Current Technology and Challenges for Medical Imaging Modalities

Terry Peters
Robarts Research Institute
London ON

Mark Henkelman
Mouse Imaging Centre,
Hospital for Sick Children
Toronto

Overview

- History and overview of current imaging systems
- Applications
- Challenges
- Small animal imaging challenges (Mark Henkelman)

Medical Imaging Modalities

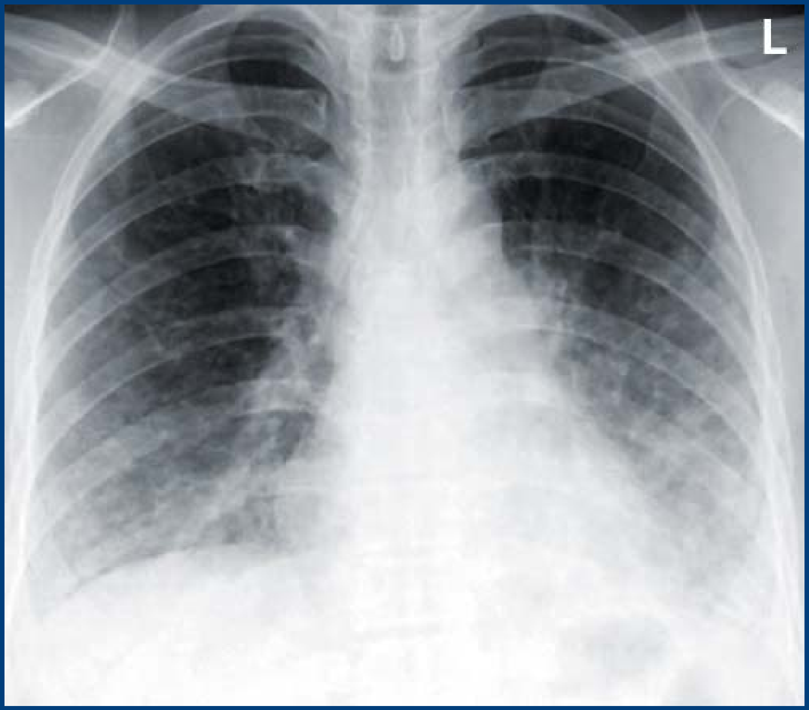
- X-ray Imaging
- CT Scanning
- Magnetic Resonance Imaging
  - anatomical Imaging
  - functional MRI
  - fibre tract imaging
- Positron Emission Tomography
- Ultrasound

In the beginning……X-rays

- Discovered in 1895

In the beginning……X-rays

- Discovered in 1895
- Mainstay of medical imaging till 1970's

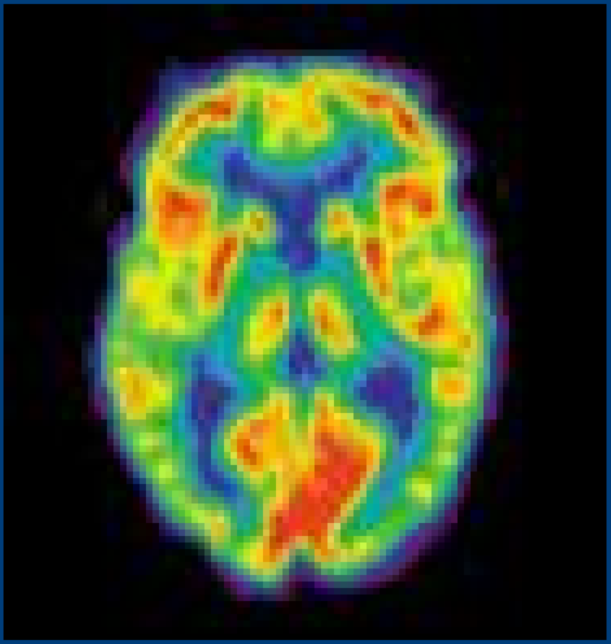


In the beginning……X-rays

- Discovered in 1895
- Mainstay of medical imaging till 1970's
- 1971 - CAT (CT) scanning

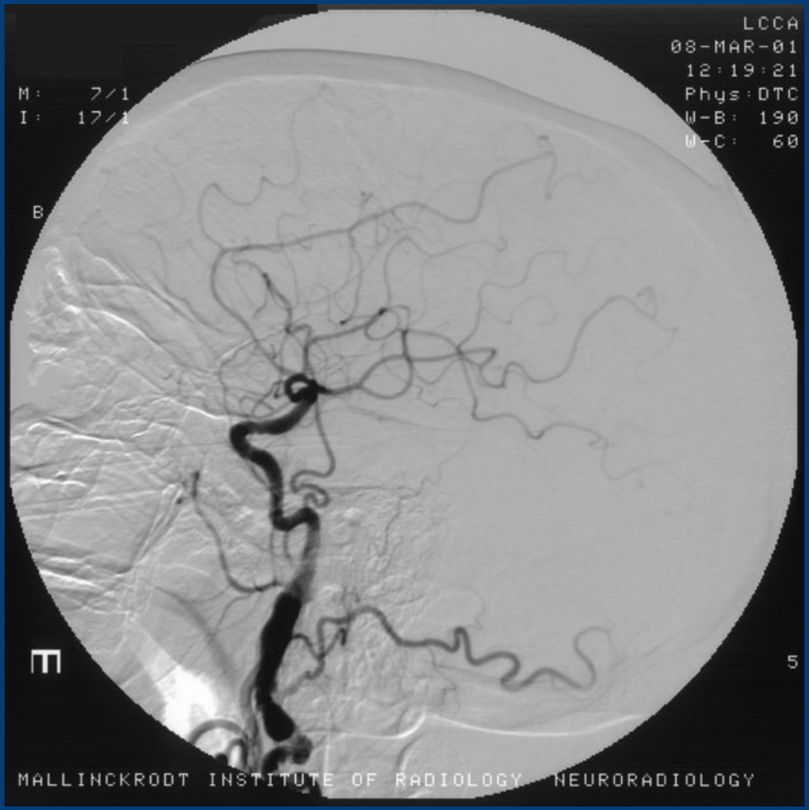
In the beginning……X-rays

- Discovered in 1895
- Mainstay of medical imaging till 1970's
- 1971 - CAT (CT) scanning
- 1977 - PET scanning



In the beginning……X-rays

- Discovered in 1895
- Mainstay of medical imaging till 1970's
- 1971 - CAT (CT) scanning
- 1977 - PET scanning
- 1978 - Digital Radiography



In the beginning……X-rays

- Discovered in 1895
- Mainstay of medical imaging till 1970's
- 1971 - CAT (CT) scanning
- 1977 - PET scanning
- 1978 - Digital Radiography
- 1980 Magnetic Resonance Imaging

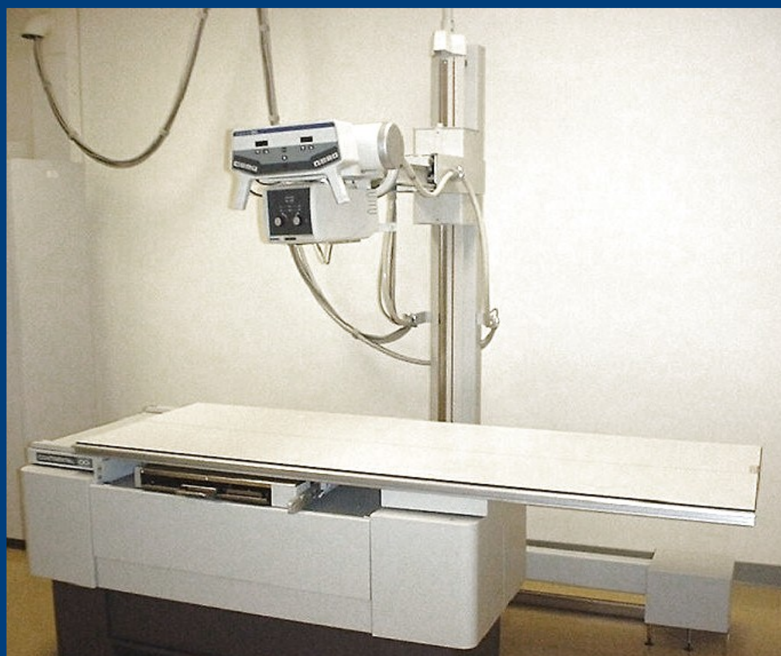
robarts RESEARCH

X-ray System

Film-screen cassette

Screen – X-ray to light conversion

Film – Receptor
Display
Storage



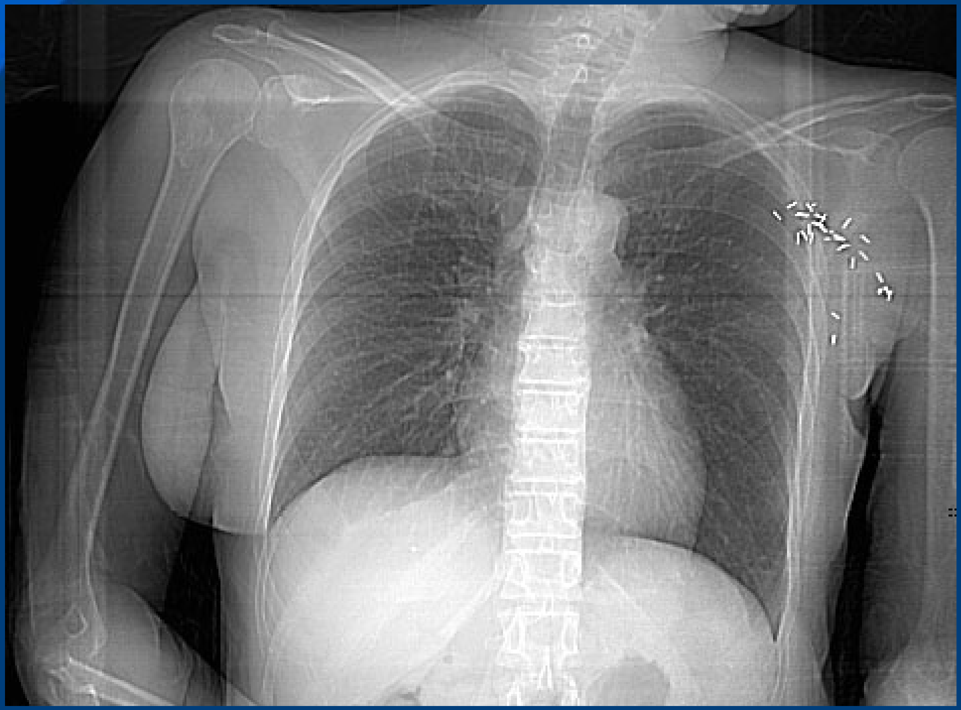
Typical X-ray system

Electronic receptor

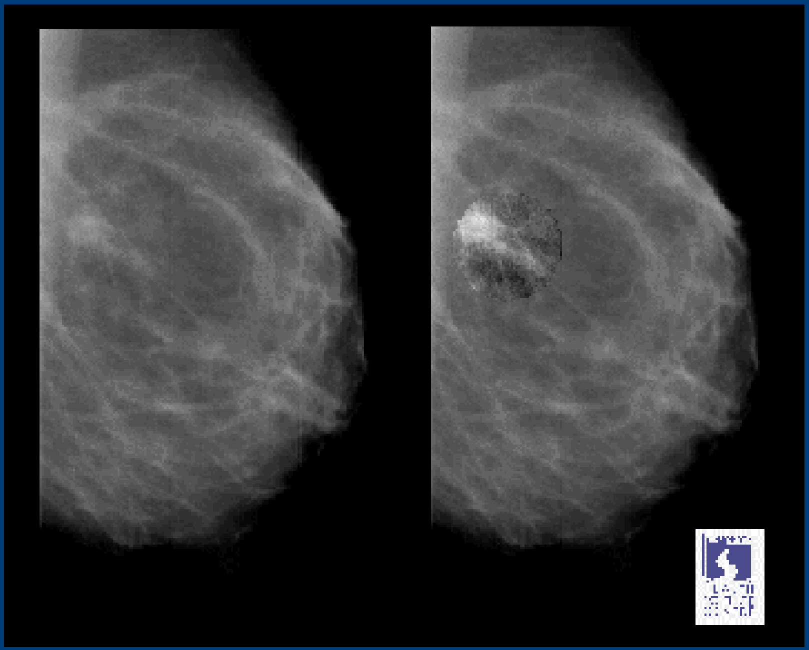
~10MB / image

robarts RESEARCH

Digital radiographs

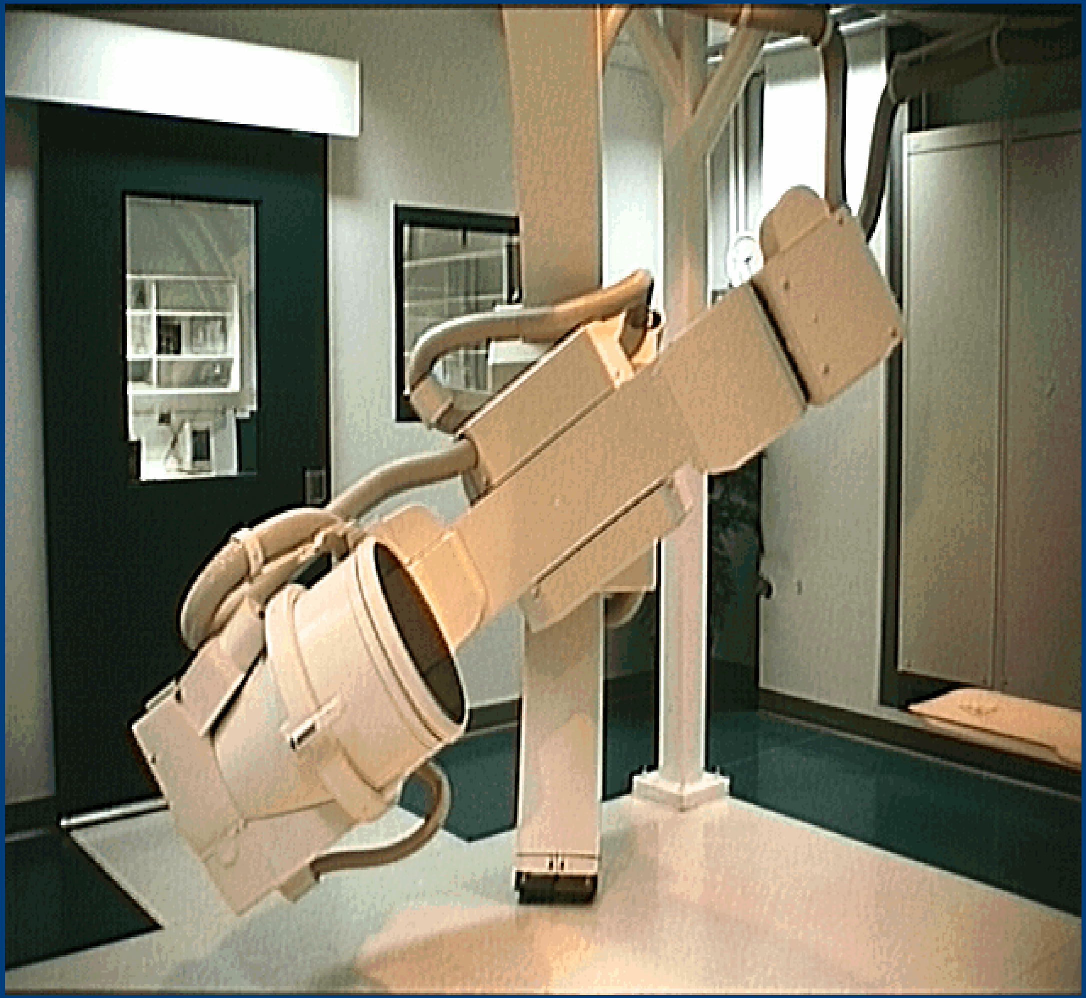


Univ Washington teaching file



Dr Martin Yaffe SWCHSC, Toronto

C-arm angiography



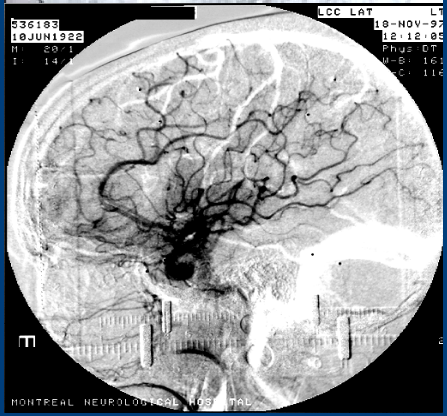
David Holdsworth RRI

Fields Workshop, Waterloo Oct 22, 2005

X-ray angiography - imaging vessels

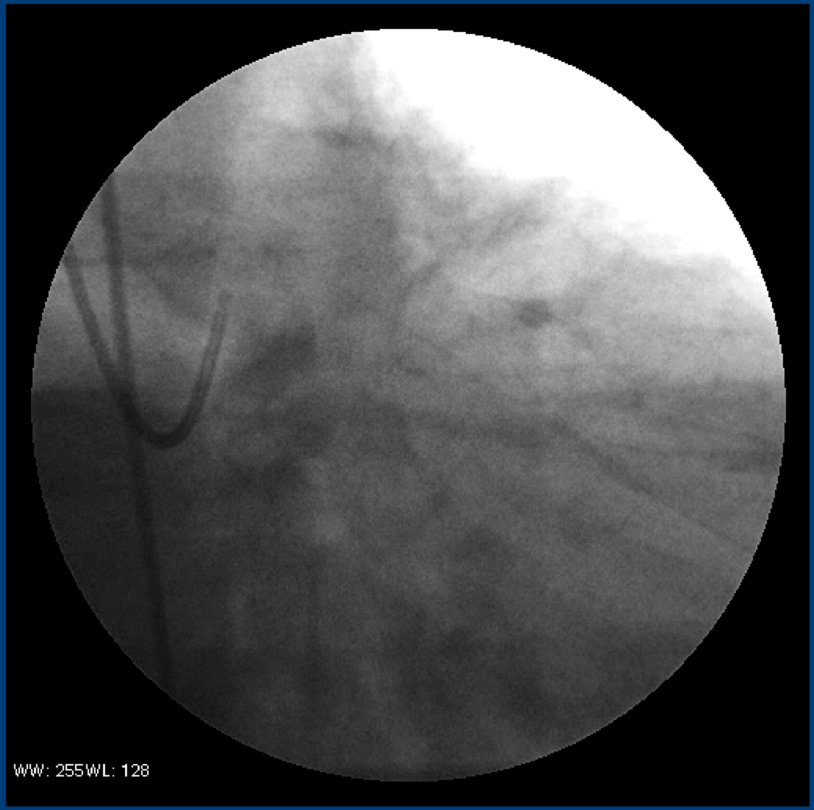
Arterial

Venous



A-V

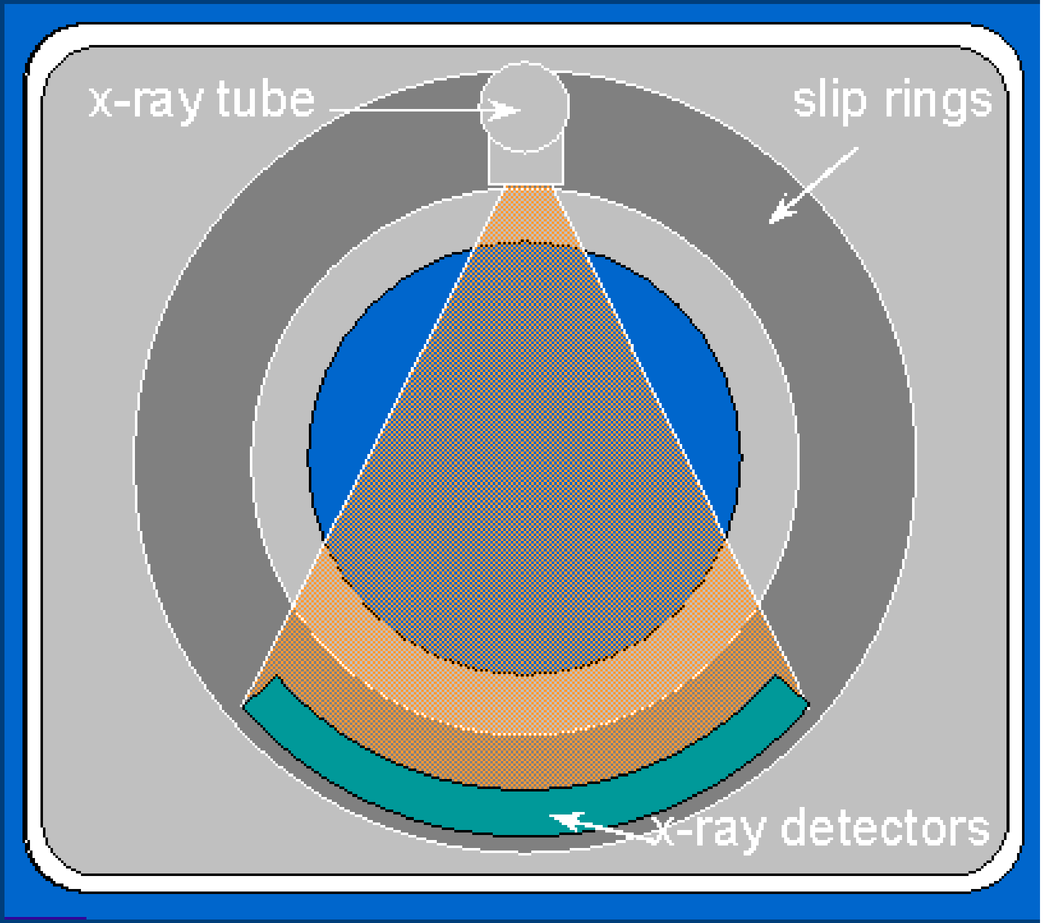
Neuro



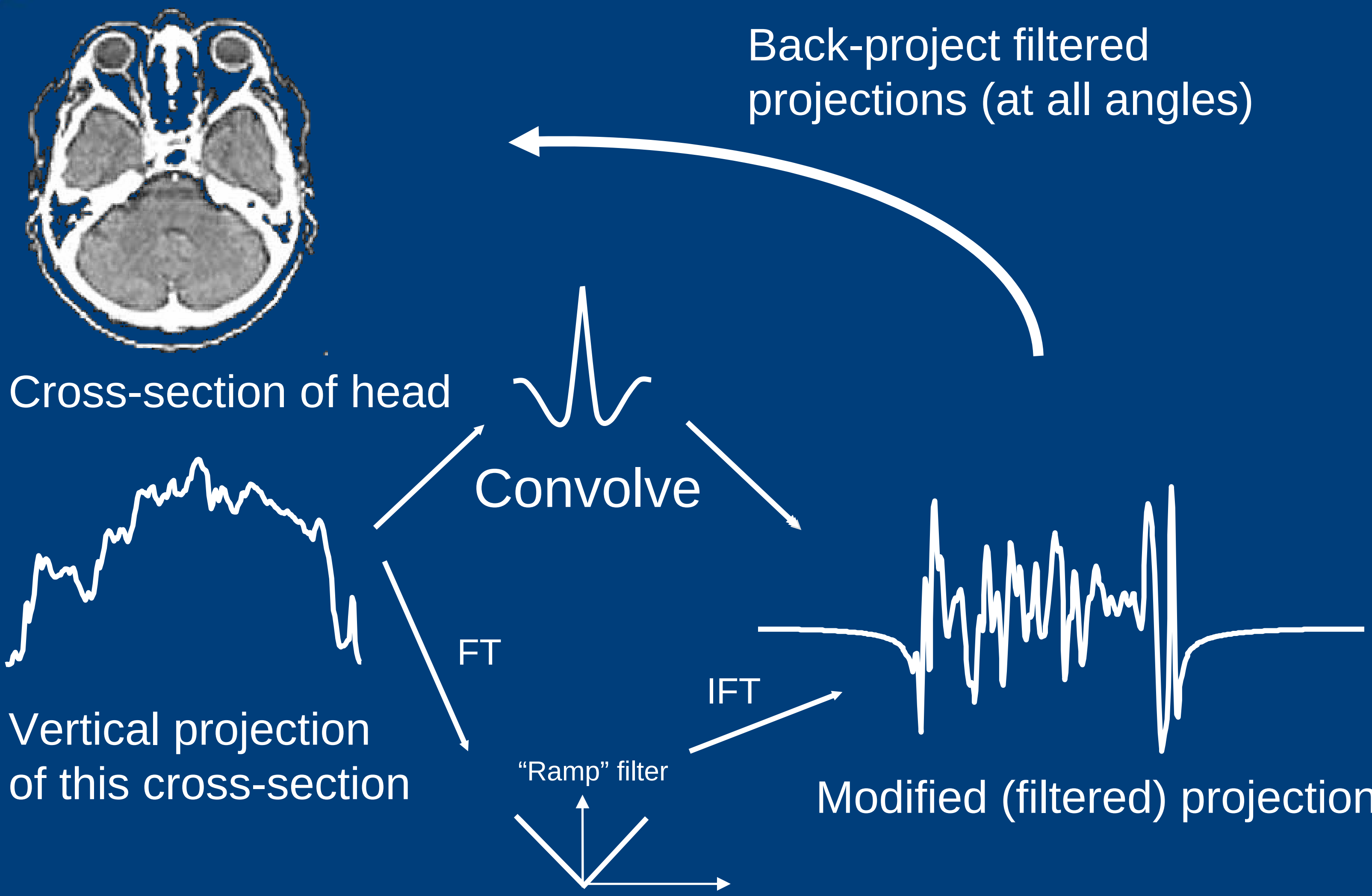
Cardiac

CT Scanning

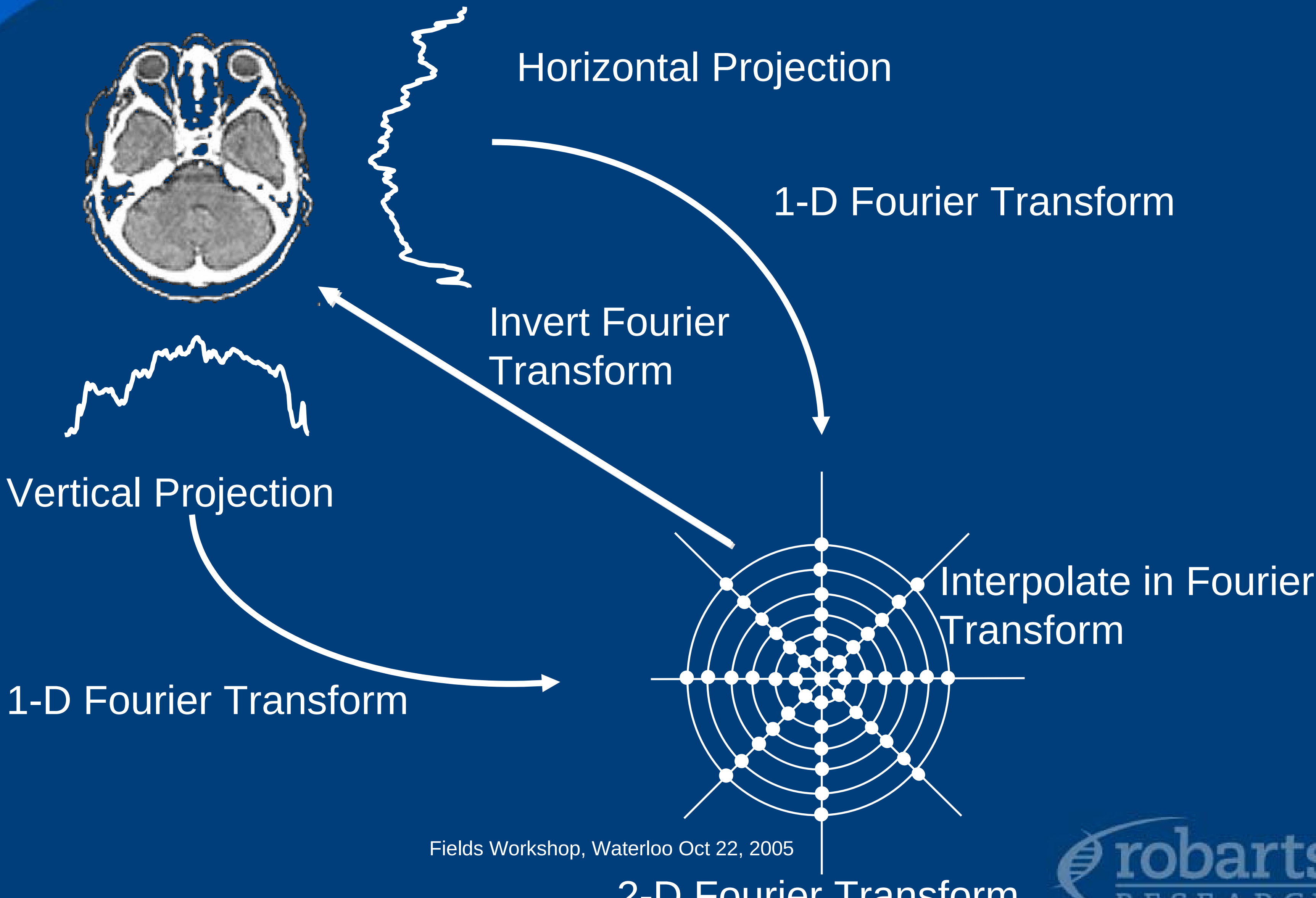
- Cross-sections using x-rays.
- Acquire projections of body from different directions
- Back-project HP filtered projections onto reconstruction plane



Back-projecting Filtered Projections

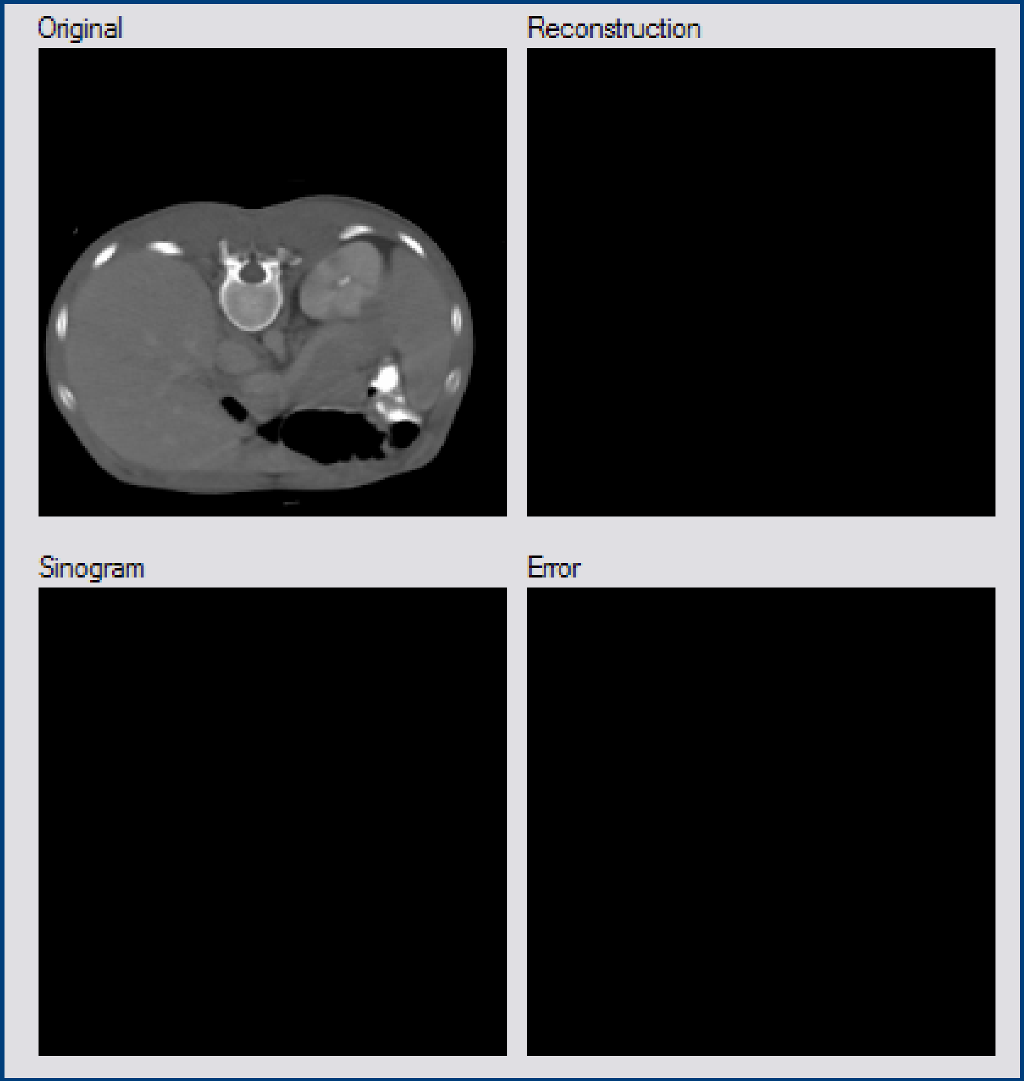


Alternative Viewpoint - Central Section Theorem



robarts RESEARCH

CT Reconstruction

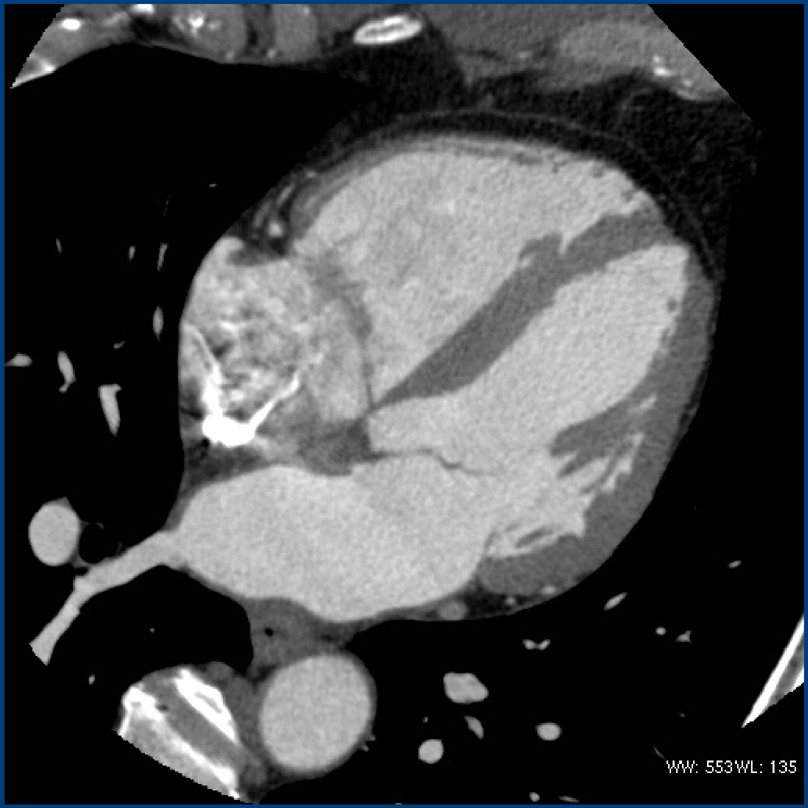


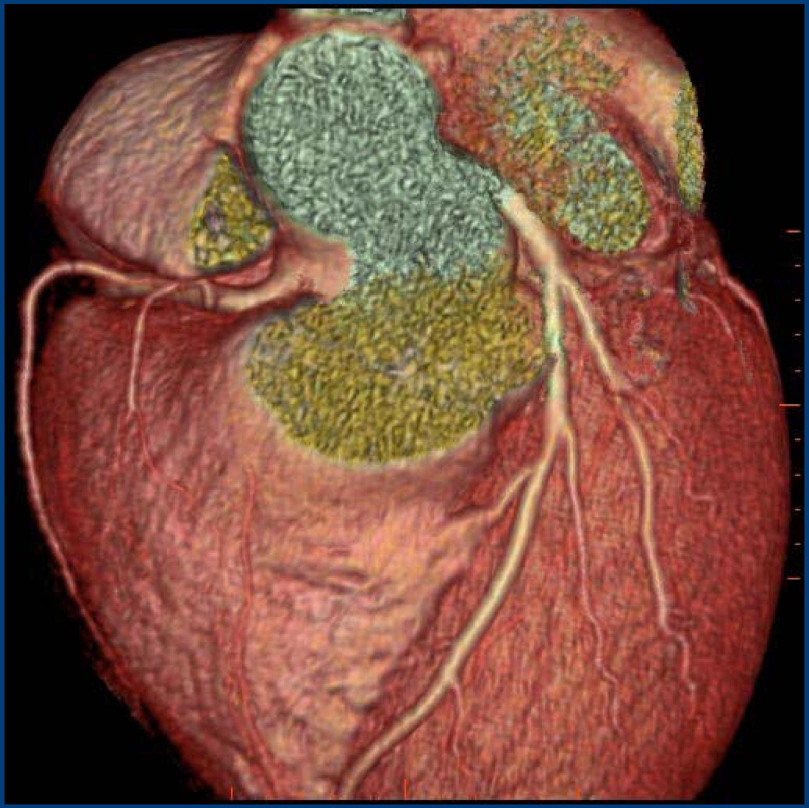
CT Scanning

- Original
  - 80 x 80 Single or two slices
  - 4 mins acquisition time
  - 4-10 mins per slice recon
- Today
  - 64 slices simultaneously
  - < 1 sec acquisition
  - ~ .25 sec/slice recon

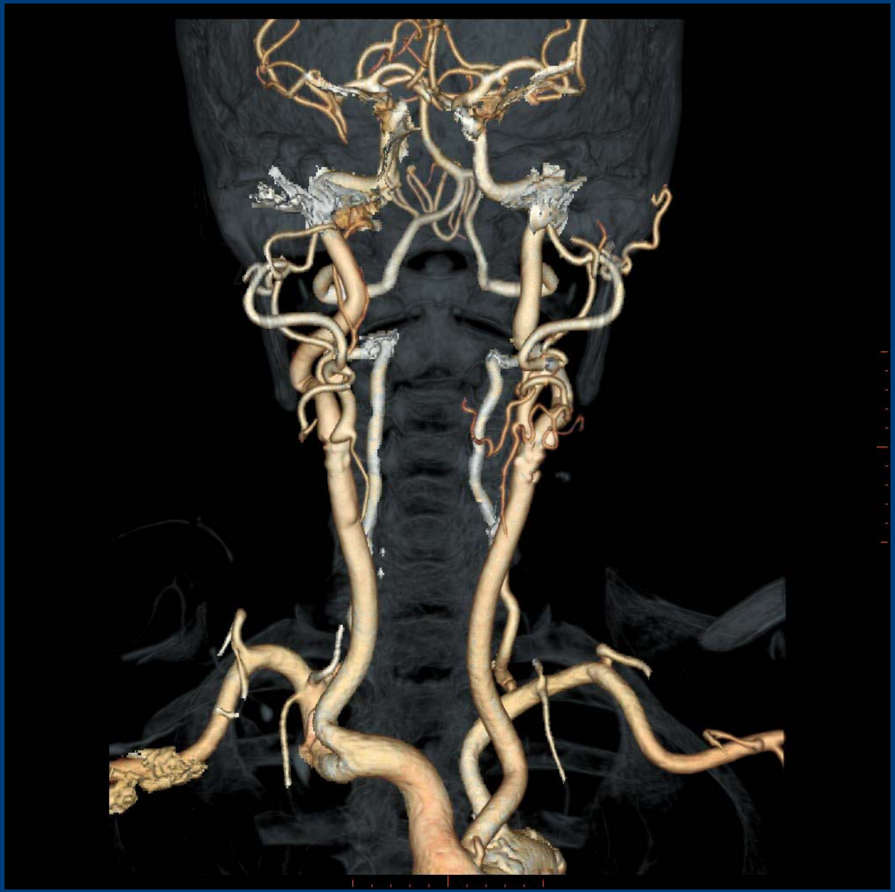
Dynamic CT

Beating Heart

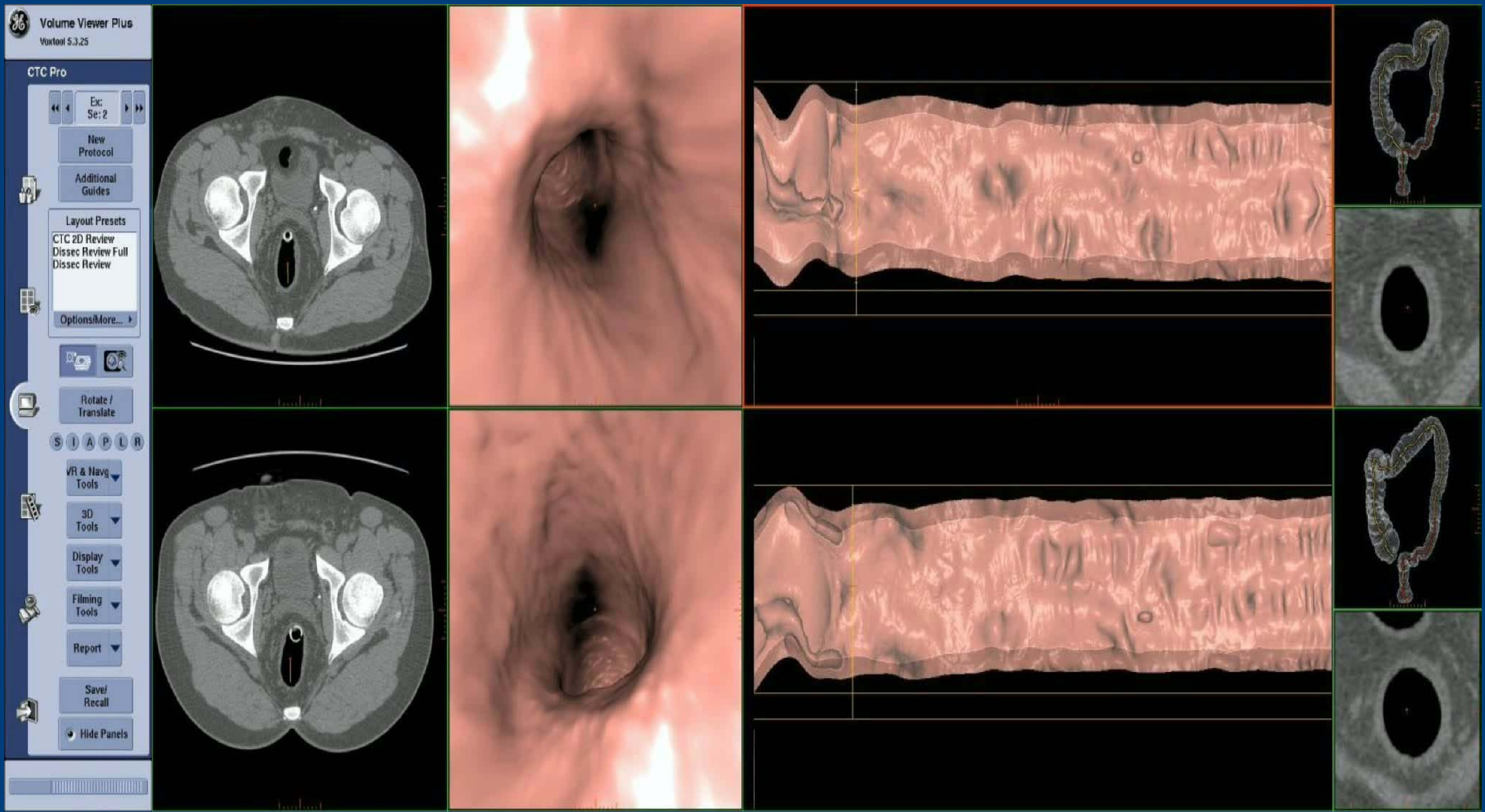




CT Angiography



Virtual Endoscopy (colonoscopy)



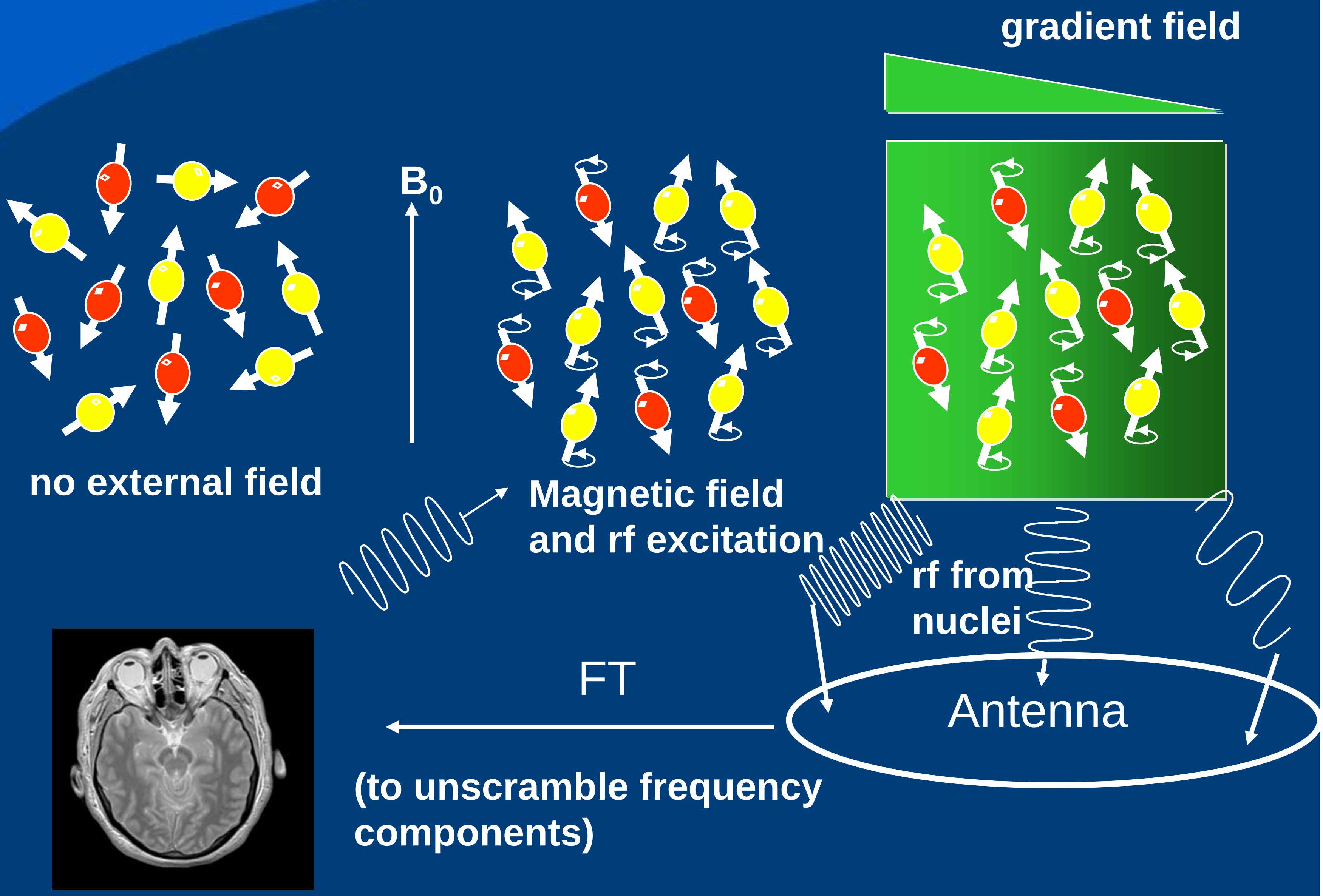
robarts RESEARCH

Magnetic Resonance Imaging

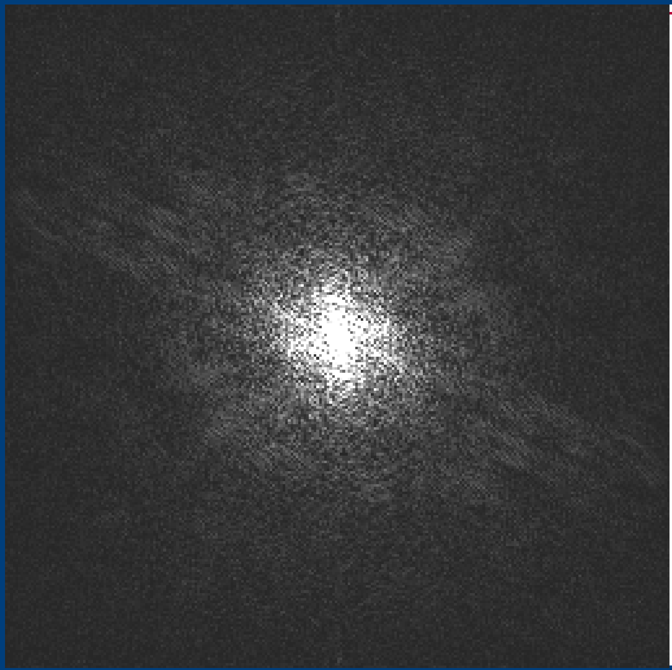
- Uses principles of Nuclear Magnetic Resonance (NMR)
- Roots in Physics and Chemistry labs
- Images magnetic properties of tissue
- Builds on mathematical foundation of CT
- Became MRI in medical imaging community …. "Nuclear" considered politically incorrect!
- "Most important medical breakthrough since the invention of Xrays"

Magnetic Resonance Imaging

- H^1 nuclei wobble (precess) in a magnetic field
- Precessing nuclei emit rf signals
- Frequency of wobble depends on magnetic field
- Place body in a spatially (and time)-varying magnetic field
- Record spectrum of emitted rf signals
- Fourier transform turns these signals into an image

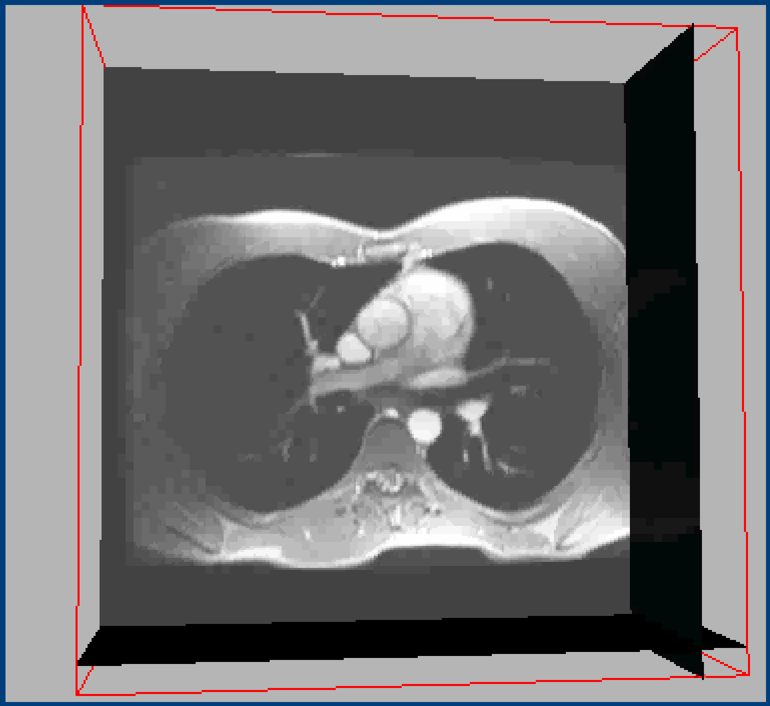

gradient field
no external field
B_0
Magnetic field
and rf excitation
rf from
nuclei
FT
Antenna
(to unscramble frequency
components)

MR data are collected in FT domain!!!



FT of image (K-space)   Reconstructed image

Dynamic MRI



Magnetic Resonance Angiography

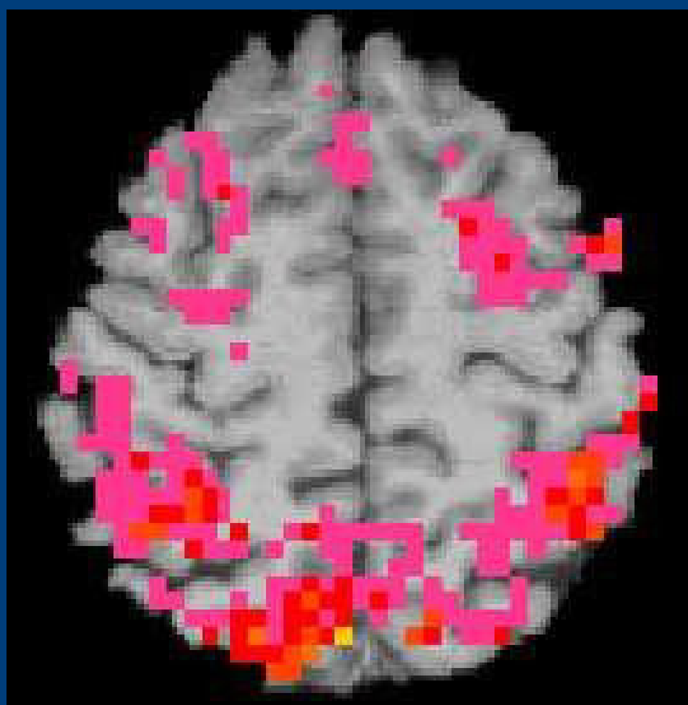
- MR scanner tuned to measure only moving structures
- "Sees" only blood - no static structure
- Generate 3-D image of vasculature system
- May be enhanced with contrast agent e.g. Gd-DTPA

Functional MRI (fMRI)

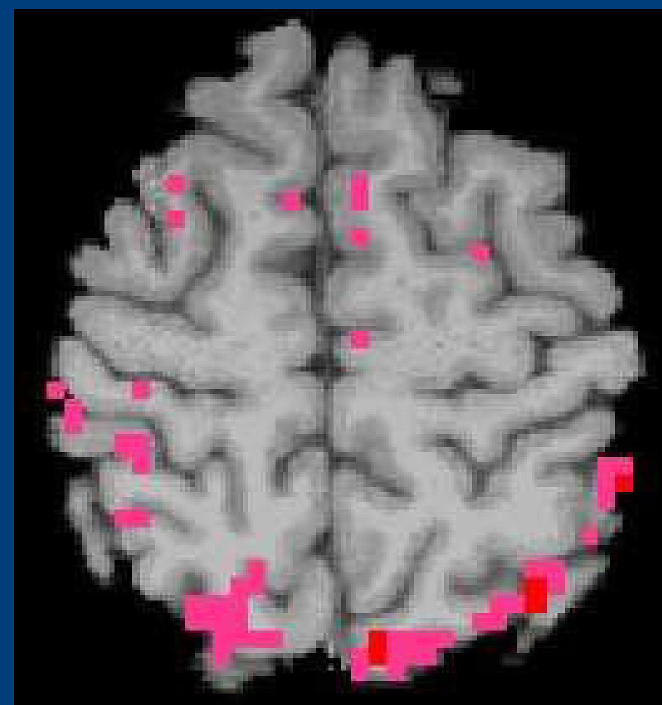
- Oxygenated and deoxygenated blood have slightly different paramagnetic properties
- Signal generated by excited protons decays more rapidly in de-oxygenated blood
- Local blood oxygenation related to brain metabolic activity
- fMRI image is map of the blood-oxygenation level dependent (BOLD) effect on anatomical MR image

fMRI

Subjects performing non-verbal working memory task:
(Mental problem solving)



Non-drinker

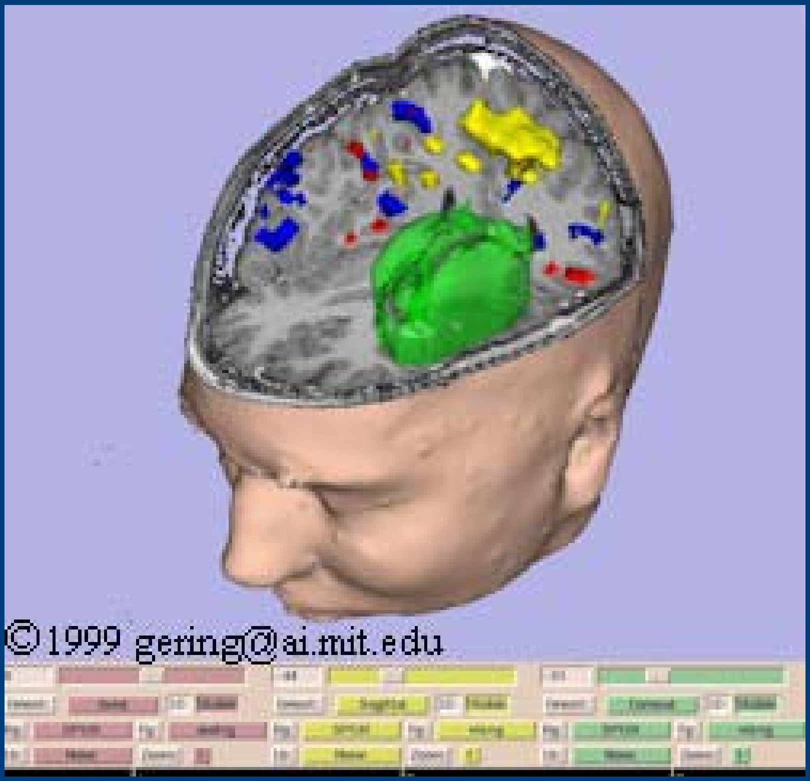


Alcoholic

S. A. Brown, and G.G. Brown, UCSD

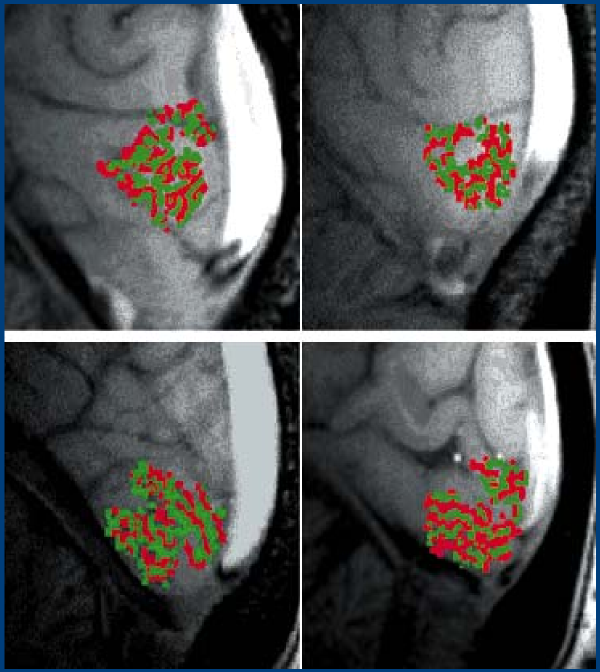
robarts RESEARCH

fMRI



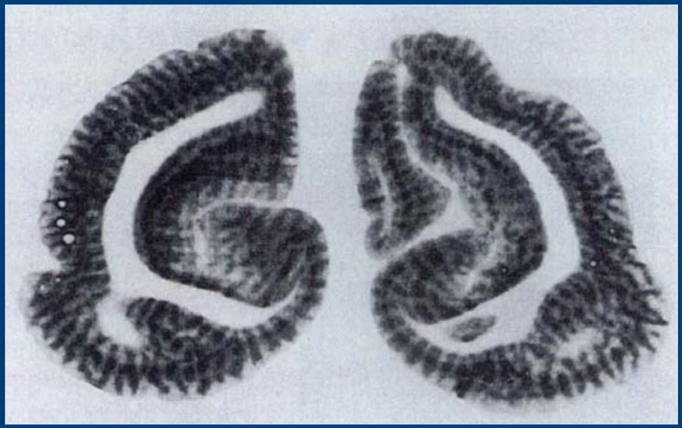
robarts RESEARCH

Ocular Dominance Columns



by Goodyear & R. Menon, 2001

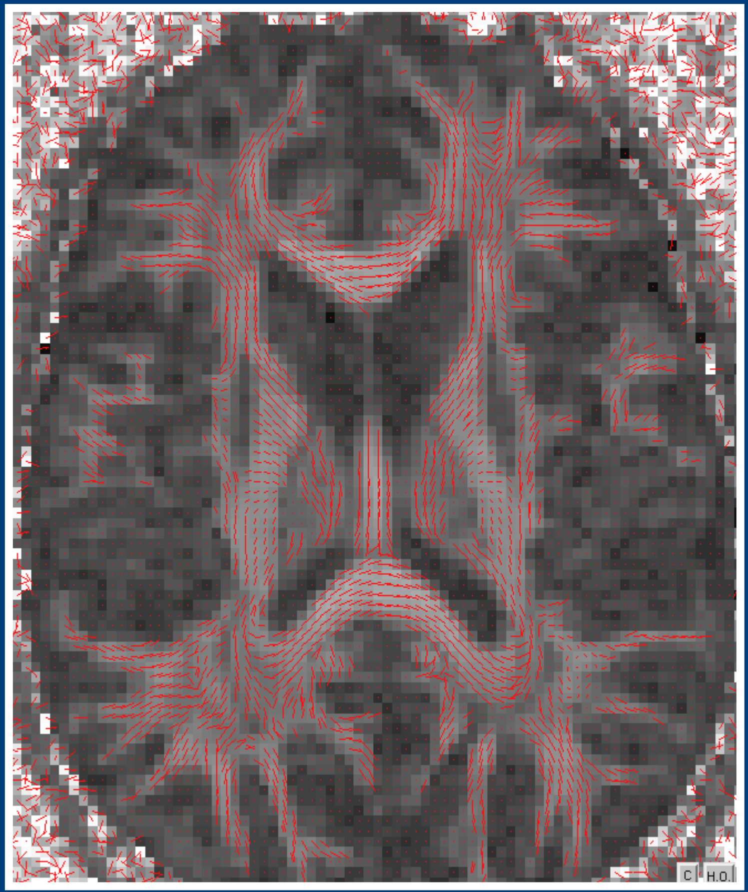
by [^{3}H] labeling (Hubel and Wiesel, 1977)



by 2-[^{14}C] deoxy-Glucose method (Kennedy et al., 1976)

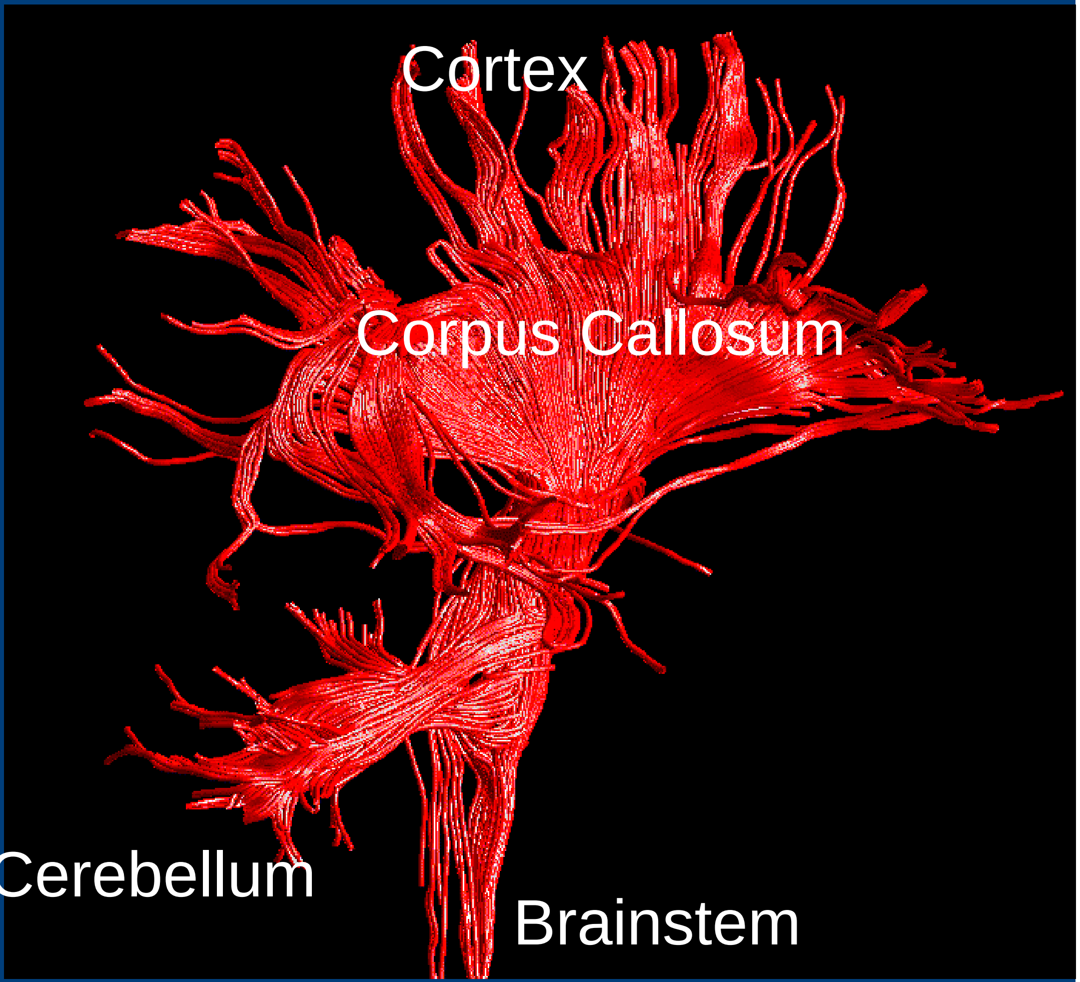
Diffusion-Weighted MRI

- Image diffuse fluid motion in brain
- Construct “Tensor image” – extent of diffusion in each direction in each voxel in image
- Diffusion along nerve sheaths defines nerve tracts.
- Connect the vectors between slices to create images of nerve connections/pathways



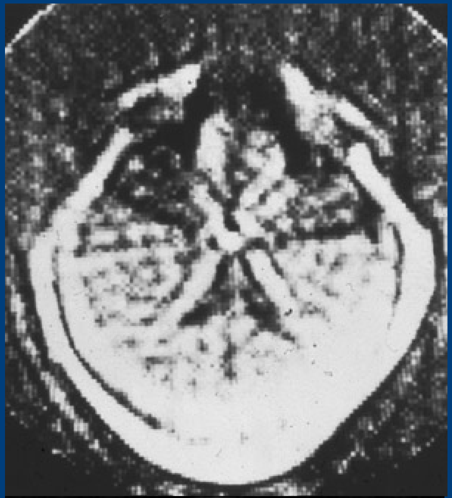
Tractography

- Data analysed after scanning
- Identify “streamlines” of vectors
- Connect to form fibre tracts
- 14 min scan time

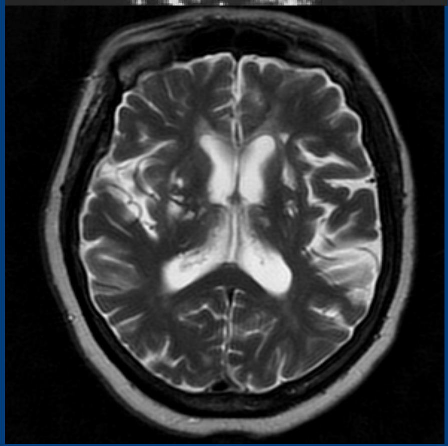


- Dr. D Jones, NIH

30 Years of MRI



First brain MR image



Typical T2-weighted MR image today

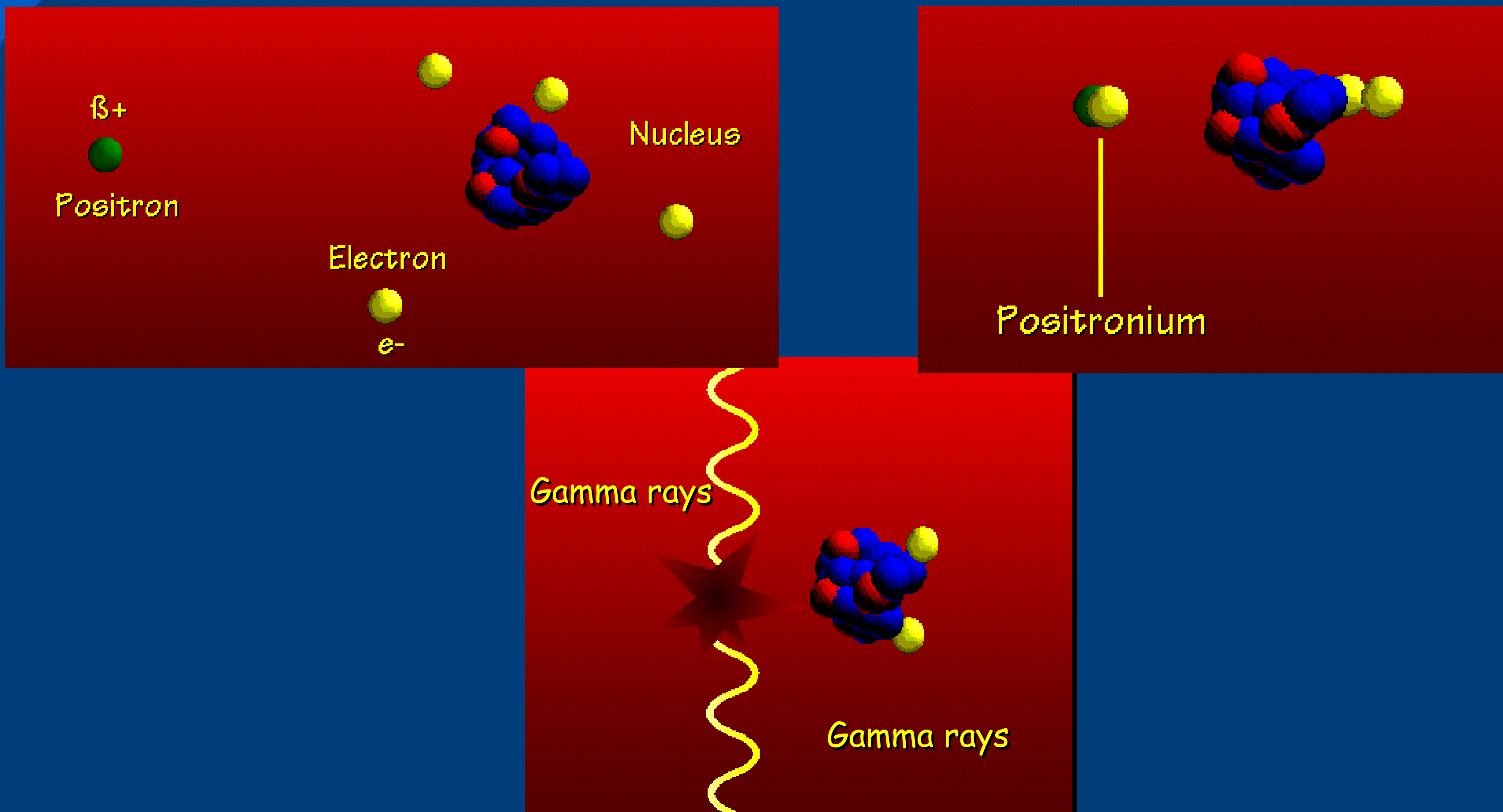
MRI

- 20 years ago
  - Single slice
  - .5 – 2 mins per slice
- Today
  - Sub-second per slice
  - Volumetric imaging
  - (Still 30 mins for volume image of beating heart – involves breath-hold)

Positron Emission Tomography

- Inject metabolically active positron emitting isotope
- Positron interacts with electron
  - Mutual annihilation
  - 511 keV gamma rays emitted
- Coincidence detection in opposing detectors give line on which annihilation occurred
- Multiple lines used in CT- style reconstruction

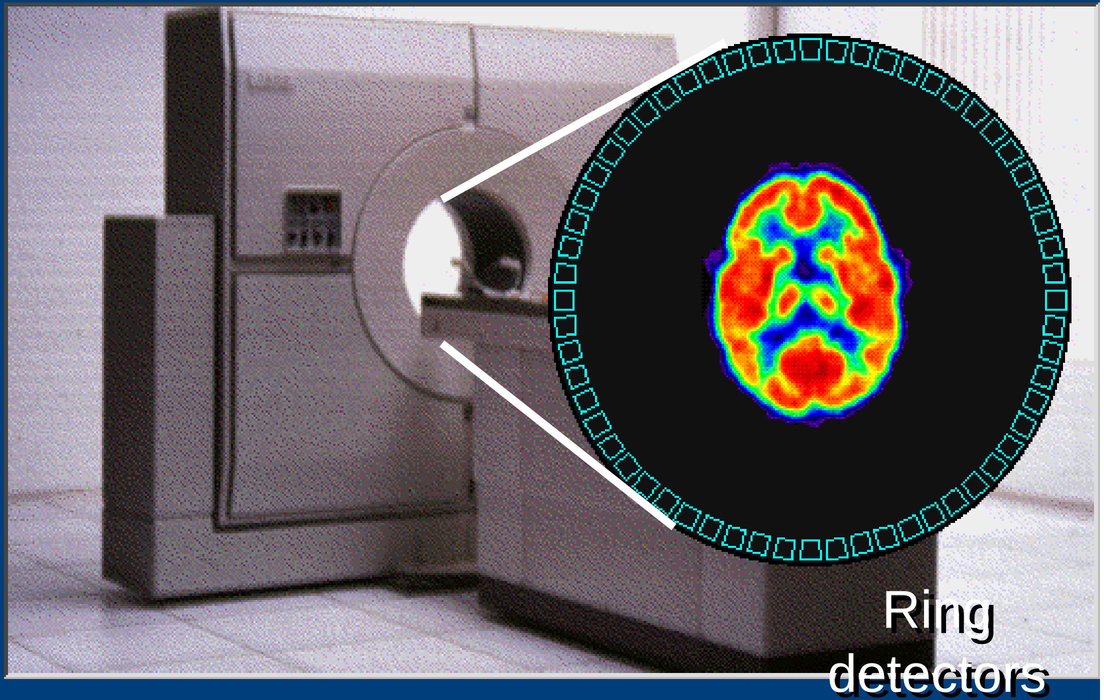
Positron Annihilation



Crump Institute for Biological Imaging UCLA

PET Scanning

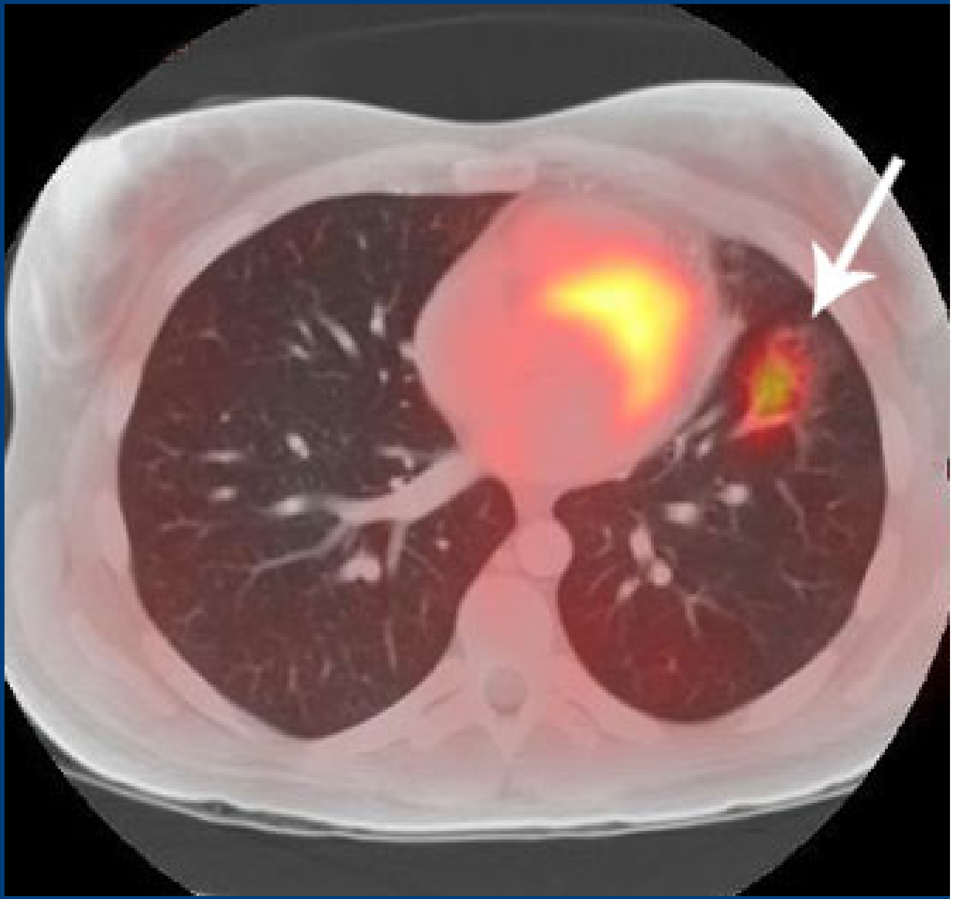
- Track dynamics of radio-labeled metabolites
- Quantitative analysis of metabolic function
- Detect abnormal organ function



robarts RESEARCH

PET-CT

- Pet scanner and CT combined in same unit
- PET provides function
- CT provides anatomy
- Intrinsic registration between both images
- CT image aids reconstruction of isotope distribution

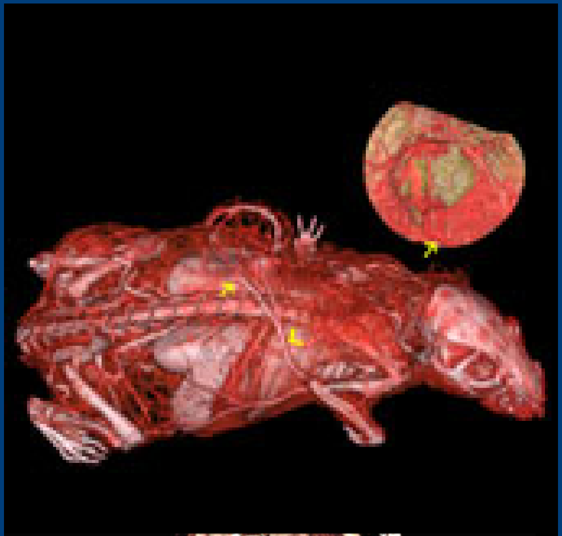


3-D Animal CT

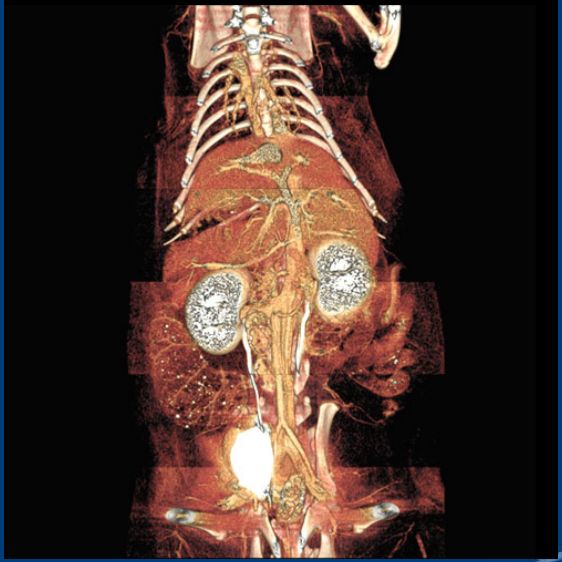
Bench-top scanner for animal specimens

Scanner for live animals

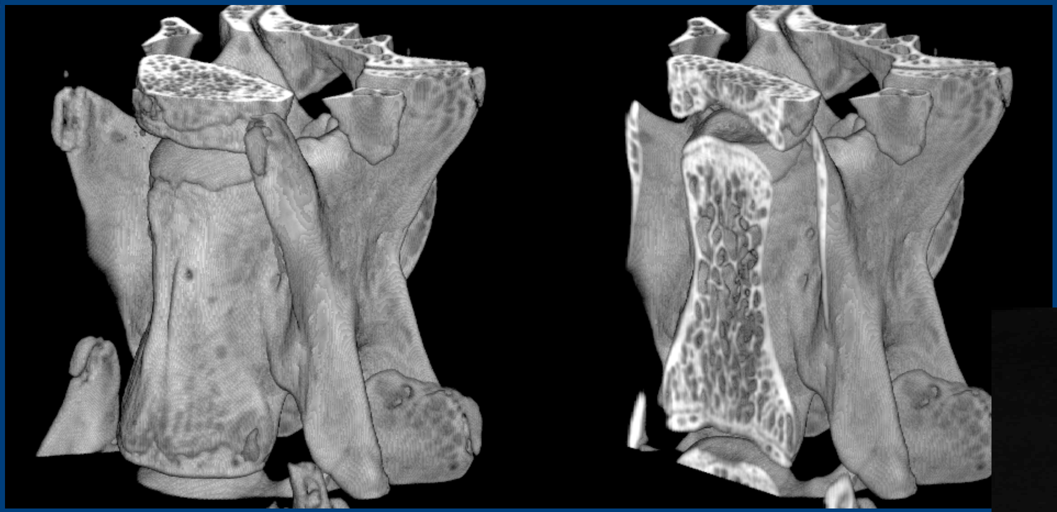
CT mouse Scans

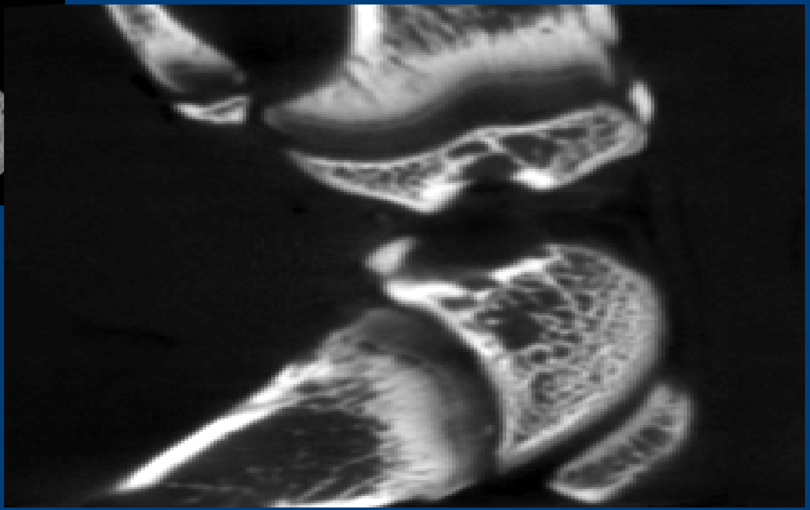


GE Health Systems



Results: in vitro 3-D µCT



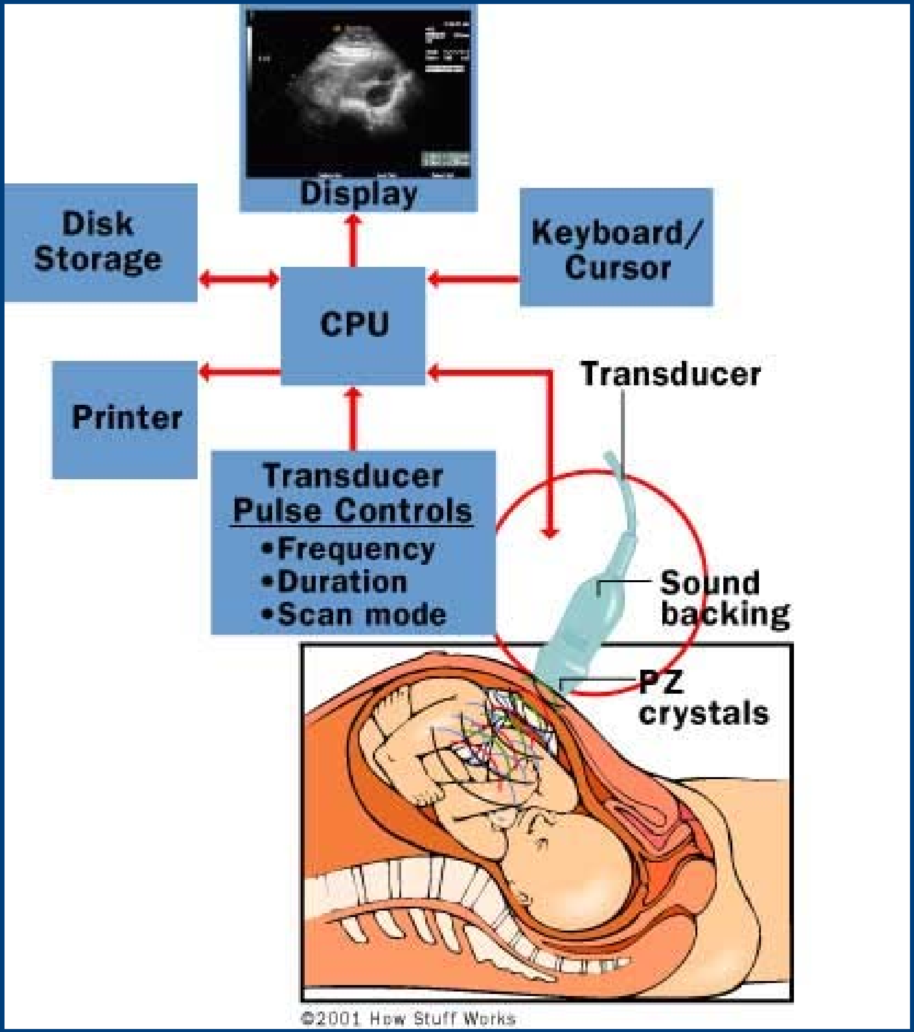


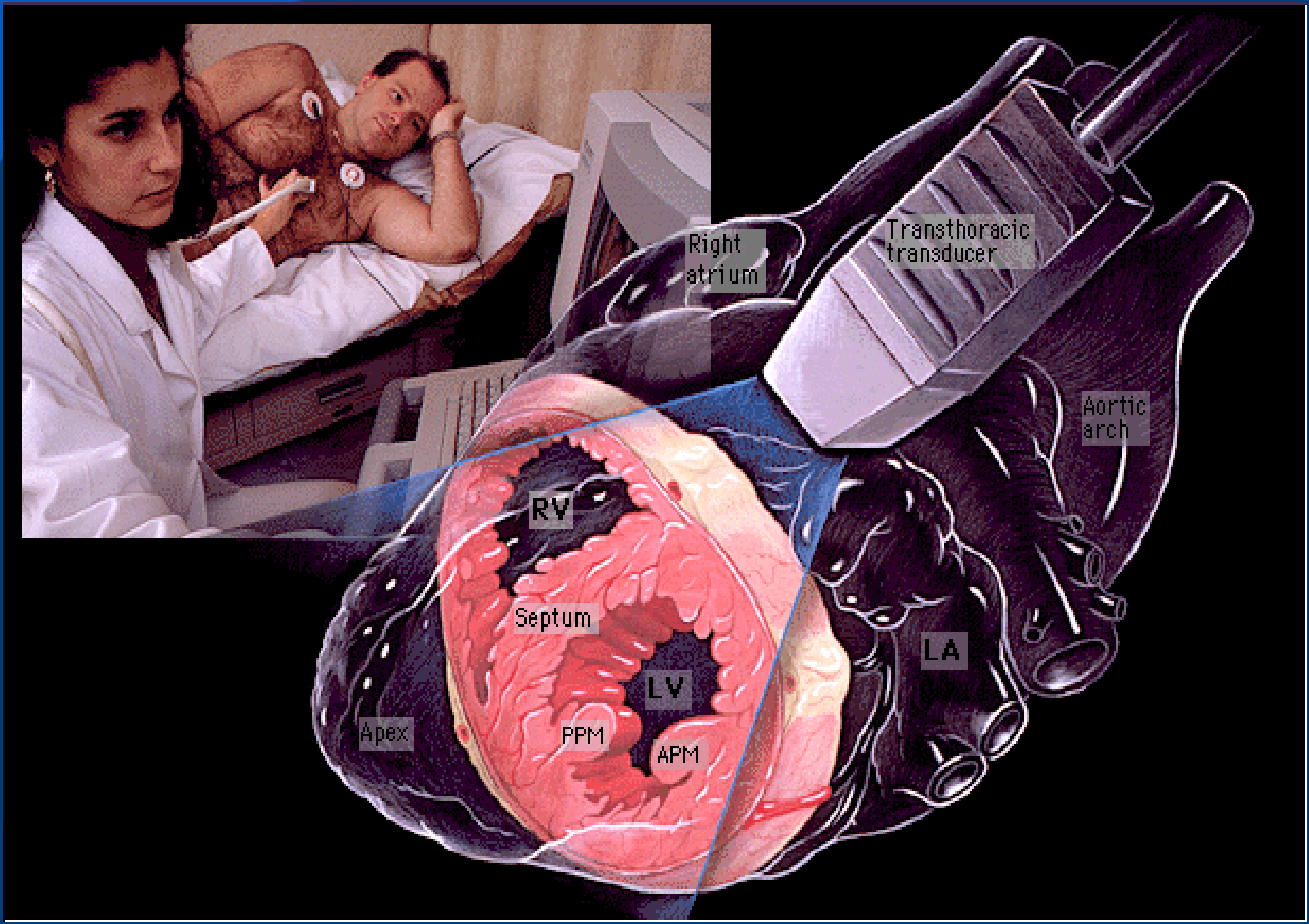
~20 µm resolution

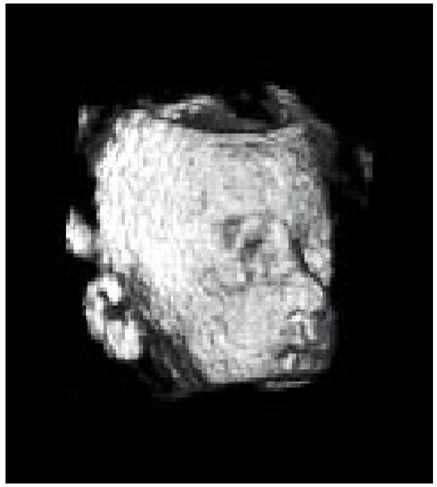
David Holdsworth RRI

Ultrasound


3V


Display
Disk Storage
Keyboard/ Cursor
CPU
Printer
Transducer
Transducer Pulse Controls
•Frequency
•Duration
•Scan mode
Sound backing
PZ crystals
©2001 How Stuff Works


Right
atrium
Transthoracic
transducer
Aortic
arch
RV
Septum
LA
LV
Apex
PPM
APM



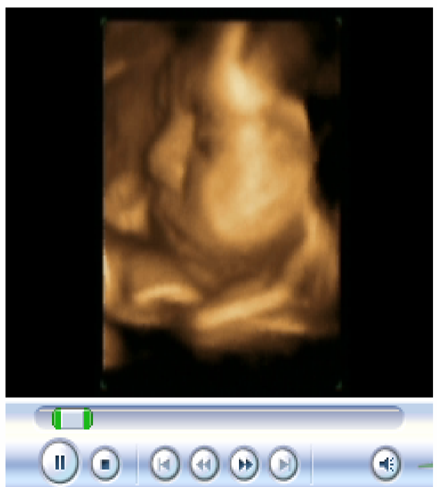
Acquisition time: 20 min

1989: 2D ultrasound used most often, taking about 20 minutes for U/S to develop and image, until 3D was invented

4 vol / sec

1995: Live 3D introduced, speeding up the time it took for an image to appear and beginning to show movement

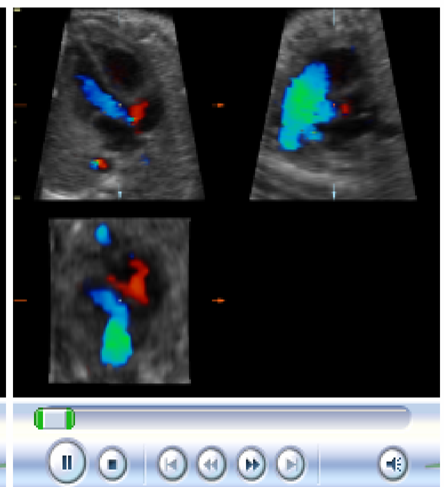
2000



16 vol / sec

2000: Improvements in ultrasound technology led to a faster time to acquire an image, creating a more "life-like" appearance of fetal anatomy

2005

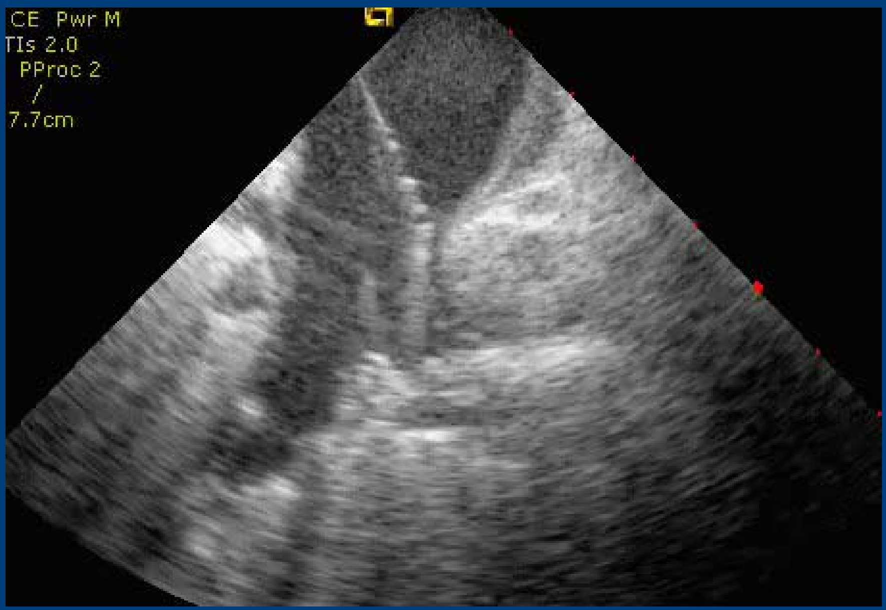


33 vol / sec

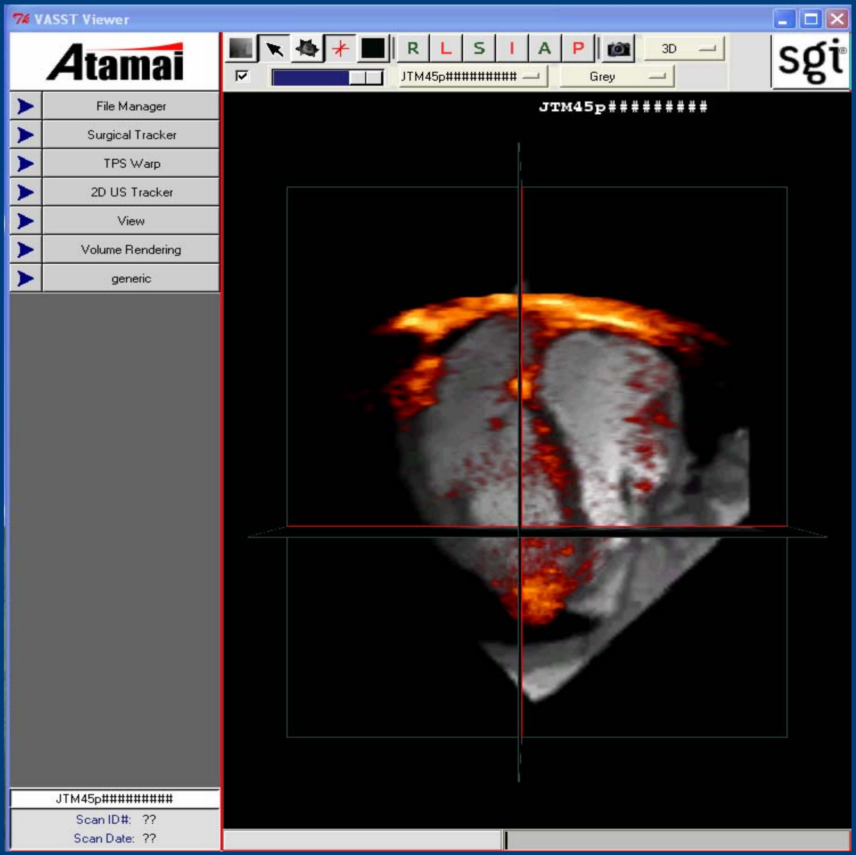
2005: Advancements in 3D and 4D ultrasound expands the usefulness of ultrasound into areas like viewing the fetal heart and blood flow


A
B

Cardiac ultrasound



Intra-cardiac echo



Registered with MRI

robarts RESEARCH

MRI

- Generally non-invasive (but new contrast agents are not!)
- Solid tissues like bone are “transparent” as signal is due to H_2O content in tissue
- Generally well tolerated with excellent safety
- Functional aspects of tissues can be determined like blood oxygenation in brain in response to stimuli
- Excellent diagnostic characteristics of tumour and other tissues due to differences in H_2O environments
- Geometrical accuracy can present problems for surgical guidance
- Need: Volumetric dynamic scanning

CT

- Very high resolution
- Intrinsic geometrical accuracy
- Isotropic imaging with modern multi-detector spiral scanners $(0.5\text{mm})^3$ voxels
- Full volume scan in several seconds
- Excellent bone contrast
- Poor soft-tissue contrast
- Vascular images with contrast agent
- "Real-time" (5-10 fps) single slice "fluoro mode"
- Need: faster scanning at lower dose

Ultrasound

- Inexpensive, portable
- Real-time
- 2D and 3D dynamic
- Images sonic interfaces between tissues
- Cannot penetrate bone/air
- Geometrical accuracy limited by US refractive index changes
- Often only choice for intra-operative imaging
- Need: miniature 4D transducers

Data Storage and Analysis

- Dynamic Cardiac CT
  - 512^3 x 20 (5.2 GB)
- Dynamic MRI
  - 256^3 x 15 (0.5 GB)
- Micro CT of Mouse
  - ~0.4 GB

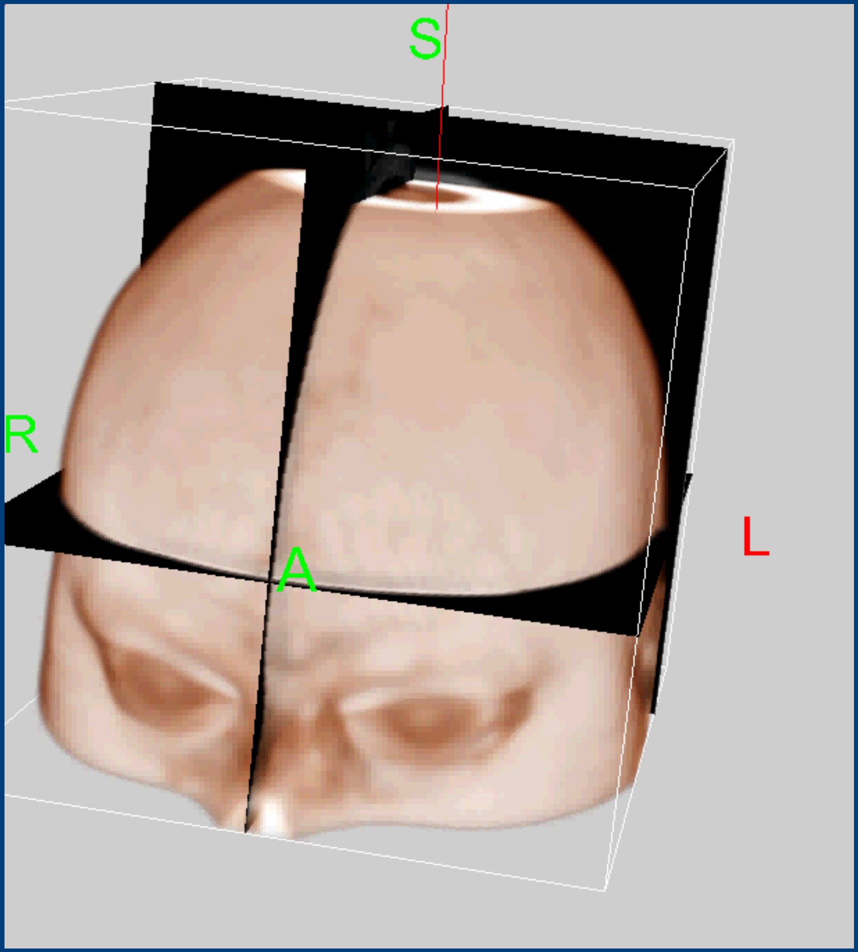
Visualization

- Data must be visualized efficiently
- Interacting with GB datasets in a dynamic image is major challenge
- Effectively combine multimodal data
- Employ combination of surface, volume and texture mapping
- Use capabilities of HW graphics boards.

Navigating the functional brain!

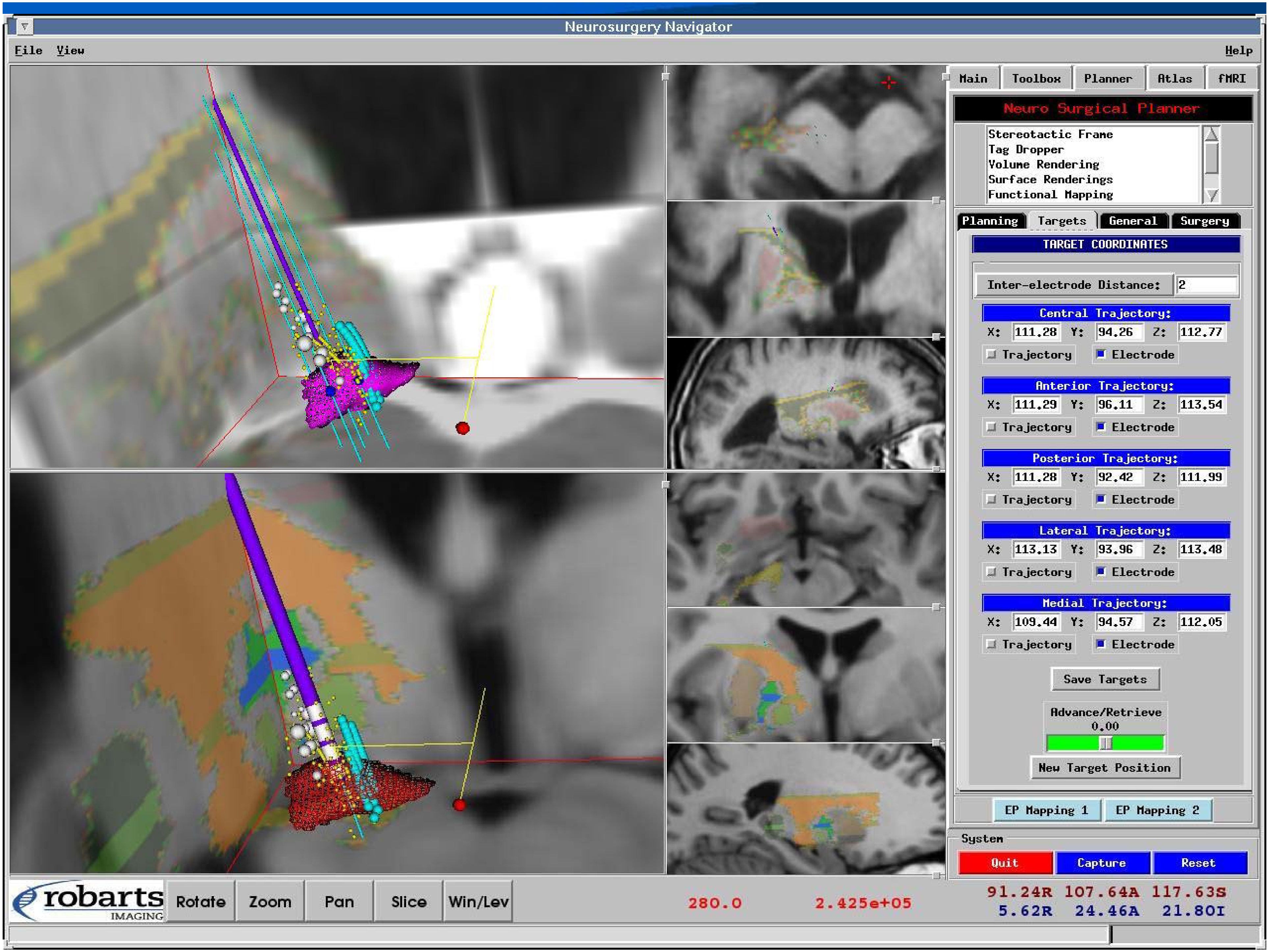
“Wow! That was a good one! Try it – just poke his brain where my finger is!”

Applications in Image-Guidance

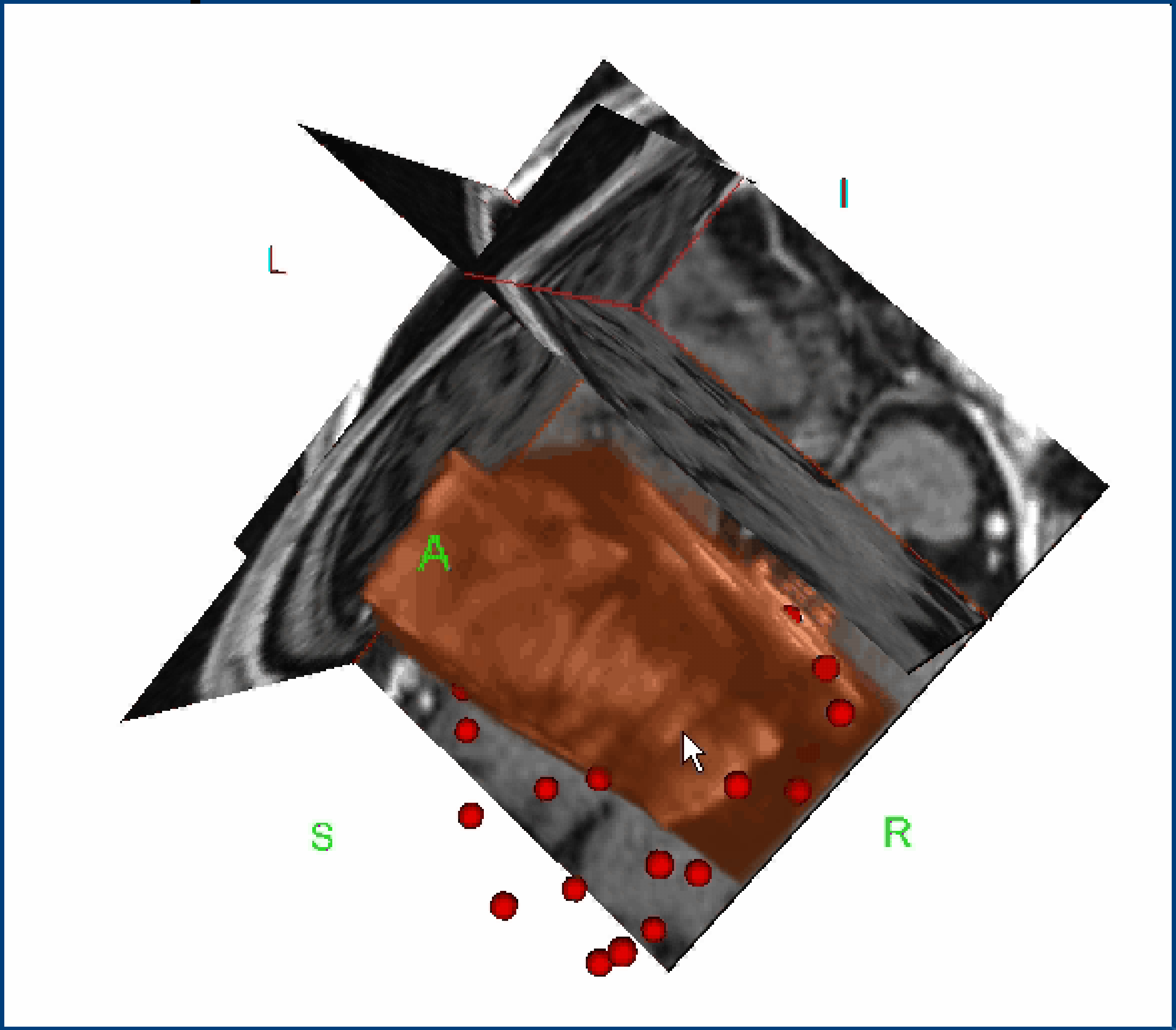


Non-rigid brain registration

- Map atlases from standard brain to patient
- Collect EP data from multiple patients in standard image volume
- Map EP database to patient


Neurosurgery Navigator
File
View
Help
Main
Toolbox
Planner
Atlas
fMRI
Neuro Surgical Planner
Stereotactic Frame
Tag Dropper
Volume Rendering
Surface Renderings
Functional Mapping
Planning
Targets
General
Surgery
TARGET COORDINATES
Inter-electrode Distance: 2
Central Trajectory:
X: 111.28 Y: 94.26 Z: 112.77
Trajectory Electrode
Anterior Trajectory:
X: 111.29 Y: 96.11 Z: 113.54
Trajectory Electrode
Posterior Trajectory:
X: 111.28 Y: 92.42 Z: 111.99
Trajectory Electrode
Lateral Trajectory:
X: 113.13 Y: 93.96 Z: 113.48
Trajectory Electrode
Medial Trajectory:
X: 109.44 Y: 94.57 Z: 112.05
Trajectory Electrode
Save Targets
Advance/Retrieve
0.00
New Target Position
EP Mapping 1
EP Mapping 2
System
Quit
Capture
Reset
robarts IMAGING
Rotate
Zoom
Pan
Slice
Win/Lev
280.0
2.425e+05
91.24R 107.64A 117.63S
5.62R 24.46A 21.80I

Intra-Operative MR/US warp



Challenges

- Ready availability of 3D/4D datasets in viewing room/OR
- Cross reference to other images of same patient
- Rapidly interrogate hi-res 3D dynamic images
- Integrate with surgical guidance

Computational Challenges

- The fusion of image data of varying modalities, over differing spatial and temporal scales and resolutions
- The extraction and display of quantitative information, with associated uncertainties
- Data archiving: raw vs. extracted parameters, development of metadata standards

*Report commissioned by DOE and NIBIB

An example - Image-guidance for Cardiac surgery

- Register pre-operative, intra-op images to patient
- Synchronize pre- and intra-op images
- Track instruments and register to dynamic environment
- Visualize and interact with volume