Photon Sensing and Imaging Laboratory (PhoSIL)

Electronics department, Faculty of Engineering, KMITL, Bangkok, Thailand,10520

Recent developments of a hybrid photonic-ultrasonic tomography for biomedical applications

Dr. Siridech Boonsang,

ดร. ศิริเดช บุญแสง

Dr. Chuchart Pintavirooj

ดร. ชูชาติ ปิณฑวิรุจน์

Outline

- Photo-Acoustic Tomography (PAT)
- Acousto-Optic Tomography (AOT)

Photo-Acoustic Tomography

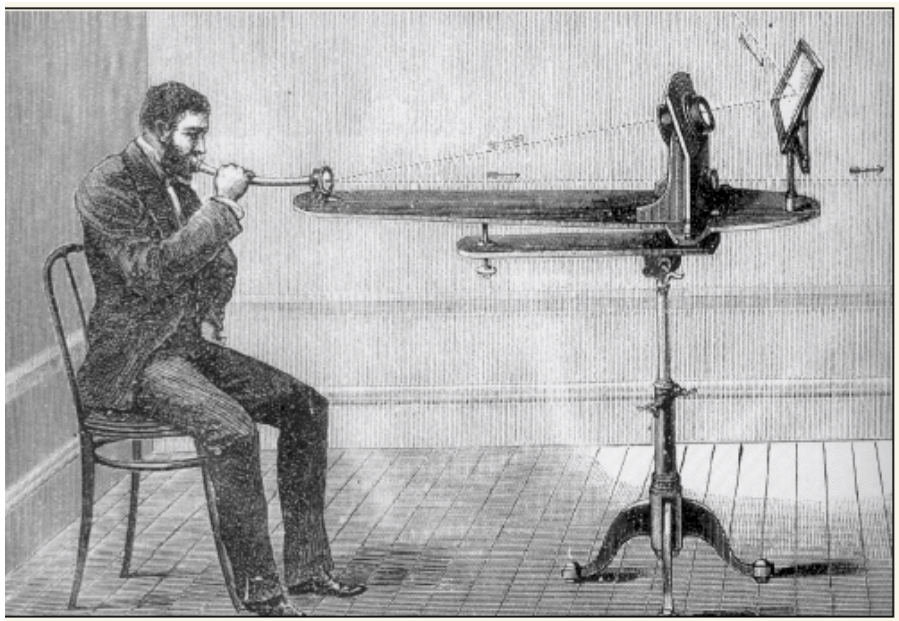
Terminology

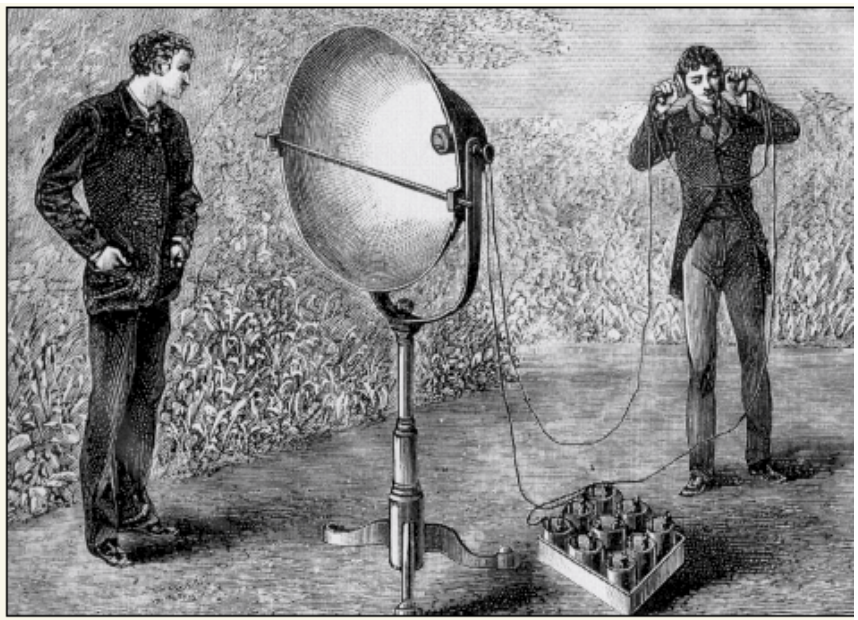
- Laser ultrasound
- Photoacoustic (UK & Europe)
  - Pulse photoacoustic
  - Photoacoustic spectroscopy
- Optoacoustic (US)
- Thermoacoustic (Microwave to ultrasound)

Historical milestones

- E.G. Bell firstly observed the conversion process from light to sound.
- The first ultrasonic signals generated by modern laser system ***(Ruby laser)*** *(Carome et al. 1964)*
- Theoretical and experimental investigation of laser-generated ultrasonic signals *(Scruby et al. 1980, Dewhurst et al. 1982, Hutchins et al.1989)*
- The first demonstration of biomedical applications of laser-generated ultrasound *(Chen et al. 1993)*
- The first *in vivo* functional brain image constructed by photoacoustic system *(Wang et al. 2004)*

Photophone 1880

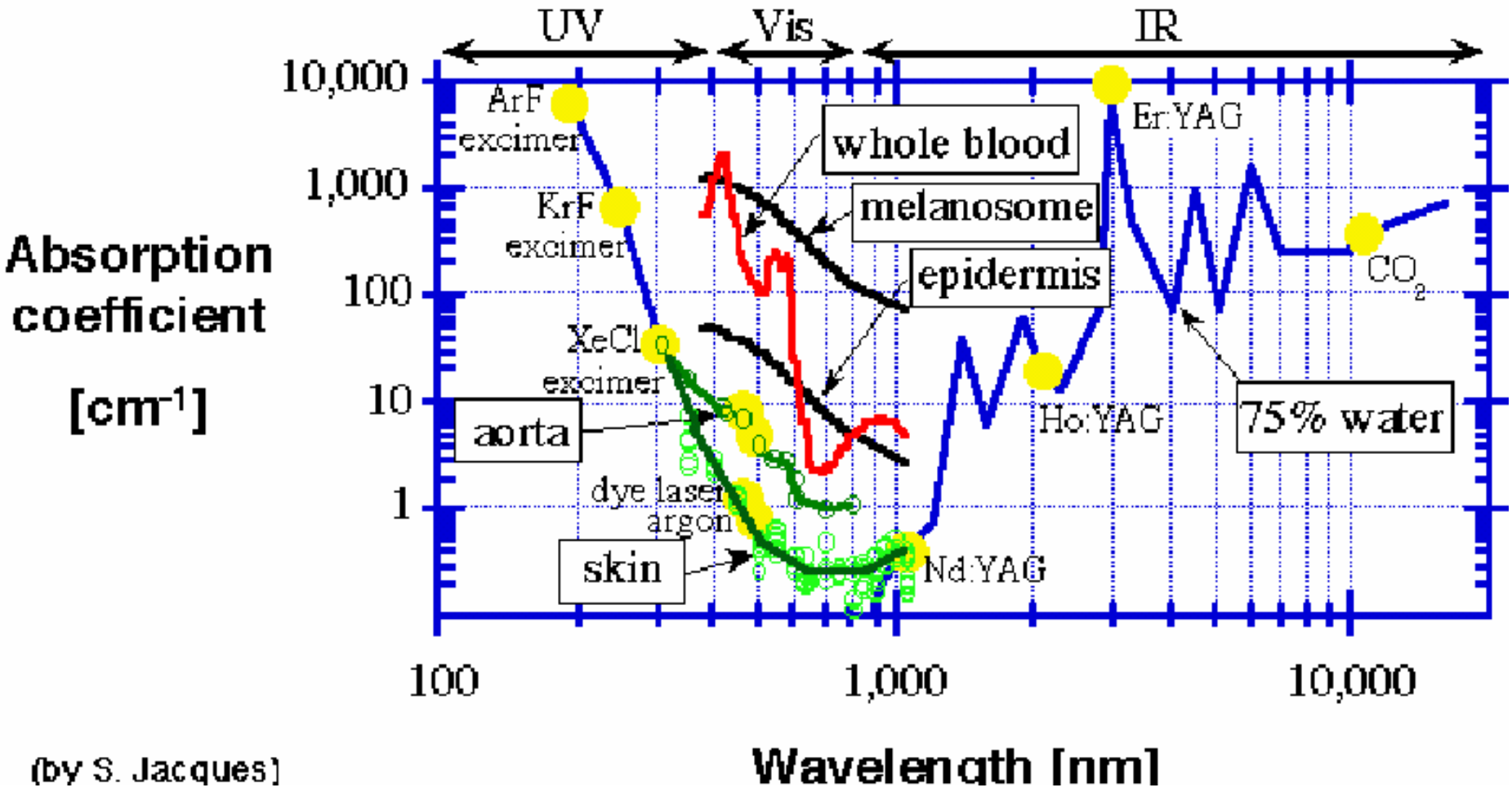




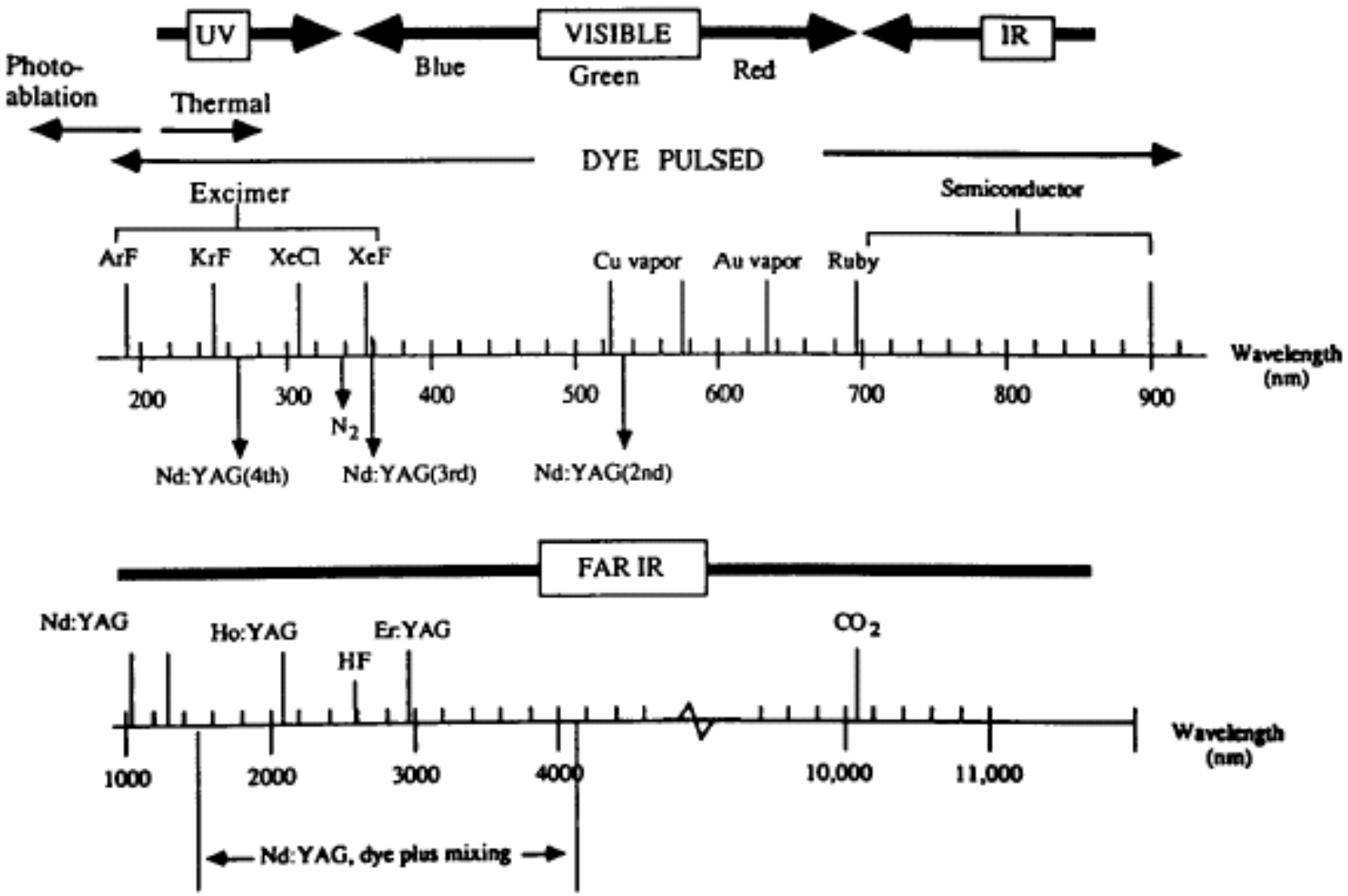
Taken from "Alexander Graham Bell's Photophone"
by D.L. Hutt, K.J. Snell, and P.A. Belanger.
Optics & Photonics News June 1993.

Potential applications

- Intra-arterial imaging and therapy (*Chen et al. 1993*)
- Monitoring of glucose level (*Quan et al. 1993*)
- Monitoring of cerebral blood oxygenation (Esenaliev et al. 2002)
- Monitoring an interface tissue layer within an eye (Payne et al. 2000)
- A diagnostic system for breast cancer (Esenaliev et al. 1999)
- Functional imaging of brain activities (Wang et al. 2004)


UV
Vis
IR
10,000
1,000
100
10
1
ArF
excimer
KrF
excimer
XeCl
excimer
dye laser
argon
Nd:YAG
Er:YAG
Ho:YAG
CO_2
whole blood
melanosome
epidermis
aorta
skin
75% water
100
1,000
10,000
Absorption coefficient [cm^{-1}]
Wavelength [nm]

(by S. Jacques)



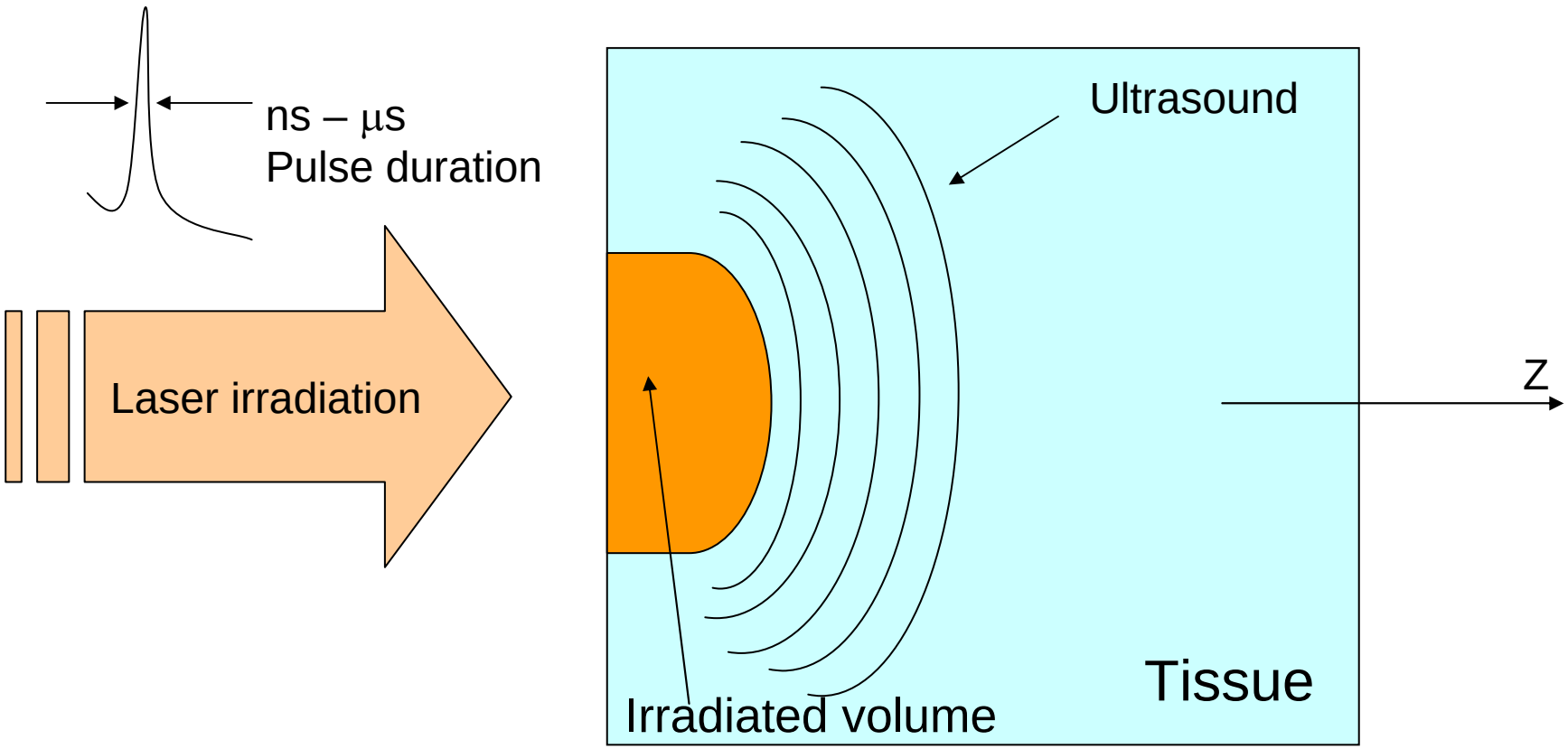
PULSED LASERS AVAILABLE FOR MEDICAL RESEARCH/APPLICATIONS

pulse durations : 10^{-15} to 10^{-4} seconds

Mechanism of photoacoustic generation

- Dielectric breakdown (Laser intensities $>10^{10}$ W.cm^{-2})
- Vaporization (conversion efficiency 1%)
- Material ablation
- ***Thermoelastic process***
- Electrostriction
- Irradiation pressure

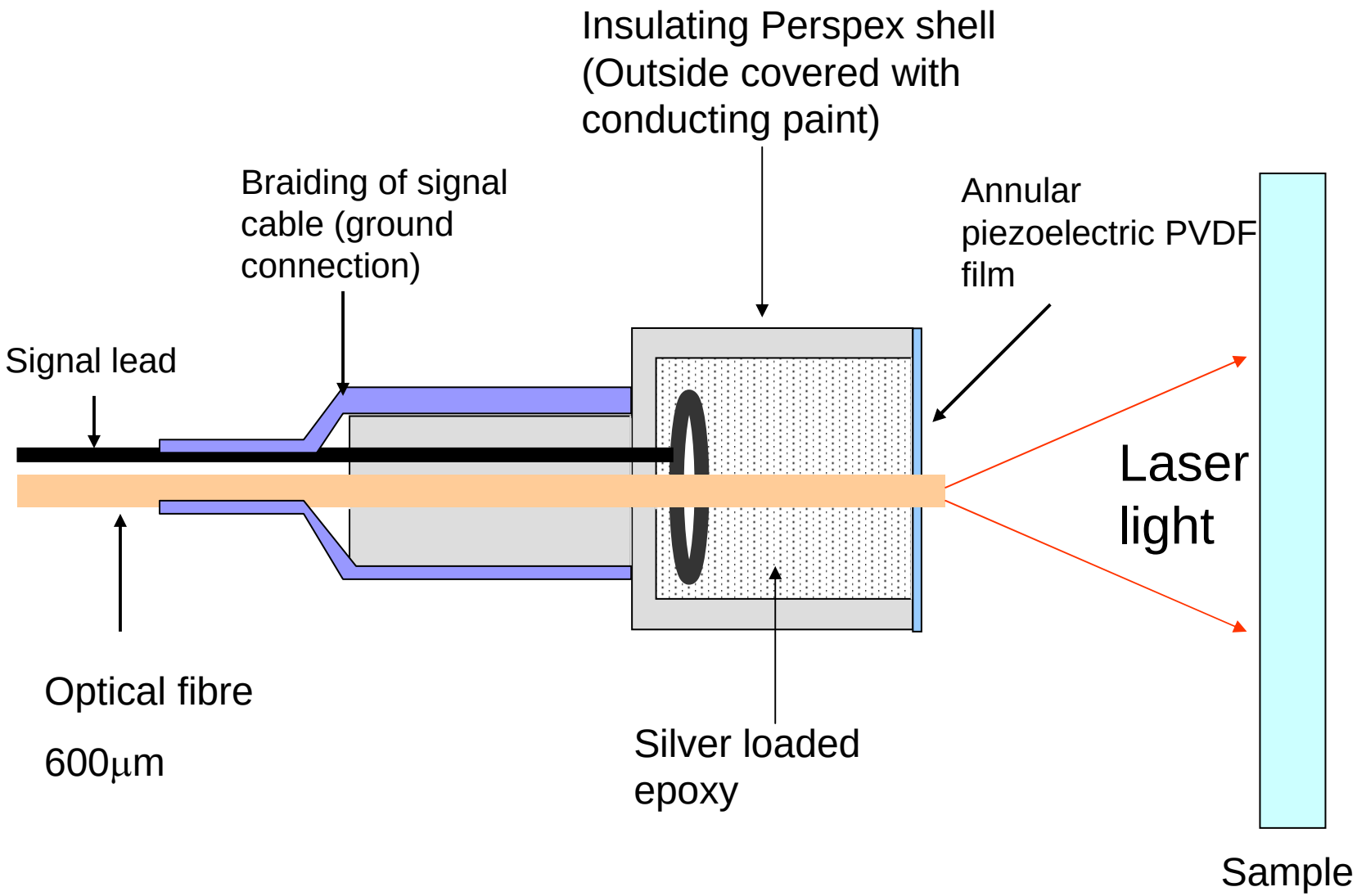
Thermoelastic process



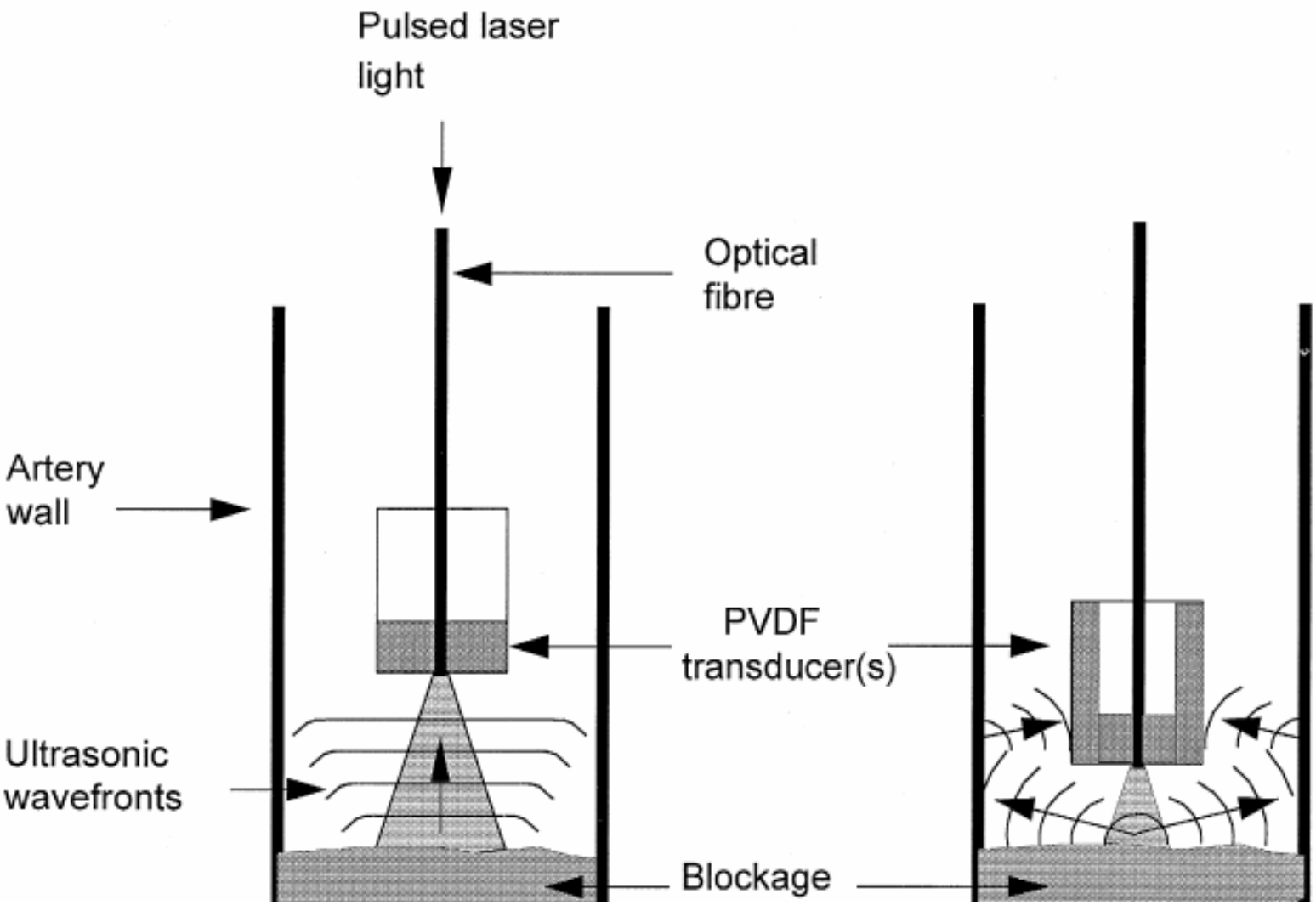
$$\nabla^2\phi - \frac{1}{c_L^2}\frac{\partial^2\phi}{\partial t^2} = \frac{\alpha\beta^*}{\rho c_p} I_o e^{-\alpha z} H(r) f(t)$$

Wave equation

Laser ultrasonic system : UMIST, UK



Laser ultrasound system

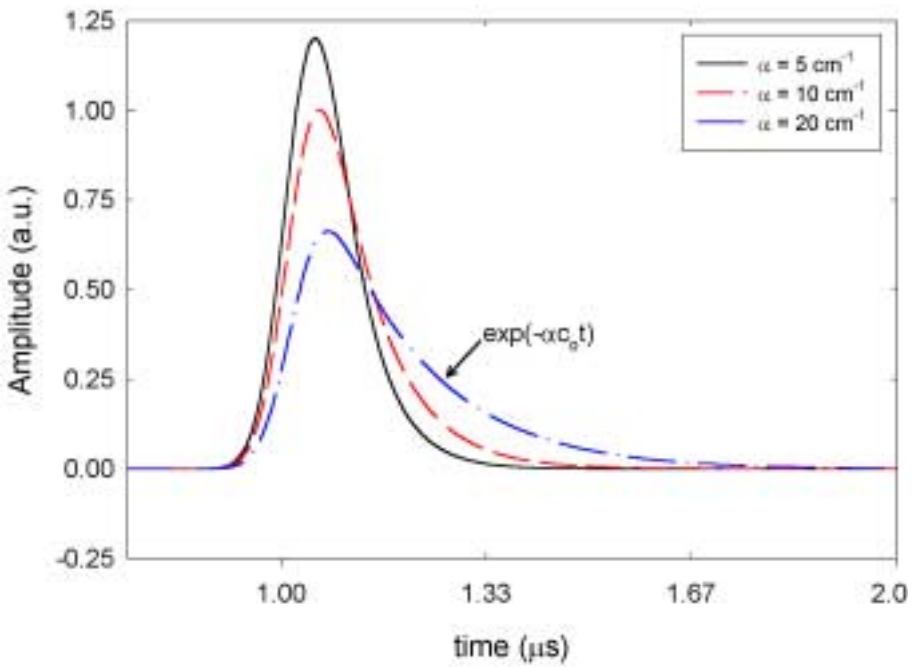


Typical photoacoustic signals

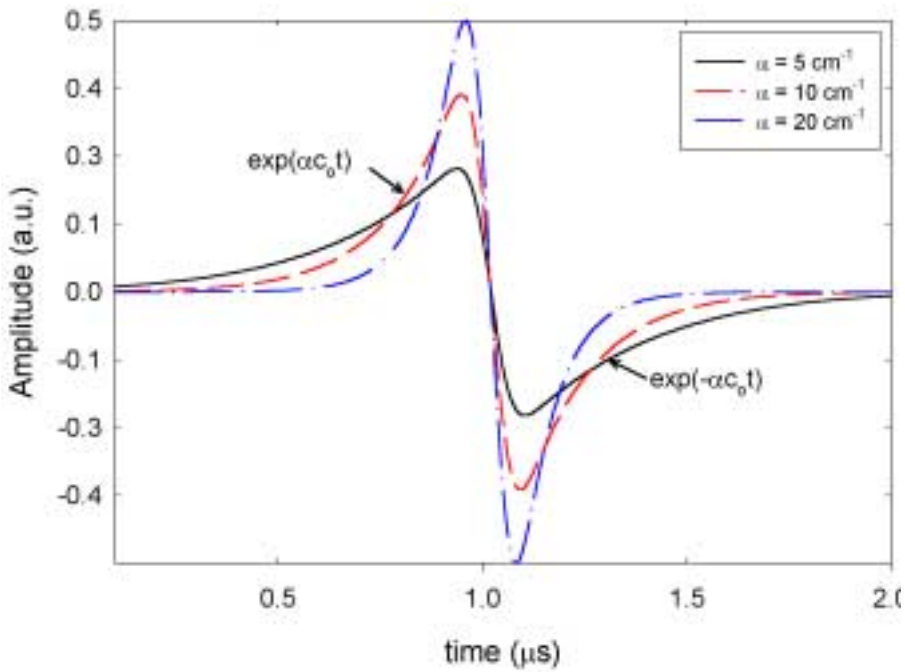
$F_L(\omega)$ → $H_{OA}(\omega)$ → $P_{OA}(\omega)$

Laser pulse spectrum

Photoacoustic pressure spectrum

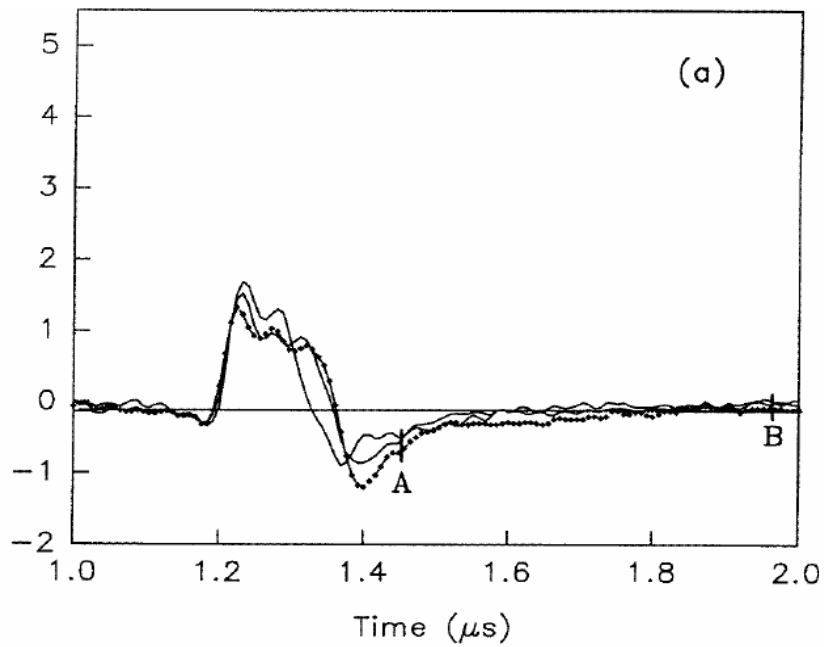


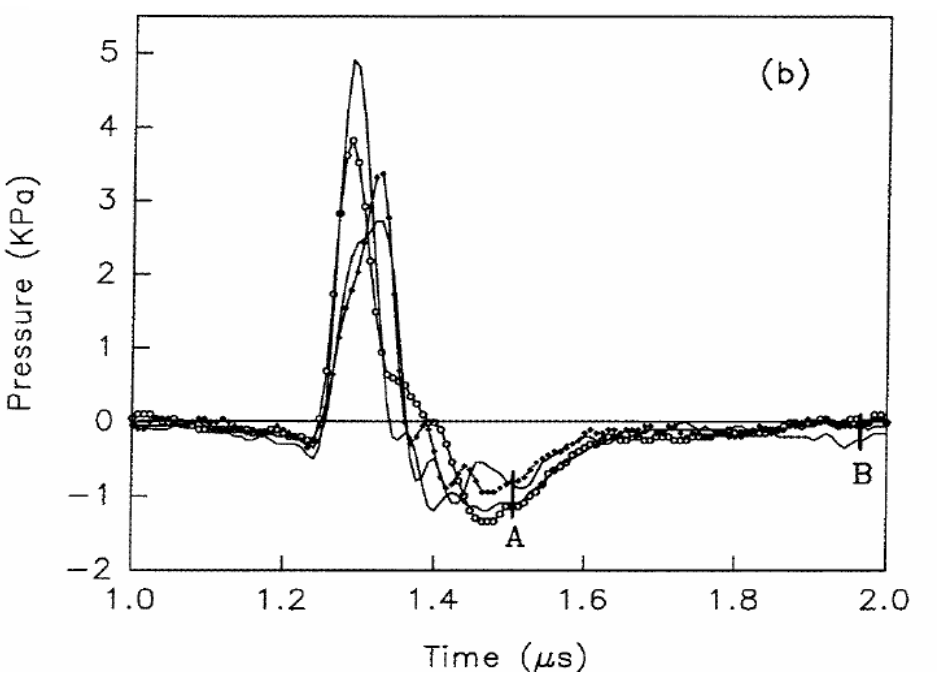
Backward/reflection mode



Forward/transmission mode

Examination of human aorta

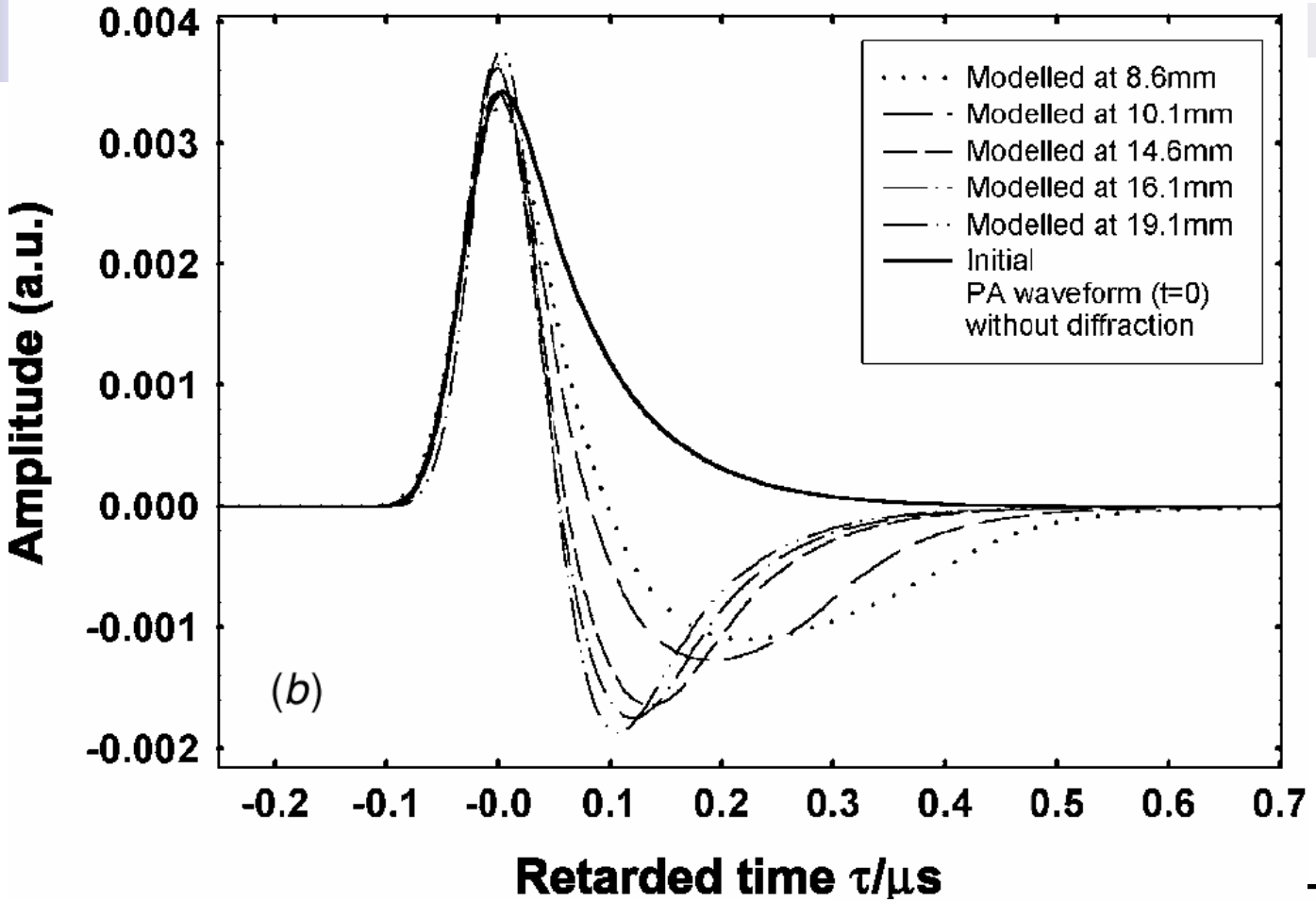




Normal aorta

Atheromatous aorta

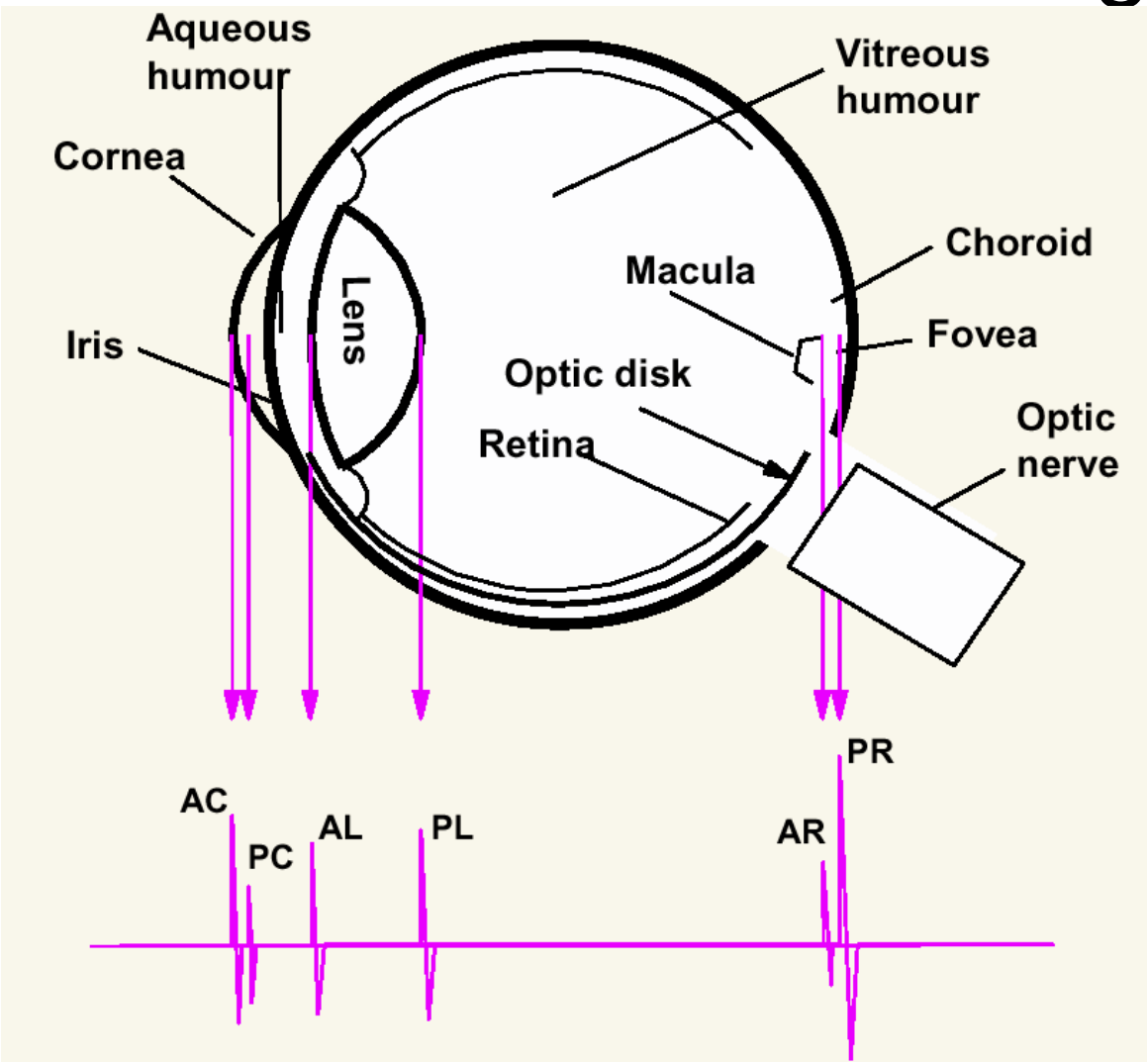
Beard et al. 1997



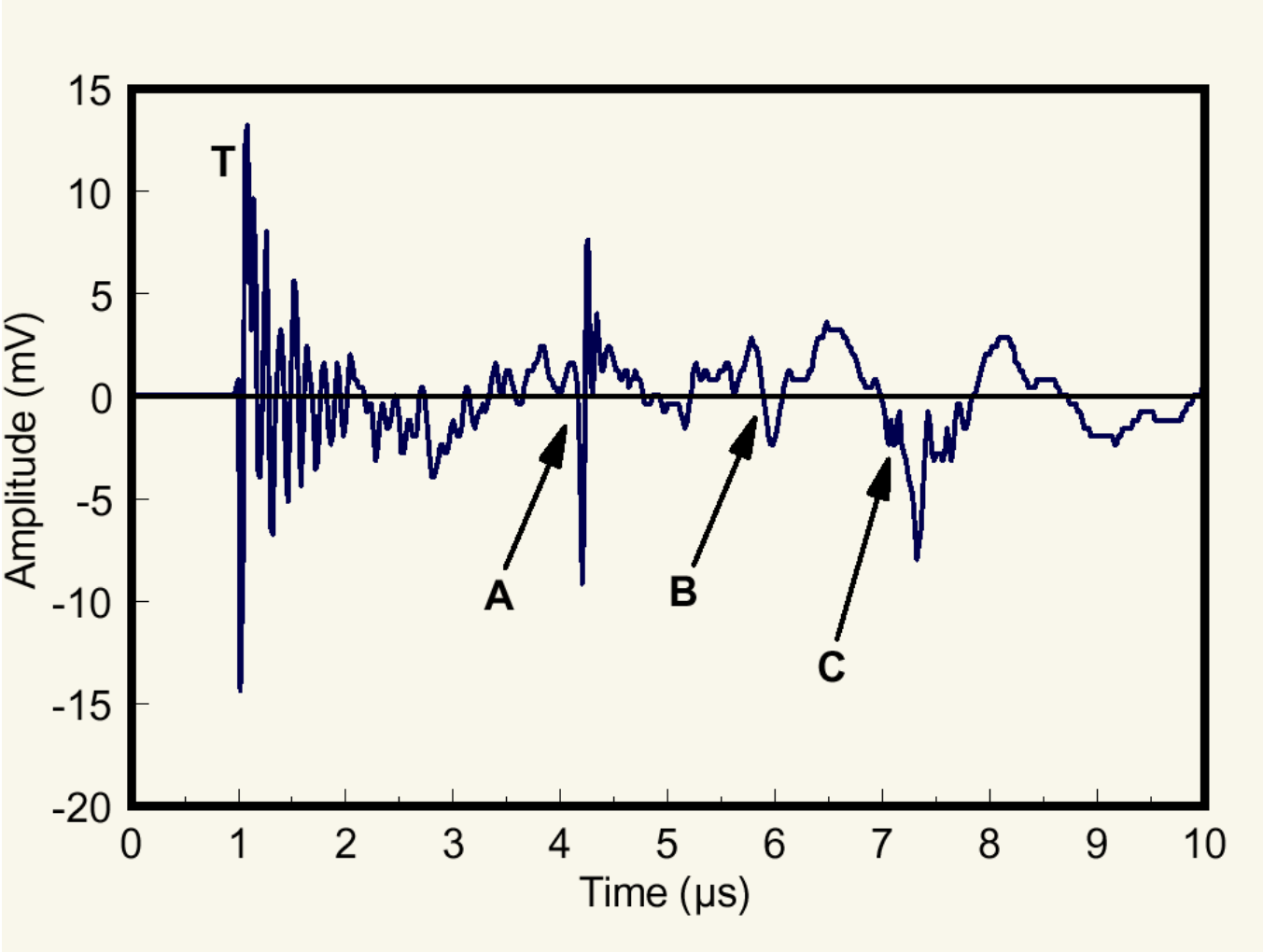
Parameters	Value from reference sources	Estimated value	
		Backward detection mode	Forward detection mode
Optical absorption coefficient, α_{ab} (cm^{-1})	21.6 ± 1[a]	23.72	26.1
Effective piston diameter of photoacoustic source, $2a$ (mm)	–	1.78	1.41
Effective piston diameter of ultrasonic receiver, $2b$ (mm)	1.0 ± 0.05[b]	0.99	1.01
Ultrasonic wave (longitudinal) velocity of glass, c_{ab} ($m\ s^{-1}$)	5640 ± 5[c]	5636.46	5632.22
Laser pulse duration, τ_L (ns)	40 ± 5	36	60.8

Boonsang *et al. 2004*

Outline diagram of bovine eye together with Photoacoustic signal



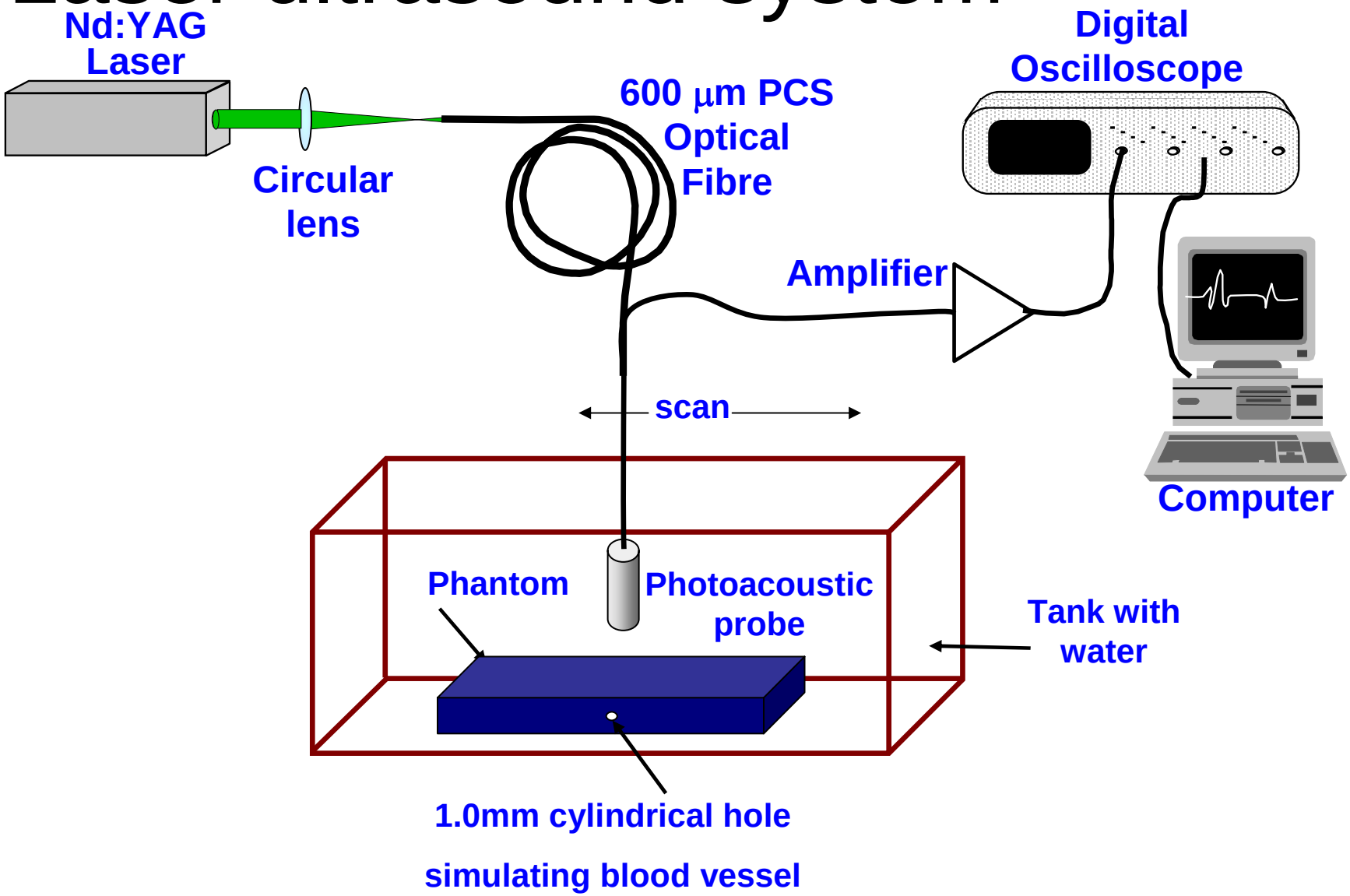
Dewhurst *et al.*

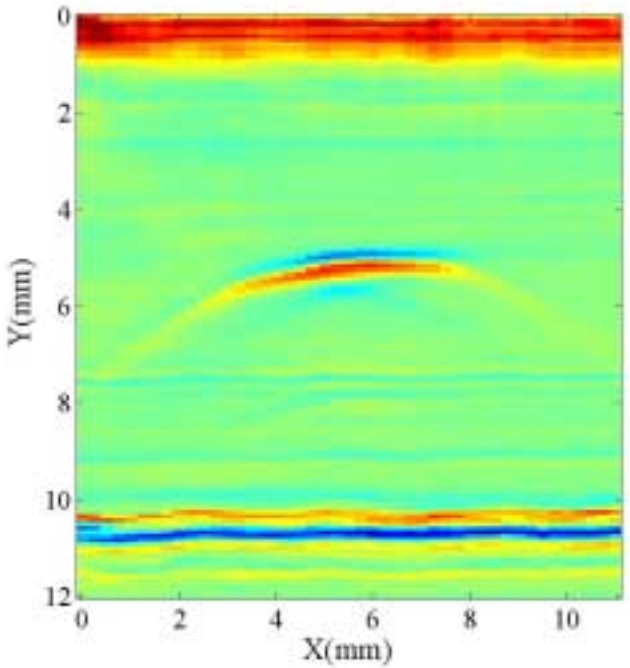


A. Water-cornea interface
B. Cornea-aqueous humor interface
C. Aqueous humor-lens interface

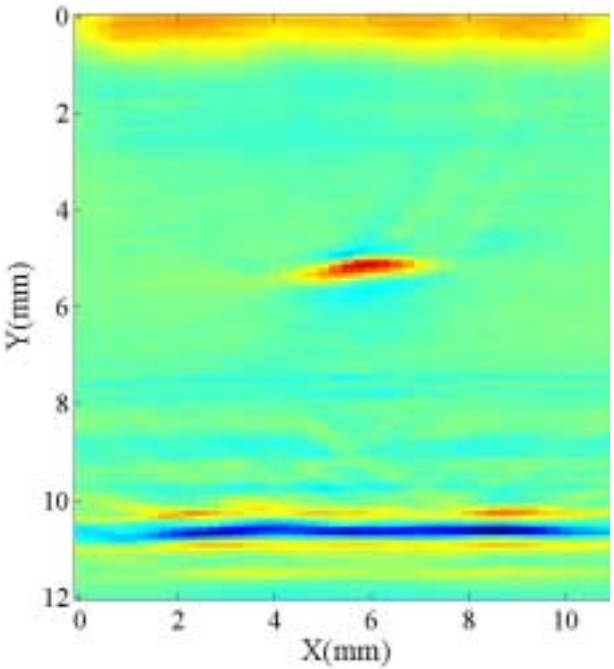
Dewhurst *et al.*

Laser ultrasound system

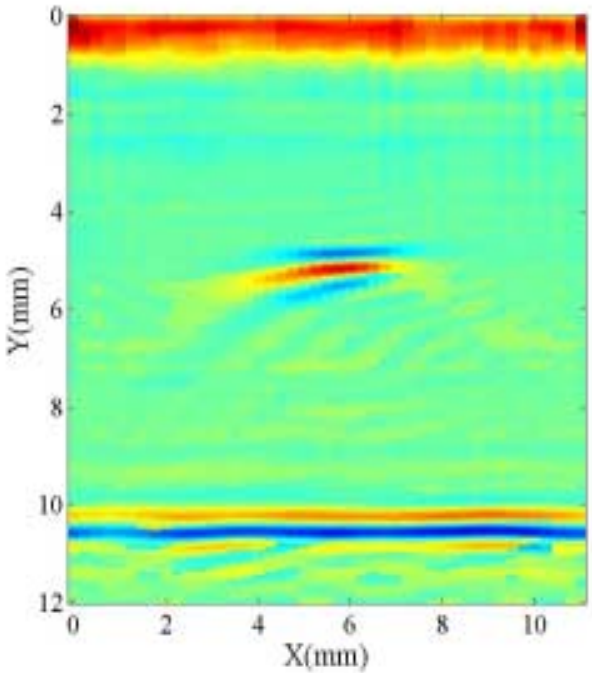




B-Mode image



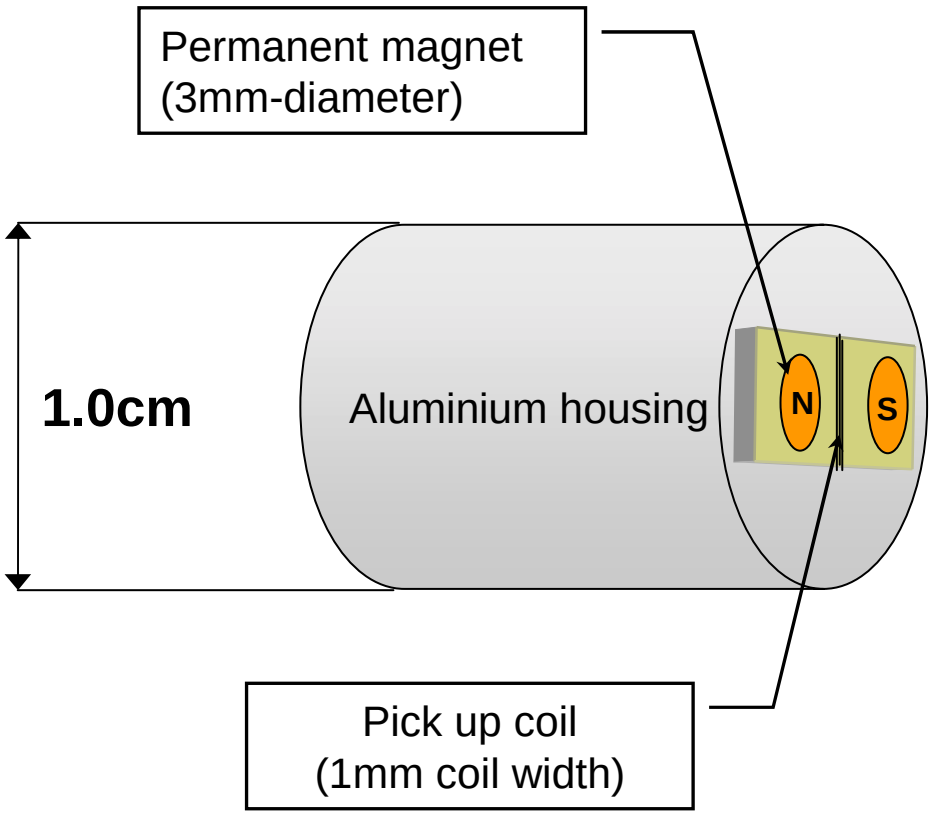
Improved by
Time domain
Synthetic aperture



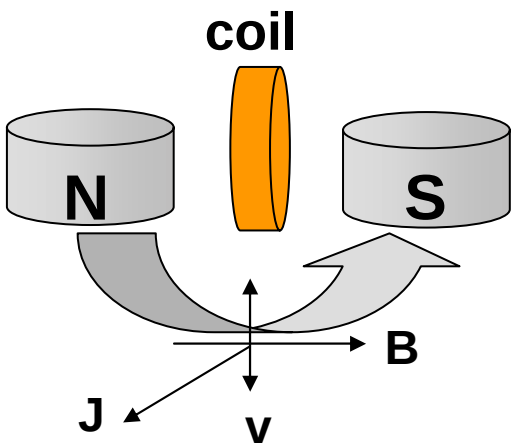
Improved by
Frequency domain
Synthetic aperture

Boonsang *et al.* 2003

Electromagnetic acoustic transducer (EMAT)

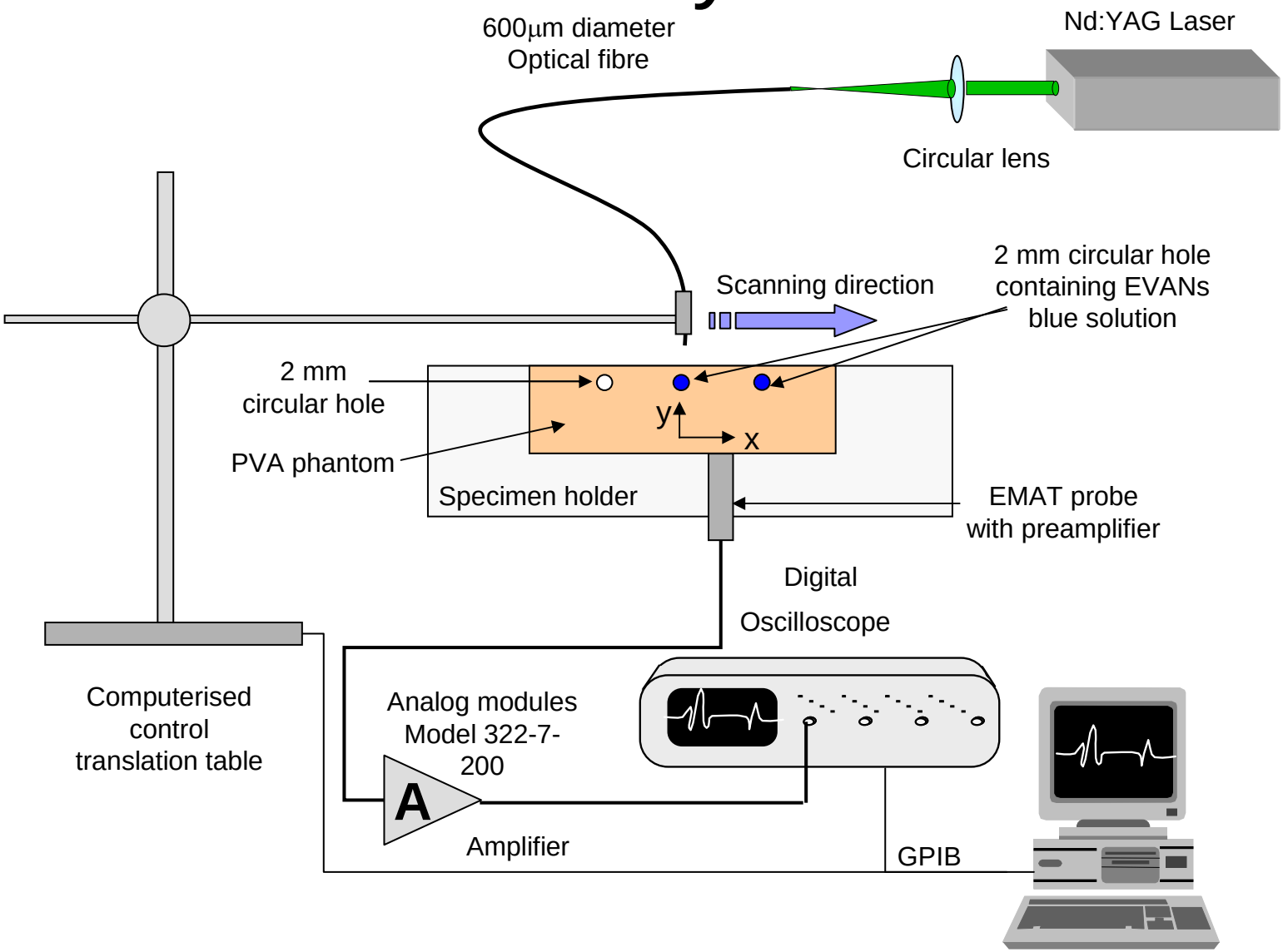


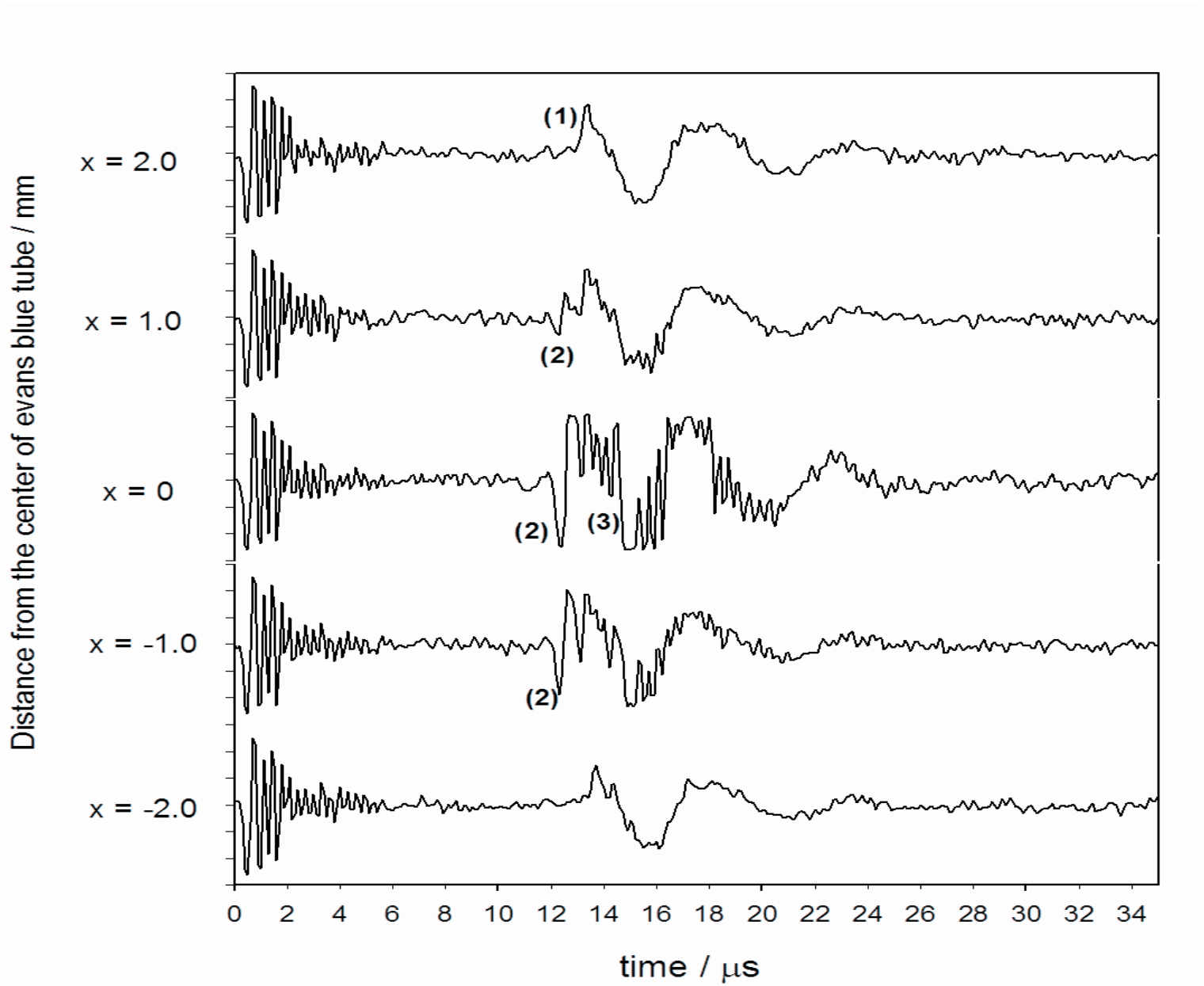
(a)

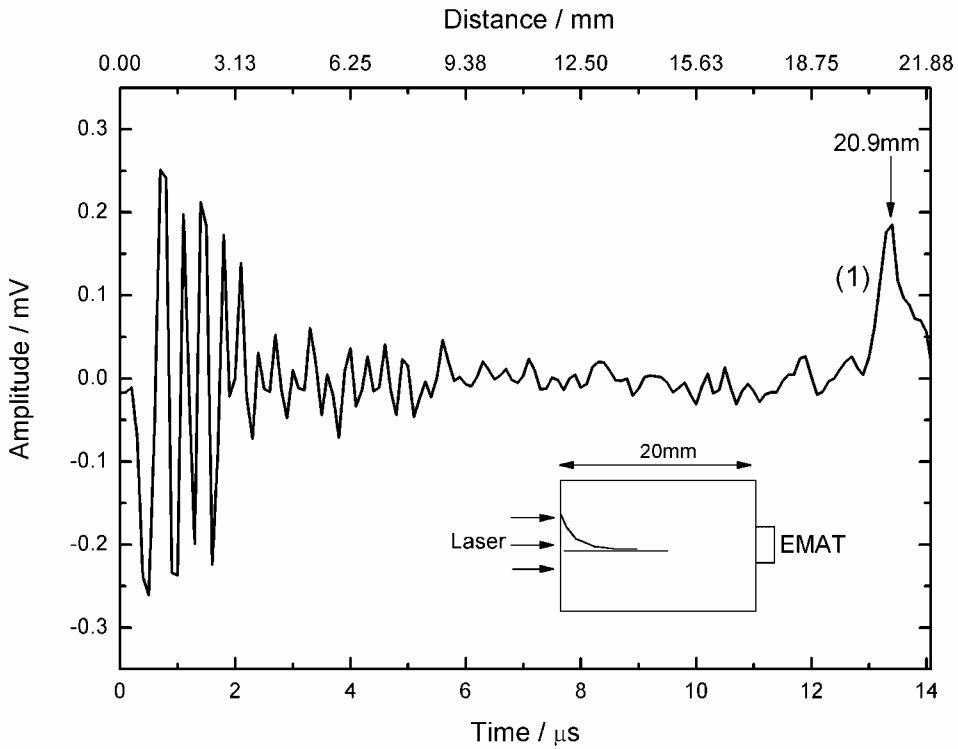


(b)

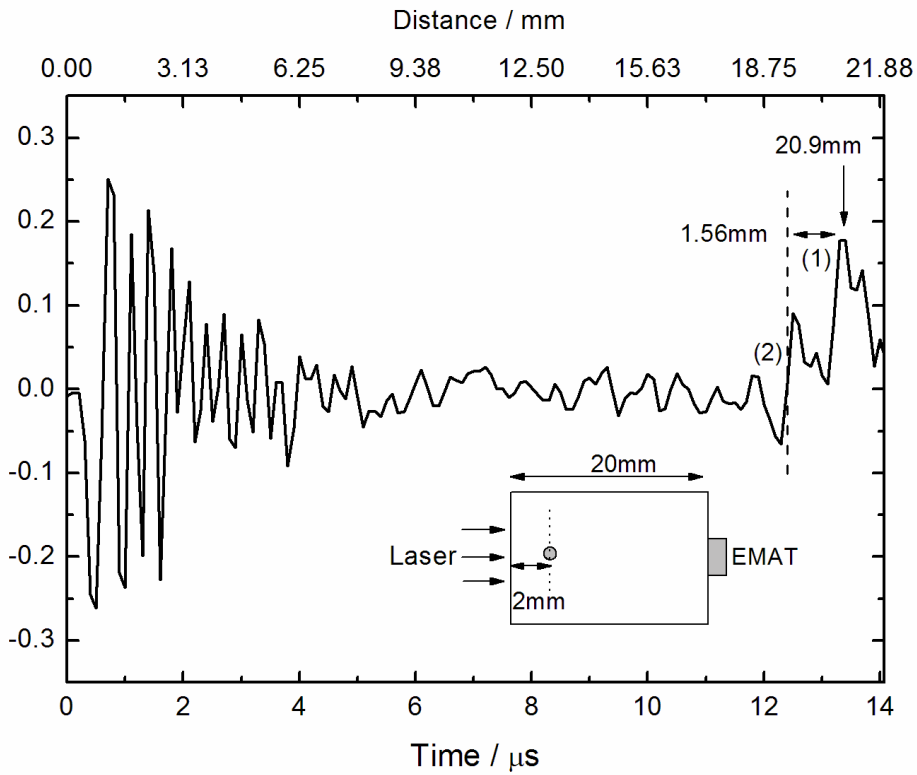
Laser ultrasound system : UMIST



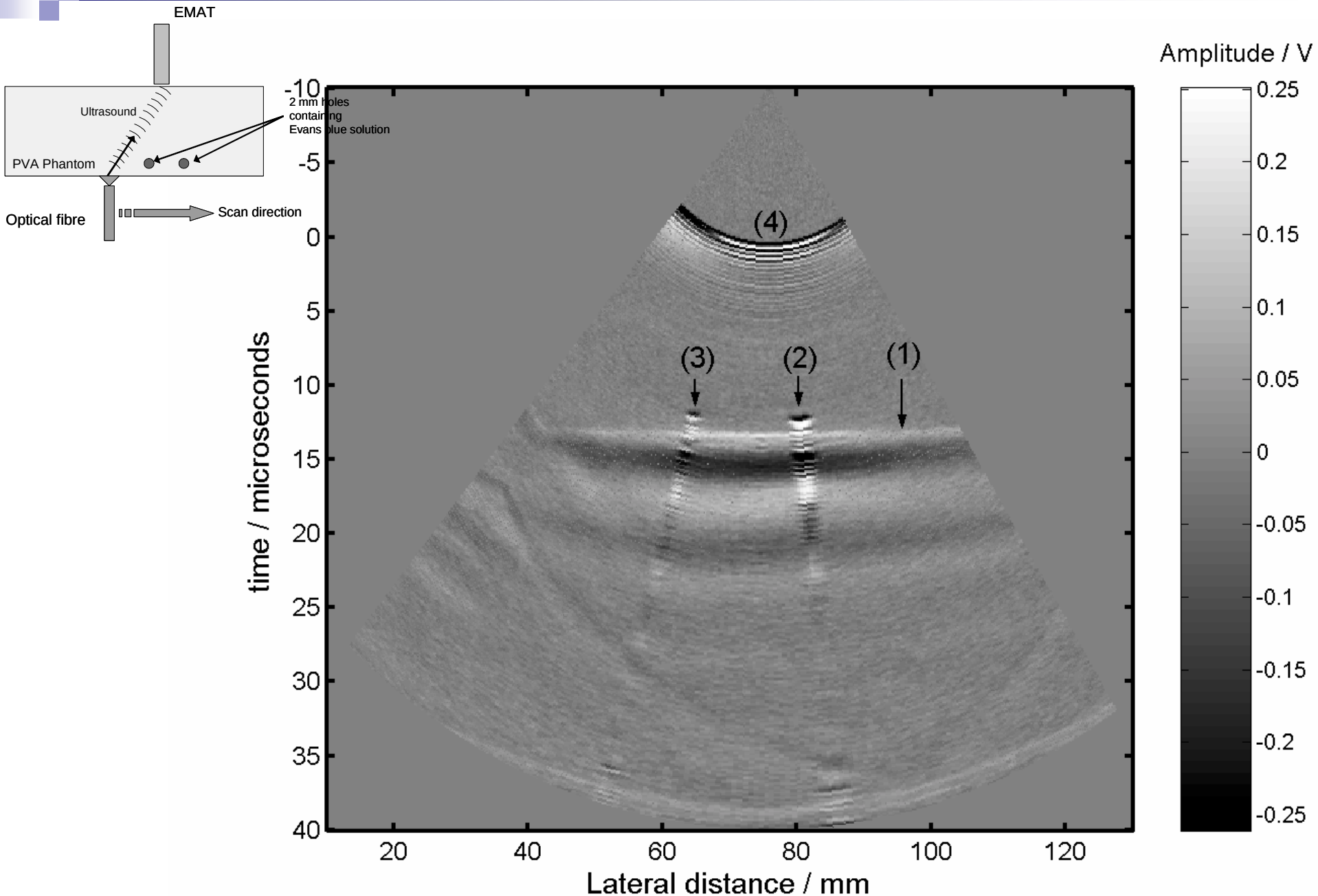

Distance from the center of evans blue tube / mm
x = 2.0
x = 1.0
x = 0
x = -1.0
x = -2.0
(1)
(2)
(2)
(3)
(2)
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
time / μs



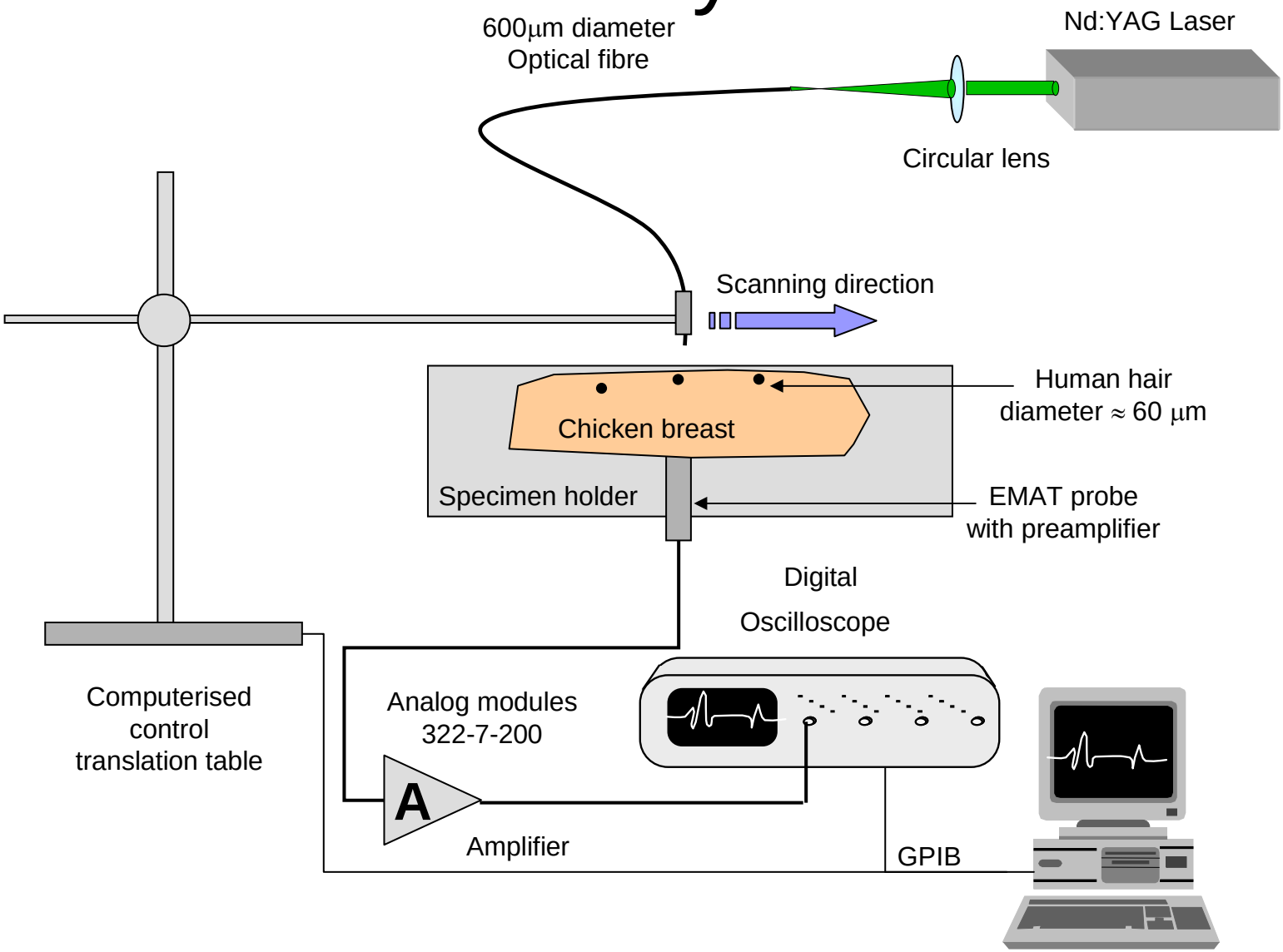
Without blood vessel

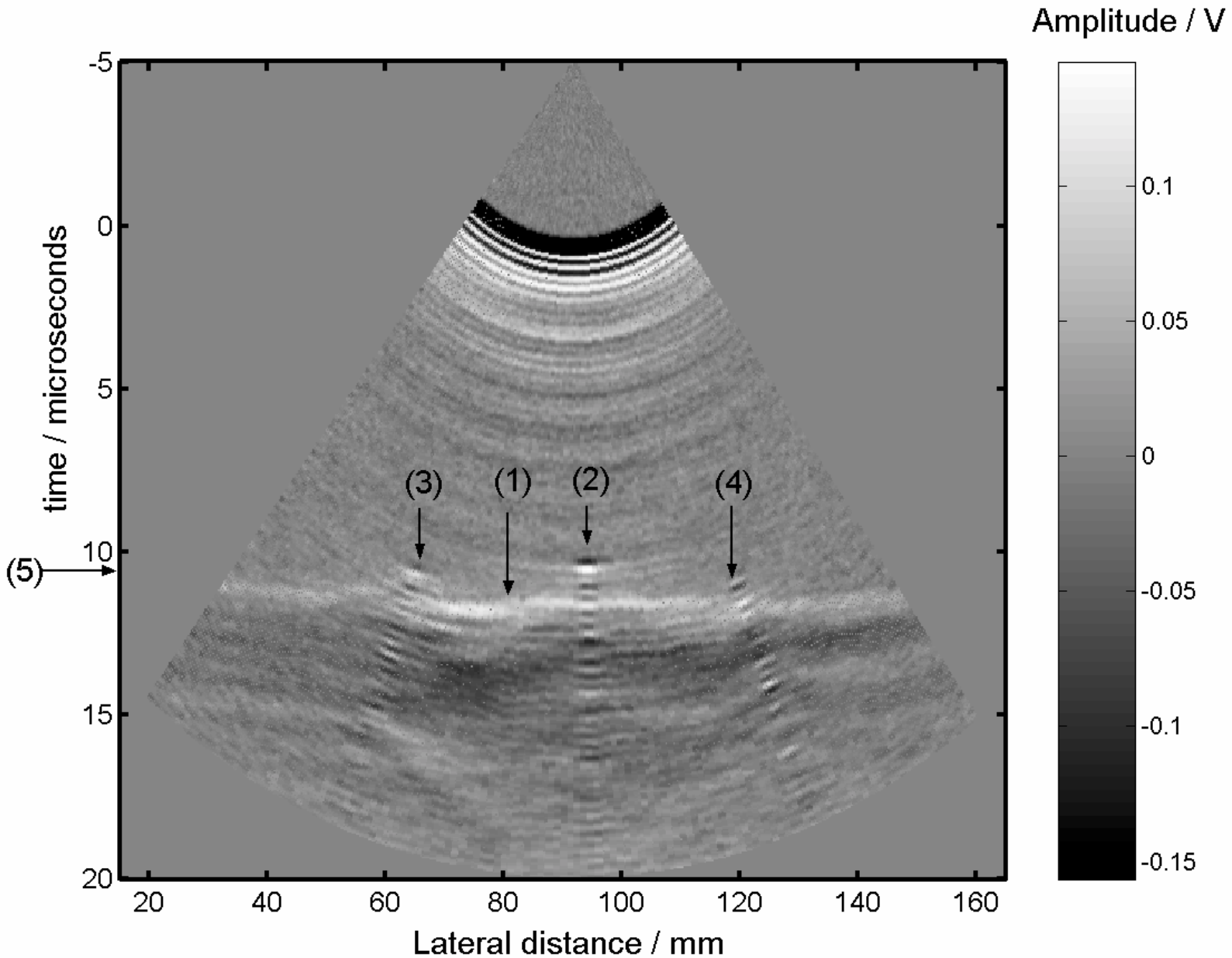


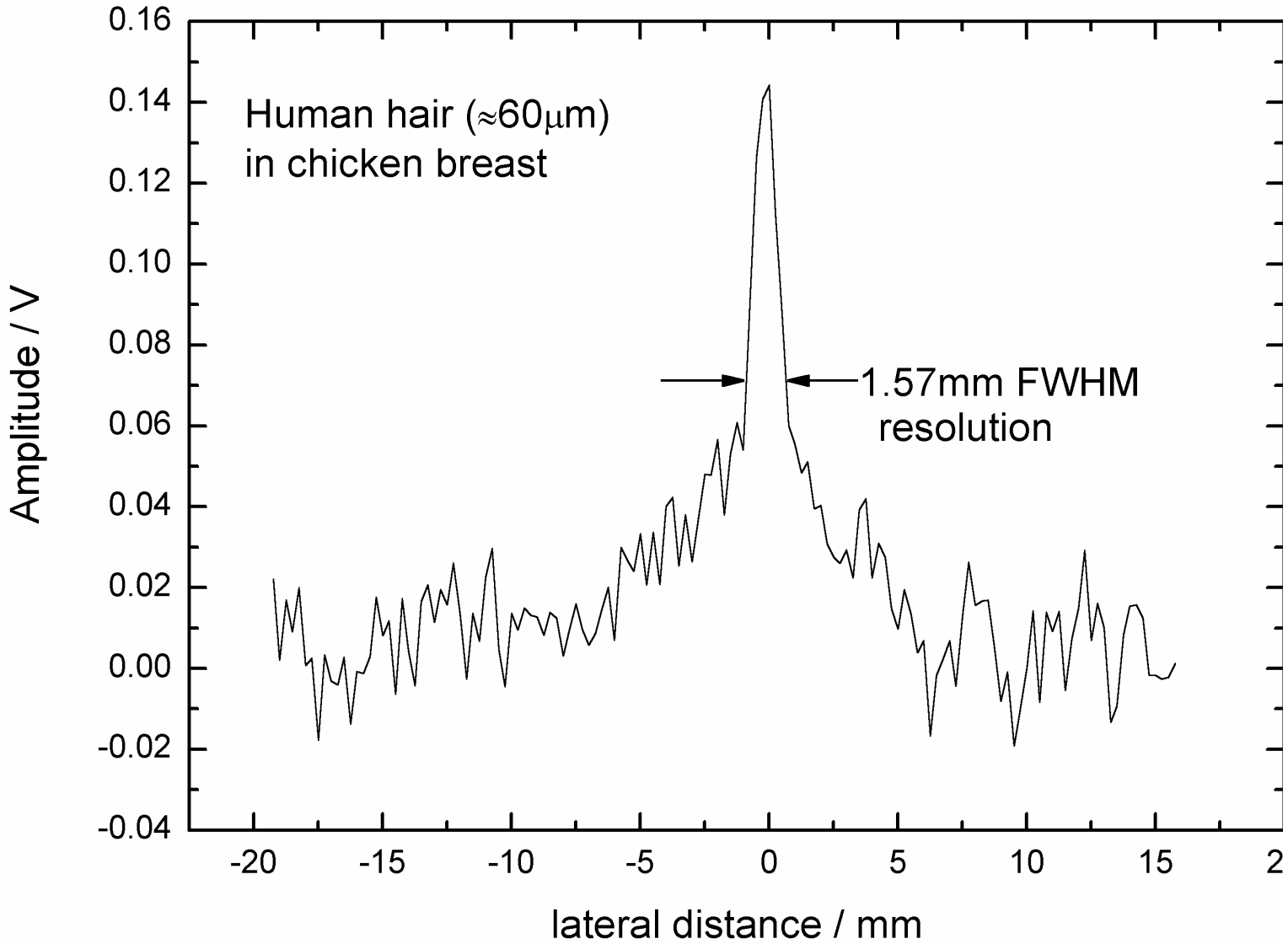
With blood vessel


EMAT
Ultrasound
PVA Phantom
Optical fibre
Scan direction
2 mm holes
containing
Evans blue solution
(4)
(3)
(2)
(1)
time / microseconds
Lateral distance / mm
Amplitude / V
-10
-5
0
5
10
15
20
25
30
35
40
20
40
60
80
100
120
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25

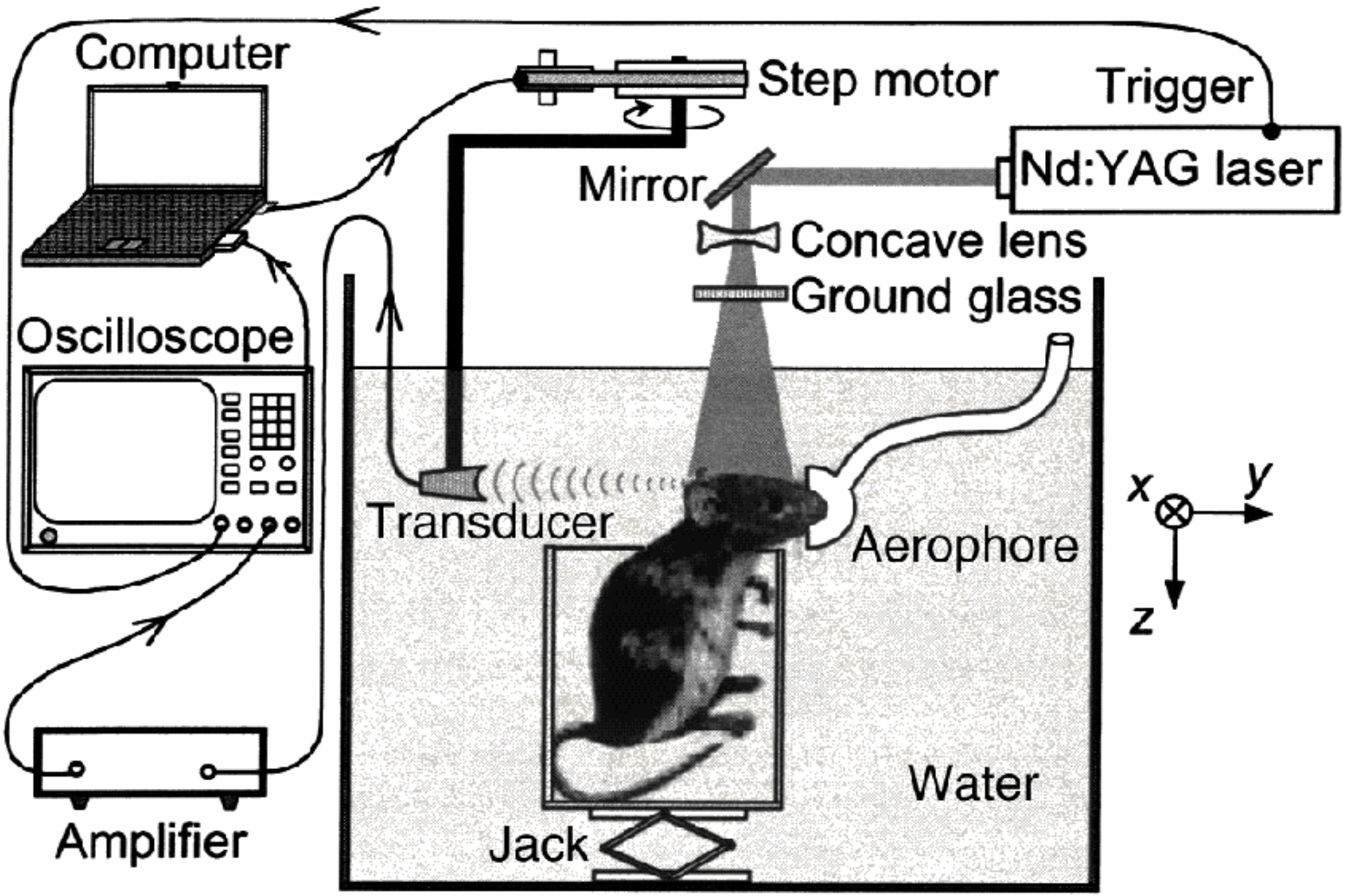
Laser ultrasound system : UMIST



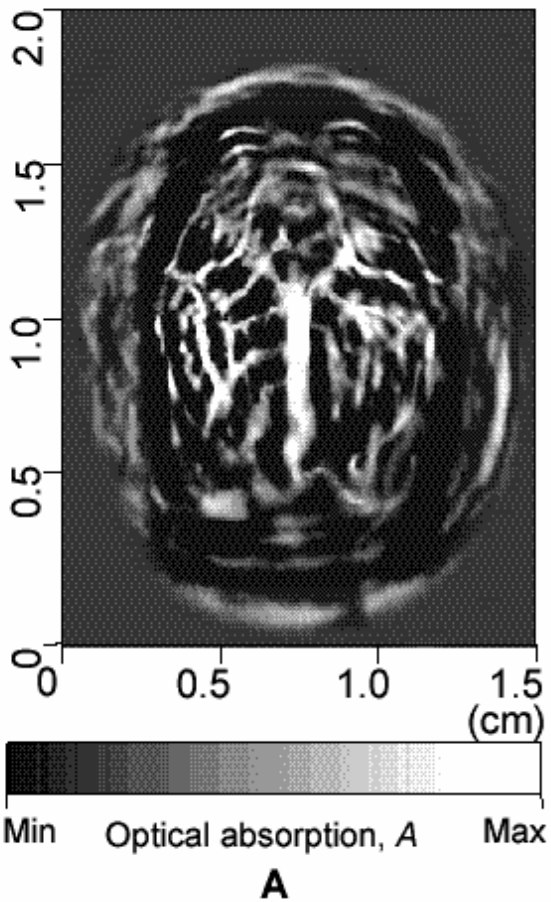

Amplitude / V
0.1
0.05
0
-0.05
-0.1
-0.15
time / microseconds
-5
0
5
10
15
20
(1)
(2)
(3)
(4)
(5)
20
40
60
80
100
120
140
160
Lateral distance / mm


Human hair (≈60μm)
in chicken breast
1.57mm FWHM
resolution
Amplitude / V
lateral distance / mm
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-20
-15
-10
-5
0
5
10
15
2

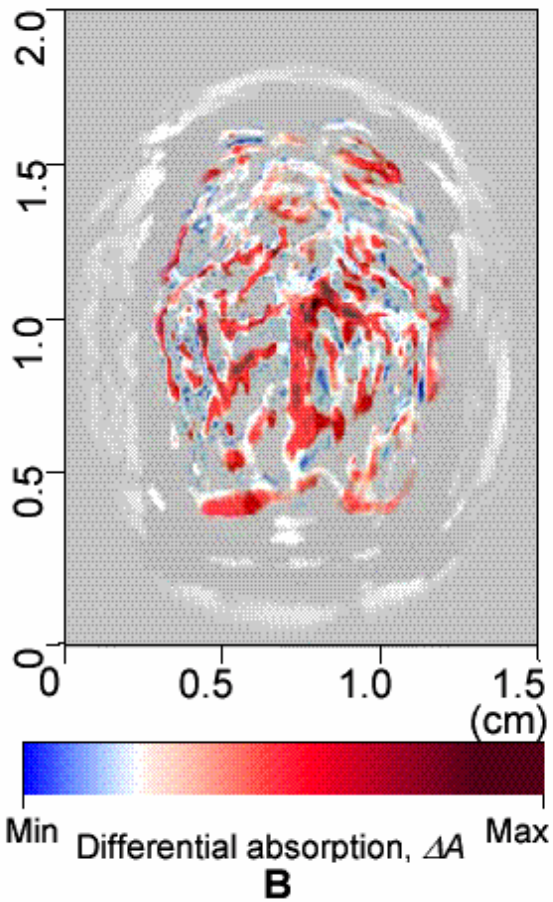
Laser ultrasound system : Texas A&M



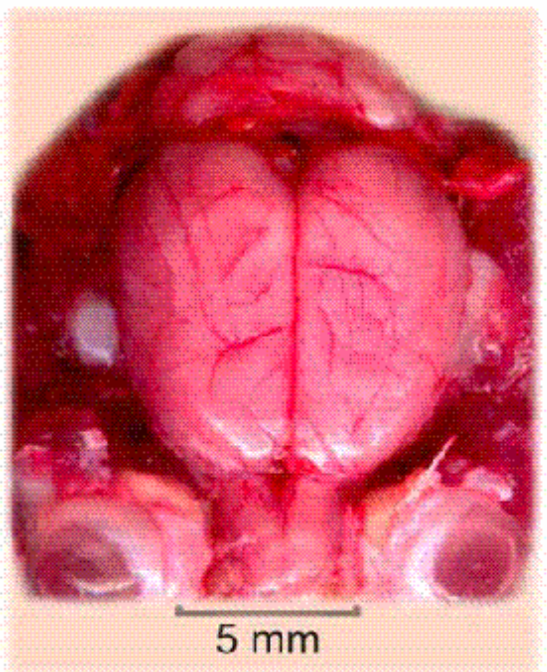
Laser ultrasound system : Texas A&M



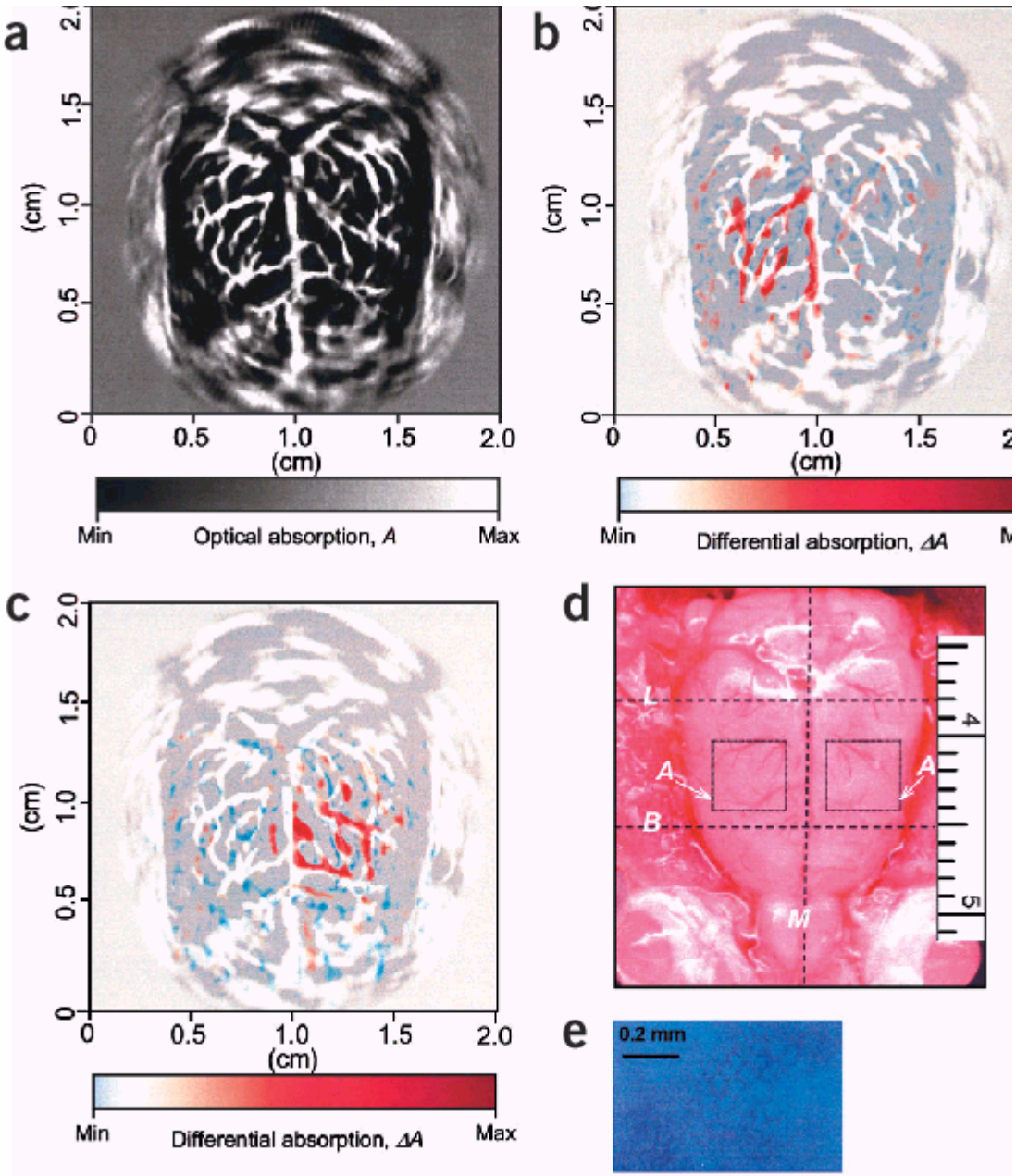
A

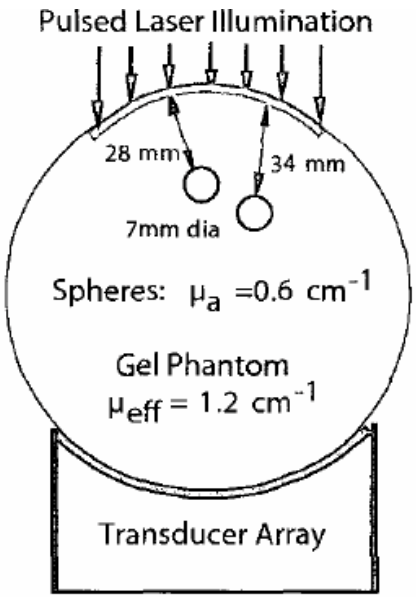


B

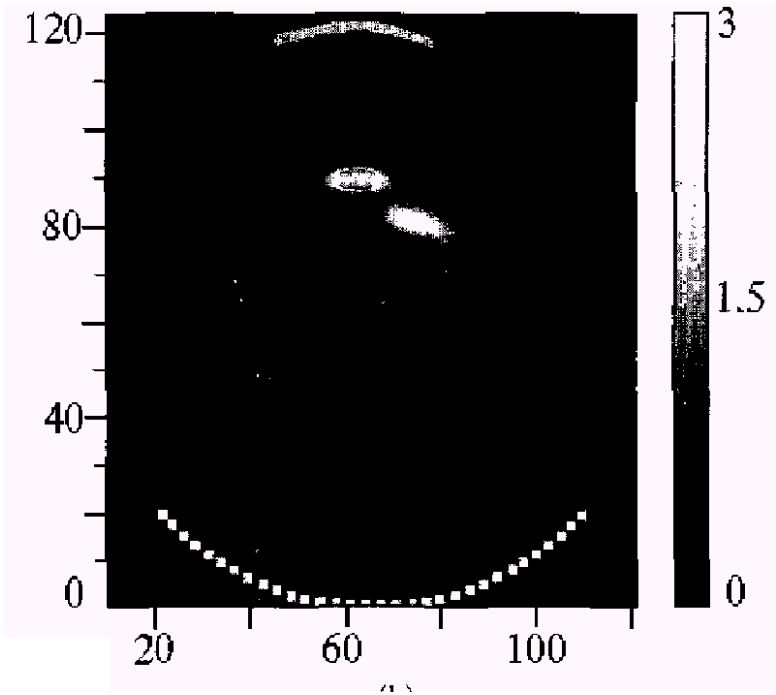


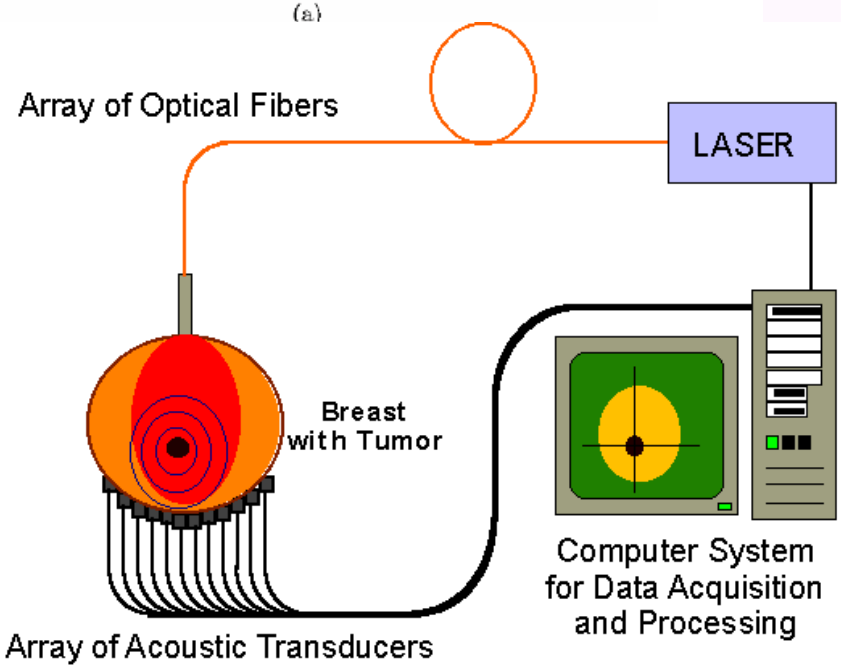
C


a
b
c
d
e
(cm)
0
0.5
1.0
1.5
2.0
Min
Optical absorption, A
Max
Differential absorption, ΔA
L
A
B
M
4
5
0.2 mm


Pulsed Laser Illumination
28 mm
34 mm
7mm dia
Spheres: μ_a =0.6 cm^{-1}
Gel Phantom
μ_{eff} = 1.2 cm^{-1}
Transducer Array

(a)

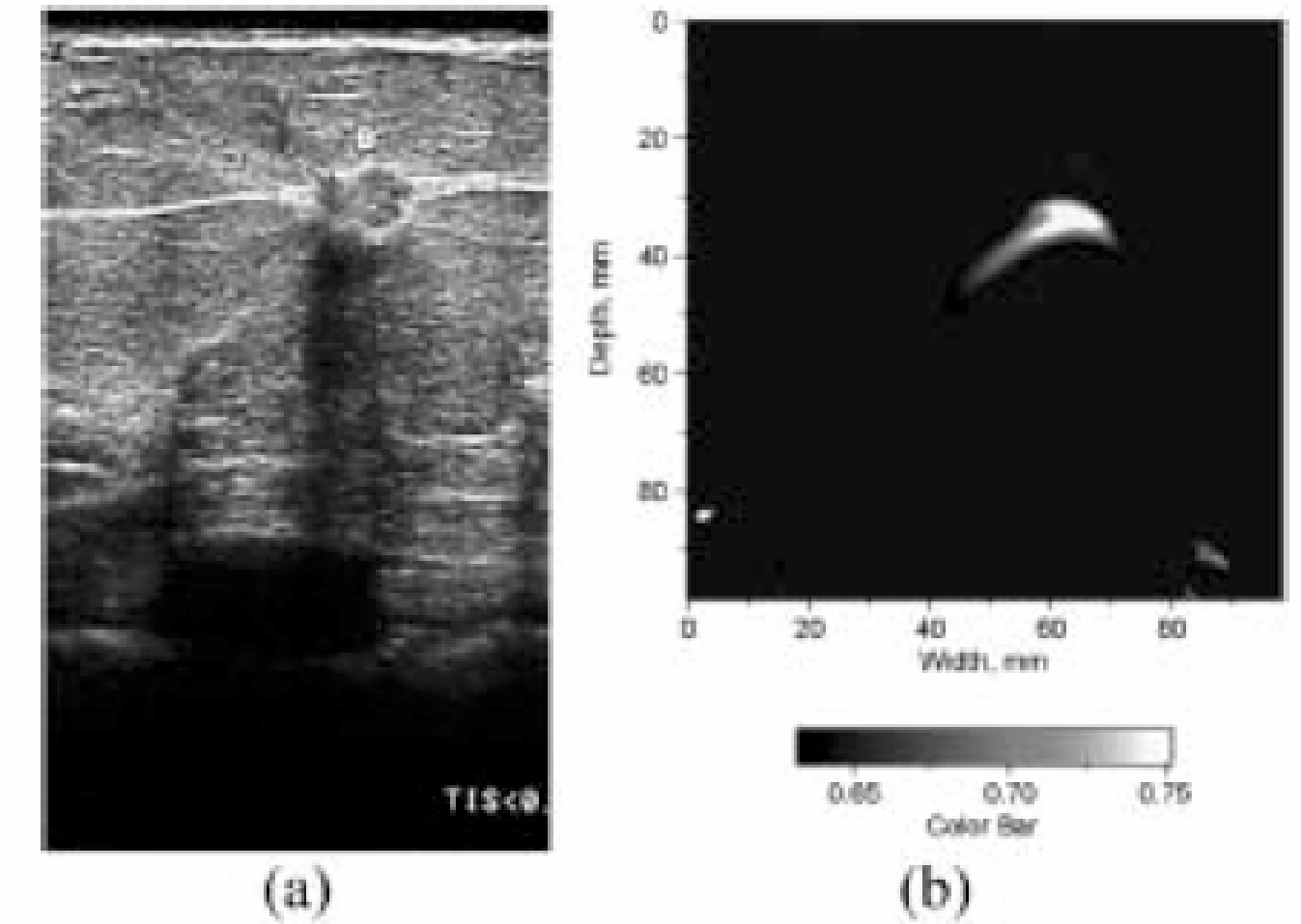

120
80
40
0
20
60
100
3
1.5
0


Array of Optical Fibers
LASER
Breast
with Tumor
Computer System
for Data Acquisition
and Processing
Array of Acoustic Transducers

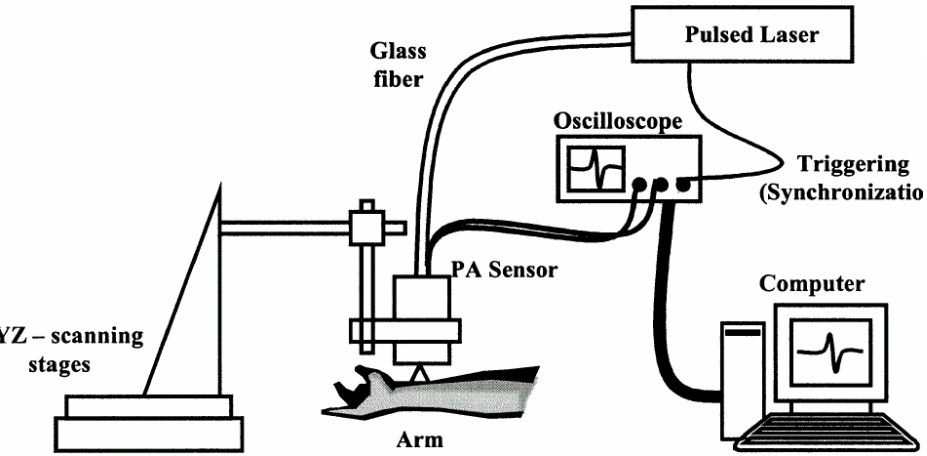
Breast cancer image

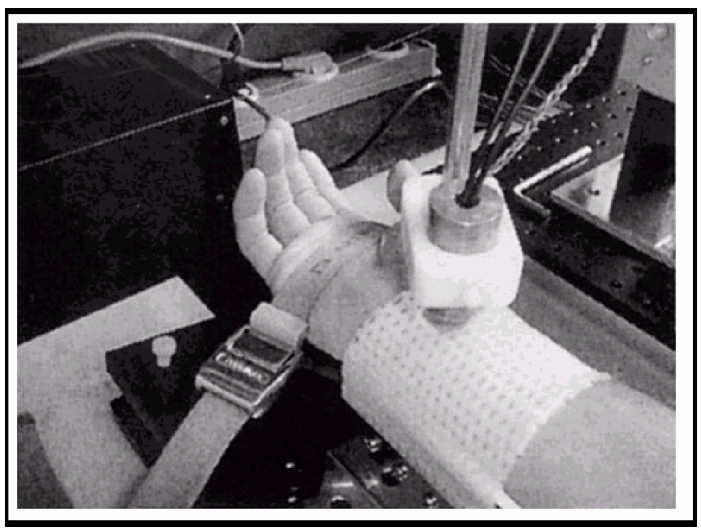
Ultrasound

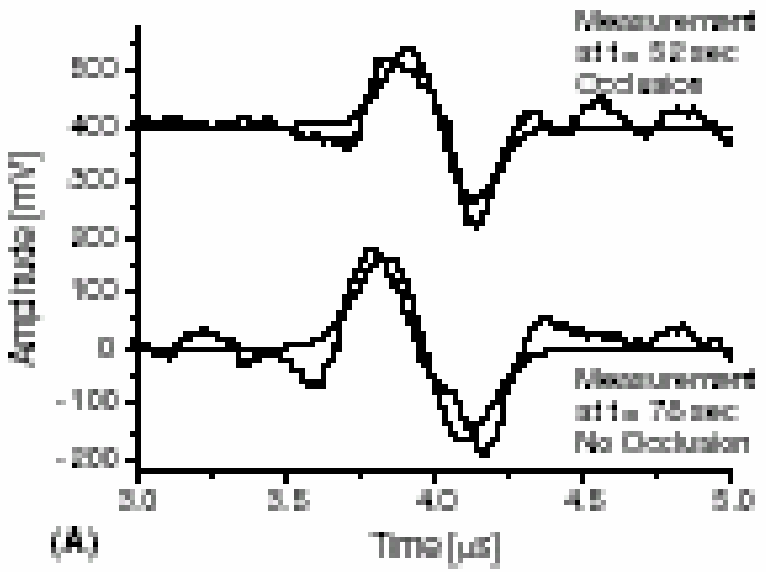
PAT

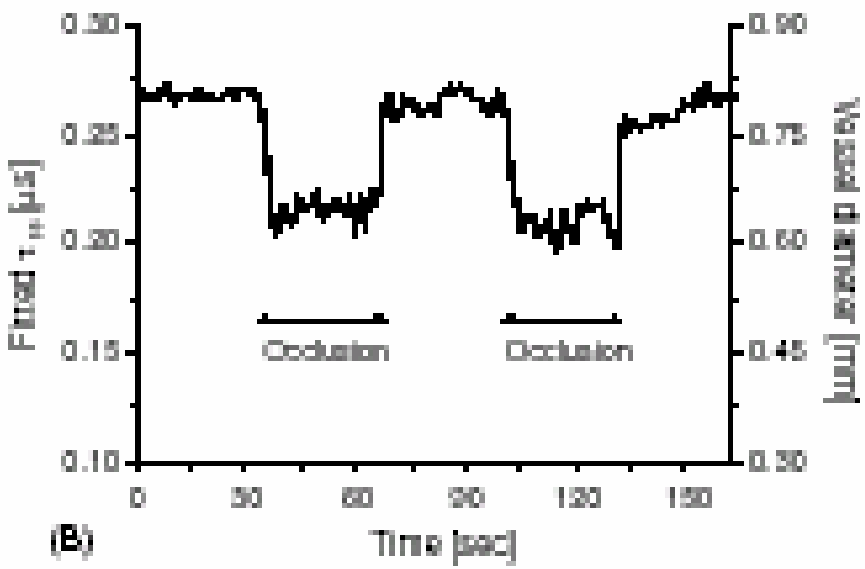


Oraesky *et al.*


Pulsed Laser
Glass fiber
Oscilloscope
Triggering (Synchronizatio
PA Sensor
Computer
YZ – scanning stages
Arm

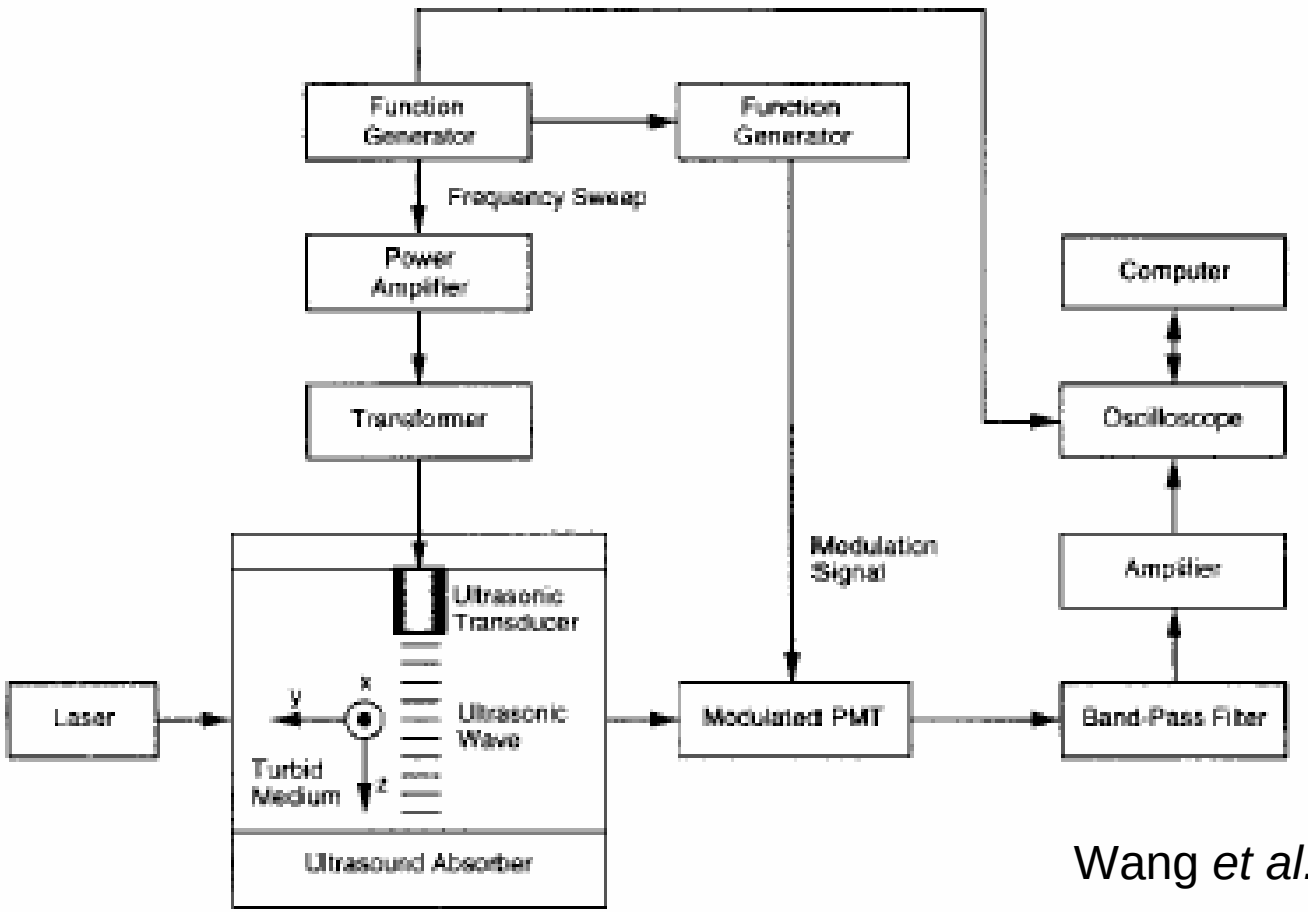



Measurement at t = 52 sec: Occlusion
Measurement at t = 75 sec: No Occlusion
Amplitude [mV]
Time [μs]
(A)

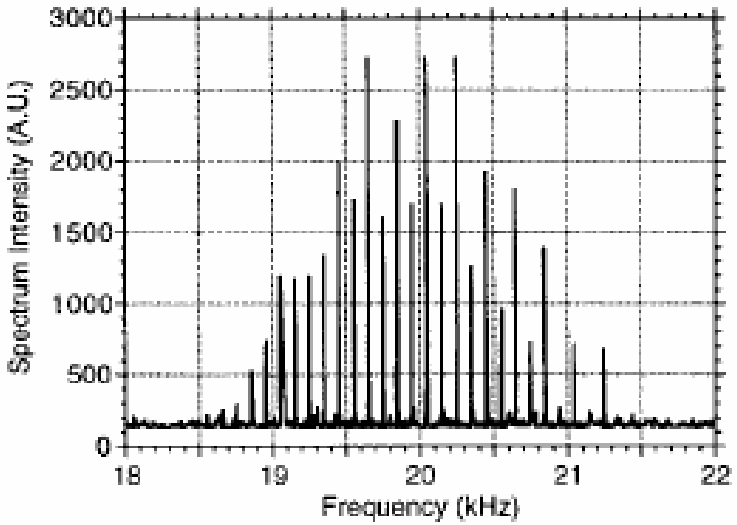

Occlusion
Occlusion
Time [sec]
(B)

Acousto-Optic tomography

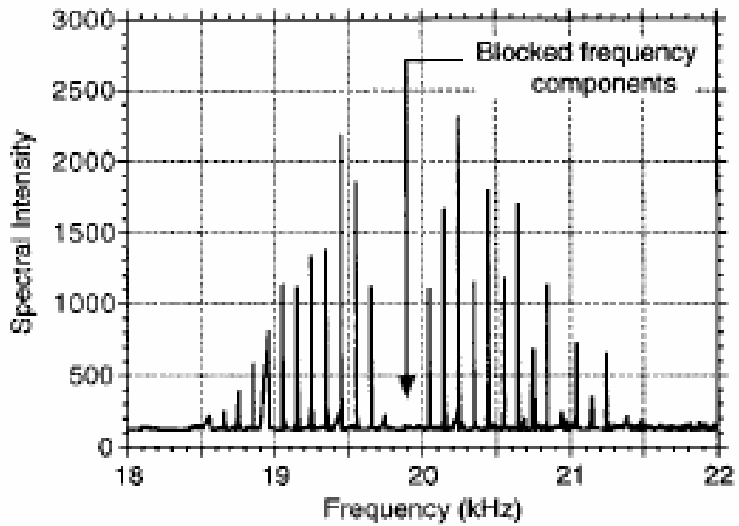
Frequency swept AOT



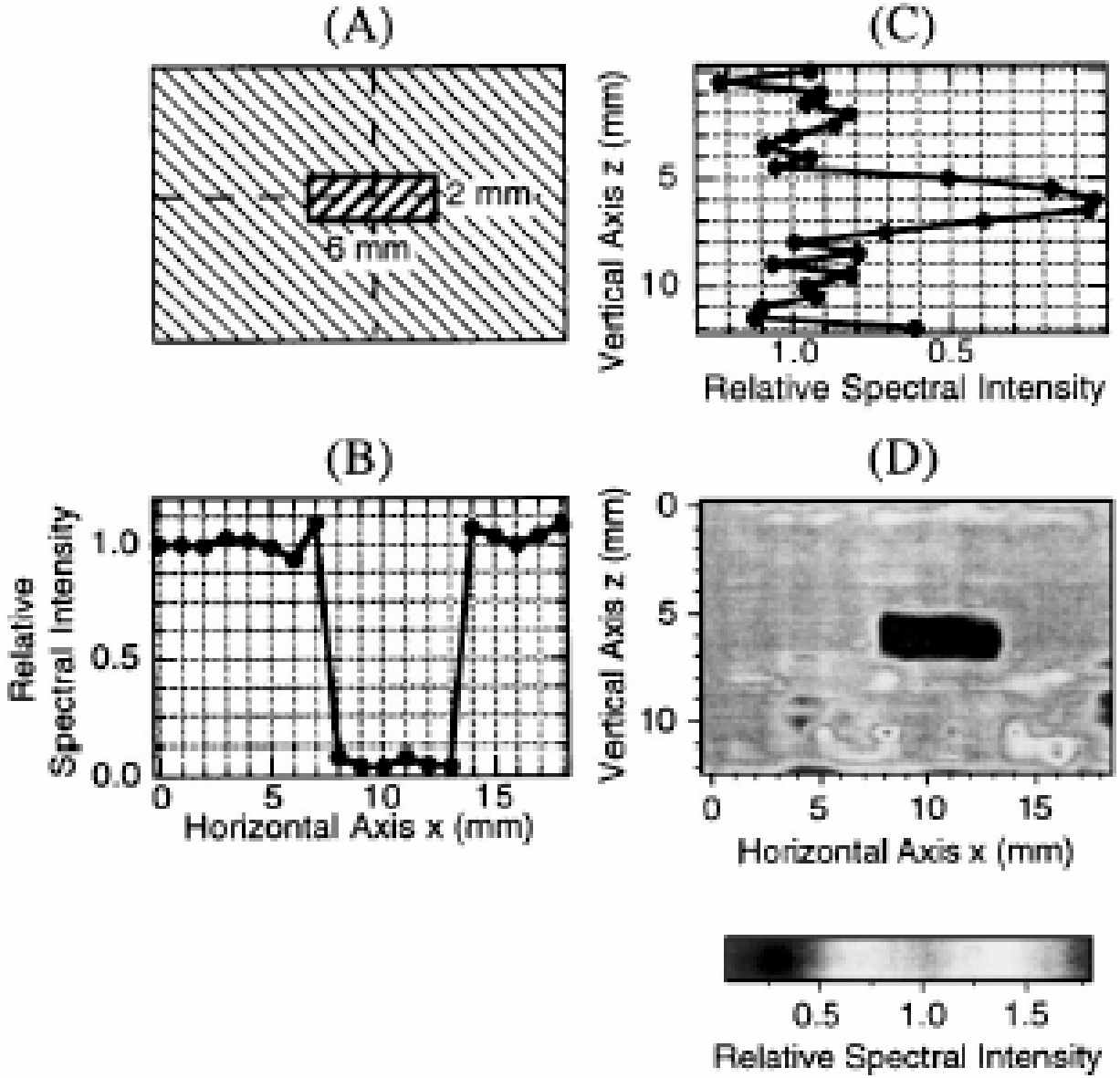
Wang *et al. 2002*

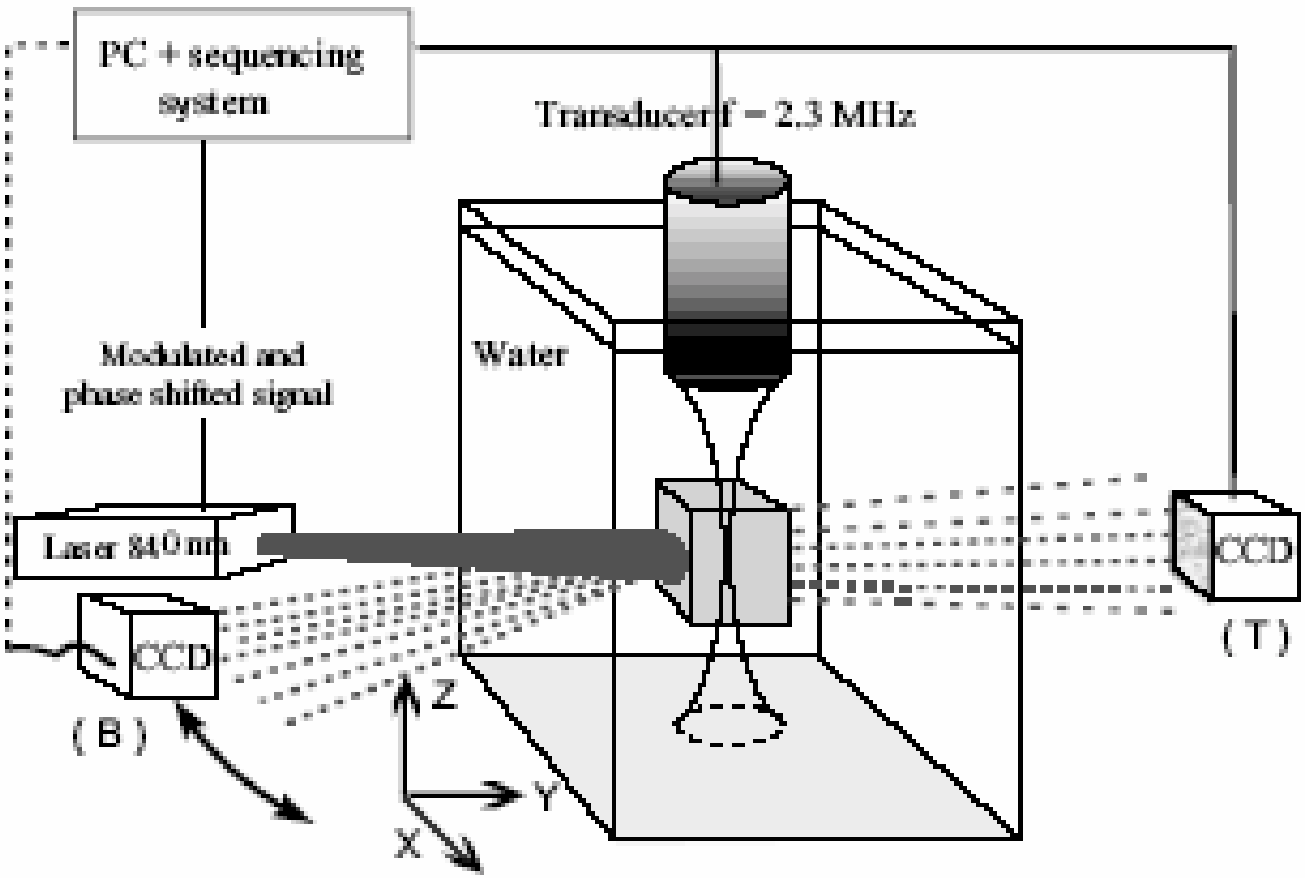

Spectrum Intensity (A.U.)
3000
2500
2000
1500
1000
500
0
18
19
20
21
22
Frequency (kHz)

(A)


Spectral Intensity
3000
2500
2000
1500
1000
500
0
Blocked frequency components
18
19
20
21
22
Frequency (kHz)

(B)


(A)
2 mm
6 mm
(C)
Vertical Axis z (mm)
5
10
1.0
0.5
Relative Spectral Intensity
(B)
Relative Spectral Intensity
1.0
0.5
0.0
0
5
10
15
Horizontal Axis x (mm)
(D)
Vertical Axis z (mm)
0
5
10
0
5
10
15
Horizontal Axis x (mm)
0.5
1.0
1.5
Relative Spectral Intensity



Levequet-Fort *et al.* 2001

Conclusions

- Hybrid photonic-ultrasonic tomographies combine the strength of optical and ultrasonic tomographies.
- Higher contrast image than ultrasonic tomography, Better resolution than optical tomography.
- Cost effectiveness (a lot lower than MRI)
- Non-Ionization unlike X-Ray CT
- However, they are at early stage of development.

Acknowledgements

- Professor Richard J. Dewhurst, University of Manchester, UK.
- Dr. Greg Gondek and Dr. S. Kaewpirom
- Mr. Ben Dutton and Mr. Jasman Zainal
- Royal Thai Government Studentship (2000-2004)