Current Status of Single Photon Emission Computed Tomography (SPECT) Imaging

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Outline

1. Review of physical principles that form foundation of SPECT
2. New generation of SPECT cameras
3. Small-animal SPECT cameras
4. Recent progress with reconstruction algorithms
5. Conclusions

Fundamentals of SPECT

- a minimum required number of projections is acquired
- the internal distribution of the imaged radionuclei does not change spatially or temporally during the scan
- the SPECT detectors have uniform detection sensitivity that does not change during the scan
- the center of rotation is accurately known

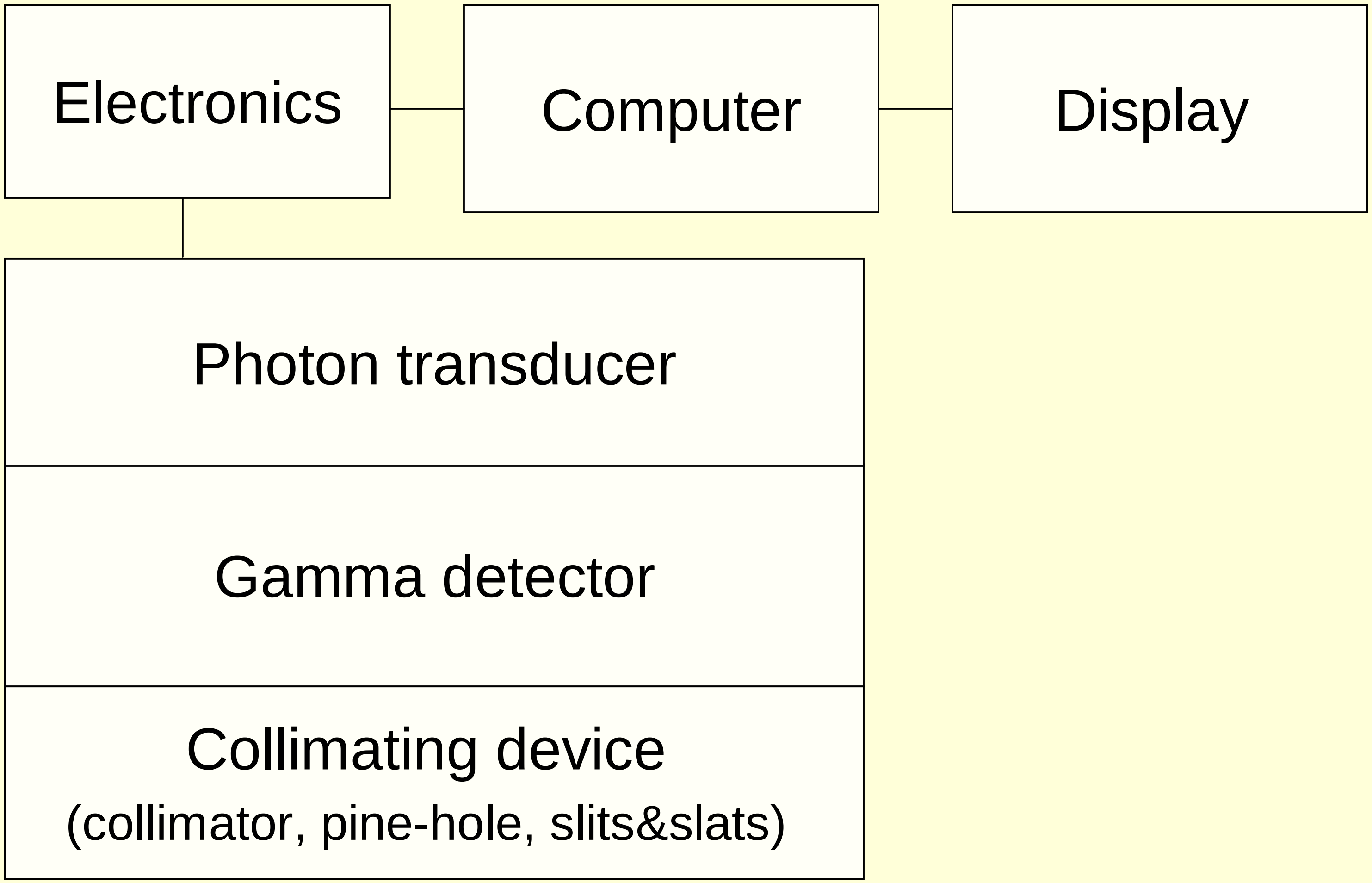
Major factors limiting the quality of SPECT images

- Attenuation
- Spatial resolution
- Scattered radiation
- Statistical fluctuations (image noise)
- Partial volume effect
- Deadtime

The advances in SPECT

- Improvement in the quality and accuracy of the acquired projections through:
  - better detector systems
  - better correction algorithms
- Improvement in the reconstruction algorithms

Basic components of SPECT camera



γ-ray detectors

Required properties:

- High intrinsic efficiency
- Good energy resolution
- Good intrinsic spatial resolution

Two basic classes:

- Scintillators
- Semiconductors

Scintillators

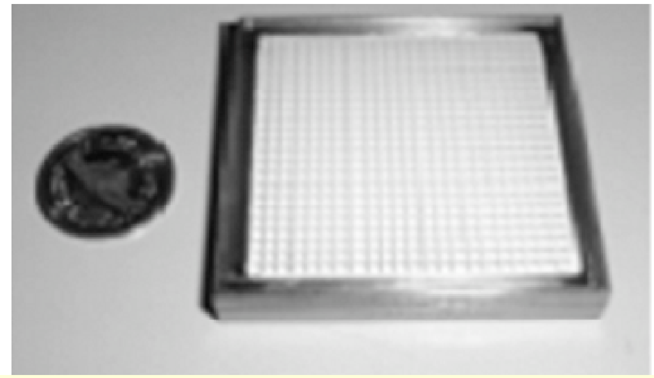
convert γ- and x-rays to visible light

Scintillator	Effective atomic number	Density (g/cm^3)	Decay time (ns)	Wavelength (nm)	Light output (% of NaI(Tl))
NaI(Tl)	50	3.67	200	415	100
CsI(Na)	54	4.51	630	420	85
CsI(Tl)	54	4.5	1,000	550	45 effective
$LaBr_3$:Ce	47	5.3	25	360	160

Pixelated vs. single crystal detectors

- Single crystal detectors use Anger position encoding but it fails near the crystal edge $\Rightarrow$ "dead" strip (1/2 PMT wide) along the edge $\Rightarrow$ problem for small detectors
- Pixelated detectors do not have "dead" edge strip $\Rightarrow$ preferred for small detectors
- Spatial resolution and sampling of pixelated detector is defined by its element size $\Rightarrow$ could be better than in single crystal detector
- Energy resolution is worse in pixelated detectors due to diminished light transmission
- Higher cost of pixelated detectors
- Hybrid solution: large 1" NaI(Tl) with machined groves has ~4 mm spatial resolution

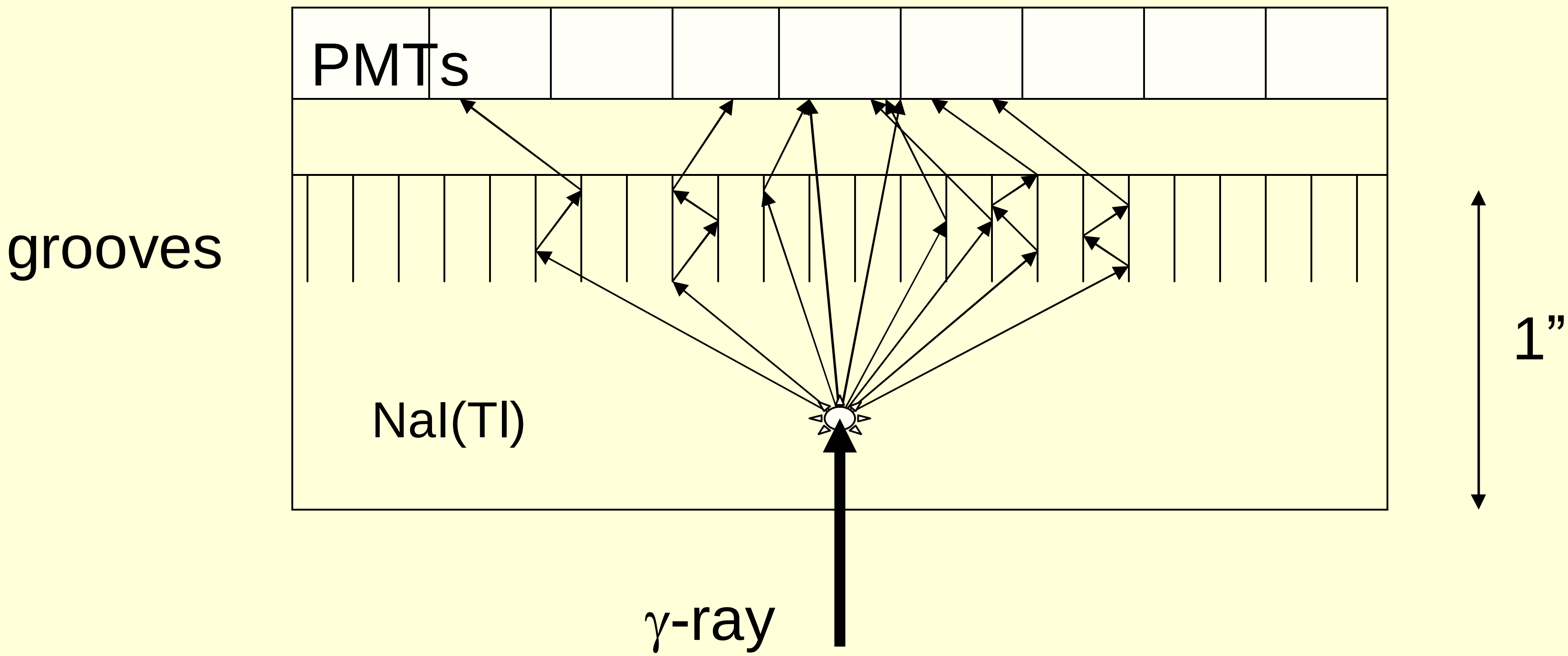
Pixelated vs. single crystal detectors



2”x 2” Pixelated NaI(Tl), Zaniya et al. 2005

Symbia HD large crystal detector, Siemens

Large and thick NaI(Tl) crystal with machined groves for improved intrinsic resolution



GE Discovery VH with 1" StarBrite crystal
e.g. for In-111 ProstaScint imaging

Visible Light Photon Transducers

Convert scintillation light into electronic signals:

- Photomultiplier tubes (PMTs)
- Position sensitive PMT(PSPMT)
- Avalanche photodiode (APD)
- Positions sensitive APD (PSAPD)
- Silicon photomultiplier (SiPMT)

PMTs

- Very large electronic gains (10^6)
- Quantum conversion efficiency is low (20%)
- Mediocre energy resolution
- Mediocre intrinsic spatial resolution
- difficult to maintain the long-term stability of PMTs because they are:
  - susceptible to environmental influences such as temperature,humidity and magnetic fields
  - their properties change as they age
- Bulky & expensive

Hamamatsu

Position sensitive PMT(PSPMT)

- 6X + 6Y cross anode plate
- Bialkali max. response at 420 nm

Hamamatsu

Avalanche photodiode (APD)

Light-sensitive solid-state diode with a very high reverse bias and the output signal proportional to the initial number of light photons

- Very compact
- Immune to environmental factors such as magnetic fields
- Operate at a lower voltage than PMTs
- Have a much higher quantum conversion efficiency than PMTs

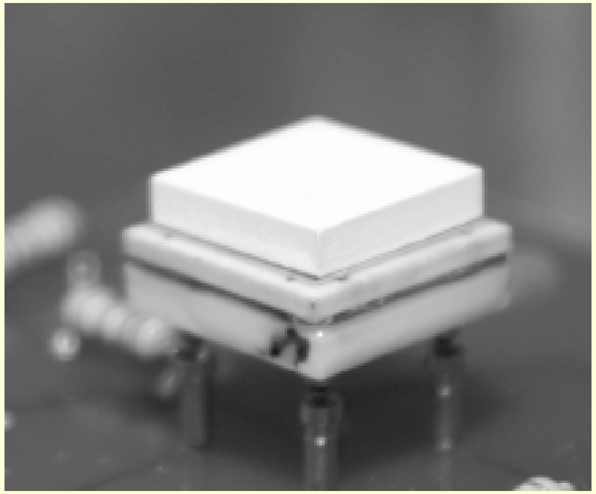
Avalanche photodiode (APD) cont'd

- Maximum gain is ~250 much lower than PMTs
- Dark current large, as compared to the signal
- Well suited for scintillators that emit light with longer wavelengths, such as CsI(Tl)
- Best suited for pixelated detectors
- Spatial resolution is limited by the channel size

Positions sensitive APD (PSAPD)

Light-sensitive solid-state diode with a very high reverse bias with charge sharing between additional electrodes on the back surface of the APD:

- same properties as APD plus
- improved spatial resolution (~0.5 mm)
- usually cooled to liquid nitrogen temperatures



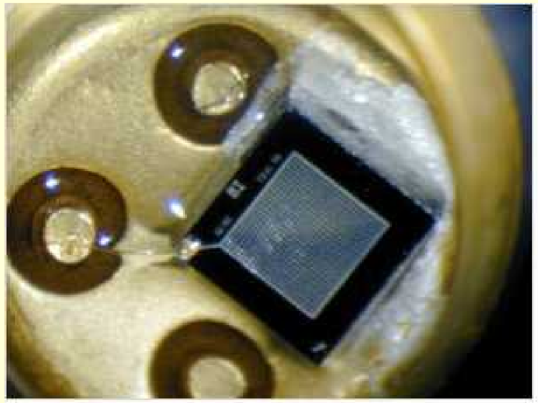
The white epoxy covered CsI:Tl crystal on the PSAPD.

Despres et al. 2006

Silicon photomultiplier (SiPMT)

Geiger photodiode

- Bias voltage is increased, as compared to APD
- Holes in addition to electrons contribute to avalanches
- Total discharge regardless of how many charge carriers were initially detected– the Geiger region
- 24 $\times$ 24 array of Geiger photodiodes packaged into a 1 $\times$ 1 mm area
- All advantages of the APDs
- Very high gain (10^5–10^6)



SiPMT,Pulsar

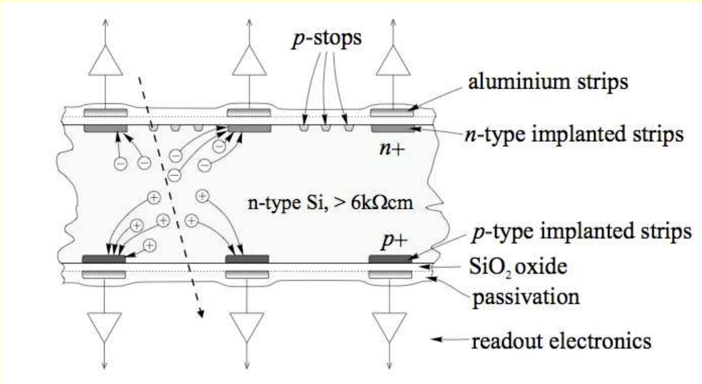
Semiconductors

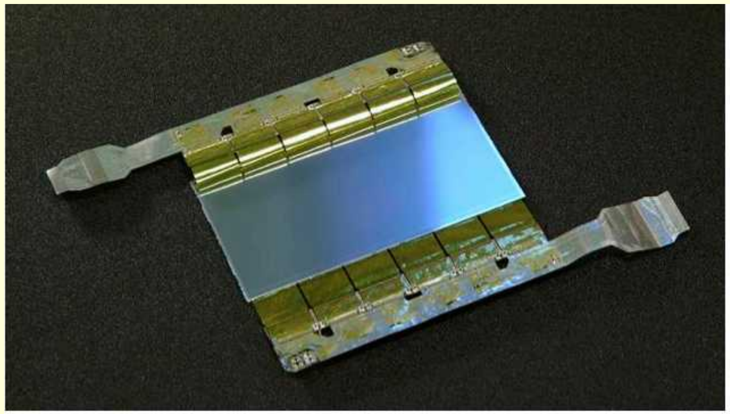
Solid-state devices that provide direct conversion of absorbed γ-ray energy into an electronic signal – no need for light transducer (CdTe, CdZnTe)

- The absorbed energy from a γ-ray interaction liberates charge carriers within the charge-free depletion zone
- The induced charge on the terminals generates an electronic pulse with an amplitude proportional to the absorbed energy
- Better energy resolution (2–5%) than scintillator (8–10 %) at 140 keV
- Lower intrinsic efficiency, especially for high-energy γ- rays, as compared to scintillators

Silicon strip detector

- Intrinsic efficiency is very low
- Suitable only for very low-energy γ-ray and x-ray emitters, such as I-125,
- Pixel sizes ~100 µm ultrahigh-resolution
- Application for Compton γ-cameras,





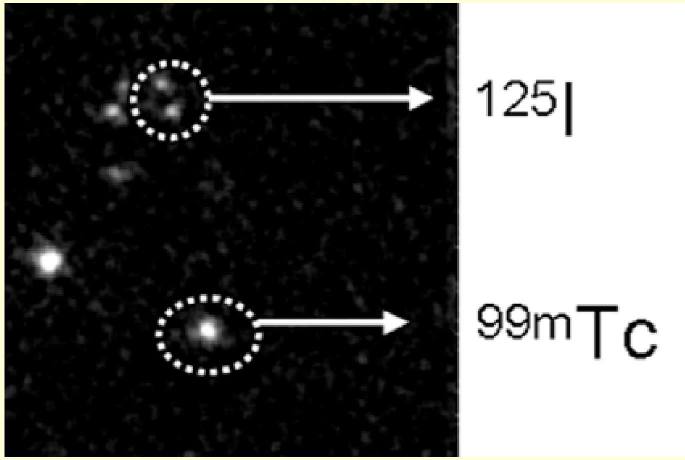
Sokolov 2005

Charge-Coupled Device (CCD)

- Very high intrinsic spatial resolution
- Directly detection of γ-rays from I-125
- Intrinsic efficiency is low–can be used for energies below 30 keV
- Used as the photon converter for columnar CsI(Tl) detector

Electron Multiplying Charge-Coupled Device (EMCCD)

- Incorporate an electron multiplying stage prior to the charge-to-voltage conversion process
- Better signal-to-noise ratio than CCD
- Used as the photon converter for columnar CsI(Tl) detector
- Can be used for Tc-99m



Teo 2006

Clinical SPECT

Most popular:

- Two scintillation NaI(Tl) detectors
- Positioned at 90° or 180°
- Can be positioned at other selected orientations
- Can perform any nuclear medicine scan but the most common application is Myocardial Perfusion Imaging

Example: Philips Forte

Typical Performance Values for a Conventional SPECT System

No. of detector heads	2
Field of view	40 × 55 cm
Energy resolution	9.5%
Intrinsic spatial resolution	3.8 mm (FWHM)
Planar count sensitivity (LEHR)	190 cps/MBq (95 cps/MBq per head)
SPECT spatial resolution (LEHR)	10.5 mm (FWHM)

Madsen, 2007

Clinical SPECT cont'dTriple

Triple-head γ-camera. Presently, not very common:

- Three scintillation NaI(Tl) detectors
- Positioned at 120°on a gantry
- Can be positioned at other selected orientations
- 33% gain in sensitivity over dual-head SPECT
- Limitation: fixed bore size
- Popular application: brain imaging

Prism triple-head camera

Need for Attenuation Correction (AC)

- Uncorrected attenuation results in **underestimation of activity**
- Especially important in:
  - Thorax imaging
  - Abdominal imaging
- transmission scans (spatially registered with SPECT images) could be acquired using:
  - an external radionuclide source with the γ-camera as the detector
  - CT scanner attached to gamma camera

Attenuation Correction (AC)

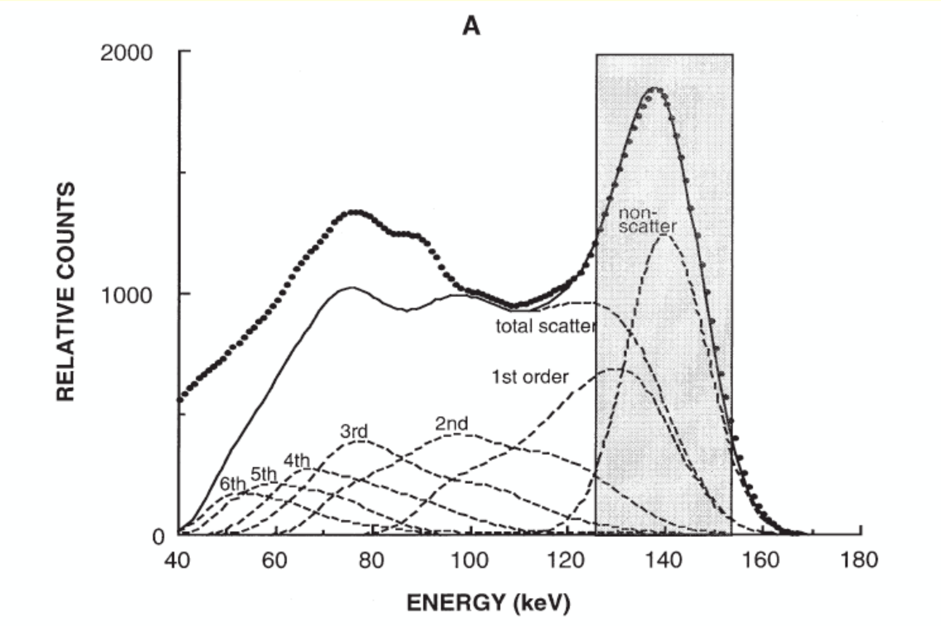
- External radionuclide source transmission images:
  - **very noisy** due to low count sensitivity of γ-camera
  - **very noisy** due to low activity in the transmission source
  - **same spatial resolution** as γ-camera
- CT scanner attached to γ-camera transmission images have:
  - **low noise**
  - **excellent spatial resolution**

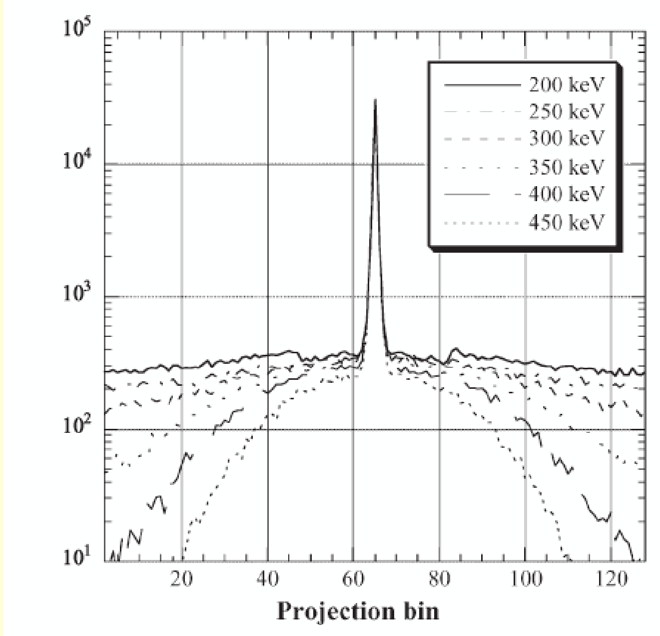
Attenuation Correction (AC)

Problems with over compensation in the inferior wall of the myocardium due to scattered radiation from the liver

- Apparently increased flux of photons from the inferior portion of the heart
- Attenuation compensation amplifies this effect
- apparent perfusion defect in the anterior wall.
- scatter correction helps but not 100% efficient

Scatter





Tc-99m line source on the axis of a water-filled cylinder simulated using the Monte Carlo method.

One-dimensional transaxial projections resulting from the simulation of a line source placed in a 20-cm-diameter

cylinder filled with water

Zaidi & Koral, 2004

Scatter

- Uncorrected scatter results in **over estimation of activity**
- Occurs mostly in the patient and in the collimator
- Especially important in myocardial imaging
- Scatter-to-primary ratio (S/P):

S/P ≈ 0.95 for Tl-201

S/P ≈ 0.34 for Tc-99m

S/P ≈ 0.75 for I-131 (HE) [47% collim. penetr.]

S/P ≈ 0.31 for I-131 (UHE) [14% collim. penetr.]

Scatter correction (SC)

- Implicit methods: scattered photons degrade the point-spread function (PSF) therefore deconvolution methods that correct the images for the PSF also implicitly correct for scatter
- The transmission-dependent convolution subtraction(TDCS) method
- The multi-energy window methods: include dual energy window (DEW) method, triple-energy window (TEW) approach, split-photopeak window method, multispectral method
- Methods based on direct calculation of scatter distribution
- Other…

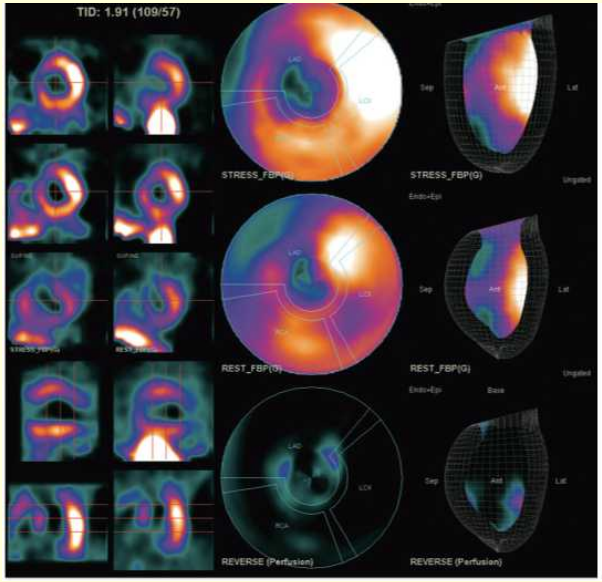
Collimator penetration

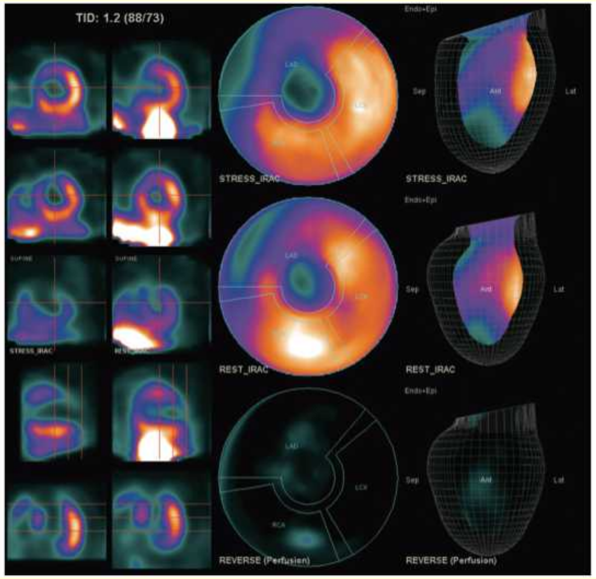
- Increases with energy:
  - not important for Tc-99m (<2%)
  - 15.5% for In-111(247 keV peak)
  - 22.1% for Ga-67 (300 keV peak, ME)
  - 29.4% for I-131 (364 keV peak, HE)

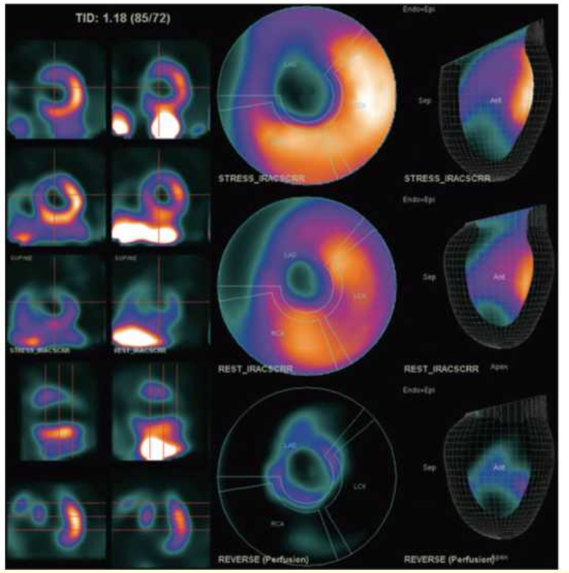
Decreases with septal thickness:

- 10.3% for I-131 (364 keV peak, UHE)

AC vs. NAC SPECT reconstruction







FBP 20 s/view

IR +AC 20 s/view

IR +AC+RR+SC
10 s/view

MPI studies with a two-day gated rest-stress Tc-99m MIBI protocol on GE Infinia Hawkeye SPECT/CT system. The stress test was performed with Dipyridamole plus cycling exercise.

IR = iterative reconstruction; RR= resolution recovery; AC= attenuation; SC= scatter correction

Patient Findings: A definitely abnormal study demonstrating a myocardial infarction in the antero-septo-apical region (LAD territory) with a peri-infarct residual ischemia.

Courtesy GE Healthcare

Best results would be obtained if attenuation, scatter and collimator penetration could applied at the same time

Presently, **too complicated** for clinical implementation

Cardiac SPECT scanners

Majority of SPECT scans are myocardial perfusion imaging (MPI)

- Conventional dual-head γ-cameras orbiting around the patient
  - most common180° arc LAO→LPO
  - scan duration ~20 minutes

New dedicated cardiac SPECT scanners

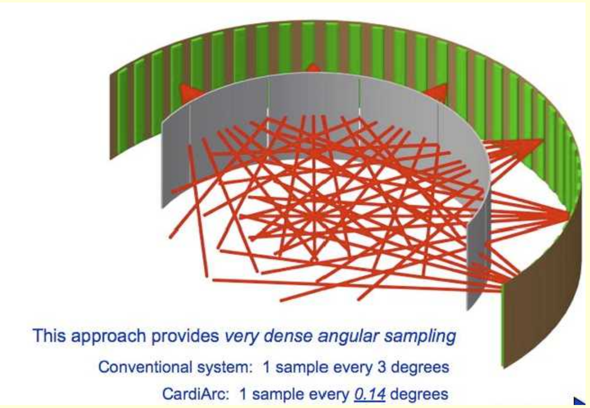
DigiRad

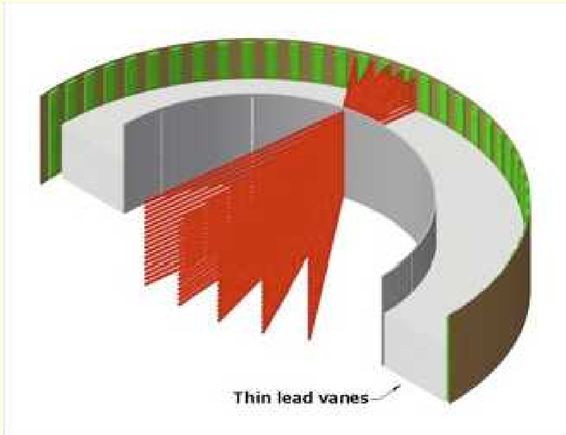
- up to 3 detector heads
- detectors: pixelated CsI(Tl)
- APD arrays as photon transducers
- the detectors are stationary during scan
- patient (in sitting position) is rotated
- very small footprint of the system
- can be installed in minutes

Courtesy DigiRad

The **CardiArc** (simliar to MarC-SPECT)

- Detectors: pixelated CZT forming 180° arc
- Axial collimation provided by a set of fixed parallel horizontal septa (*slats*)
- In-plane collimation provided by a curved movable lead plate with a set of slits in front of slats
- Effectively pinhole sampling performed by motion of slits in front of slats
- Motion of slits is not visible to the patient
- patient (in sitting position) is stationary
- Higher sensitivity $\Rightarrow$ short scan time ~ 3 minutes!
- Better spatial resolution than conventional γ-camera

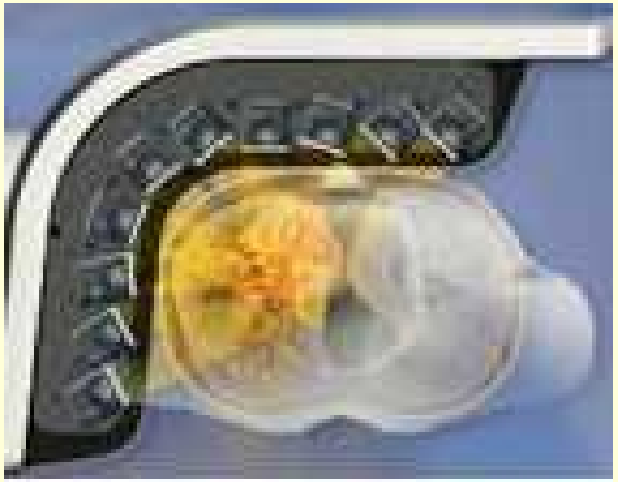




Courtesy CardiArc

The **D-SPECT** cardiac SPECT system:

- detectors: 10 individual pixelated CZT modules forming 180° arc
- each detector module rocks back and forth to independently acquire the heart projection data
- motion of detectors is not visible to the patient
- patient (in sitting position) is stationary with the semicircular gantry positioned over the chest
- a scout scan is done to determine the location of the heart
- detectors only sample volume-of-interest centered at the heart
- gated SPECT can be done in 2 minutes!



Coutresy Spectrum Dynamics

SPECT/CT

Advantages of SPECT/CT

1. Improved attenuation correction from accurate attenuation map produced by CT
2. Improved diagnostic performance of SPECT studies with coregistered anatomic images
3. Complementary diagnostic CT studies in the same setting immediately before SPECT scan are possible

Disadvantages of SPECT/CT:

1. Increased cost of SPECT/CT scanner, as compared to SPECT only
2. Increased cost of SPECT/CT room due to necessary shielding in some configurations
3. During CT scan:
   - metal artifacts
   - sensitivity to patient motion
4. Regulatory issues: nuclear medicine technologist are not certified to operate CT
5. Need for new normal databases with normals obtained using AC
6. Additional training necessary for nuclear medicine physicians
7. Additional radiation dose to the patients and the personnel

Major commercial SPECT/CT systems

Manufacturer	GE Healthcare	Philips	Siemens
	Infinia Hawkeye	Precedence	True Point
SPECT System	Infinia	Skylight	Symbia
CT system	Hawkeye	Brilliance	Emotion T, T2, T6
Slice thickness (mm)	5 or 10	0.6–12	0.6 for T6, 1.0 for T2, 4.25 for T[a]
No. of CT slices	1 or 4	6 or 16	2 or 6
Tube rotation (s)	23	0.5	0.6–1.5
Standard HC[b] resolution (lp/cm @ 2% MTF) .	>3	13	15 (4.3 for T)
Room dimensions (cm)	419 × 470	711 × 442[c]	640 × 358[c]

[a]low-dose only; slice thickness same as in SPECT

[b]HC = high contrast; lp/cm = line pairs/centimeter; MTF =modulation transfer function

[c]additional room shielding required (with exception of Emotion T)

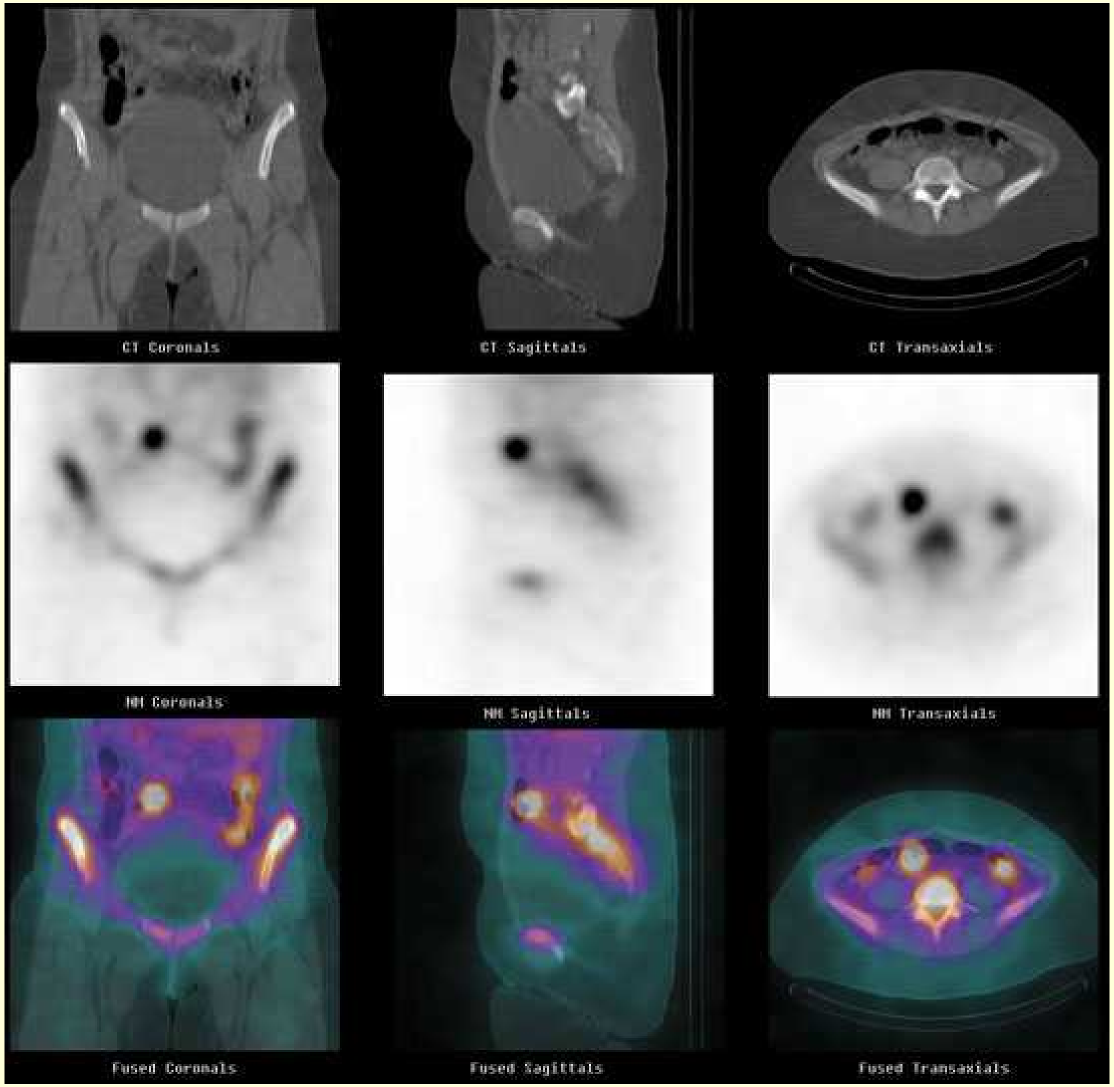
Major commercial SPECT/CT systems

Infinia Hawkeye,
GE Healthcare

Infinia, Philips

Symbia, Siemens

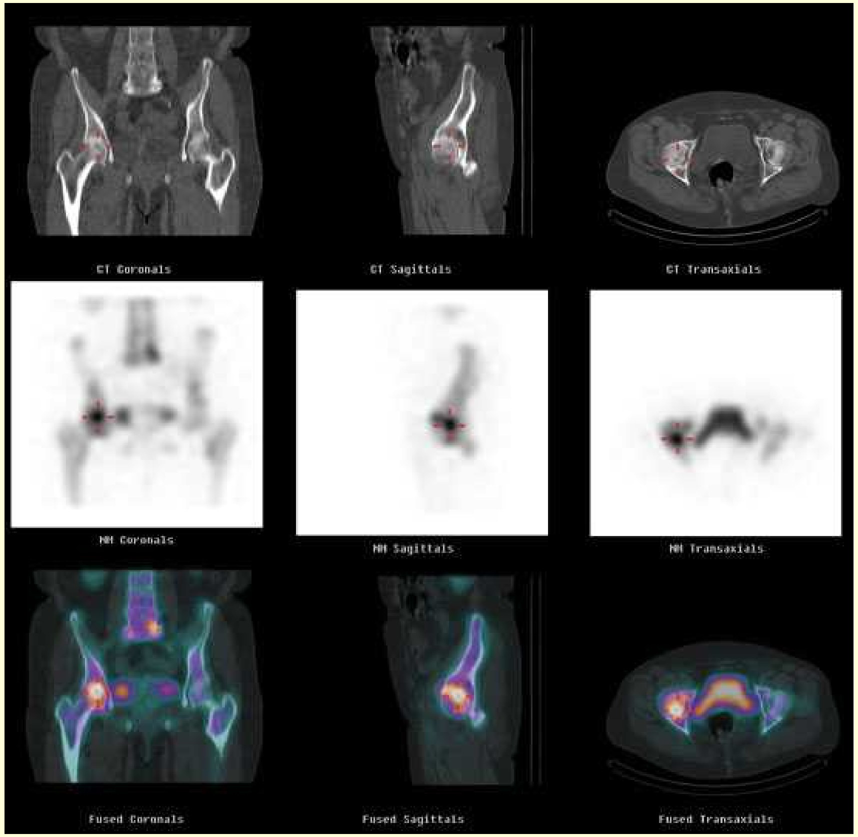
SPECTCT Ga-67 Tumor Study



Non-Hodgkin's Lymphoma. In addition to the mediastinal mass, SPECT/CT images clearly revealed bilateral cervical lymph nodes and splenic involvement. A physiological bowel uptake is unequivocally seen on the SPECT/CT images. Based on the SPECT/CT Ga-67 images, the patient is up-staged from stage I/II to III/IV in comparison to the conventional work-up including WB planar plus SPECT imaging.

Courtesy GE Healthcare

AC and Localization



Hawkeye SPECT/CT
Tc-99m Bone Scan

68 year-old female with right hip pain. SPECT image shows a small area of intense uptake in medulla of the right femoral head. CT images show a small area with lack of contrast. The fused data set confirms co-registration of these areas. This study is suggestive for avascular necrosis in the right femoral head.

Courtesy GE Healthcare

Need for Small-Animal SPECT

- Development of new radiopharmaceuticals is done mostly on transgenic and knock-out mice
- Transgenic and knock-out mice are now widely used in medical research to non-invasively and repetitively investigate the molecular mechanisms of disease, normal physiology and development
- Quantitative investigation of dynamic biological processes in living organisms include apoptosis, angiogenesis, blood perfusion, cell proliferation and trafficking, metabolic activity, oxygen perfusion and extraction, receptor occupancy, reporter gene expression and others
- Longitudinal and serial studies –the same animal can be investigated at various time points and the same animal could be used as each own control, thus improving quality of studies and reducing the number of animals that need to be scarified
- Lower animal cost and more ethical research

micro-SPECT vs. micro-PET

micro-SPECT

- Wide range of tracers developed for human studies labeled with Tc-99m, I-123, Ga-67, In-111
- Longer physical half-lives $\Rightarrow$ better match to kinetics of radiotracers
- Possibility of simultaneous multiple energy studies
- ~ 0.5 mm spatial resolution better than micro-PET
- Disadvantage: low detection efficiency ~0.1%

micro-PET

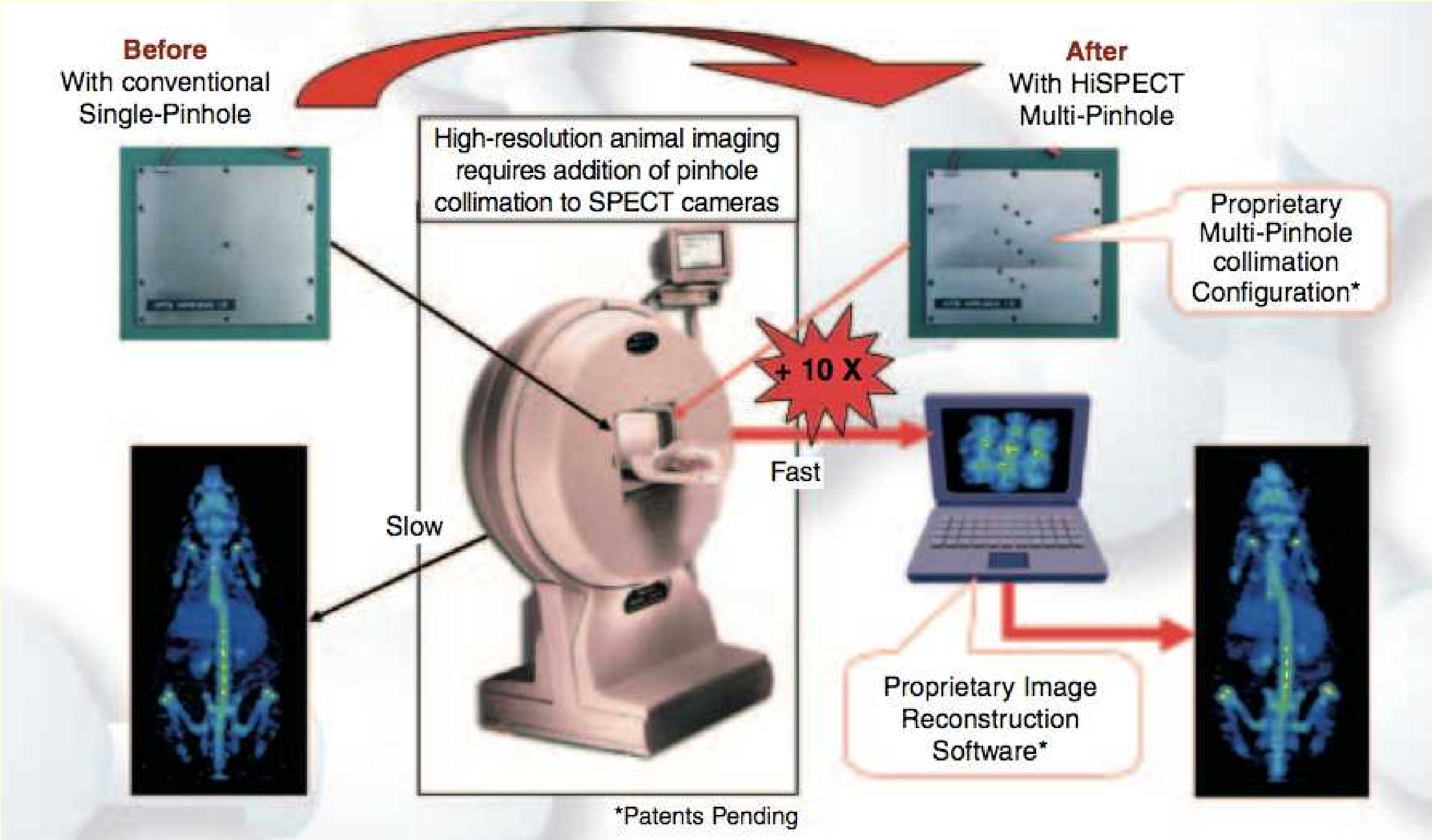
- Advantage: high count sensitivity of coincidence detection up to 10%
- Advantage: large number of tracers that can be labeled with C-11 ($T_{1/2}$=20 min), N-13 (10 min), F-18 (110 min) Cu-64 (12 hrs), I-124 (4 days)
- Disadvantage: very short half-life for most PET isotopes
- Disadvantage: ~1.2 mm spatial resolution i.e. worse than in micro-SPECT
- Disadvantage: very high cost of the micro-PET scanner (<$0.5M)

Commercial micro-SPECT systems

Manufacturer	Model	Design	Detectors	Spatial resolution	Count sensitivity
Bioscan	NanoSPECT HiSPECT	Mulitpinhole 1-10 pinholes	NaI(Tl)	0.8 mm 1.2 mm	up to 4,000 cps/MBq
Gamma Medica	X-SPECT SuperSPECT	Pinhole interchange-able apertures or parallel hole collimator	2x2x6 mm NaI(Tl) and PSPMT CZT	0.6 mm 0.3mm	Up to 855 cps/MBq 137cps/MBq*
Linoview Systems	LOrA-SPECT	Tunable slit-rake collimators	CsI(Na)2.2x2.2 mm pixels	0.60 mmm	1100 cps/MBq
Molecular Imaging	U-SPECT	75 pinholes arranged in 5 rings of 15 pinholes	CsI(Tl)	<0.5 mm (mouse) <0.9 mm (ra)	120 -2200 cps/MBq
NeuroPhysics	MollyQ Scanning Focal-Point Microscope	9 cone-beam collimators 10,042 343 µm diameter entry apertures	CaF or NaI(Tl)	0.5 mm	31,000/MBq Can image 100 nCi of I-125 (23 keV)

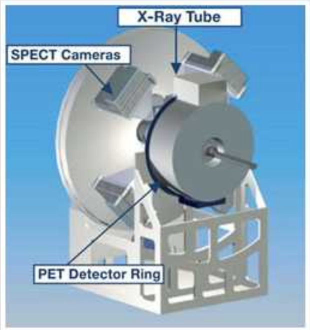
*0.0137% efficiency

HiSPECT



http://www.bioscan.com/

Gamma Medica Multimodal scanners



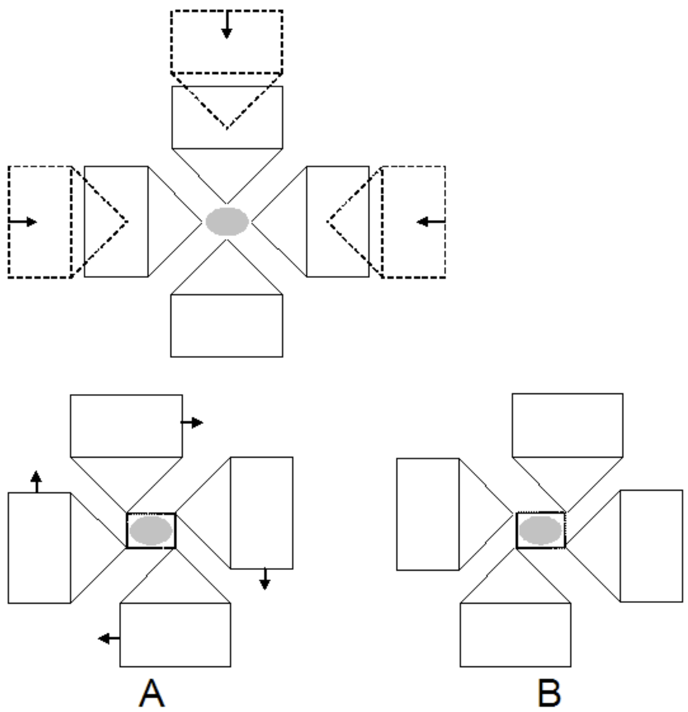
micro-SPECT/micro-PET/micro-CT

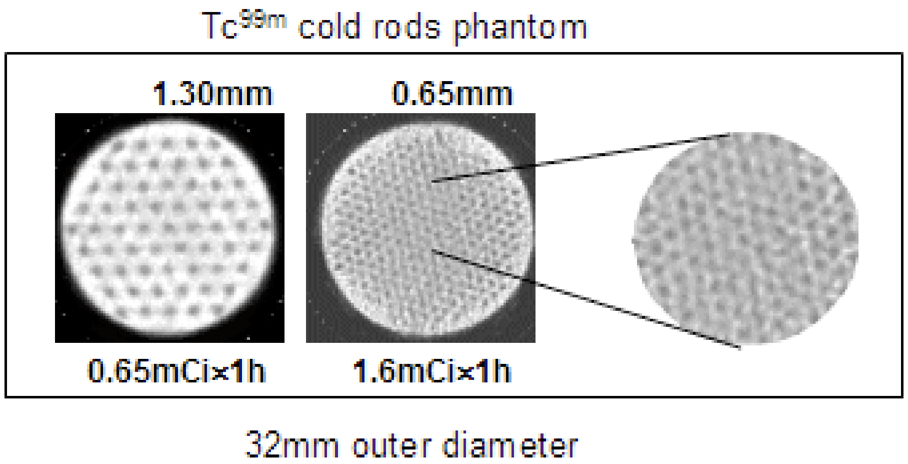
micro-SPECT/micro-MRI

Helical micro-SPECT scan

http://www.gm-ideas.com/

Linoview



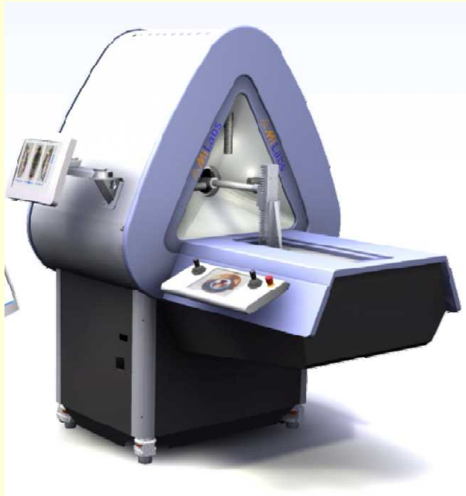


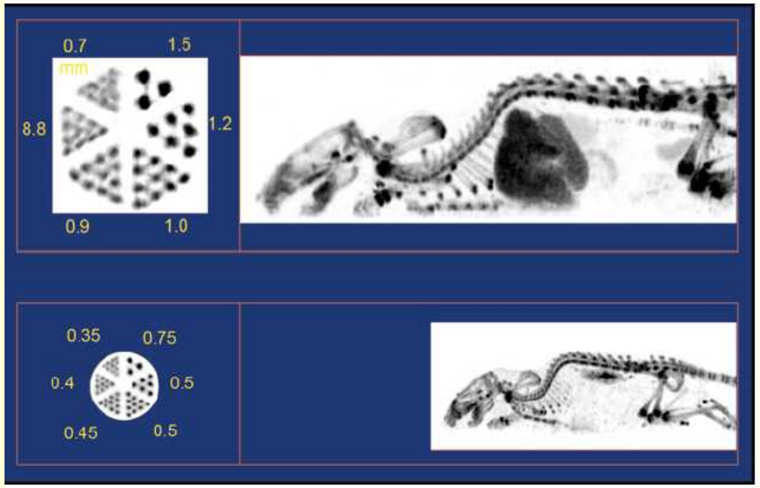
The detectors are moved radially close to the animal and the parameters of the rectangle orbit are automatically computed. The detectors then move automatically to the start position A, the acquisition is initiated and the detectors move to the end position B.

Linograms are then acquired.

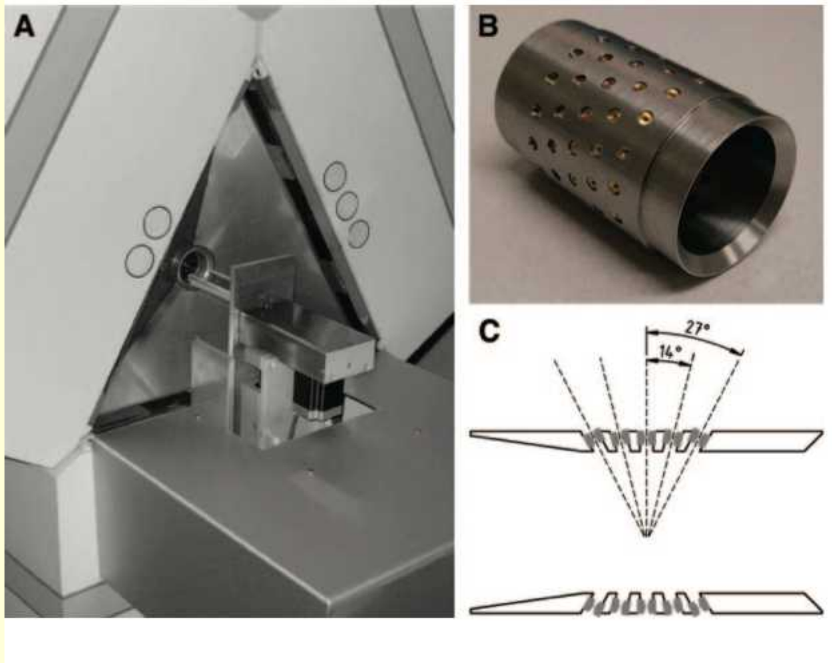
http://www.linoview.com/

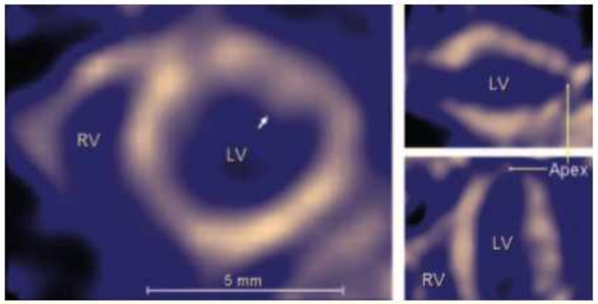
U-SPECT





Rat image right and left ventricles can be seen (SNM 2007 highlights)

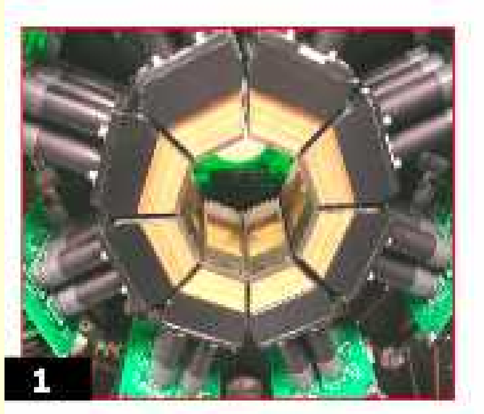




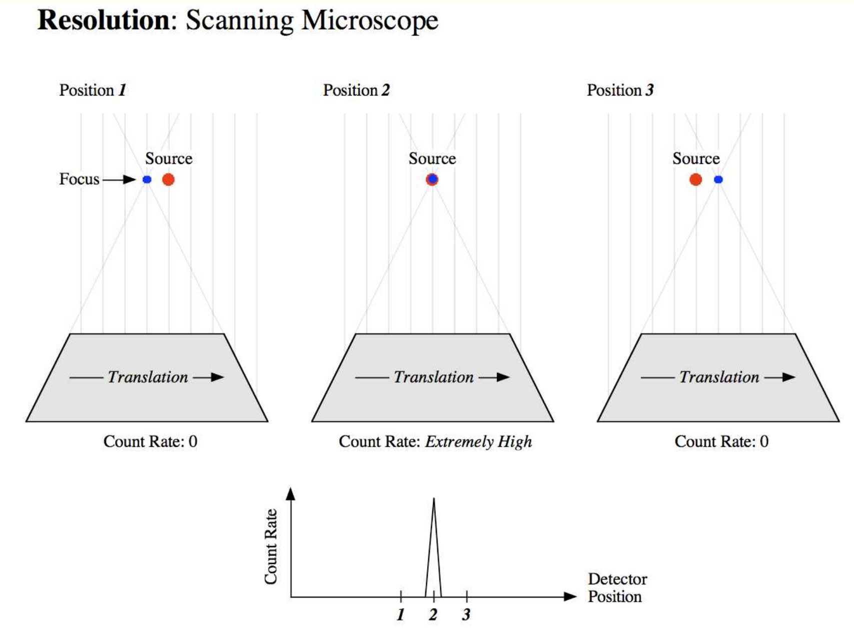
MPI images of live mouse 6 mCi of Tc-99m tetrofosmin acquired in 30 min (1/2 hr after administration)

http://www.milabs.com/

MollyQ
Scanning Focal-Point Microscope



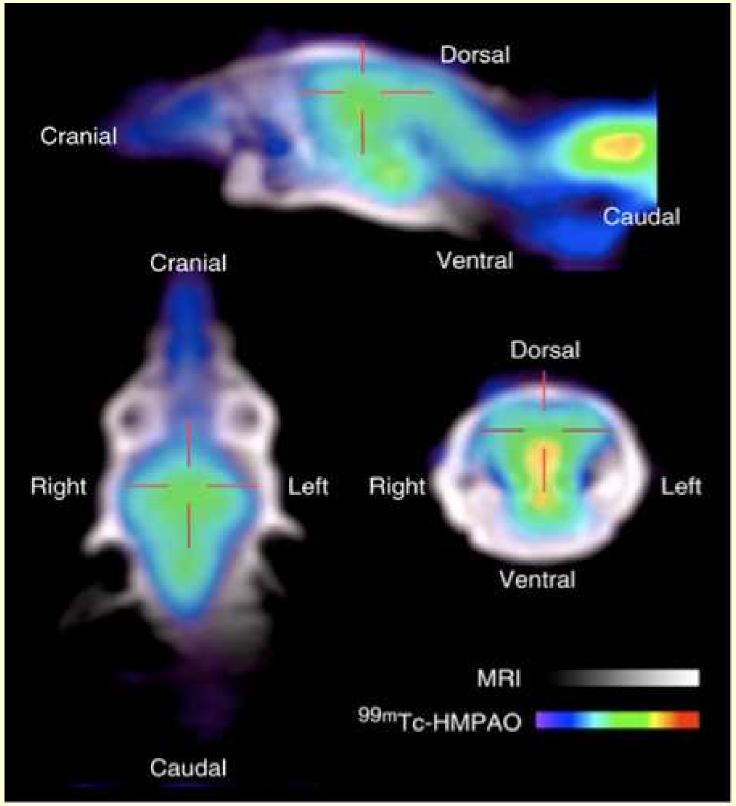
Crossection



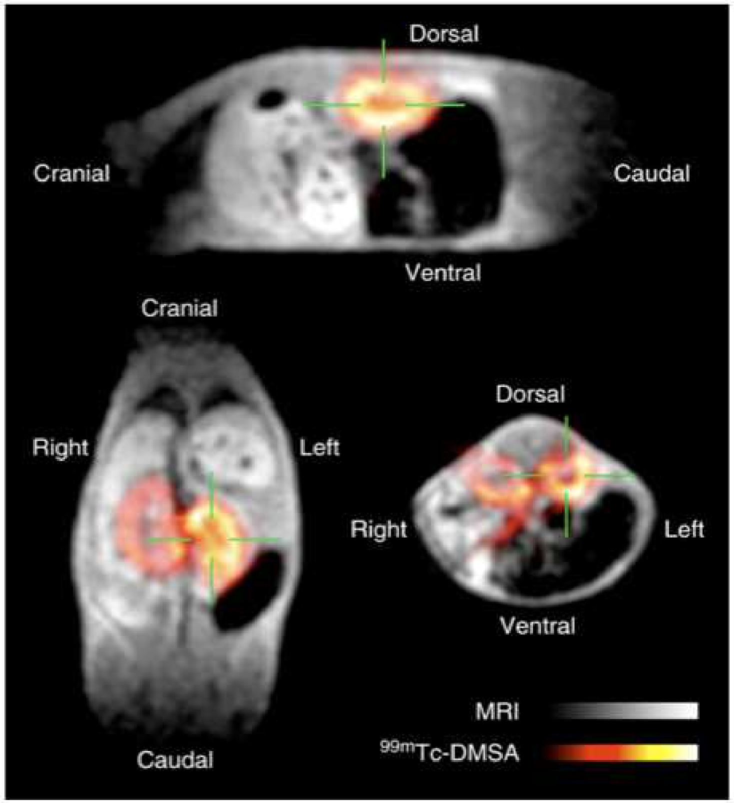
Principle of operation

Courtesy Neurophysics

New trend: micro-SPECT/micro-MRI



HMPO SPECT brain perfusion in nude mouse coregistered with low field MRI (Goetz, et al 2008)



Tc-99m DMSA kidney uptake in nude mouse coregistered with low field MRI (Goetz, et al 2008)

RECONSTRUCTION AND IMAGE PROCESSING

Tomographic slices need to be reconstructed from the acquired projection data.
Filtered backprojection is not optimal for SPECT (due to high noise in the data) – streak artifacts present.
Iterative algorithms is better method for SPECT reconstruction due to better noise modeling and accurate corrections can be done for:

- attenuation
- scatter
- septal penetration
- spatial resolution

Improved image quality and reduced acquisition time

Commercial software with advanced corrections for attenuation, spatial resolution, noise suppression and scatter

Astonish – Philips
Flash 3D – Siemens
Evolution – GE Healthcare
HOSEM – Hermes Medical Solutions
Wide Beam Reconstruction – UltraSPECT
…

Conclusions

In the last few years we have observed major improvements in clinical SPECT scanners design resulting in improved projection images and faster scans.

Improvement and clinical availability of advanced iterative reconstruction methods along with fast computers with accurate corrections for attenuation, spatial resolution, sensitivity, scattered radiation and other factors has resulted in more accurate reconstructed tomographic images.

Conclusions cont'd

Increasing proliferation of SPECT/CT scanners allows correlated anatomic and functional imaging further improving image quality and diagnostic performance of SPECT.

There has been significant progress in small-animal SPECT instrumentation and ever increasing use of this technology in biomedical research.

There is still room for improvement in terms of spatial resolution and sensitivity for both applications.

The end