Conflict of interest disclosure

I receive funding support from Philips Healthcare for research collaboration.

Outline

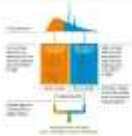
- Advantages and disadvantages of dual-layer DECT
- St. Jude clinical implementation experience
- General RT and proton-specific applications
- Reducing proton range uncertainty with DECT
- Phantom and animal tissue experiments
- Future outlook

Dual-layer CT is a special type of dual-energy CT

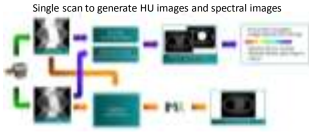
http://clinical.netforum.healthcare.philips.com

Top layer is yttrium-based garnet scintillator designed to absorb low-energy X-rays (very high light output, and very low afterglow).

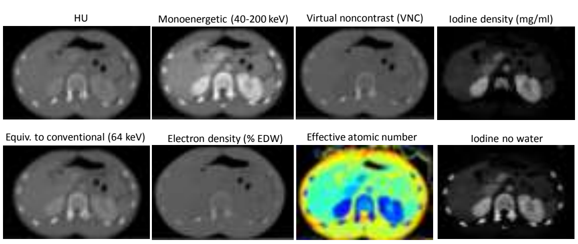
Bottom layer is gadolinium oxysulphide (GOS) scintillator to stop 99% of the X-rays, transmitted through the top layer.



Single scan to generate HU images and spectral images



What can be obtained with a single acquisition?

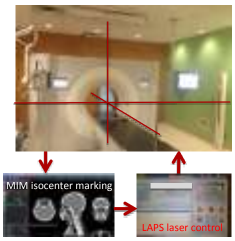


Advantages and disadvantages of dual-layer DECT

- Simultaneous acquisition (better immunity to motion)
- No changes to conventional work flow
- Up to 50 cm FOV vs. 35-50 cm (pitch dependent) in dual-source approaches
- Angular mA modulation possible during gantry rotation (challenging for fast kVp switching)
- Material decomposition on projection space

- Spectral separation not as large as one from dual sources (80/140kVp)
  - Vendor emphasized the high energy tail of the low energy spectrum actually improves the noise.
  - End results (accuracy of spectral images) also depend on model-based reconstruction.
- One more layer scintillator increases the complexity of read out electronics and the detector cost (vendor decision to first roll out 4cm detector width).

IQon spectral CT at St. Jude Radiation Oncology



- Installed at St. Jude Radiation Oncology in 2016
- >400 patients scanned since then

- 4 cm Z coverage, 0.27s rotation time
- 50 cm FOV for conventional and spectral images
- NEMA XR-29 (dose optimization) compliance

- Iterative reconstruction (iDose4 and iMR) for conventional polychromatic images
- Metal artifact reduction (OMAR) reconstruction
- Single acquisition at 120 or 140 kVp to reconstruct both polychromatic and monoenergetic images

Acceptance testing

Conventional image quality and dose performance

- CT number accuracy of tissue inserts
- Slice thickness accuracy
- Low contrast detectability
- High contrast spatial resolution
- HU uniformity
- Presence of image artifact
- Radiation beam width
- Displayed CTDI accuracy
- mA/mAs linearity
- Displayed image orientation
- Table movement accuracy

Spectral performance

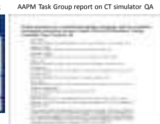
ACR phantom was also used to evaluate accuracy of CT# values for
- monoE (40-200 keV)
- Virtual non contrast (VNC)
- Zeff
- Iodine-no-water
- Iodine density images

ACR CT Accreditation Testing

Previous institutional CT QA

Literature publications of DECT performance testing

AAPM Task Group report on CT simulator QA



Applications of DECT in RT (incl. proton therapy)

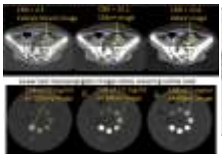
- Reducing **proton range uncertainty** by better estimating the tissue properties along the beam path
- Improved **Monte Carlo simulation accuracy** of brachytherapy, photon, and proton therapy
- Better **visualization of tumor and vessels** and feasibility of reducing contrast doses (by viewing low keV monoE images)
- Improve **image quality** (↓ beam hardening and metal artifacts) for tumor delineation (monoE images)
- **Virtual contrast removal** for treatment planning (VNC)
- Quantitative assessment of **normal tissue function** before and after RT (e.g. lungs, bone marrow)
- Improved **tumor characterization and tissue segmentation** (e.g. bone and marrow extraction, anatomical structures) and **response assessment** (iodine uptake, spectral HU curves)

Enhancing blood vessel visibility with low mono-energetic images

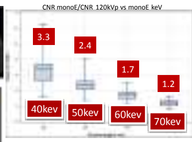
Tsang, Merchant, Merchant, Smith, Yagil, Hua. Estimating potential reduction in contrast dose with mono-energetic images synthesized from double-layer detector spectral CT. BJR 2017.

- 51 RT patients
- 2 mL/kg (270 mg iodine/mL) Iodixanol, max 150 mL
- 2 mL/s rate via IV line, implanted port, or central venous access device
- 15-30 s delay prior to CT acquisition
- 120 kVp, 35-497 mA, 1-2 mm slice
- 120 kVp iDose4 (level 3) vs. 40-70 keV monoE images

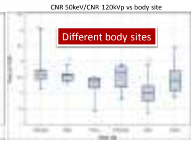
Site	N	Blood vessel	Background tissue
Brain	13	Sigmoid sinus/jugular foramen	Cerebellum
Neck	12	Internal jugular vein	Adjacent muscle
Chest	11	Aorta	Esophagus or thymus
Abdomen	6	Inferior vena cava	Liver
Pelvis	5	Internal/external iliac arteries	Adjacent muscle
Extremities	4	Brachial/popliteal arteries	Adjacent muscle



CNR monoE/CNR 120kVp vs monoE keV

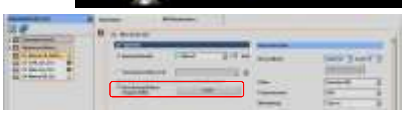


CNR 50keV/CNR 120kVp vs body site



When all vessels were included, a median 3.3-fold CNR increase with 40 keV was seen.

Process of generating ED and Zeff with dual-layer DECT



In scan protocols, spectral base images (SBI) can be programmed to automatically save in the server for later reconstruction of spectral images, such as ED and Zeff.

ED and Zeff accuracy of dual-layer DECT

Dual-layer DECT

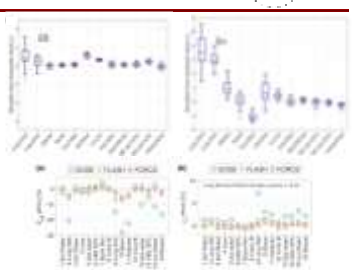
Hua et al. Accuracy of electron density, effective atomic number, and iodine concentration determination with a dual-layer dual-energy computed tomography system. Med Phys 2018.

Accuracy: ED within 1%, Zeff within 2% except for lung materials (small absolute deviations).

Dual-source and twinbeam DECT

Almeida et al. Dual-energy CT quantitative imaging: a comparison study between twin-beam and dual-source CT scanners. Med Phys 2017.

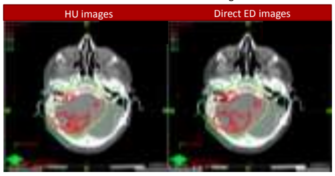
Dual source scanners produced more accurate ED and Zeff than twinbeam.

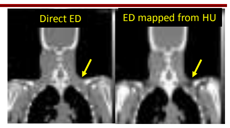


Direct use of electron density for photon treatment planning

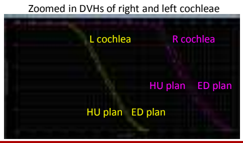
Conventional: map HU to ED via the stoichiometric calibration curve
New: Directly calculate ED for planning

Note the difference in dose distributions near right cochlea

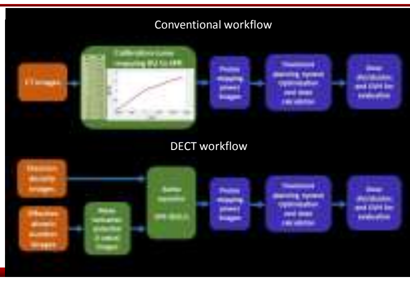




Zoomed in DVHs of right and left cochlea



Direct use of stopping power images for proton planning



Proton range uncertainty

Moyers 2001 IJROBP:

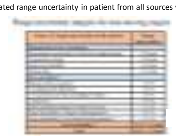
Range uncertainty from CT number accuracy and conversion to proton SPR was accounted for with 3.5%×distal CTV depth in lung proton therapy. Additional 3mm accounts for uncertainty in accelerator energy, bolus construction, various scattering system thickness.

Moyers 2010 Med Dosim:

Total range uncertainty in SPR calculation was estimated to be ±3.5%.

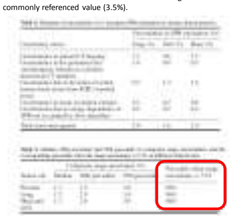
Paganetti 2012 PMB:

Estimated range uncertainty in patient from all sources was 4.6% + 1.2 mm.



Yang 2012 PMB:

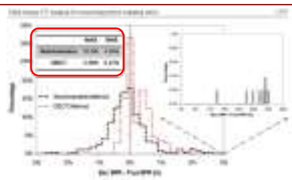
Overall uncertainty (95th percentile) in SPR estimation from CT number conversion for different treatment sites agreed with the commonly referenced value (3.5%).



DECT for reducing proton range uncertainty

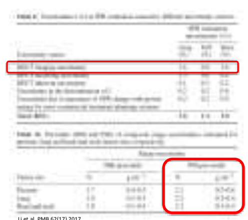
In 2010, DECT was proposed for reducing SPR uncertainty by directly calculating ED and Zeff images, rather than relying on the calibration curve to map HU to SPR.

Yang (2010 PMB) suggested their method can reduce the uncertainty to <1%. But caution that beam hardening, image noise, and patient movement between two scans affect the CT number accuracy.



DECT for reducing proton range uncertainty

A recent comprehensive uncertainty analysis using DECT by Li and Yang et al (2017 PMB) concluded the overall range uncertainty is approximately 2.2% (2σ) in clinical scenarios, in contrast to previously reported 1%.



Li et al, PMB 62(17) 2017

Conclusion was reached based on acquiring two separate scans with dual-source CT and using an image-based approach (as opposed to projection based) to derive ED and Zeff images.

Image-based method for SPR estimation could be sensitive to image noise and beam hardening effect.

Phantom and animal tissue experiments on SPR and proton range

First author	Institution	Journal	Year	Phantom or tissues	DECT system	Major findings
Hünemohr	DKFZ (Germany)	Z Med Phys	2013	Animal tissues (Pig head)	Siemens Definition Flash	[Tissues] WET deviation reduced from -2.1% (SECT) to 0.3% (DECT)
Taasti	Aarhus Univ Hospital (Denmark)	PMB	2018	Animal tissues	Siemens AS64 (SECT, dual spiral), Siemens Flash and Force (dual source), Siemens Edge (twin beam)	[Tissues] RMSE on SPR= 2.8% (SECT), 1.5% (twin beam), 1.4% (dual spiral), 1% (dual source)
Bär	National Phys lab (UK)	Med Phys	2018	Phantom Animal tissues	Siemens Somatom Flash	[Phantom] RMSE on SPR reduced from 1.59% (SECT) to 0.61% (DECT) [Tissues] Bias and standard deviation in WER error both reduced from SECT to DECT
Möhler	DKFZ (Germany)	PMB	2018	Animal tissues	Siemens Definition Flash	Mean absolute error of 65 tissue samples reduced from 1.27% to 0.10% for carbon ion beam
Xie	U Penn (USA)	PMB	2018	Phantom Animal tissues	Siemens Sensation Open	[Tissues] Bias reduced from 0.55% (SECT) to 0.07% (DECT). Standard deviation reduced from 1.94% (SECT) to 0.58% (DECT)
Zhu	St Jude (USA)	AAPM	2018	Phantom	Philips IQon	[Phantom] RMSE on SPR reduced from 2.18% (SECT) to 0.83% (DECT)

Complied for 2018 AAPM DECT for RT session

Summary and future outlook

- Dual-layer CT an attractive option for dual-energy imaging
  - Large FOV (50cm), same imaging workflow, no dose penalty, high accuracy of ED, Zeff, and SPR
  - Used for CT simulation in a RT department
  - Tissue validation and comprehensive uncertainty analysis are underway to replace current 3-3.5% uncertainty
- Phantom studies and animal tissue validations for proton therapy
  - Improvements demonstrated over SECT
  - Mostly focused on dual-source or sequential scans on motionless tissues
  - Dosimetric benefits and normal tissue sparing on patients yet to be estimated
  - Other sources of uncertainty (e.g. I-values of tissues) need to be reduced
- Outlook
  - Vendors developing/releasing TPS features to support DECT for planning and dose calculation
  - Anticipate more DECT installations in RT departments (especially proton therapy centers)
  - Clinical translation to proton patients in the next few years

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