National Central University
國立中央大學

Introduction to Radiological Imaging Physics

放射影像物理簡介

Yi-Chun Chen, 陳怡君
光電科學與工程學系/照明與顯示科技研究所
國立中央大學

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Declaration

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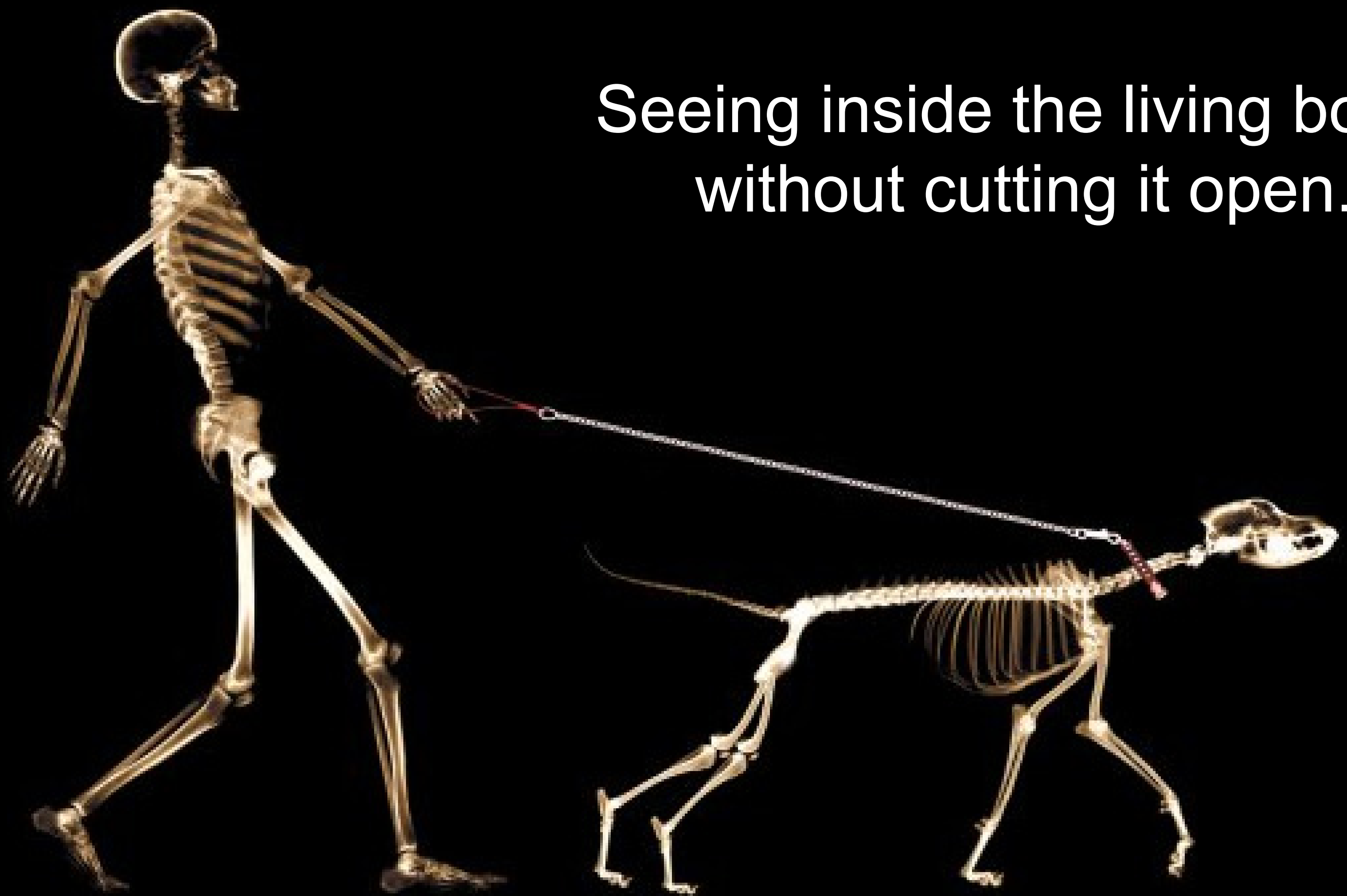
Outline

- Medical Examinations: Some Personal Experience
- Biomedical Imaging
  - Radiological Imaging: Physics & Modalities
    - X-Ray Imaging
    - Gamma-Ray Imaging
  - Magnetic Resonance Imaging (MRI)
  - Ultrasound
  - Optical Imaging
- What's in my Lab?

What is Medical Imaging?

Seeing inside the living body without cutting it open.



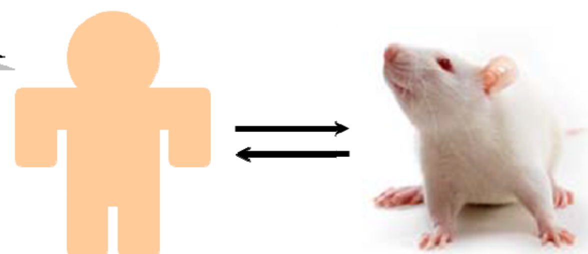
Why Biomedical Imaging?

Medical Imaging
- Diagnoses
- Treatments
- Cures
- Preventive Measures

Genetic Homology

Small Animal Models
- Disease Mechanism
- Drug Development
- Genetic-based Health Cares

Feedback



System Requirements

Imaging Tasks
- Cardiac Imaging
- Tumor Imaging
- Skeletal Imaging
- Brain, Lung, etc.

Preclinical Applications

- High Resolution
- High Sensitivity
- Economy
- Simple Configuration

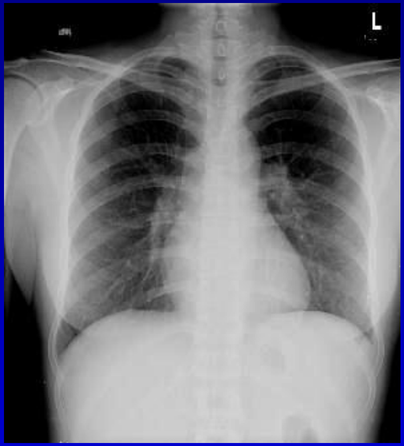
★ **Pinhole SPECT**

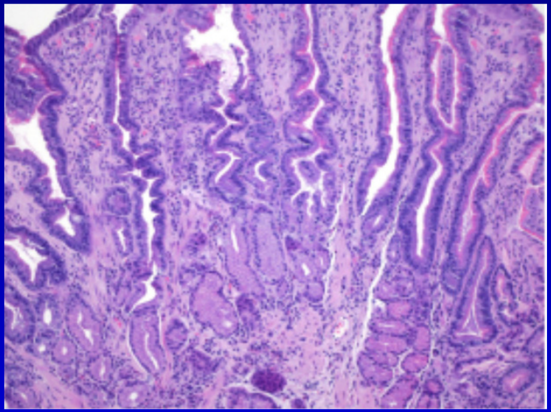
生醫影像技術

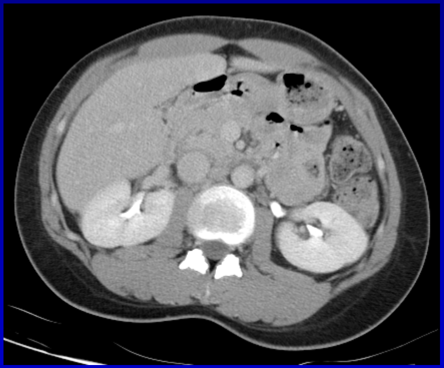
- X-ray Radiography
- X-ray CT (Computed Tomography)
- Ultrasound
- MRI (Magnetic Resonance Imaging)
- Nuclear Medicine Imaging
  - Planar
  - PET (Positron Emission Tomography)
  - SPECT (Single Photon Emission Computed Tomography)
- Optical Imaging
  - Microscopy & Endoscopy
  - Bioluminescence
  - Fluorescence

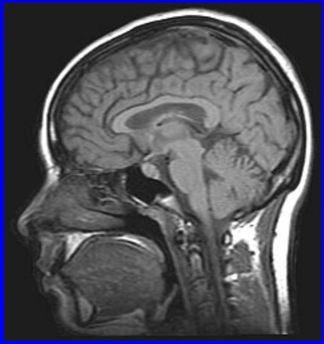
- X 光攝影
- X 光電腦斷層掃描
- 超音波
- 磁振造影
- 核子醫學影像
  - 平面影像
  - 正子斷層掃描
  - 單光子放射電腦斷層掃描
- 光學影像
  - 顯微鏡 & 內視鏡
  - 生物冷光
  - 螢光

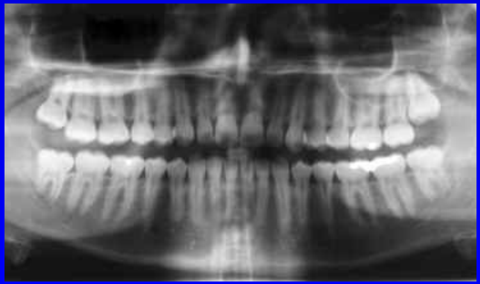
What is What?











Radiological Imaging

Optimal Compromise between

Clinical Utility and Radiation Dose

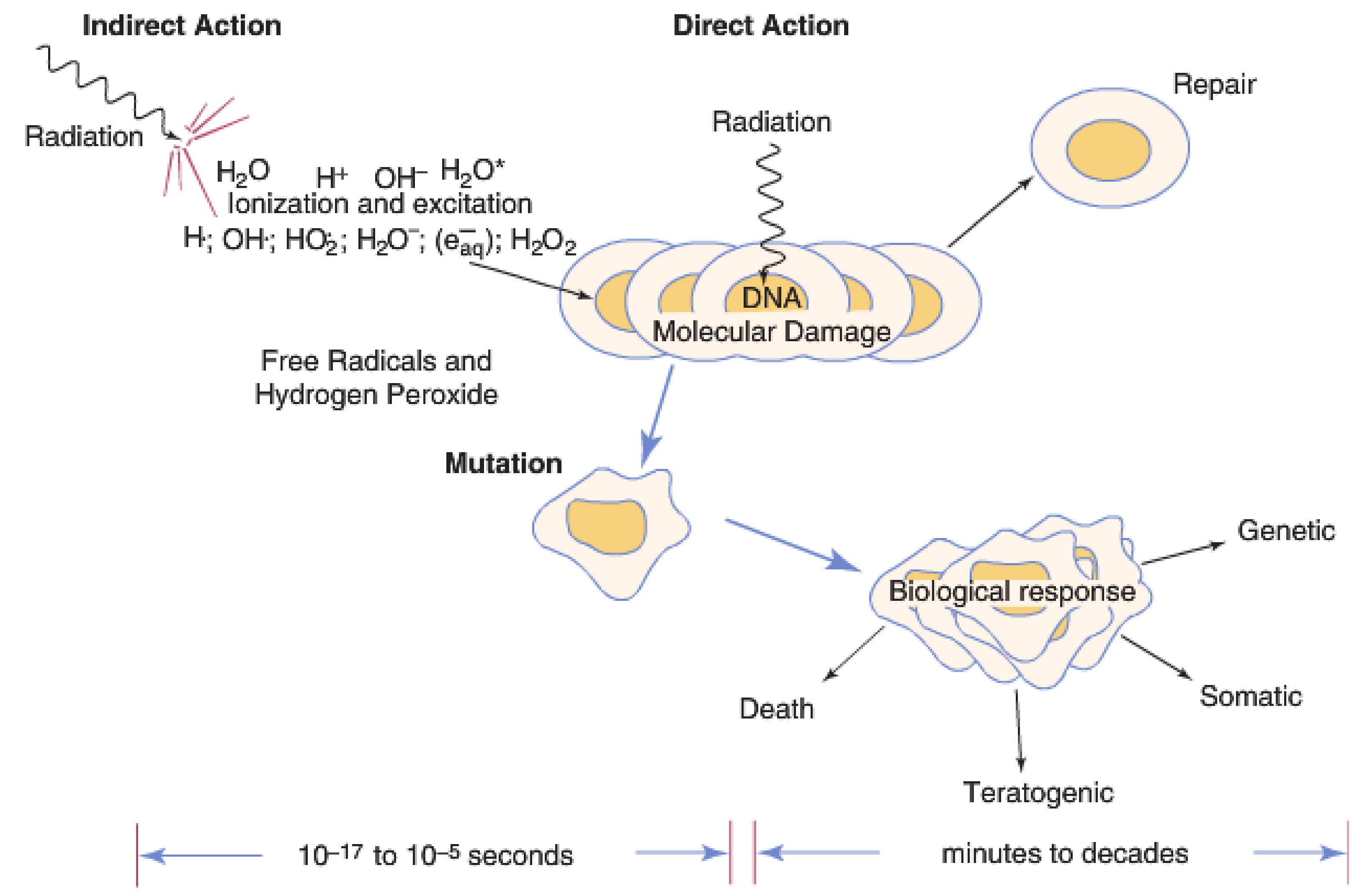
Discovery of Ionizing Radiation

- 1895 Wilhelm Conrad Röntgen
  → discovery of X-ray
- 1896 Antoine Henri Becquerel
  → research on natural radionuclide (uranium)
- 1898 Marie Skłodowska Curie
  → discovery of radioisotope of radium

Classifications of Ionizing Radiation

- Particulate Radiations: α, β^+, β^-, p, n, and heavy ion
- Electromagnetic Radiations: γ-rays & X-rays

Biologic Effect of Ionizing Radiation



(Bushberg *et al.*, The Essential Physics of Medical Imaging, p. 756)

Chronic Low Level Exposure Risk

- Annual average radiation exposure per person from natural occurring sources ~ 300 mrem
- One chest X-ray ~ 0.25 mGy (25 mrad)

(1 Gy = 1 J/kg)

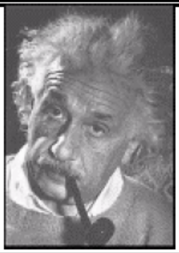
Risky Business !!

Things that increase your chance of death by One in a Million

Smoking 1.4 cigarettes	Drinking ½ liter of wine	1 hour in a coal mine
Pollution from living 2 days in New York City	Traveling 30 miles in a car	
Flying 6,000 miles by jet	Cosmic radiation from living 2 months in Denver	
One chest X-ray	Living 2 months with a cigarette smoker	
Drinking Miami water for a year	Eating 100 charbroiled steaks	

(http://www.radcon.arizona.edu/training/BRPC-CH.pdf)

Biologic Effect of Ionizing Radiation



Acute Radiation Syndrome

(1000 rad ~= 40000 chest X-ray at once)

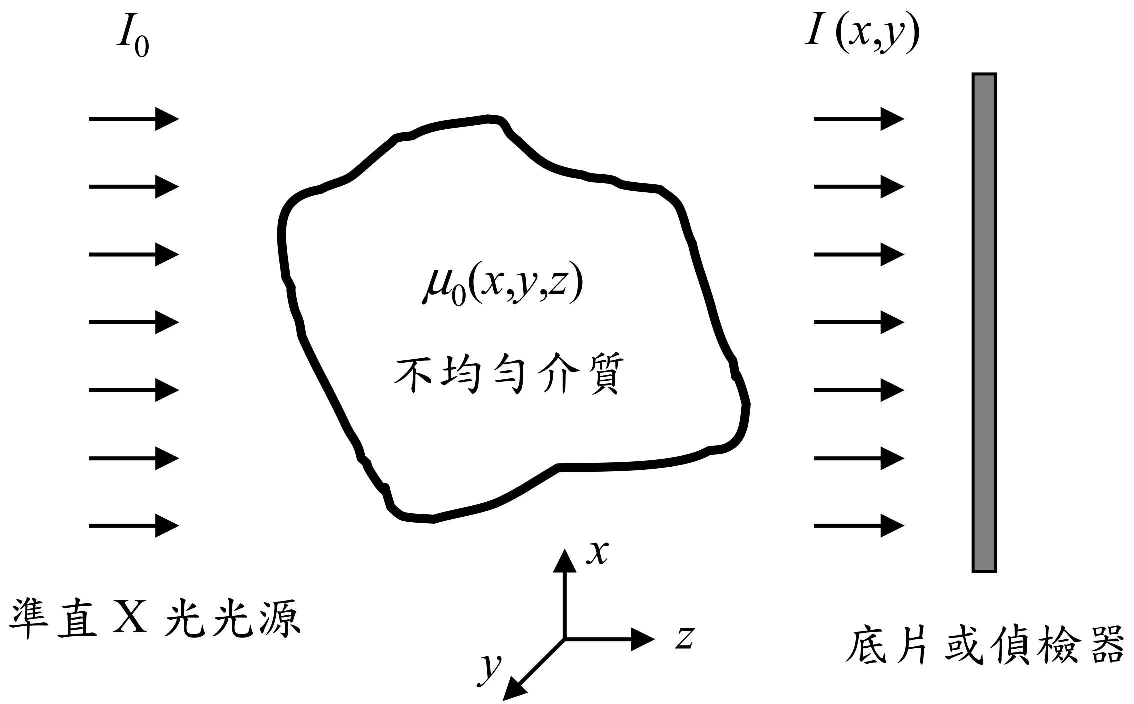
	Hematopoietic Syndrome	Gastrointestinal Syndrome	Central Nervous System Syndrome
Dose (rad)	200-1000	> 1000	> 2000
Time of Death	3-8 weeks	3-10 days	< 3 days
Organ/System Damaged	Bone Marrow	Small Intestine	Brain
Signs & Symptoms	Decreased number of stem cells in bone marrow, increased amount of fat in bone marrow, pancytopenia, anemia, hemorrhage, infection	Denudation of villi in small intestine, neutropenia, infection, bone marrow depression, electrolyte imbalance, watery diarrhea	Vasculitis, edema, & meningitis
Recovery Time	Dose dependent, 3 weeks to 6 months; some individuals do not survive.	None	None

(http://www.radcon.arizona.edu/training/BRPC-CH.pdf)

X-Ray & Gamma-Ray

- 醫學上所使用的放射線一般是指能量介於 10 千電子伏特到 100 百萬電子伏特（10 keV ~ 100 MeV）之間的電磁波，所對應的波長大約在 1 Å 到 10^{-4} Å。
- X 射線與伽瑪射線在本質上並無差異，都是高能量的光子/電磁波，其主要的差別在於來源不同：
  - X 射線是由高速電子撞擊金屬，在靠近金屬原子核時因為受到庫侖力的影響轉彎減速時輻射出來的（這個現象稱為制動輻射，Bremsstrahlung），或是原子內的電子進行能階躍遷時所放射出來的特徵 X 射線（characteristic X-ray）；
  - 伽瑪射線是由放射性同位素在核衰變的過程中輻射出來，或是由正子衰變同位素所放出的正子（positron），在介質內遇到一個電子時發生互毀反應（annihilation reaction），而產生一對行進方向相反的 511 keV 伽瑪射線。

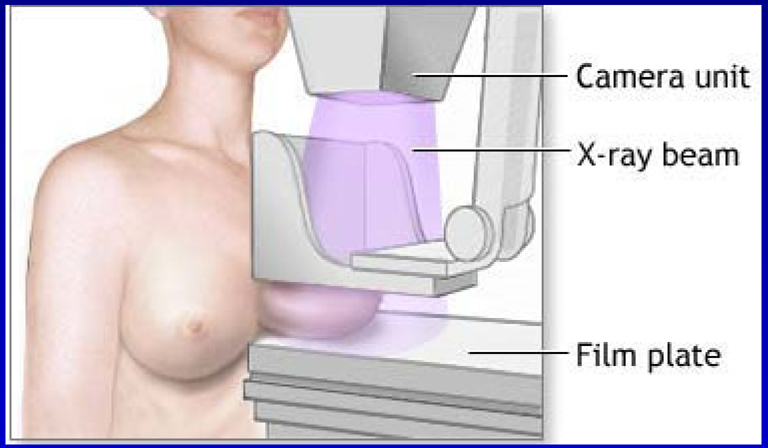
X-ray Imaging

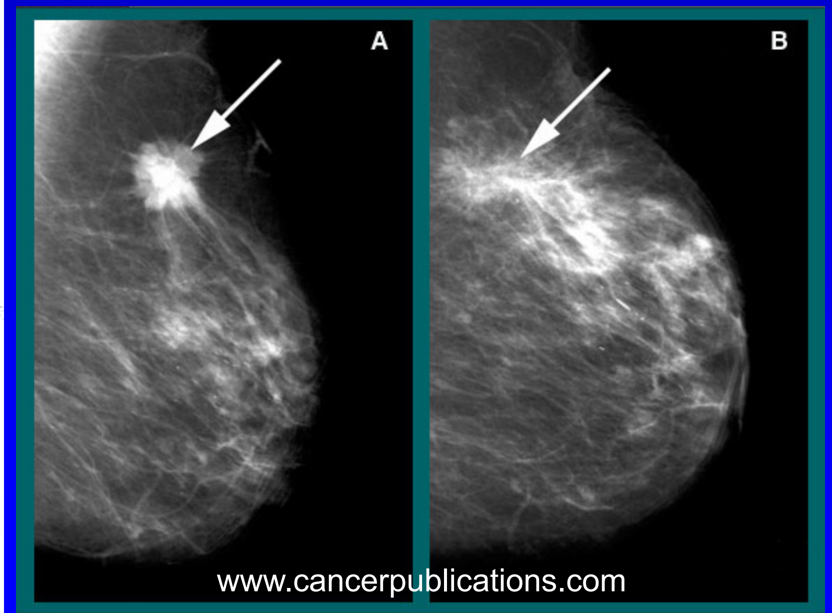


Beer's law: $I(x,y) = I_0 \exp\left[-\int \mu(x,y,z)dz\right]$

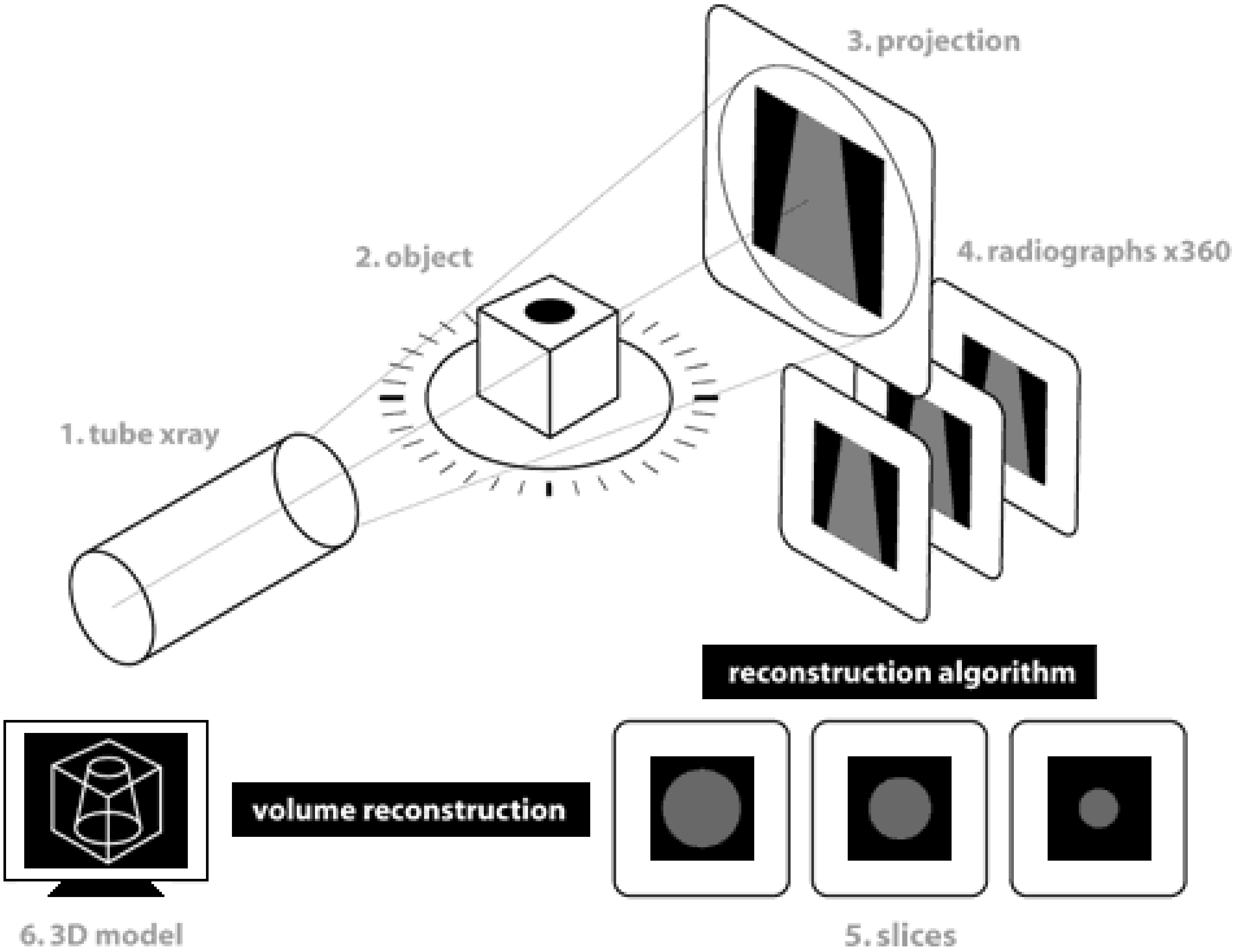
其中 $\mu(x,y,z)$ 為介質的線性衰減係數（linear attenuation coefficient）

Radiography & Mammography





Tomography – from 2D to 3D

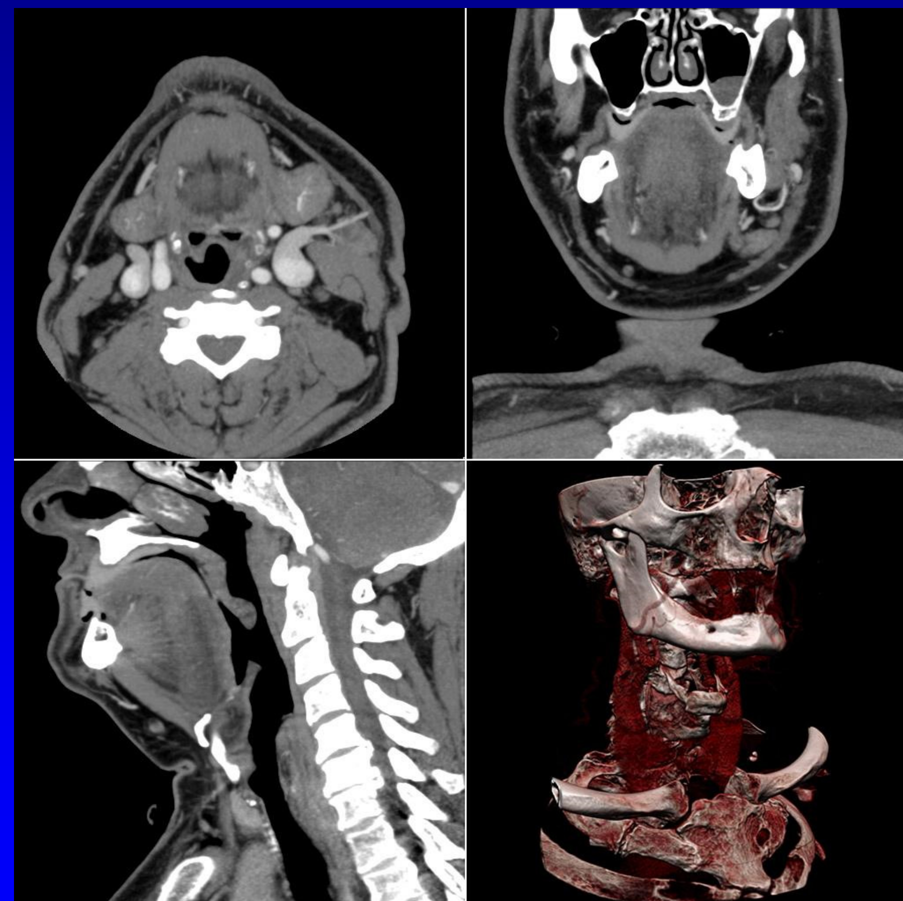


(http://www.digitalscanservice.com/tomography.php)

X-ray Computed Tomography (CT)

Spiral CT video

Axial slice Coronal slice

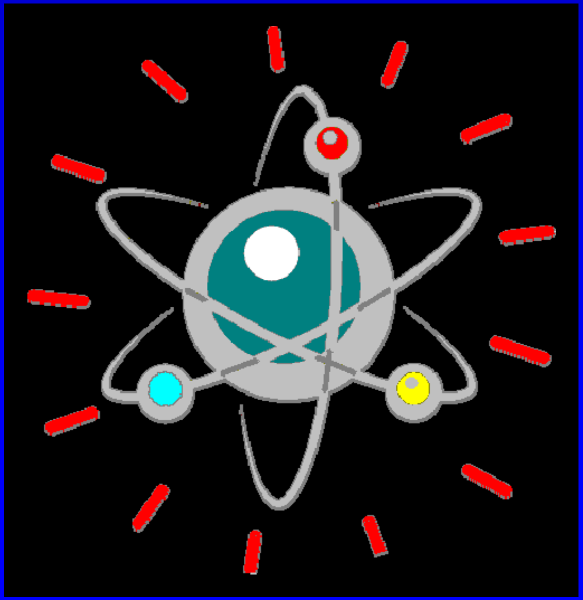


Sagittal slice Volume rendering

Find a tumor before it gets BIG – Functional Imaging

Imaging tracer selectively taken up by organ of interest

Radiopharmaceuticals



Fluorescence agents

Nuclear Medicine Imaging Basis

- 放射性同位素的產生
  - 核分裂
  - ^{99}Mo-^{99m}Tc 產生器
  - 粒子迴旋加速器

$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n}_{\mathrm{thermal}} \rightarrow {}^{236}_{92}\mathrm{U}^{*} \rightarrow {}^{134}_{50}\mathrm{Sn} + {}^{99}_{42}\mathrm{Mo} + 3\,{}^{1}_{0}\mathrm{n}_{\mathrm{fast}} + \gamma$$

$$^{99}_{42}\mathrm{Mo} \rightarrow {}^{99m}_{43}\mathrm{Tc} + \beta^{-}$$

$$^{18}_{8}\mathrm{O} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{18}_{9}\mathrm{F} + {}^{1}_{0}\mathrm{n}$$

- 放射藥物化學標記
  將放射性同位素標記在藥物、抗體或是配位基上
- 器官功能診斷原理
  藥物注射於生物體內時，依其生化特性會聚集到特定的器官、組織或病灶，而藥物上標記的放射性核種會向四面八方射出伽瑪射線（或正子）
- 影像偵測儀器
  取得核醫藥物在生物體內的分佈情形

Planar Imaging by a Gamma Camera

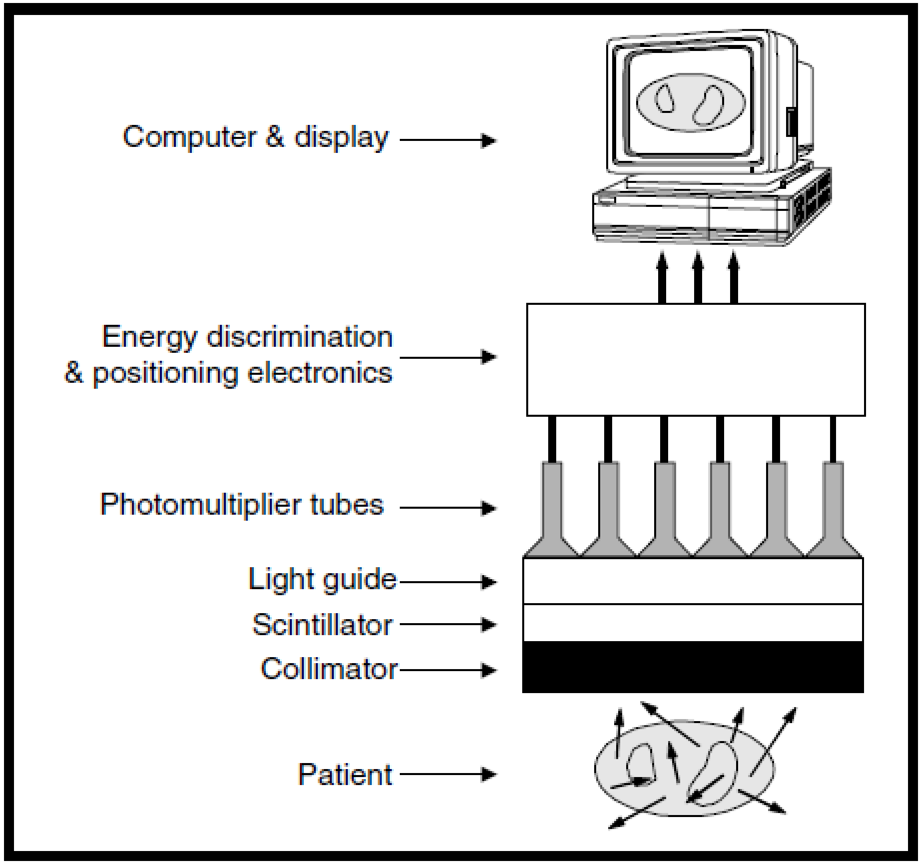


FIGURE 4 Fundamental components of a conventional gamma camera. Most gamma cameras have a collimator, a scintillation crystal, a light guide, an array of photomultiplier tubes, radiation shielding, energy discrimination and positioning electronics, and a computer and display for acquisition, processing, and display of data and images.

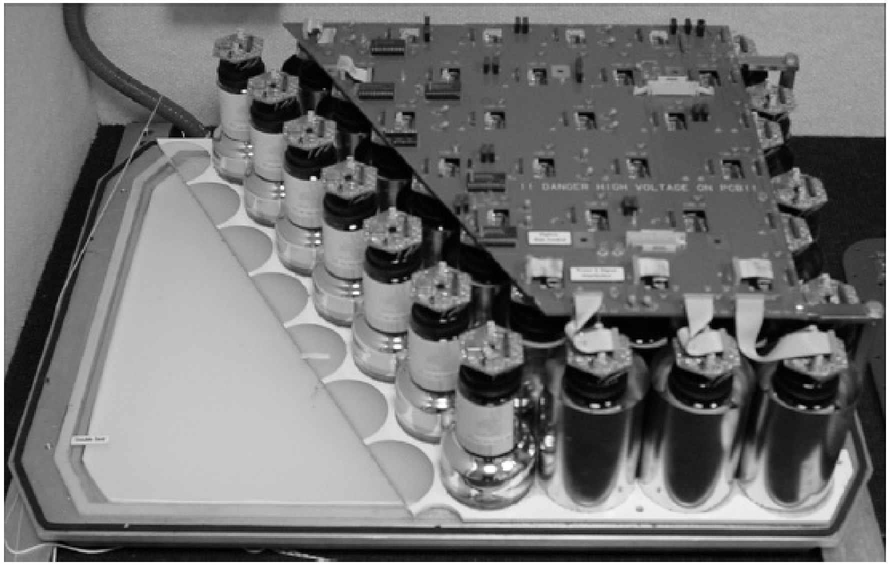
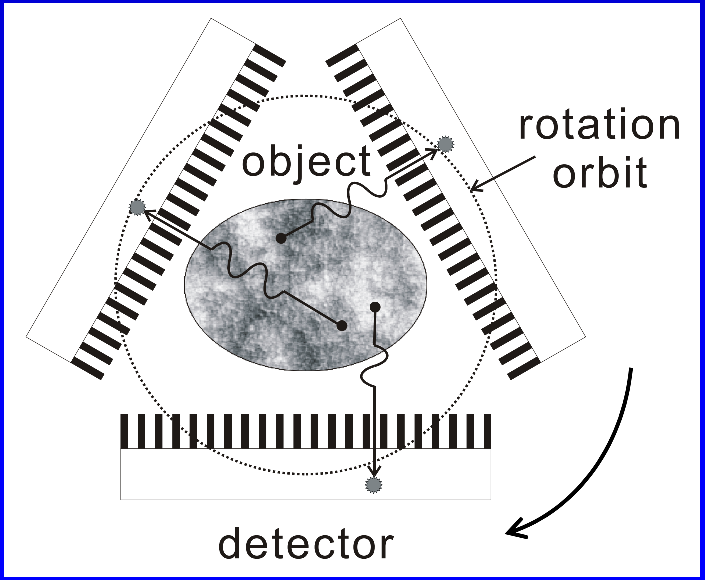
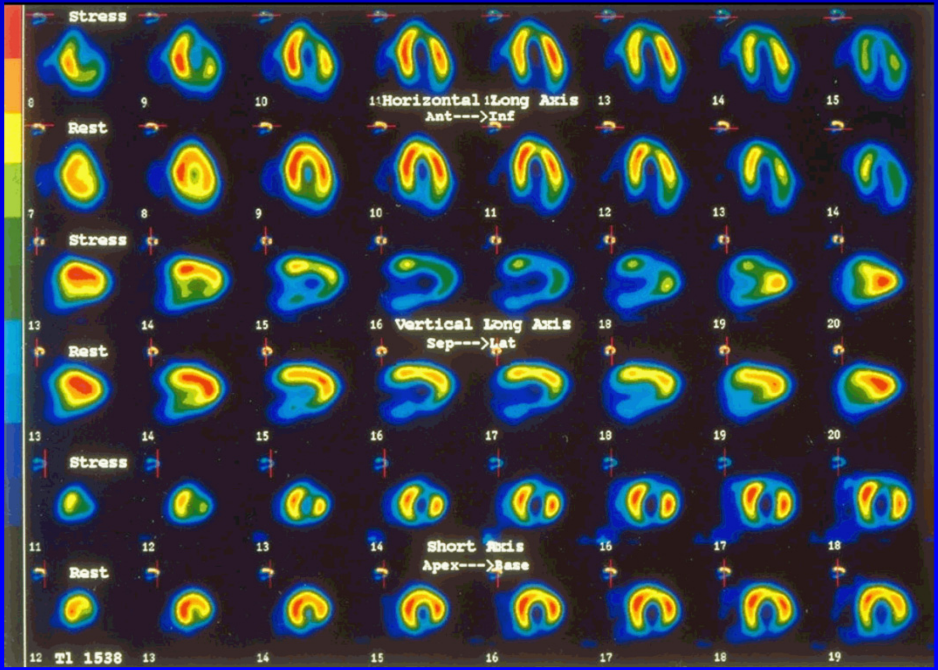


FIGURE 7 Scintillation-detector components. Displayed are components of a scintillation detector of a gamma camera, including scintillation crystal, light guide with masking, circular-face PMTs, magnetic shielding of PMTs, and signal-processing electronics.

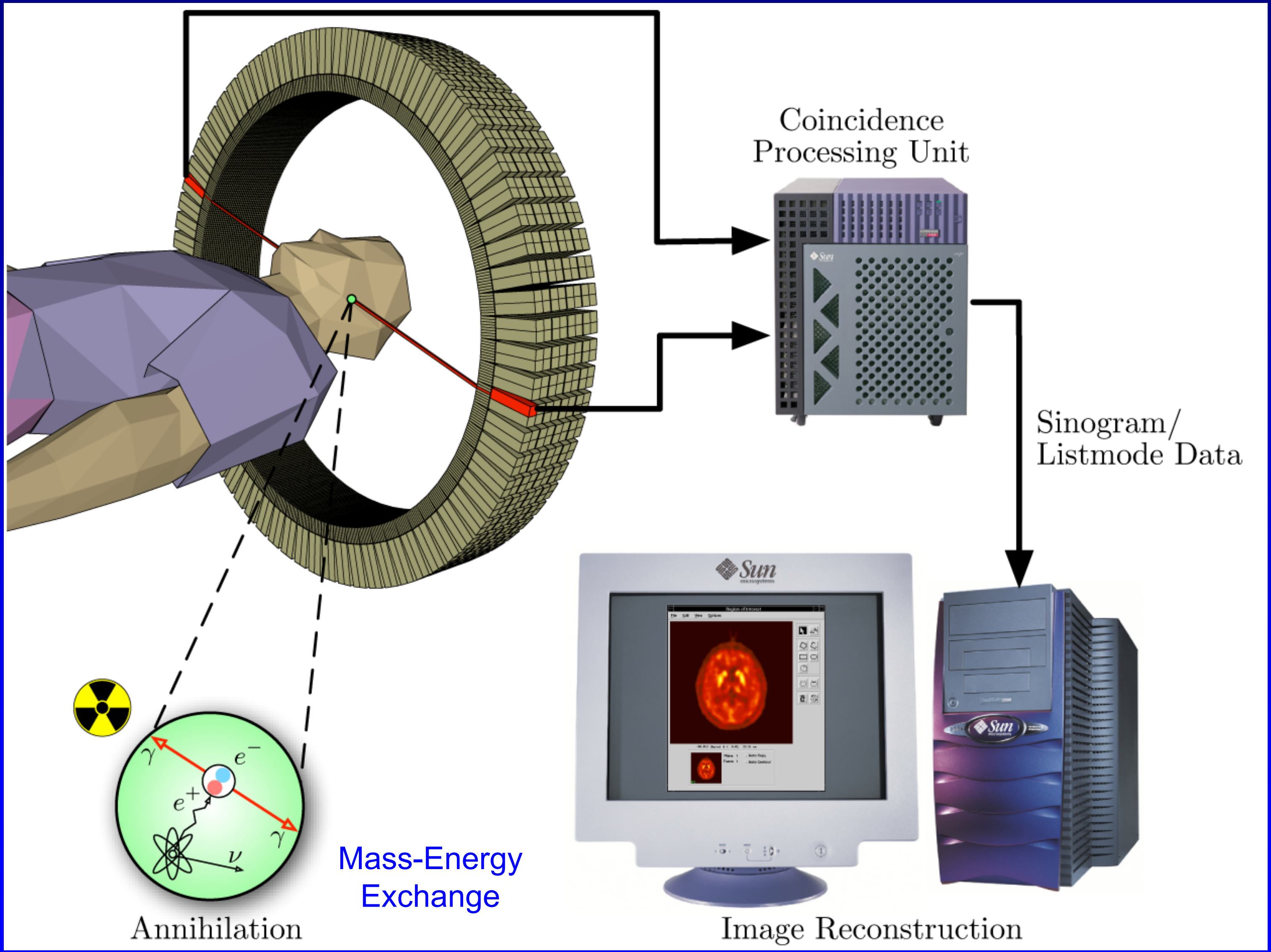
Zeng *et al.*, "Single-Photon Emission Computed Tomography," in *Emission Tomography*, Wernick and Aarsvold eds., Elsevier Academic Press, pp. 130-131, 2004.

Single-Photon Emission Computed Tomography (SPECT)





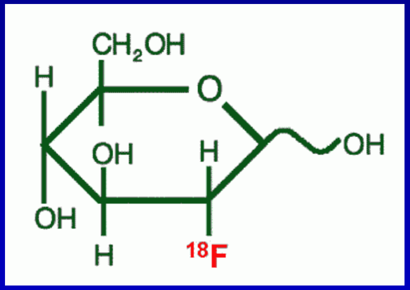
Positron Emission Tomography (PET)

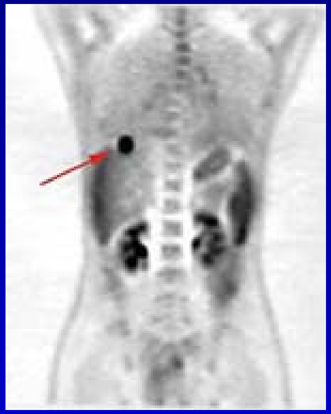


Positron Emission Tomography

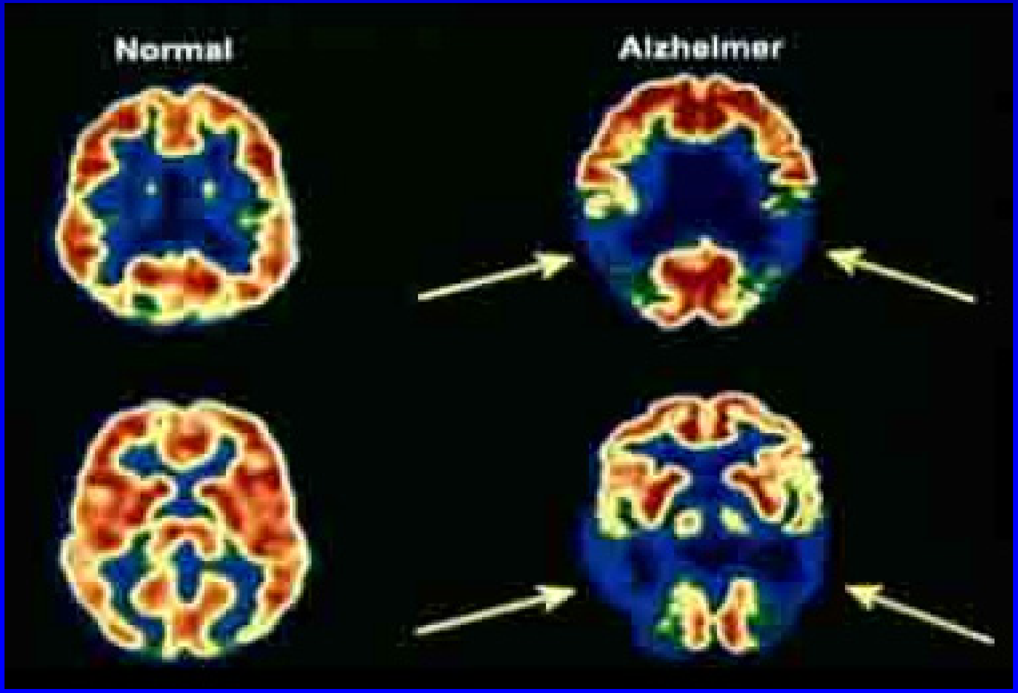
cyclotron

18F-FDG

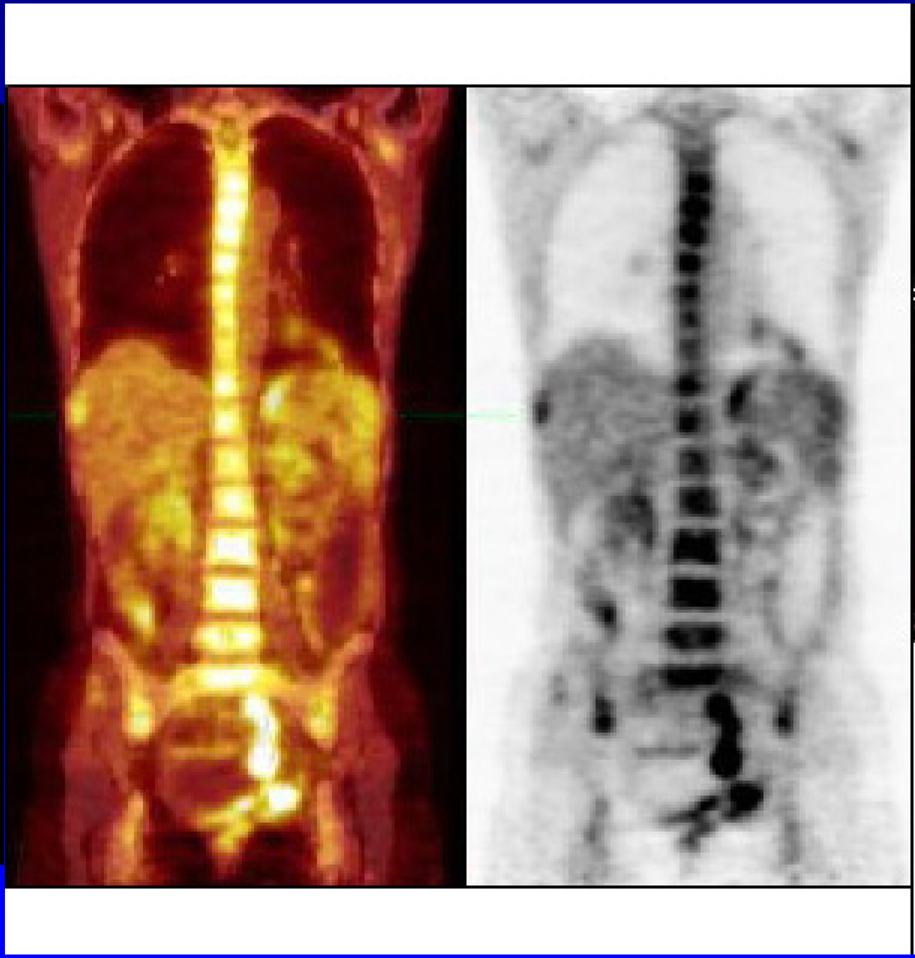


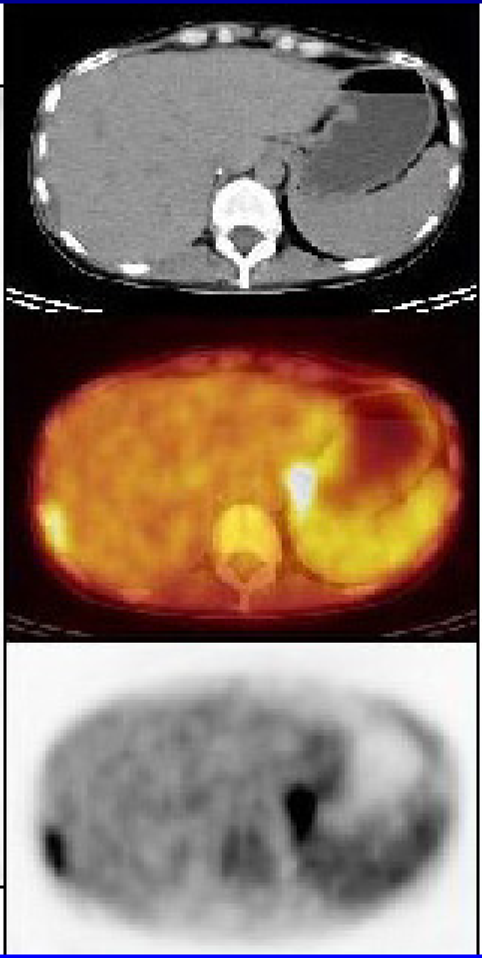


WB video

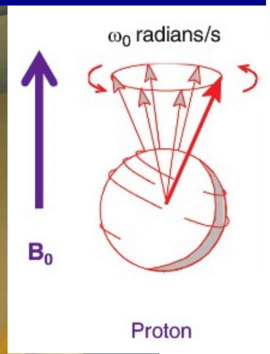


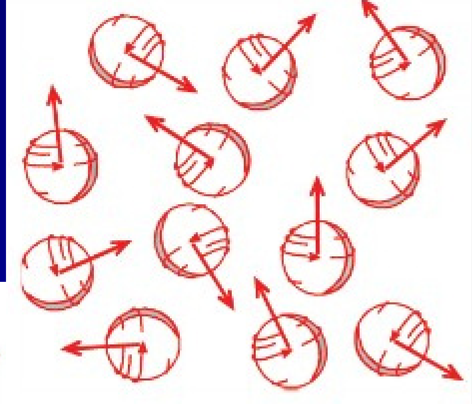
Multi-Modality Imaging

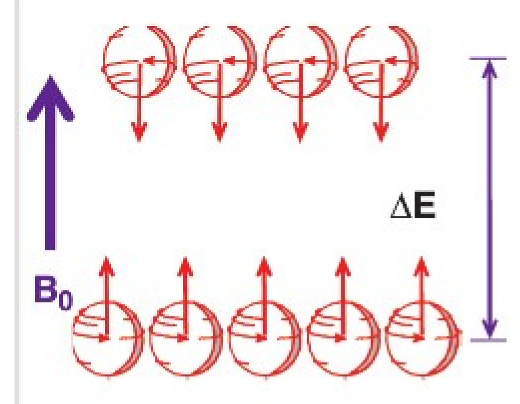


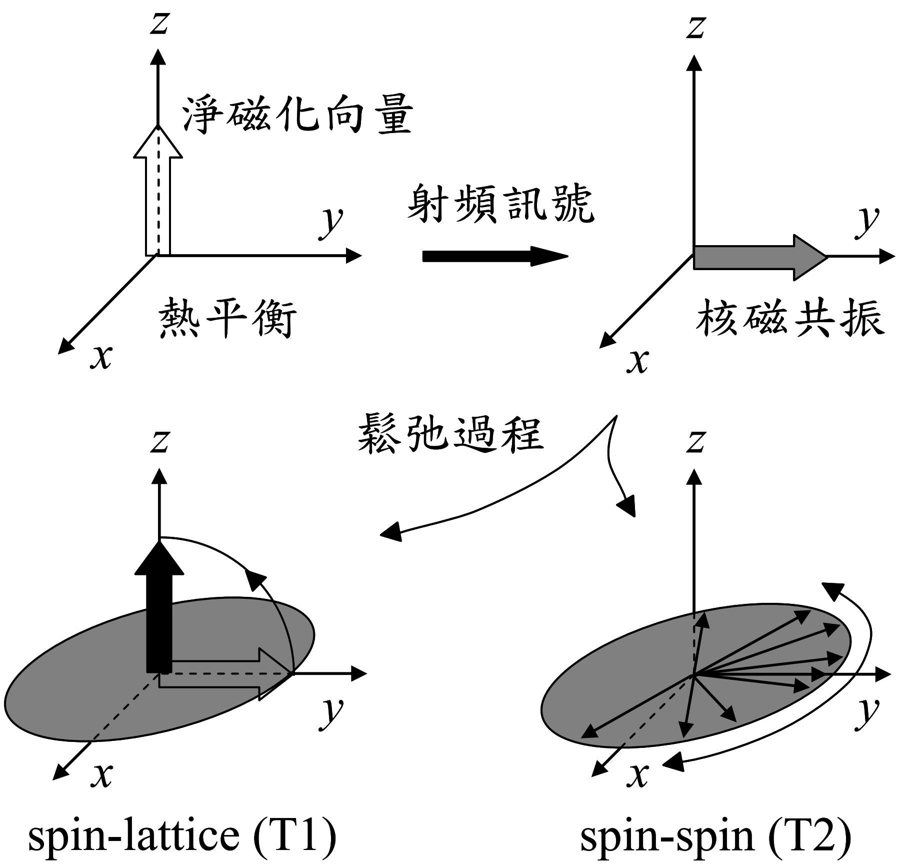


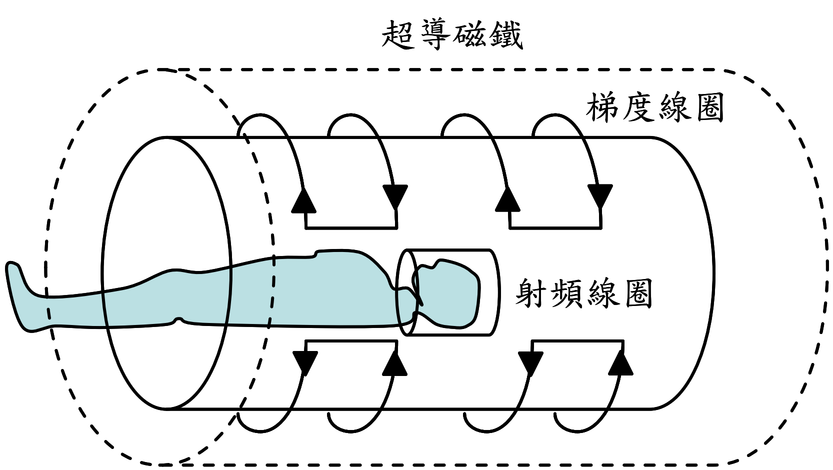
Nuclear Magnetic Resonance (NMR)



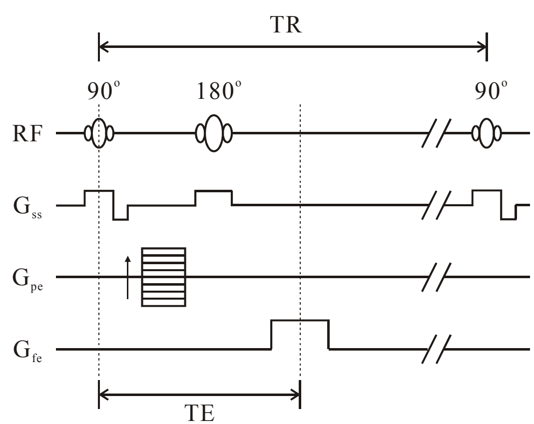


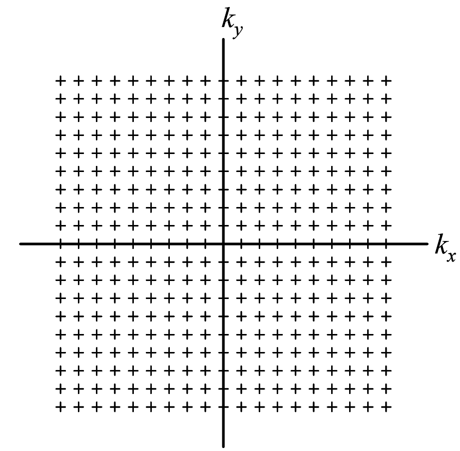


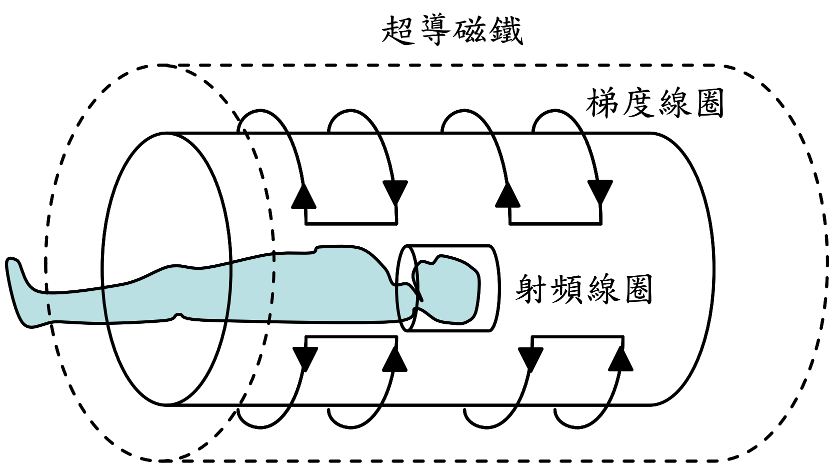




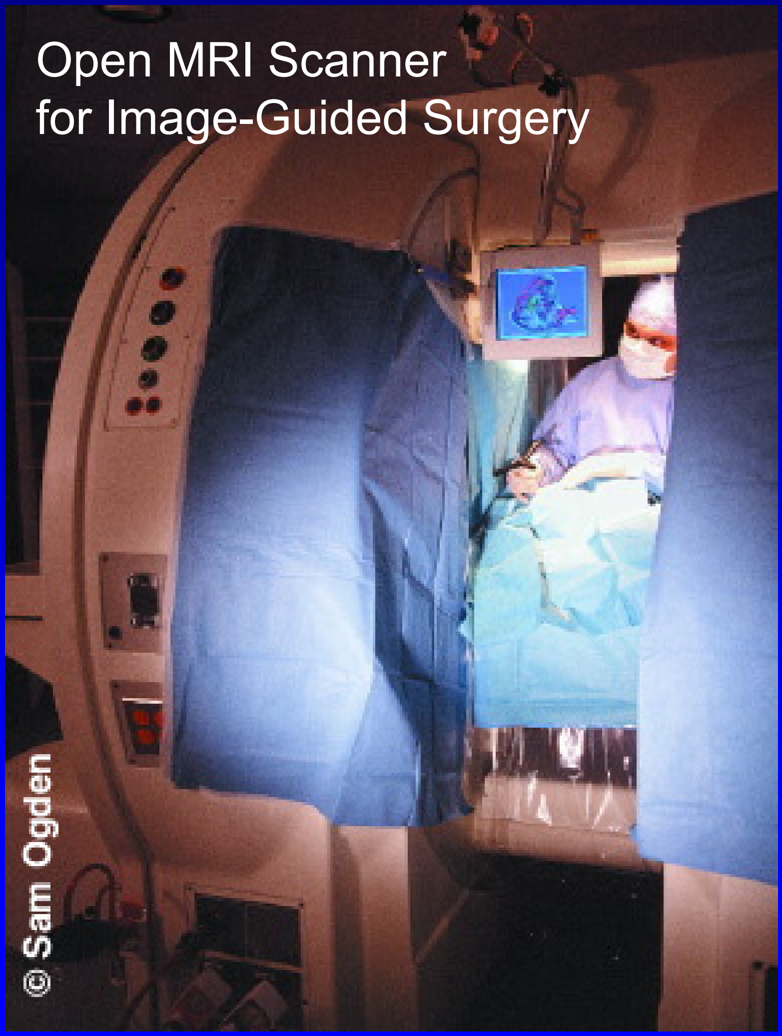
Magnetic Resonance Imaging (MRI)





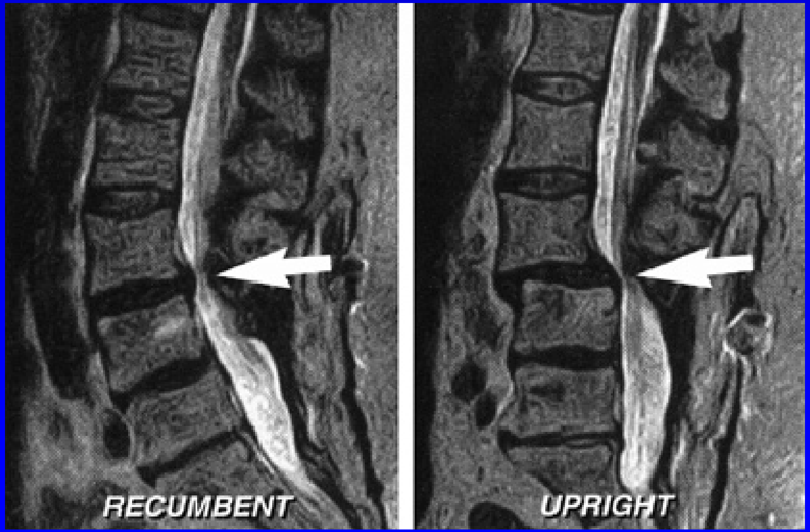


Magnetic Resonance Imaging (MRI)

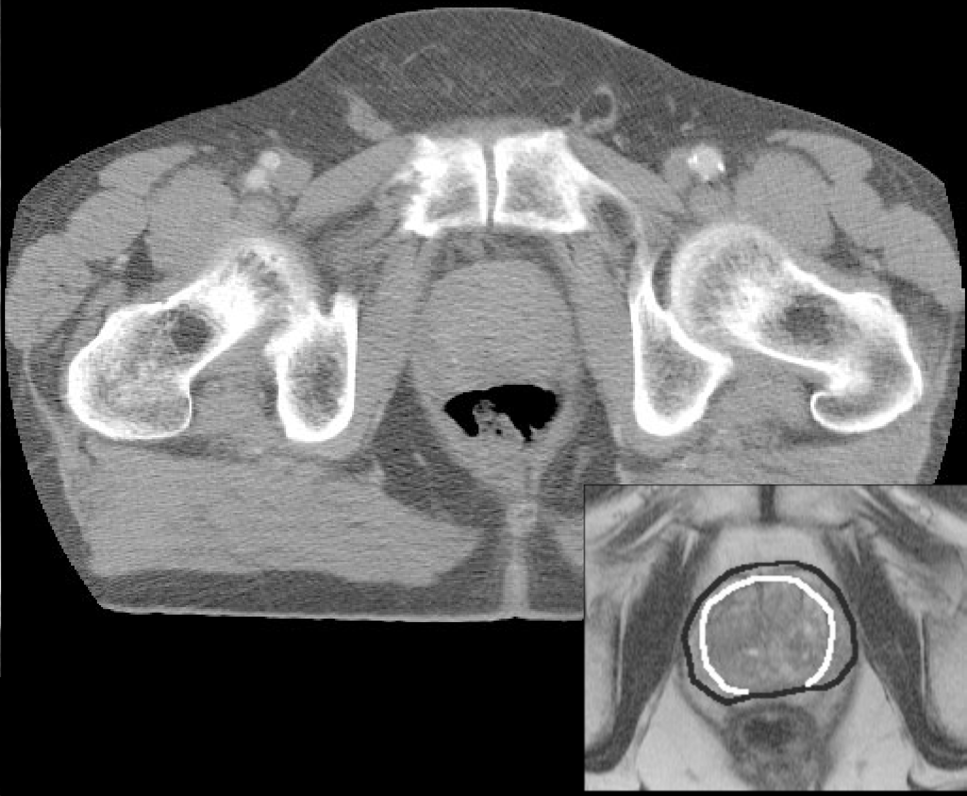


Open MRI Scanner
for Image-Guided Surgery

Upright MRI Scanner



MRI vs. CT

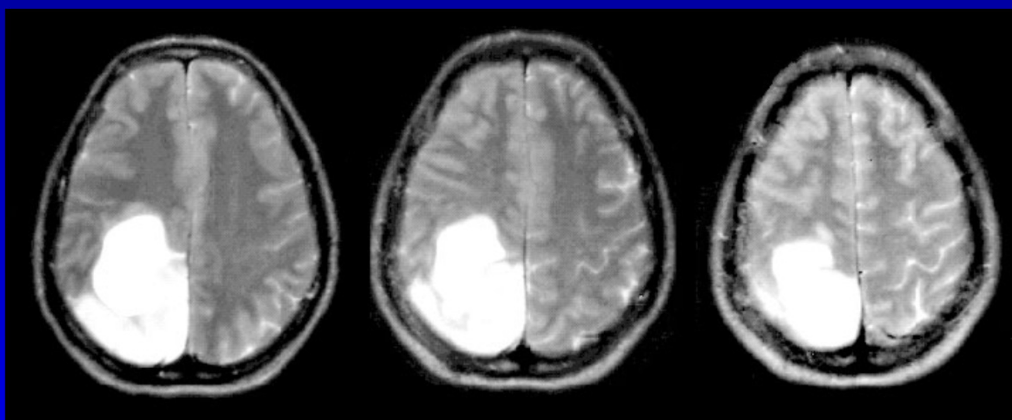


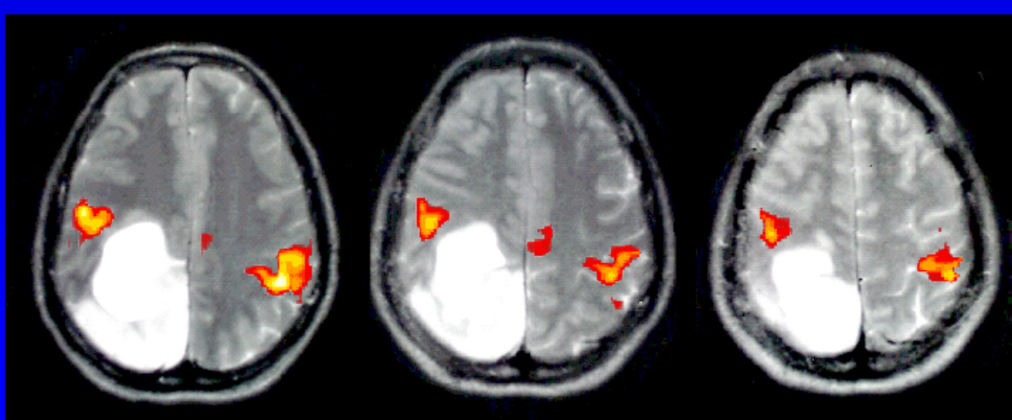
Functional MRI

Blood-oxygen-level-dependent (BOLD) Effect

Regions in brain with neuronal activation:

oxyhemoglobin ↗, deoxyhemoglobin (paramagnetic) ↘



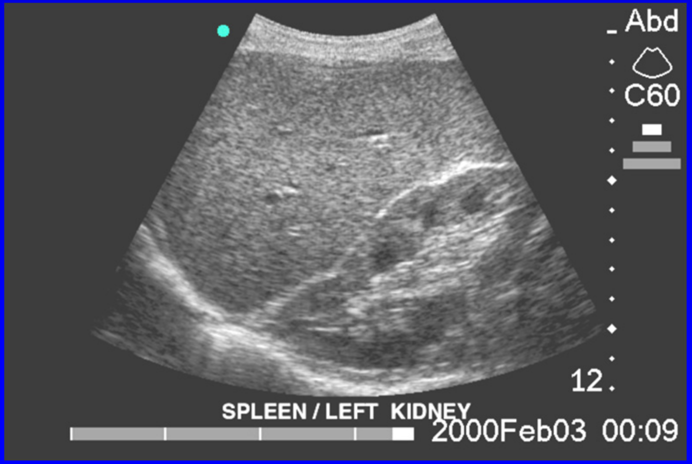


Ultrasound

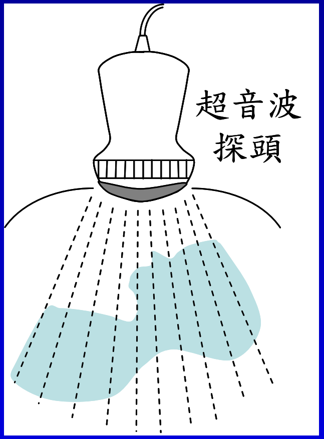
- Mechanical wave propagates in medium
- Human auditive frequency range: 20 Hz ~ 20 kHz
- Medical Ultrasound: 1 MHz ~ 10 MHz

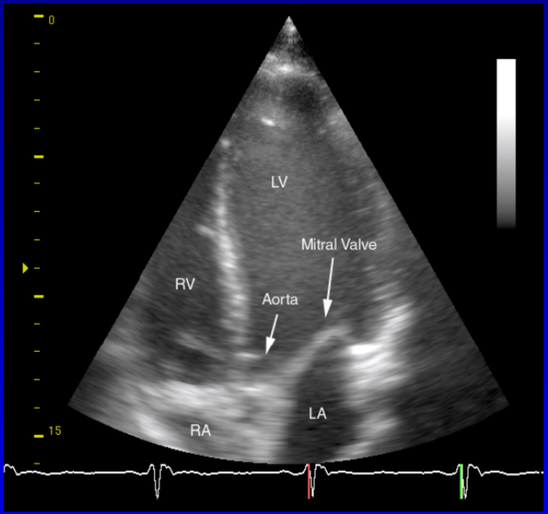
Diagnostic Ultrasound Basis

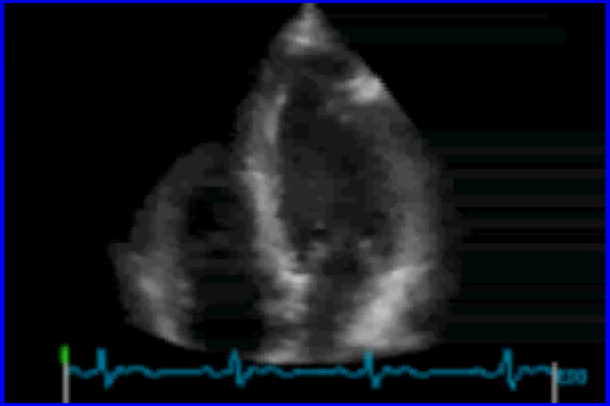
- 超音波發射源
- 組織介面形成反射
- 接收器接收反射波
- 計算距離以形成影像

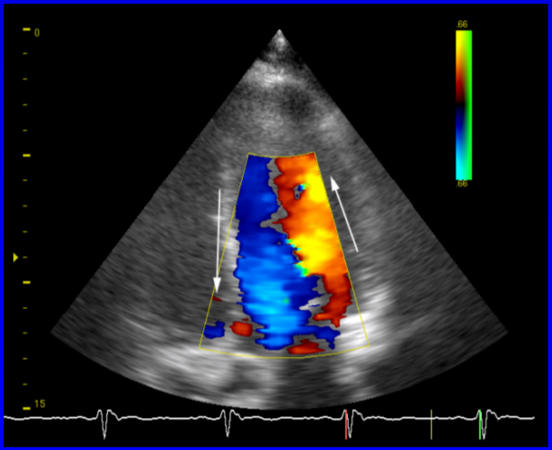


Medical Ultrasonic Imaging

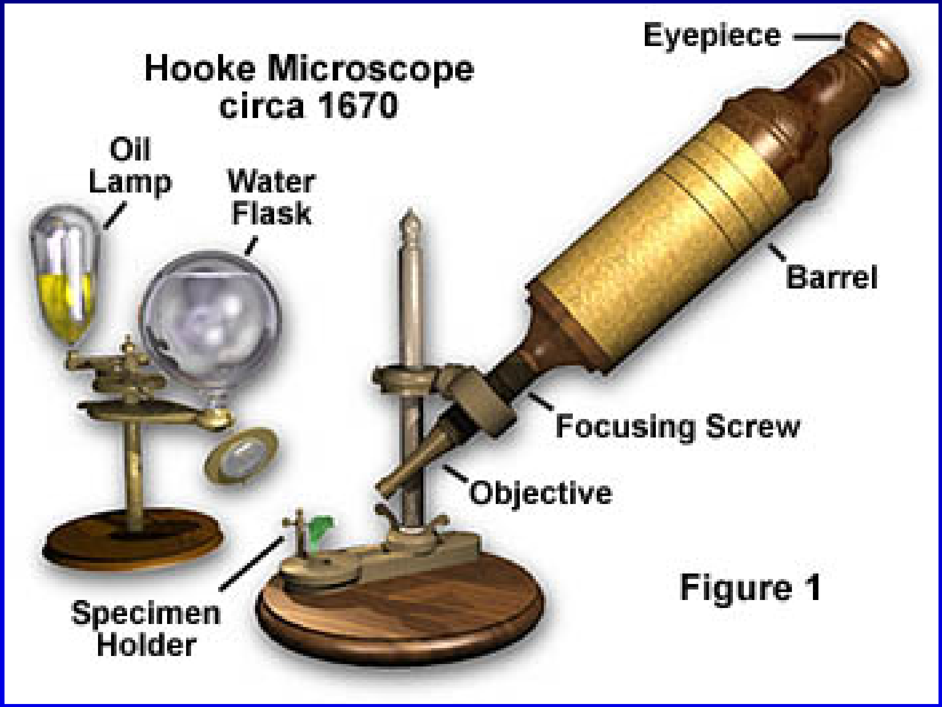


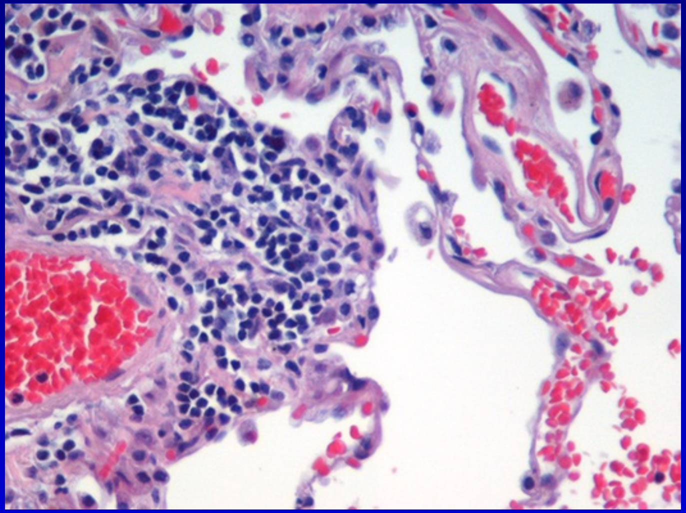






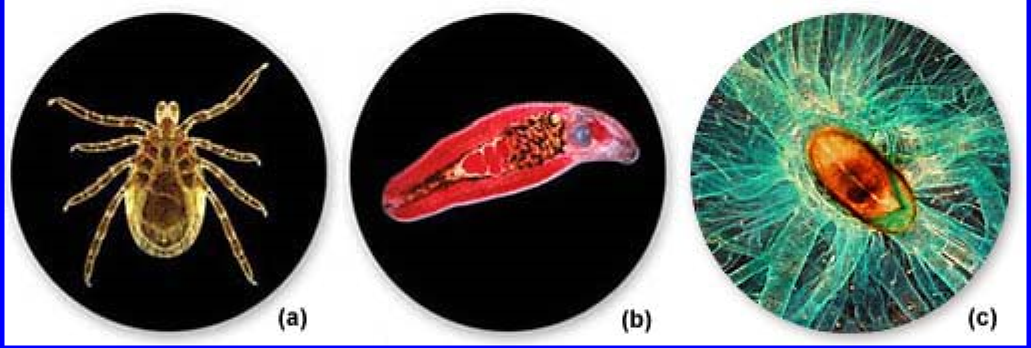
Optical Imaging - Microscopy





H&E (haematoxylin and eosin) stain:
Cell nuclei are blue-purple, red blood cells are red, other cell bodies and extracellular material are pink, and air spaces are white.

Stained and Unstained Specimens in Darkfield Illumination



(a) Deer tick 扁蝨 (b) Helminth trematode 蠕蟲、吸蟲 (c) 蠶的氣管及氣孔

Living Cells in Brightfield and Phase Contrast

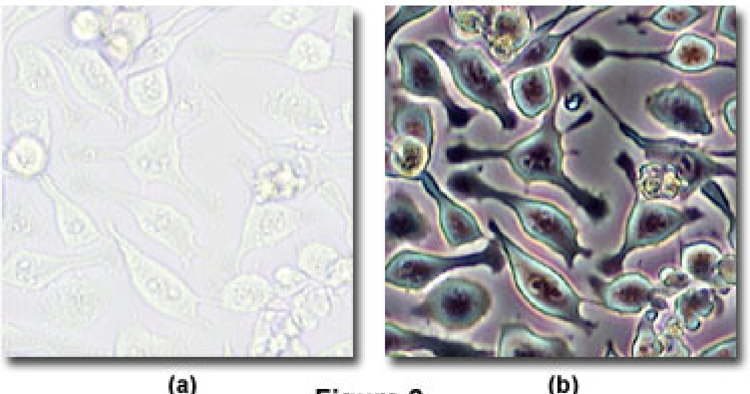
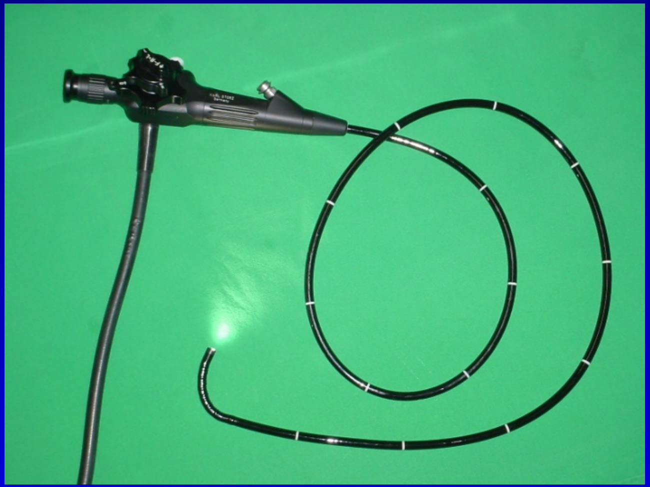
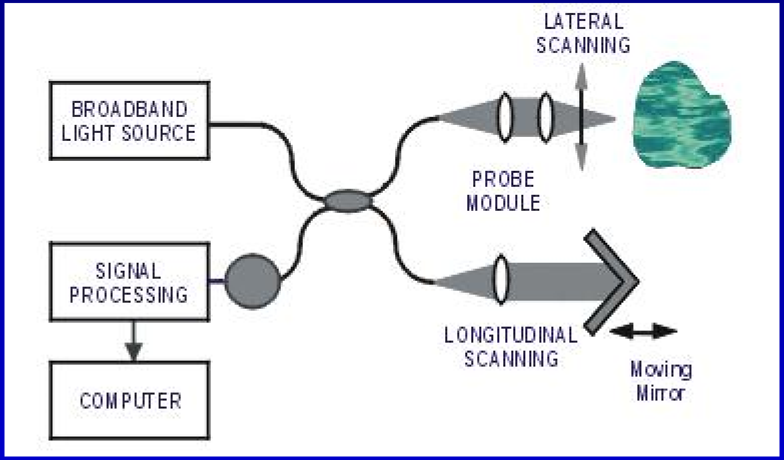
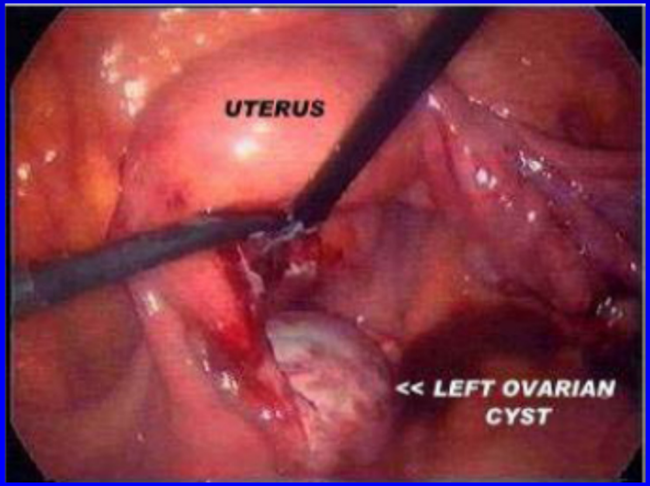


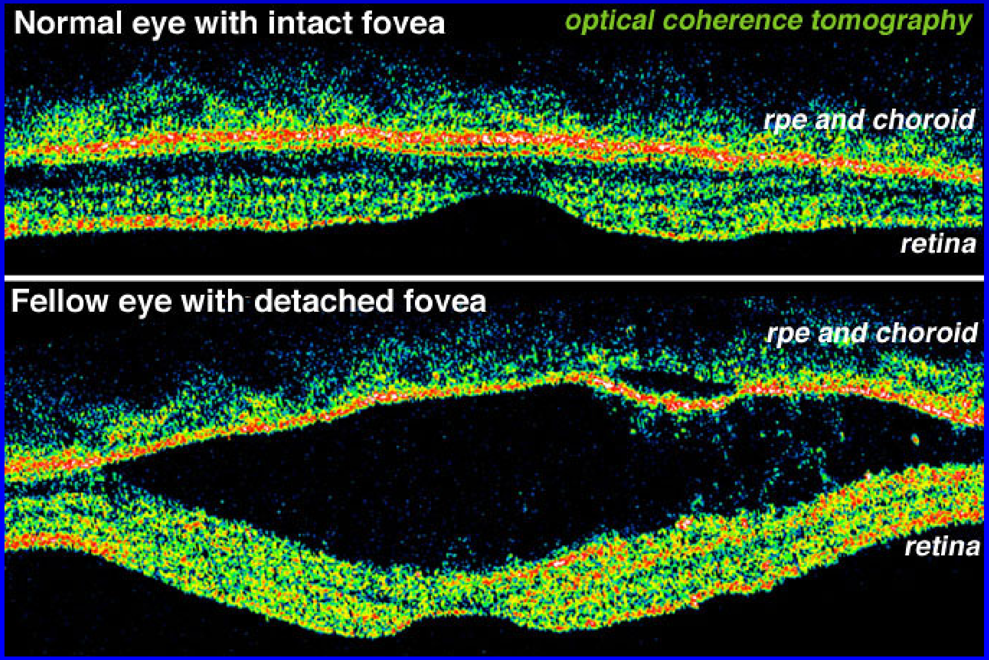
Figure 2

Optical Imaging

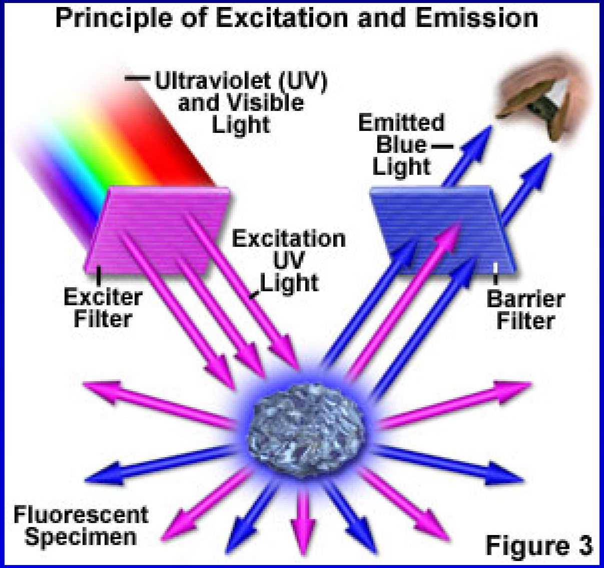




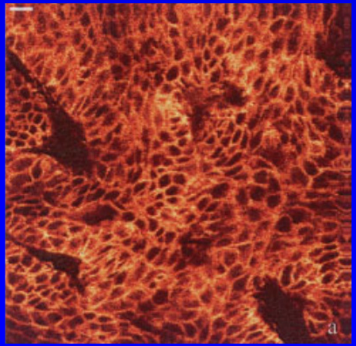




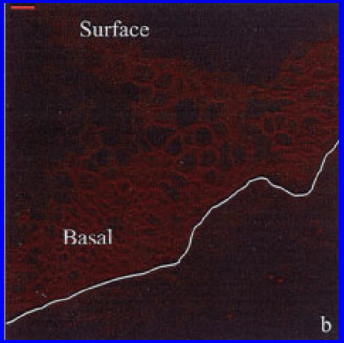
Fluorescence Imaging



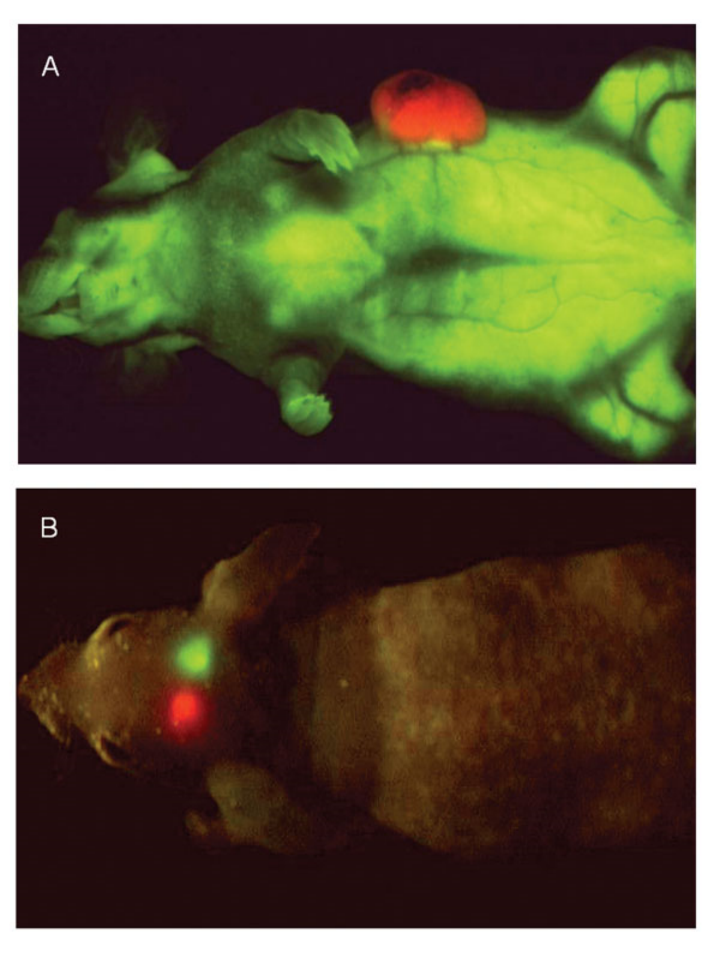
Tongue Biopsies



ABNORMAL

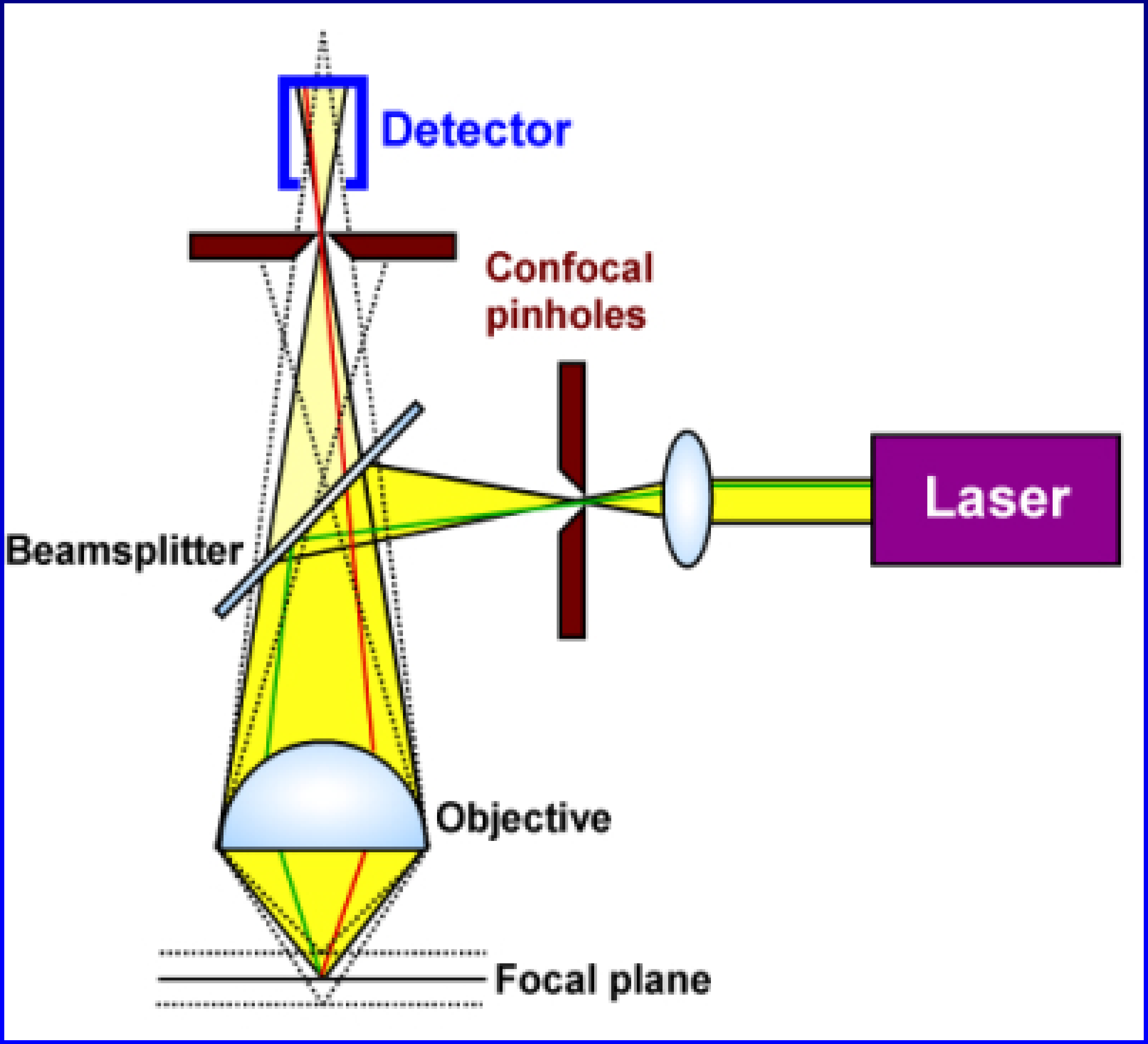


NORMAL



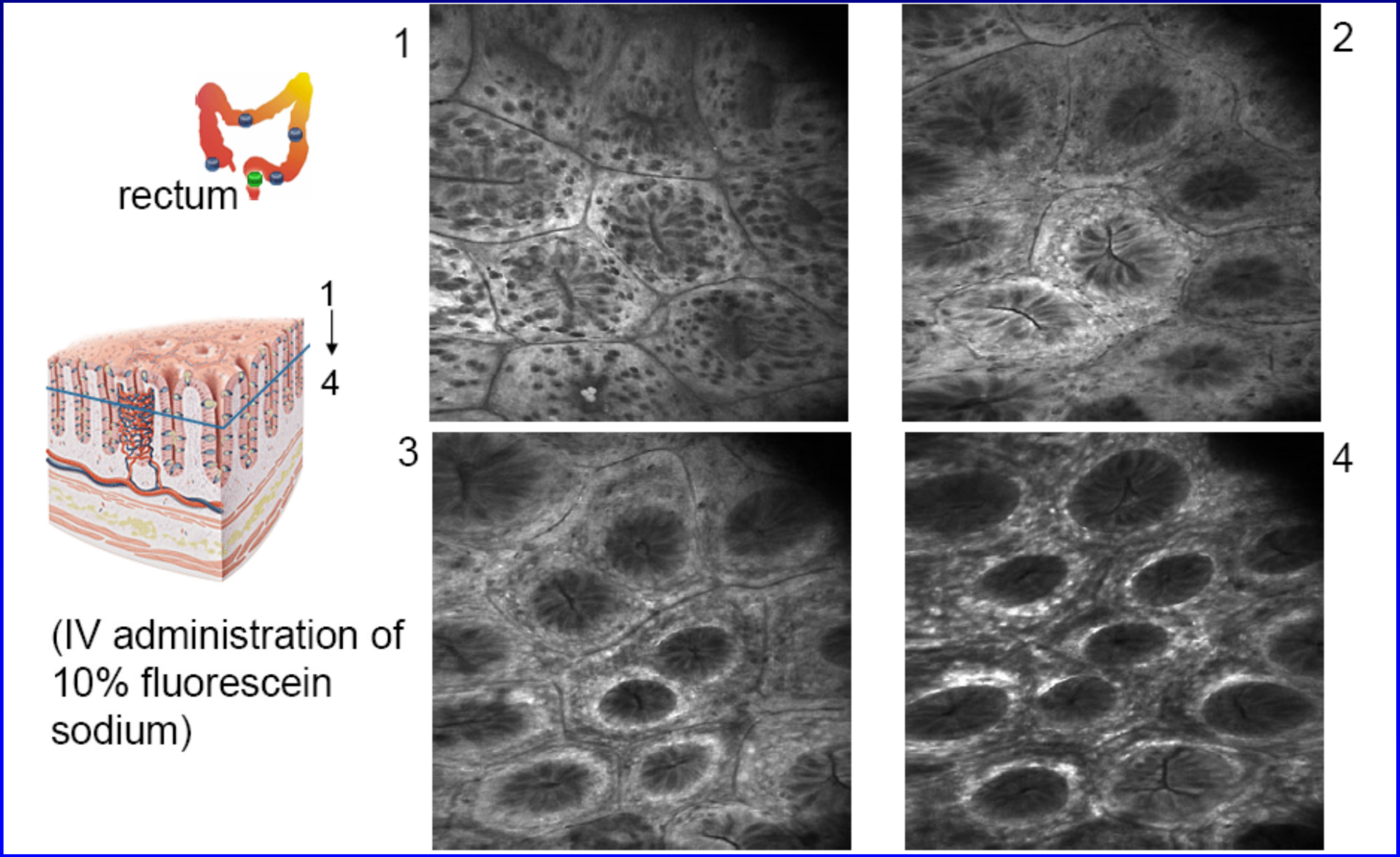
Multicolor with GFP and RFP

Confocal Fluorescence Imaging



(http://www.bio.brandeis.edu/marderlab/microscopyB.html)

Confocal Fluorescence Imaging



(IV administration of 10% fluorescein sodium)

Significance of Small-Animal Imaging

- Mice models, in particular, have following advantages:
  - Low maintenance cost
  - Rapid breeding cycles
  - High genetic homology with humans
  - Well-developed methodology for genetic manipulation
- *In vivo* imaging enables longitudinal studies:
  - Reduce the number of laboratory animals used
  - Reduce intersubject variability
- Imager Prerequisites
  - High Sensitivity
  - High Resolution

Comparison of Medical Imaging Modalities

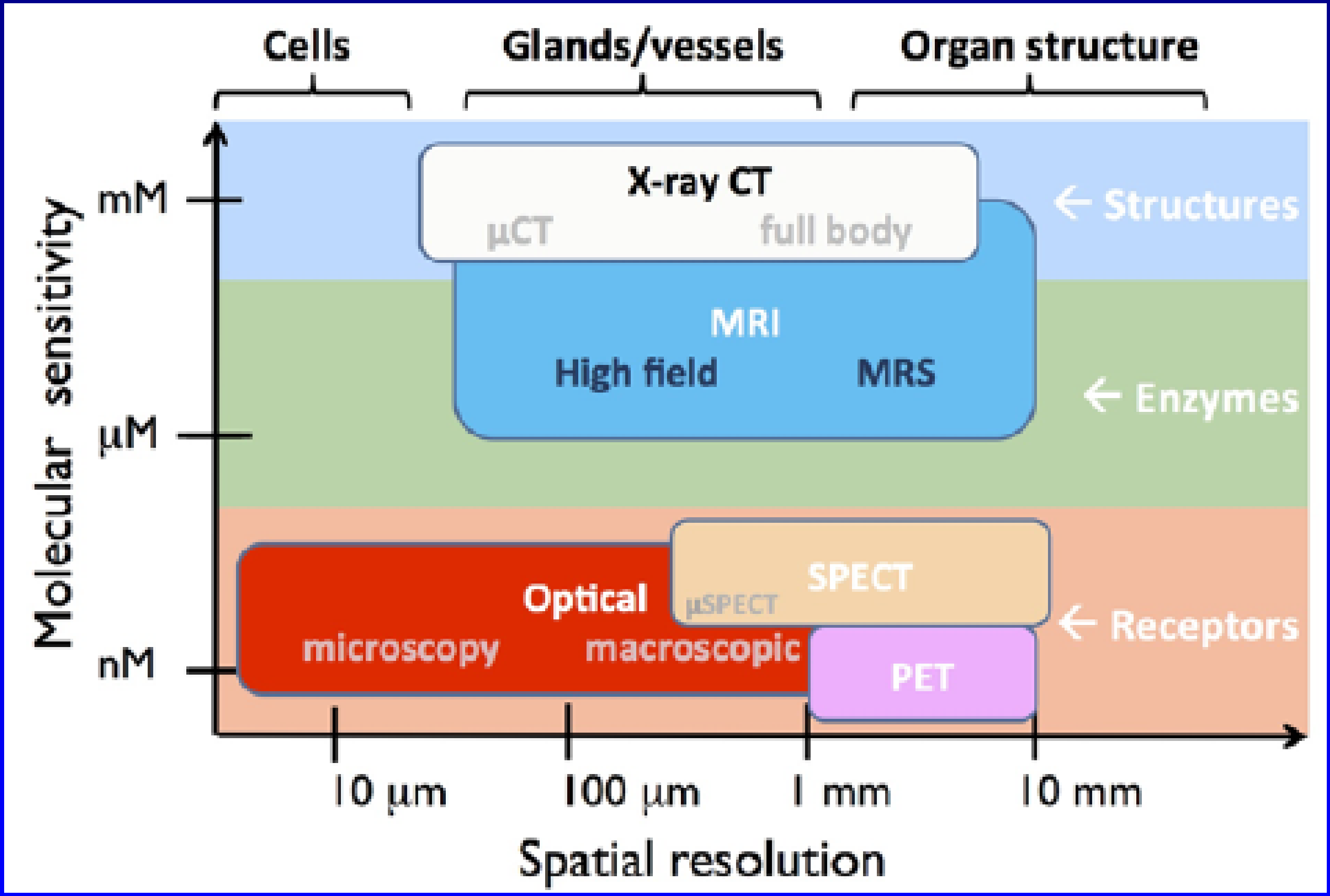


Figure 1 from Quantitative in vivo cell-surface receptor imaging in oncology: kinetic modeling and paired-agent principles from nuclear medicine and optical imaging
Kenneth M Tichauer et al 2015 Phys. Med. Biol. 60 R239 doi:10.1088/0031-9155/60/14/R239

各種活體生醫影像技術比較

生醫影像技術	X 光及電腦 斷層影像	核子醫學影像	磁振造影	超音波影像	光學影像
影像資訊	解剖	功能	解剖或功能	解剖	解剖或功能
影像對比來源	衰減係數	核醫藥物 濃度分佈	解剖：氫原子核 密度分佈、T1、T2 功能：血氧濃度	聲波阻抗	解剖： 反射或穿透係數 功能： 螢光藥物分佈
使用頻率、波長 或能量等級	電磁波 幾十 keV, Å	電磁波 幾百 keV	射頻線圈磁場調制頻率 幾十 MHz	超音波 MHz	電磁波 μm
穿透深度	無限制	無限制	無限制	15 cm	cm
三維資料 取得方式	斷層掃描	斷層掃描	傅立葉空間取樣	直接掃描	直接掃描
橫向解析度等級					
臨床	mm	cm	mm	mm	μm/cm
臨床前 (小動物專用)	0.1 mm	mm	0.1 mm	0.1 mm	μm/mm

Summary

- Medical imaging is a powerful tool for medical diagnoses, treatment planning, and therapy evaluation.
- Mouse models of human diseases are important in biomedical research to study disease mechanisms and investigate potential therapies.
- Design and development of new small-animal imagers that measure the biological processes at better sensitivity and spatial resolution remain an expanding research area.
- GOAL: to permit diagnosis before symptoms appear and provide individualized, genetic-based therapy.