CT, Dual energy CT and spectral CT for treatment planning. What are the requirements?

Marco Brambilla

Past President of EFOMP

Head of Medical Physics Department

University Hospital “Maggiore della Carità” Novara

marco.brambilla@maggioreosp.novara.it

Joint ICTP-IAEA Workshop on Radiation Protection in Image-Guided Radiotherapy (IGRT)

Summary

- State of the art of conventional CT simulators
- State of the art of dual energy CT scanners (DECT)
- State of the art of spectral CT scanners (SCT)
- Conclusions

CT simulators

CT simulators have become the standard of care for radiotherapy in the developed world.

CT imaging data provide a complete 3-D view of the patient's anatomy, allowing for more accurate delineation of the tumor and the surrounding normal tissues.

In addition, the CT data inherently include the associated tissue density information, which is a necessity for 3-D radiotherapy treatment planning.

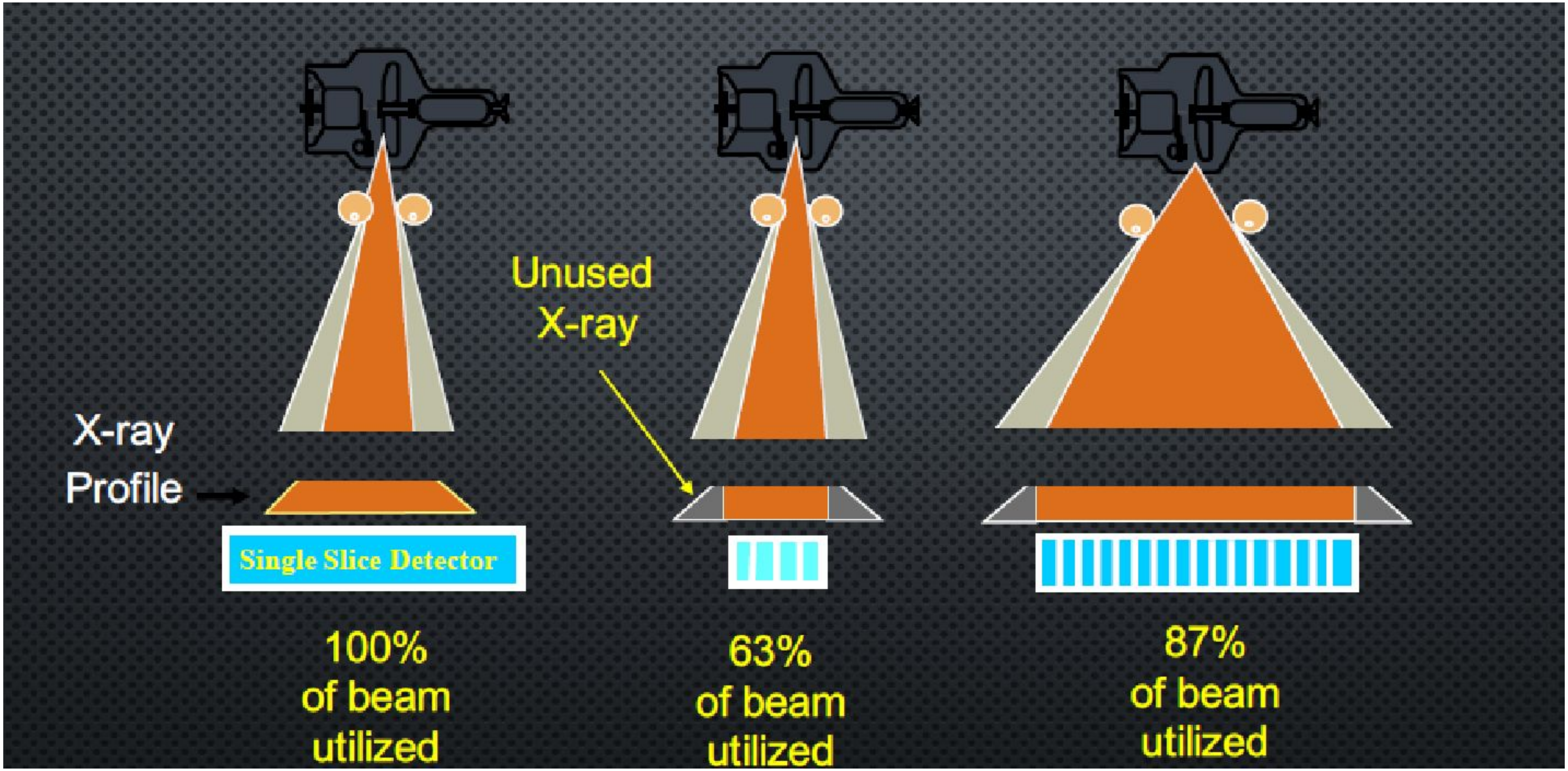
Dedicated CT simulators are based on diagnostic CT scanners, with a few modifications. CT simulators typically include

- a laser alignment system as a reference for patient positioning
- a 3-D imaging workstation for image visualization and manipulation
- a larger bore size to accommodate patient immobilization devices
- a flat tabletop to replicate the radiotherapy treatment unit couch.

Innovations in MSCT

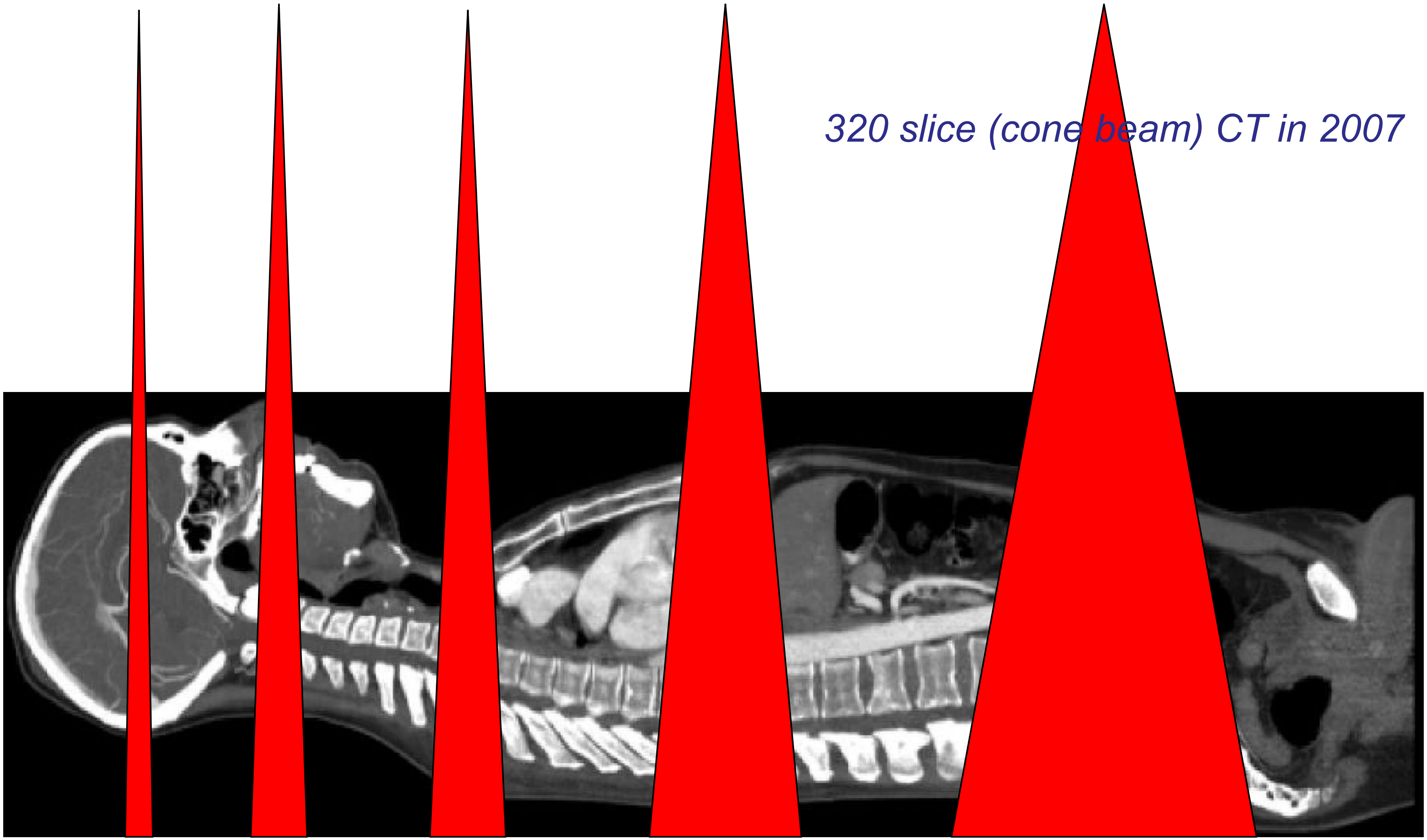
- Z axis coverage
- X-ray Tube
- Tube current modulation
- Iterative reconstruction
- Correction of metal artifacts

Multi-slice Z-axis Dose Efficiency



A longer detector length is more dose efficient

Coverage of detectors along Z axis



1 x5

4x1
1998

16x0.5
2001

64x0.5
2004

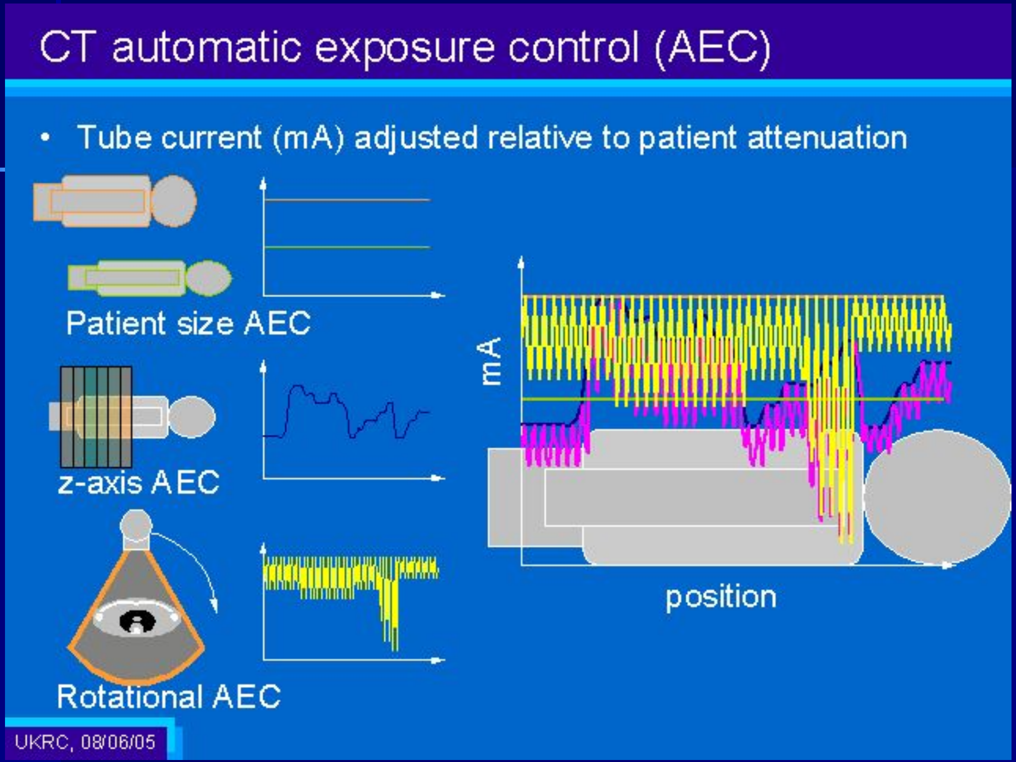
320x0.5
2007

STRATON: ROTATING ENVELOPE TUBE

Direct anode cooling
- high cooling rate
- No delays
- Heat storage is irrelevant
- Enormous heat reserve

Compact design
- Enables 0.27s rotation
-Withstands high g-forces
- High temporal resolution

Tube Current Modulation

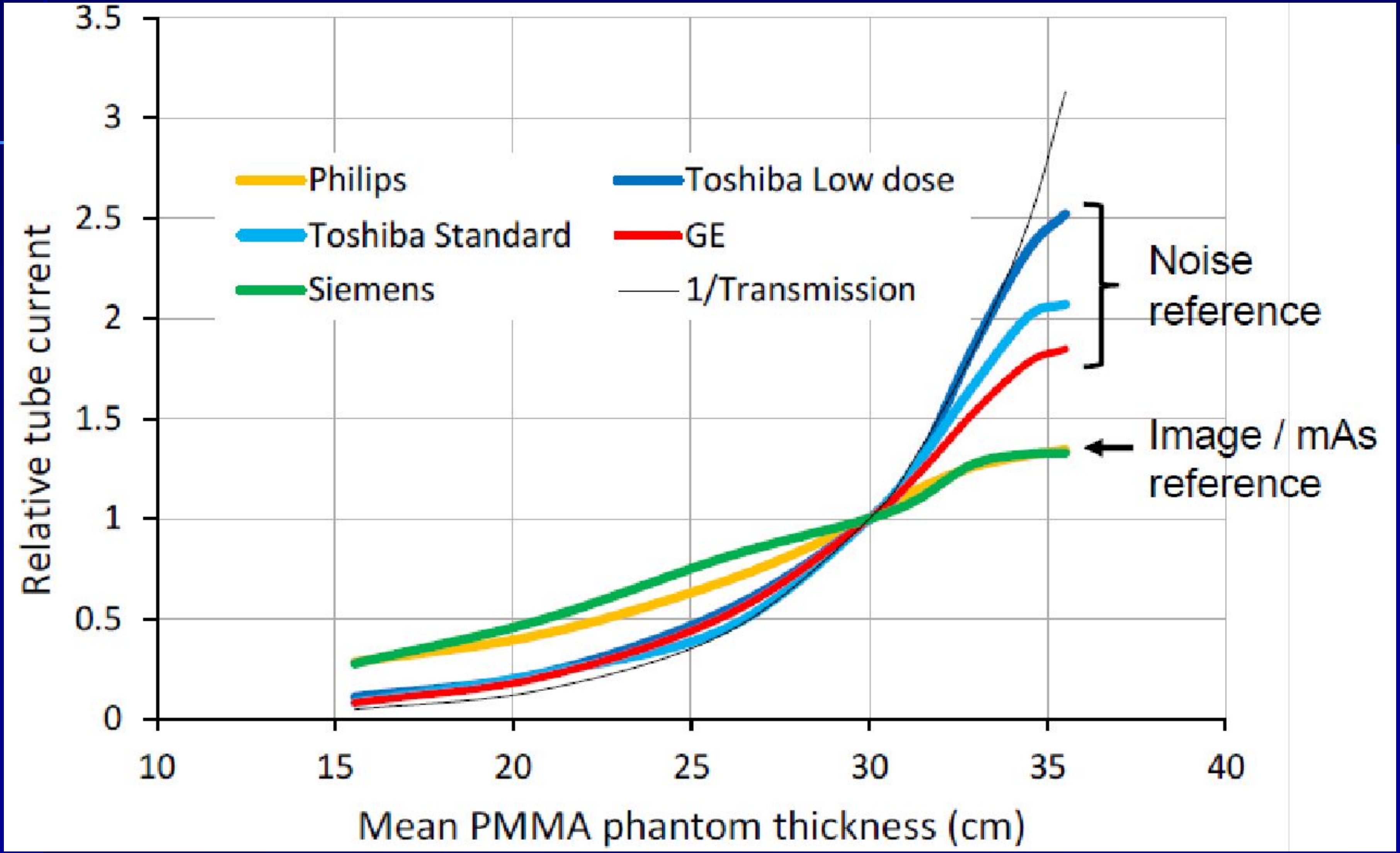


- Image quality kept constant
- Dose optimized (40% 60% overall dose reduction reported)
- Reduced X-ray tube heating
- Constant signal to the detectors
- Artifacts reduction

1. **According to the patient**
2. **Longitudinal modulation (along the z axis)**
3. **Angular or Rotational modulation**

Resulting current is the product of three components

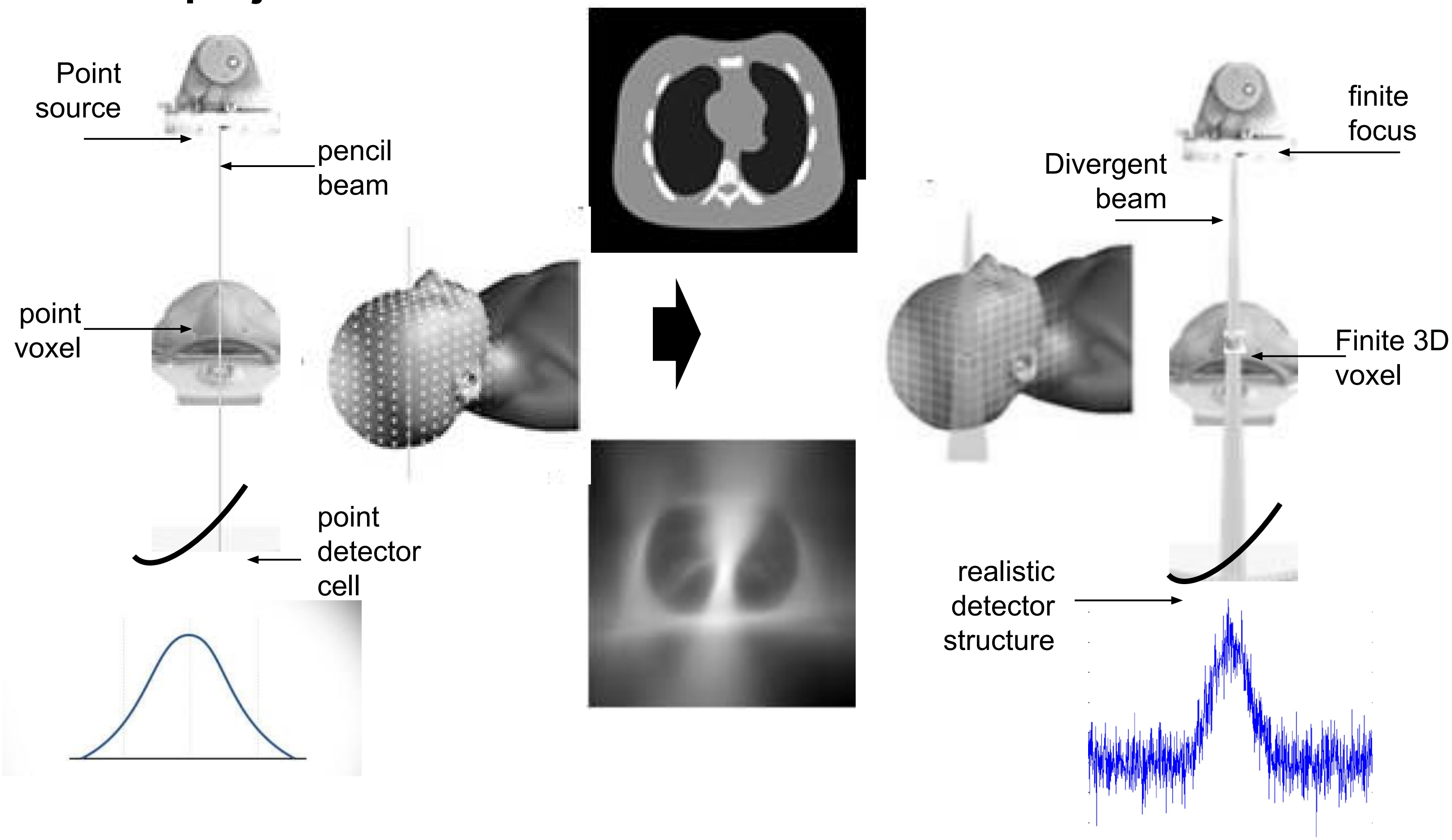
Variations of TCM with Patient Cross-Sectional Area



Courtesy of Colin Martin

From idealistic assumptions to more realistic modeling

Traditional filtered back projection | **Model based iterative reconstruction**



Assumes perfect noise sample

J.B. Thibault

Realistic noise modeling (quantum + electronic)

Iterative methods as a CT simulator

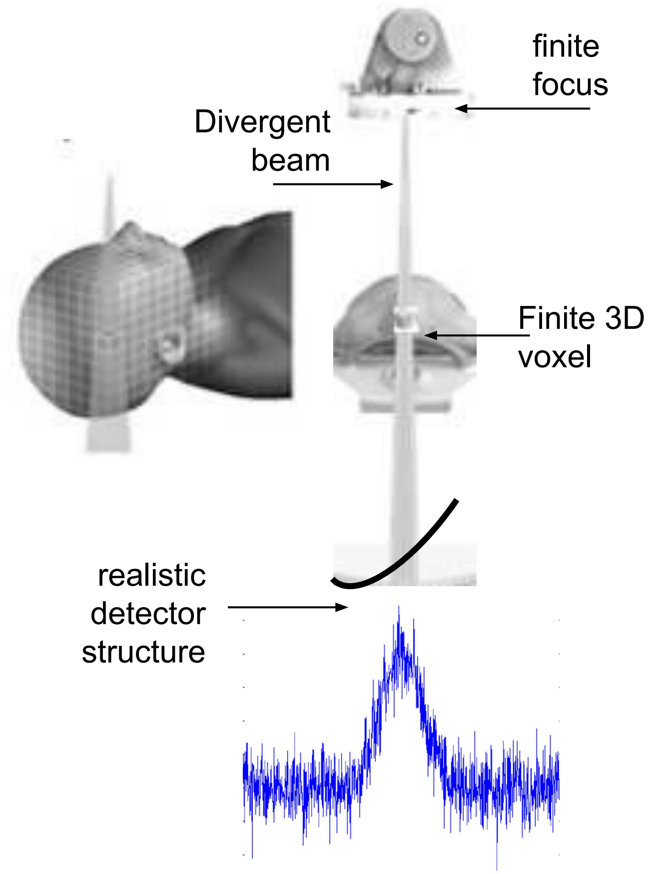
- IR algorithm can be considered as a CT scan simulator in physical level; for accurate results, it is essential to use a **sufficiently accurate** simulator.

- Models the fact that there are a finite number of measured rays (and samples), whereas analytical methods assume a continuum of rays.

- System model in IR (involving discretised object and detectors) is fundamentally different from analytical algorithms (where the object is assumed continuous).

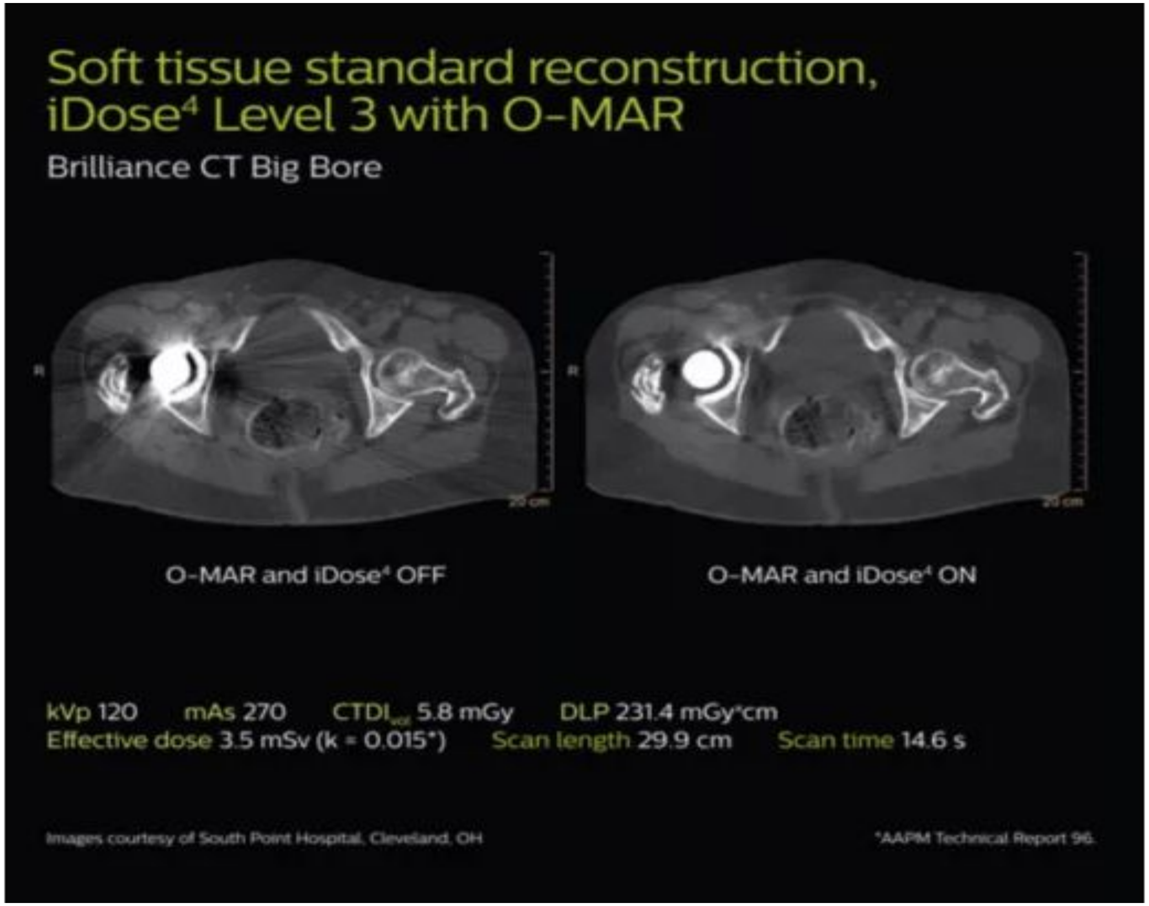
- Various numerical methods and alternatives to optimize the (local or global) convergence properties.

Model based iterative reconstruction



Realistic noise modeling
(quantum + electronic)

Correction of Metal artifacts



DECT principles

- If we are able to measure the attenuation of an object at two different energies, we would get additional information regarding the type of material (spectroscopic imaging).
- The basic assumption is that the attenuation of the material changes significantly with the energy (DE property). This is not true for the majority of tissues in human body.
- Calcium, uric acid, collagen and fat have some weak DE properties. Most of the DE clinical application require the use of iodine, or other materials with k-edge in the clinical energy range.

DECT principles

- If the difference in the attenuation coefficient value for different energies is very low, it can be easily masked by noise and/or artifacts.
- It is extremely important to:
  - Reduce noise and artifact → limit or avoid any source of attenuation coefficient value changes which are not due to energy change.
  - The two energies at which the attenuation coefficients are measured have to be as much distant as possible (spectral separation).

DECT Technical implementation

In the clinic:

- Multiple scans at different spectra mid-range
- Dual source CT (DSCT), generations 2, and 3 high-end
- Fast tube voltage switching high-end
- Dual layer sandwich detectors high-end
- Split filter mid-range

SPECTRAL CT

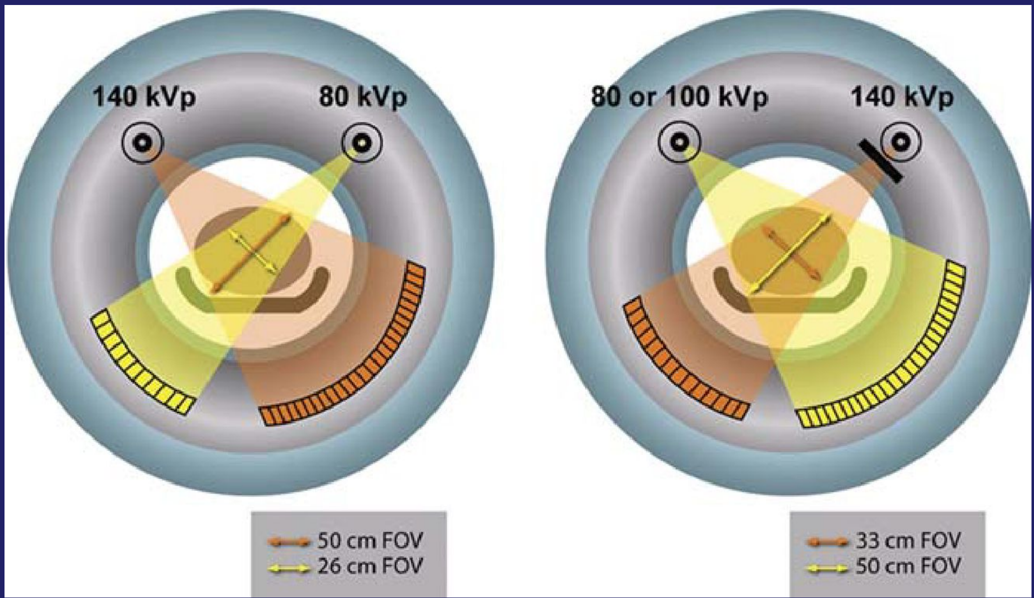
- Photon counting detectors ultra high-end

Dual source CT (Siemens)

Each X-Ray tube can operate on different kV & Tube current (mAs)

ADVANTAGES

- Different X-Ray filters for X-Ray tubes > separation of low and high energy spectra
- Near simultaneous acquisition of DECT data
- Dose is almost equal to SE-CT



DISADVANTAGES

- Time difference between 2 kV
- Processing time
- Interpretation time
- Cost of the DSCT

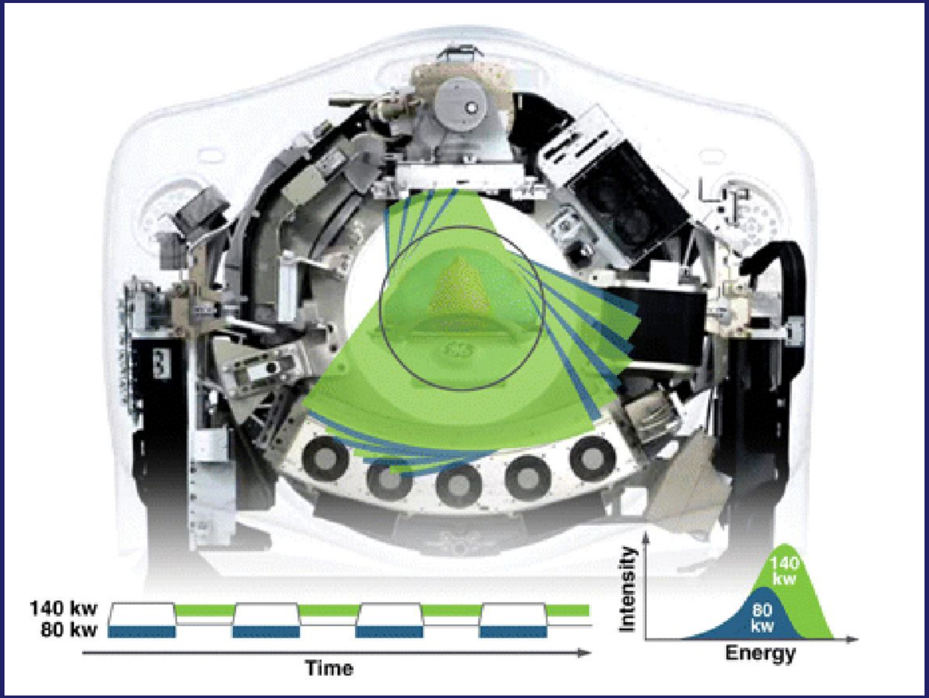
J Thorac Imaging 2012;27:7-22

Rapid kV switching (GE)

Single X-Ray source
kV switches from 80 to 140 kV (<0.5 msec) during same tube rotation

ADVANTAGES

- Good temporal resolution > Spectral data acquired almost simultaneously
- Projection space processing



DISADVANTAGES

- Processing time
- Interpretation time
- Cost of the CT

Kang et al, Radiographics 2010;30(3):685-98.

Dual- Layer Detector Assembly (Philips)

IQon Spectral CT

- Double Layer of Detector:
  - Superficial detector absorb lower photon energy
  - Deep detectors take the higher photon energy
- Spectral information: Blend of data from two layers

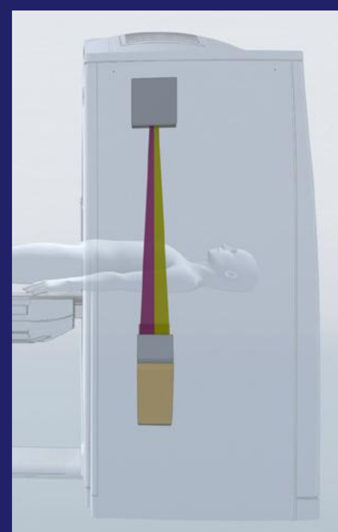
ADVANTAGES

IQon Spectral CT images capture spectral information every time — without special planning or set-up. That means you can analyse the spectral data in any image retrospectively, using a variety of spectral viewing tools. You can do things like adjust the monoenergetic level and isolate material composition.

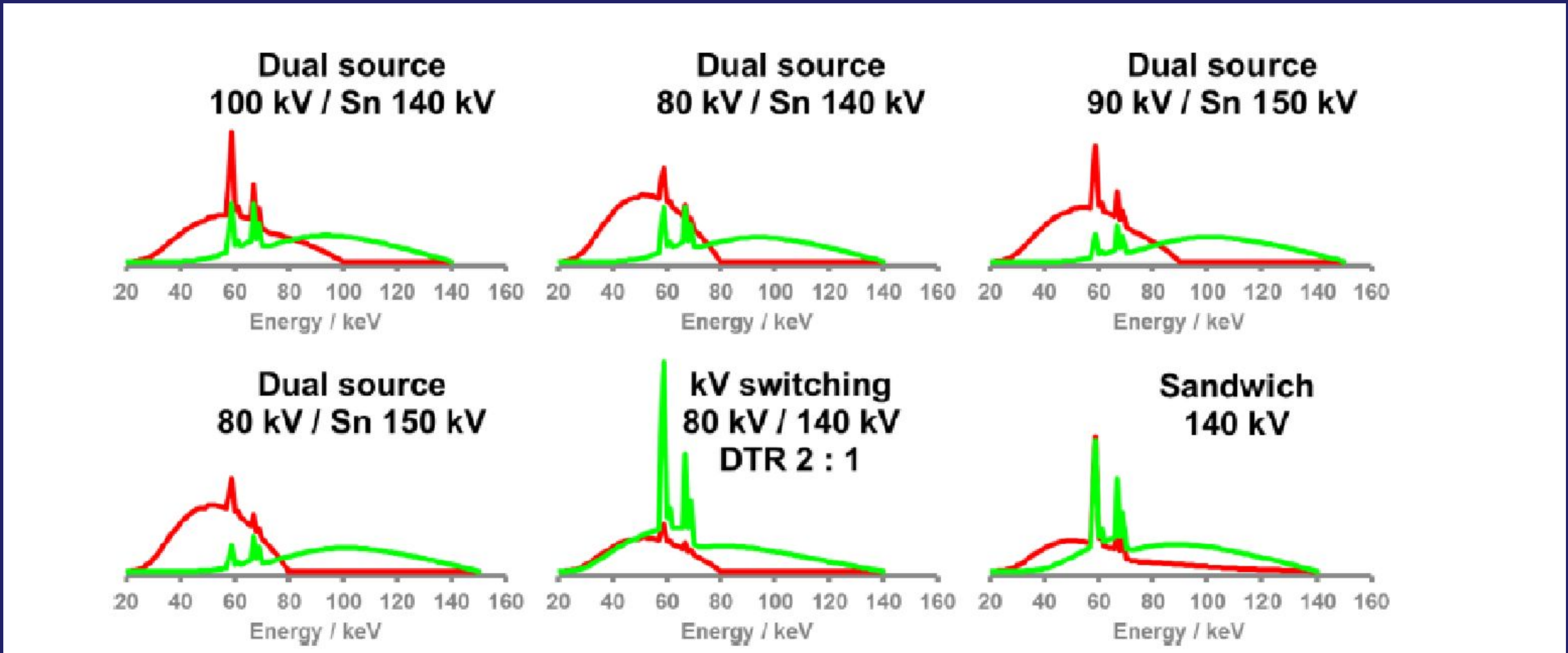
Split filters (Siemens)

Definition Edge TwinBeam

- Dual energy is created by splitting the filter



Spectral Separation



Since a material decomposition can be expressed as a weighted subtraction, the spectral overlap between the low and the high energy spectra is a measure of the material decomposition performance. The larger the overlap, the larger the mutual information in the low and high energy data, and the larger the noise introduced by the subtraction.

Faby S and Kachelrieß M.: “Performance of today’s dual energy CT and future multi energy CT in virtual non-contrast imaging and in iodine quantification: A simulation study”, *Med Phys* **42**, 4349 (2015);

Functional computed tomography using energy resolved photon counting detectors

What is the tissue?

What is its behaviour?

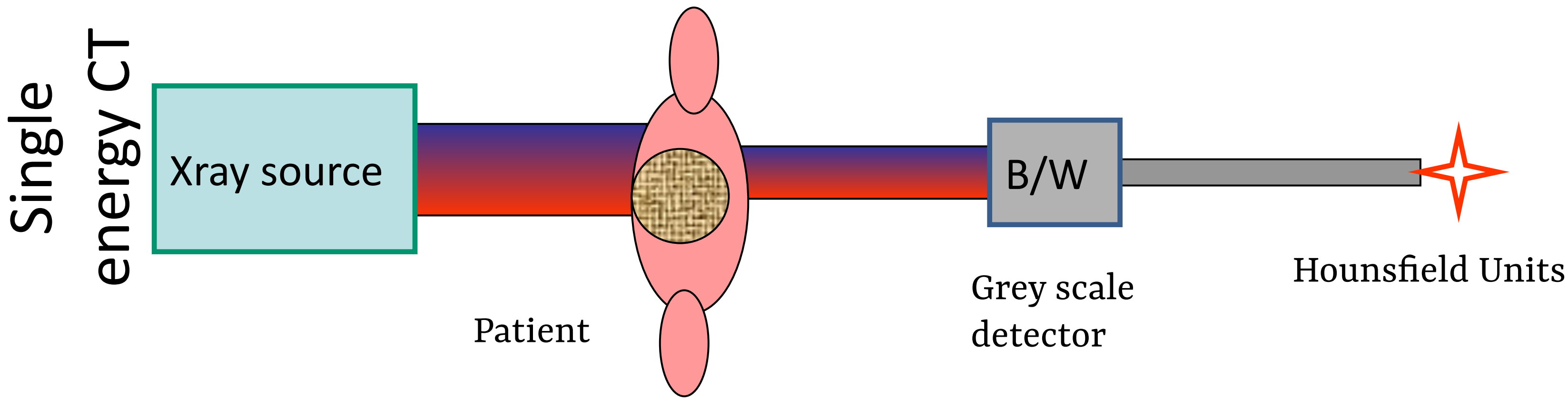
Is the treatment working?

(not just size, shape, location)

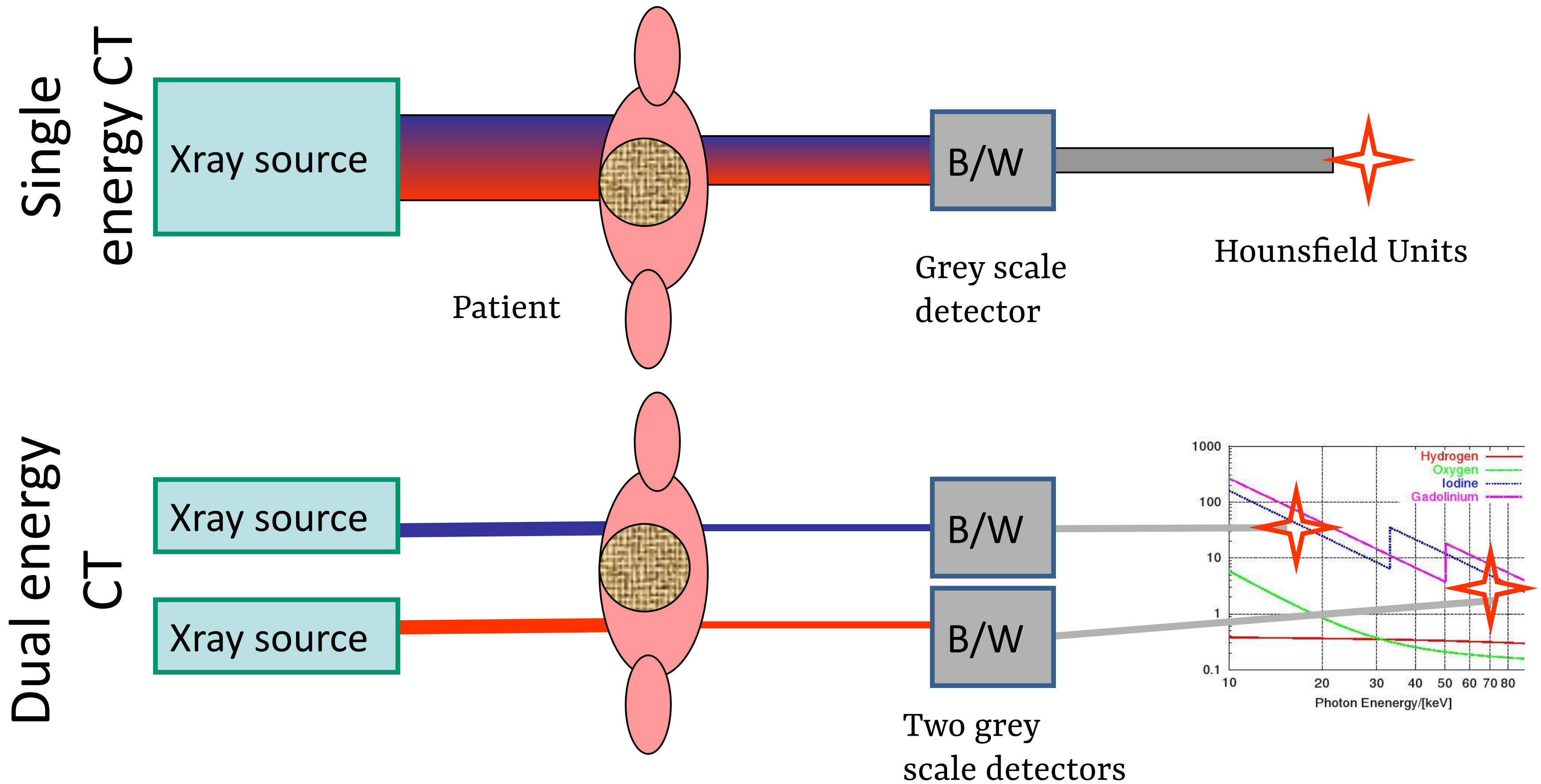
What the diagnostician wants to know

- *Constituents (fat, water, calcium, iron)*
- *Cancer and pathogen labels*
- *Physiological markers*
- *etc*

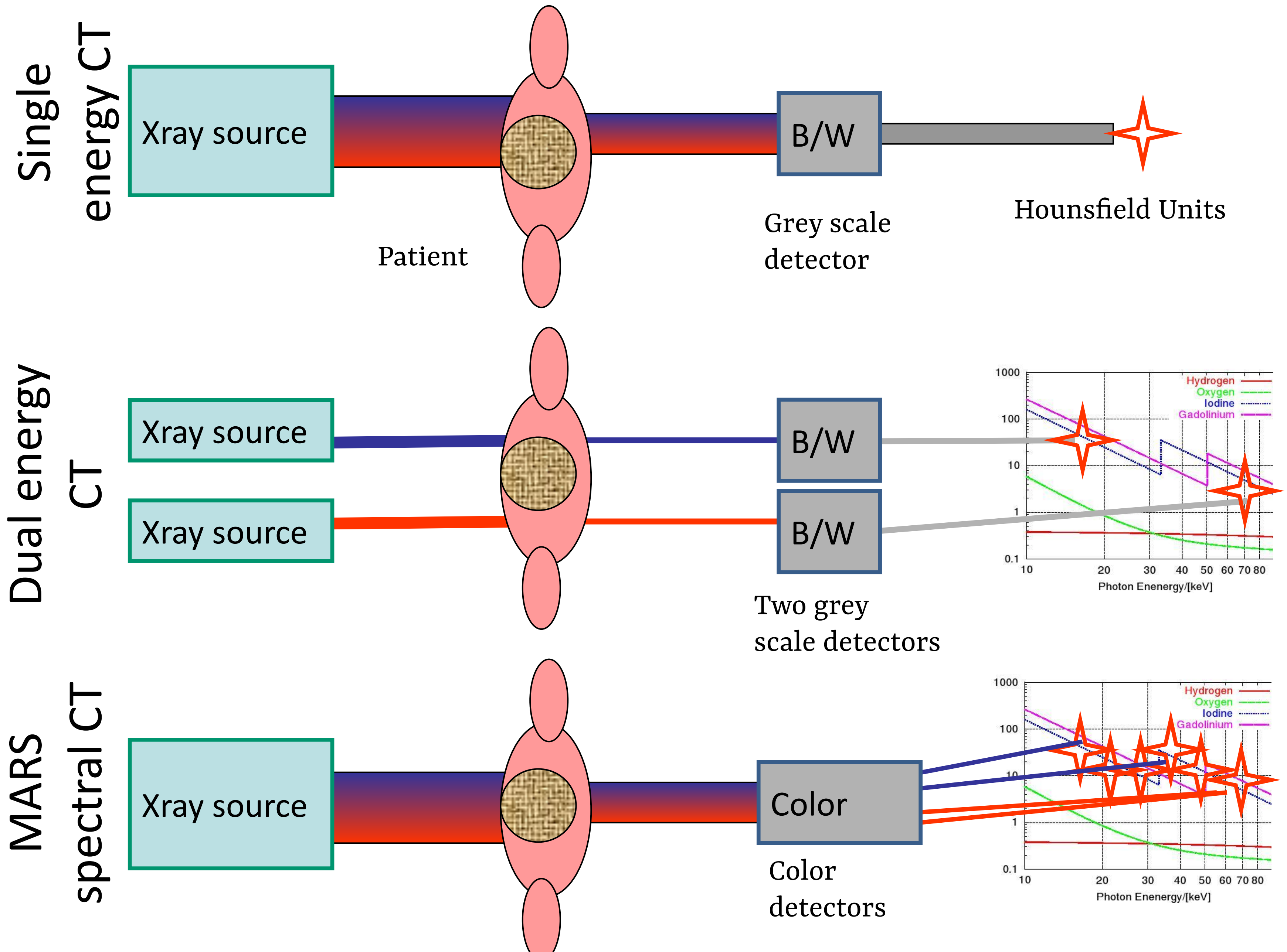
Single- , dual-, and spectral CT



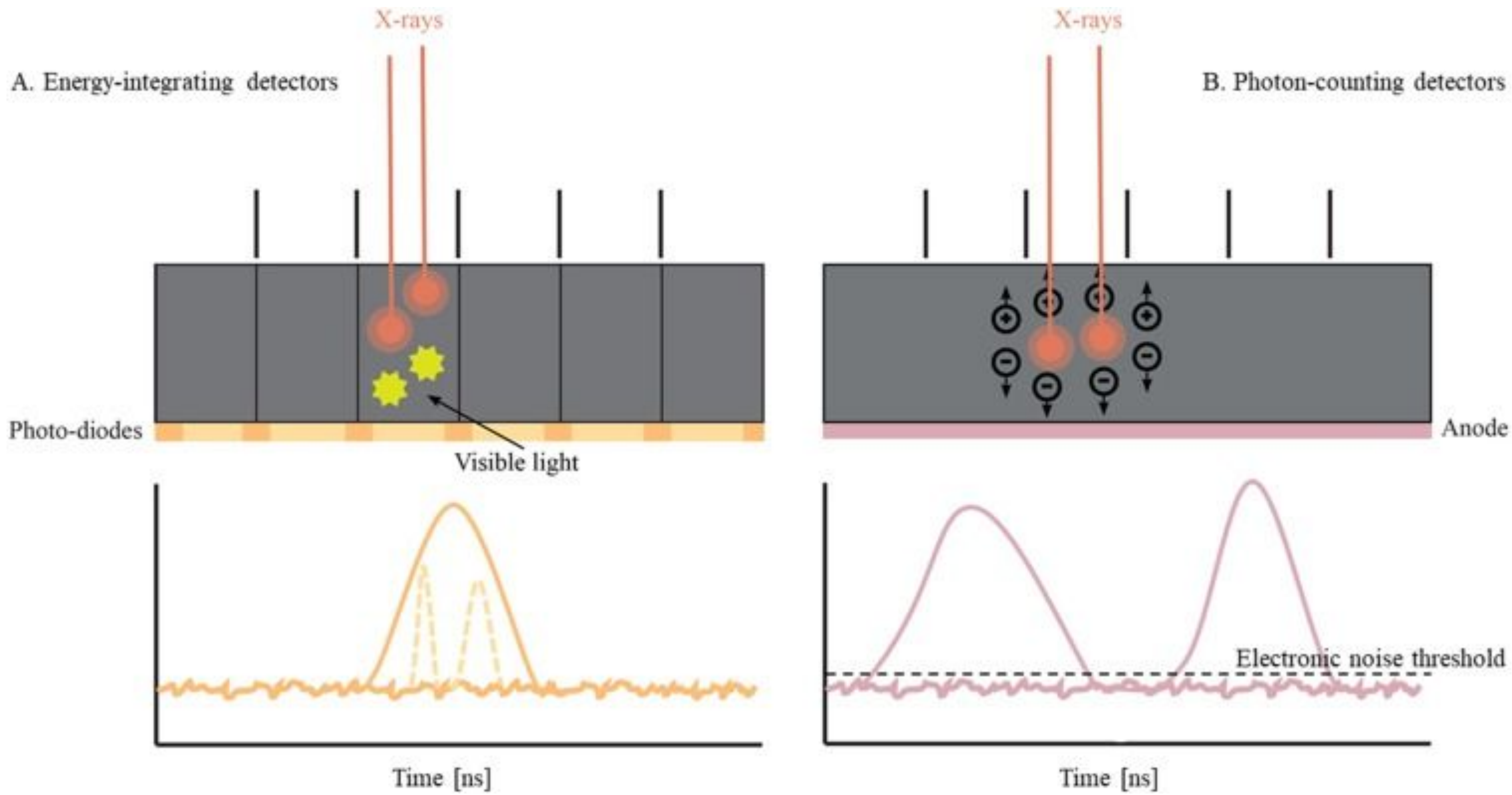
Single- , dual-, and spectral CT



Single- , dual-, and spectral CT



Detectors CdTe



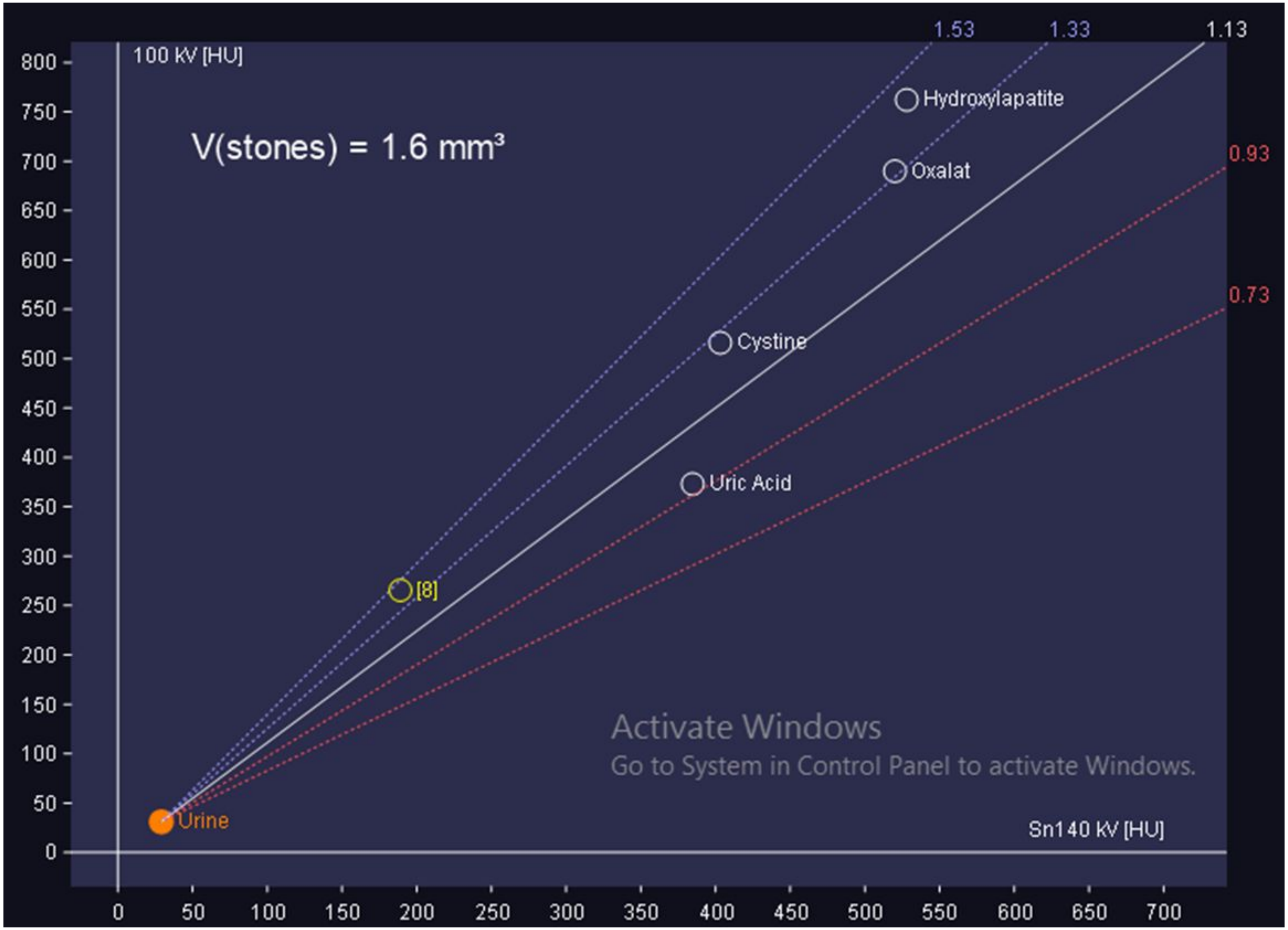
- Smaller detectors pixels
- Elimination of electronic noise
- Intrinsic spectral sensitivity

Clinical applications and protocol optimization

- Material classification
- Material quantification (decomposition)
- Pseudo-monoenergetic images
- Electron density and effective atomic number images
- Stopping power estimation in particle therapy
- Metal artifacts reduction

Material classification

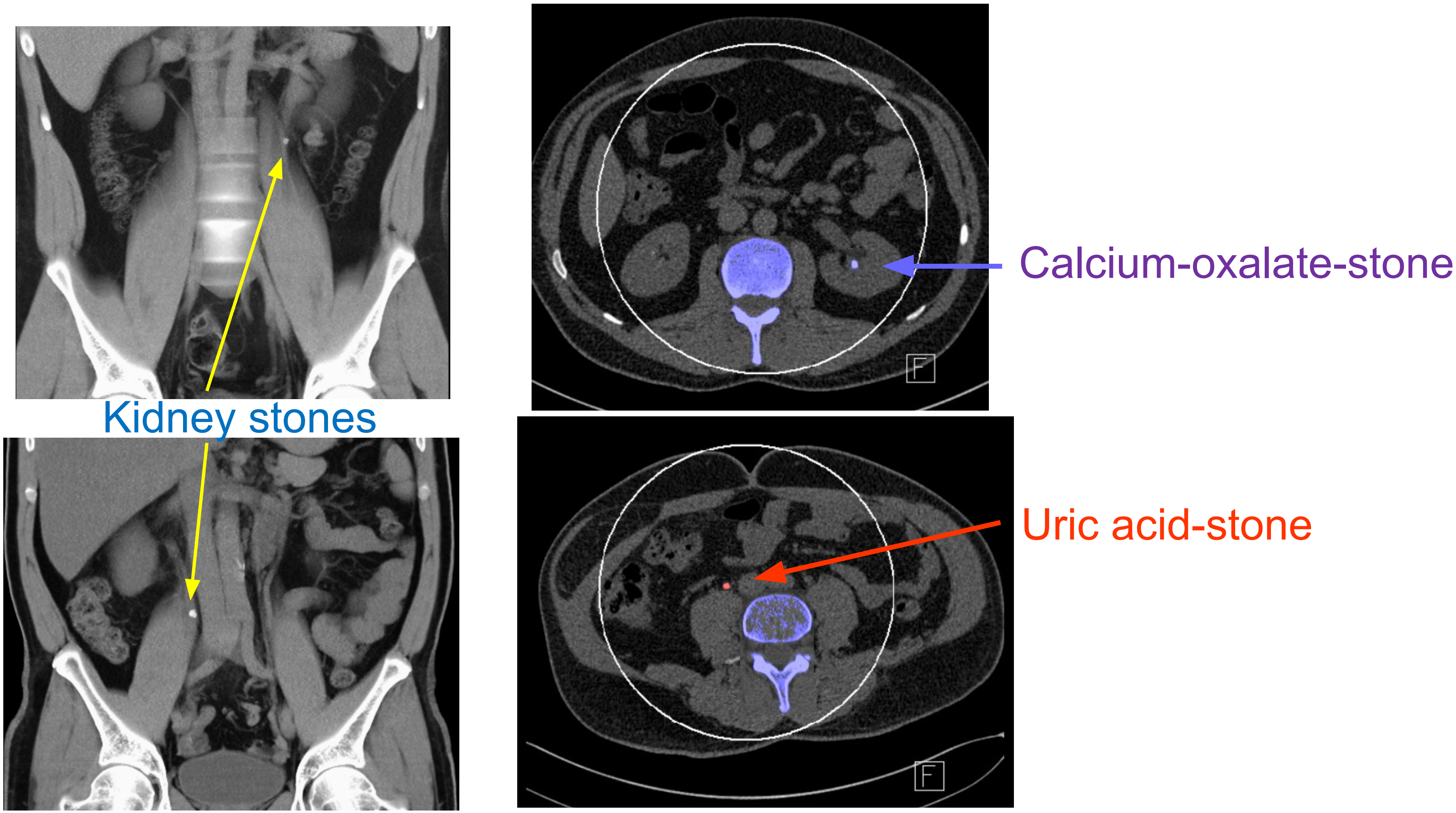
Kidney stones



Slides courtesy of Siemens Healthcare GmbH

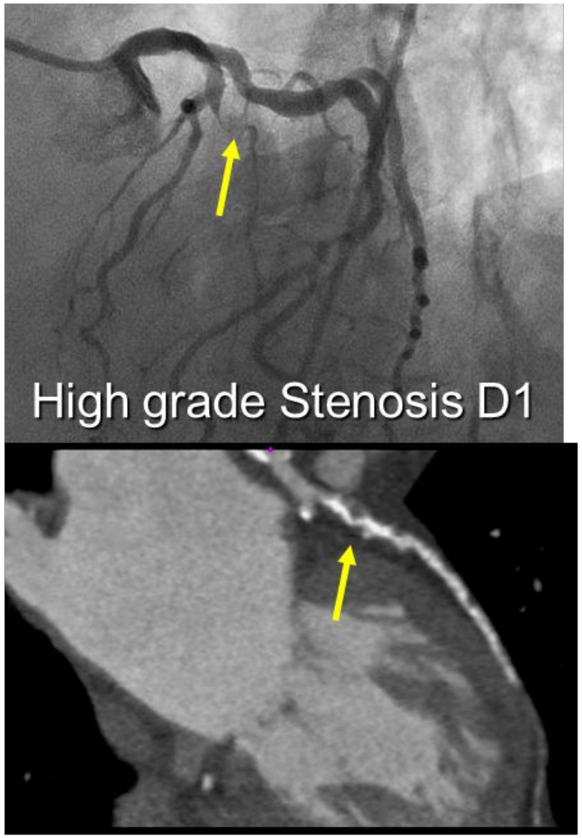
Material classification

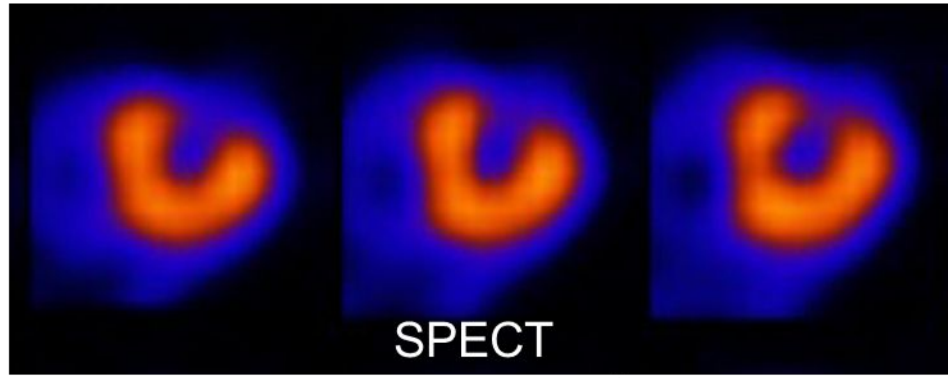
Kidney stones

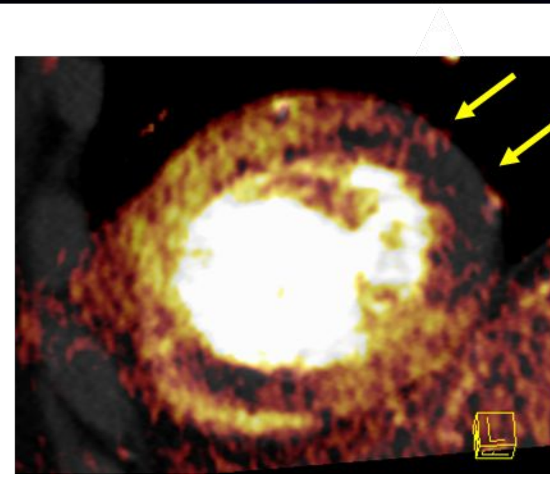


Courtesy of V Pisana and M Kachelries

Material Quantification

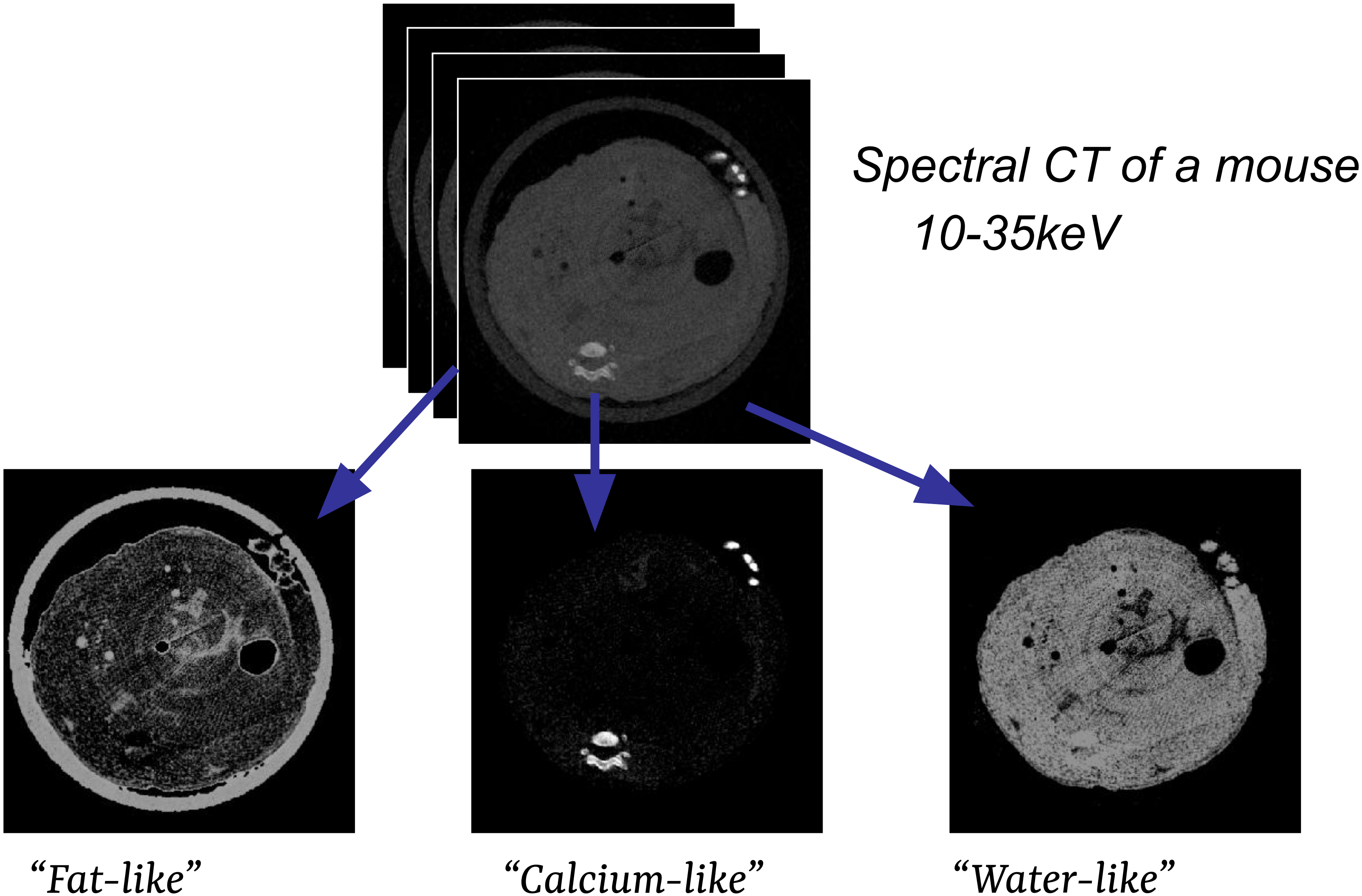




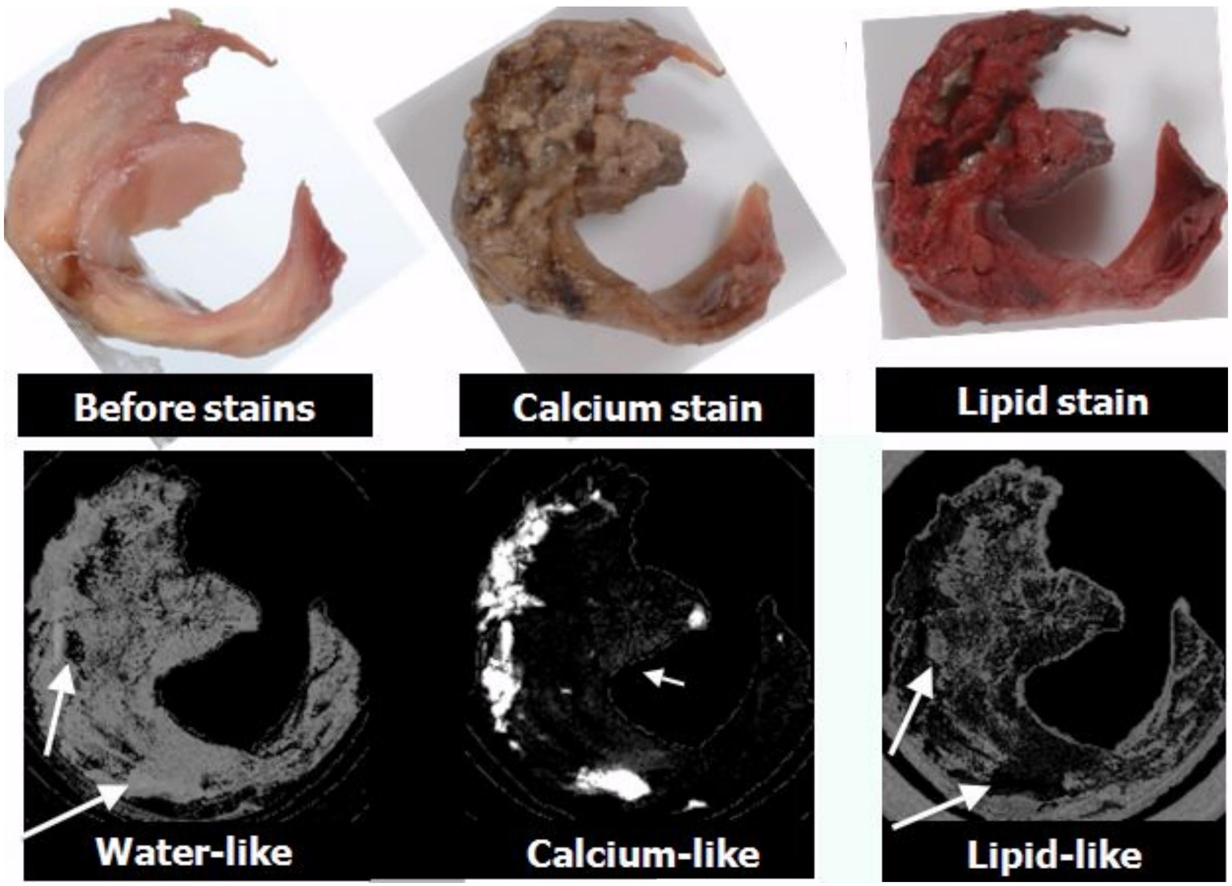


Courtesy of V Pisana and M Kachelries

Quantification of fat and water



Atheroma characterization



Aim to indentify plaque components

Unstable plaques need therapy

Next Steps:

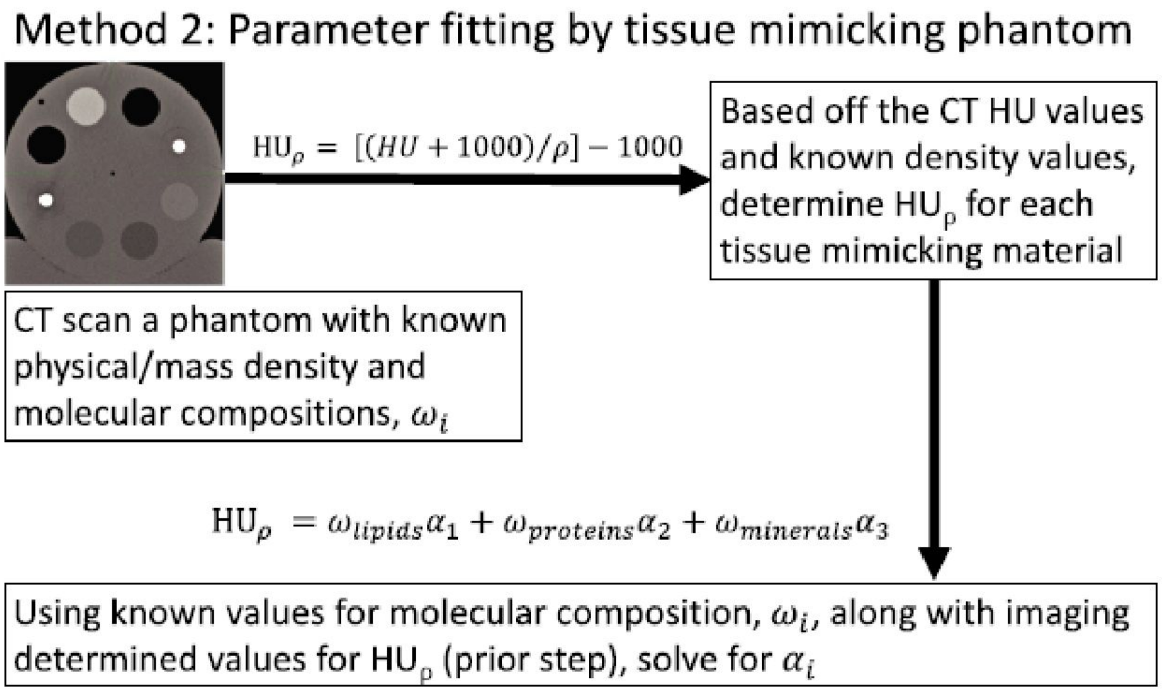
- Ca versus Fe
- Inflammatory markers

Electron density estimation in photon radiation therapy

Conventional single-energy CT can only provide a raw estimation of electron density (ED) for dose calculation by developing a calibration curve that simply maps the HU values to ED values through their correlations.

Spectral CT, also known as dual-energy CT (DECT) or multi-energy CT, can generate a series of quantitative maps, such as ED maps.

Using spectral CT for radiotherapy simulations can directly acquire ED information without developing specific calibration curves.



Where w is the percentage by mass of the respective molecule within X such that Sum of omega =1

Zhu Q, et al. Feasibility of dose calculation for treatment plans using electron density maps from a novel dual-layer detector spectral CT simulator. Radiat Oncol. 2024;19(1):93.

Stopping power estimation in particle therapy

Range uncertainty has been a key factor preventing particle radiotherapy from reaching its full physical potential.

One of the main contributing sources is the uncertainty in estimating particle stopping power (ρs) within patients.

Currently, the ρs distribution in a patient is derived from a single-energy CT (SECT) scan acquired for treatment planning by converting CT number expressed in Hounsfield units (HU) of each voxel to ρs using a Hounsfield look-up table (HLUT), also known as the CT calibration curve.

HU and ρs share a linear relationship with electron density but differ in their additional dependence on elemental composition through different physical properties, i.e. effective atomic number and mean excitation energy, respectively.

Because of that, the HLUT approach is particularly sensitive to differences in elemental composition between real human tissues and tissue surrogates as well as tissue variations within and among individual patients.

The use of dual-energy CT (DECT) for ρs prediction has been shown to be effective in reducing the uncertainty in ρs estimation compared to SECT. The acquisition of CT data over different x-ray spectra yields additional information on the material elemental composition. Recently, multi-energy CT (MECT) has been explored to deduct material-specific information with higher dimensionality, which has the potential to further improve the accuracy of ρs estimation.

Even though various DECT and MECT methods have been proposed and evaluated over the years, these approaches are still only scarcely implemented in routine clinical practice..

Yang M, Wohlfahrt P, Shen C, Bouchard H. Dual- and multi-energy CT for particle stopping-power estimation: current state, challenges and potential. Phys Med Biol. 2023 Feb 6;68(4). doi: 10.1088/1361-6560/acabfa. PMID: 36595276.

Conclusions

- MSCT is the standard for CT simulators.
- Feasibility studies have been reported recently of utilizing electron density (ED) maps generated by a DECT simulator for dose calculation in radiotherapy treatment plans.
- Even though various DECT and MECT methods have been proposed and evaluated over the years, these approaches are still only scarcely implemented in routine clinical practice due to the high costs of the technology