Medical applications round table

Radiotherapy

Diagnostic radiology

Nuclear medicine

Radiation protection

Will be discussing

- Ion beam therapy/radiotherapy
- Diagnostic radiology
- Nuclear medicine
- Radiation protection
- Detectors covered during the School:
  - silicon,
  - photodetectors
  - gaseous detectors
  - calorimetry
- Storage capacity/medical data
  - Images
  - Reports
  - Plans

Ion beam therapy

- Has anyone ever seen such installation?
- Why do you think the patient would ever been referred (directed) to the ion beam therapy, and NOT to conventional therapy?
- Does anyone know a patient who was referred to ion beam therapy?
- Do you know any facility that conducts such therapy and which?

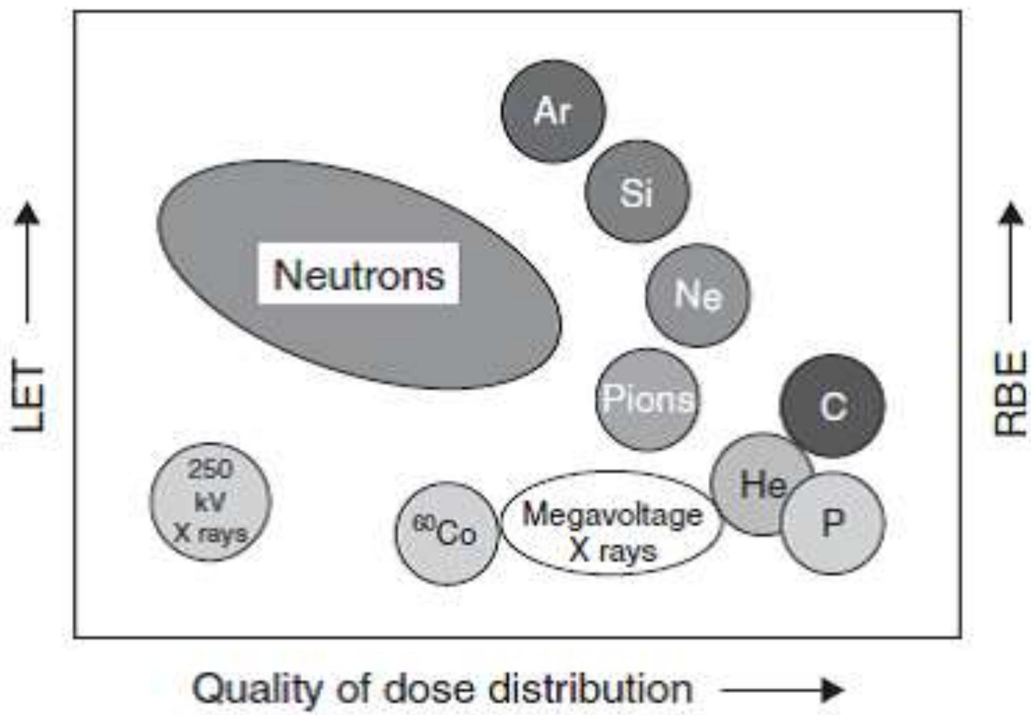
Ion beam therapy (protons, carbon ions)

- Current
  - Size and complexity of facility?
  - Cost of facility? (~ 130 million USD, 1/3 goes to cost of accelerator)
  - Cost of treatment?
  - Benefits to patients?
    - Mayor is depth control by Bragg peak
- Future
  - Disdvantages of the ion beam therapy?
    - RBE uncertainity (carbon)
    - Bragg peak NOT going beyond the tumor (carbon)
    - Cost of facility and size
  - Development?

For you information size is…

Medaustron facility construction works-slides courtesy of dr Stanislav Vatnitsky

- A high linear energy transfer (LET) correlates with a high relative biological effectiveness (RBE), as more ionisation events results in a higher probability of causing clustered DNA damage and is thus effective for tumour control. This varies depending on the particle or photon, as seen in figure below, and is due to variations in charge and mass.



Protons (~40 facilities worldwide)

- Radiobiological effectiveness (RBE)
- Relative cost for proton therapy versus conventional therapy currently is around 2.5 times higher, if a recovery of the capital investments is required. The ratio may decrease to 2.1–1.7 in the next two years
- Without a recovery of investment costs, the ratio could be lowered to a value between 1.6 and 1.3.

Carbon ions
(few centers worldwide)

- Radiobiological effectiveness (RBE) even higher than protons
- The costs for a single fraction of carbon beam therapy currently is around 1000 € based on a 20 fraction treatment and this is nearly identical to the costs per fraction for proton therapy.

Any ideas, suggestions, questions related to ion beam therapy…

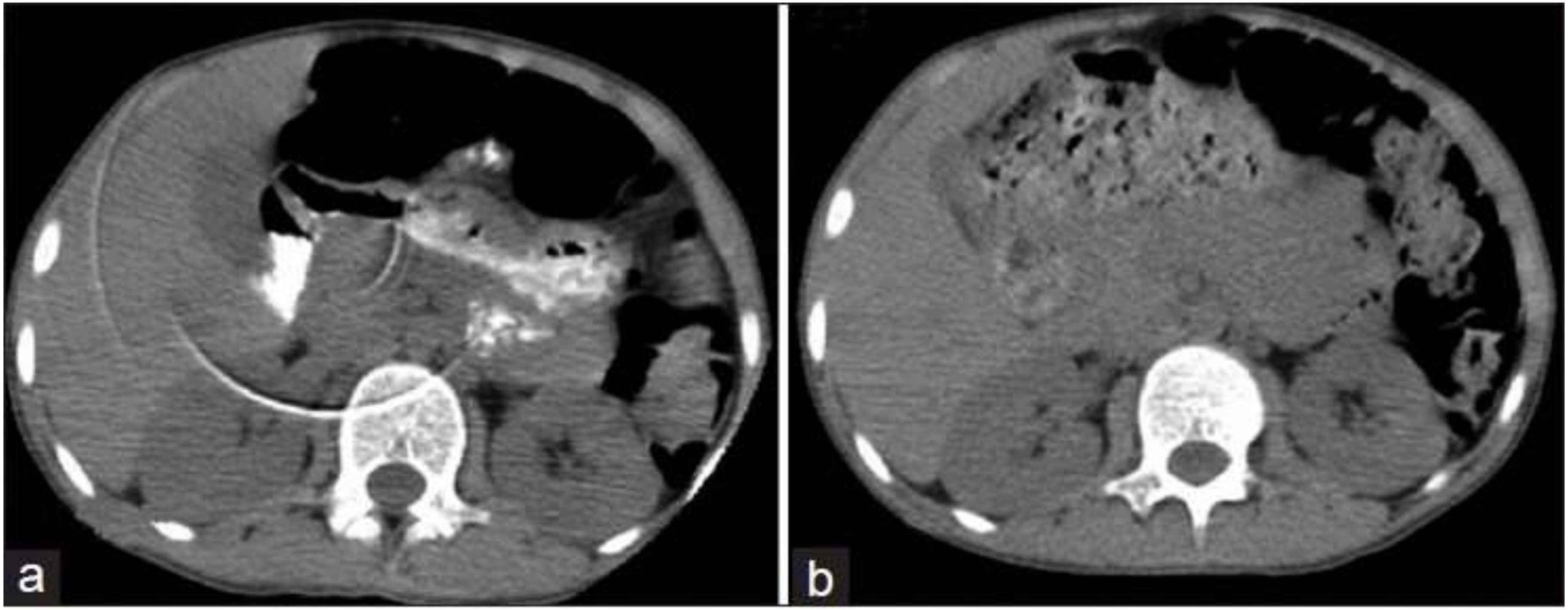
Diagnostic radiology

Artifact reduction in medical imaging techniques

- ARTIFACT-discrepancy between expected and real CT number
- licence for artifacts reduction at the CT console (software- for artifical hip, contrast, etc)
- Image noise, beam hardening, ring artifacts,…

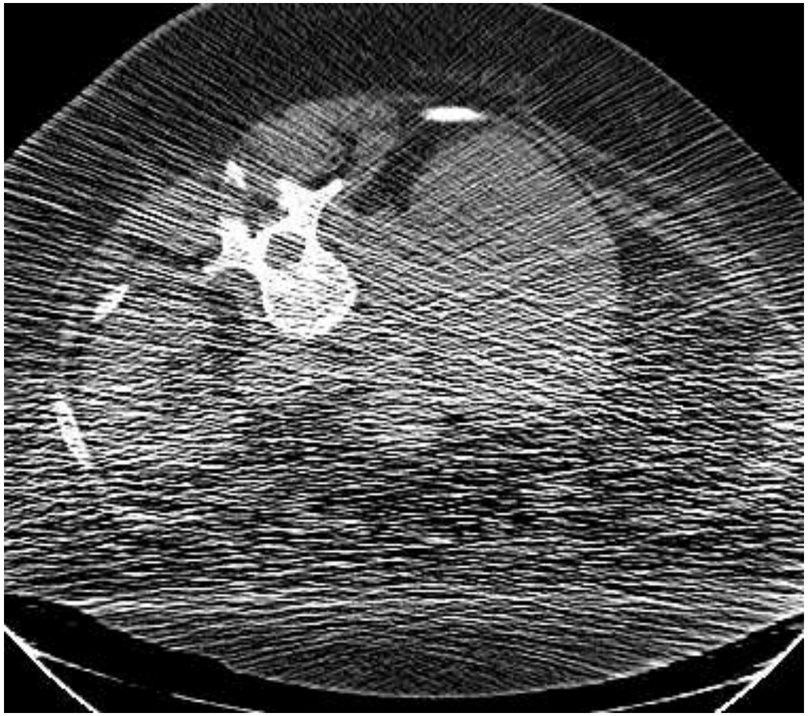
Ring artifacts

- miscalibrated or defective detector element

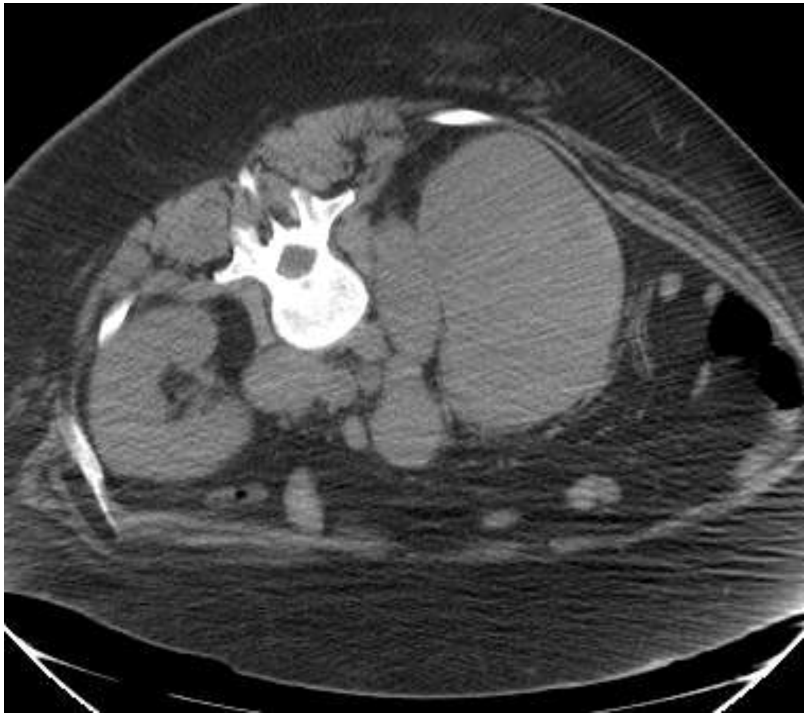


Noise

- Increase of mA or iterative reconstruction



60 mA, 120 kVp, slice thickness 5 mm



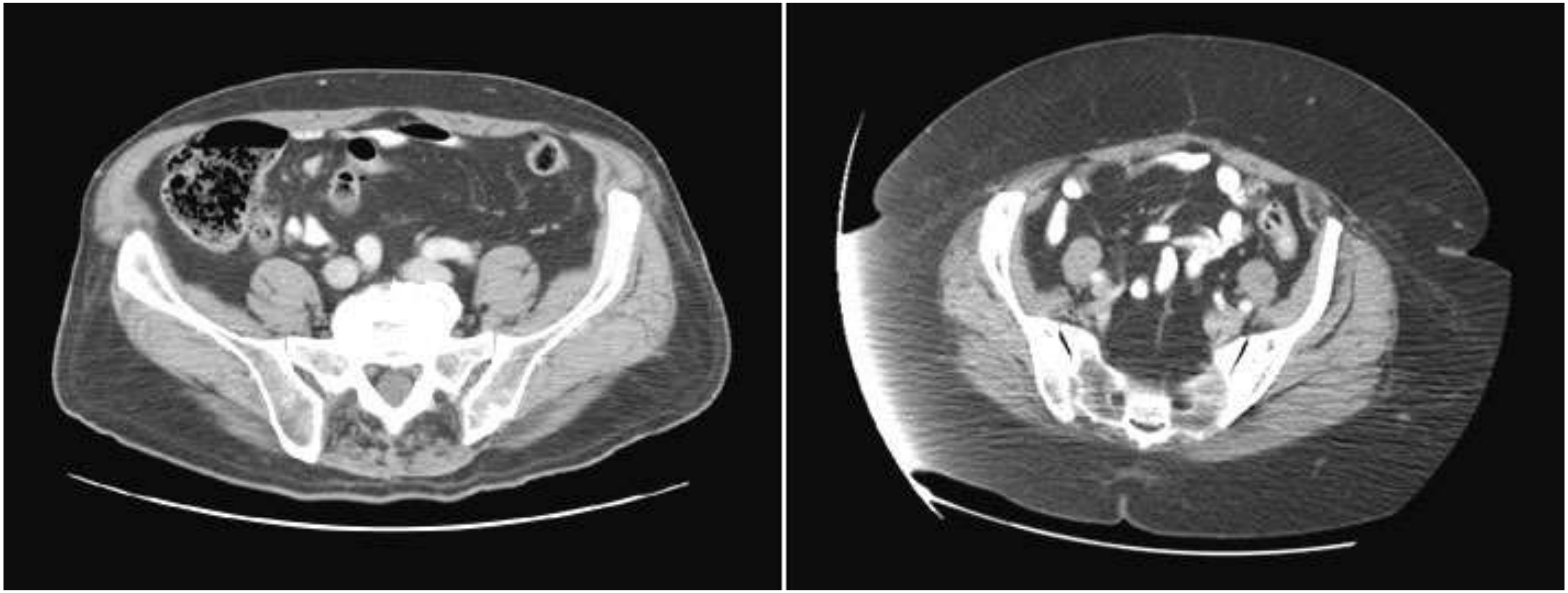
440 mA, 120 kVp, slice thickness 5 mm

Iterative reconstruction reduces noise and improves image quality

A. FBP image obtained at low dose is extremely noisy.
B. The same low dose scan reconstructed using Model Based Iterative Reconstruction (MBIR) results in dramatically reduced noise, revealing new soft tissue details

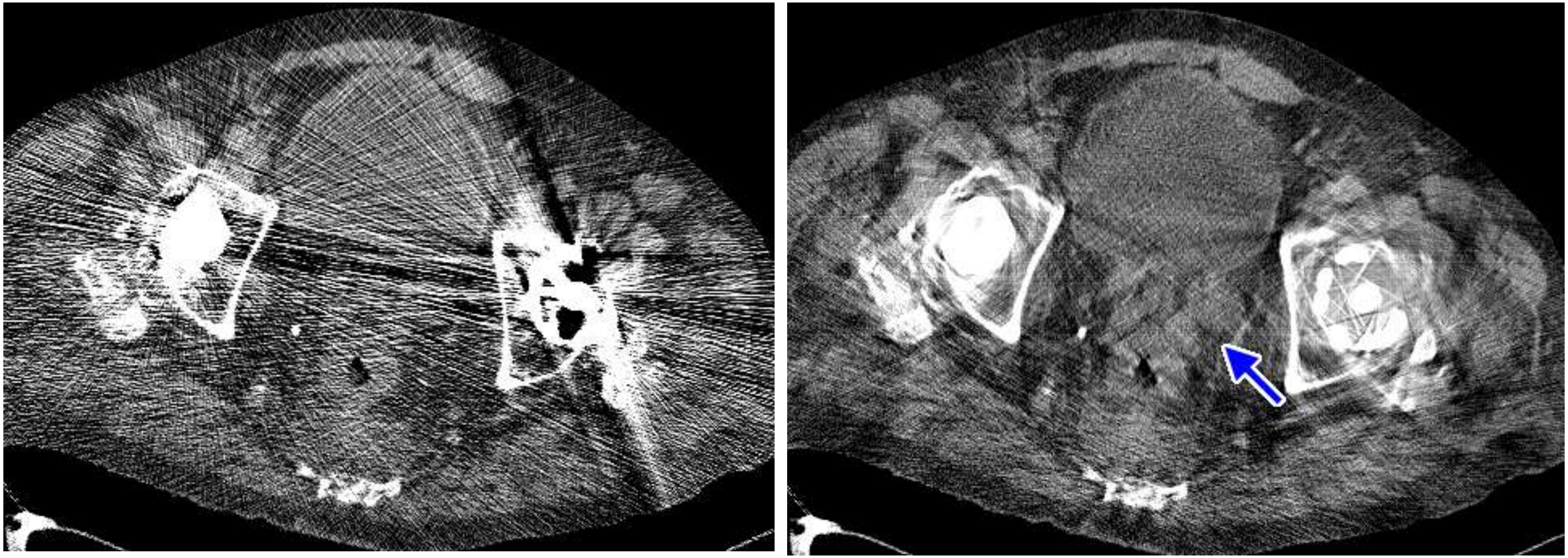
Patient contact with bore

- At obese patients



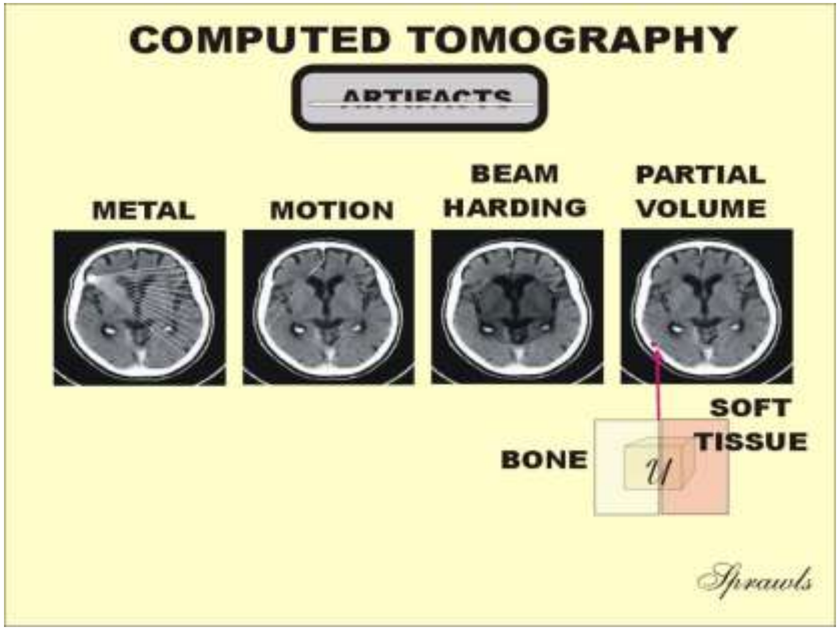
Artificial hip

- Software licence for reduction of artifacts



Further reading

- CT artifacts: Causes and reduction techniques F Edward Boas & Dominik Fleischmann, Imaging Med (2012) 4(2), 229-240



Dose reduction in CT imaging

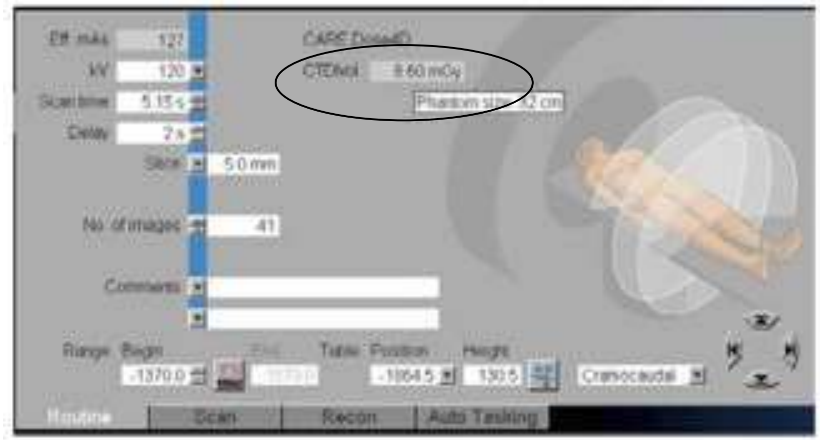
- Imaging dose has been regarded as negligible
- Increased use of imaging highlights the importance of managing dose
- In CT diagnostic:Increasing Source of Radiation Exposure

  nearly 1/3 of all CTs may be inappropriate– increased risk of cancer induction*
- Number of CT or MR use is trippled since 1998-2007

*** Brenner DJ & Hall EJ, N Engl J Med 2007; 357: 2277-84**

Radiation Dose reduction Strategies CTDI

- Optimal tube current (mA) selection
- Reduce tube voltage in suitable patients
- Minimize scan range
- Iterative reconstruction
- Dynamic collimation
- Improved CT detectors



Factors affecting CT radiation dose and Image quality

- Primary factors: Tube current (mA), tube voltage (kV), scan time, Scan acquisition type
- Secondary factors: Scan field of view, Display field of view, Beam collimation, Reconstructed slice width, reconstruction interval, reconstruction algorithm
- Other factors: Patient size, Patient Motion, Scan length, Geometry and detector efficiency
- TRAINING AND EXPERIENCE!

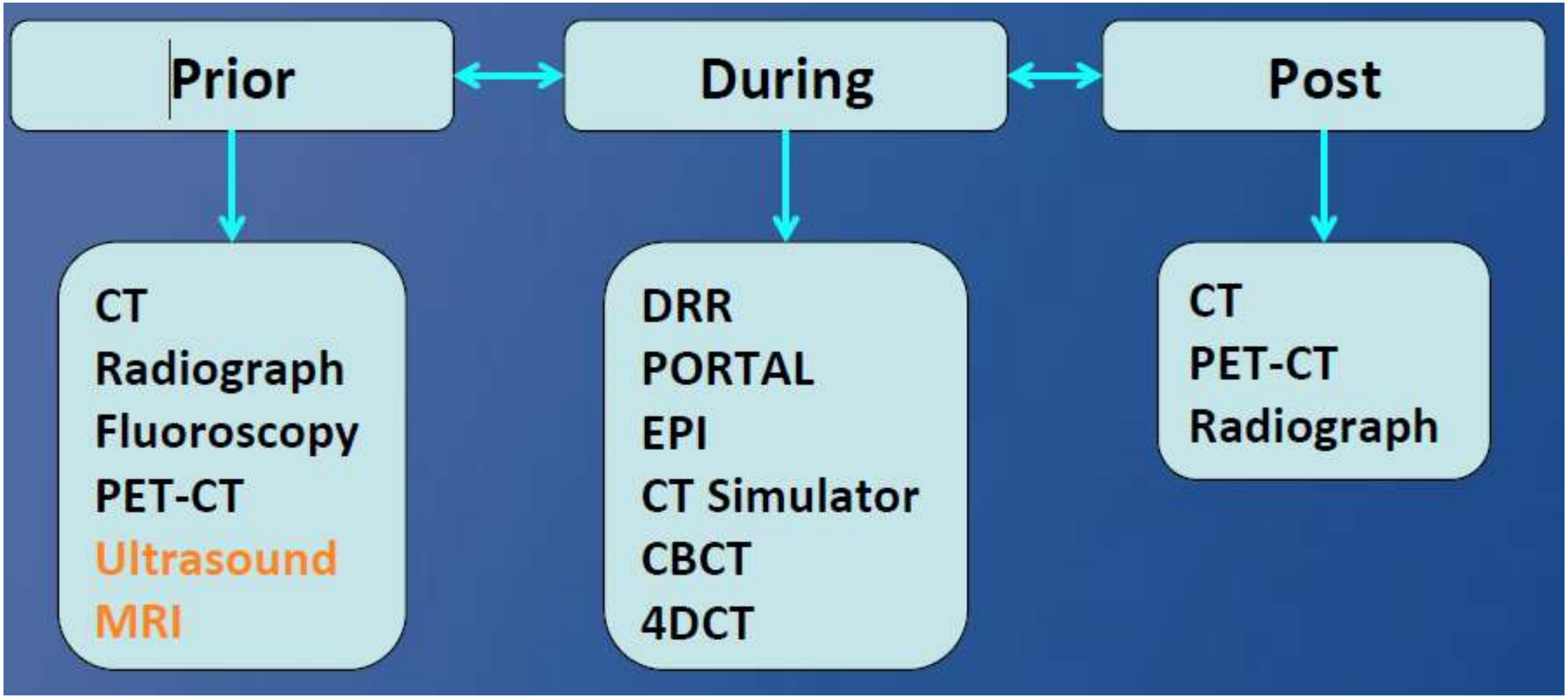
Automatic Exposure Control (AEC)

- Lower tube voltage improves image contrast and reduces dose
- But! as voltage decreases, tube current has to be increased to maintain image noise
- Siemens- CARE dose

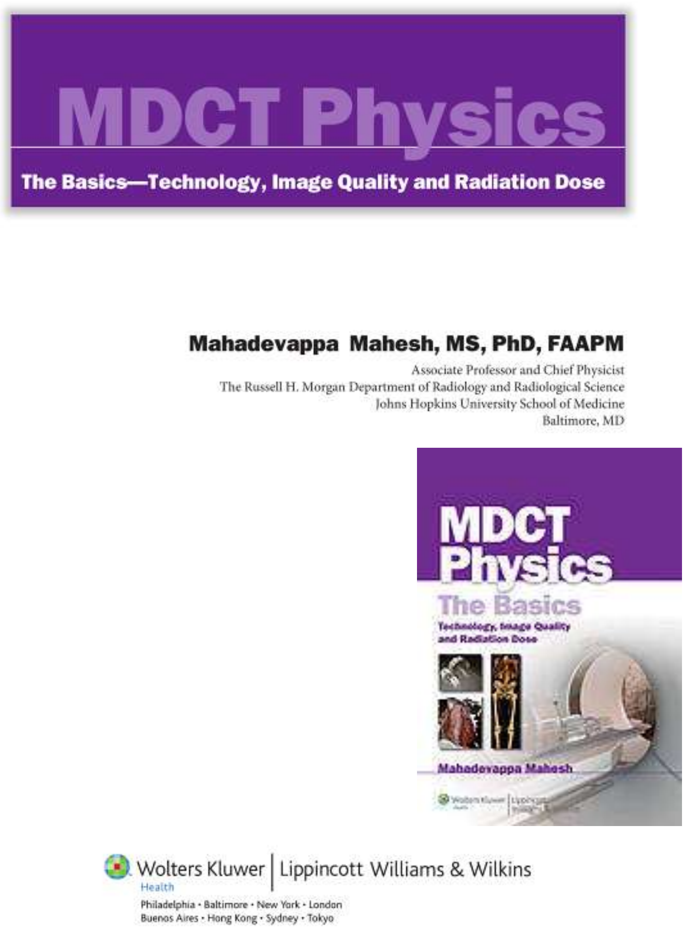
What can be done?

- Educate all stakeholders regarding radiation dose and risks
- Ensure x ray imaging studies are justified and benefits outweigh the risks always
  - Avoid repeat studies(if follow up scan in 3 months can be replaced by 4 months- dose to patient lowered by 25%)
  - Minimize multiphase studies
  - Decrease frequency of follow up imaging
- Coordinate efforts with radiation oncologists, radiologists, medical physicists and technologists to optimize modalities and protocols to minimize radiation exposure
- Radiation therapy involves multiple exposure to ionizing radiation from different sources

RT cancer patients



Further reading

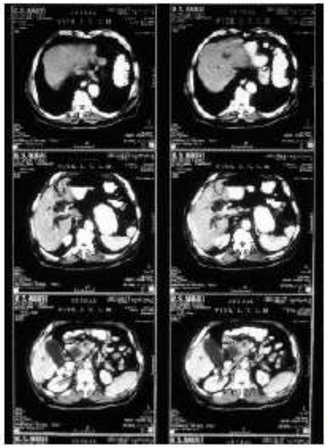


MDCT Physics: The Basics - Technology, Image Quality and Radiation Dose

Mahadevappa Mahesh

Lippincott Williams &Wilkins, 2009

Imaging Modalities



CT

A

Tissue Density, Z

20-50 µm

Ultrasound

A F

Structure

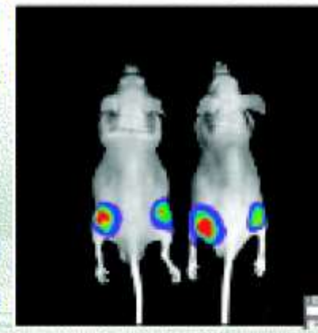
0.1 mm

Doppler

Optical

(Bioluminescence, fluorescence)

A M



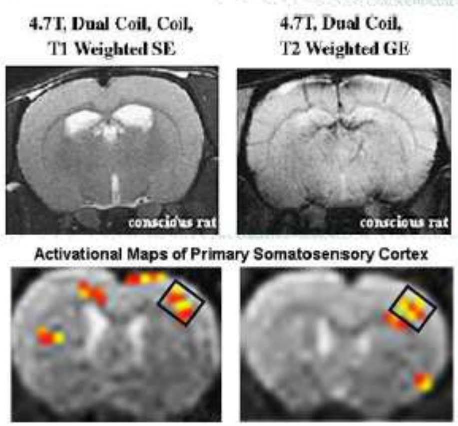
Topography

µm to mm

~10^3 cells

≠ quantitative

MRI



A F M

H Concentration

0.1 mm

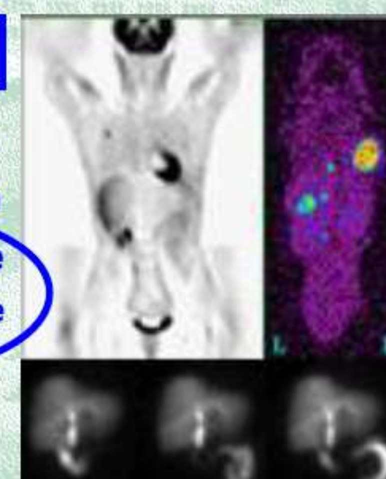
BOLD, DCE

β-galactocidase

0.1 µmole H / µmole ^{31}P

PET/SPECT

F M



Radiotracer

~1-2 mm

<10^{-12} mole

= quantitative

Detectors in medicine

The detector is a fundamental base in all practice with ionizing radiation

Knowledge of instrumentation potential as well as their limitation is essential for proper interpretation of the measurements

From HEP to Medical

*Where **techniques** are transfered to developments in bio- medical field*
Medical Imaging has only partially benefited from new technologies developed for telecommunications and High Energy Physics detectors

- **New scintillating crystals and detection materials →**
  - CMS (WPbO4) → Luap ...(Crystal Clear col),
- Photodetectors : **Highly segmented and compact** → PMT → APD → SiPM
  - APD : SSC/SDC (1991) → CMS (1996) → MicroTEP→ TEP
- Electronics & signal treatemnt→ Highly integrated
  - Fast, low noise,low power preamp
  - Digital filtering and signal analysis
- Trigger/DAQ →
  - **High level of parallelism and event filtering algorithms**
  - Pipeline and parallel read-out, trigger and on-line treatment
- Computing
  - Modern and modular simulation software using worldwide recognized standards (GEANT)

Detector technologies used in medical imaging:

- Silicon, Selenium - (X-ray)
- CdTe, CdZnTe – (X-ray, gamma, PET)
- Crystal scintillators (gamma, PET)
- Cherenkov – (TOFPET)
- Vacuum Photomultipliers (including MCP based, position sensitive, etc)
- PIN diodes
- Avalanche photodiodes (APD)
- "Silicon photomultipliers" – SiPMs, Geiger avalanche diodes
- Time of Flight PET
- Compton gamma imaging

Areas of involvement

-The most obvious field: nuclear medicine: SPECT and PET

-Diagnostic tools (early detection of abnormalities, such as cancer)

-Beam radiation therapy (proton and ion beams, and the latest promise of antiprotons !)

-Monitoring chemo- and radio-therapy

-Organ specific imagers:

-Breast

-Prostate

-Brain

-Small animal SPECT and PET imagers

Special features: MRI compatibility, Time of Flight (TOF) PET

Selected detector technologies used in medical imaging as the best particle physics spin-off :

- APDs and SiPMs
- Crystal scintillators
- Fast electronics, ASICS
- Fast simulation and reconstruction software
- TOF

“Among the many applications of nuclear energy and ionising radiation, medical imaging certainly is least subject to negative perception or outright opposition from the general public. Proponents of nuclear power correctly refer to it as an example of a very positive use of nuclear technology.” - **By Frank Deconinck, 2006.**

Photon detection

The detection of the photons is based on the transfer of their energy to the detector through the photo-electric and the Compton effect.

Examples are

- Scintillators, e.g. NaI, BGO and LSO (cfr. talk by C. van Eijk)
- Semiconductor detectors, e.g. Si, Ge
- Gas detectors, e.g. with a wire chamber read-out (MWPC, HIDAC, …)

Detector Principles

- Gas filled detectors
  - ionisation chambers
  - proportional counters
  - Geiger Müller (GM) - tubes
- Scintillation detectors
  - solid
  - liquid
- Other detectors
  - Semi conductor detectors
  - Film
  - Thermoluminescence detectors (TLD)

How to select detector for the your purpose?

- Many manufacturers…
- Many brochures
- Many modern looking, but..
  - What do you need it for, which particle/medium/beam energy/field size/conditions of measurement
  - Consult recommendations
  - Consult protocols

Detector Types

1) Counters

- Gas filled detectors
- Scintillation detectors

2) Spectrometers

- Scintillation detectors
- Solid state detectors

3) Dosimeters

- Gas filled detectors
- Solid state detectors
- Scintillation detectors
- Thermoluminescent detectors
- Films

Gas-filled Detectors

Ionization Chambers

Applications in Medicine

- **Activity Meter**
- **Monitoring Instruments/ Survey Meters**

General Properties of Ionization Chambers

- High accuracy
- Stable
- Relatively low sensitivity

Proportional Counters

Applications in Medicine

- **Monitoring Instruments**

Properties of Proportional Counters as Monitor

- A little higher sensitivity than the ionization chamber
- Used for particles and low energy photons

Geiger Müller – Tube

Applications in Medicine

- **Contamination Monitor**
- **Dosemeter (if calibrated)**

General Properties of Geiger Müller - Tubes

- High Sensitivity
- Lower Accuracy

Development of a new generation of micropattern gaseous detectors for high energy physics, astrophysics and medical applications

In the last two decades very fast developments happened in the filed of gaseous detectors of photons and particles. Traditional gases detectors: wire–type and parallel plate-type (RPCs) -which are widely used in high energy and astrophysics experiments have now serious competitors:

Micropattern Gaseous Detectors (MPGDs)

The main advantage of MPGDs is that they are manufactured by means of microelectronics technology, which offers high granularity and consequently an excellent position resolution.

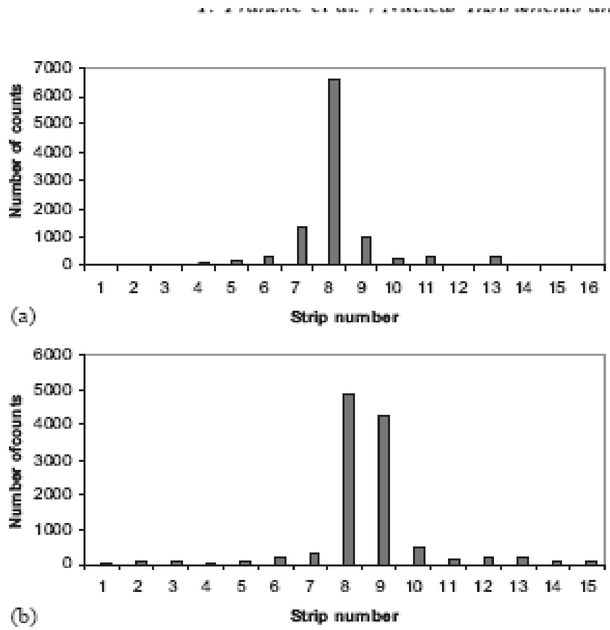
Microstrip-microgap for imaging applications

Scanners:

a) X-ray
(edge on)

Pos. resol. 50μm in digital form,
rate 10^5 Hz/strip

T. Francke et al., NIM A508, 2003, 83



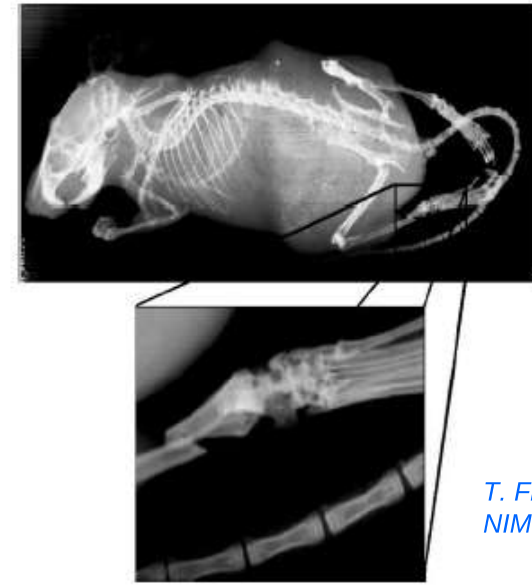
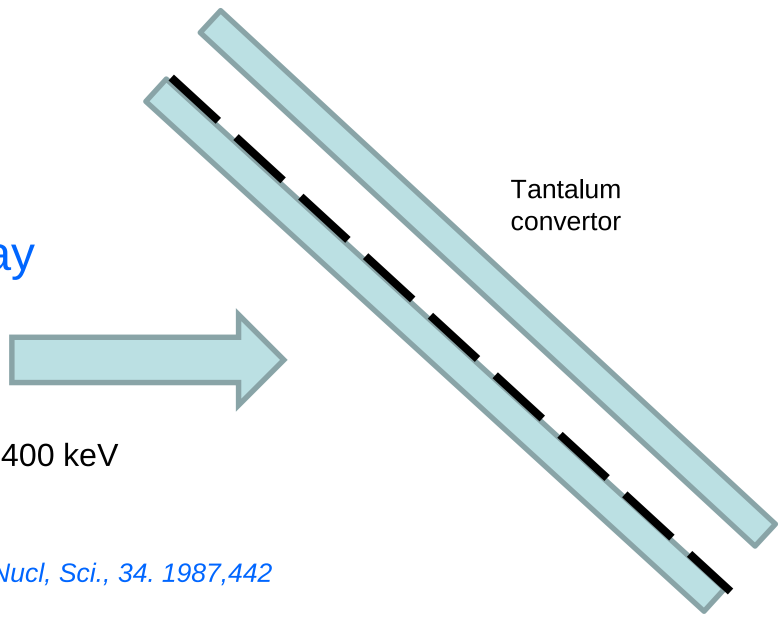


Fig. 3. A 4cm long mouse imaged with the photon counting system.

T. Francke et al., NIM A471, 2001, 85

b) Gamma ray



30% efficiency for 400 keV at shallow angle

I. Dorion et al., IEEE Nucl, Sci., 34. 1987,442

Contacts with industry are established; they already evaluate our prototypes

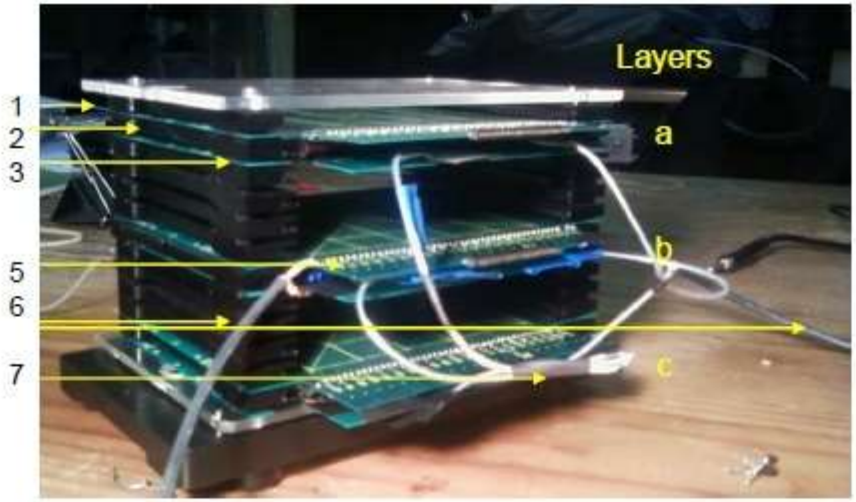


Fig. 3 - View of the telescope. Legend: 1-X strips; 2-RPC; 3-Y strips; 5-signal division network; 6-equal length cables connecting to the timing amplifier; 7-HV connections.

Another goal was/is to combine high pos. resolution with high time resolution.

First step in this direction was already successfully done by Fonte et al ***(see Proc. of Science, RPC 2012, 081).***

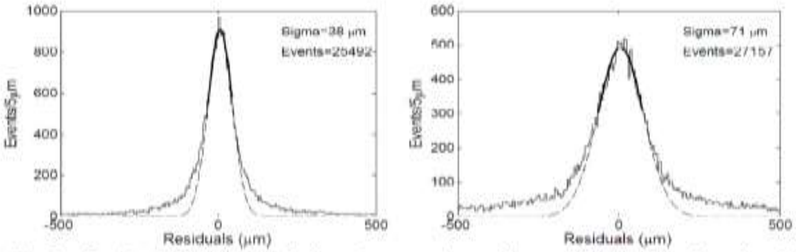


Fig. 9 - Residuals to the straight-line fits to each coordinate of the collected tracks after correction of systematic errors, taking in consideration the full effective area and tracks with moderate, but not negligible, inclination.

Bidimentional position resolution 70µm in with combination 80 ps timing

Besides the particle detections another application is TOF- PET on which Fonte group is actively working

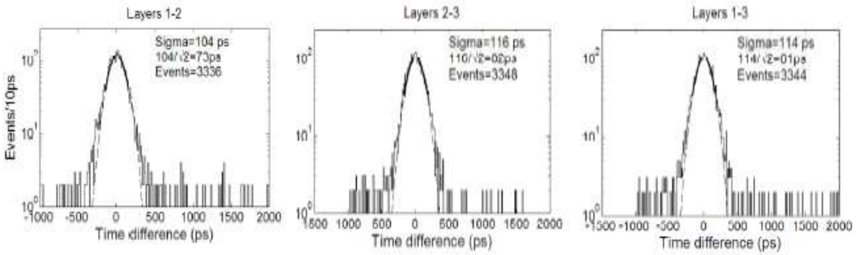


Fig. 10 – Time difference between successive telescope layers after time-charge corrections. The gaussian fit was performed within ±1.5 σ of the peak. The average single-layer resolution is 77 ps and the telescope resolution (combination of the 3 layers) is 77/√3=44 ps.

Multiwire gas counters

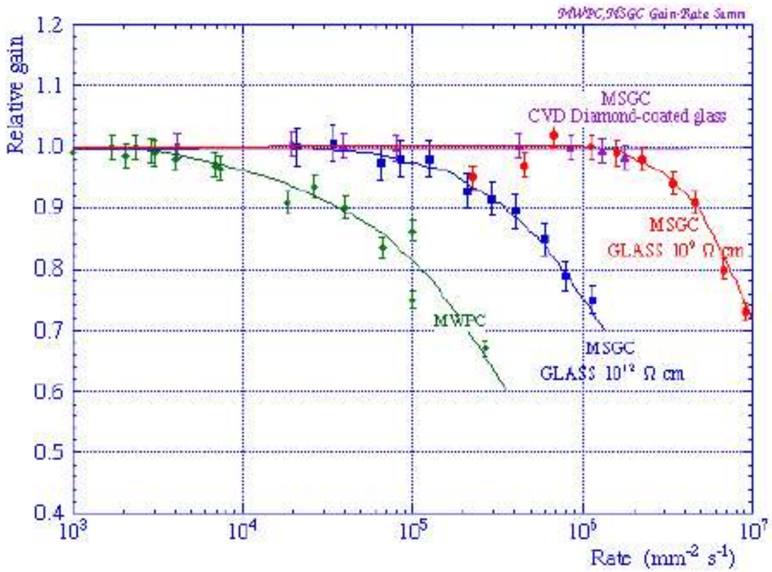
Multiwire gas counters are based on the ionization effects of radiation in gas.

Despite their low efficiency for detecting γ-radiation they have several advantages because they can cover fairly large areas with good resolution.

This makes them usable for PET applications which depend on many large detector arrays located at several angles around the patient.

The production costs are very low compared to the costs for a scintillator system covering the same area.

Gaseous Detectors

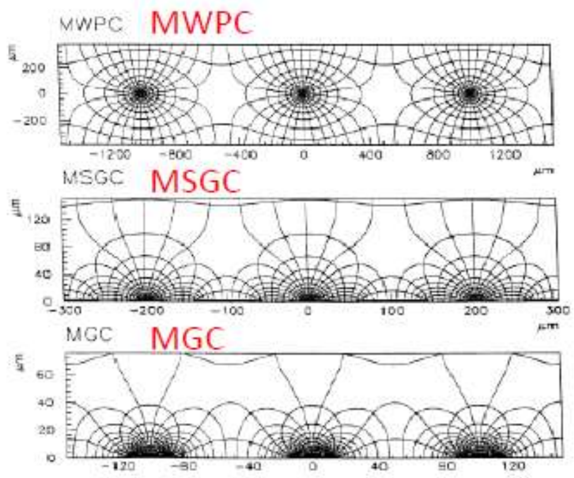


scale factor

1

5

10



Advantages of gas detectors:

- low radiation length
- large areas at low price
- flexible geometry
- spatial, energy resolution …

Limitation:

- rate capability limited by space charge defined by the time of evacuation of positive ions

Solution:

- reduction of the size of the detecting cell (limitation of the length of the ion path) using chemical etching techniques developed for microelectronics and keeping at the same time similar field shape.

Scintillation Detectors

Scintillation Detectors

Applications in Medicine

- **Sample counters**
- **Single- and multi-probe systems**
- **Monitoring instruments**
- **Gamma camera**
- **PET Scanners**

They are characterized by large efficiency for low energy γ-radiation which is limited by the thickness of the crystal $d \leq 2$ cm. This results in a optimum for the of efficiency attenuation conditions for γ energies $E_\gamma \approx 100 - 200$ keV.

The scintillation detectors have a resolution of $\Delta E/E \approx 10\% - 15\%$.

Timing parameters

- General assumption , based on Hyman theory

$$\Delta t \propto \frac{\sqrt{\tau}}{\sqrt{N_{phe} / ENF}}$$

decay time of the fast component

Photodetector excess noise factor

number of photoelectrons generated by the fast component

- For the scintillator the important parameters are
  - Time structure of the pulse
  - Light yield
  - Light transport
    - affecting pulse shape, photon statistics and LY

Other Detectors

Semi-conductor Detector as Spectrometer

- Solid Germanium or Ge(Li) detectors
- Principle: electron - hole pairs (analogous to ion-pairs in gas-filled detectors)
- Excellent energy resolution

Semi-conductor Detectors

Applications in Medicine

- **Identification of nuclides**
- **Control of radionuclide purity**

However the large costs for the production of pure Germanium crystals is prohibitive.

Why Semiconductors ?

- Presently most medical devices are based on photo-imaging (film) => excellent resolution but low sensitivity and lack of image uniformity => long exposure times in β- and x-ray imaging and development time.

- Lately, digital imaging based on integrating devices (i.e. MWPC (multi-wire proportional chambers, gas devices). Sensitivity better than film but resolution poorer (~400 μm)

- New idea: single particle counting using semiconductor detectors has the following advantages:
  - High sensitivity (low exposure time)
  - High dynamic range and excellent linearity
  - Energy discrimination of particles
  - Direct digital imaging and online image display
  - Very good resolution (< 50 μm)

Which Semiconductors ?

- Generally available: Ge, Si, GaAs, CdTe
- Ge needs liquid nitrogen cooling to yield good resolution
- GaAs and CdTe have higher X-ray absorption efficiency than Si in relevant range (<E>=10-70 keV) At 20 keV the detection efficiency for a 200 μm thickness GaAs layer is 98%, which is four times higher than the equivalent efficiency in Silicon.
- GaAs is more advanced than CdTe but both technologies are in their prototype stages compared to Silicon.

Medical Applications

X-ray applications

- Digital mammography <E> = 20 keV
- Dental X-ray tube <E>= 35 keV
- Fast frame medical diagnostics

Nuclear medicine

- Thyroid measurements, <E> = 60-140 keV photons
- DNA probe array, β-emitter (^{32}P, ^{14}C, ^{35}S), <E> = 50-700 keV

Silicon detectors are used at many places

- in astrophysics satellites and telescopes to detect visible and infrared light, X ray and gamma rays
- in synchrotrons to detect X-ray and synchrotron radiation
- in nuclear physics to measure the energy of gamma rays
- in heavy ion and particle physics experiments to detect charged particles
- **in medical imaging**
- in homeland security applications

What makes silicon detectors so popular and powerful?

Why are silicon detectors so popular ?

- **Start from a large signal** ⇔
  good resolution; big enough for electronics
- **Signal formation is fast**

- **Radiation-hardness**
- **SiO_2 is a good dielectric**

- **Ride on technological progress of Microelectronics industry**
  ⇔ extreme control over impurities; very small feature size; packaging technology

- **Scientist and engineers developed many new concepts over the last two decades**

Advantages and disadvantages of silicon diodes

Advantages

- High sensitivity(18000× equal volume ion chamber)
- Real time on-line readings
- Efficient (fast) in use
- Waterproof
- Durable

Disadvantages

- Temperature dependence
- Cumbersome cables on most systems
- Angular dependence
- Different detectors for photon and electron beams
- Energy dependence
- Radiation damage – change of sensitivity with accumulated dose

MOSFETs
Metal Oxide Semiconductor Field Effect Transistor

Advantages

- Instantaneous readouts (on-line dosimetry)
- Very small active volume, dual detectors eliminate most correction factors
- Efficient use (doesn’t consume much time)
- Waterproof

Disadvantages

- Finite life expectancy
- Temperature dependence
- for single MOSFET detector

Digital Mammography (DM)

- **Main features**
  - Linear response with X-ray exposure
  - Wide dynamic range ($10^4 – 10^5$)
    - Mammography of dense breast
  - Reduced radiation dose
    - Exposure determined as a function of the Signal to Noise Ratio (SNR) not of the Optical Density of the film (OD)
      - Dose reduction from 20 to 80 %
  - Image processing
  - time required for the examination (t_{exp}<1s; T_{proc}~minutes)

- Limitations (?)
  - Spatial resolution
    - Film-screen systems $\geq$ 20 lp/mm
    - Digital systems $\leq$ 5 lp/mm (spatial frequency is smaller, but image is sharper)
  - Monitor resolution
    - Monitor 2000x2500 pixels, resolution 0.1 mm

Film

Principle: As normal photographic film

Silver halide grains, via changes due to irradiation and development to metallic silver

Application in Medicine: Personal dosemeter

Problems

- Requires processing ---> problems with reproducibility
- Two dimensional dosimeter
- High spatial resolution
- High atomic number ---> variations of response with radiation quality

Luminescence dosimetry

Thermoluminescence Dosimetry (TLD)

- Small crystals
- Tissue equivalent
- Passive dosimeter - no cables required
- Wide dosimetric range (μGy to 100s of Gy)
- Many different applications

Thermoluminescence Dosimetry (TLD)

Applications in medicine

- Personal Dosemeters (body, fingers…)
- Special Measurements

Disadvantages:

- **Time consuming**
- **No permanent record**

Advantages and disadvantages of OSL

Optically Stimulated Luminescence dosimeters

Advantages

- Size
- Real - time dosimetry
  for RL mode of operation

Disadvantages

- Energy dependence
- off-line dosimetry for OSL
  mode of operation
- Some temperature dependence

Calorimetry

- Where applicable?
  - In absolute dose determination
- Who works with it?
  - Primary Standards laboratories
  - Dosimetry for ion beam therapy installation
- Types: water, graphite, optical

General ideal detector

- Water proof and small
- No temperature and humidity dependence
- No radiation damage
- Inexpensive
- Dose rate independence
- Easy to produce
- Energy independence
- Stable response to measurement
- Linearly responces to dose to large dose range
- Non destructive and long life expectancy
- Online reading
- Efficient for use (not time consuming)
- Wireless

- …that is where development should go…

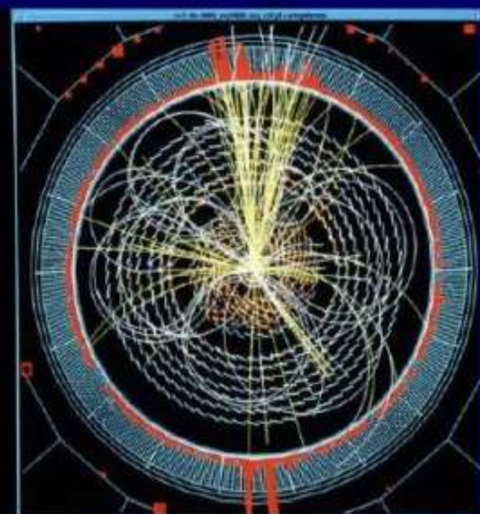
Nuclear medicine

Why PET ?

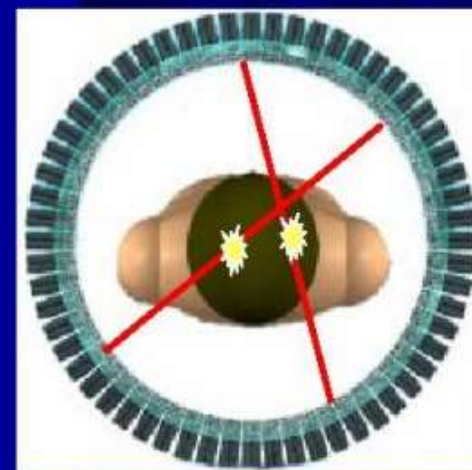
Similarities and differences

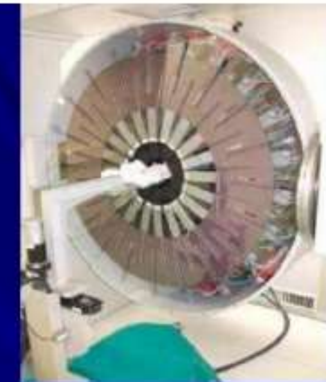
Calorimeter

HEP



M_{Higgs} = 100 GeV





PET Camera

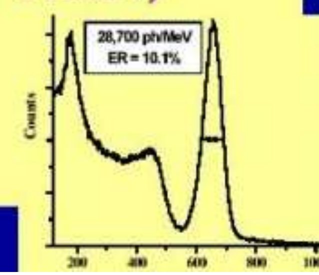
Biomedical Imaging

Similarities

- Geometry and granularity
- Detector (Crystals & scintillator)
- Photo Sensor (PM,APD)
- Electronics:Fast and compact
- Event rate & Data volume

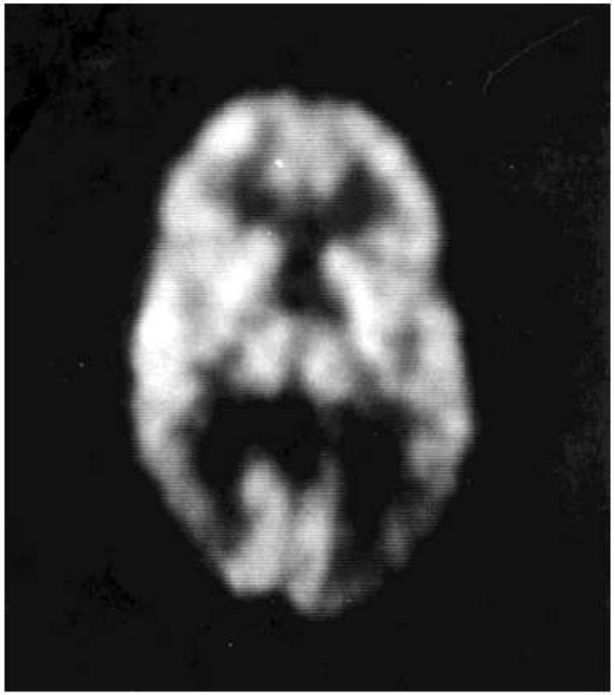
Differences

- Energy range (10GeV-511keV)
- No synchronisation
- --> free running electronics



Advances in PET

PET in 1986



- 8 mm Resolution
- 5 cm Axial Extent
- Cardiology / Neurology
- Academic Research

PET in 2010

- 4 mm Resolution
- >15 cm Axial Extent
- Oncology
- Routine Clinical

Contributions from "Physics"

-Physics concepts: positron range, annihilation, imaging via efficient detection of two 511 keV annihilation gamma rays, two gamma rays co-linearity, TOF, etc

-Instrumentation: detectors, electronics

-Radioactive labels (in radiopharmaceuticals)

-Simulations (modeling) of the detection process and electronics

-Reconstruction, filtering algorithms (tomography, inlcluding limited angle)

How to Detect Smaller Lesions with PET

- Improve spatial resolution
- Improve sensitivity (SNR)
- Improve reconstruction algorithms
- Synergistic use of PET and CT information
- New radiotracers for specific targets

Motivation to Combine PET and MRI

- **Strengths**

- "Near-perfect" registration of structural and molecular imaging data
- Anatomically-guided interpretation of PET data
- Anatomic priors for PET reconstruction and data modeling
- PET can be combined with advanced MRI techniques such as DWI, DCE MR, MRS, cell tracking and MR molecular imaging agents

- **Weaknesses**

- Technically difficult and likely expensive
- Uncertainty regarding throughput, cost effectiveness and ultimate clinical role

Future, questions and challenges: Improving time resolution

$$\tau^2 = \tau_0^2 \frac{1}{N_0}\frac{1}{QE}\frac{1}{\alpha_{crystal}}\frac{1}{\alpha_{BLK}} + \Delta\tau^2_{PL-crys} + \Delta\tau^2_{PL-LG} + \Delta\tau^2_{PMT-TTS} + \Delta\tau^2_{PMT-\mathrm{var}} + \Delta\tau^2_{DISCR} + \Delta\tau^2_{TDC} + \Delta\tau^2_{SysNoise} + \ldots$$

Scintillator timing

Scintillator Light output

Light sensor properties (PMT)

Statistical part

Crystal losses

Block losses

Path length spread in crystal

Path length spread in light guide

Transit time spread in PMT

PMT variations

Discriminator Time spread

TDC Time spread

System noise contributions: Power supplies, clocks, cables, etc

Storage od medical data

Storage capacity/medical data

- Images and patient data
  - Size ~ 500 kB of one Dicom image
  - Size of plan/report/… few kB
  - One CT set contains 50-60 images which is 30 MB of data,
  - treatment planning CT also has 50-60 DICOM images, also 30 MB of data, plus verification DICOM images (simulator films and portal images)
  - Additional SPECT, PET, US, MRI (few sets of data different sequences)… each set for SINGLE patient ~ 30 MB, comes easily to at least 500 MB of data for one diagnosis and treatment
  - For the medium size clinic such as Institute of oncology Vojvodina, large storage is required.

Storage in 1 year

- Daily admission to radiotherapy~ 10-15 new patients
- Each has CTs, MRI, PETs,…and requires 200-500 MB at least
- Per year: 2000 patients come to radiotherapy only~ 2000*500 MB= 1 000 000 MB (1 TB) of storage space excluding other data

Cloud storage future?

- Is personal patient data safe with clouds?

Conclusions

- Techniques of experimental particle/nuclear physics have played and still play a substantial role in medical imaging: detection concepts, detector materials, electronics, simulations, reconstructions,…
- "Even" gas detectors and Silicon detectors are used in medical imaging
- PET invented many years ago but only from 2001 it got full recognition for its unique clinical role after it was combined with CT (power of multi-modality)
- SPECT and PET imaging as molecular imaging is providing critical assistance with patient diagnosis and treatment, as well as with work on understanding disease origin and cures (also in small animal studies)
- SPECT and PET improvements are under way to reach the physical limits of the techniques (the role for particle physicists !)
- Rebirth of TOF PET
- New technologies: scintillators, photodetectors, solid state materials – spin-offs from particle physics
- Organ-specific PET imagers are becoming available with better performances and at a lower cost
- MRI – compatibility is becoming an important and necessary feature