Summary:
Prospects in Detectors and Medical Imaging

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1. New detectors for imaging
2. Combined imaging modalities
3. Imaging for radiation therapy
4. Image evaluation
1. New detectors for imaging
State of the art in solid state detector technology

S. Ziegler: The technology of solid state detectors in Nuclear Medicine

Nuclear Medicine Imaging

Goal: 3D Distribution of radiotracer in vivo
Based on detection of gamma rays (140 keV, 511 keV)

- High resolution (mm)
  • Low parallax error: DOI
  • High granularity

- High sensitivity (dose, acquisition time)
  • Inorganic scintillators

- Minimizing measurement of randoms and scattered events
  • High coincidence time and energy resolution

- Compactness, scalability
  • Solid state photon detectors (APD, SiPM)

- Insensitivity to magnetic fields: MR/PET
  • Solid state photon detectors (APD, SiPM)
1. New detectors for imaging
State of the art in solid state detector technology

S. Ziegler: The technology of solid state detectors in Nuclear Medicine

MADPET-II Prototype with 384 Channels
Transaxial reconstruction of 10 line sources

With DOI

Without DOI

Mean FWHM in central slice: (1.25±0.08) mm
1. New detectors for imaging
State of the art in solid state detector technology

S. Ziegler: The technology of solid state detectors in Nuclear Medicine

Biograph mMR, Siemens
- First fully integrated whole-body MR/PET system
- Based on a clinical 3 T MR scanner
1. New detectors for imaging
State of the art in solid state detector technology

S. Ziegler: The technology of solid state detectors in Nuclear Medicine
Solid state detectors for direct conversion

- Low noise
- Excellent energy resolution

Cadmium-Zinc-Telluride CZT:
  - high Z material
    - 4 cm CZT >86% efficiency for 511 keV
  - room temperature
  - energy resolution <3% at 511 keV

individual pixels, size: 330 µm...5 mm

SPECT detector module
1. New detectors for imaging

Detectors for TOF-PET: the limit of time resolution

D. Schaar: Prospects for achieving < 100 ps FWHM coincidence resolving time in time-of-flight PET

The holy grail: “10-picosecond PET”

With a CRT less than ~20 ps events can be localized directly:
- image reconstruction no longer necessary!
- only attenuation correction
- real-time image formation

\[
\begin{align*}
\Delta x &= c \cdot \text{CRT} / 2 \\
\text{Aim: } \Delta x &\leq d \\
\Rightarrow \text{CRT} &\leq 2d / c
\end{align*}
\]

Clinical PET:
- \(2 \text{ mm} \leq d \leq 4 \text{ mm}\)
- \(\Rightarrow \text{CRT} \leq 20 \text{ ps}\)
1. New detectors for imaging

Detectors for TOF-PET: the limit of time resolution

D. Schaar: Prospects for achieving < 100 ps FWHM coincidence resolving time in time-of-flight PET

Conclusions

With existing scintillators and photosensors, CRT's of ~100 ps FWHM are close to the lower bound imposed by photon counting statistics

⇒ further improvement only possible by decreasing the lower bound!

Key enablers required:

- Bright (>> 10^3 ph/MeV), ultrafast (∼ 1 ns) scintillation materials
- Ultraprecise (<< 100 ps TTS), highly efficient (PDE → 1) photon counters
- Detector design mitigating optical transit time spread (<< 100 ps) while maintaining high gamma detection efficiency (→ 1)

⇒ None of these are available yet, but none are physically impossible
1. New detectors for imaging
Gaseous detectors: RPC

F. Sauli: A compact multi gap RPC detector for TOF-PET

Δz~3 mm
Δx~2 mm
Δy~5 mm

10 modules
30x12 cm
5 cm thick
ε ~ 7%

MRPC ADVANTAGES:
• TOF RESOLUTION  200 ps (σ), 470 ps (FWHM)
• DEPTH OF INTERACTION 5 mm
• MULTIHIIT RESOLUTION 10 mm
• LARGE AREAS (FULL BODY)
• LOW COST

MAJOR DRAWBACKS:
• LOW EFFICIENCY
• NO ENERGY RESOLUTION
1. New detectors for imaging
Liquid Xe for Compton imaging

D. Thers: Towards a new "gamma" medical imaging technique: the XEMIS project

With instruments containing dense liquid as detection medium

Incident MeV γ-rays

\[ \cos \theta = \left(1 - \frac{m^2 c^2}{E_0}\right) \frac{E_1}{E_0 (E_0 - E_1)} \]

Time of the interaction:
Scintillation light (PMT) \( T_0 \) measurement

Energy end position:
Ionization with Micromegas and FEE
Drift time \( T_1, E, x, y \)

TPC characteristics
- Intrinsic energy resolution: 5% @ 511 keV
- Spatial resolution: 0.5 mm (X, Y and Z)
2. Combined imaging modalities
From PET/CT to MR/PET

O. Ratib: Hybrid systems in medical Imaging: from PET/CT to PET/MR

Changes in clinical staging
(n = 583)

- Lung Cancer (n = 285)
- Non-Lung (n = 298)

<table>
<thead>
<tr>
<th>Changes</th>
<th>Lung Cancer</th>
<th>Non-Lung</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>31</td>
<td>25</td>
</tr>
<tr>
<td>Down</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>No Change</td>
<td>49</td>
<td>56</td>
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<tr>
<td>No Answer</td>
<td>5</td>
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</table>

Seltzer et al, UCLA School of Medicine
2. Combined imaging modalities
From PET/CT to MR/PET

O. Ratib: Hybrid systems in medical Imaging: from PET/CT to PET/MR
2. Combined imaging modalities
From PET/CT to MR/PET

O. Ratib: Hybrid systems in medical Imaging: from PET/CT to PET/MR

- Soft tissue contrast
- Functional imaging
2. Combined imaging modalities

Endoscopic PET/US

P. Lecoq: Goals and challenges of the EndoTOFPET-US FP7 project

External PET Plate (16cm X 16cm)

Endoscopic Probe (diameter ≤ 25mm, length ≤ 50mm)
3. Imaging for radiation therapy
Range verification of $^{12}$C beams from secondaries

M. Martisikova: Investigation of the Timepix detector for beam range verification in ion therapy

... in a therapy like situation?

\[ E = 88.8 \text{ MeV/u}, \quad r_{\text{water}} = 2 \text{ cm} \]

Beam intensity \( 8 \times 10^9 \text{ s}^{-1} \)
1 ms acquisition time

This kind of response corresponds to ions
1. New detectors for imaging
An innovative, compact in-beam PET detector

M.G. Bisogni: An innovative PET detector concept for TOF-in-beam PET dosimetry in hadrontherapy

- 4 Dimensions Module for PET based on a continuous fast scintillating crystal coupled on both sides to arrays of Silicon PhotoMultipliers (SiPM).
- The SiPMs collect the scintillation light providing the impact point, the trigger for the acquisition of the event, the timing and the energy released in the crystal at the pixel level.
- First goal of this project is to achieve a timing resolution as low as 200 ps FWHM to cope with requirements of TOF-in-beam PET dosimetry.
- Depth Of Interaction (DOI) information to improve the spatial resolution of the detector to the ultimate goal of 0.5 mm FWHM in X-Y and of 1mm FWHM in DOI determination.
- High integration level, compactness, modularity, cost effective

<table>
<thead>
<tr>
<th>Performance Overview</th>
<th>FWHM</th>
<th>FWTM</th>
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<tbody>
<tr>
<td>x, y</td>
<td>1.1 mm</td>
<td>0.39 mm</td>
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<tr>
<td>z</td>
<td>1.3 mm</td>
<td>1.4 mm</td>
</tr>
<tr>
<td>time</td>
<td>97 ps</td>
<td>160 ps</td>
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</tbody>
</table>
3. Imaging for radiation therapy

Range verification by means of $\gamma$-ray imaging

J. Krimmer: Progress in using prompt gammas for ion range monitoring during hadrontherapy

First measurements at a proton beam

- Proton beam 160 MeV at WPE (Essen)
- 2 LYSO detectors
  - $3 \times 40 \times 50$ mm$^3$
- 1 LaBr$_3$ detector
  - $25.4$ mm x $50.1$ mm
- W collimator (100 mm)

Setup

Results of a scan

- Preliminary
- Count per incident proton

Without TOF selection

With TOF selection

Background reduction
3. Imaging for radiation therapy
Range verification by means of $\gamma$-ray imaging

J. Krimmer: Progress in using prompt gammas for ion range monitoring during hadrontherapy

First measurements at a $^{12}$C beam

350 AMeV

- single rates
  - silicon detector: $8.9 \cdot 10^{-6}$ cts/ion (scaler, thres. 350 keV)
  - absorber: $4.3 \cdot 10^{-4}$ cts/ion (scaler, thresh 180 keV)
- coincidence rates
  - all events: $1.7 \cdot 10^{-7}$ cts/ion (scaler)
  - uncharged: $9.2 \cdot 10^{-8}$ cts/ion (software cuts)
- extrapolation to prototype dimensions
  - silicon det.: $5 \cdot 10^{-4}$ cts/ion single
  - absorber: $6.3 \cdot 10^{-3}$ cts/ion single
- for protontherapy conditions ($10^{10}$ p/s)
  absorber needs to be segmented
3. Imaging for radiation therapy
In-beam PET for moving targets

K. Laube: Reconstruction of 4D in-beam PET data for quality control of moving target irradiation in ion beam therapy

Motion table for precise 1-dimensional motion patterns
3. Imaging for radiation therapy
In-beam PET for moving targets

K. Laube: Reconstruction of 4D in-beam PET data for quality control of moving target irradiation in ion beam therapy

<table>
<thead>
<tr>
<th></th>
<th>Tracking</th>
<th>Rescanning</th>
<th>Gating 30%</th>
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<tbody>
<tr>
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<td>3D MLEM</td>
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<td><img src="image6.png" alt="Image" /></td>
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<tr>
<td>Static</td>
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<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
</tbody>
</table>
3. Imaging for radiation therapy
Range verification by means of offline PET

C. Kurz: First Steps towards 4D Offline PET-Based Treatment Verification at the Heidelberg Ion Beam Therapy Center

- **Clear correlation** between simulation and measurement despite **low activity level**
- **4D gated PET** analysis **hindered** by extremely low counting **statistics**
3. Imaging for radiation therapy
Some considerations on „painting“ (LET, dose)

The sniper is excellent

The marker is blind

Unfortunately there is no better marker
3. Imaging for radiation therapy

Some considerations on „painting“ (LET, dose)

The sniper is excellent

The marker is blind

20 ions/dot, M. Scholz, GSI

Great succes in radiotherapy would be:

• Delivery of a daily adapted fluence distributions
• Homogeneous dose along PTV
• Full utilization of the therapeutic window

See also: G. Dollinger‘s talk on Monday morning

Planning CT

Beam stops at distal edge

CT after 5 w. RT

Beam overshoot
4. Image evaluation
An example from MRI

N. Amoroso: Structural MRI analysis and hippocampal segmentation in the assessment of Alzheimer's disease

Application of
• Random Forest
• Support Vector Machine classifiers

**Classification**
- Normalcy vs. *probable* Pathology
- Pathology "X" vs. pathology "Y"

**“Continuous” index**
- Proportional to pathology degree
- Usable for follow-ups, decline rate, subject ranking, drug trials...
4. Image evaluation
An example from MRI

N. Amoroso: Structural MRI analysis and hippocampal segmentation in the assessment of Alzheimer's disease

Clinical potential

- Structural imaging based on magnetic resonance is an integral part of the clinical assessment of patients with suspected AD.

- The ability to detect changes in structural and functional markers from preclinical to overt stages of Alzheimer disease is radically changing how the disease is diagnosed and will influence its future treatment.

- Rates of whole-brain and hippocampal atrophy are sensitive markers of neurodegeneration, and they are increasingly used as measures in trials of potentially disease-modifying therapies.

- The utility of structural (and non) imaging will be highly increased by the development of robust fully automated assessment algorithms.