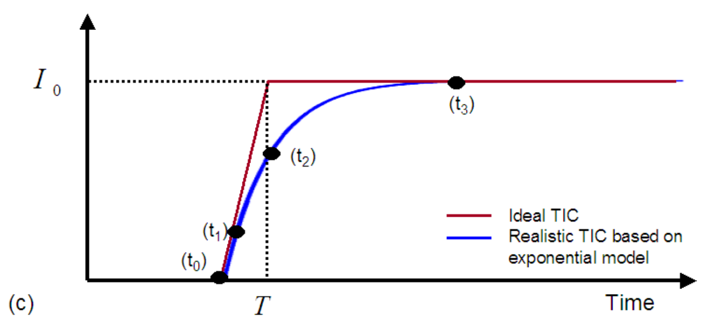
50 MHz results

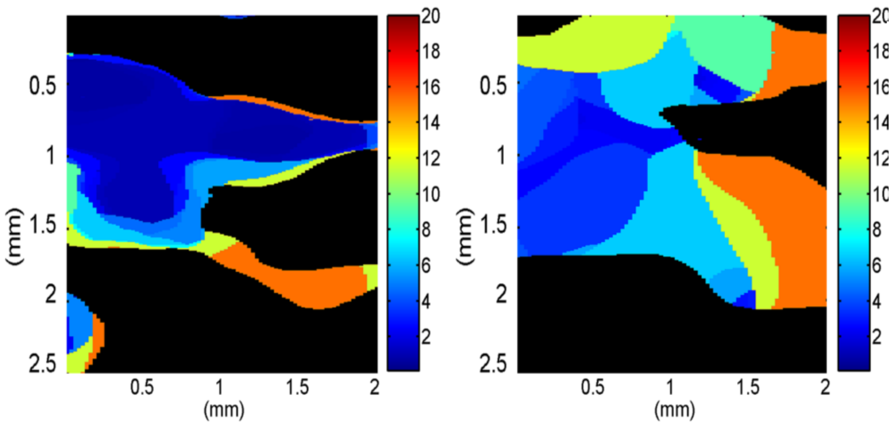


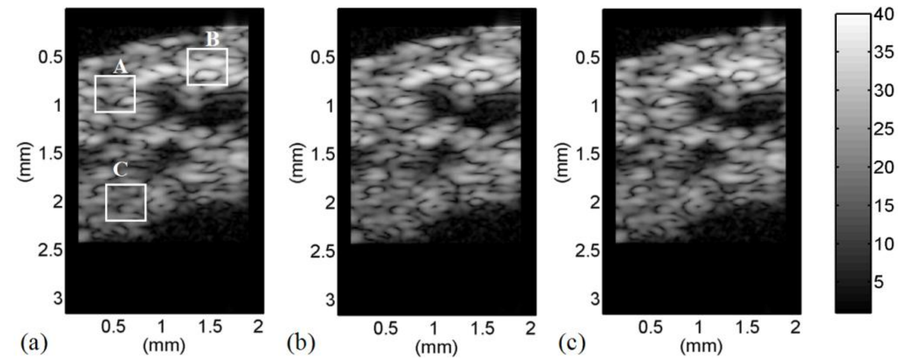
60 MHz results

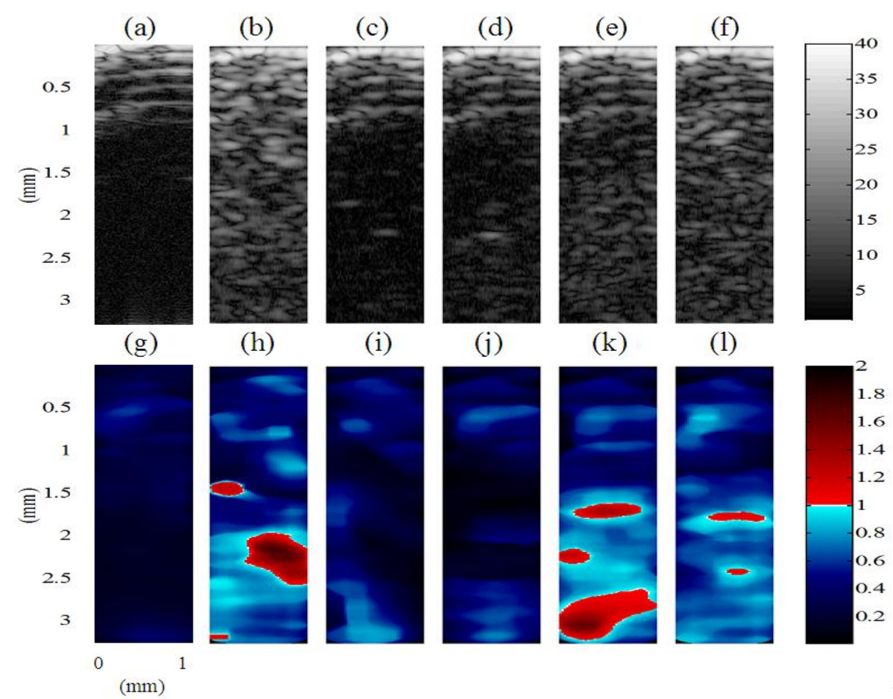
Blood flow estimation



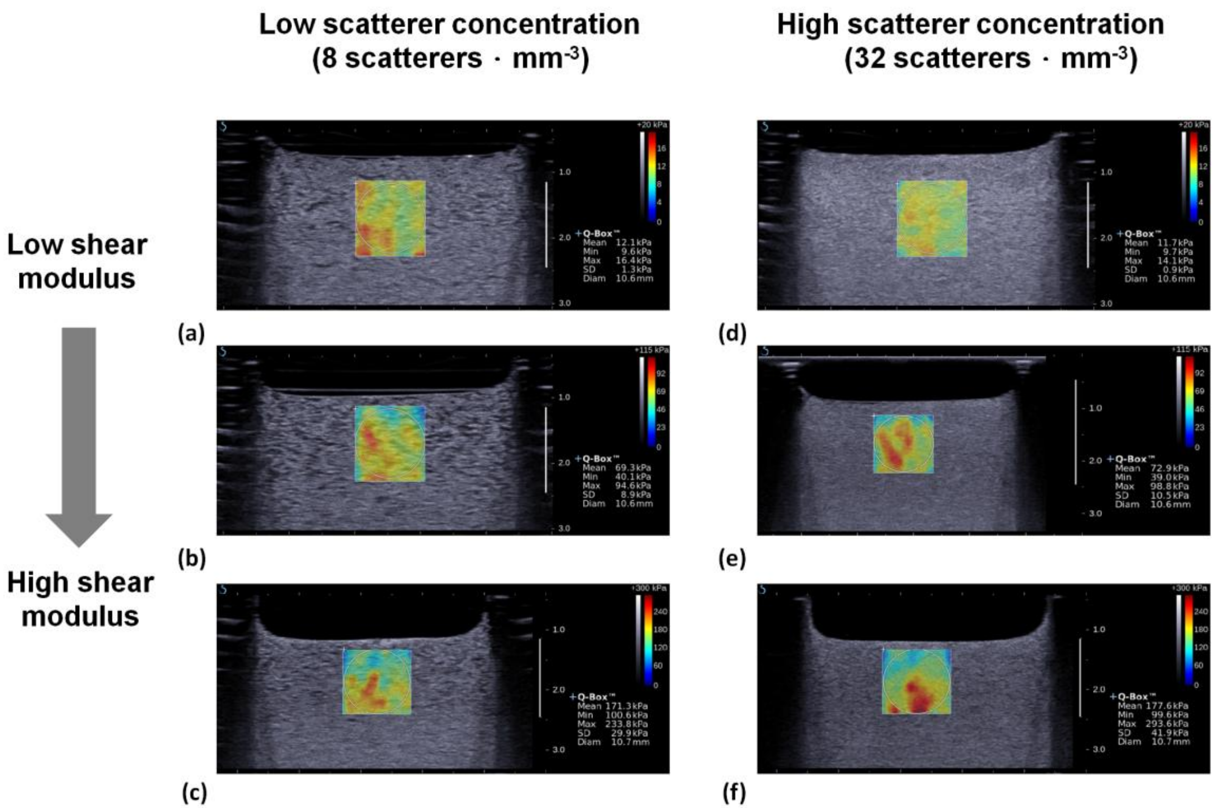


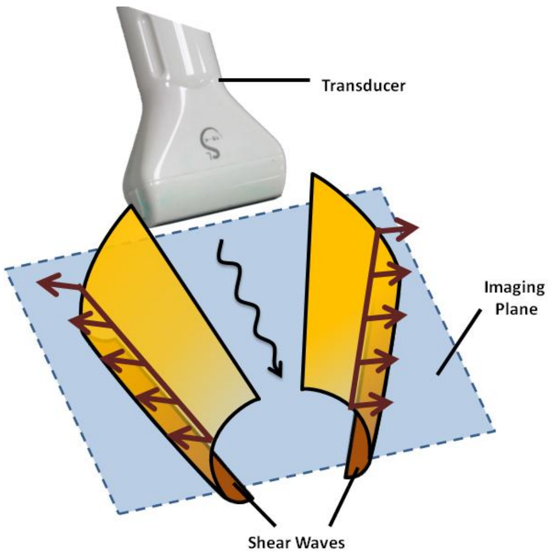




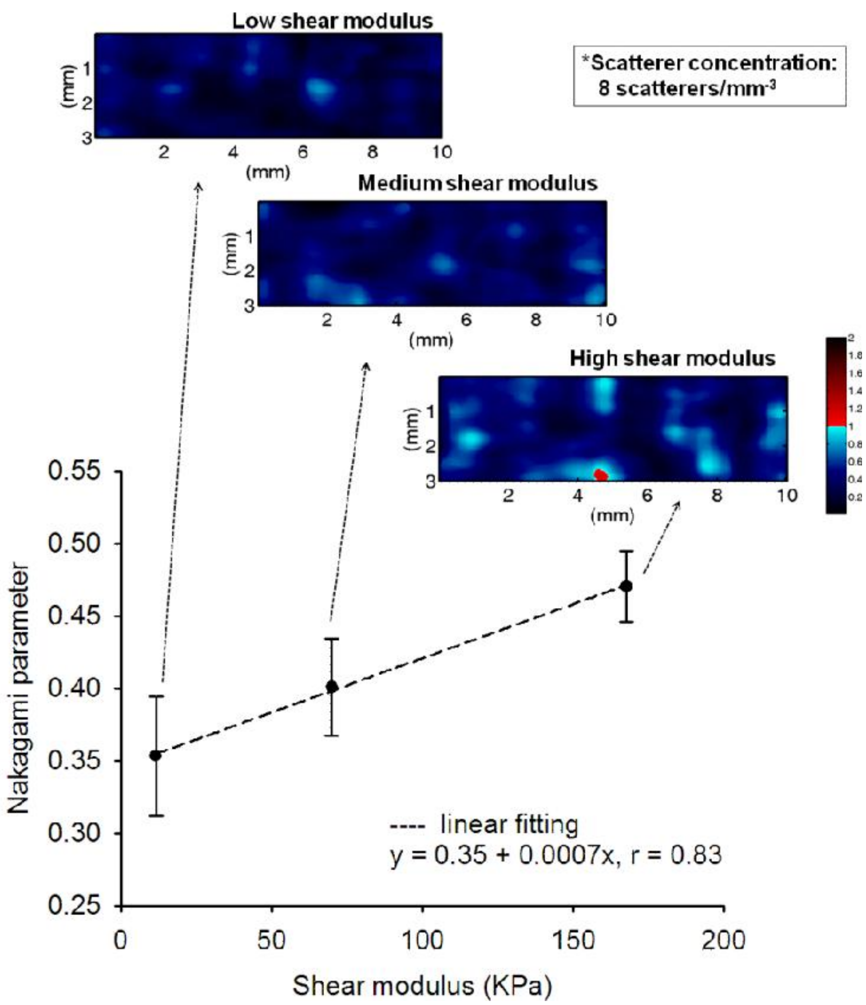


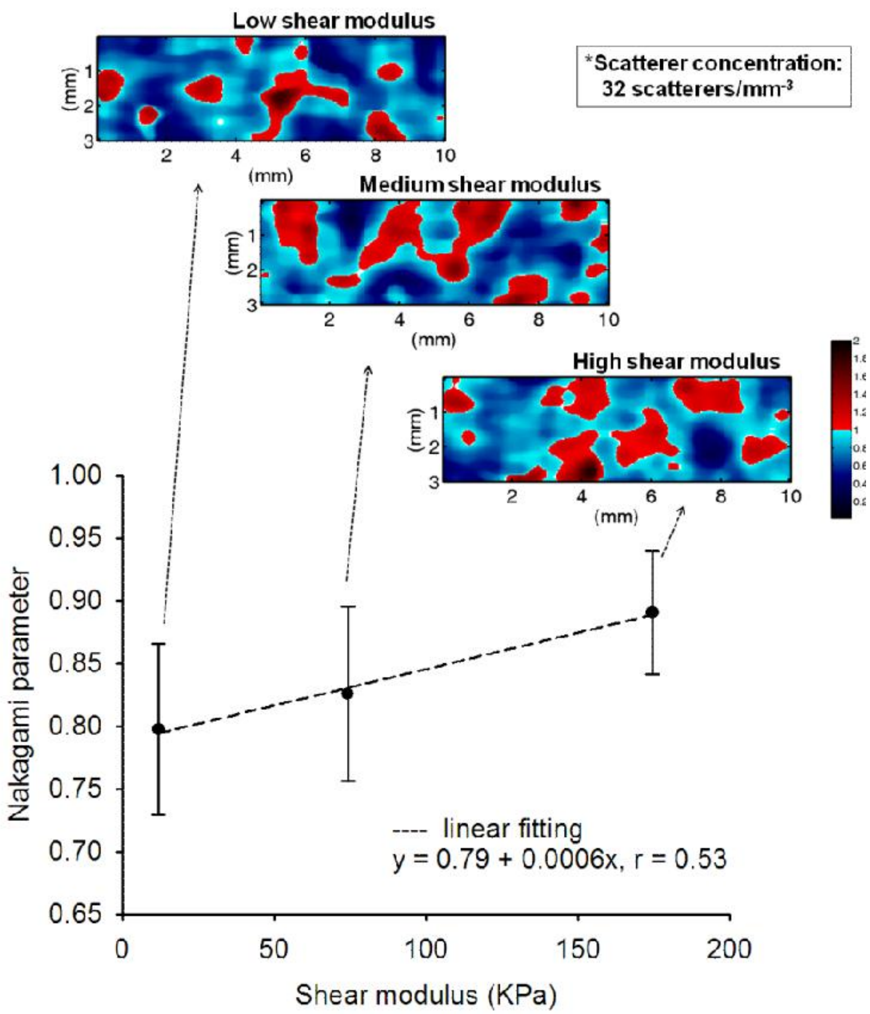
Medium hardness assessment



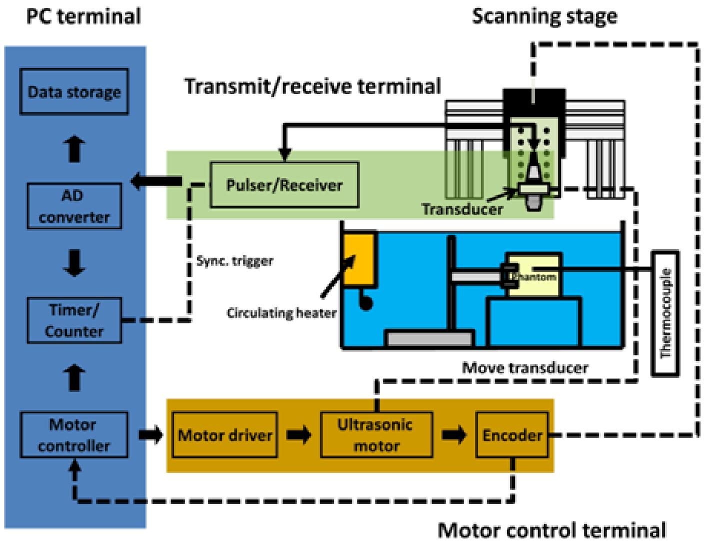


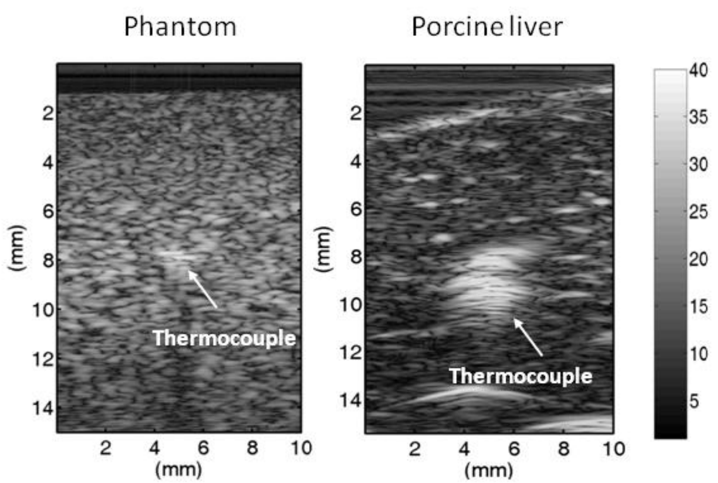
Medium hardness assessment

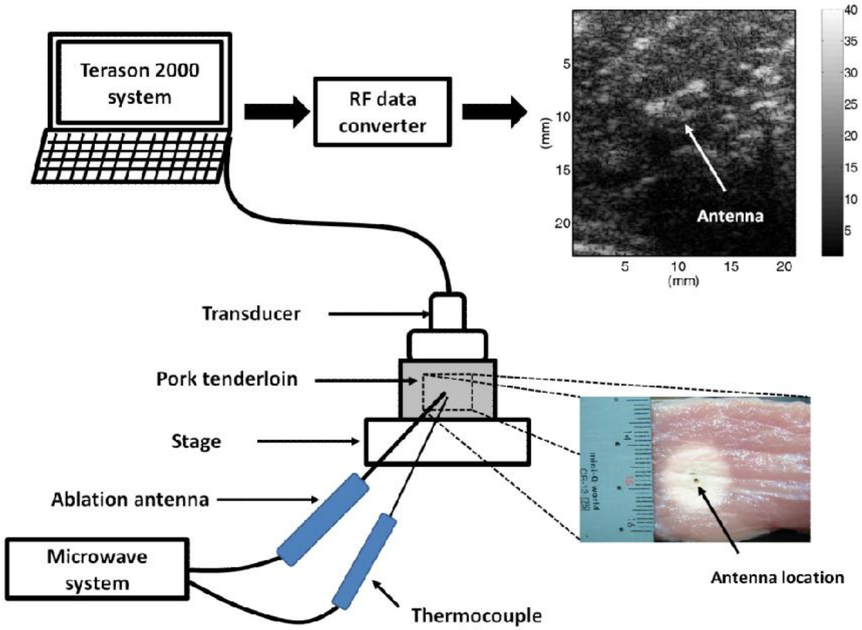


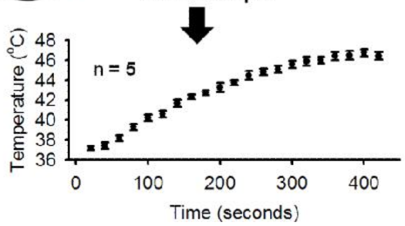


Temperature estimation

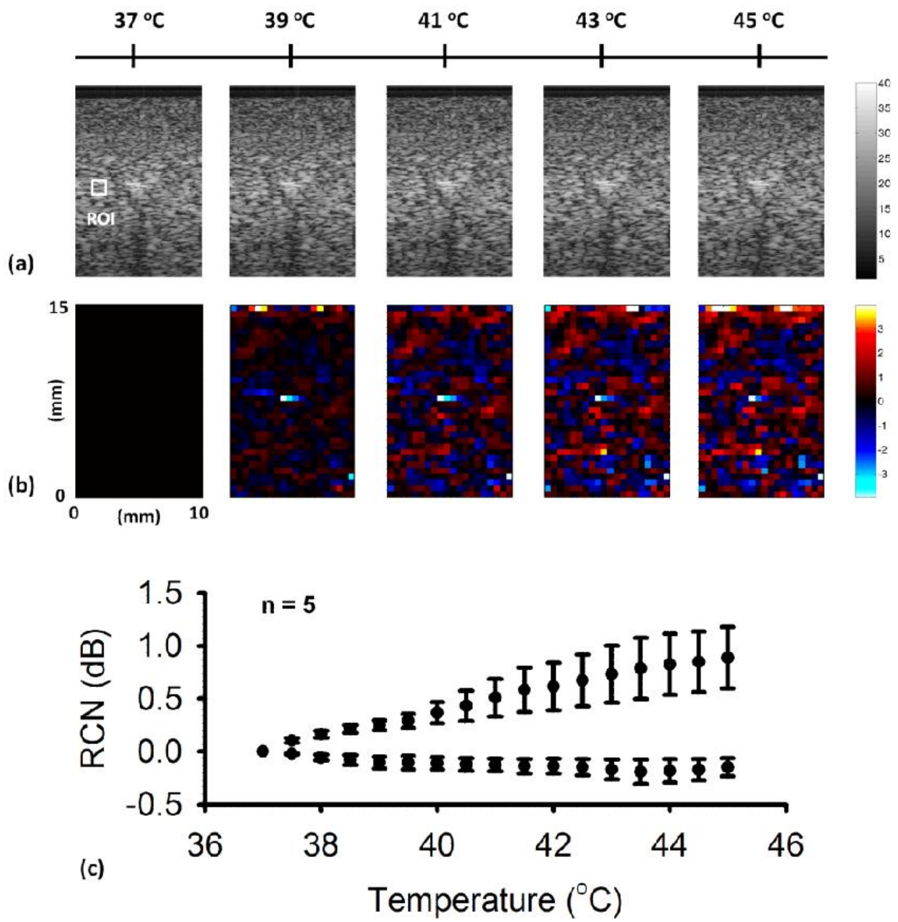


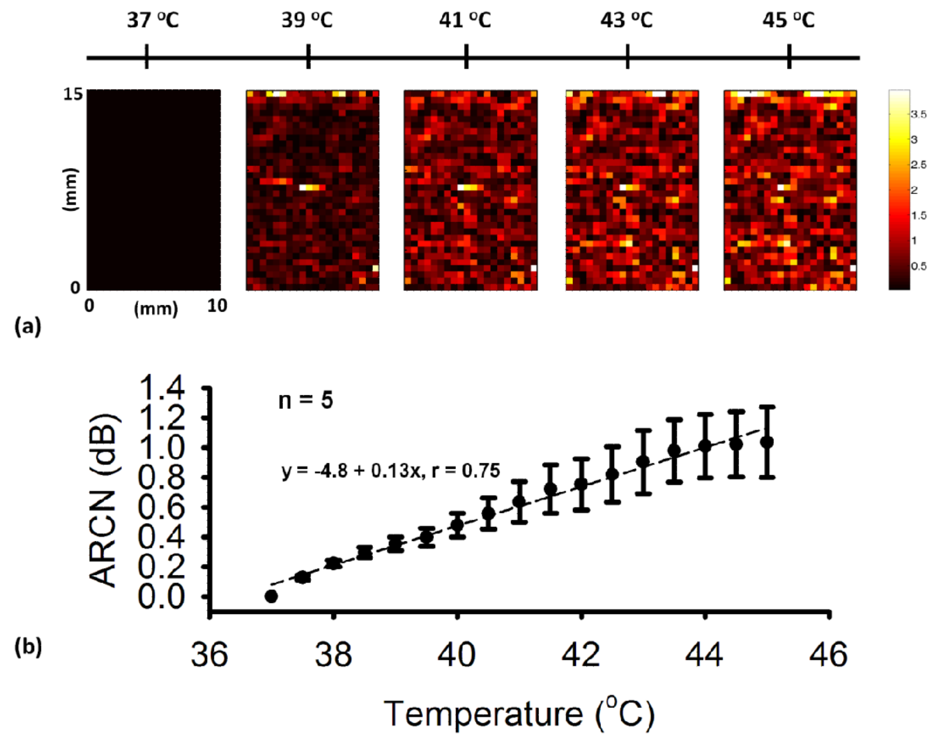




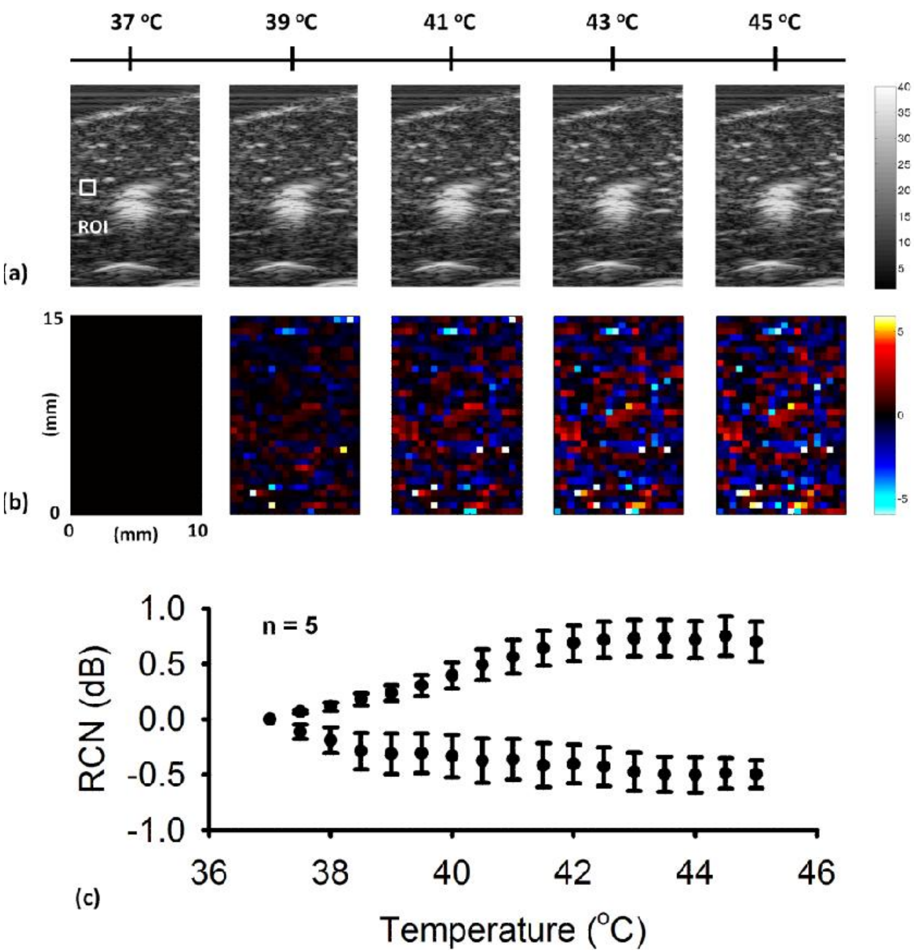


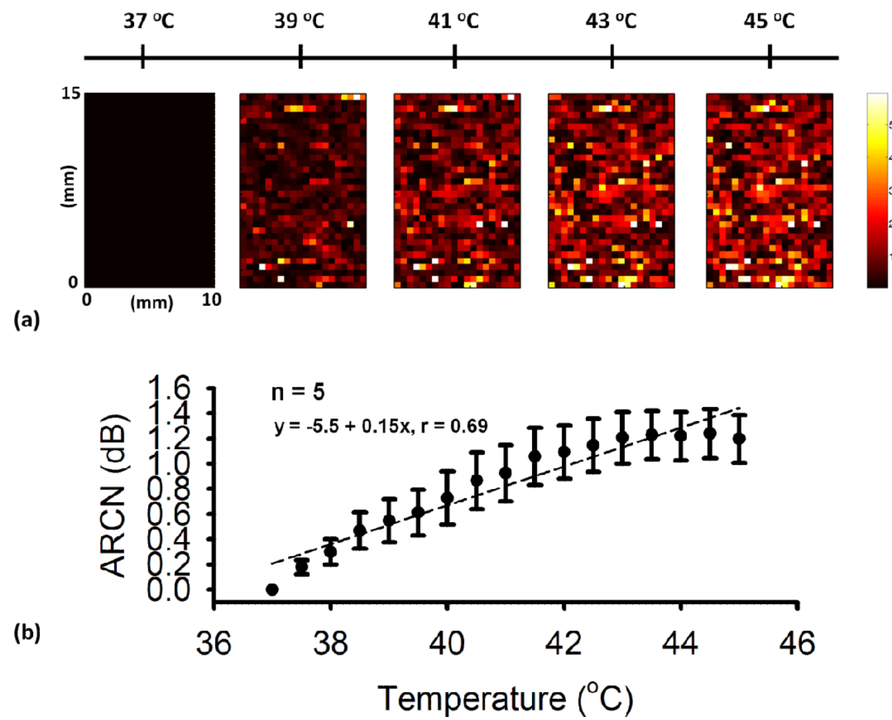
Results of phantoms



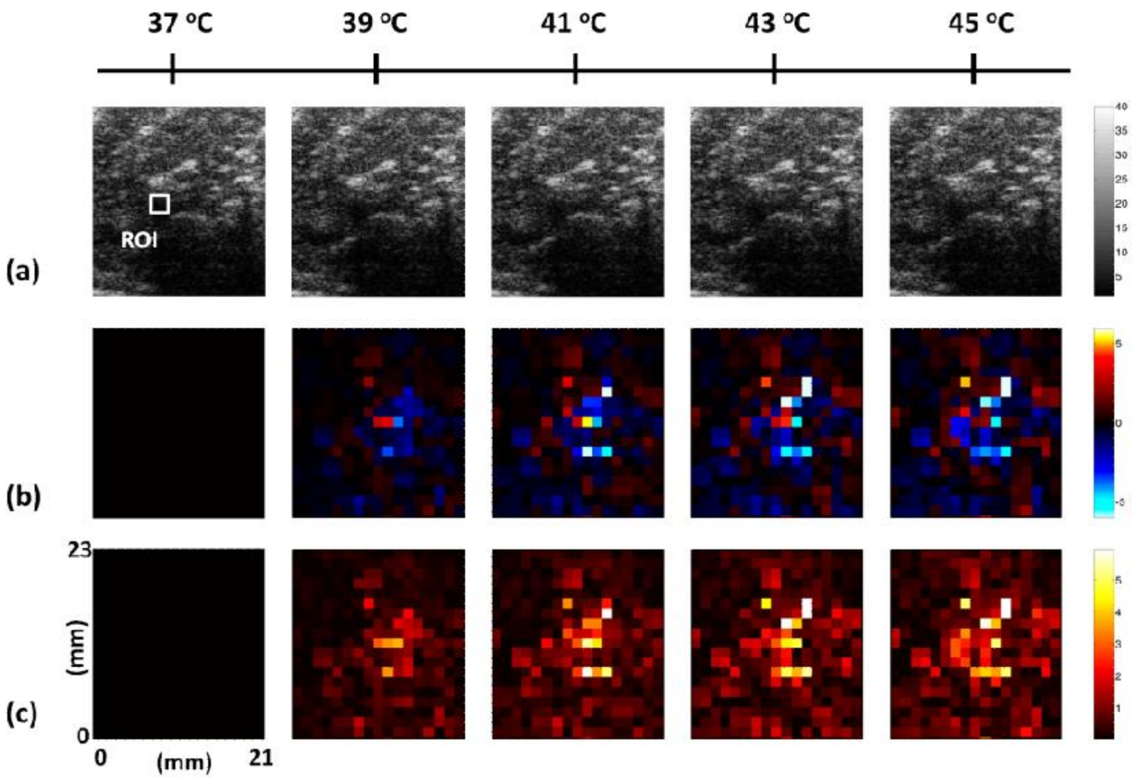


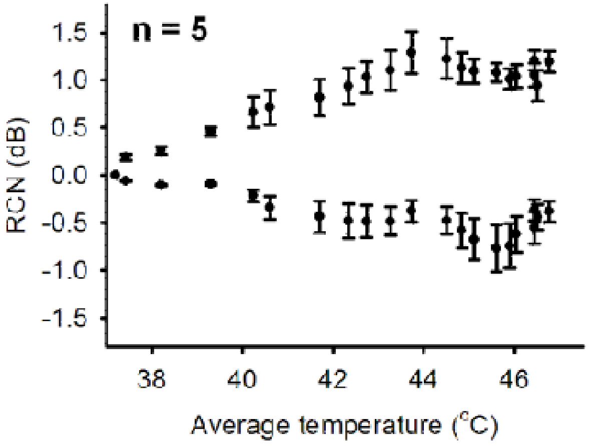
Results of liver tissues

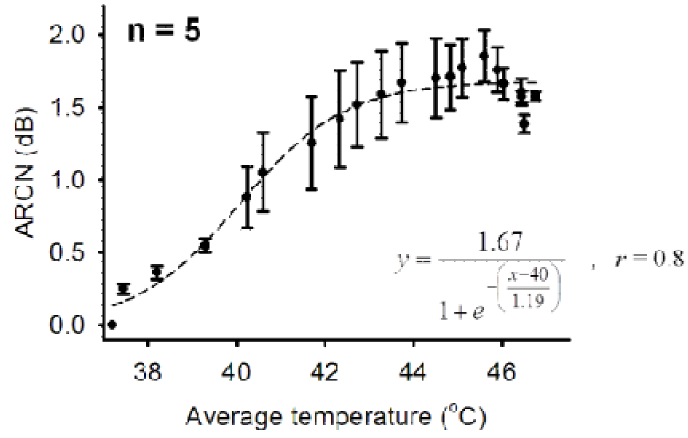




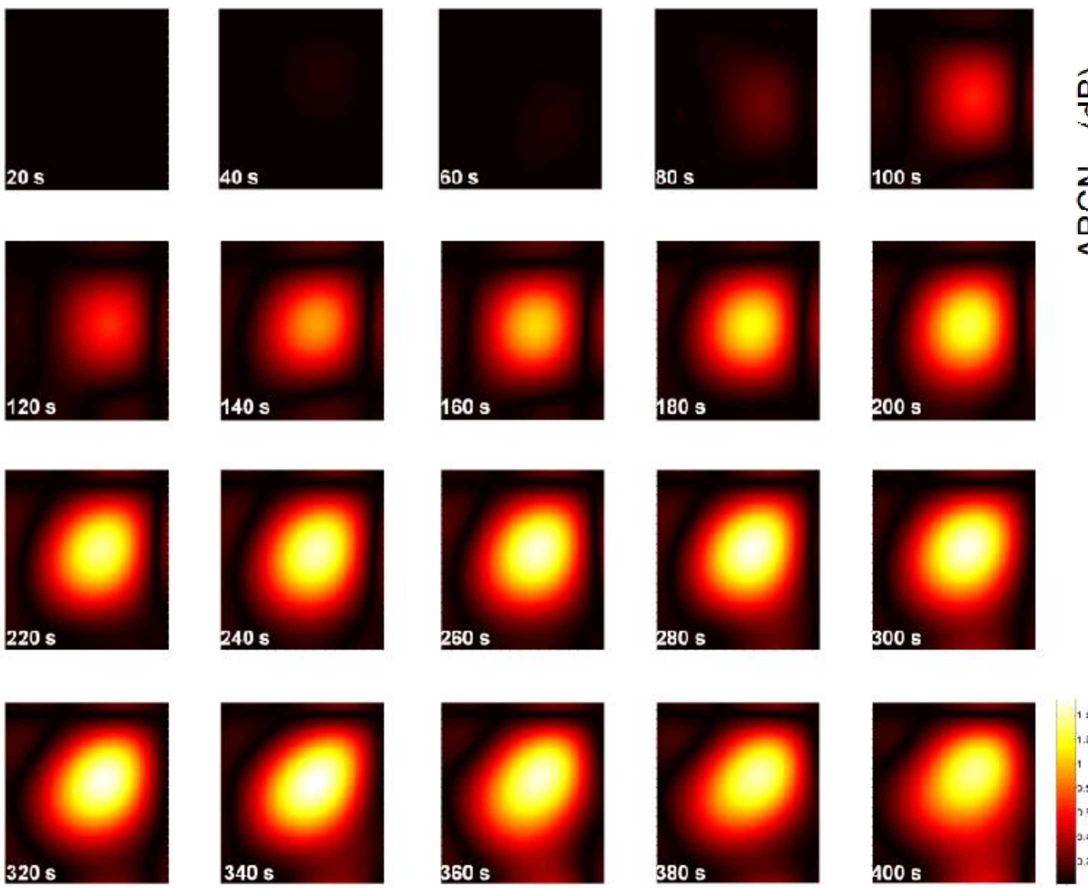
Results of ablation (1)

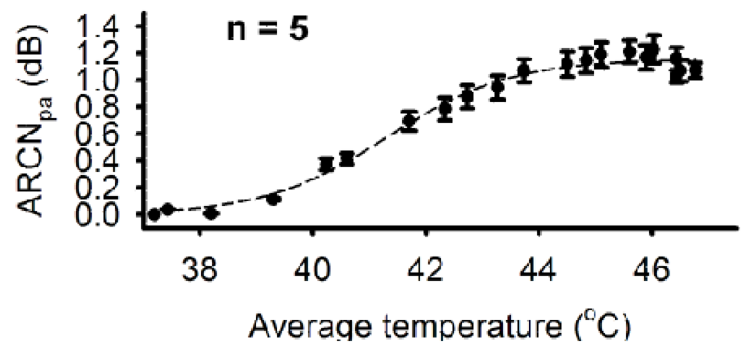






Results of ablation (2)





$$y = \frac{1.16}{1 + e^{-\left(\frac{x-41}{1.09}\right)}} \quad , \quad r = 0.94$$

Comparison

	B-mode image	Nakagami image
Image pixel	Grayscale	Nakagami parameter
Image physical meaning	Echo intensity	Envelope statistics
Image type	Qualitative	Quantitative
Resolution	Relatively better	Relatively poor
Medical applications	Morphology analysis	Scatterer characterization

Thank you for your attention