Educational Objectives

• Radiation dosimetry in diagnostic imaging
  – Review current state of patient specific dosimetry
  – Discuss strategies to aggregate radiation dose in multi-modality imaging
  – Provide examples for COG based
  – Neuroblastoma & Wilms' tumor patient populations
  – Discuss dose management strategies and limitations

• Radiation dosimetry for Image Guided Radiotherapy (IGRT)
  – Discuss current use of imaging during therapy
  – Provide examples for dose values
  – Discuss dose reduction strategies for IGRT

Educational Objectives

• Goal: calculate radiation dose burden from all forms of imaging
  – Dx: X-ray, CT, Nuc Med, PET & Fluoroscopy
  – Tx: CBCT, X-ray, orthogonal X-ray, fluoro

• Challenge to understanding complete dose picture involves:
  – Data collection & interpretation
    • Each modality has unique geometry constraints
    • Each modality has unique dose descriptors
    • How do we collect and analyze the data?
Data Collection: National & Local

- National databases
  - ACR, National radiology data registry (NRDR), Dose Index (> 50 M studies)
  - Bayer, all customers, state of NJ, U of California hospitals
  - Siemens, all customers

- Local databases (limitations):
  - Only account for CT radiation dose
  - Some account for fluoroscopy & Nuclear Medicine/PET but do not aggregate the doses
  - A Walk Through the Market Dr. Sarah McKenney (SPR/RSNA)
  - 16 vendors
  - https://goo.gl/CMRgpt

Data Interpretation

- Infrastructure is present for data collection
  - Lacks aggregation of all ionizing radiation modalities

- Limited means to compare inter-modality imaging dose
  - Each modality has its own dose metric

CTC Tvol, DLP, SSDE, air kerma, KAP/DAP, EI/DI, KAP/DAP, MBq/mCi

Effective Dose
  - Population based
  - Age/sex independent

Data Interpretation

- How can we be more patient-specific for dosimetry?
  - Develop the science to relate each dose metric to organ dose

CT
  - CTDvol, DLP, SSDE, air kerma, KAP/DAP, EI/DI, KAP/DAP, MBq/mCi

Organ Dose
  - Patient specific
  - Age/sex/weight/size dependent
Computed Tomography

- Calculate patient dose from CT examinations
  - Monte Carlo (Gold Standard)
    - Patient-specific requires organ-based segmentation
  - Fully automated (machine learning) tissue segmentation
    - Accuracy: liver 0.99, fat 0.98, muscle 0.94, solid organ 0.75, blood/contrast 0.82, and bone 0.90
  - Still need fully automated organ segmentation

- Population-specific requires computational phantoms
  - Size specific dose estimate (SSDE*)
    - Limitation: head SSDE not defined yet

*Nuclear Medicine & PET

- Radiopharmaceutical kinetic models derived for age specific biodistribution
  - Derived from MIRD formulation
    \[
    d(r, T) = \sum_i \left( \frac{1}{A_i} \right) \left( \frac{1}{\rho_i} \right) \left( \frac{1}{\phi_i} \right) \left( \frac{1}{\gamma_i} \right) \left( \frac{1}{\alpha_i} \right)
    \]
  - Calculated by MIRDOS/Onda software
  - Online calculators
    - RADAR website & SNMMI website**
  - Take ICRP discretized data
    - Fit the data for patient dosimetry of all ages
      \[
      D_{\text{organ}}(mc) = PD(\text{mc}) + 37 \left( \frac{3}{37} \right) \left( \frac{1}{\phi_i} \right) \left( \frac{1}{\gamma_i} \right) \left( \frac{1}{\alpha_i} \right)
      \]
    - PD = pharmaceutical dose
    - A = ICRP organ dose factor
    - B = organ specific parameter (e.g., colon = 0.50)

*http://www.doseinfo-radar.com/RADARDoseRiskCalc.html
**http://www.snmmi.org/ClinicalPractice/doseTool.aspx?ItemNumber=11216&navItemNumber=11218
X-Ray and Fluoroscopy

- Calculate patient dose from DR examinations*
  - Fluoroscopy mostly the same except uses dose rate
  - (1) characterize machine output & (2) use examination metadata
- \( ESD = k_{\text{air}} \times BSF \times (SSD)^2 \times \mu_{\text{en}} \times \rho_{\text{air}} \);
  - \( ESD \) ≡ entrance skin dose
  - \( k_{\text{air}} = 0.0093 \times k_{\text{Wp}}^2 - 0.0165 \times k_{\text{Wp}} \times m_{\text{As}} \)
  - \( BSF = 0.18 \times \ln(k_{\text{Wp}}) + 0.57 \)
  - \( SSD = \text{STD} - \text{thickness}_{\text{patient}} \); \( \text{STD} \equiv \text{source to table distance} \)

*Brady, SL & Kaufman, RA; Med Phys 42(5) 2015, 2489 - 2497

X-Ray

- To calculate other organ dose:
  - Monte Carlo (PCXMC) code & mathematical phantoms*
  - Create organ/skin conversion factors
  - Apply factors to your institutional ESD

*Ladia et al, J of physics conf series 637 (2015) 012014

Aggregate Patient Organ Dose

- IRB approved retrospective study
  - Neuroblastoma: 74 patients
  - Wilms tumor: 80 patients
Diagnostic Ionizing-radiation Examinations (n = 45±11)

- XR (n = 28±8)
  - 1.6 mSv (~0.06 mSv/exam)
- CT (n = 17±6)
  - 13 mSv (~3 mSv/exam)
- SPECT/CT (n = 0)
- PET/CT (n = 0)

Omitting Pelvic CT from routine off-therapy follow-up
- Pelvic relapse symptomatic
  - Dose savings: 10-45%

Diagnostic Ionizing-radiation Examinations (n = 51±9)

- XR (n = 18±11)
  - 0.4 mSv (~0.02 mSv/exam)
- CT (n = 16±4)
  - 45 mSv (~3 mSv/exam)
- SPECT/CT (n = 14±1)
  - 126.2 mSv (~9 mSv/exam)
- PET/CT (n = 3±3)
  - 60.2 mSv (~12 mSv/exam)

Omitting chest CT from routine off-therapy follow-up
- Chest relapse symptomatic
  - Dose savings: 45%

Dose Management Strategies

Multi-modality general dose management strategies

CT
- Size-based optimization (TCM, ODM, etc.)
- Enhanced reconstruction algorithms (iterative recon, deep learning)

XR
- Size-based protocols
- Increased filtration

Fluoro
- General fluoro dose rates ≤ 7.5 fps (line placement can be as low as 1-2 fps)
- Enhanced filtration & software (smart denoising algorithms)
- Shorter pulse widths for peds

PET & SPECT
- Weight-based pharmaceutical dosing
- New digital technology has the potential to reduce injected dose by
  - Lower CTAC dose
Image Guided Radiotherapy (IGRT)

- IGRT has become standard in most radiotherapies
  - Portal imagers
  - X-ray/fluoro/cone beam flat panel system
  - Floor mounted orthogonal system
- Imaging for IGRT is often performed daily
- Need to consider implications for imaging for therapy delivery
  - Dose to sensitive organs, secondary cancers, etc.
- AAPM Reports 95 & 180
  - TG180: recommend considering impact of therapy regimen when imaging dose ≥ 5% therapeutic dose (PVT)
    - E.g., CBCT can add upwards of 1-3% of PVT total dose

Image Guided Radiotherapy (IGRT)

- Cone beam CT (CBCT)
  - Exposes normal tissue when used
- MV-CBCT using EPID
  - Can exceed 100 mGy
  - Siemens Artiste has 4.2 MeV e-carbon target
    - Improved soft tissue contrast
    - 1/3 MV radiation dose
- kV-CBCT (e.g., OBI or XVI)
  - Typically 15-60 mGy (lower by ~10x from a decade ago)
  - Better dose management
    - Lower kV (110 vs. 125 kV)
    - Better collimation
    - Sparse angle reconstruction (e.g., 200 views vs. 360)

Image Guided Radiotherapy (IGRT)

- Planar x-ray
  - Single plane & fixed floor orthogonal units
    - 10 mGy
  - Use of Bow-tie filters*
    - Improves image quality & reduces dose
  - In some cases the # of acquired planar images may exceed 80 treatments**

- Fluoroscopy
  - $D \propto \text{time}$
  - 5-11 mGy/min (30 fps, 100 – 120 kVp @ isocenter)
  - Dose reduction using pulse rates < 30 fps

* Ding and Munro; Radiother Oncol. Jul 2013;108:91–98
** TG180
Image Guided Radiotherapy (IGRT)

- AAPM Report 95: The management of imaging dose during image-guided radiotherapy (’07)
- Estimated effective dose for a treatment regimen (e.g. 30 fractions)*
  - Daily pre-treatment CTs (40-400 mSv)
  - 2 pairs of MV portal images (40-400 mSv)
  - 2 mins of daily fluoro (40-120 mSv)
  - 100 orthogonal kV images (10-100 mSv)

Example (combination real & hypothetical)

- mIBG avid Stage 3 NB patient (represents a generic high risk patient)
  - Dx imaging over 4-5 years resulted in
    - X-ray: 0.5 mSv
    - CT: 45 mSv
    - PET/CT: 60 mSv
    - SPECT/CT: 126 mSv
  - Tx imaging from a 14 fraction course
    - Daily CBCT setup: 60 mSv
    - Daily fluoro tracking: 20 mSv
  - Total dose burden ~300 mSv

Conclusion

- Pediatric Tx patients are most sensitive to secondary cancer
  - Alternative is most likely death
  - No question that radiation dose from imaging is beneficial
- No longer can we say imaging dose is negligible in the context of therapy
  - Aggregate Dx imaging along with Tx imaging
- Still room to adopt better dose management
Conclusion

- Still need better dose reporting and storage capabilities
- Scientific field continuing to develop methods to combine multi-modality imaging dose
- Need to aggregate all imaging dose throughout hospital enterprise
  - Radiology
  - Rad Onc
  - Ortho
  - Cardiology
  - etc.

Thank you

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