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Seoul National University & University of Tokyo
Remote Course @ Bioengineering Department

Advanced X-ray Imaging

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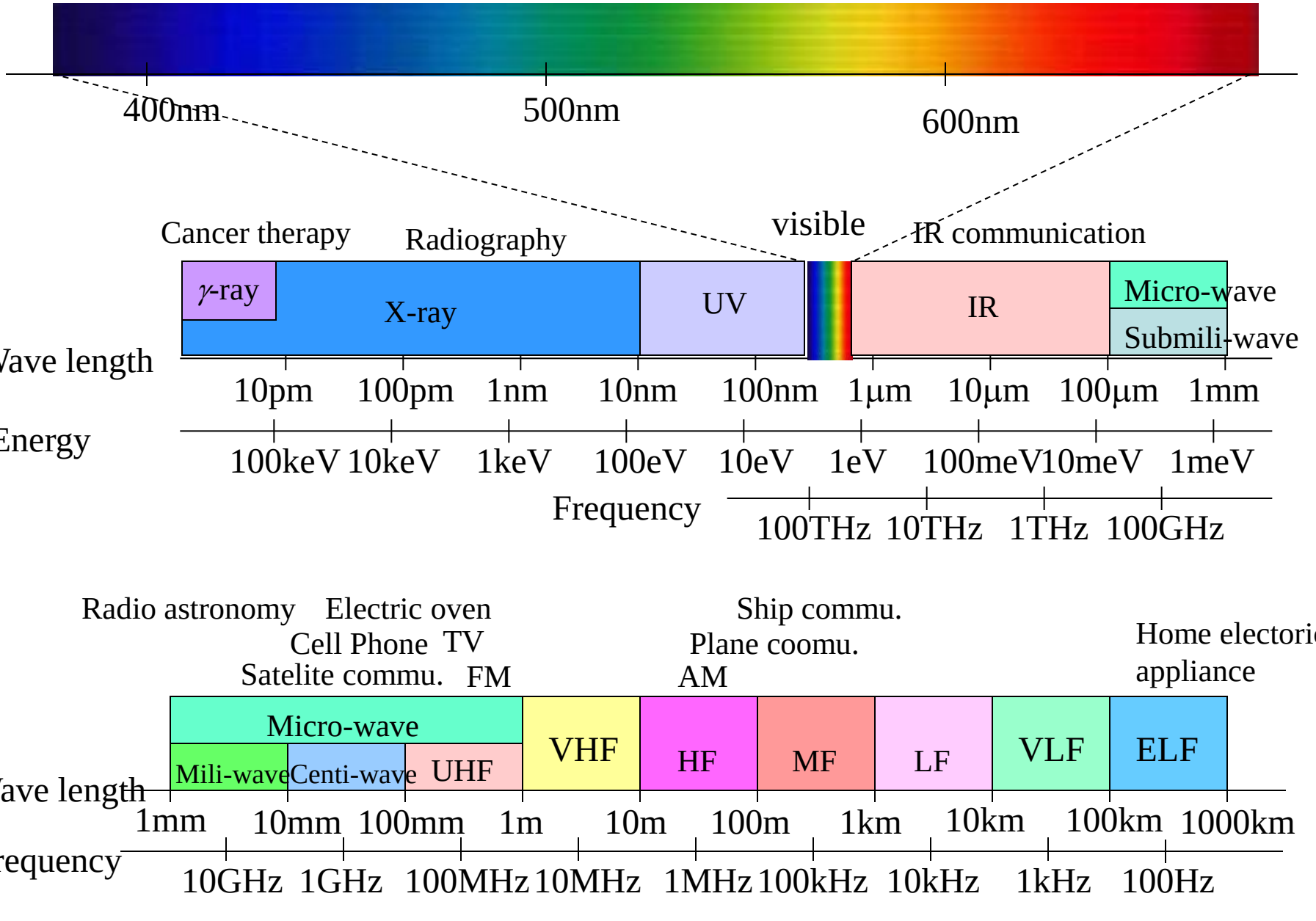
1. Generation of X-rays
2. Light Property of X-rays
3. X-ray Tube and Poly-chromatic Imaging
4. Synchrotron Radiation and Mono-chromatic/coherent Imaging
5. Extremely High Sensitivity Imaging by High Vision Camera

Name and wavelength of the EM wave



X-ray is Electromagnetic Wave

Maxwell Equations

$\vec{E}$

Coulomb's law $\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0}$

Faraday's law $\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$

$\vec{B}$

Ampere-Maxwell's law $\nabla \times \vec{B} = \mu_0 \vec{J} + \mu_0 \varepsilon_0 \frac{\partial \vec{E}}{\partial t}$

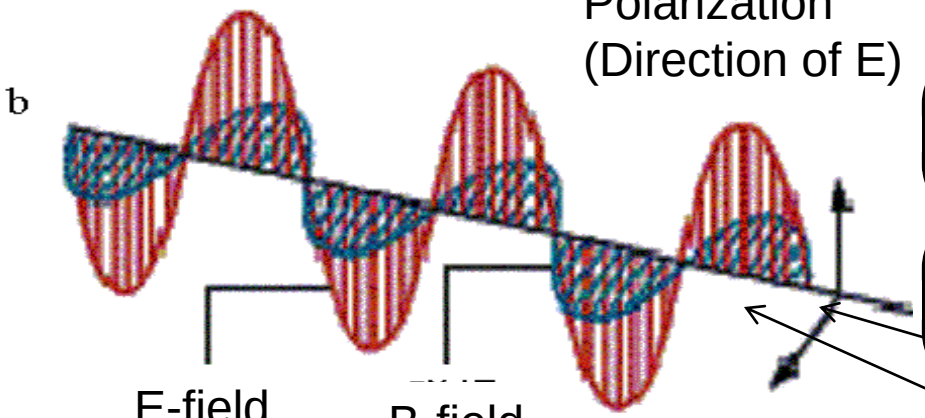
Law of no magnetic dipole $\nabla \cdot \vec{B} = 0$

⇩

Electromagnetic wave equation

$$\left(\nabla^2 - \frac{\partial^2}{c^2 \partial t^2}\right)\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix} = \vec{f}\left(\rho, \vec{J}\right)$$

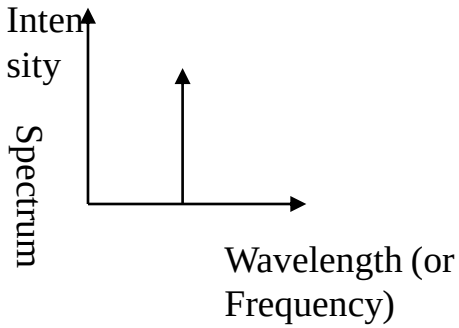
$$\begin{pmatrix}\vec{E}\\ \vec{B}\end{pmatrix} = \begin{pmatrix}\vec{E}_0\\ B_0\end{pmatrix} e^{i\left(\vec{k}\bullet\vec{x} - \omega\bullet t + \theta\right)}, \; k_i = \frac{2\pi}{\lambda_i}$$



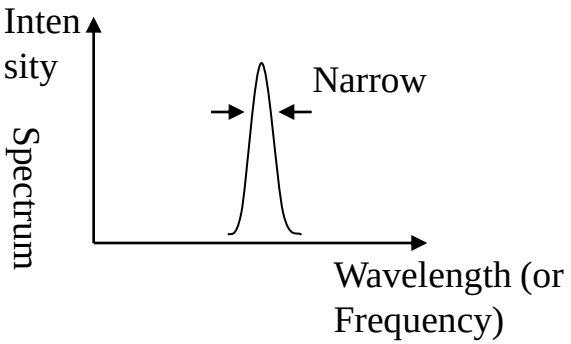
What is the Laser ?

LASER (Light Amplification by Stimulated Emission of Radiation)

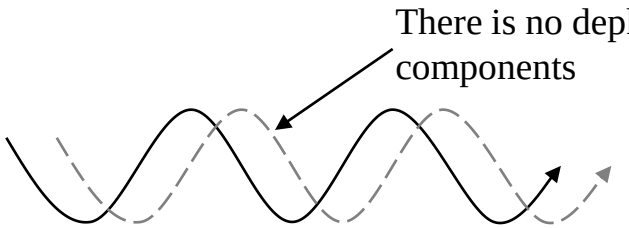
One wavelength (monochromatic)



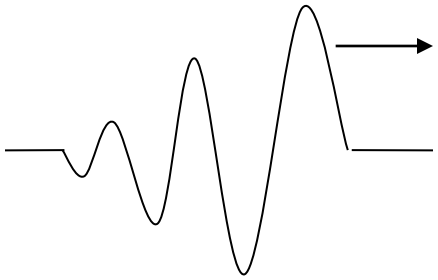
Actually



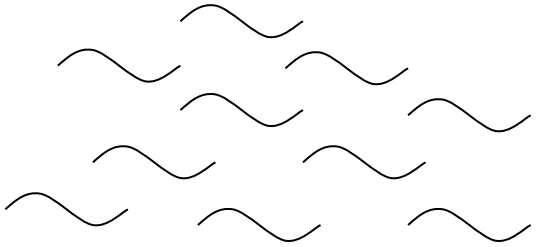
Coherent



See the wave in the sea surface



tidal wave is coherent



Little wave is incoherent

Steep rise in brightness

the second wave

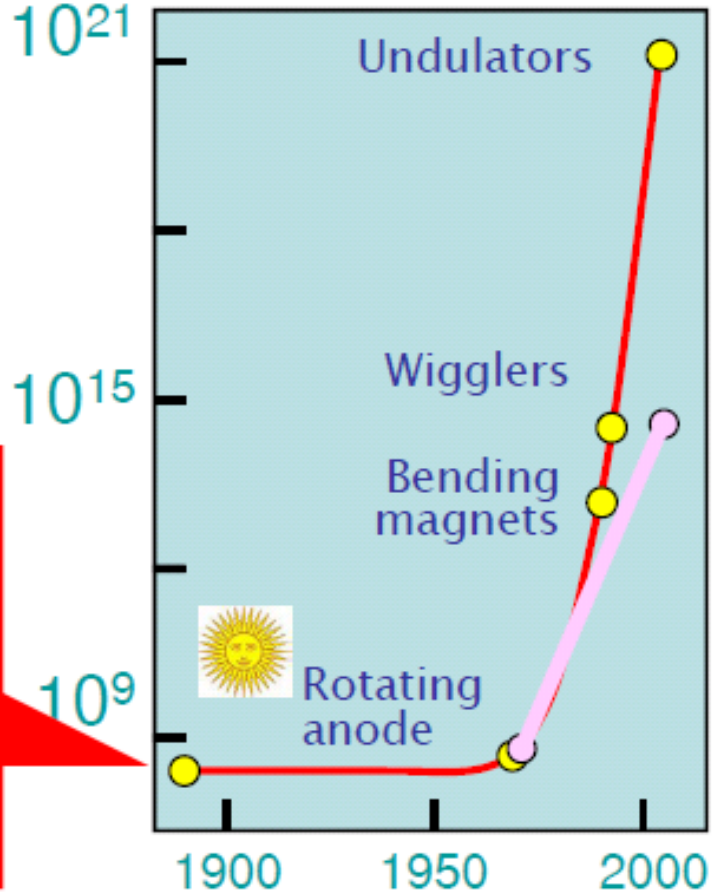
XFEL

SLS
SOLEIL (F)
DIAMOND (UK)
...

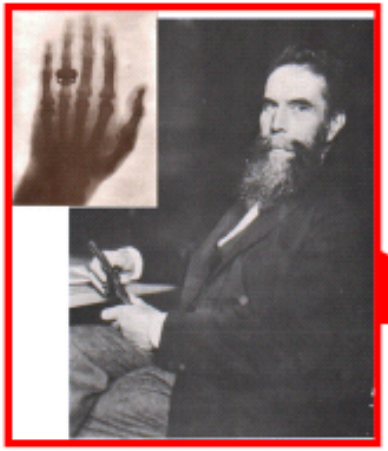
ESRF

SPring8

APS



Moore's Law for semiconductors



Bertha Roentgen's hand
(exposure: 20 min)

The x-ray tube

The tube consists of a glass envelope which has been evacuated to high vacuum. At one end is cathode(negative electrode) and at the other an anode(positive electrode), both hermetically sealed in the tube. The cathode is a tungsten filament which when heated emits electrons, a phenomenon known as thermionic emission。 The anode consists of a thick copper rod at the end of which is placed a small piece of tungsten target.

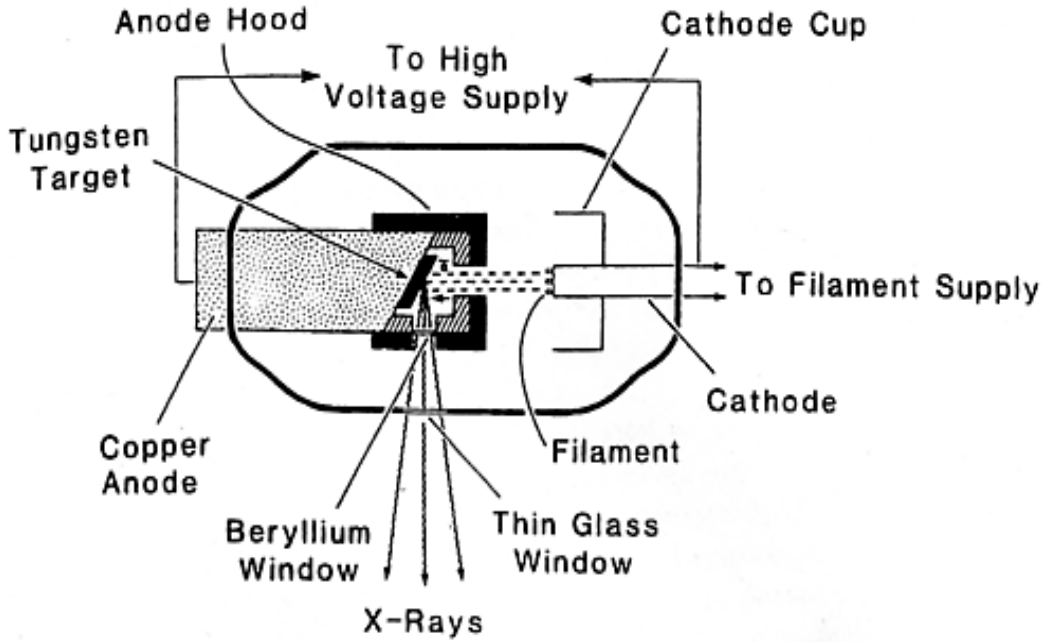
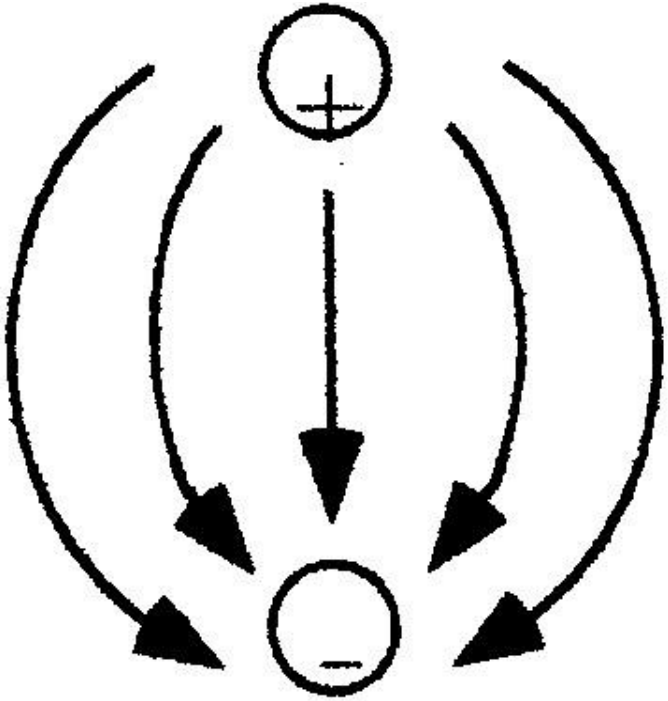


FIG. 3.1. Schematic diagram of a therapy x-ray tube with hooded anode.

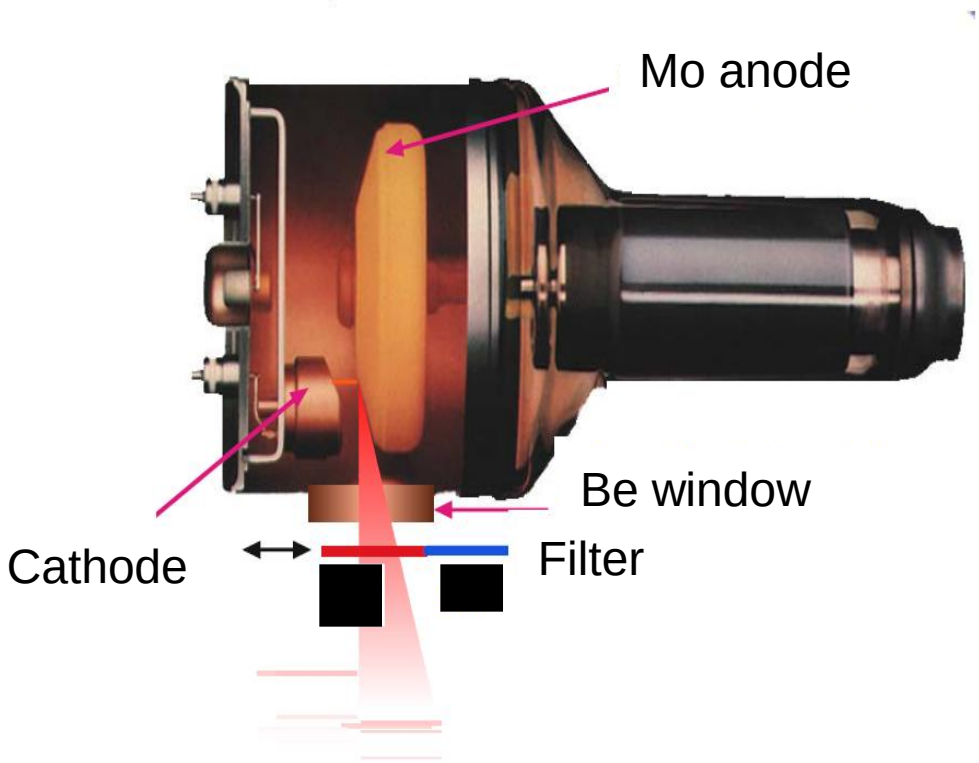
When a high voltage is applied between the anode and the cathode, the electrons emitted from the filament are accelerated toward the sudden deflection or acceleration of the electron caused by the attractive force of the tungsten nucleus.

Electric Field Line

It can be regarded as expanded rubber strings.



X-ray Tube



Background

Courtesy of Prof.Atsushi Momose
(Graduate School of Frontier Sciences , UniV.Tokyo)

CT scanner

mammography

X-ray image contrast is conventionally generated by the difference in absorption.

Poor sensitivity to biological soft tissues and polymer materials and so on.

Use X-ray phase information!

Baggage inspection

Mail screening

Poly-chromaticity, Mono-chromaticity, Coherence, Polarization vs Visibility and Resolution

Visibility and Resolution

Poly-chromatic/ In-coherent	X-ray tube(Bremsstrahlung) Synchrotron radiation (bending magnet)
Mono-chromatic/ In-coherent	Monochrometer Compton scattering
Mono-chromatic/ Coherent	Synchrotron radiation **(**Undulator**)**
Mono-chromatic/ Coherent/Polarization	Laser

better

Mammography by Polychromatic X-rays by X-ray Tube

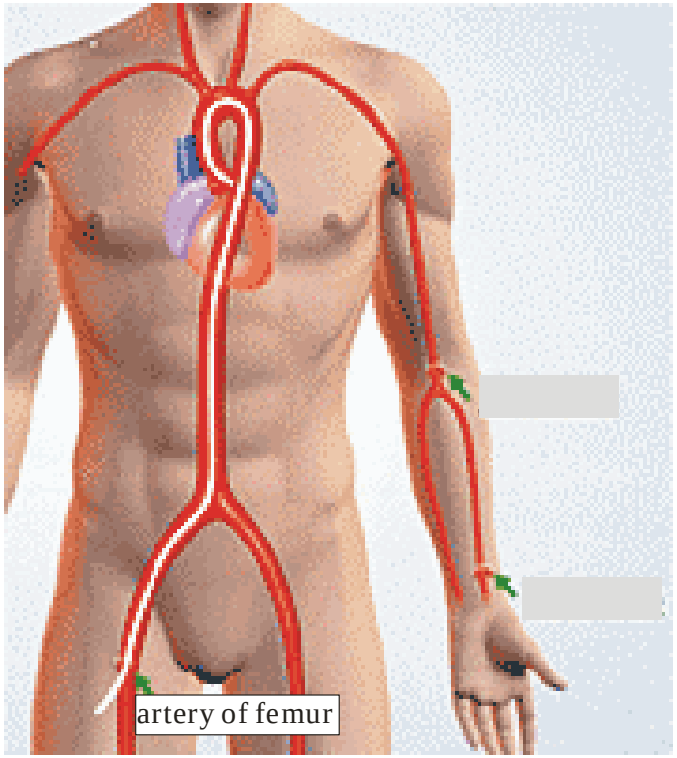
1.normal tissue irradiated high dose.

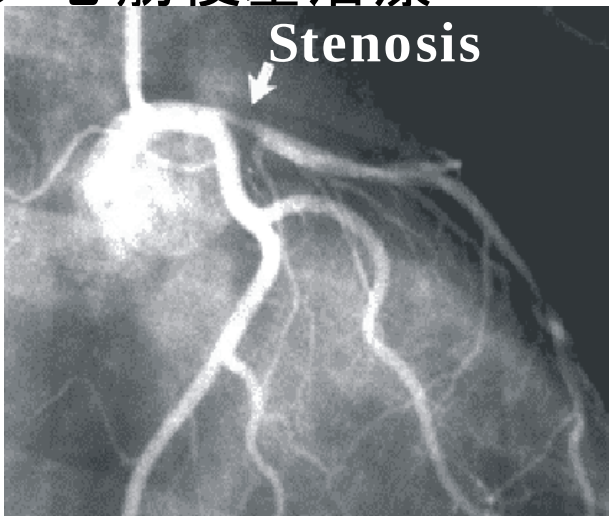
2.low resolution and low image quality.

Commercial Coronary Arteriography(CAG) by 50 keV X-ray tube
Treatment for myocardial infarction
心臓冠動脈血管造影・心筋梗塞治療

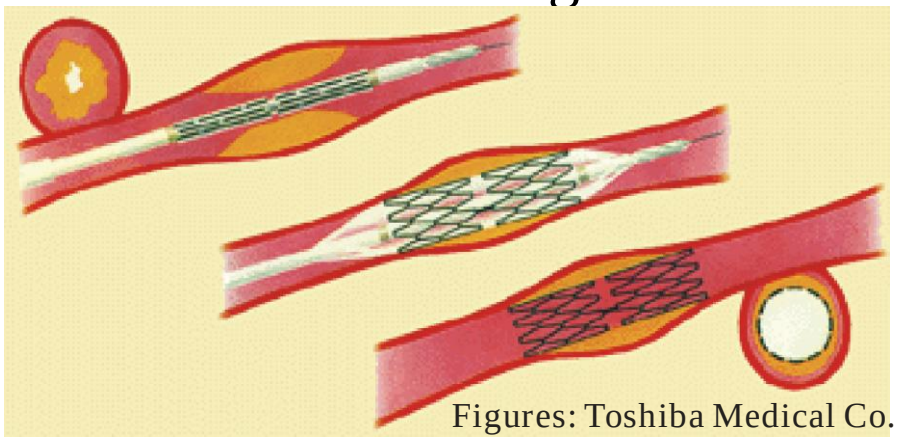
Insert catheter into coronary artery

and inject contrast agent(^{53}Iodine) to the artery





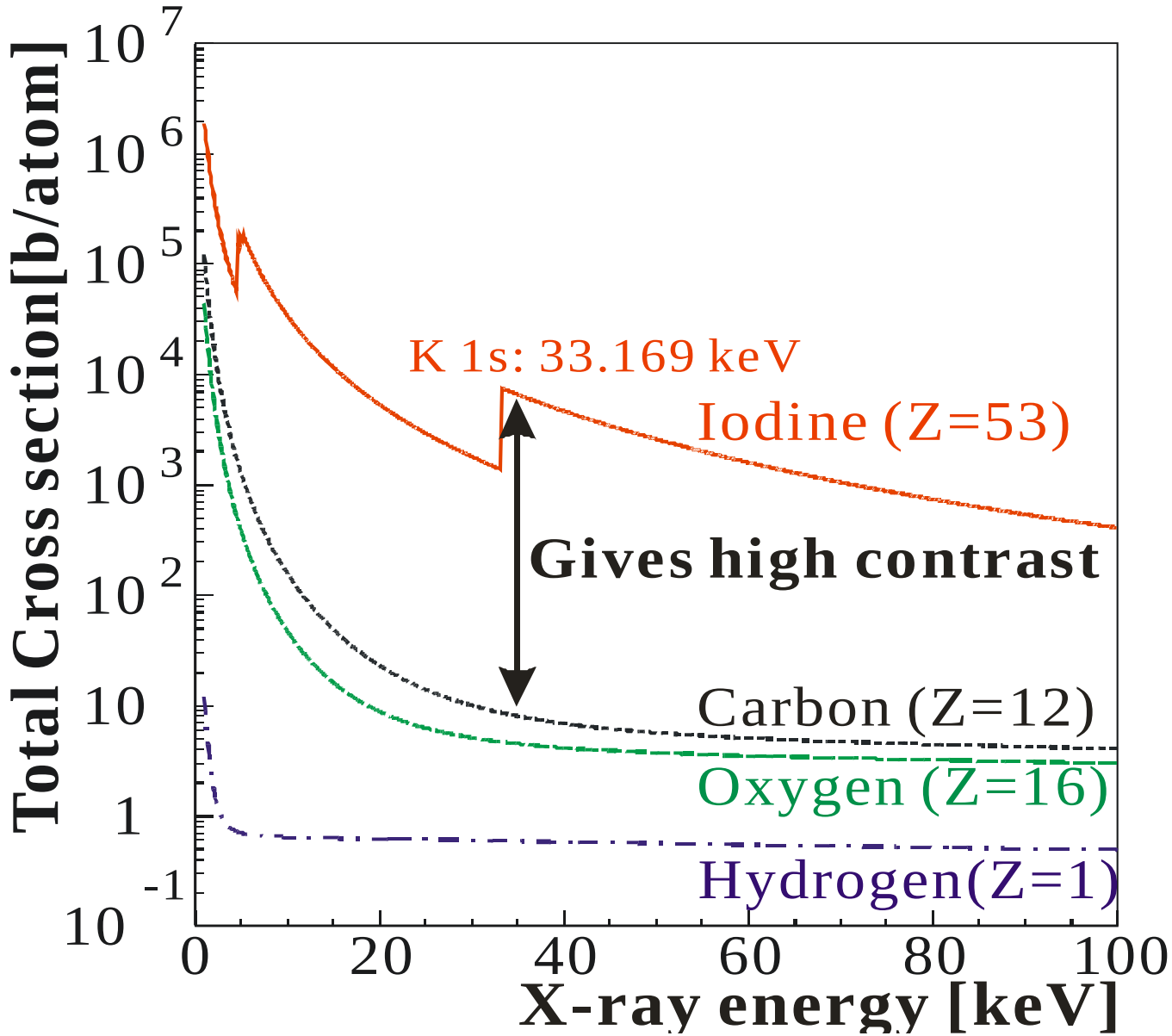
Treatment using "stent"



Figures: Toshiba Medical Co.

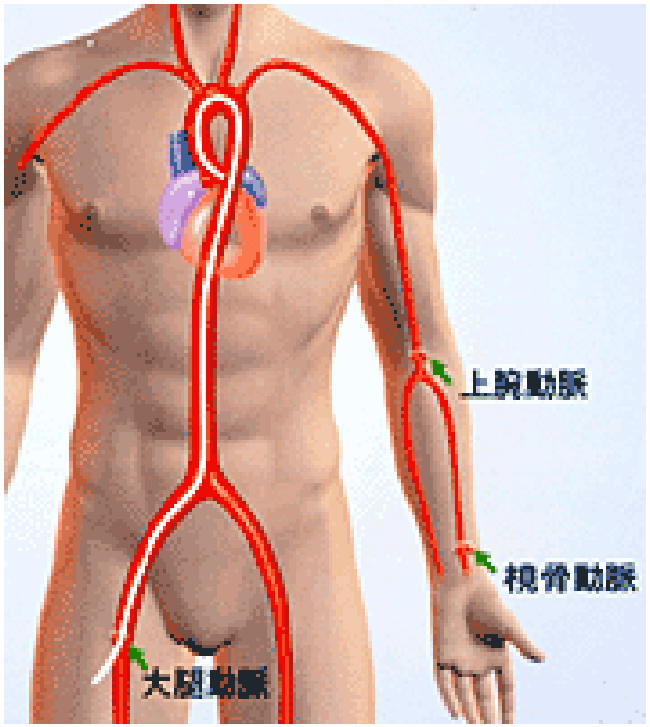
- Serious invasiveness and heavy irradiation dose
- Physical and mental distress for patients

Contrast Agent - Iodine-

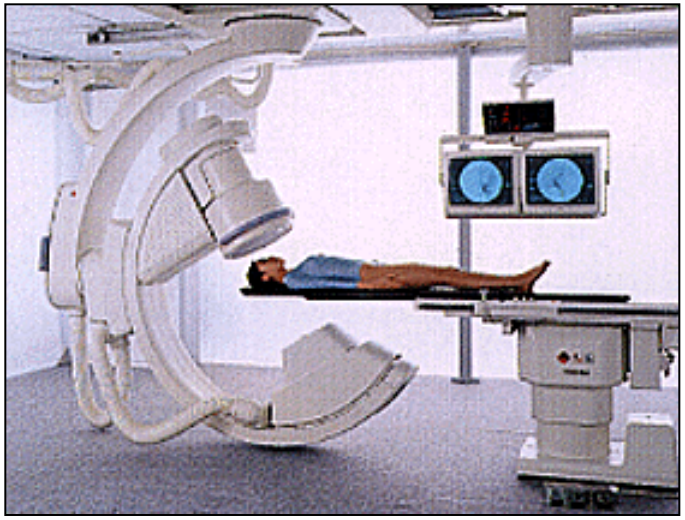


Total Cross Section of X-ray attenuation for various elements

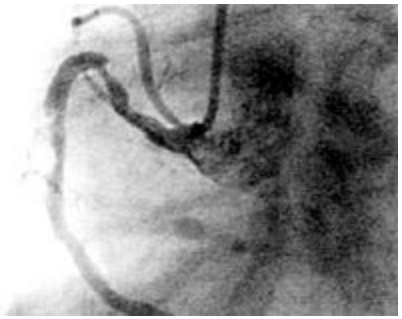
Cather Injection by Stupefaction（麻酔）and Operation



Updated system



Toshiba : infinix vc



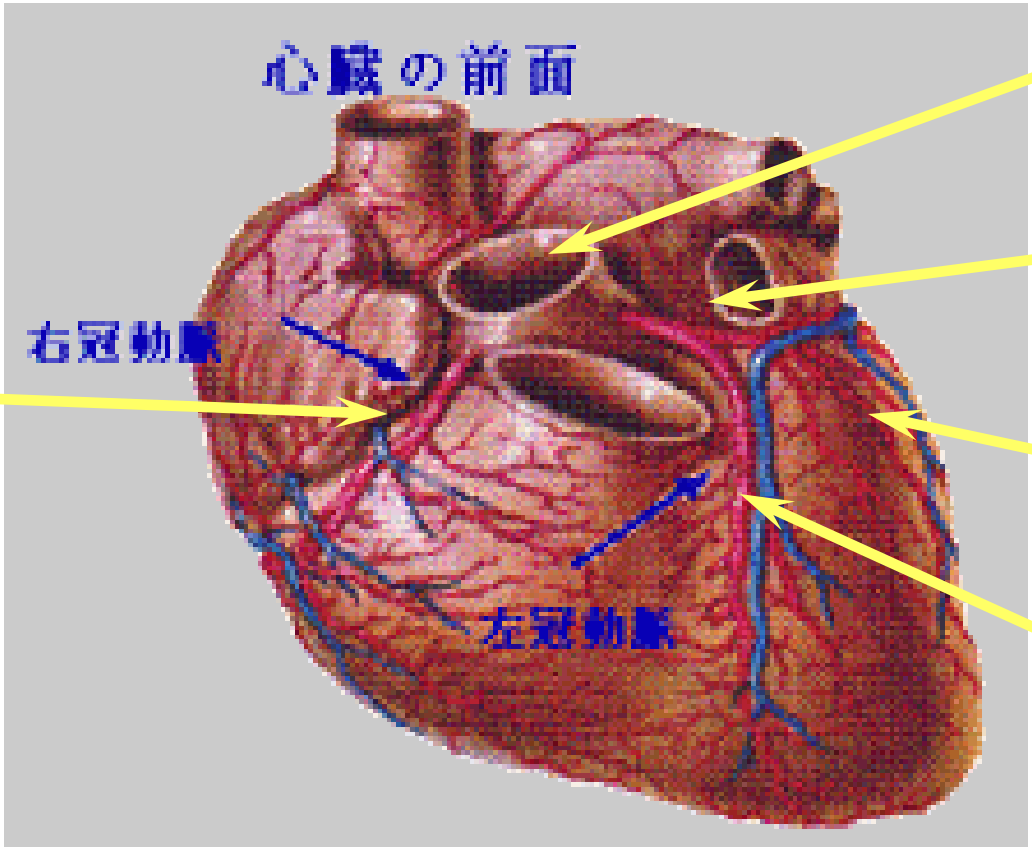
Before operation

Operation room

After operation

Heart Configuration

■冠動脈（Coronary　Artery）の解剖



RCA
右冠動脈

Ao(Aorta)
大動脈

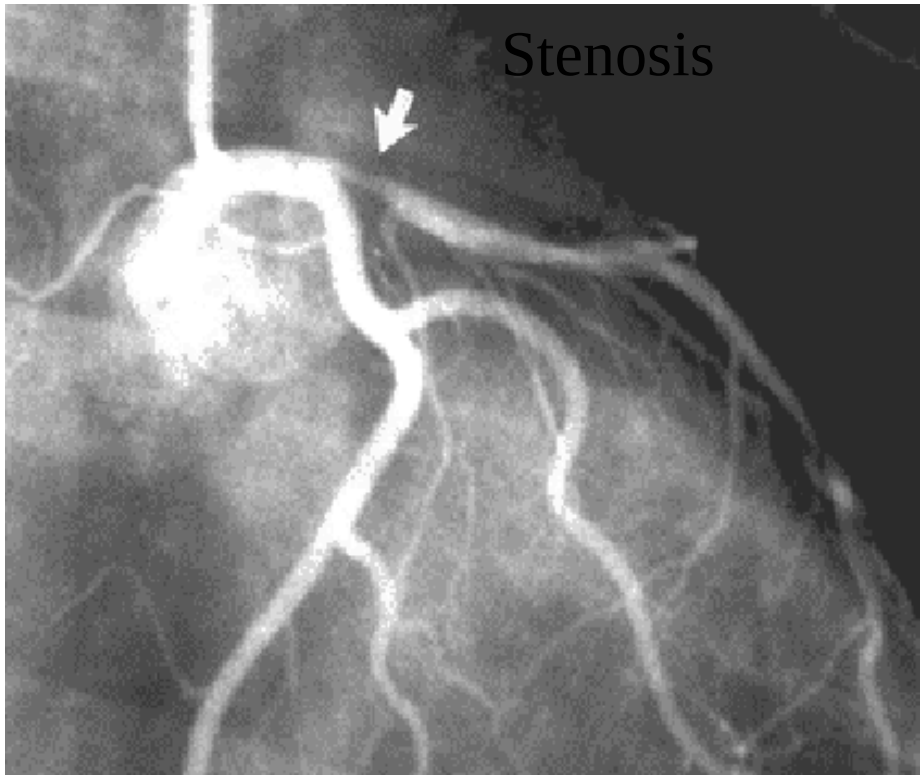
LCA
左冠動脈

LCX
左回旋枝

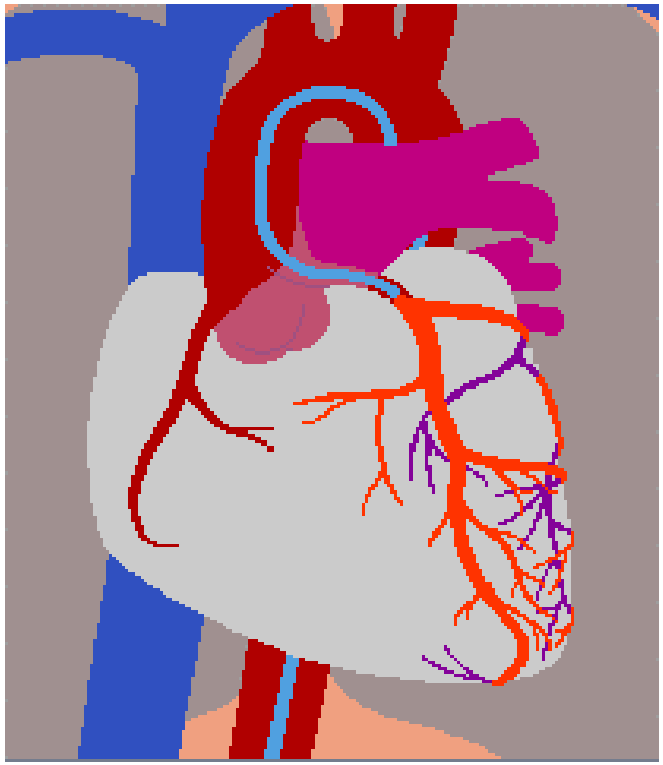
LAD
左前下行枝

冠動脈造影検査(Coronary Angio)

■冠動脈造影（CAG）



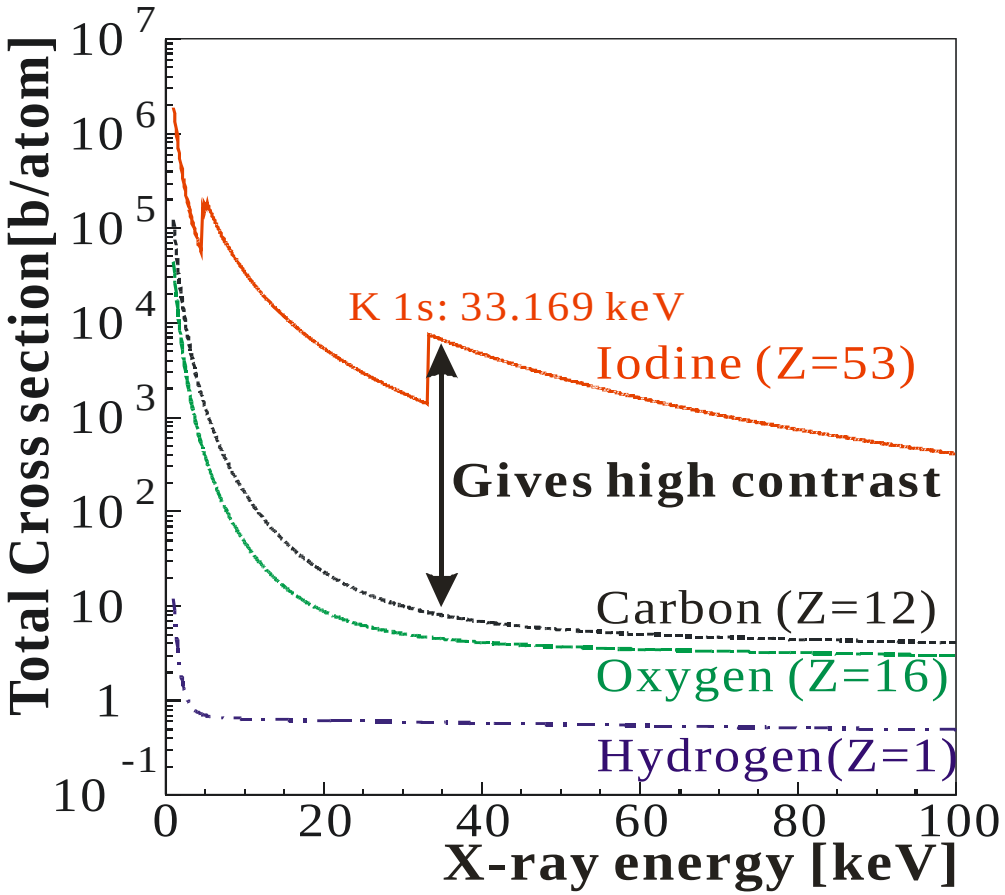
RAO/CRA



Dual Color and Subtraction Imaging

Total Cross Section of X-ray attenuation

for various elements



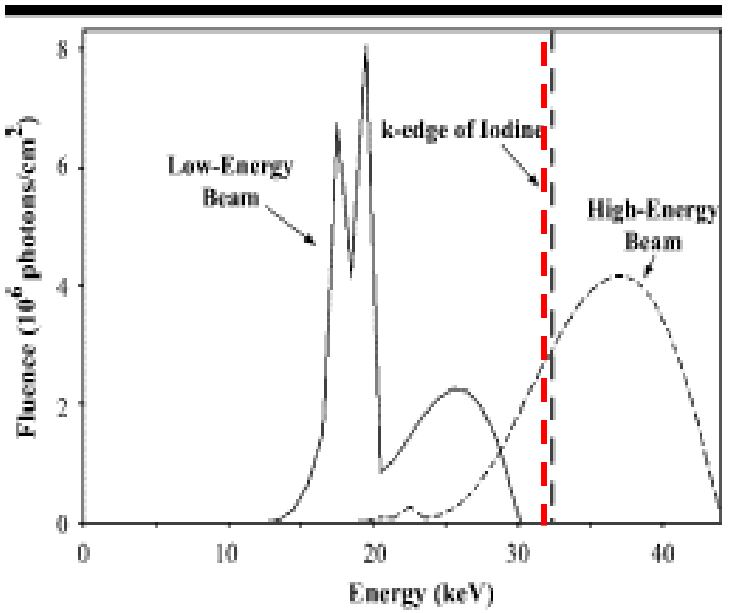
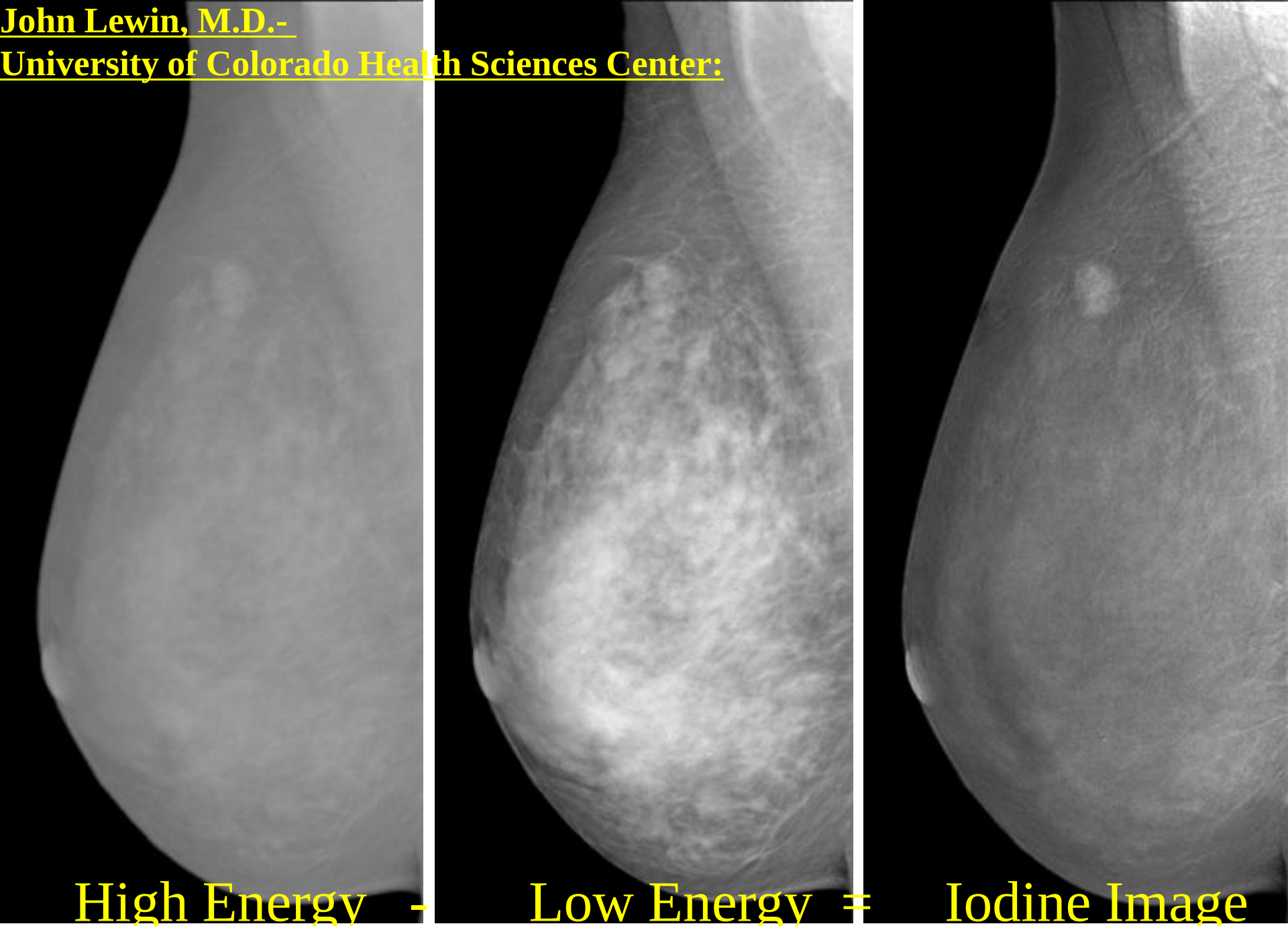
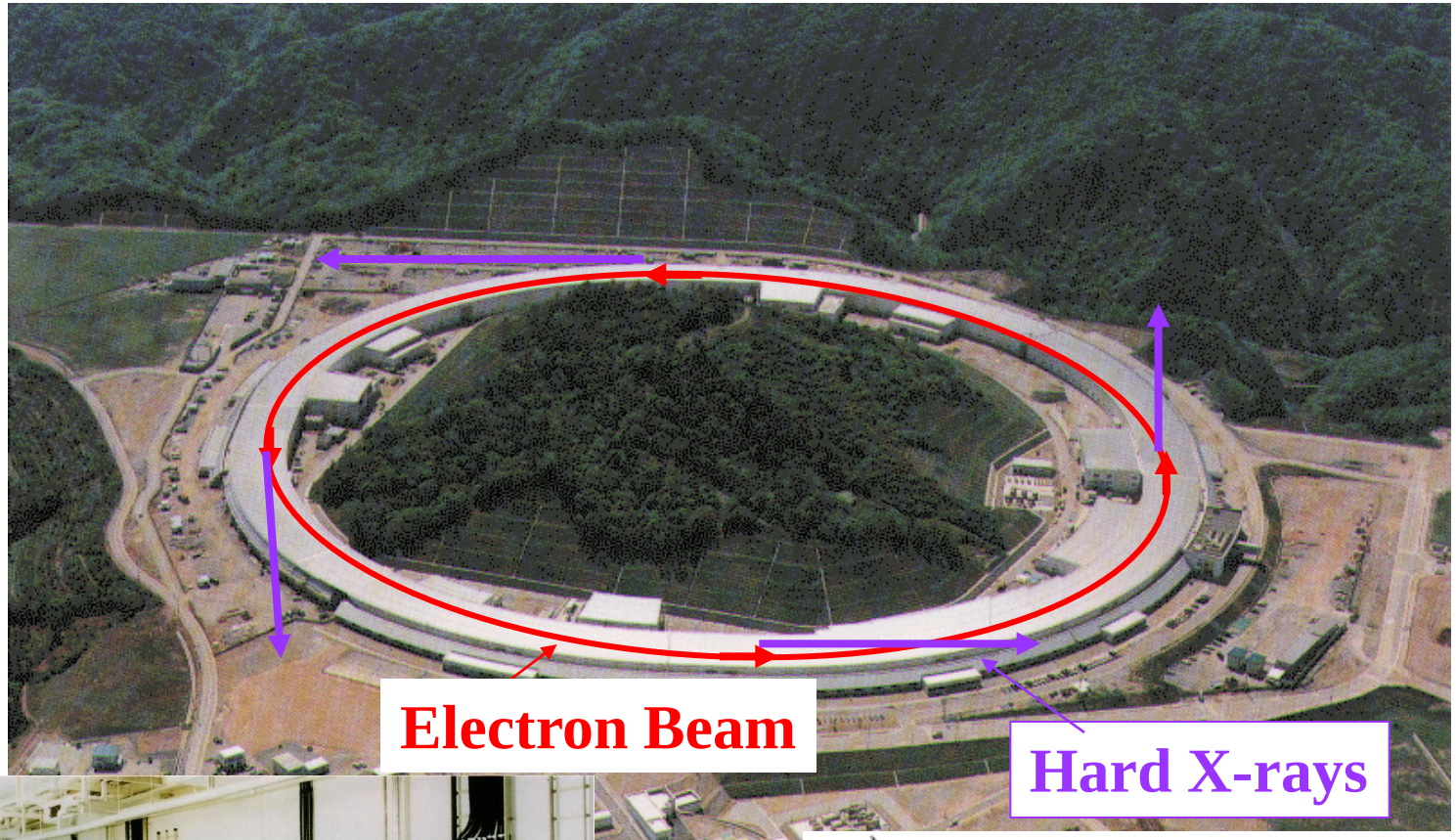


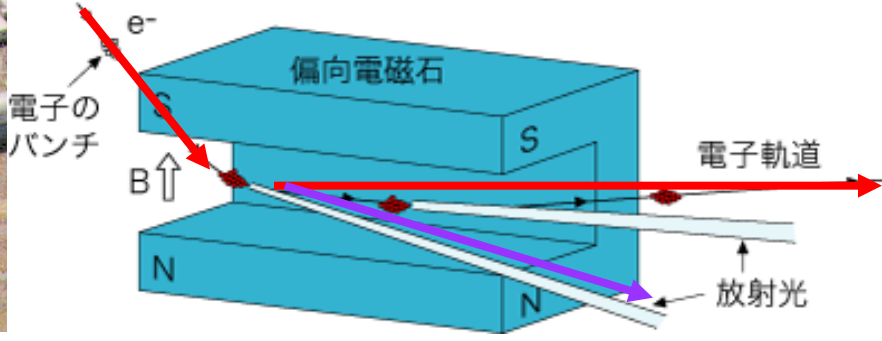
Figure 1. X-ray spectra calculated for high- and low-energy beams. Each curve is scaled to represent exposure through a 4.5-cm-thick 50% glandular–50% fat breast. High-energy parameters include 44 kVp, rhodium anode, 0.025-mm-thick rhodium and 8-mm-thick aluminum filters, and 200 mAs. Low-energy parameters include 30 kVp, molybdenum anode, 0.03-mm-thick molybdenum filter, and 140 mAs. The k edge of iodine, at 33.2 keV, is marked by a dashed line. (Modeling program courtesy of General Electric Corporate Research and Development, Niskayuna, NY.)

John Lewin, M.D.-
University of Colorado Health Sciences Center:



SPring-8 (Super Photon ring 8GeV)

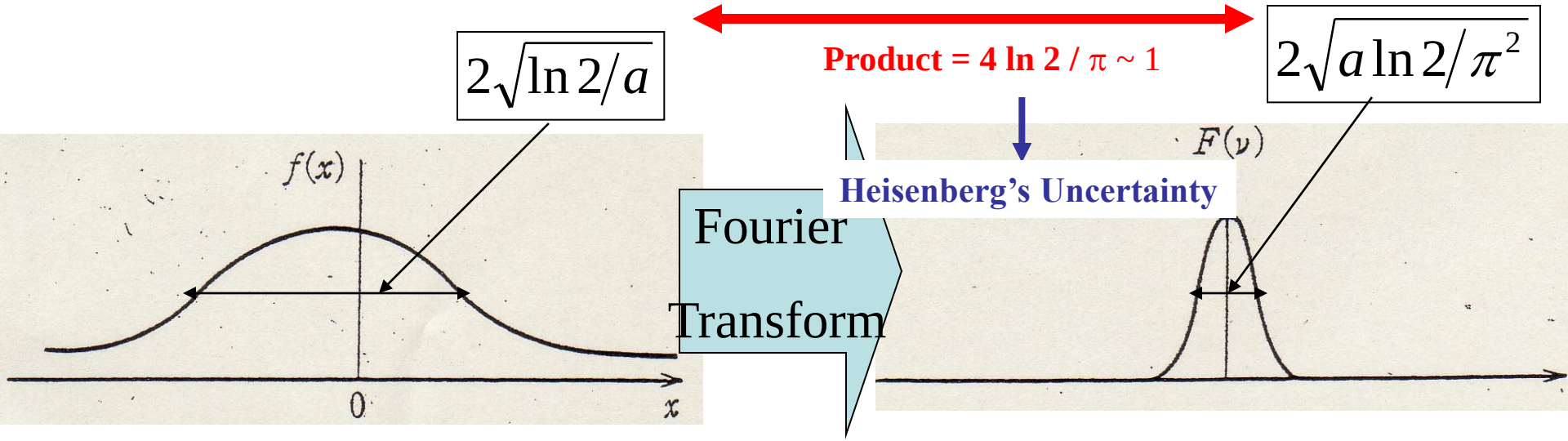




Fourier Transform

Fourier Transform: $F(\nu)=\int_{-\infty}^{\infty} f(x)\exp(-2i\pi\nu x)dx$ ——— (1)

Inverse Fourier Transform: $f(x)=\int_{-\infty}^{\infty} F(x)\exp(2i\pi\nu x)d\nu$ ——— (2)



Gaussian distribution

$f(x)=\exp(-ax^2)$

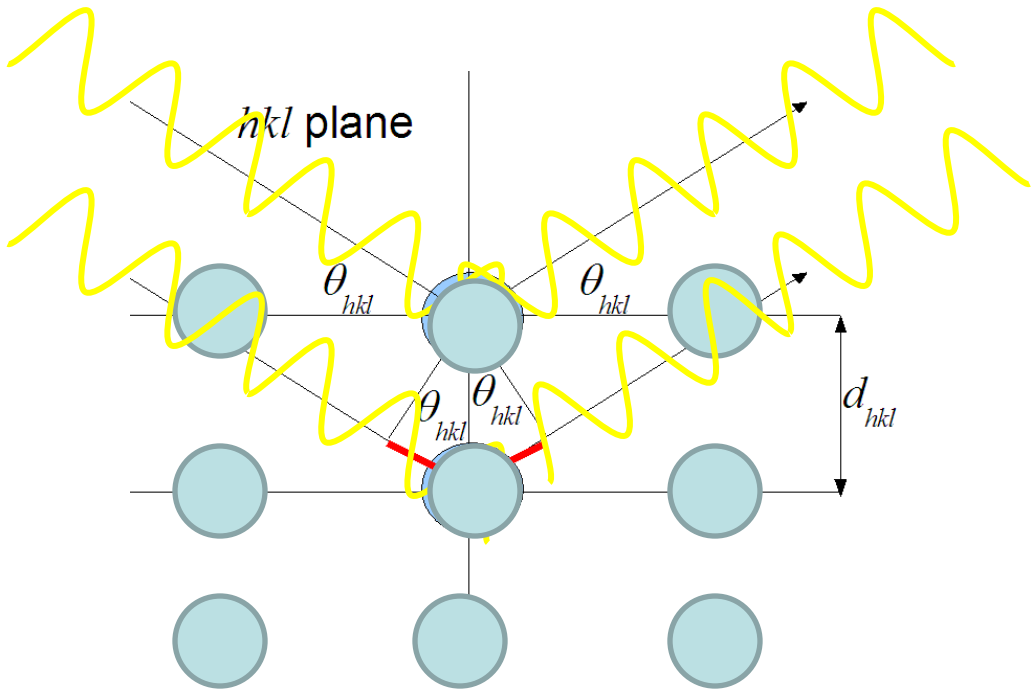
Gaussian distribution

$F(\nu)=\sqrt{\pi/a}\exp(-\pi^2\nu^2/a)$

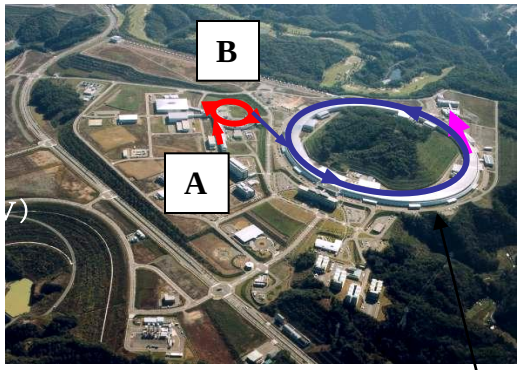
Silicon Mono-crystal Monochrometer

Bragg's Law

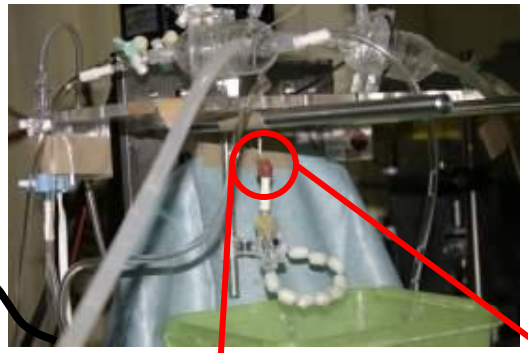
$$2d_{hkl}\sin\theta_{hkl} = n\lambda$$



An illustration of an experimental arrangement for synchrotron microangiography in rats



Langendorf



8GeV Electron Beam

Monochromatic X-Ray

object

Synchrotron radiation

Single-clystal monochromator

MI heart

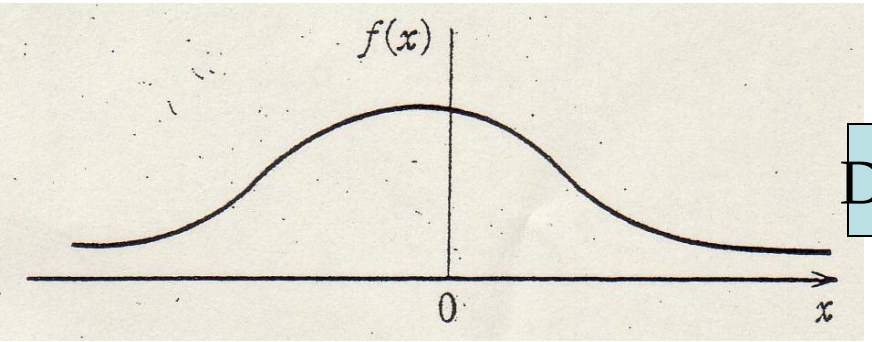
X-ray Shutter

X-Ray Saticon Camera

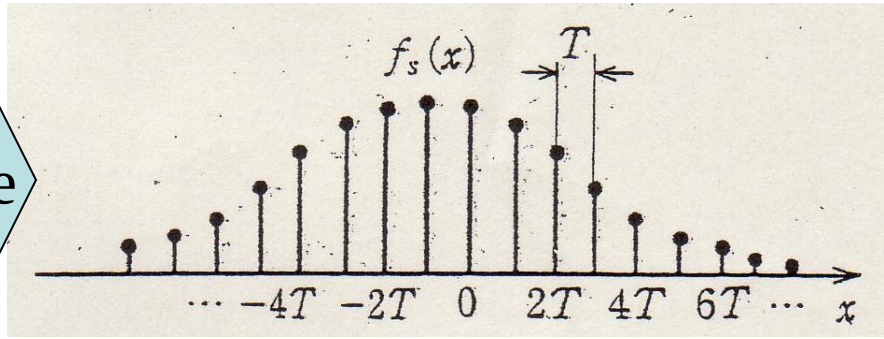
Discrete Fourier Transform（DFT）1

Discrete of the continuous function $f(x)$:

$$f_s(x) = f(x) \times \sum_{n=-\infty}^{\infty} \delta(x - nT)$$



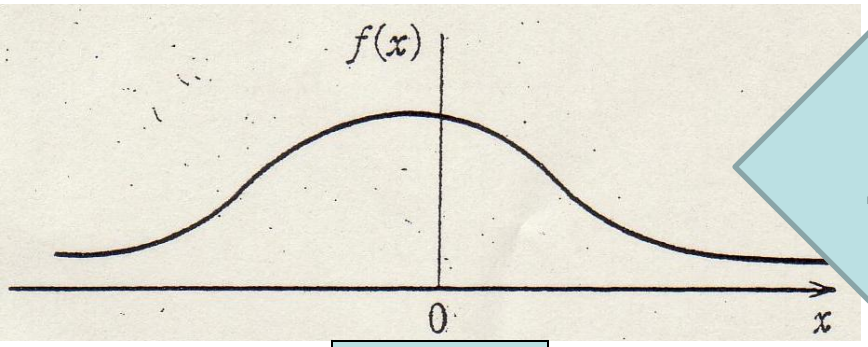
Discrete



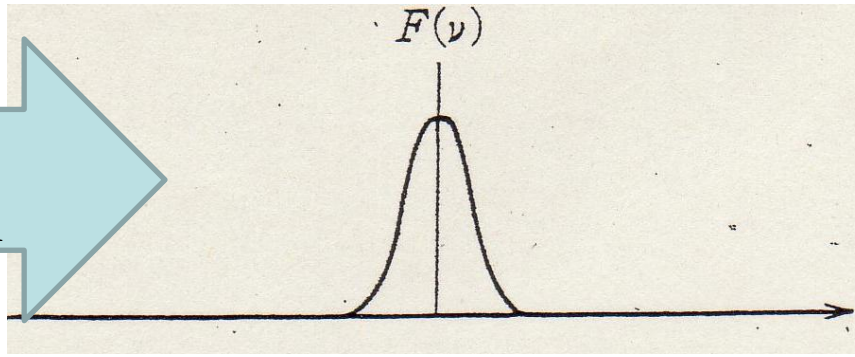
Gaussian distribution

Discrete Gaussian distribution

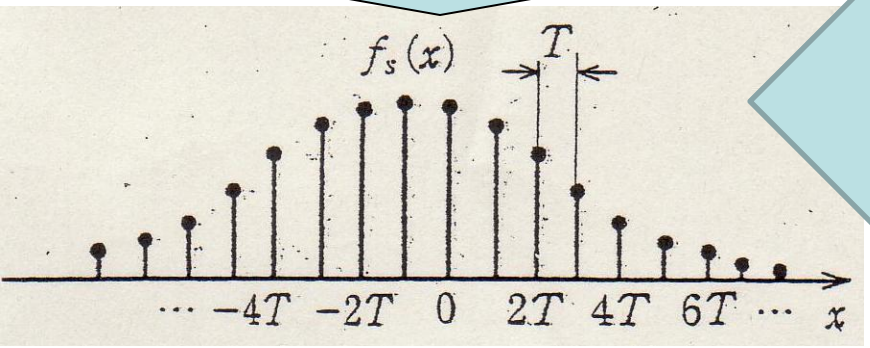
DFT



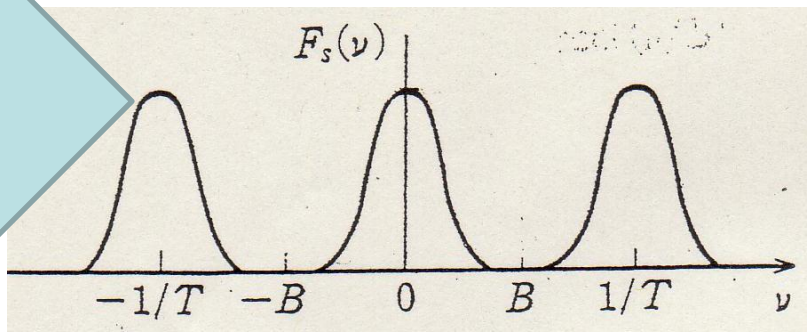
Fourier Transform

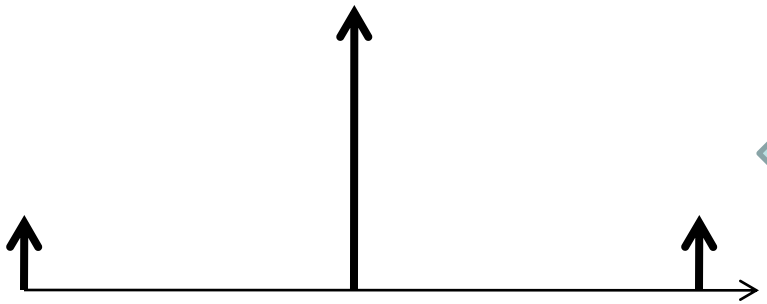


Discrete

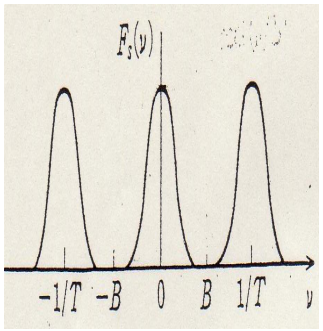


Fourier Transform

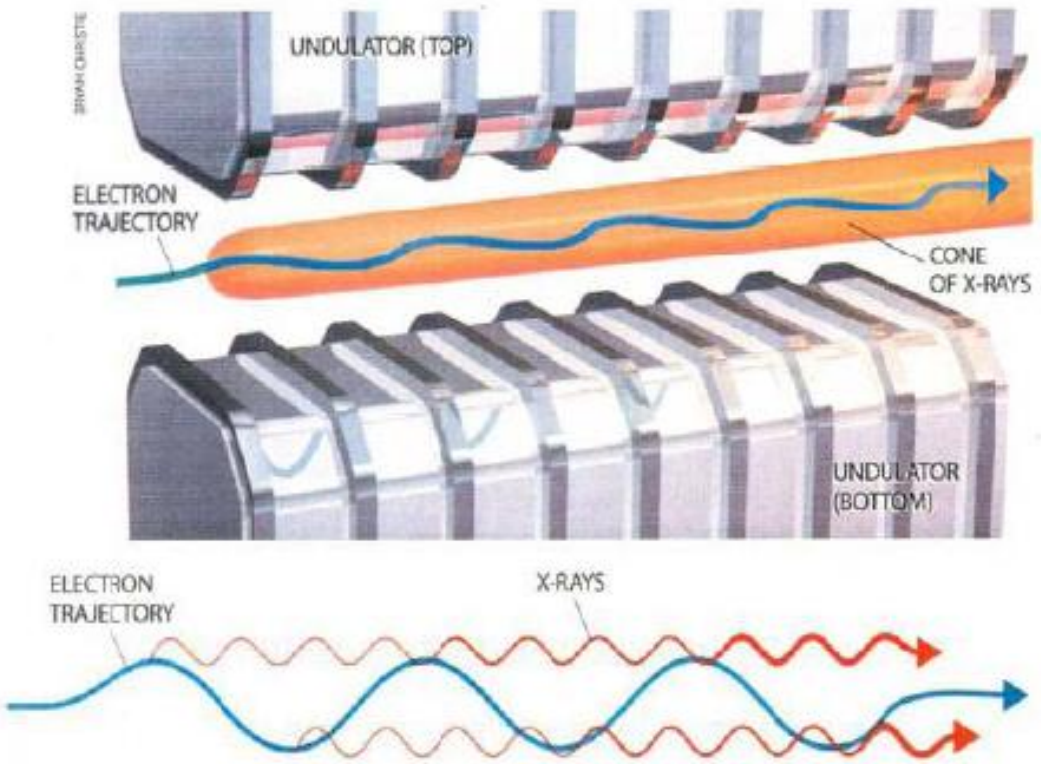




Fourier Transform



Undulators



$$T_{obs} = T_{emit}(1-\beta)$$

$$\lambda_{light} \approx \frac{\lambda_u}{2\gamma^2}$$

1st:parasitic to physical machine 2nd:specialized 3rd:X-ray source

Third Generation Light Sources in Operation

Poly-chromaticity, Mono-chromaticity, Coherence, Polarization vs Visibility and Resolution

Visibility and Resolution

Poly-chromatic/ In-coherent	X-ray tube(Bremsstrahlung) Synchrotron radiation (bending magnet)
Mono-chromatic/ In-coherent	Monochrometer Compton scattering
Mono-chromatic/ Coherent	Synchrotron radiation **(**Undulator**)**
Mono-chromatic/ Coherent/Polarization	Laser

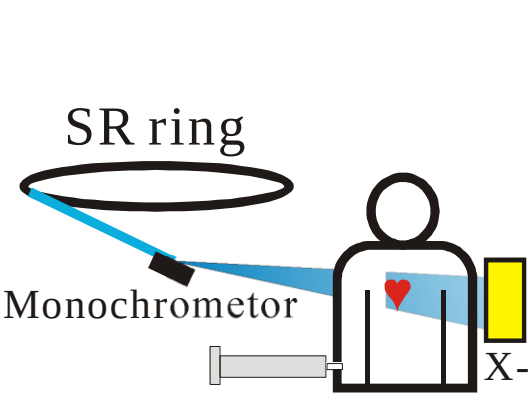
better

Dynamic Intravenous Coronary Arteriography (IVCAG) by SR

Clinical testing at KEK-AR ring by KEK & Tukuba Univ.

(check the progress after the treatment)

S. Otsuka et al. The British Journal of Radiology, 72(1999), 24-28



Intravenous injection

X-ray: 37kev, 10^{11} photons/s.

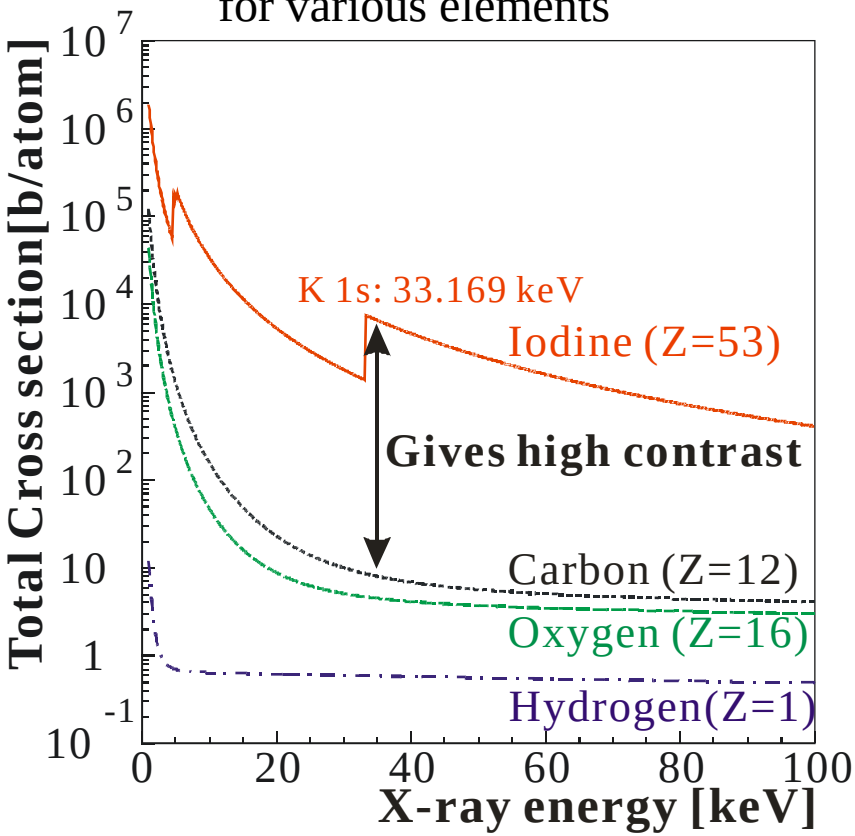
Intravenous injection of a contrast agent (20ml/2sec)

Area adopted X-ray: 150mm x 80mm.

(2.0×10^{10} photons mm^2/s at the patient)

Dynamic image with 30 shots/s.

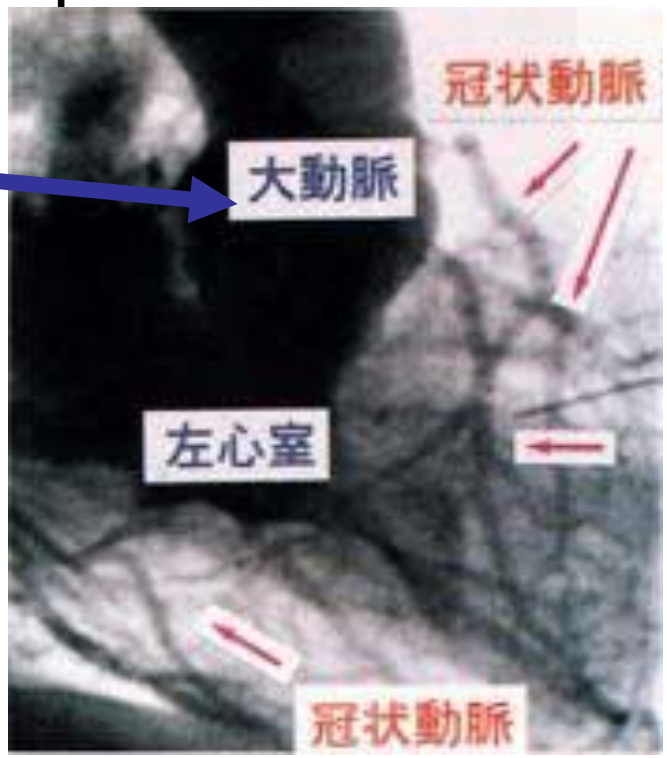
Total Cross Section of X-ray attenuation for various elements



Intravenous Dynamic Coronary arteriography(CAG)

- Injection of contrast agent via vein
- Use of monochromatic X-rays over 33 keV
- Dynamic inspection for about 40 patents so far

Main artery

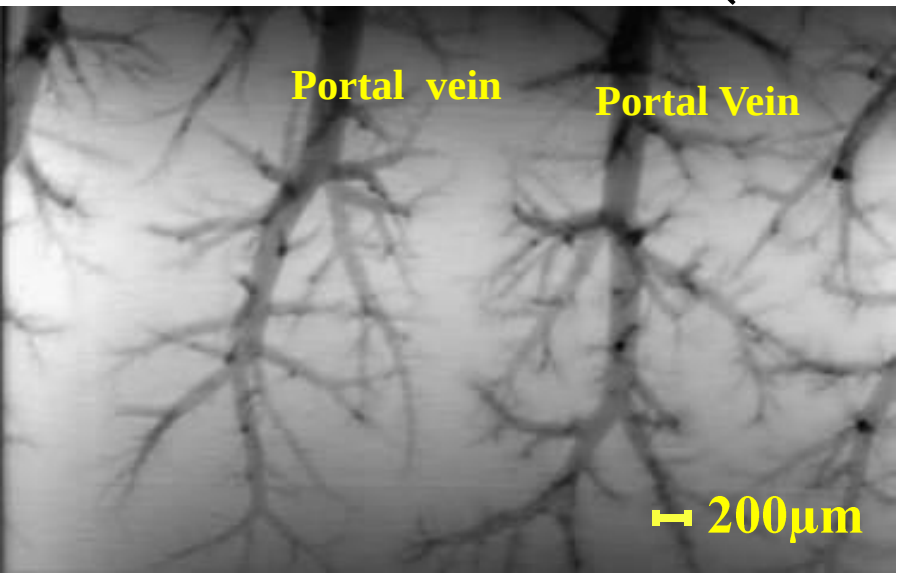


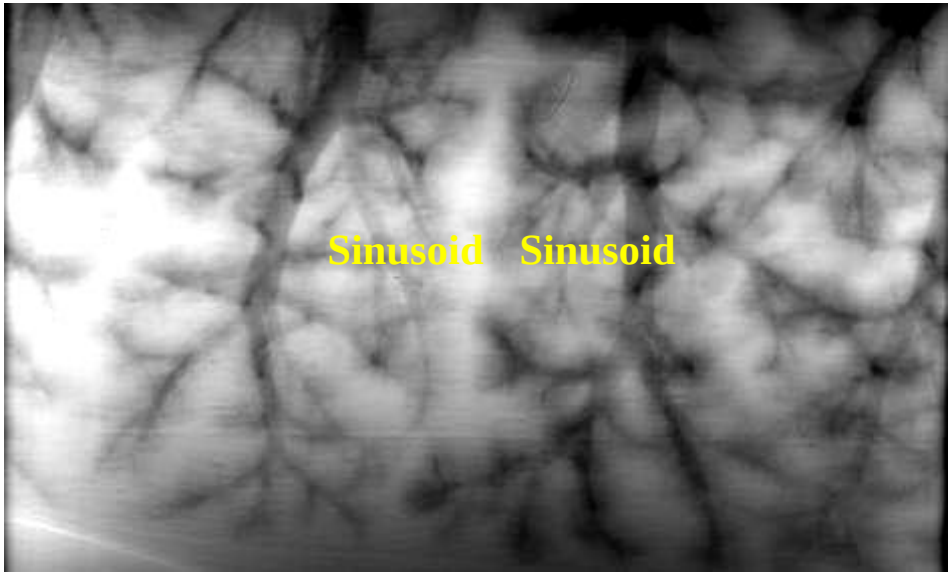
Left chamber

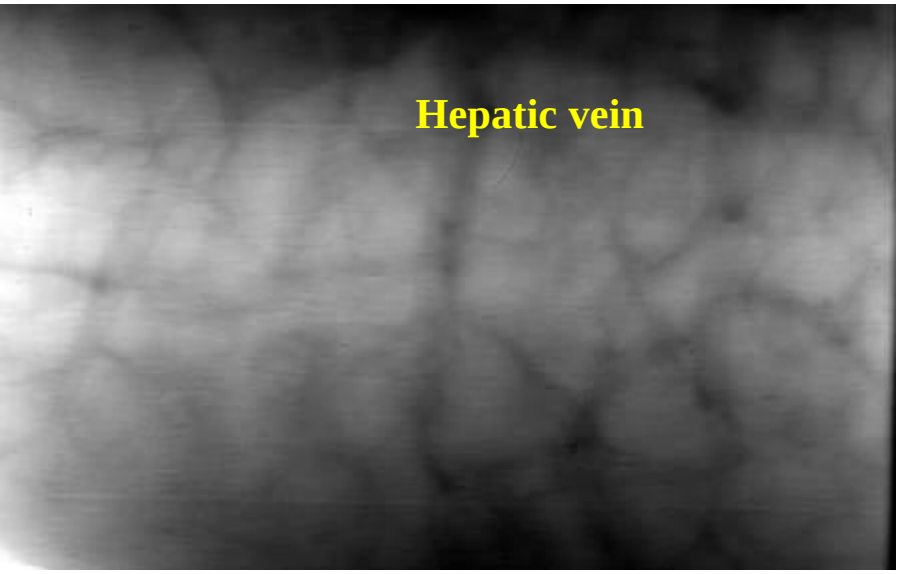
Coronary Arteries

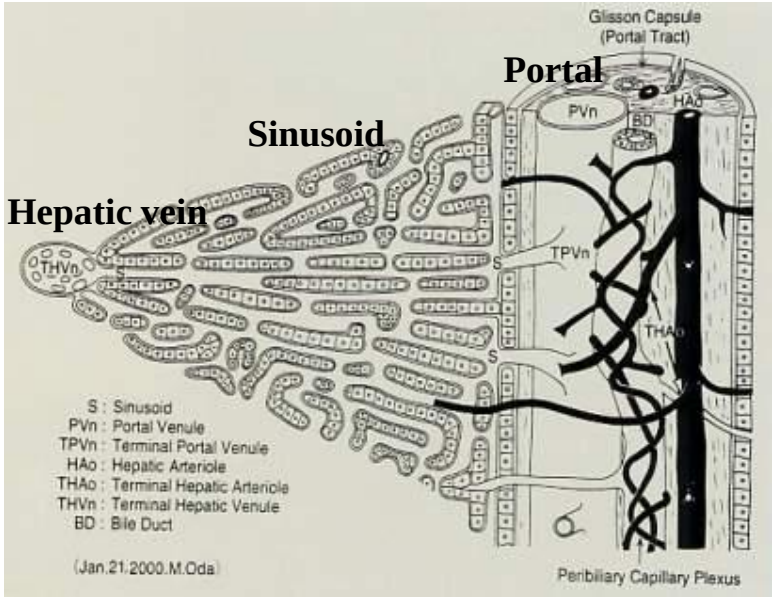
By Dr.Sadanori Ohtsuka
(Univ.Tsukuba Hospital)

Portal vein by SR microangiography (normal rat)







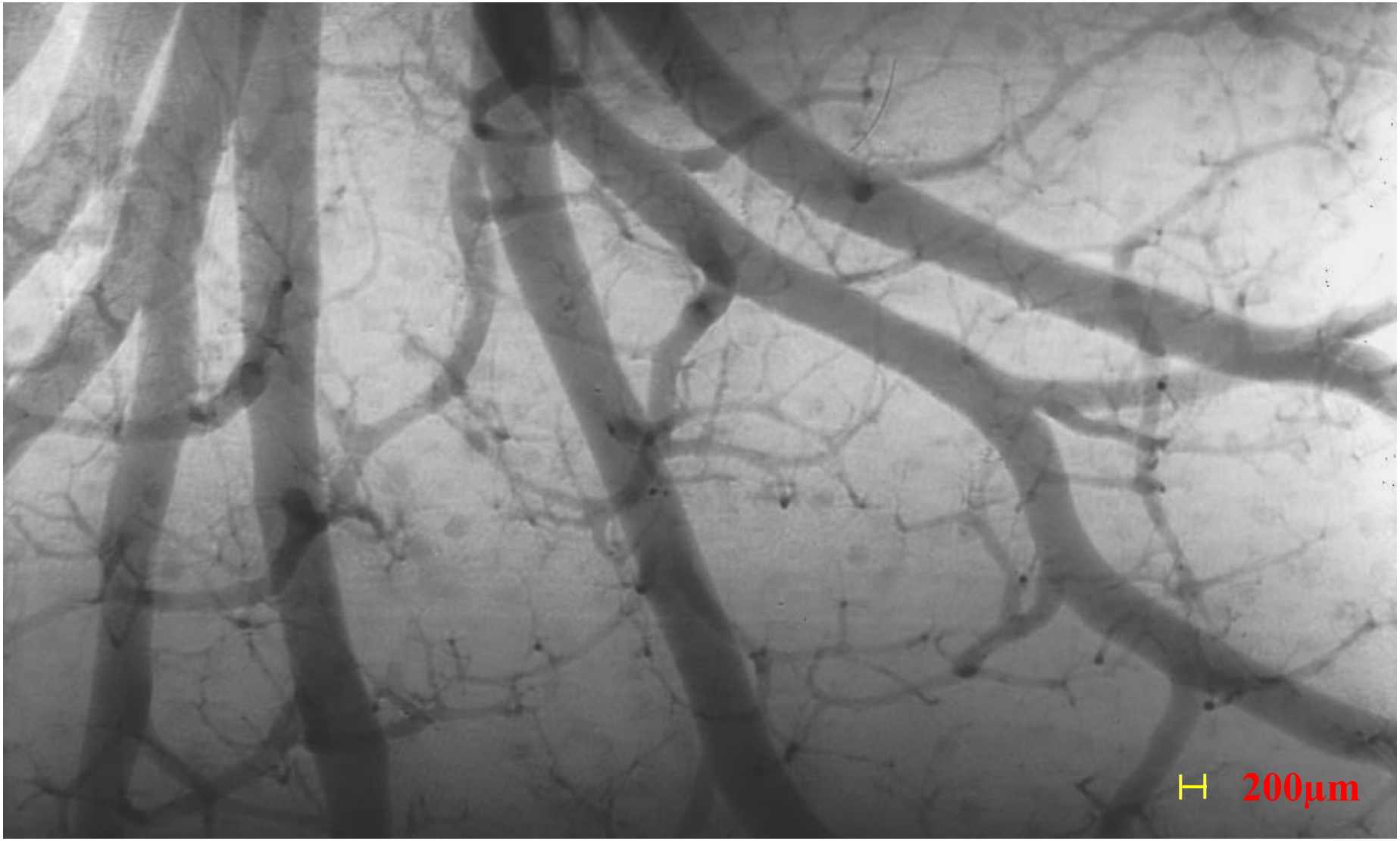


提供：国立循環器病センター　福島和人

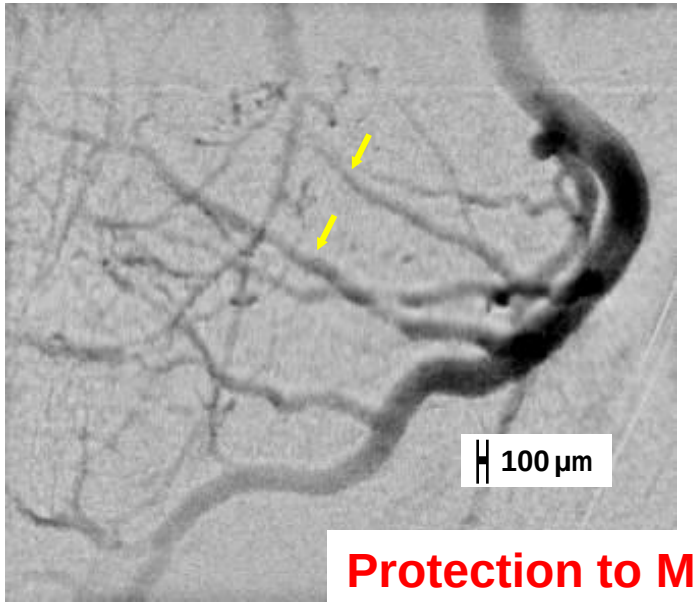
Renal artery by SR angiography（normal rat）

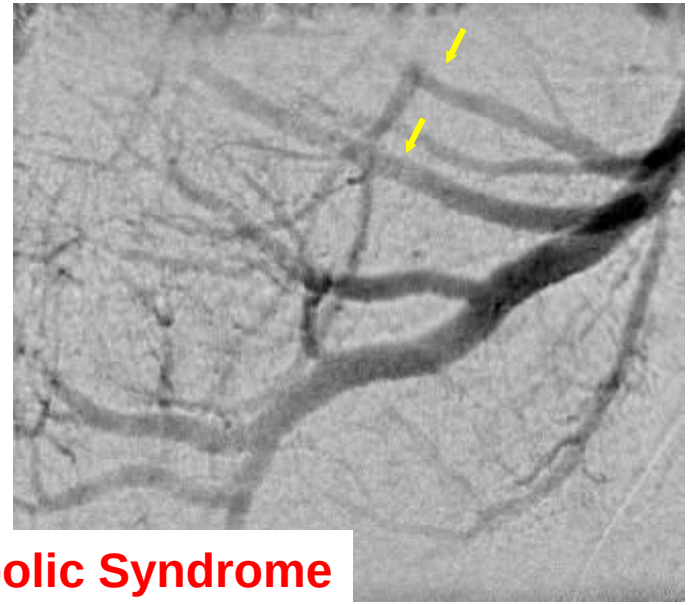
腎臓動脈

Dr.H.Mori, Dr.K.Fukushima
(National Cardiovascular Center)



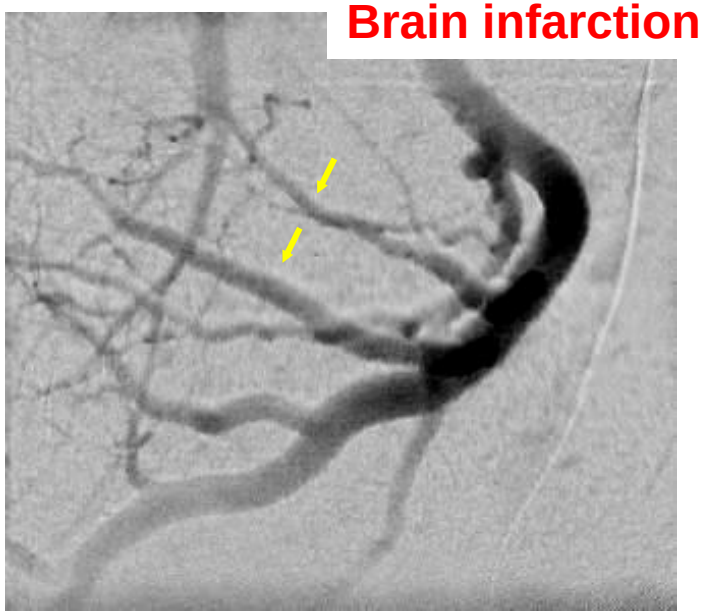
Detection of vessel size changes by drugs



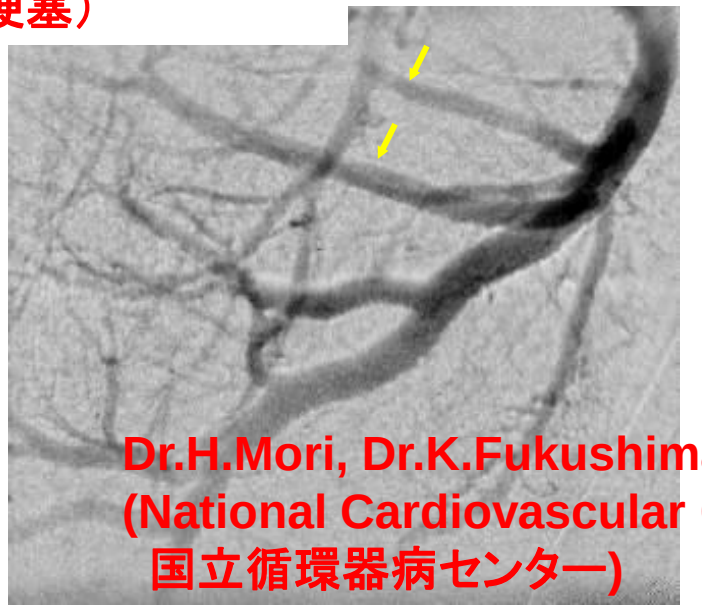


Bas e triphosphate

Protection to Metabolic Syndrome
Myccardinal infarction（心筋梗塞）
Brain infarction（脳梗塞）



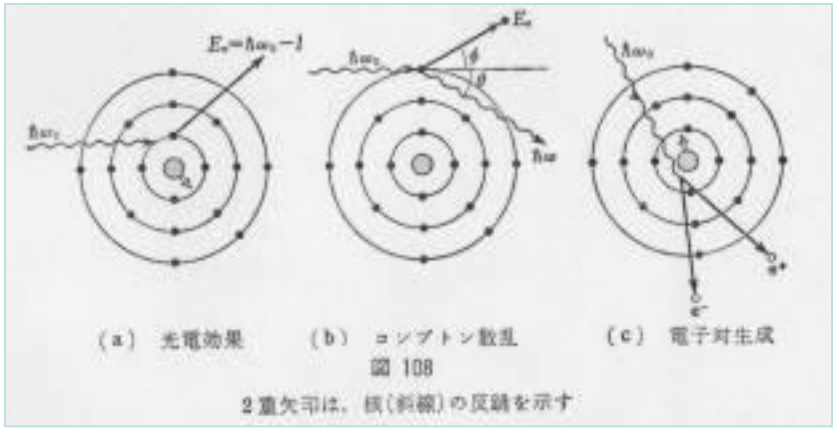
ACh: Acetylcholine

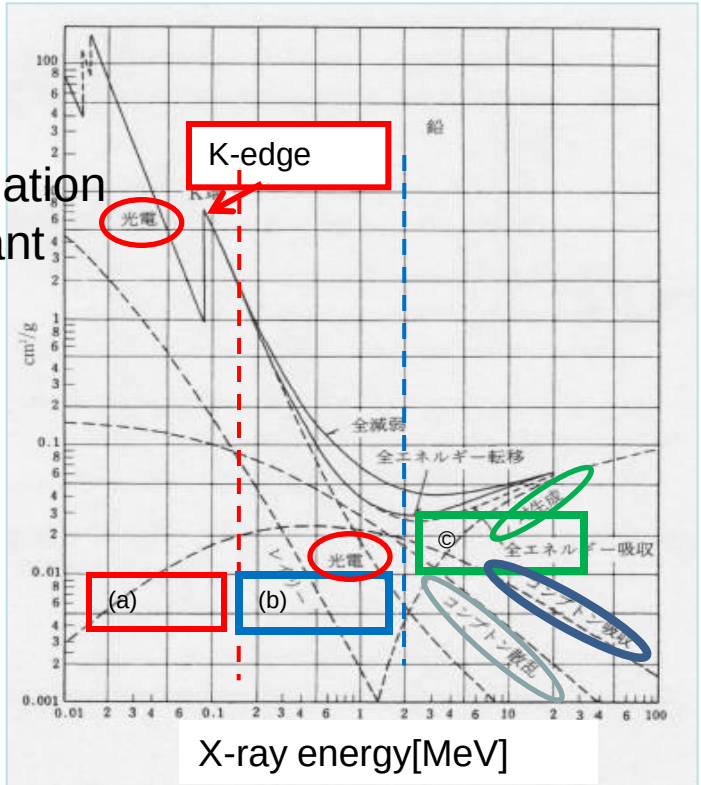


SNP: Sodium nitroprusside

Dr.H.Mori, Dr.K.Fukushima
(National Cardiovascular Center
国立循環器病センター)

Interaction of X-ray with Matter





Attenuation constant

(a) Photoelectric effect

X-ray is absorbed by atom and mainly K-shell electron is emitted. It is the main interaction in low energy (<1 MeV) region.

(b)Compton scattering/absorption

Injected X-ray is elastically scattered by bound electrons and its energy is reduced. The X-ray energy is almost equal to the binding energy.

(c) Electron/positron pair generation

If the X-ray energy is more than1.02MeV, it is converted to a pair of electron and positron via several strong influence of nuclear.

Dual Energy CT for 3D Distribution of Atomic-Number- and Electron Densitis for Lighter Atoms up to ^{43}Tc

Linear attenuation coefficient is approximately written as a function of Z and E

$$\mu \cong \rho \frac{N_A}{A} Z \left(4\sqrt{2} Z^4 \alpha^4 \left(\frac{mc^2}{E} \right) \phi_0 \sum_{nll'} f_{nll'} + \sigma_{KN} + \frac{Z\left(1 - Z^{b-1}\right)}{Z'^2} \sigma_{SC}^{coh}(Z', E') \right)$$

$$= \rho_e \left(Z^4 F(Z, E) + G(Z, E) \right)$$

ρ: mass density

N_A: Avogadro's number

σ_{KN}: Klein-Nishina cross section

σ_{SC}: Coherent scattering cross section of standard element Z'

Z'=8 (Oxgen) and $E'=(Z'/Z)^{1/3}E$

Effective atomic number and electron density are derived from linear attenuation coefficients for two energies

$$\mu(E_1) = \rho_e \left(Z^4 F(Z, E_1) + G(Z, E_1) \right)$$

$$\mu(E_2) = \rho_e \left(Z^4 F(Z, E_2) + G(Z, E_2) \right)$$

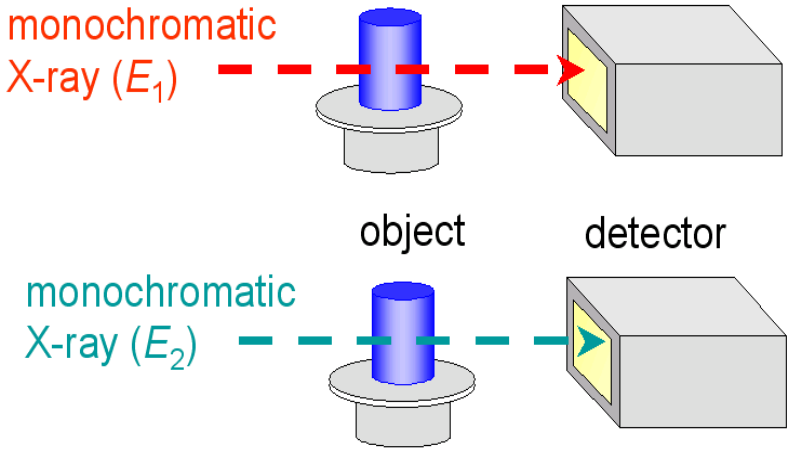
Effective atomic number

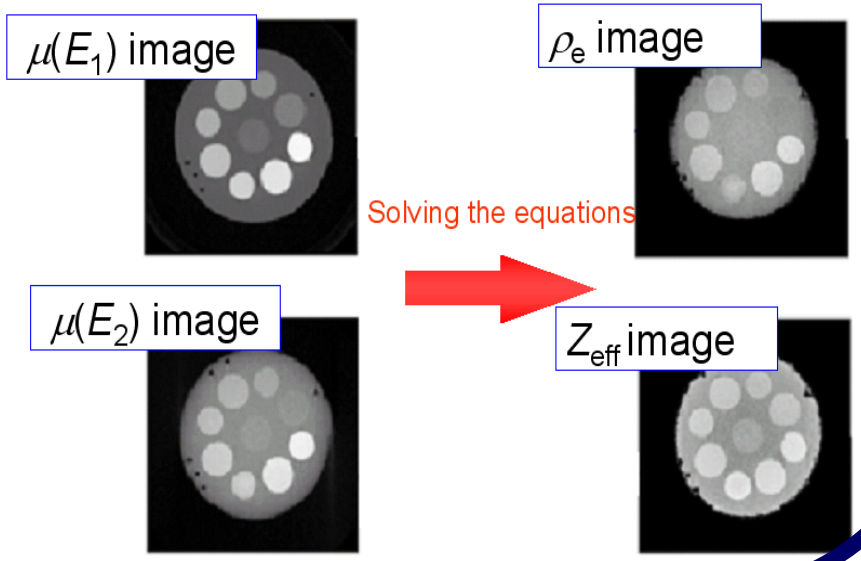
$$Z^4 = \frac{\mu(E_2) G(Z, E_1) - \mu(E_1) G(Z, E_2)}{\mu(E_1) F(Z, E_2) - \mu(E_2) F(Z, E_1)}$$

Electron density

$$\rho_e = \frac{\mu(E_1) F(Z, E_2) - \mu(E_2) F(Z, E_1)}{F(Z, E_2) G(Z, E_1) - F(Z, E_1) G(Z, E_2)}$$

Dual-energy X-ray CT experiment

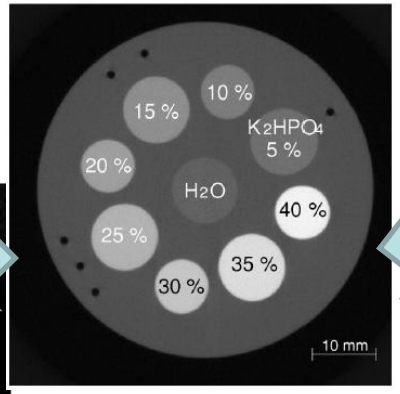




Torikoshi(NIRS), et al.

Result K_2HPO_4 リン酸水素ニカリウム

Sample : large



Electron density

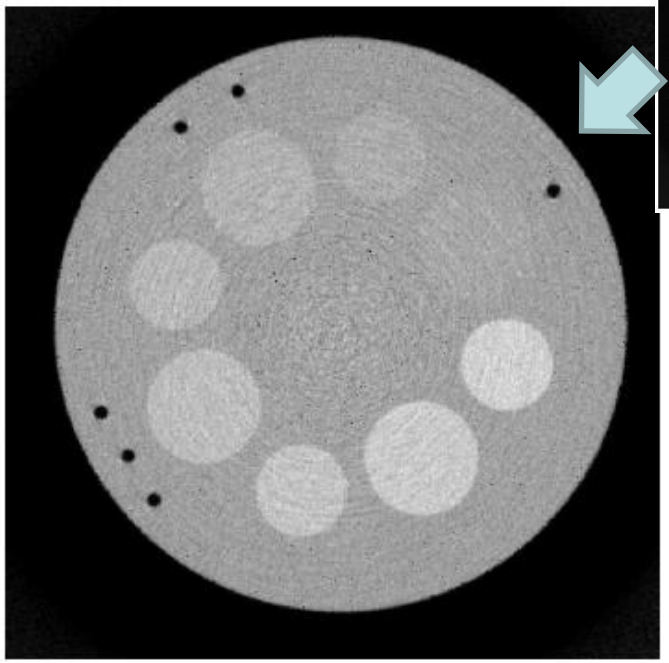


Fig. 3. The image consists of the electron densities. As the pixel color becomes brighter, the electron density becomes higher. The image was displayed with the grayscaling from 0 to 5×10^{23} cm^3.

水や濃度の薄いものの識別は難しい
→容器のポリエチレンと水の電子密度の差が3%しかないため

Effective atomic number

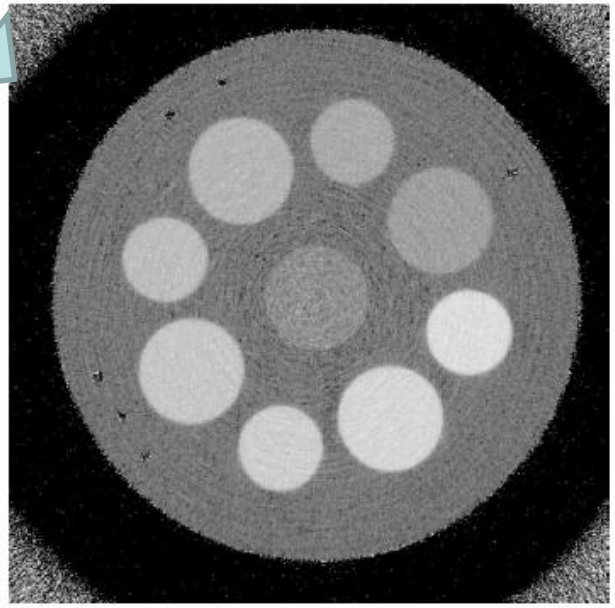


Fig. 4. The image consists of the effective atomic number. As the pixel color becomes brighter, the effective atomic number becomes higher. The image was displayed with the grayscaling from 0 to 15.

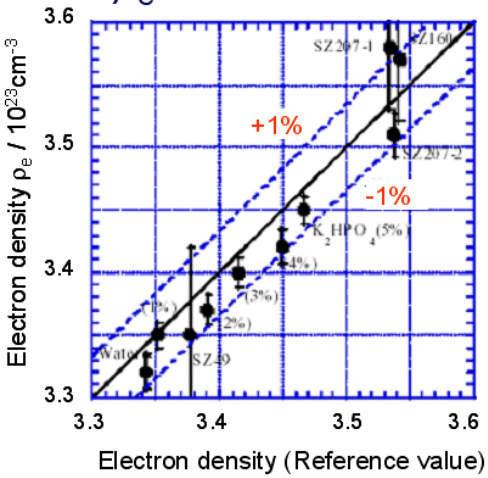
水やどの濃度でも比較的はっきりと識別
→容器のポリエチレンと水の実効原子番号では5.56と7.54と差があるため

論文4：T. Tsunoo et.al “Distribution of Electron Density Using Dual-Energy X-Ray CT”

Dual-energy X-ray CT by SR light sources

Electron density and atomic number have been measured for biological materials consist of light elements ($Z \leq 20$) [1,2]

ρ_e measurement



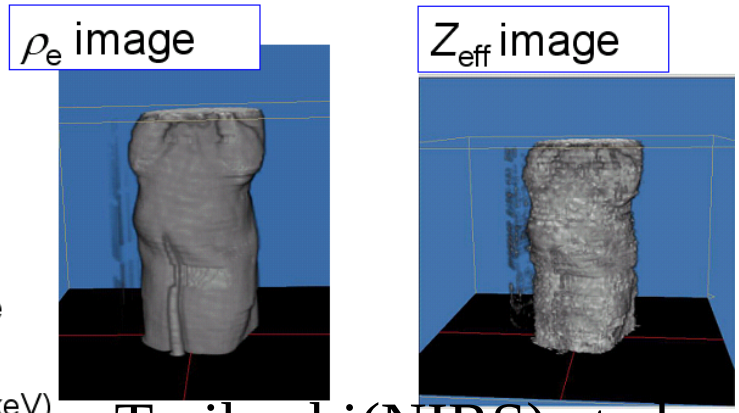
Precise electron density can be measured in agreement with 1 % of the theoretical values

(X-ray energy : 40 keV, 70 keV)

Volume data of a rat are constructed

(X-ray energy : 40 keV, 70 keV)

Volume rendering of a rat



Torikoshi(NIRS) et al.

Dual-energy CT for atomic number identification in a material

Can we apply the method to medium *Z* elements?

- The dual-energy analysis cannot be used below K-edge energy of a atom
- When maximum X-ray energies are 21.9 keV and 43.8 keV, elements up to Z = 38 should be identified
- Energy spread $\Delta E/E$ of the monochromatic X-ray

  SR light :10^{-1} – 10^{-2} % (negligible), Compact X-ray source : 1 to 10%

Numerical simulation to examine applicability

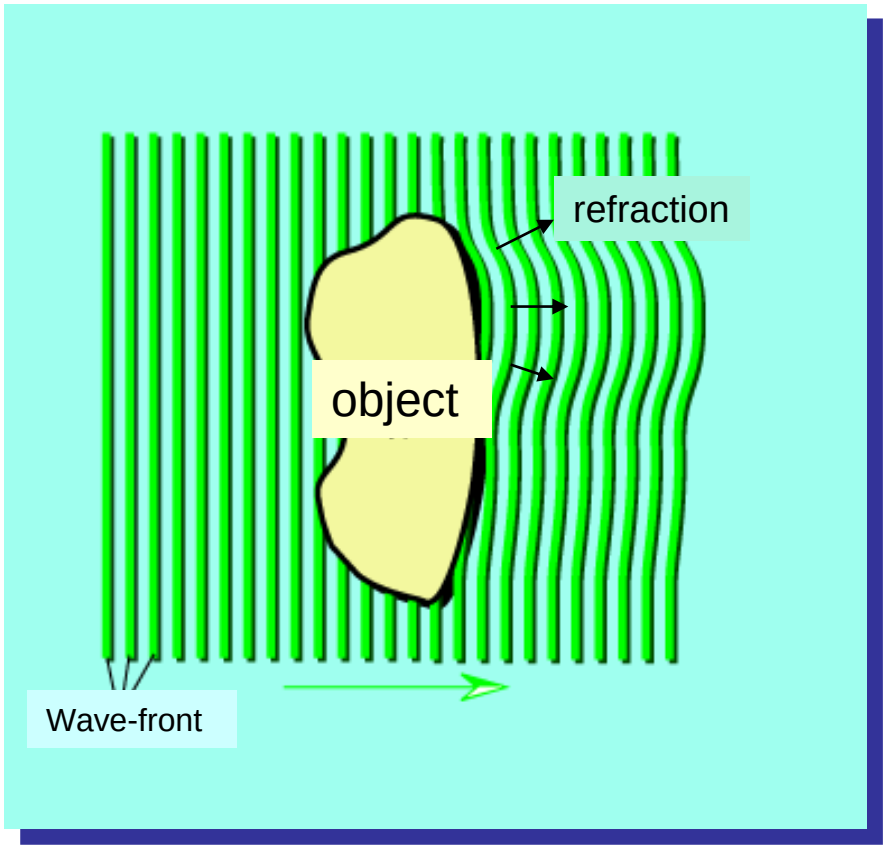
Poly-chromaticity, Mono-chromaticity, Coherence, Polarization vs Visibility and Resolution

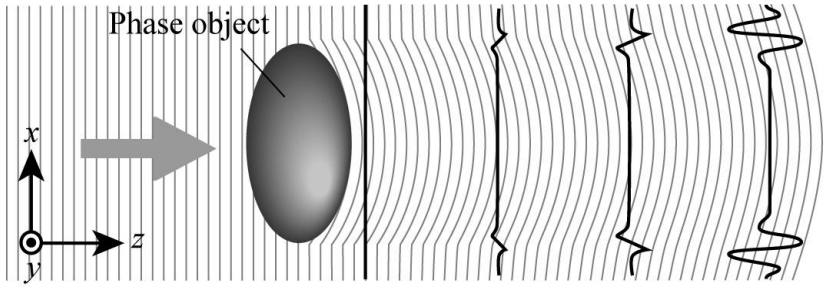
Visibility and Resolution

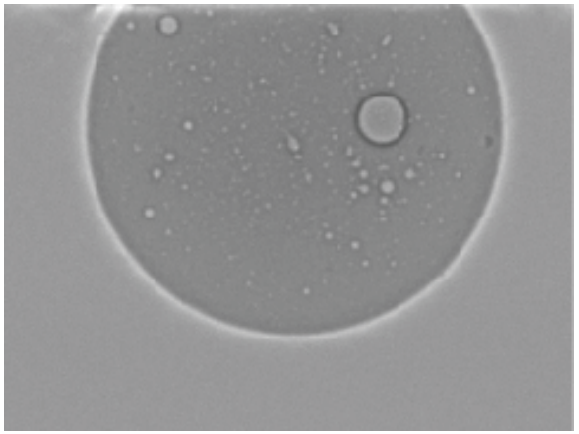
Poly-chromatic/ In-coherent	X-ray tube(Bremsstrahlung) Synchrotron radiation (bending magnet)
Mono-chromatic/ In-coherent	Monochrometer Compton scattering
Mono-chromatic/ Coherent	Synchrotron radiation **(**Undulator**)**
Mono-chromatic/ Coherent/Polarization	Laser

better

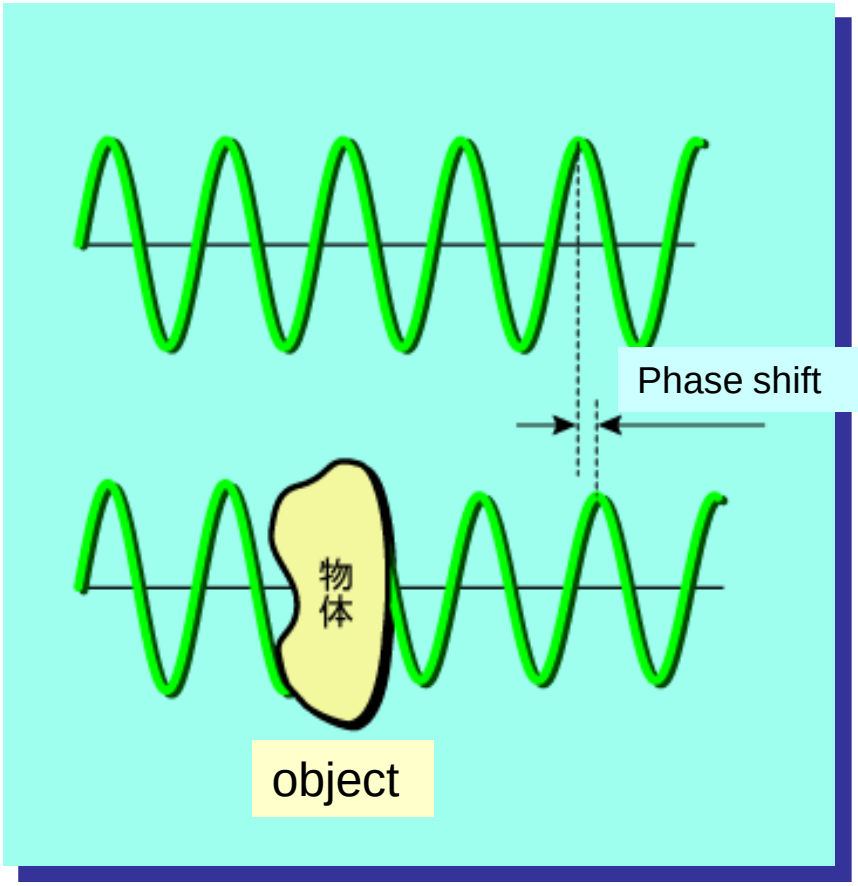
Phase shift and refraction







amplitude attenuation and phase shift



- Amplitude attenuate by object absorbance
- Phase shift by the difference of wave transmission velocity in material

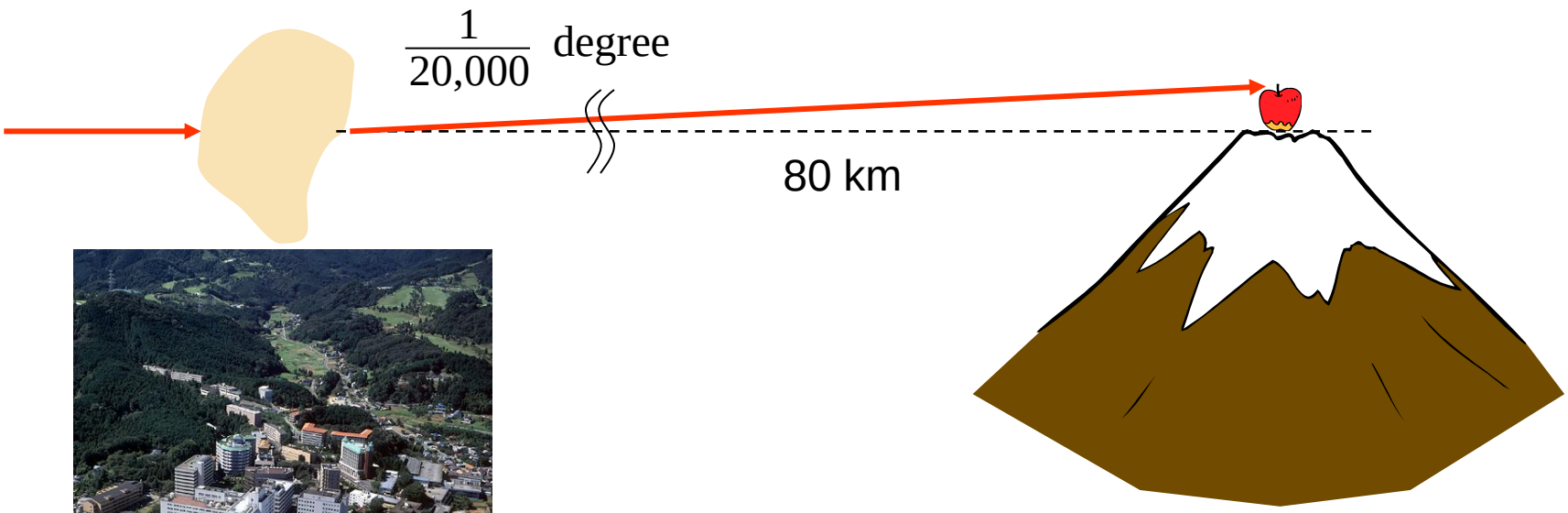
$$\text{Refractive index} = \frac{\text{wave transmission velocity in material}}{\text{wave transmission velocity in vacuum}}$$

Amplitude attenuation → absorbance contrast

Phase shift → phase contrast
refraction contrast

Refracting angle of X-ray

Refractive index: $1 - \delta$ $\delta \sim 10^{-6}$

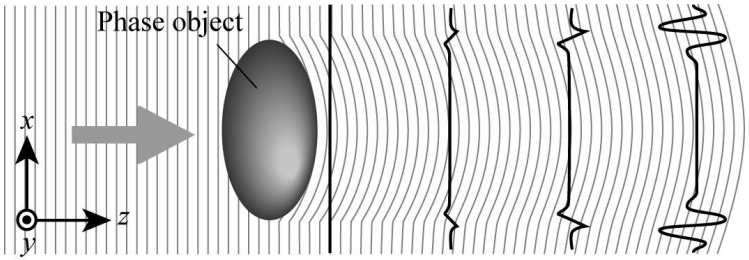


It is difficult to detect X-ray refraction from displacement of beam directly !

Method for generating X-ray phase contrast

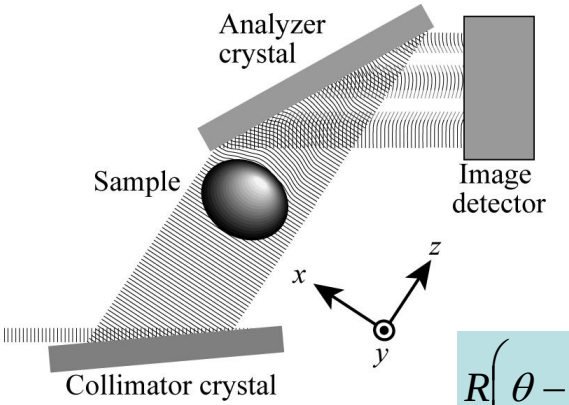
Φ : phase shift

Propagation-based method



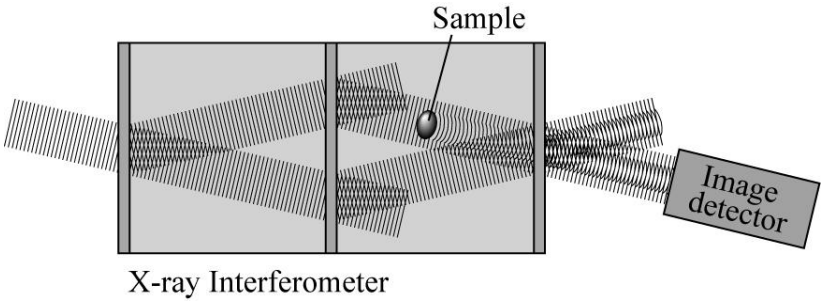
$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2}$$

Analyzer-based method



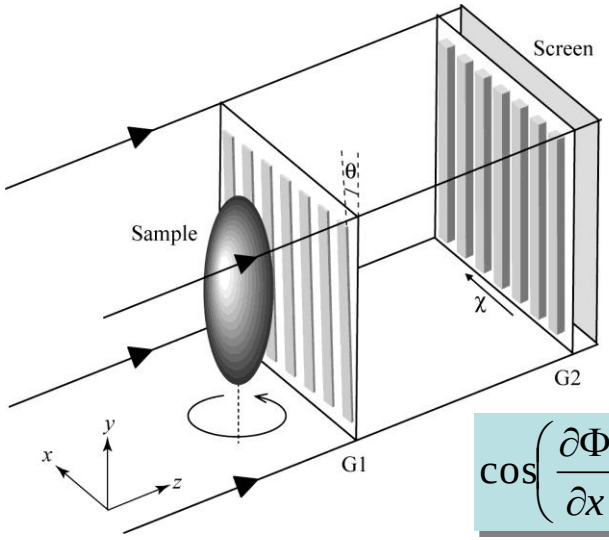
$$R\left(\theta - \frac{\partial \Phi}{\partial x}\right)$$

Interferometric method



$$\cos\Phi$$

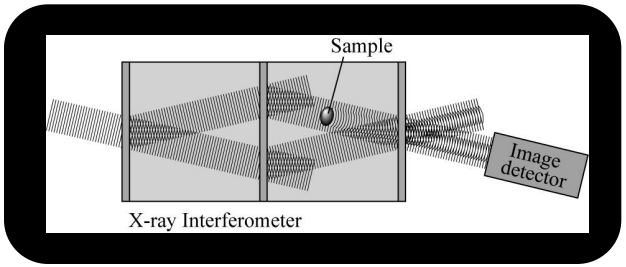
Differential-interferometric method

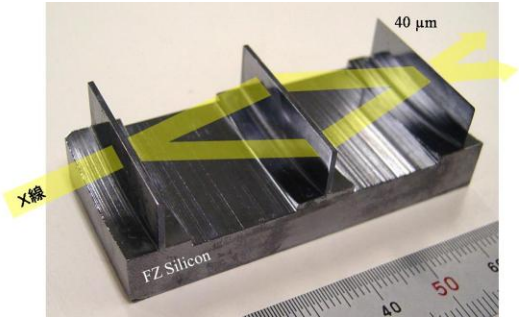


$$\cos\left(\frac{\partial \Phi}{\partial x}\right)$$

Application used interferometric method①

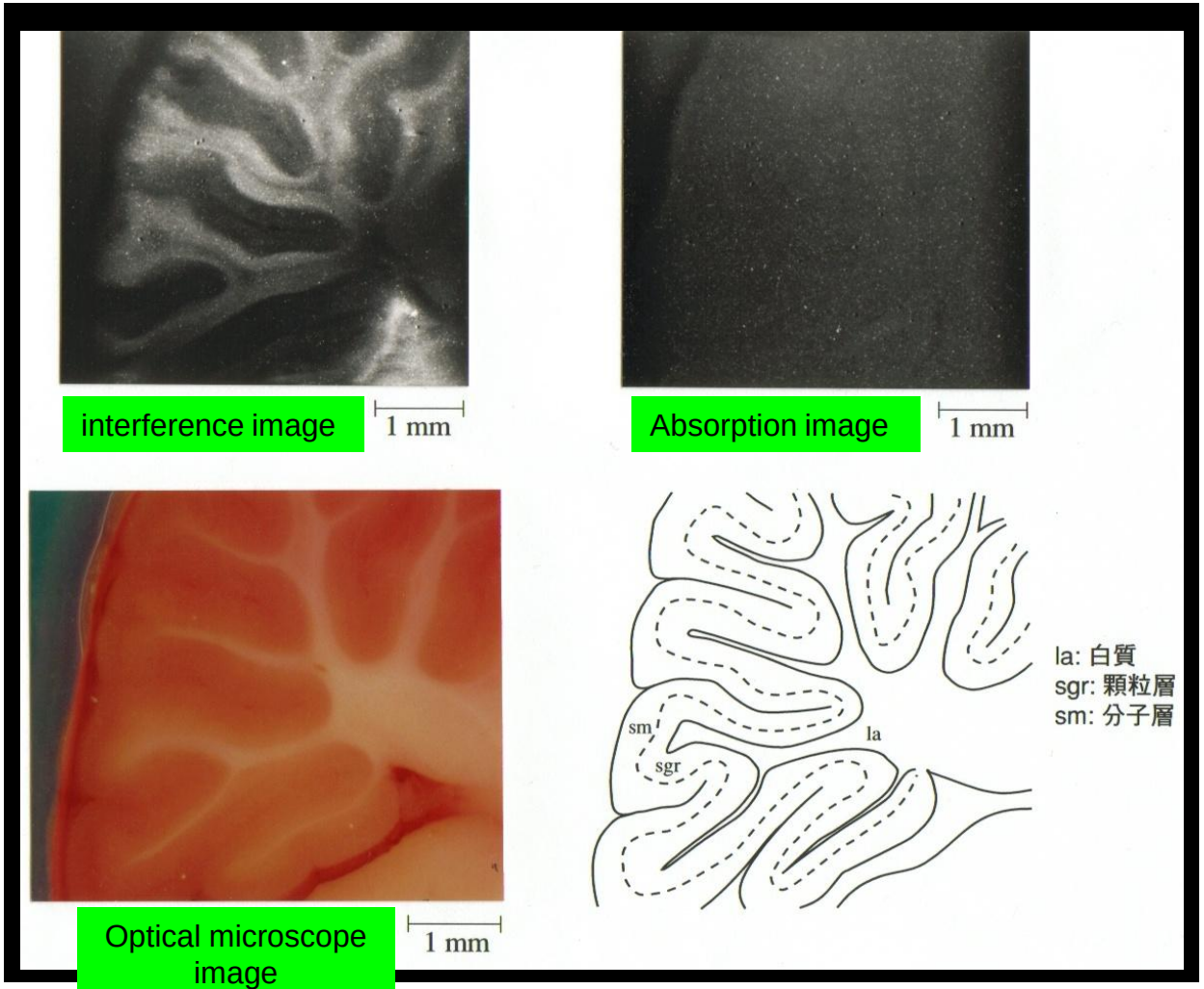
A. Momose & J. Fukuda, *Med. Phys.* 22 (1995) 375



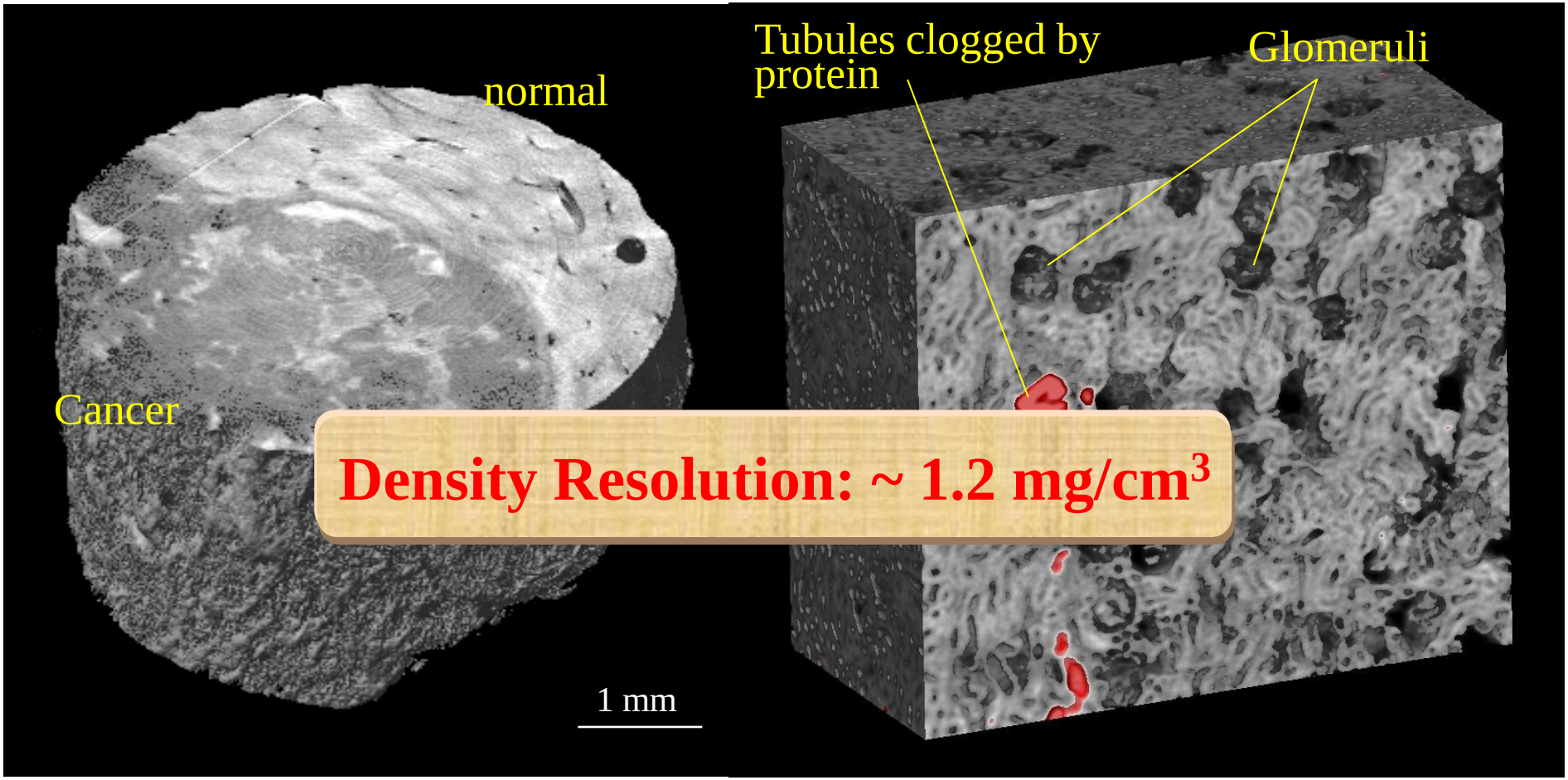


X-ray interferometer

Slice of rat cerebellum（小脳）
（1mm thickness）
@ 12.4 keV



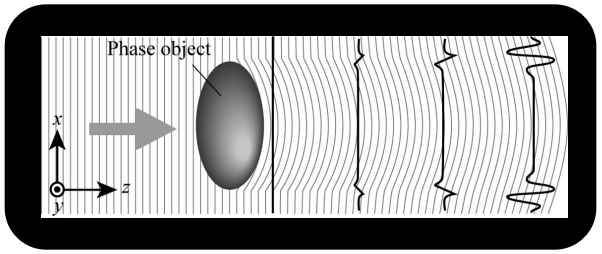
Biological Imaging by X-ray Phase Tomography



Rabbit liver

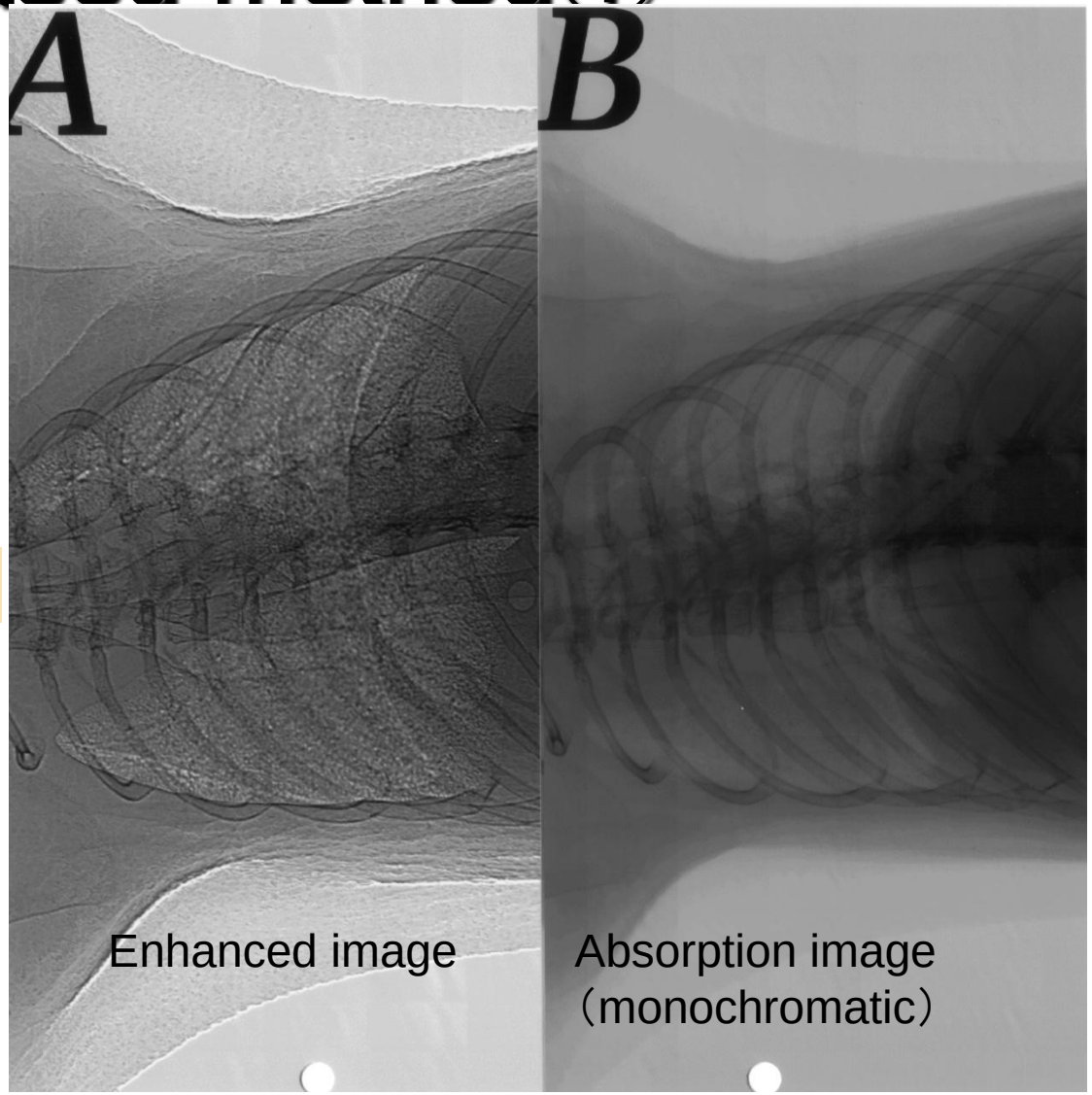
Rat kidney（腎臓）

Application used propagation-based method①



nude mouse chest

28.8 keV SR



N. Yagi *et al.*
Med. Phys. **26** (1999) 2190.

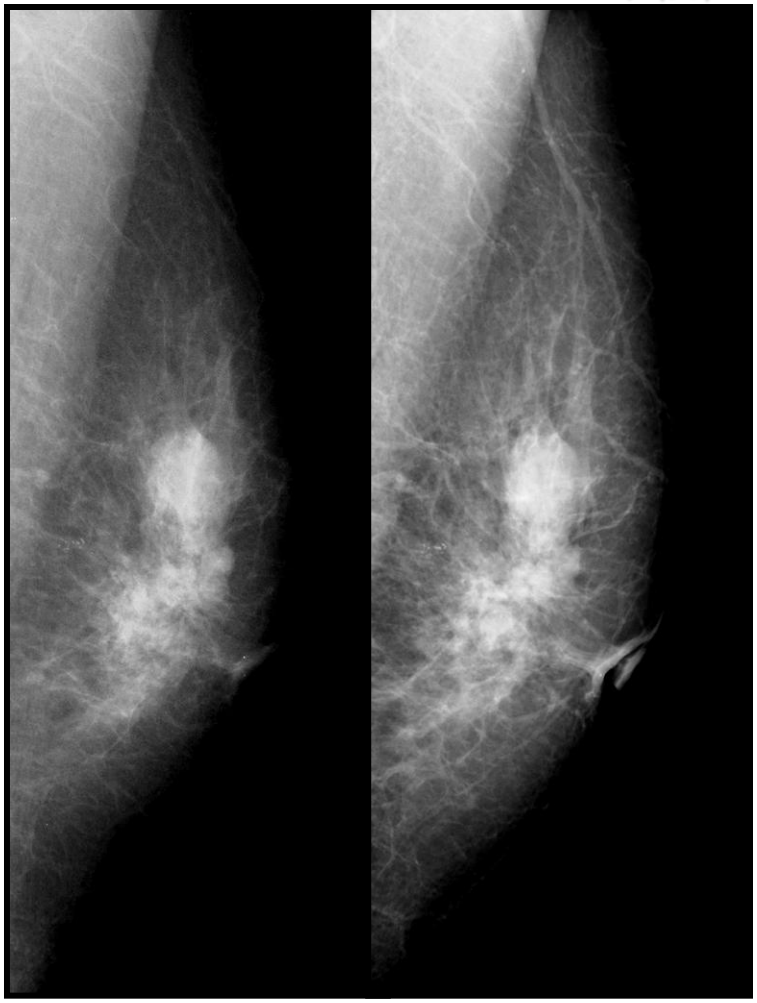
Application used propagation-based method ②

PCM　—コニカミノルタ㈱—

Breast Cancer-1

65 years old

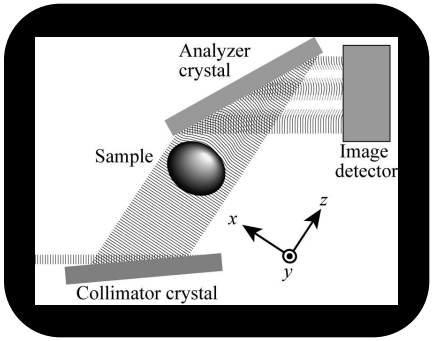
28kVp, Mo-filter



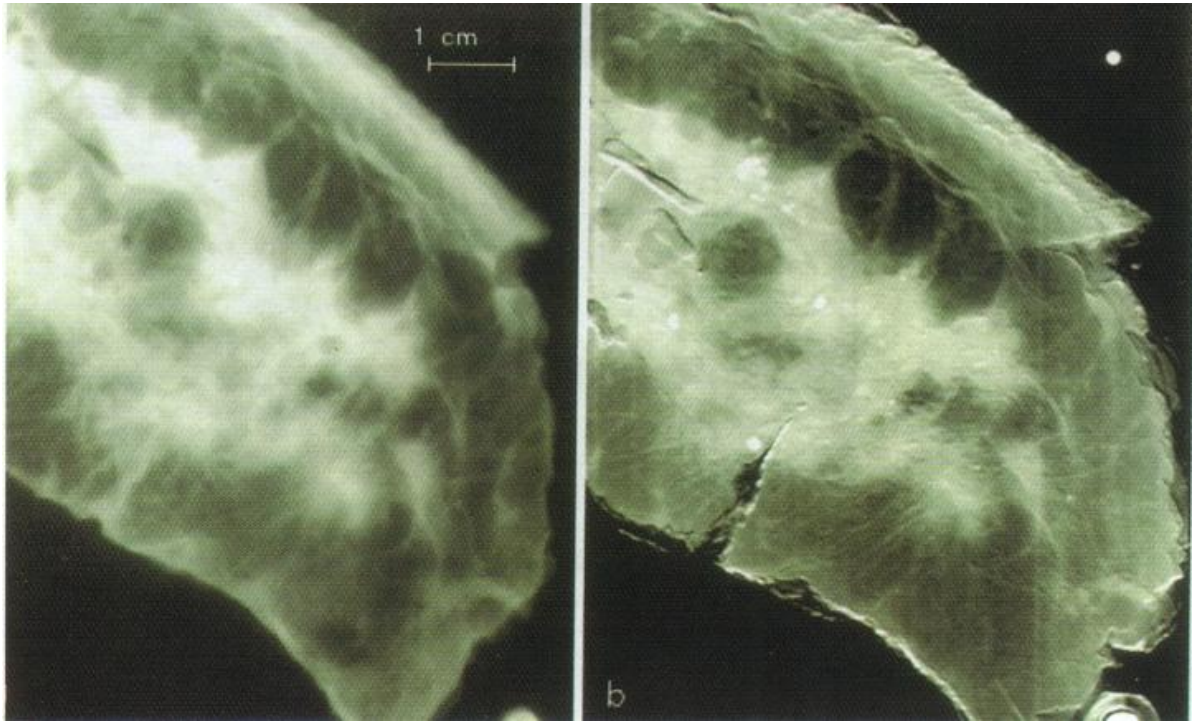
Conventional screen-film (SF) mammography

Phase contrast mammography (PCM)

Application of diffraction wave-selective method①



Diffraction Enhanced Imaging (DEI)



Conventional Mammogram (22 kVp)

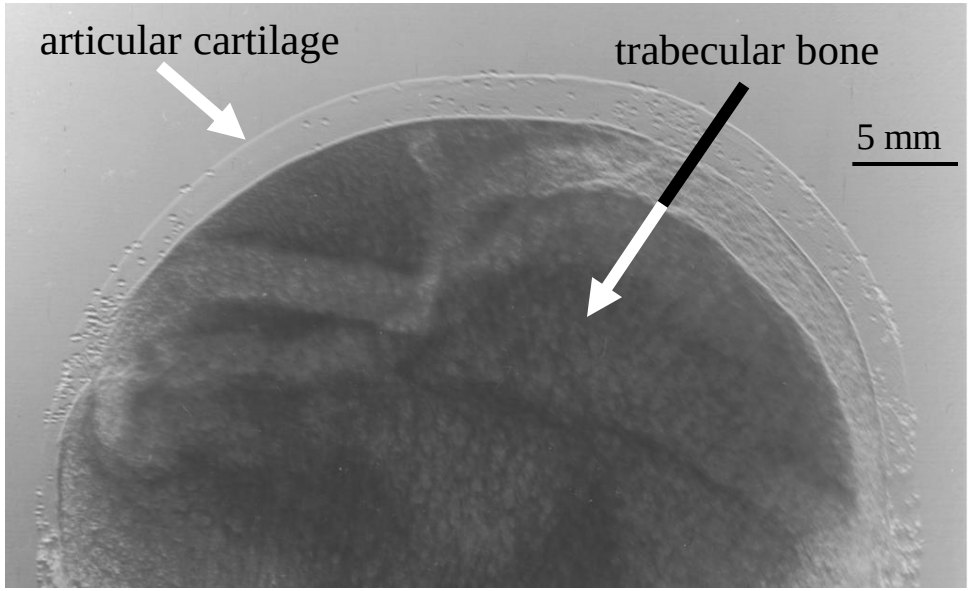
DEI Image @ 18 keV

Cancerous Breast Tissue

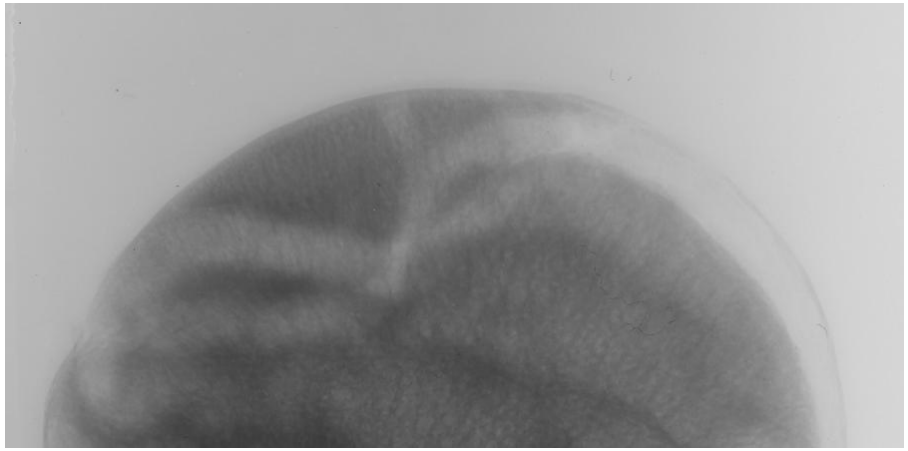
D. Chapman et al.,
Synchrotron Radiation News, Vol. 11, No. 2 (1998) 4.

Application of diffraction wave-selective method ②

35 keV SR



Hospital X-rays

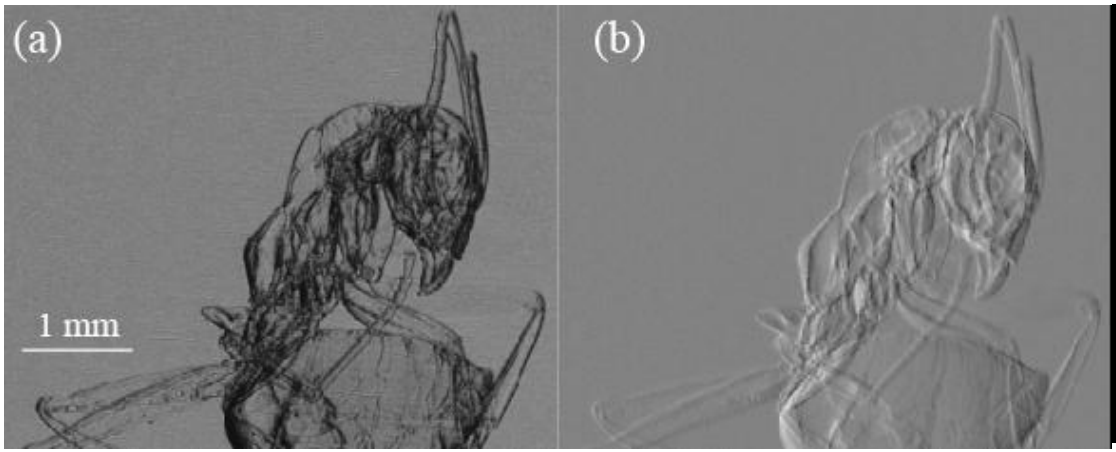


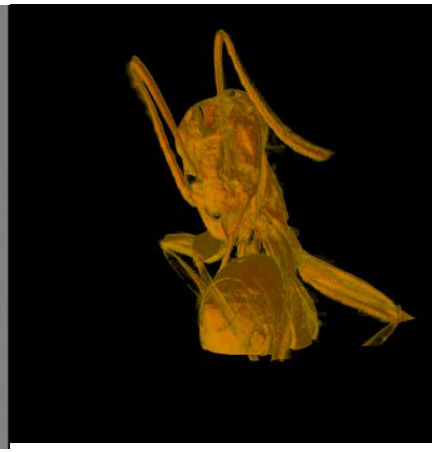
X-Ray Image of Femor Head Excised due to Vascular Necrosis

M. Ando et al., *Jpn. J. Appl. Phys* **43** (2004) L1175.

Application of diffraction wave-selective method③

20.7 keV SR



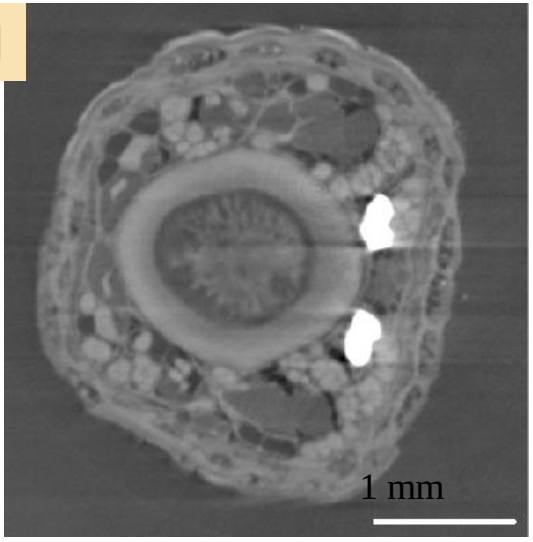


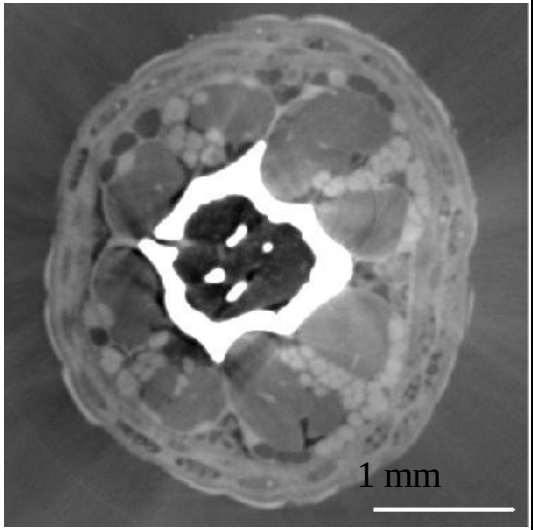
ant

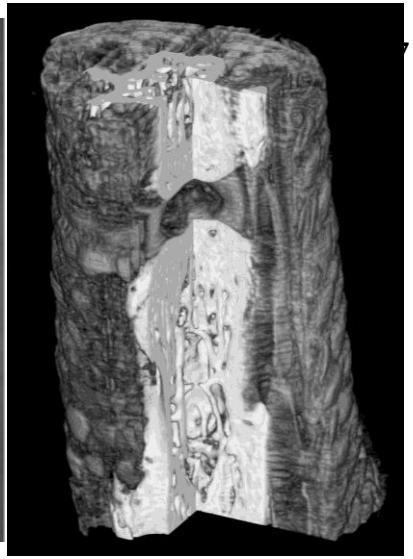
I. Koyama et al.,
AIP Proc. **705** (2004) 1283.

DEI image　　Image mapping X-ray refraction　　Phase tomogram

Mouse tail



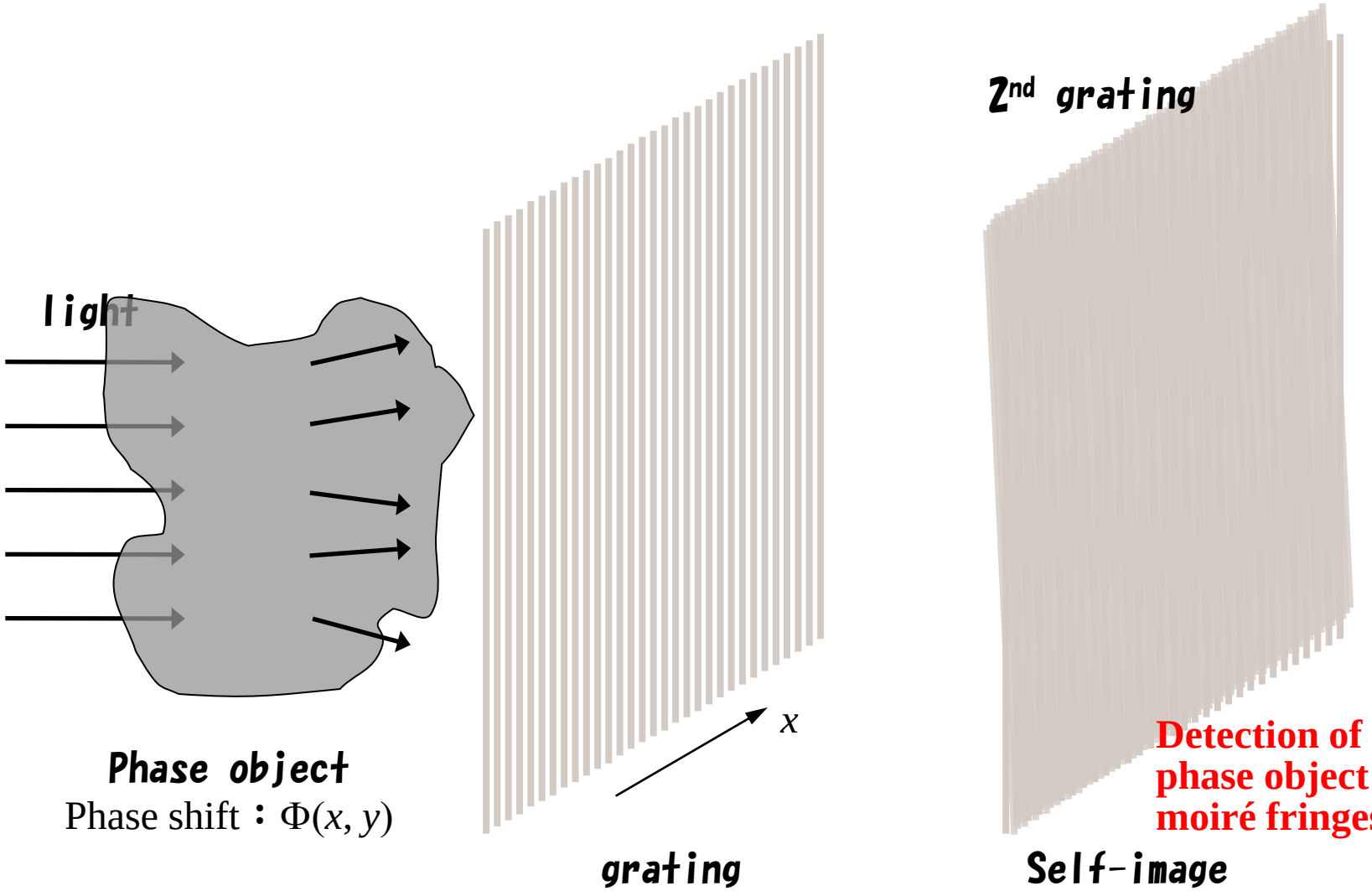




7 keV SR

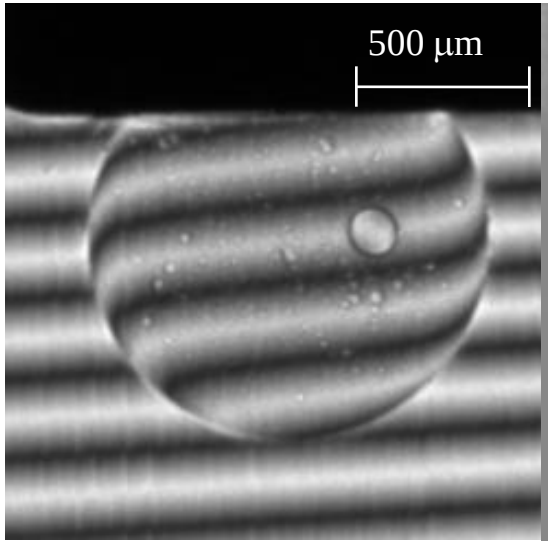
I. Koyama et al., *Jpn. J. Appl. Phys* **44** (2005) 8219.

Principle of Talbot interferometer

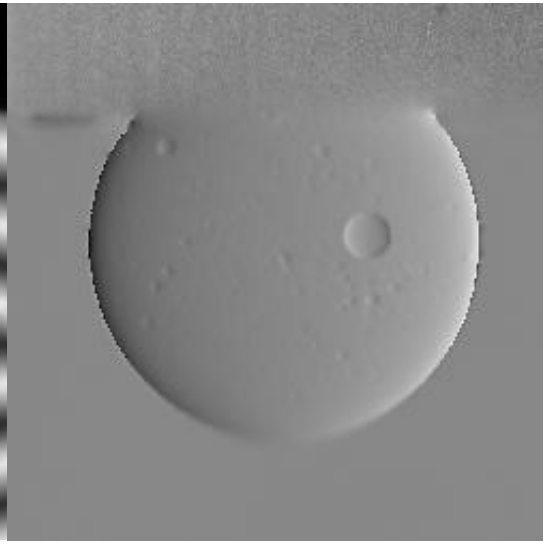


Phase imaging by X-ray Talbot interferometer

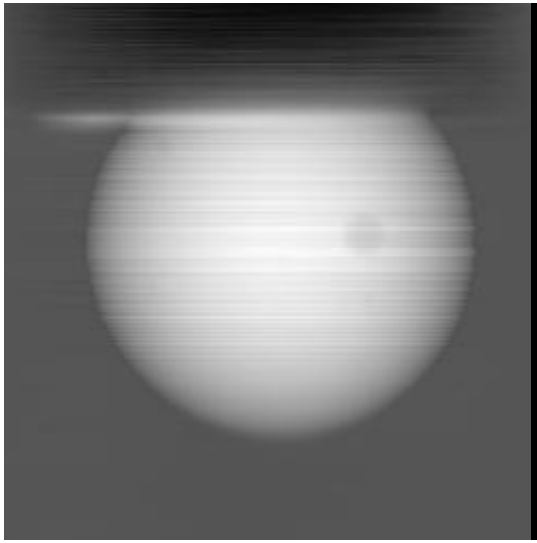
Plastic standard sphere@12.4 keV



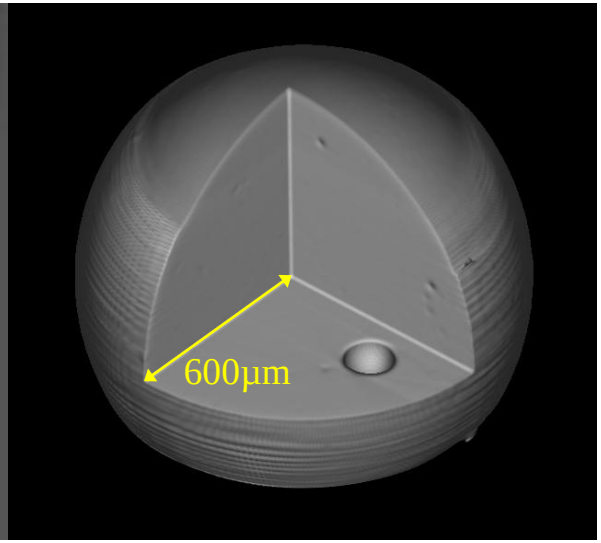
Moiré image



Differential phase image



Phase image

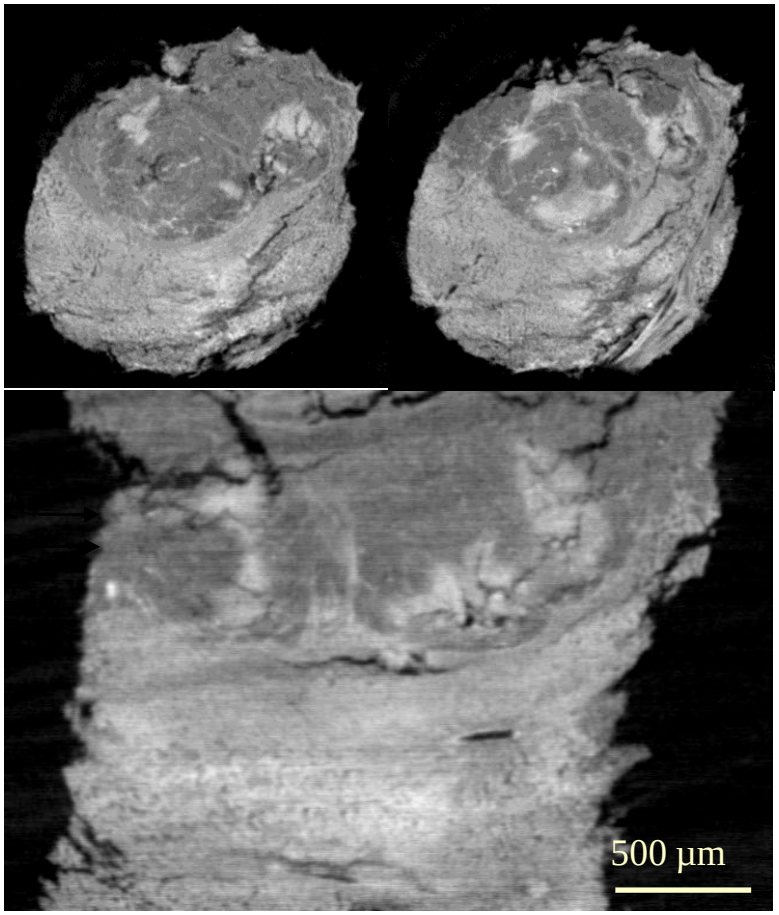


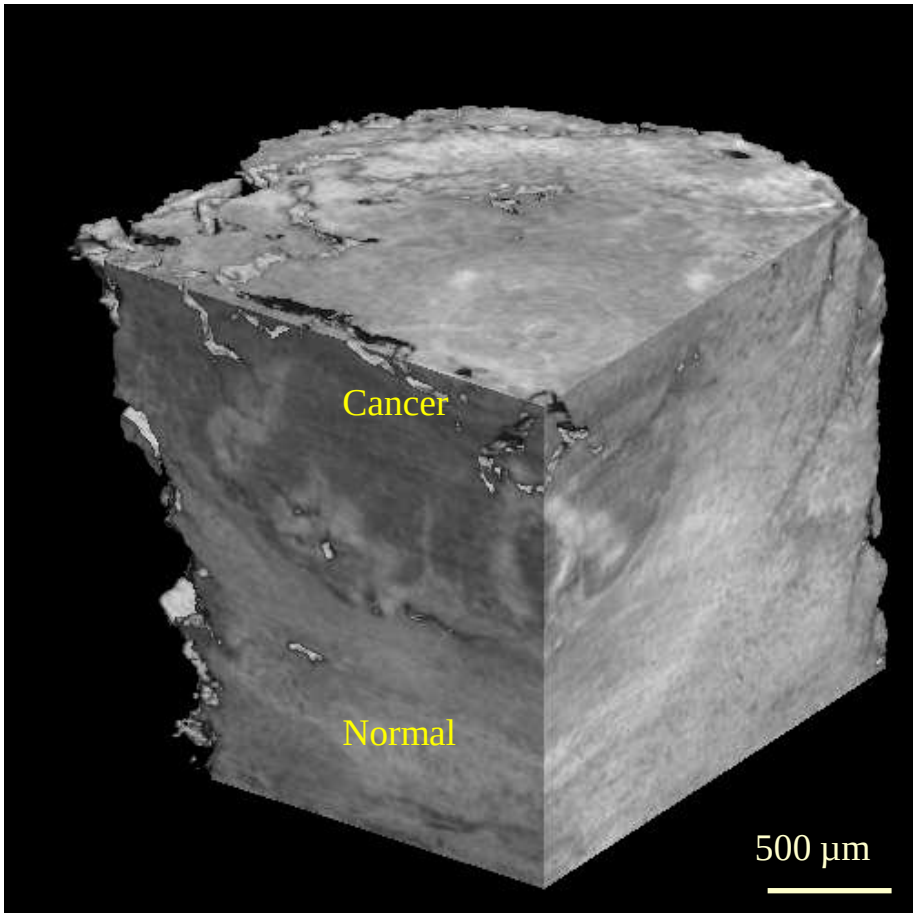
Phase tomogram

PHASE TOMOGRAPHY

Rabbit liver with cancer (VX2)

SPring-8, BL20XU
@12.4 keV



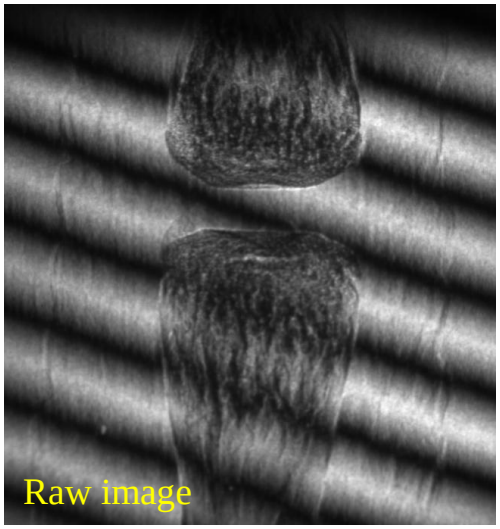


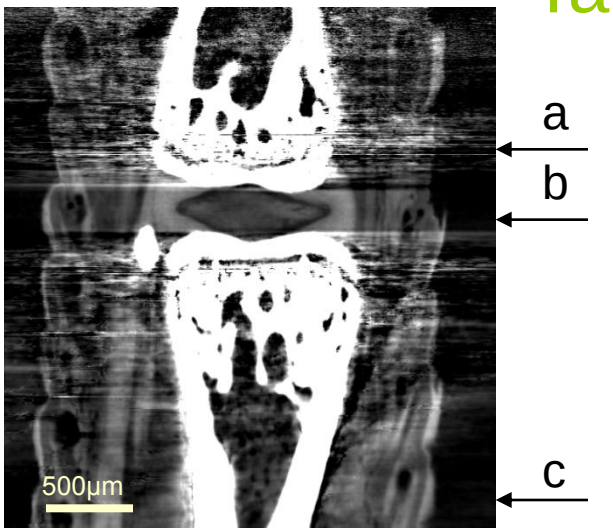
0 — 9.0×10^{-8}

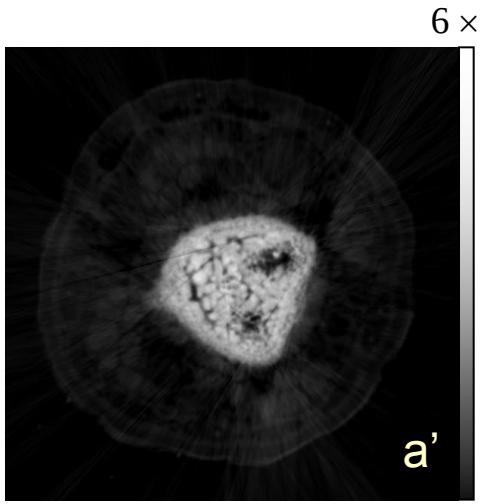
Refractive index difference

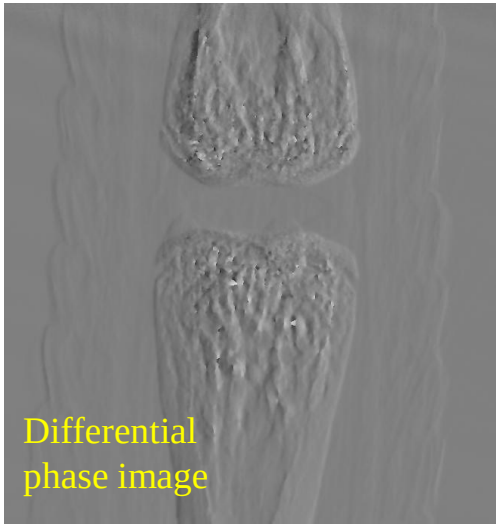
PHASE TOMOGRAPHY

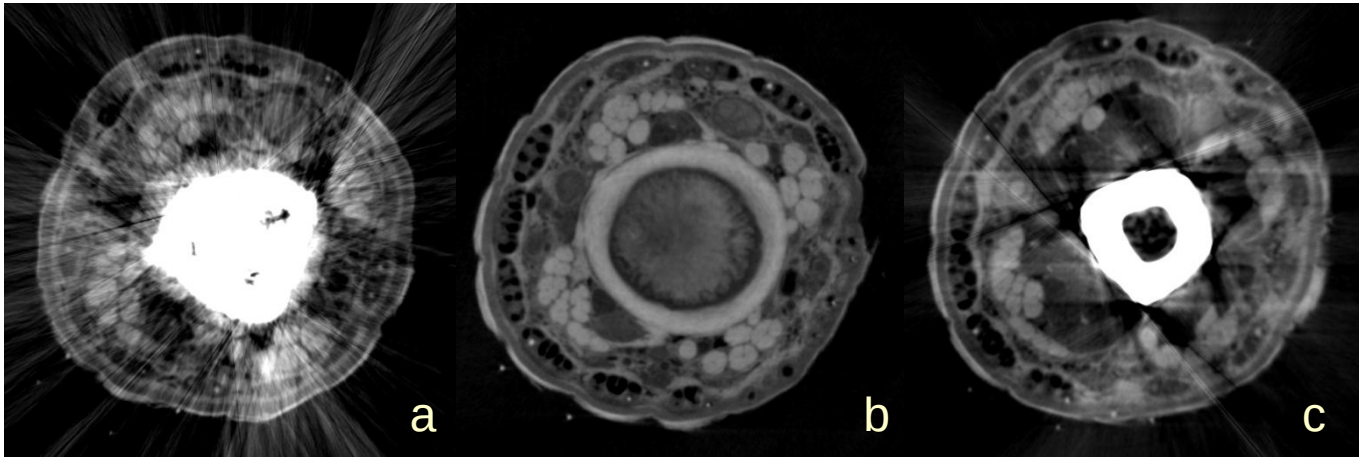
Mouse Tail











-17.5 μrad 17.5 μrad

Beam deflection by refraction

0 Refractive index difference 1.5×10^{-7}

Poly-chromaticity, Mono-chromaticity, Coherence, Polarization vs Visibility and Resolution

Visibility and Resolution

Poly-chromatic/ In-coherent	X-ray tube(Bremsstrahlung) Synchrotron radiation (bending magnet)
Mono-chromatic/ In-coherent	Monochrometer Compton scattering
Mono-chromatic/ Coherent	Synchrotron radiation **(**Undulator**)**
Mono-chromatic/ Coherent/Polarization	Laser

better

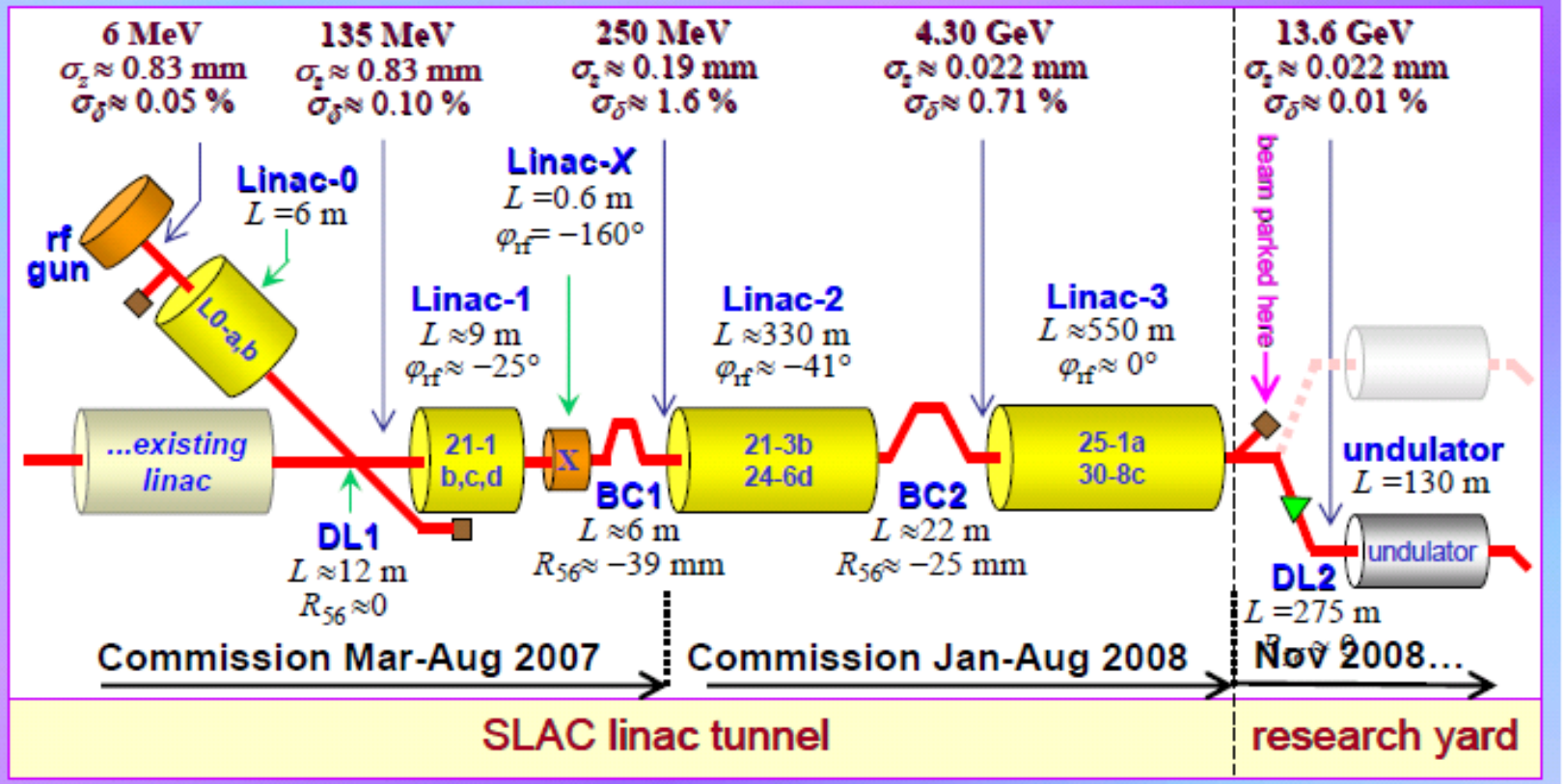
X-FEL facilities

European XFEL
DESY 2013

Japan
SCSS – SPring8 2010

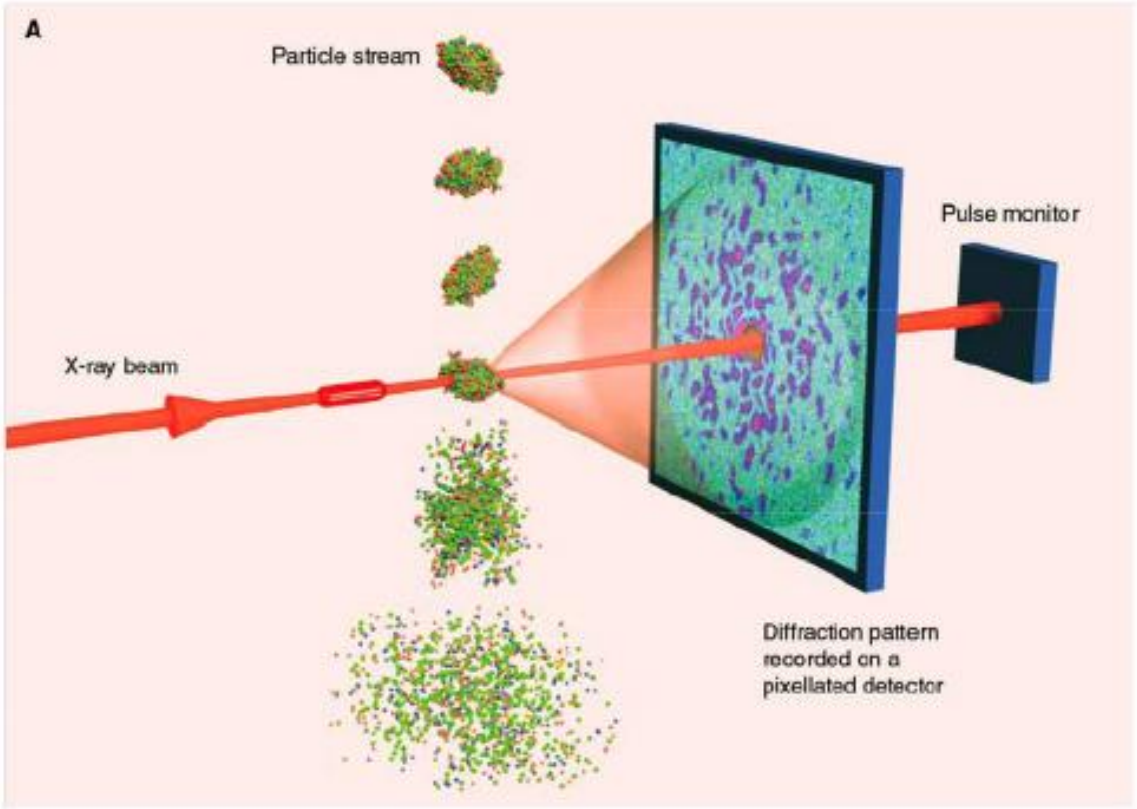
USA
LCLS – SLAC 2009

LCLS Accelerator Layout

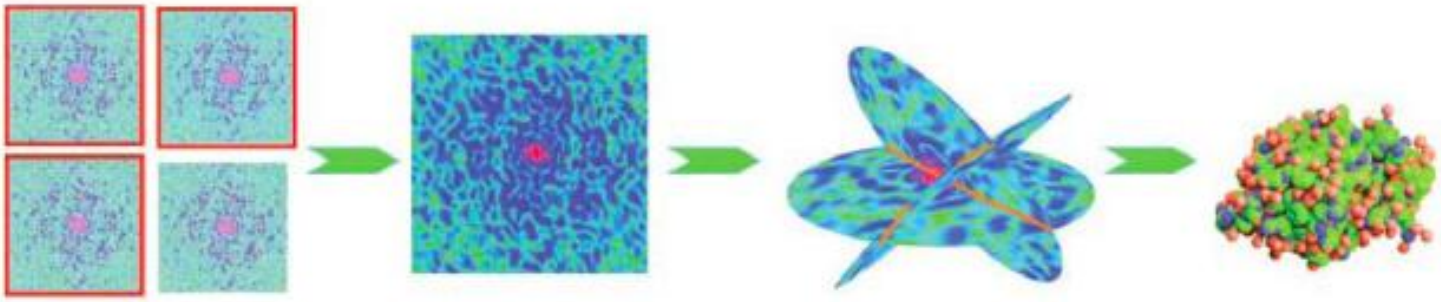


X-rays in spring 2009

Structure determination of single molecules before the Coulomb explosion

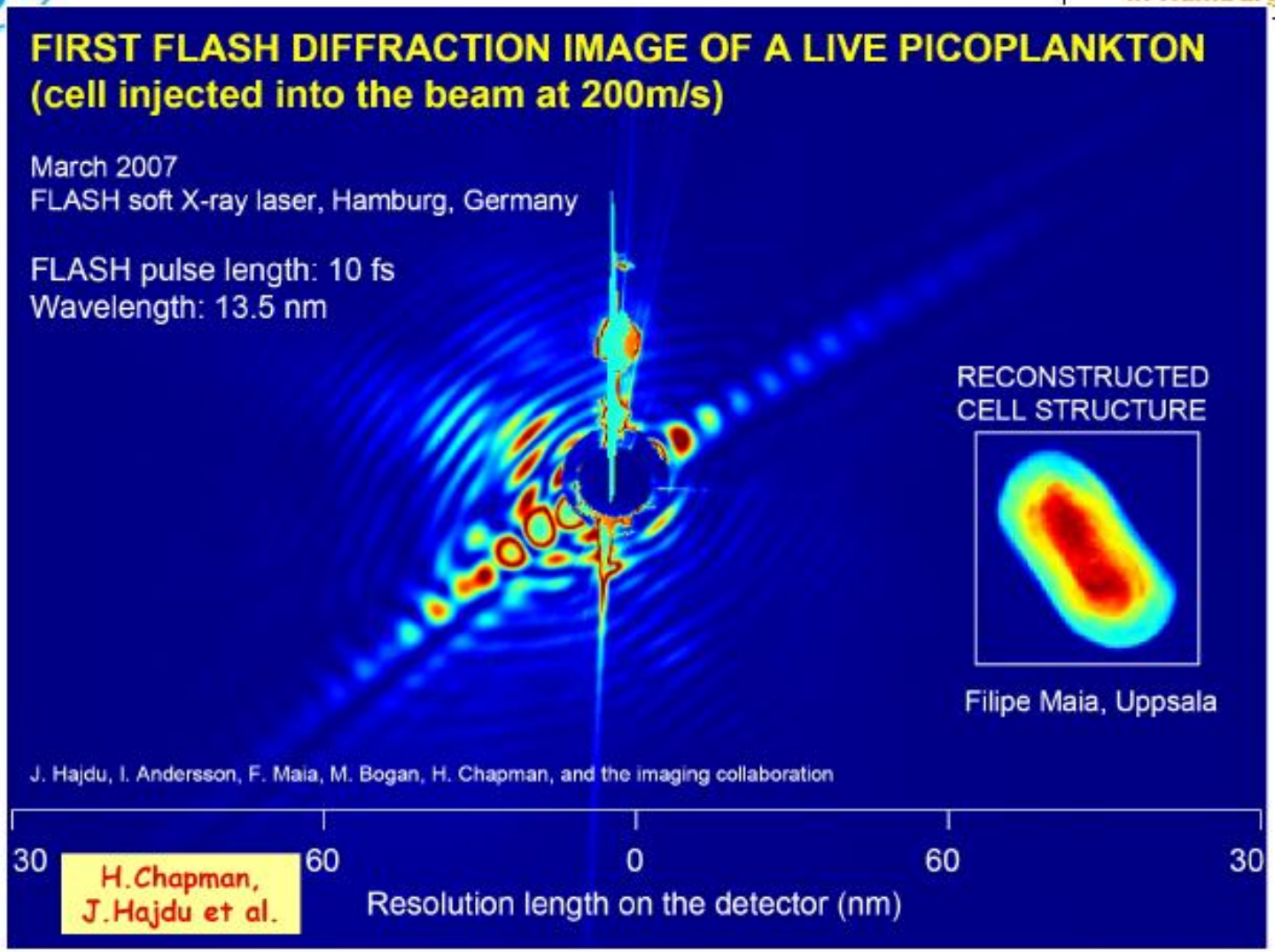


H. Chapman (2007)



Example: diffraction imaging

FLASH
Free-Electron Laser in Hamburg



HARP (High-gain Avalanche Rushing amorphous Photoconductor) detector

Kenkichi Tanioka

NHK Science & Technical Research Laboratories
Japan Broadcasting Corporation

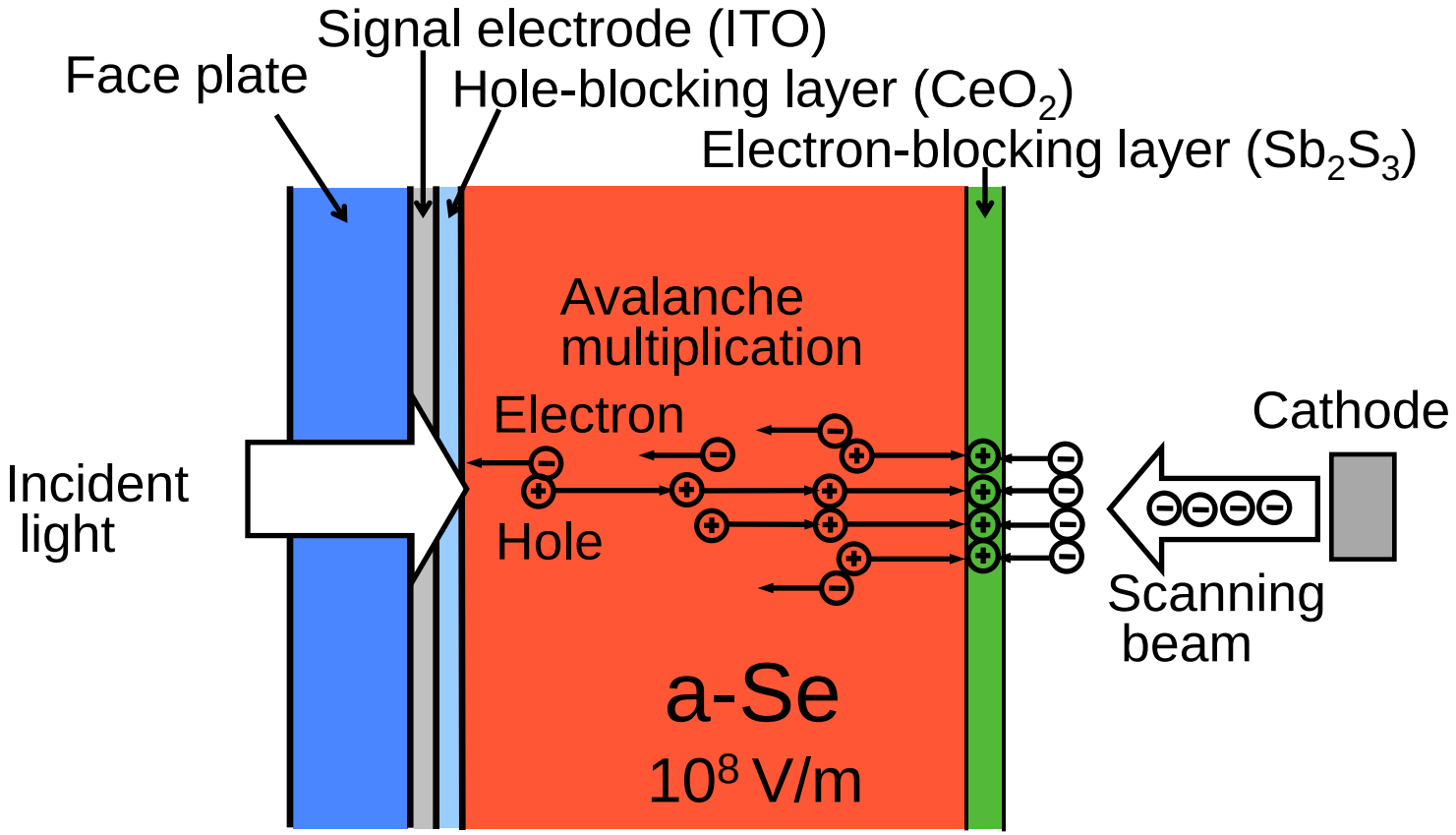
Workshop on Compton Sources for X/g Rays
Sep. 10, 2008

What is the HARP pickup tube?

A highly sensitive image sensor using avalanche multiplication phenomenon in an amorphous selenium photoconductive target

HARP: High-gain Avalanche Rushing amorphous Photoconductor

Operational representation of the HARP



HARP: High-gain Avalanche Rushing amorphous Photoconductor

(a) Image taken with the HARP (2-μm thick) camera

(b) Image taken with the SATICON camera

Monitor pictures produced by color cameras with HARP tubes and SATICON tubes. Illumination is 180 lx and lens irises are at F4

NTSC HARP color camera equipped with the newly developed tubes

SPECIFICATIONS

Maximum sensitivity: 11 lx, F8

Minimum scene illumination:

0.03 lx, (F1.7, +24 dB)

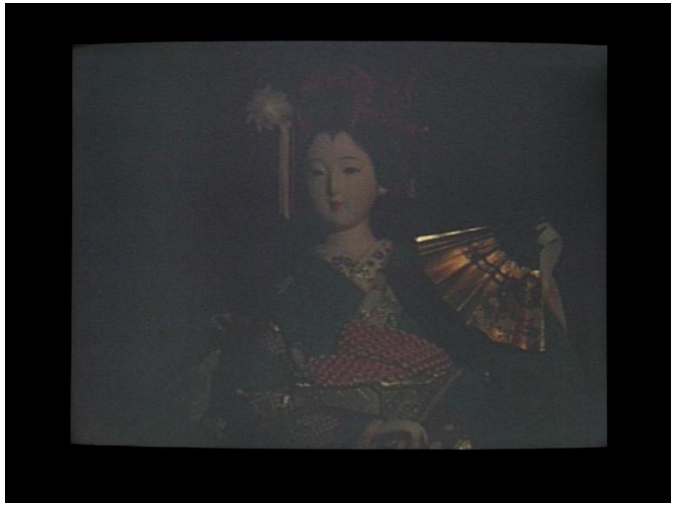
Signal-to-noise ratio: 59 dB

Limiting resolution: 800 TV lines

Weight: 5 kg

Power consumption: 25 W

(a) Image taken with the HARP camera



(b) Image taken with a CCD camera (+18dB)

Monitor pictures produced by color cameras with HARP tubes and CCDs. Illumination is 0.3lx and lens irises are at F1.7

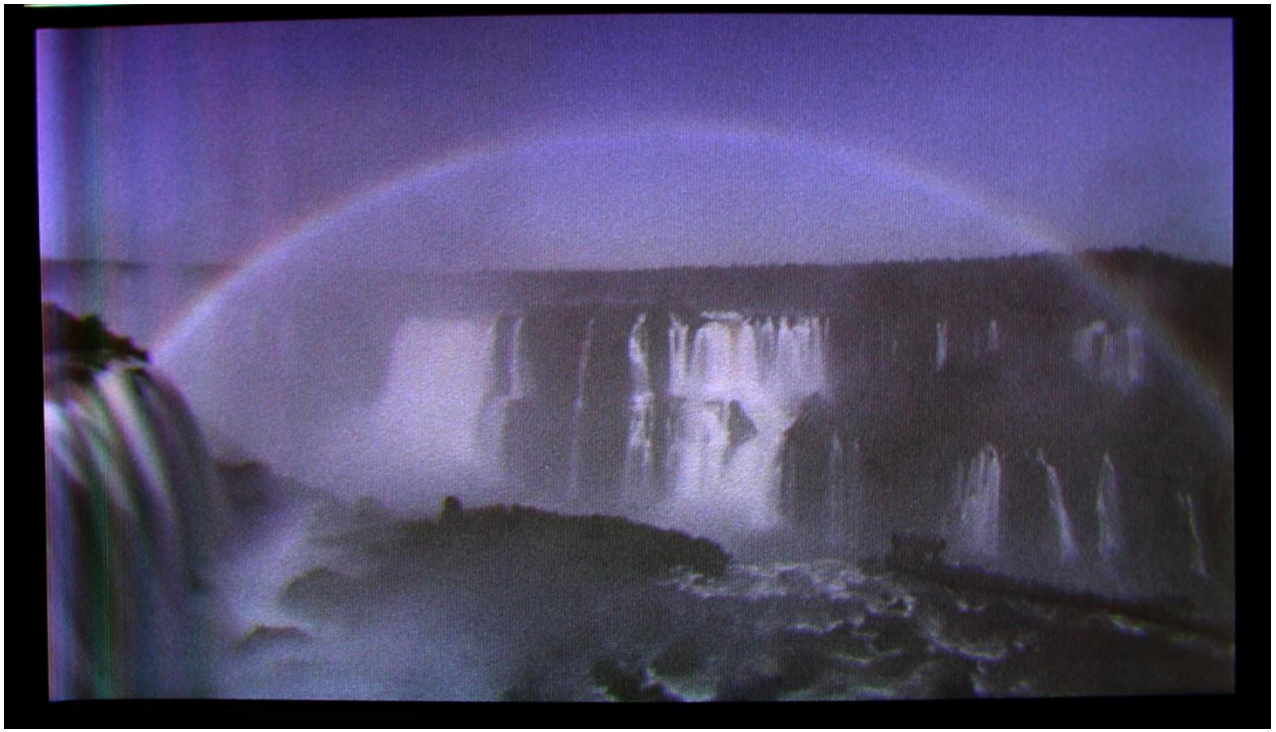
High definition (HD)TV HARP camera

(a) Image taken with the HDTV HARP camera

(b) Image taken with a HDTV CCD Camera (+42dB)

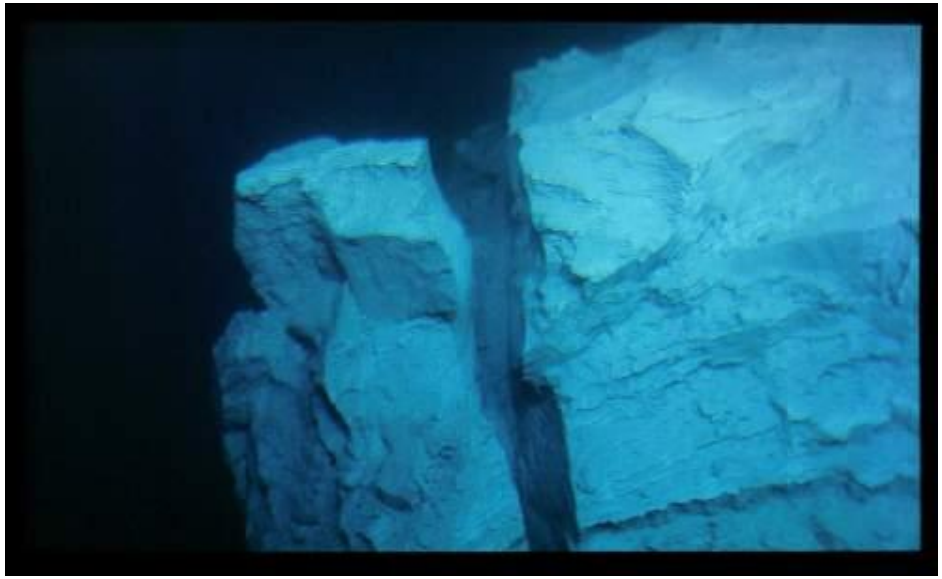
Monitor pictures produced by HDTV cameras with HARP tubes and CCDs

Shooting of aurora (Northern Europe)



Rainbow at night in Iguassu Falls

Mt. Fuji

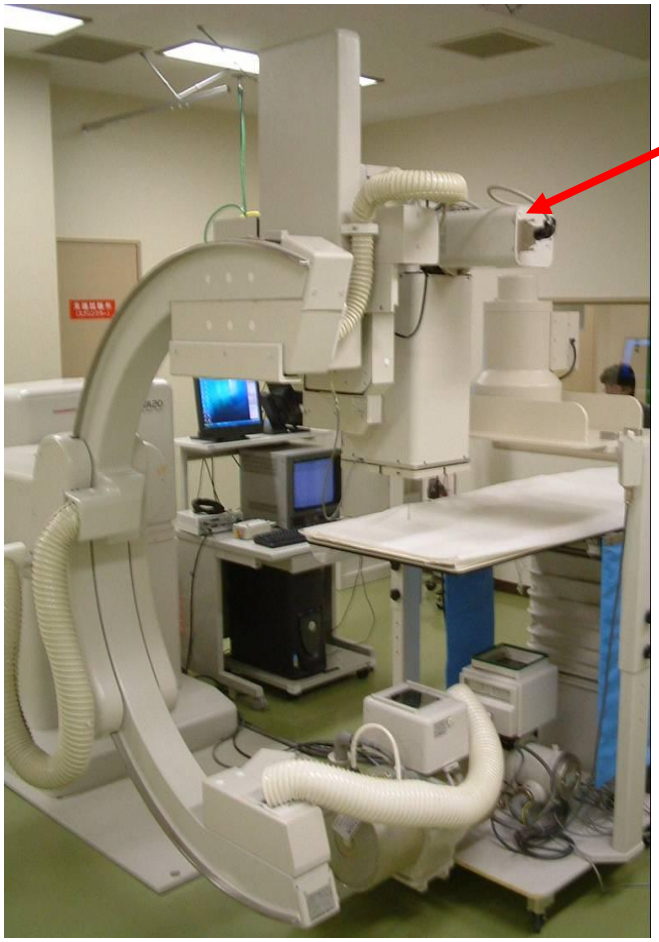


Images of the sea floor captured by the unmanned deep-sea vehicle equipped with the HDTV HARP camera at the epicenter of the Sumatra (Indian Ocean) earthquake in December 2004

JAMSTEC

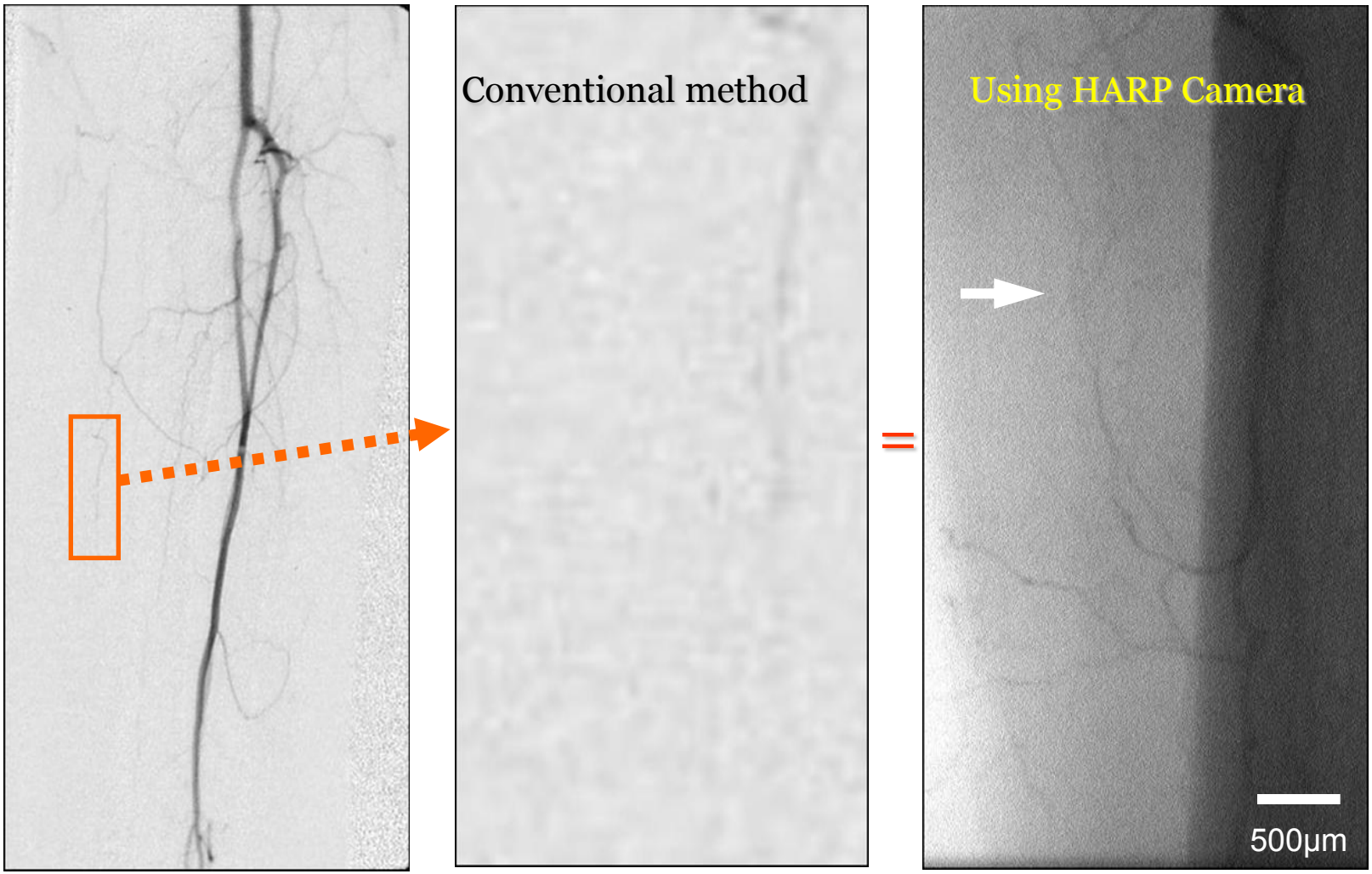
Practical application in field of medicine

Next generation X-ray diagnostic apparatus using HARP camera



(Dr. Mori, The National Cardiovascular Center)

New-Minute blood vessels



(Dr. Mori, The National Cardiovascular Center)