Dual-energy CT:

Considerations in Radiation Therapy

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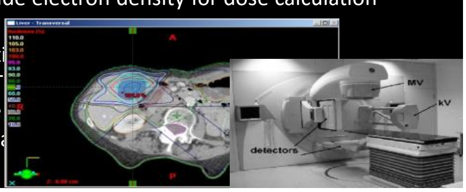
UHN — University of Toronto — TECHNA

Disclosures

- **Commercialization License Contrast CT QA Phantom**
  - **Modus Medical Devices Inc.**
- **Commercialization License DCE Phantom**
  - **Shelley Medical Imaging Technologies**

CT in Radiotherapy: Planning + Verification

- Simulation of individual treatment plan
  - Anatomical representation to delineate target volume and organs at risk (OAR)
  - Provide electron density for dose calculation
- Verificat
  - CBCT
  - Dose
  - Plan a



CT in Radiotherapy Process

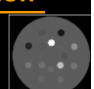
- Image Quality
  - Anatomical representation to delineate target volume and organs at risk (OAR)
  - Provide electron density for Dose calculation
- Electron density?
  - CT number Hounsfield Unit (HU) represent attenuation (μ) <u>at the scanner's energy</u>:

$$HU = (\mu/\mu_{water} - 1) \times 1000$$

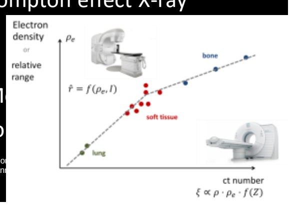
CT in Radiotherapy: Dose calculation

- μ is a function of X-ray energy, material density and atomic number *Z. For CT energies:*
  - $\mu \sim C\,\rho_e$
  - $\mu \sim C\,Z^4$
  - $\mu \sim C\,E^{-4}$
- *μ (CT) ≠ μ (6 MV) photons or stopping power S of charged particles*
  - $\mu \sim C\,\rho_e$
  - $S \sim C\,\rho_e$ Conversion is necessary

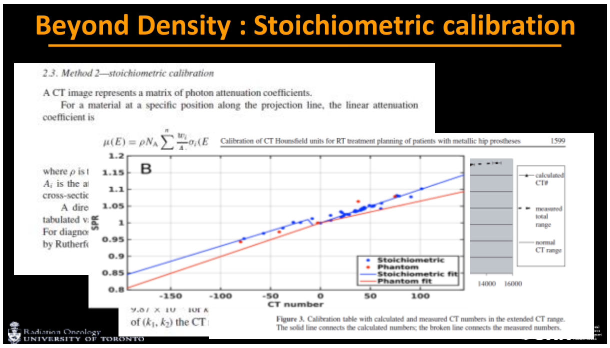
CT in Radiotherapy: Density Calibration



- Calibration of CT numbers using known densities
- Empirical look-up tables
- Tissue: $Z_{eff} \sim 7.4$ so mostly Compton effect X-ray interactions at CT energies
- External photon beams ≤ 5M
- >5 MeV: material compositio



- Seco & Evans. Assessing the effect of electron density in photon calculatio
- Coolens & Childs. Calibration of CT Hounsfield units for RT treatment plan prostheses. Phys Med Biol 2003. Vol 48


Beyond Density : Stoichiometric calibration
2.3. Method 2—stoichiometric calibration
A CT image represents a matrix of photon attenuation coefficients.
For a material at a specific position along the projection line, the linear attenuation coefficient is
Calibration of CT Hounsfield units for RT treatment planning of patients with metallic hip prostheses
B
SPR
CT number
Stoichiometric
Phantom
Stoichiometric fit
Phantom fit
calculated CT#
measured total range
normal CT range
Figure 3. Calibration table with calculated and measured CT numbers in the extended CT range. The solid line connects the calculated numbers; the broken line connects the measured numbers.
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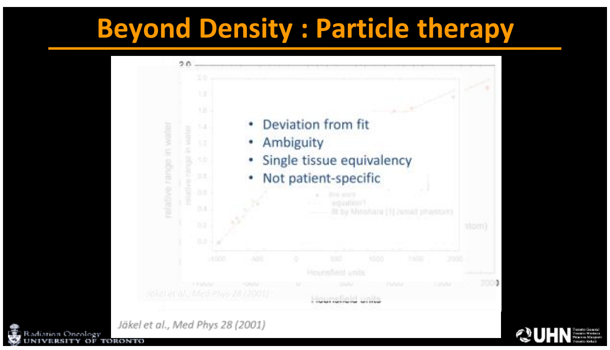
Beyond Density : Particle therapy
Deviation from fit
Ambiguity
Single tissue equivalency
Not patient-specific
Jäkel et al., Med Phys 28 (2001)
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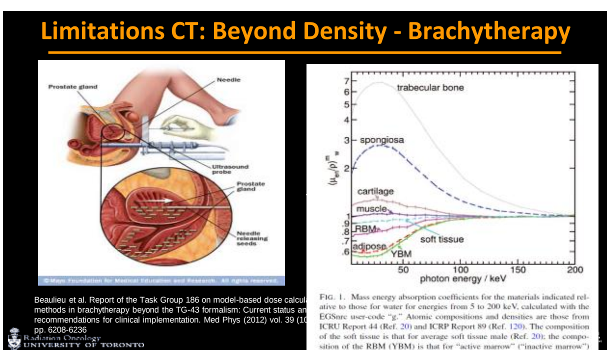
Limitations CT: Beyond Density - Brachytherapy
Prostate gland
Needle
Ultrasound probe
Prostate gland
Needle releasing seeds
trabecular bone
spongiosa
cartilage
muscle
RBM
adipose
YBM
soft tissue
photon energy / keV
Beaulieu et al. Report of the Task Group 186 on model-based dose calculation methods in brachytherapy beyond the TG-43 formalism: Current status and recommendations for clinical implementation. Med Phys (2012) vol. 39 (10) pp. 6208-6236
FIG. 1. Mass energy absorption coefficients for the materials indicated relative to those for water for energies from 5 to 200 keV, calculated with the EGSnrc user-code "g." Atomic compositions and densities are those from ICRU Report 44 (Ref. 20) and ICRP Report 89 (Ref. 120). The composition of the soft tissue is that for average soft tissue male (Ref. 20); the composition of the RBM (YBM) is that for "active marrow" ("inactive marrow")
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DECT in Radiotherapy: Applications

Dose calculation

- Improved electron density accuracy
- Improved material composition accuracy (Zeff, SPR)
- Improved tissue segmentation

Image Quality

- Improved image quality for delineation
- Artefact reduction (metal, high density inserts)
- Treatment follow up (DCE CT)

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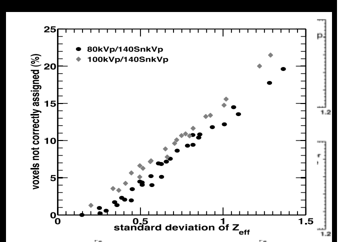
DECT: Tissue segmentation

- Use Mahalanobis distance
- Minimize distances from reference Z_{eff} and ρ_e
- Imaging protocol and reconstruction important



Courtesy G. Landry

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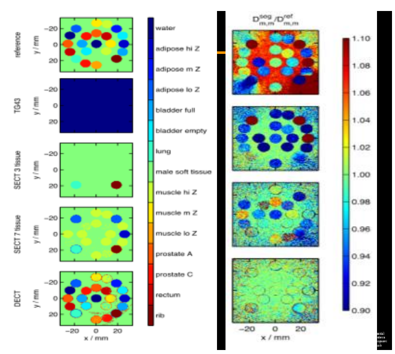
Segmentation Cont'd

- ^{125}I dose calculation
- Simulated phantoms
- SECT vs DECT

Landry et al. PMB (2011) vol. 56 (19) pp. 6257-78



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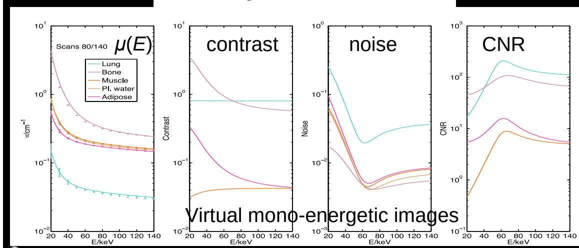
DECT: metal artifact reduction strategies

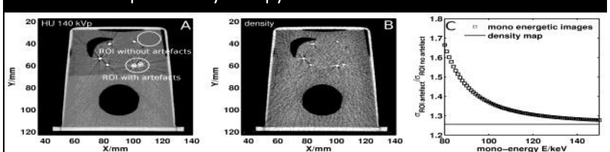
$$\mu(E) = \rho_e'(Z^4 F(E,Z) + G(E,Z))$$



Courtesy G. Landry

DECT: metal artifact reduction strategies

- Intrinsic metal artefact reduction
  - example: brachytherapy seeds



Courtesy G. Landry

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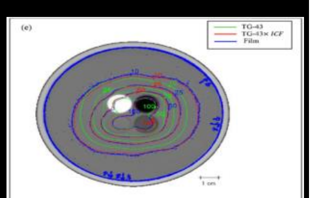
Processing DECT: ^{125}I dose calculation

- ^{103}Pd sources in inserts (bone, lung, muscle and adipose)
- Film measurements
- DECT based calculation (ICF) compared to water kernel approach (TG-43)



Mashouf et al. Dose heterogeneity correction for low-energy brachytherapy sources using dual-energy CT images. Phys Med Biol (2014) vol. 59 (18) pp. 5305-5316

Courtesy G. Landry

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DECT– Proton Therapy

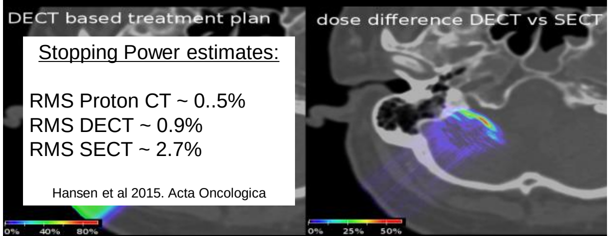
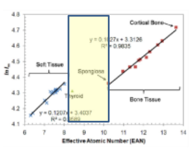


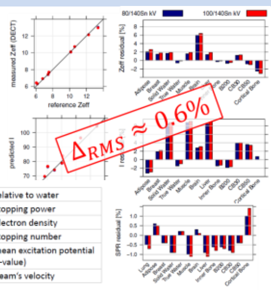
Figure courtesy of N. Hudobivnik

dkfz. SPR/WEPL/rel. range benchmark

Courtesy Steffen Greilich



Yang et al., PMB 55 (2010)



Stopping power via Bethe formula:

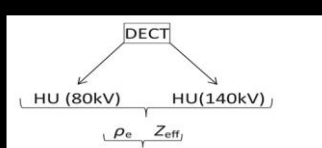
$$\hat{S} = \hat{n}\,\hat{L}$$

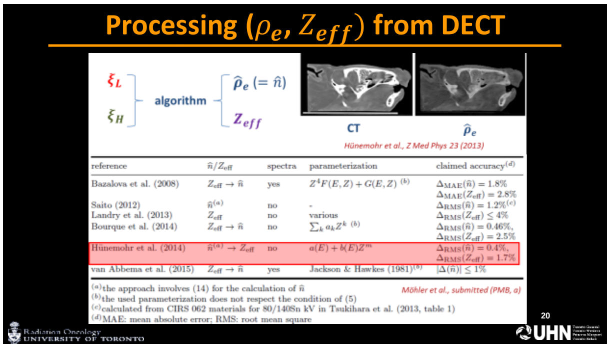
$$L(I,\beta) = \ln\left(\frac{2m_e c^2 \beta^2}{1-\beta^2}\right) - \beta^2 - \ln(I)$$

^	relative to water
S	stopping power
n	electron density
L	stopping number
I	mean excitation potential (I-value)
β	beam's velocity

Processing (ρ_e, Z_{eff}) from DECT

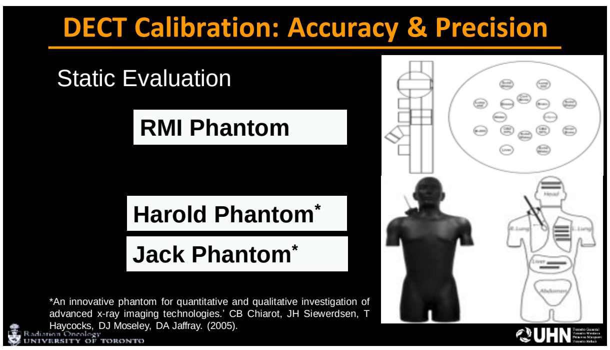
- Convert CT number pairs in relative electron density (ρ_e) and effective atomic number (Z_{eff})
- Calibration based procedure with known phantom

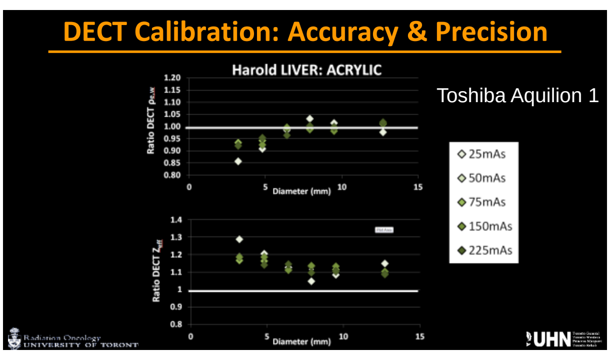


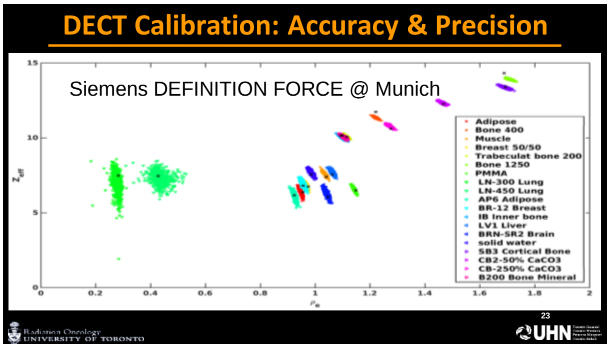


reference	$\hat{n}/Z_{eff}$	spectra	parameterization	claimed accuracy[d]
Bazalova et al. (2008)	$Z_{eff} \to \hat{n}$	yes	$Z^4F(E,Z)+G(E,Z)$ [b]	$\Delta_{MAE}(\hat{n}) = 1.8\%$ $\Delta_{MAE}(Z_{eff}) = 2.8\%$
Saito (2012)	$\hat{n}$[a]	no	-	$\Delta_{RMS}(\hat{n}) = 1.2\%$[c]
Landry et al. (2013)	Z_{eff}	no	various	$\Delta_{RMS}(Z_{eff}) \leq 4\%$
Bourque et al. (2014)	$Z_{eff} \to \hat{n}$	no	$\sum_k a_k Z^k$ [b]	$\Delta_{RMS}(\hat{n}) = 0.46\%$, $\Delta_{RMS}(Z_{eff}) = 2.5\%$
Hünemohr et al. (2014)	$\hat{n}$[a] $\to Z_{eff}$	no	$a(E)+b(E)Z^m$	$\Delta_{RMS}(\hat{n}) = 0.4\%$, $\Delta_{RMS}(Z_{eff}) = 1.7\%$
van Abbema et al. (2015)	$Z_{eff} \to \hat{n}$	yes	Jackson & Hawkes (1981)[b]	$\lvert\Delta(\hat{n})\rvert \leq 1\%$

[a] the approach involves (14) for the calculation of $\hat{n}$
[b] the used parameterization does not respect the condition of (5)
[c] calculated from CIRS 062 materials for 80/140Sn kV in Tsukihara et al. (2013, table 1)
[d] MAE: mean absolute error; RMS: root mean square






DECT Calibration: Accuracy & Precision
Siemens DEFINITION FORCE @ Munich
Adipose
Bone 400
Muscle
Breast 50/50
Trabecular bone 200
Bone 1250
PMMA
LN-300 Lung
LN-450 Lung
AP6 Adipose
BR-12 Breast
IB Inner bone
LV1 Liver
BRN-SR2 Brain
solid water
SB3 Cortical Bone
CB2-50% CaCO3
CB-250% CaCO3
B200 Bone Mineral
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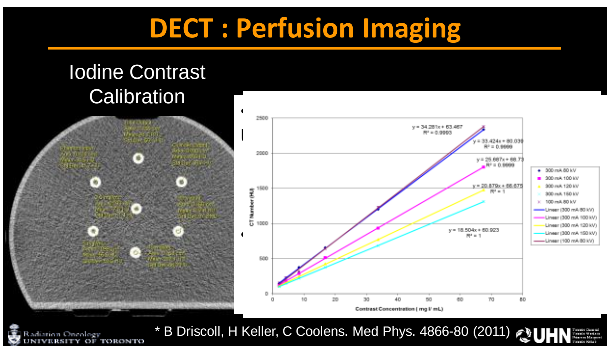
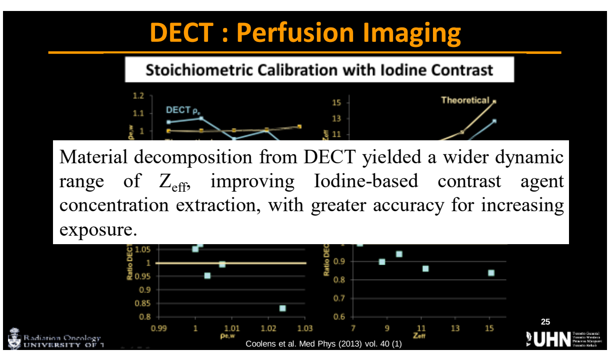
UHN


DECT : Perfusion Imaging
Iodine Contrast
Calibration
CT Number (HU)
Contrast Concentration (mg I/ mL)
* B Driscoll, H Keller, C Coolens. Med Phys. 4866-80 (2011)
UHN


DECT : Perfusion Imaging
Stoichiometric Calibration with Iodine Contrast
Theoretical
Material decomposition from DECT yielded a wider dynamic range of Zeff, improving Iodine-based contrast agent concentration extraction, with greater accuracy for increasing exposure.
Coolens et al. Med Phys (2013) vol. 40 (1)
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DECT : Perfusion Imaging

Physics in Medicine and Biology

PAPER

In vivo characterization of tumor vasculature using iodine and gold nanoparticles and dual energy micro-CT

Darin P Clark[1], Ketan Ghaghada[2], Everett J Moding[3], David G Kirsch[3] and Cristian T Badea[1]

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Physics in Medicine and Biology, Volume 58, Number 6

Phantom and primary mouse sarcoma model

Conclusions and Outlook

- DECT scanners are entering RT clinics and nearing clinical evaluation but need standardisation and testing of analysis mechanisms against adapted phantoms
- Several different applications show potential improvement from DECT
  - Dose calculations: (photon) brachy and particle therapy
  - Image quality: artifact reduction, staging, delineation, some segmentation, target tracking
  - Functional information

Selected RT Applications

- Algorithms and evaluation
  - Bazalova et al. Radiother Oncol (2008) vol. 86 (1) pp. 93-8
  - Landry et al. Radiother Oncol (2011) vol. 100 (3) pp. 375-9
  - Landry et al. Phys Med Biol (2013) vol. 58 (19) pp. 6851-66
  - Saito. Med Phys (2012) vol. 39 (4) pp. 2021-30
  - Tsukihara et al. physics (2012) vol. 39 (4) pp. 2021-30
  - Bourque et al. Phys Med Biol (2014) vol. 59 (8) pp. 2059-88
  - van Abbema et al. Phys Med Biol (2015) vol. 60 (9) pp. 3825-46
- Brachytherapy
  - Williamson et al. Med Phys (2006) vol. 33 (11) pp. 4115-29
  - Landry et al. Phys Med Biol (2011) vol. 56 (19) pp. 6257-78
  - Evans et al. Med Phys (2013) vol. 40 (12) pp. 121914
  - Malusek et al. Phys Med Biol (2013) vol. 58 (4) pp. 771-85
  - Mashouf et al. (2014) vol. 59 (18) pp. 5305-5316
- Protons
  - Yang et al. Phys Med Biol (2010) vol. 55 (5) pp. 1343-62
  - Hünemohr et al. Z Med Phys (2013) pp.
  - Hünemohr et al. Phys Med Biol (2014) vol. 59 (1) pp. 83-96
  - Hansen et al. Acta Oncol (2015) pp. 1-5
- Tissue segmentation
  - Landry et al. Phys Med Biol (2013) vol. 58 (15) pp. 5029-5048
  - Hünemohr et al. Med Phys (2014) vol. 41 (6) pp. 061714
- MV Photons
  - Bazalova et al. Physics in Medicine and Biology (2008) vol. 53 (9) pp. 2439-56
  - Tsukihara et al. Med Phys (2015) vol. 42 (3) pp. 1378-88
  - Coolens et al. Med Phys (2013) vol. 40 (1)
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  - Van Elmpt et al. Radiot. & Oncol 2016 vol. 119 (1)

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