Dose Optimization in PET / CT & PET / MR

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NIH, Gordon & Alpert Endowments

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HARVARD MEDICAL SCHOOL
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OUTLINE : Approaches to Dose Optimization

- Rationale
- Image Quality, Dose Reduction
- PET-CT, PET-MR and Dedicated PET Scanners
- Discussion

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RATIONALE : Excess Atributable Risk

Excess Attributable Risk (Deaths) from All Solid Tumors per 10,000 Person-Year-Sv by 60Y (BEIR VII 2006)

Age at Exposure (Y)	EAR (Mortality)	Relative to >30Y
1	35.1	2.92
5	30.3	2.52
10	25.2	2.10
20	17.4	1.45
>30	12.0	1.00

Thus, if 1,000,000 10 YOs receive 10 mSv,
25 will die from solid tumors at age 60 due to this exposure

Biologic Effects of Ionizing Radiation

PET or PET/CT not in Top 20

Procedure	Ave ED (mSv)	Ann' l ED per cap	% Total ED
1. Myo Perf Img	15.6	0.540	22.1
2. CT Abdomin	8	0.446	18.3
3. CT Pelvis	6	0.297	12.2
4. CT Chest	7	0.184	7.5
5. Dx Card Cath	7	0.113	4.6
6. Rad Lumbar	1.5	0.080	3.3
7. Mammo	0.4	0.076	3.1
8. CT Ang Chest	15	0.075	3.1
12. Bone Scan	6.3	0.035	1.4
17. Thyroid Uptk	1.9	0.016	0.7

R. Fazel et al., NEJM 2009; 361:841-843

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- SPECT, SPECT-CT and Dedicated SPECT Scanners
- PET-CT, TOF-PET, PET-MR and Dedicated PET Scanners
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METHODS : MIRD Equation

$$D = \tilde{A} \Delta f / m$$

Where:

D is radiation dose in Gy

$\tilde{A}$ is the cumulated activity in MBq-h, $\tilde{A}$ proportional to A_0

Δf is mean energy per disintegration in g-Gy/MBq-h

m is mass of the target organ in g

Δf / m is S factor, i.e., the mean dose to target organ per cumulated activity of the source organ

Committee on Medical Internal Radiation Dose

METHODS : Approaches to Dose Optimization

Bases for Approaches to Dose Optimization :

- Assess Image quality objectively by signal-to-noise ratio (SNR) for a clinical task (e.g., lesion detection, activity estimation)
- Assume Poisson statistics, a doubling of counts (and dose) yields 41% ($\sqrt{2}$) improvement in SNR (and image quality)
- Conversly, if a physics or instrumentation approach yields an improvement of SNR of 41%, this gain could be used to halve the injected dose without changing image quality.

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Factors Affecting Radiation Dose in Multi-Detector CT

- Tube current or time (α mAs)
- Reduce tube voltage (α kVp^2)
- Beam collimation
- Pitch (table speed) (α 1/pitch)
- Patient size
- Region of patient imaged

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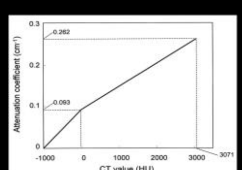
CT-Based Attenuation Correction

- Acquire CT Scan and reconstruct
- Apply energy transformation
- Reproject to generate correction matrix
- Smooth to resolution of PET
- Apply during reconstruction



Fahey et al. *Radiology* 2007;243:96-104

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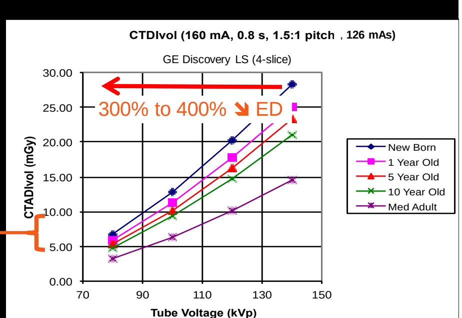
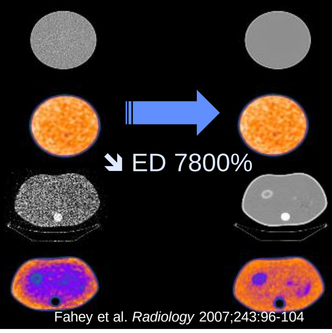
Dose from CTA of PET-CT

ED from 10 mCi of FDG 5-7 mSv



Quality of CTAC

80 kVp
10 mA
0.5 s/rot
1.5:1



↘ ED 7800%

140 kVp
160 mA
0.8 s/rot
1.5:1

Fahey et al. *Radiology* 2007;243:96-104

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OUTLINE : Physics Approaches to Dose Optimiztion

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- Dose Reduction by using iterative reconstruction and 3D geometry
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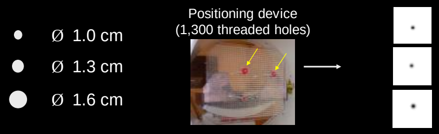
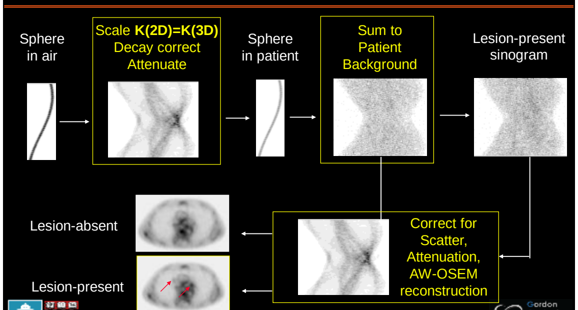
Assessment of Dose Reduction with 3D vs. 2D PET

- 3 sphere sizes were acquired in 10 different locations (e.g., lungs, soft tissue, bone) to avoid errors associated with lesion simulation



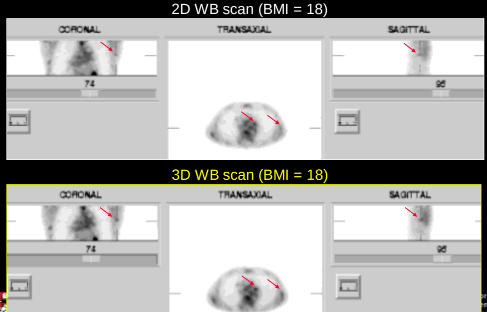
- Each sphere was acquired separately in 2D and 3D and scaled to ensure marginal detectability in each patient

Generation of synthetic lesion-present WB studies

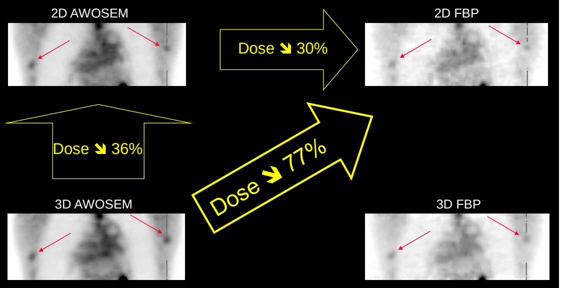


El Fakhri et al. JNM 2007 (48): 1951-1960

Lesion-present patient studies



Assessment of Dose Reduction with 2D/3D and Processing



Typical BMI of 26

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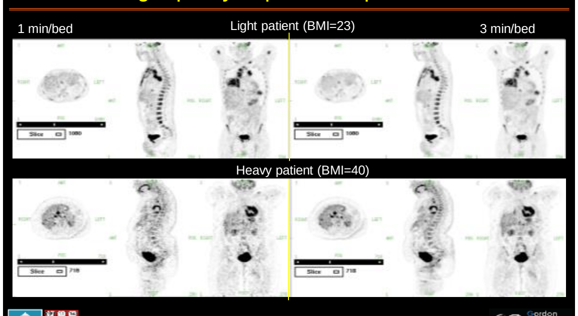
Image quality depends on patient size



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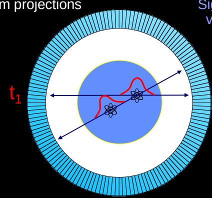
How can TOF improve image quality (reduce dose)?

Image reconstruction from projections

Signals from different voxels are coupled
SNR ≠ N / $(N)^{1/2}$



$\Delta t = t_1 - t_2$

$\Delta x = c \cdot \Delta t/2$

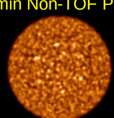
TOF information reduces coupling, thus improves SNR

D/Δx ~ reduction in variance = gain in sensitivity (NEC) = gain in SNR^2

D	Δt = 600 ps (Δx = 9 cm)	Δt = 300 ps (Δx = 4.5 cm)
20 cm	2.2	4.4
35 cm	3.9	7.8

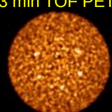
Dose Reduction with TOF-PET: how much can we gain?

5 min Non-TOF PET



5 min TOF PET

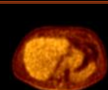
3 min TOF PET



6:1 sphere to background contrast;
35-cm diam. cyl.;
1-cm spheres

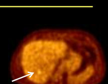
Dose Reduction with TOF-PET

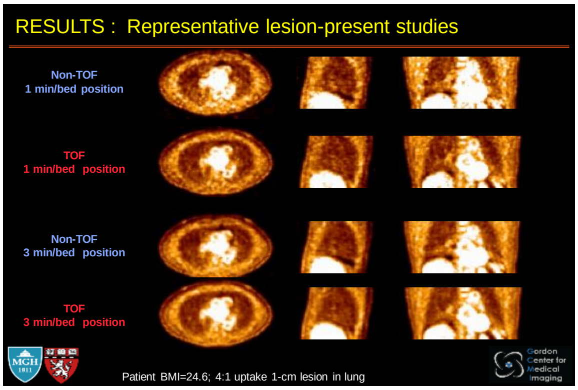
Normal patient list data
CT image
→ 1. Fully-corrected reconstructed lesion absent volume
2. Scatter estimate
3. Background activity level, C_B



Sphere in air list data
Lesion uptake ratio + C_B
→ Extracted sphere list data
CT image
→ Normal patient list data
Attenuated sphere list data
→ Fused list data

Fused list data
Scatter
CT image
→ Fully-corrected reconstructed lesion present volume




RESULTS : Representative lesion-present studies
Non-TOF
1 min/bed position
TOF
1 min/bed position
Non-TOF
3 min/bed position
TOF
3 min/bed position
Patient BMI=24.6; 4:1 uptake 1-cm lesion in lung
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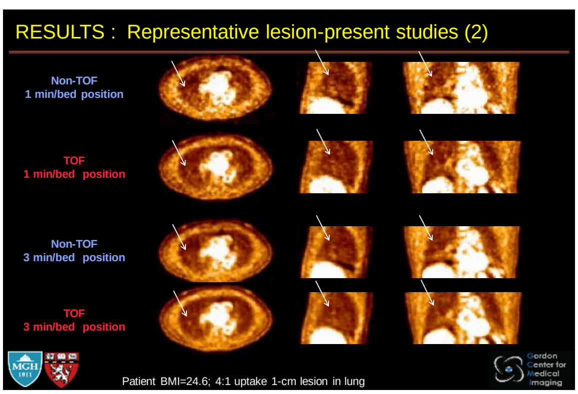
RESULTS : Representative lesion-present studies (2)
Non-TOF
1 min/bed position
TOF
1 min/bed position
Non-TOF
3 min/bed position
TOF
3 min/bed position
Patient BMI=24.6; 4:1 uptake 1-cm lesion in lung
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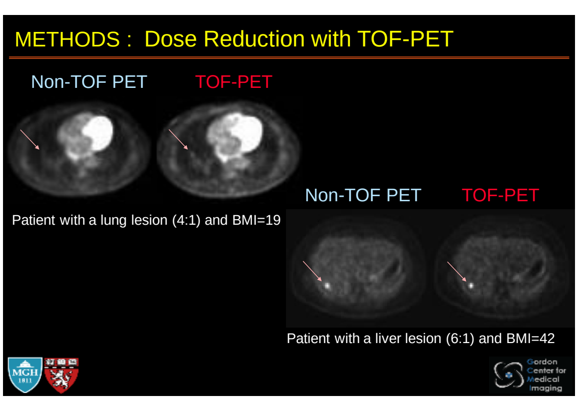
METHODS : Dose Reduction with TOF-PET
Non-TOF PET
TOF-PET
Patient with a lung lesion (4:1) and BMI=19
Non-TOF PET
TOF-PET
Patient with a liver lesion (6:1) and BMI=42
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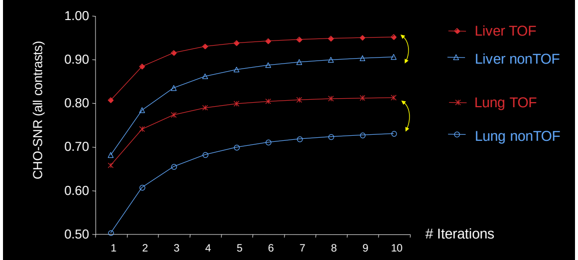
METHODS : Dose Reduction with TOF-PET



• SNR improvement of 8% in liver, 14% in lung → dose reduction of 14-30%

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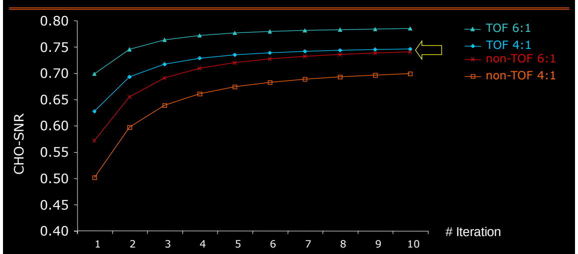
RESULTS : Dose Reduction with TOF-PET



• Similar SNR with TOF-PET for 33% less TBR

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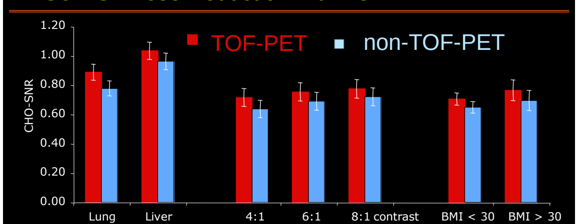
RESULTS : Dose Reduction with TOF-PET



• Dose reduction of 16% in the liver and 30% in the lungs
• Dose reduction of 18% for for BMI< 30 and 22% for BMI>30

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- Dose Reduction in PET-MRI *vs.* PET-CT
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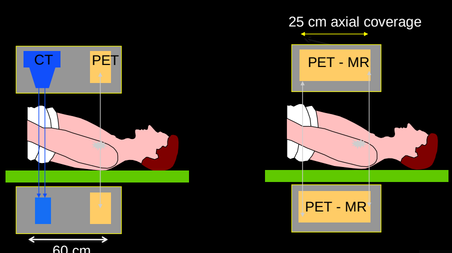
Integrated Whole-Body PET-MR

Sequential PET-CT *vs* Simultaneous PET – MR



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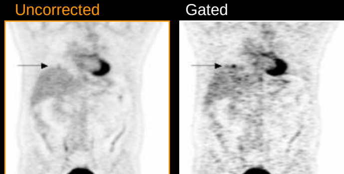
Rationale : Motion deterioration vs Gating

- Blurring
- Lower Noise

Uncorrected | Gated



- Freezing Motion
- Higher Noise

- Using all PET data at all motion phases without motion correction
- Using some PET data only at one motion phase

Using all PET data *with* MR-based motion correction

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Methods: Motion Corrected OSEM

• List-mode MLEM reconstruction algorithm with motion modeled in the system matrix:

$$a_{ni}(f) = \sum_{j=1}^{M} a_{nj} \times m_{ji}(f)$$

Static system matrix

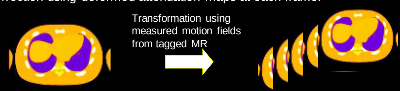
Motion interpolation matrix (i.e., contribution of pixel i in the ref. frame to pixel j in the deformed frame)

$$\rho_i^{(a+1)} = \frac{\rho_i^{(a)}}{\sum_{f=1}^{F} s_i(f)} \sum_{n=1}^{N} \frac{a_{ni}(f_n)}{\sum_{j=1}^{M} a_{nj}(f_n)\rho_j^{(a)}}$$

Number of counts in list-mode

Motion dependent system matrix

• Attenuation correction using deformed attenuation maps at each frame:



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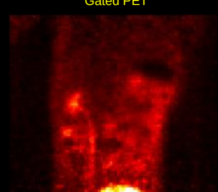
Petibon et al . *Med. Phys.*, 2014

Primate Results: Acquisition

• Motion Correction with *Primate* in simultaneous PET-MR

Gated tagged MR

Gated PET



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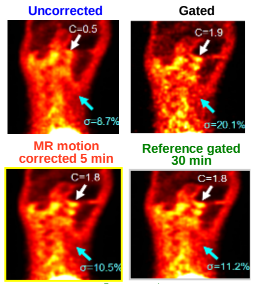
Chun et al. J. Nucl. Med. 2012

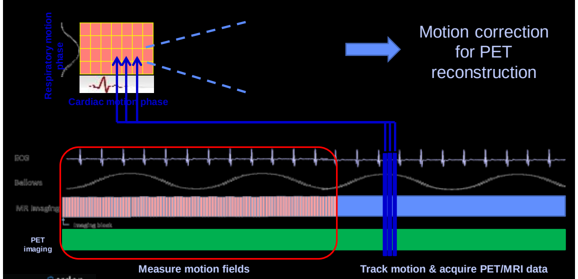
Nonhuman Primate Results



Dose Reduction 600%

Chun S.Y., et al *J. Nucl. Med.* 2012

Measure Motion Fields and Track Motion Phases



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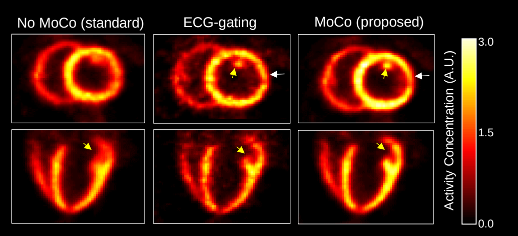
Cardiac PET/MR: pig studies (^{18}F-Flurpiridaz)



Petibon et al *Phys Med Biol* 2017

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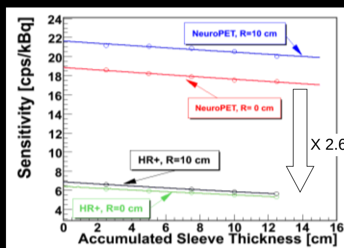
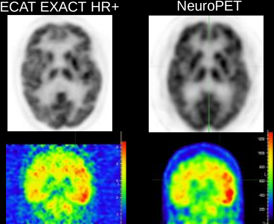
Dose Reduction with Dedicated PET Scanners

Dedicated brain PET
FOV 35cm x 24 cm long



Dose ↘ 260%

Dose Reduction with Dedicated PET Scanners



Injected dose: 200 MBq of ^{18}FDG.
HR+ scan: 54 min post injection, 30 min acquisition.
NeuroPET scan: 90 min post injection, 30 min acquisition.

Injected dose: 1840 MBq of ^{11}C-PIB.
HR+ scan: 45 min post injection, 15 min acquisition.
NeuroPET scan: 70 min post injection 15 min acquisition

Same concept applies to other Hi-sensitivity scanners, for example:
If axial FOV = 21.6 instead of 16.2 ⇨ sensitivity ↑ 75% and dose ↘ 75%

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SCIENCE TRANSLATIONAL MEDICINE | FOCUS

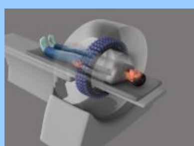
IMAGING

Total-body imaging: Transforming the role of positron emission tomography

Simon R. Cherry,[1*] Ramsey D. Badawi,[1] Joel S. Karp,[2] William W. Moses,[3] Pat Price,[4] Terry Jones[1]

The first total-body positron emission tomography (TB-PET) scanner represents a radical change for experimental medicine and diagnostic health care.

Cherry *et al., Sci. Transl. Med.* **9**, eaaf6169 (2017) 15 March 2017



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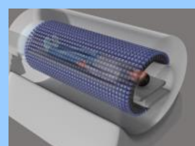
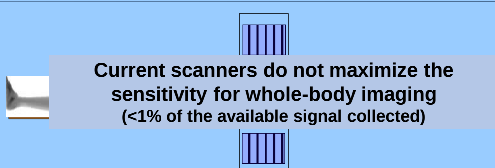


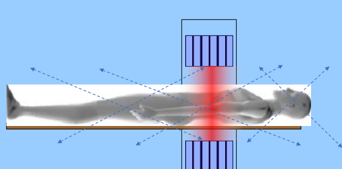
Conventional PET Scanner (2018)

EXPLORER Total Body PET Scanner (2018)

All PET studies are limited by statistics, radiation dose, or both



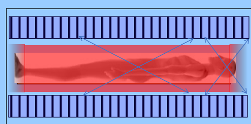
T. Jones



<1% of the potential return on the investment in:

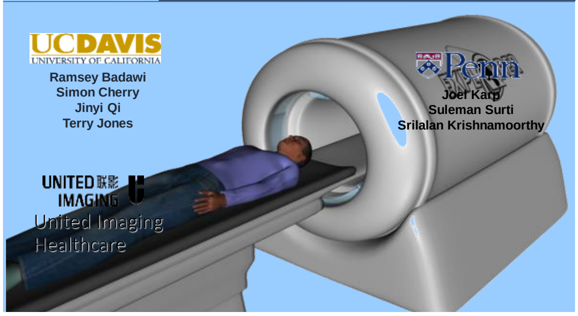
- Cyclotron operation
- Labelled tracer production
- PET scanning facilities and resources
- The radiation dose to the patient

Total-Body PET: Maximizing sensitivity and simultaneously imaging the whole body



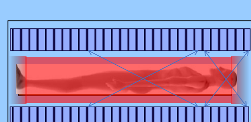
T. Jones

EXPLORER Team



Total-Body PET: Maximizing Sensitivity

- 40x gain in effective sensitivity for total-body imaging!
- 4-5x gain in sensitivity for single organ imaging



EXPLORER Image Gently (Low Dose)

- **40-fold reduction in dose**
  - Whole-body PET at ~0.15 mSv
  - Annual natural background is ~2.4 mSv
  - Return flight (SFO-LHR) is ~0.11 mSv
  - PET can be used with minimal risk – new populations

Conventional PET

EXPLORER

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DISCUSSION : Physics Approaches to Dose Reduction

- Achievable dose reduction today:
  - 300% to 400% with low (KVp, mAs) CTA instead diag CT
  - 30% in WB with iterative reconstruction
  - 16% in liver with TOF-PET
  - 30% in lungs with TOF-PET
- Achievable dose reduction with PET/MR today:
  - PET-MR eliminates CT dose, reduces PET dose by 600%
- Potential dose reduction with Total Body in the future:
  - Total Body PET can reduce PET dose by 4000%

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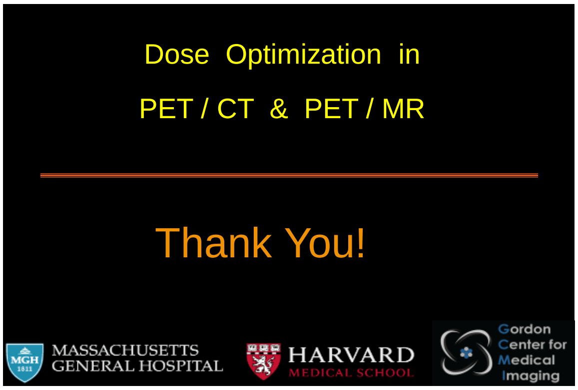
Dose Optimization in
PET / CT & PET / MR
Thank You!
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