Total-Body Positron Emission Tomography

State-of-the-Art in Scanner Design and Technology

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Disclosures

Research Agreements
Canon Medical Research Unit
United Imaging Healthcare

UC Davis has a revenue sharing agreement with
United Imaging Healthcare
PET provides the most sensitive non-invasive molecular assay of the human body.

All PET studies are limited by low signal, radiation dose, or both.

Current scanners collect <1% of the available signal!
Predictions

<table>
<thead>
<tr>
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<th>Sensitivity Gain</th>
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<tbody>
<tr>
<td>Adult</td>
<td>40</td>
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<tr>
<td>Pediatric</td>
<td>20</td>
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<tr>
<td>Cardiac</td>
<td>10</td>
</tr>
<tr>
<td>Brain</td>
<td>5</td>
</tr>
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Poon, *Ph.D. Thesis*, University of California, 2013
Total-Body PET: Maximizing Sensitivity

CONVENTIONAL PET

TOTAL-BODY PET
Total-Body PET: Maximizing Sensitivity

CONVENTIONAL PET

TOTAL-BODY PET
Claims

What can we do with 40 times more signal?

• Improve Signal-to-Noise Ratio by ~6.5
  – Better quality images
  – Detect smaller lesions
  – Detect lower grade disease
  – Fast dynamic imaging

• Increase dynamic range
  – Acquire images for 5 more half-lives

• Acquire total-body PET scans in 30 seconds
  – Less motion
  – Single breath-hold PET?

• Acquire total-body PET scans at 0.15 mSv
  – Equivalent radiation dose to roundtrip transatlantic flight
  – 40 scans in an individual for same dose as 1 current scan
Applications

• Systemic disease and therapies:
  – Cancer: Ultra-staging and micrometastasis
  – Inflammation
  – Infection
  – Cellular therapy and trafficking
  – Mind-body interactions

• Total body pharmacokinetics
  – Drug development
  – Toxicology
  – Biomarker discovery

• Low dose opens up new populations:
  – Expanded use in pediatrics
  – Use in chronic disease
  – Studies of normal biology

Cherry et al., Science Trans Med 9; eaaf6169 (2017)
Goal of EXPLORER Consortium: Build the world’s first total-body imaging system.

Total-Body PET

Challenges:

- **Scale of system**
  - >500,000 detectors
  - >50,000 channels of electronics

- **Big data**
  - ~100 GB for 5 min static scan
  - ~1-2 TB for 60 min dynamic scan

- **Cost**
How Long Should the Scanner Be?

192.5 cm (99%)

103.8 mm (99%)
Scanner Length Considerations

- **LARGE AXIAL FOV PET**
  (~ 1 meter)

- **TOTAL-BODY PET**
  (~ 2 meters)
EXPLORER Consortium

NIH R01 CA206187

UC DAVIS
UNIVERSITY OF CALIFORNIA

uEXPLORER
- High spatial resolution
- Total-body imager (~2m)
- UIH technology platform

PennPET EXPLORER
- High TOF resolution
- Torso imager (~1.4m)
- Philips technology platform
Detector Module:
Crystals: 2.76 x 2.76 x 18.1 mm LYSO
Array: 7 (transaxial) x 6 (axial)
SiPMs: 4 - Sensl 6 mm J-series
uEXPLORER Scanner

# of crystals: 564,480
# crystal blocks: 13,440
# of SiPMs: 53,760
# of LORs: 92 x 10^9

Ring diameter: 78.6 cm
Transaxial FOV: 68.6 cm
Axial FOV: 194.8 cm
80-row CT

Performance:
174 kcps/MBq sensitivity*
  (<20 kcps/MBq industry standard)
2.9 mm spatial resolution*
505 psecs time of flight*
11.7% energy resolution

*NEMA NU 2-2018 protocol
Collect 40 times more signal

- Improve Signal-to-Noise Ratio by ~6.5
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- Increased dynamic range
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EXPLORER Capabilities:

Higher Quality
Less Time
Lower Dose

20 mins High-Quality Imaging
30 secs Fast Imaging
5% Dose Low Radiation Dose Imaging
Data Handling

- 1 host computer + 8 node server for acquisition and reconstruction
  - one redundant node
  - scalable for reconstruction

- Node configuration:
  - Dual Intel Xeon 6126 CPU
  - 96 GB memory
  - 2 Tesla V100 GPUs

- Data volume and recon times:
  - 10 min clinical scan, 5 mCi injection
    ~100 GB, 10-15 minutes
  - 60 min dynamic scan, 10 mCi injection
    ~1.5-2 TB, several hrs
HIV Infection imaging with immunoPET (\(^{89}\)Zr-VRC01)

- 0.9 mCi of \(^{89}\)Zr-VRC01
- Imaged 2 days after injection, ~ <0.6 mCi
- Only ~23% positron fraction from \(^{89}\)Zr

Equivalent to < 1/100\(^{\text{th}}\) of the normal dose of FDG!

Conventional PET
GE PET/MR; 48 min scan

EXPLORER
20 min scan
Dynamic FDG Movie

Age: 61
Gender: Female
Height: 156 cm
Weight: 56 kg

Tracer: FDG
Dose: 255 MBq (6.9 mCi)
60 min dynamic scan

in collaboration with Zhongshan Hospital
Total-Body Dynamic Imaging

Gender: Male
Weight: 87 kg
Tracer: FDG
Dose: 388 MBq (10.5 mCi)
60 min. dynamic scan
Image-Derived Arterial Input Function

FIGURE 2. OSEM image-derived ROI-based blood input functions and major organs/tissues...

(a) Early 2-minute
(b) 1-hour zoom in < 20 kBq/ml
(c) (early 2-minute)
Total-Body Parametric Imaging

Age: 79
Gender: Male
Height: 170 cm
Weight: 71 kg
Tracer: FDG
Dose: 348 MBq (9.4 mCi)
Last 30 mins used

FDG Influx Rate Constant, $K_i$ ($ml/min/g$)

$$K_i = \frac{K_1 k_3}{k_2 + k_3}$$
Total-Body Dynamic PET of Metastatic Cancer

$^{18}$F-FDG PET images of a patient with metastatic kidney cancer scanned on uEXPLORER (10 mCi injection; Patient weight: 76 kg; one-hour dynamic scan)

t = 0.5-1 min.  1-2 min.  10-12 min.  30-35 min.  55-60 min.

Courtesy of Dr. Guobao Wang
Multi-Parametric Imaging of Metastases and Organs

\[ K_i: \text{Overall FDG influx rate (ml/g/min)} \]

\[ v_b: \text{fractional blood volume} \]

\[ K_1: \text{glucose transport rate (ml/g/min)} \]

Courtesy of Dr. Guobao Wang
Clinical Case

$^{18}$F-FDG

Protocol:
5 mCi (187 MBq) dose
20 min scan
Imaging at 120 mins p.i.

1.17 mm isotropic voxels
Clinical Case

$^{18}$F-flucyclovine

68-yr old male

Castration-resistant metastatic prostate cancer

2.5 mm pulmonary nodule
Technology for PennPET Explorer

Imaging chain components

3.86 x 3.86 x 19 mm³ LYSO
PDPC digital SiPM
64-channel array
1:1 coupling

Tile Stack → Detector module

Per ring

Detector ring:
23-cm axial length
PennPET Explorer: FDG studies

Prototype Configuration: 3 rings
Expansion to 6 rings summer 2020

F 62 y.o, 164 cm
BMI 26.5
15 mCi FDG, 1.5 hr p.i.

10 min
5 min
2½ min
1¼ min
37 sec

2 min scan

16 min scan

NEMA performance measures
- Spatial resolution: 4 mm
- **TOF resolution: 250 ps**
- Sensitivity: 55 kcps/MBq
Delayed Imaging: capture slower biology

Comparison of brain to heart activity at 24 hrs (10 half-lives) better defines kinetic model

- Activity in the brain decreases over time implying that $k_4$ is non-zero and that G6Pase is activated to break down $[^{18}\text{F}]\text{FDG}-6\text{P}$
- Activity in the myocardium decreases more slowly over time implying that $k_4$ is near zero and that G6Pase is not active in the myocardium
We have come a long way...

1976

Courtesy Abass Alavi

2019
First total-body and long axial FOV PET/CT scanners have been built.

Early clinical and research results are very promising.

Future areas for focus:

- Handling big data
- Cost
- Motion correction
- Total-body modeling

- Developing impactful research and clinical applications
Acknowledgements

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