Computed Tomography (CT) – Part 2

EPFL course – 01/11/2024

Dr Anaïs VIRY, Medical physicist SSRPM (medical imaging)

What do you remember about CT (True or false)

1. Increase **the tube current** in CT, increase **the noise and the patient dose**
2. **Overranging** is a phenomenon that increases the patient dose for helical acquisitions
3. Decrease **the tube voltage** improve the **contrast** for high Z structures
4. CT is the **most frequent** exam in Switzerland

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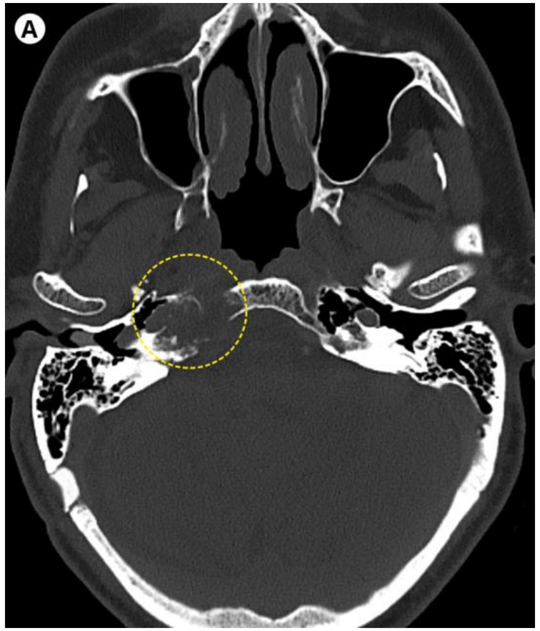
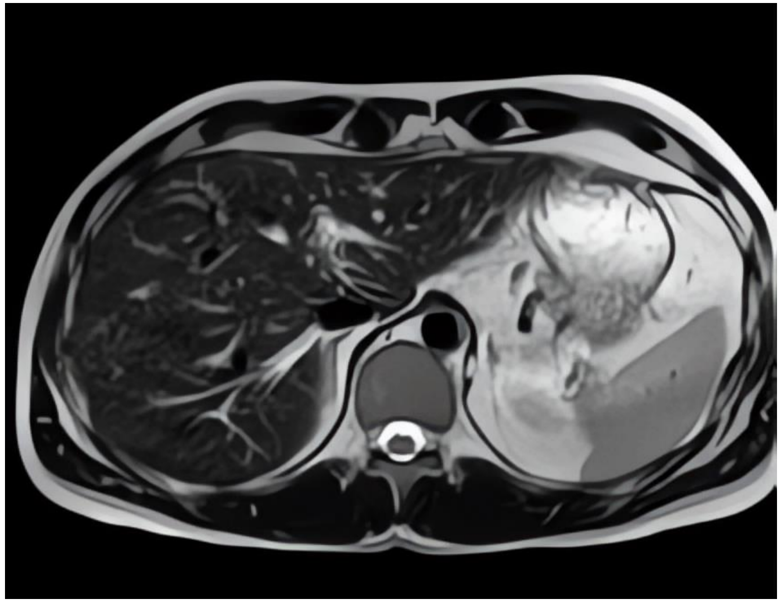
CT exams



- Very good vizualization of bone structures and air/ soft tissues transition
- Poor visualization of soft tissues (ex Abdomen)

CT exams

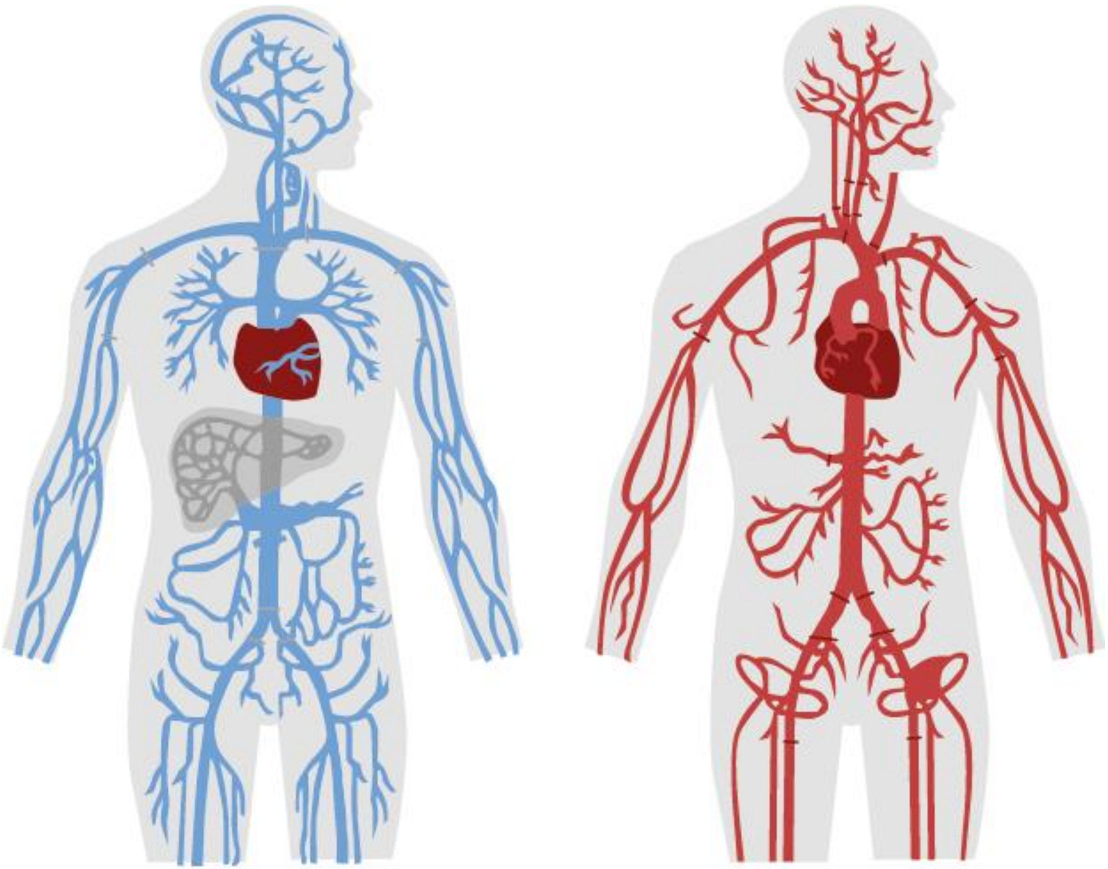


IRM Abdominal

CT Abdominal

CT exams : contrast media injection (iodine)

Visualization of arterial and venous systems



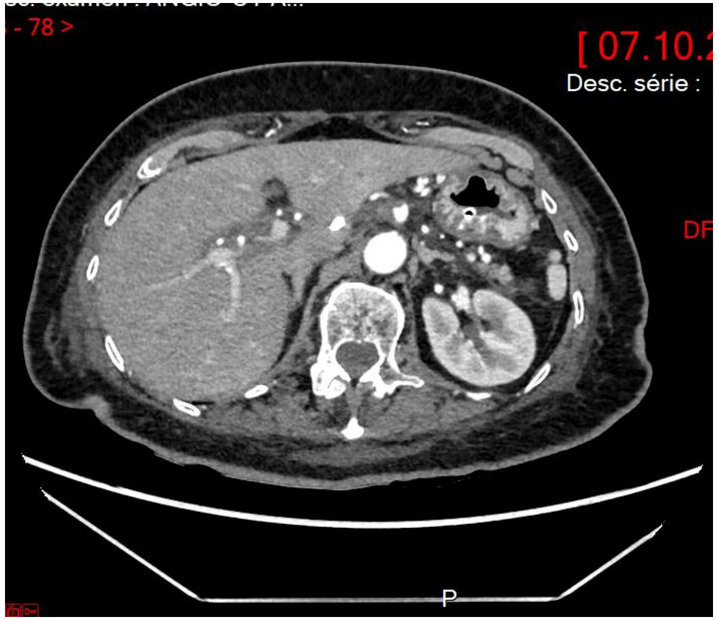
Principales veines du corps

Principales artères du corps

CT exams : contrast media injection (iodine)

Abdominal CT contains generally three (or four) phases :

1. CT scan without contast media (native)
2. CT scan few seconds after contrast media injection (arterial)
3. CT scan 1 minute after contrast media injection (venous)
4. CT scan fifteen minutes after contrast media injection (late)



Objectives

- Synthesize image quality metrics used in CT
- Distinguish the various CT techniques (single-energy CT, dual-energy CT, photon-counting CT)
- Compare dual-energy CT techniques
- Describe photon-counting detectors

Content of the lecture today

- Image quality in CT – Advanced metrics (1h)
  - Link between human observers behaviour and physical image quality metrics

- The last technologies in CT nowadays (1h15) :
  - Dual-Energy CT
    - Motivations for dual-energy CT
    - Dual-energy CT techniques
  - Photon-Counting CT
    - Motivations for photon-counting CT
    - New detectors

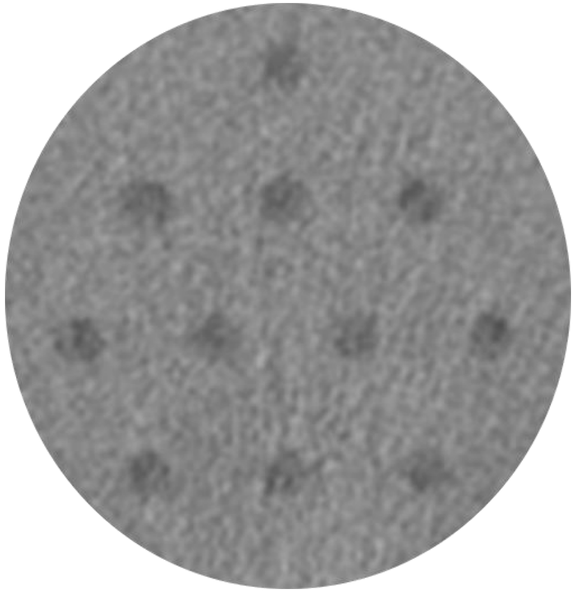
Content of the lecture today

- **Image quality in CT – Advanced metrics (1h)**
  - **Link between human observers behaviour and physical image quality metrics**

- The last technologies in CT nowadays (1h15) :
  - Dual-Energy CT
    - Motivations for dual-energy CT
    - Dual-energy CT techniques
    - Emerging clinical applications
    - A new challenge for medical physicists
  - Photon-Counting CT
    - Motivations for photon-counting CT
    - New detectors

Do you think the image quality is good ?

1. I can see that there is some lesions
2. I can count the number of lesions
3. I can localize each lesion



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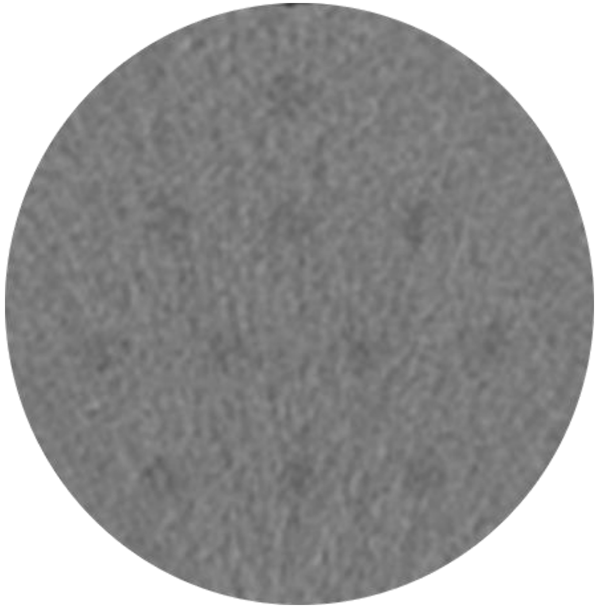

1. I can see that there is some lesions
2. I can count the number of lesions
3. I can precisely localize each lesion

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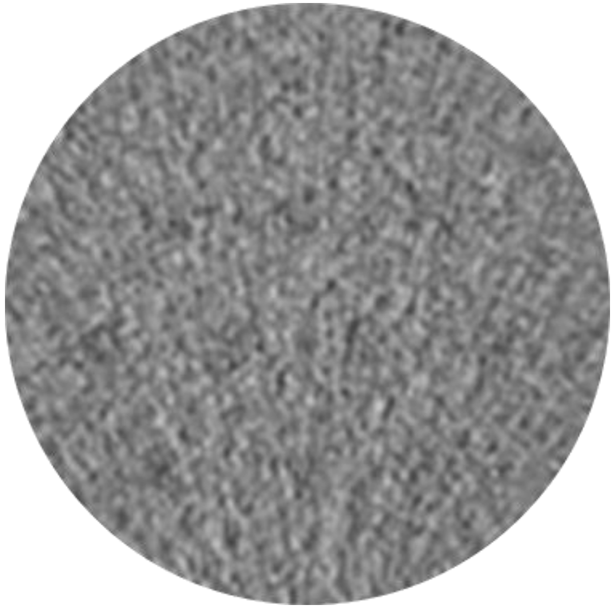

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Image quality in CT – Advanced metrics

CT exposition and risk for the patient

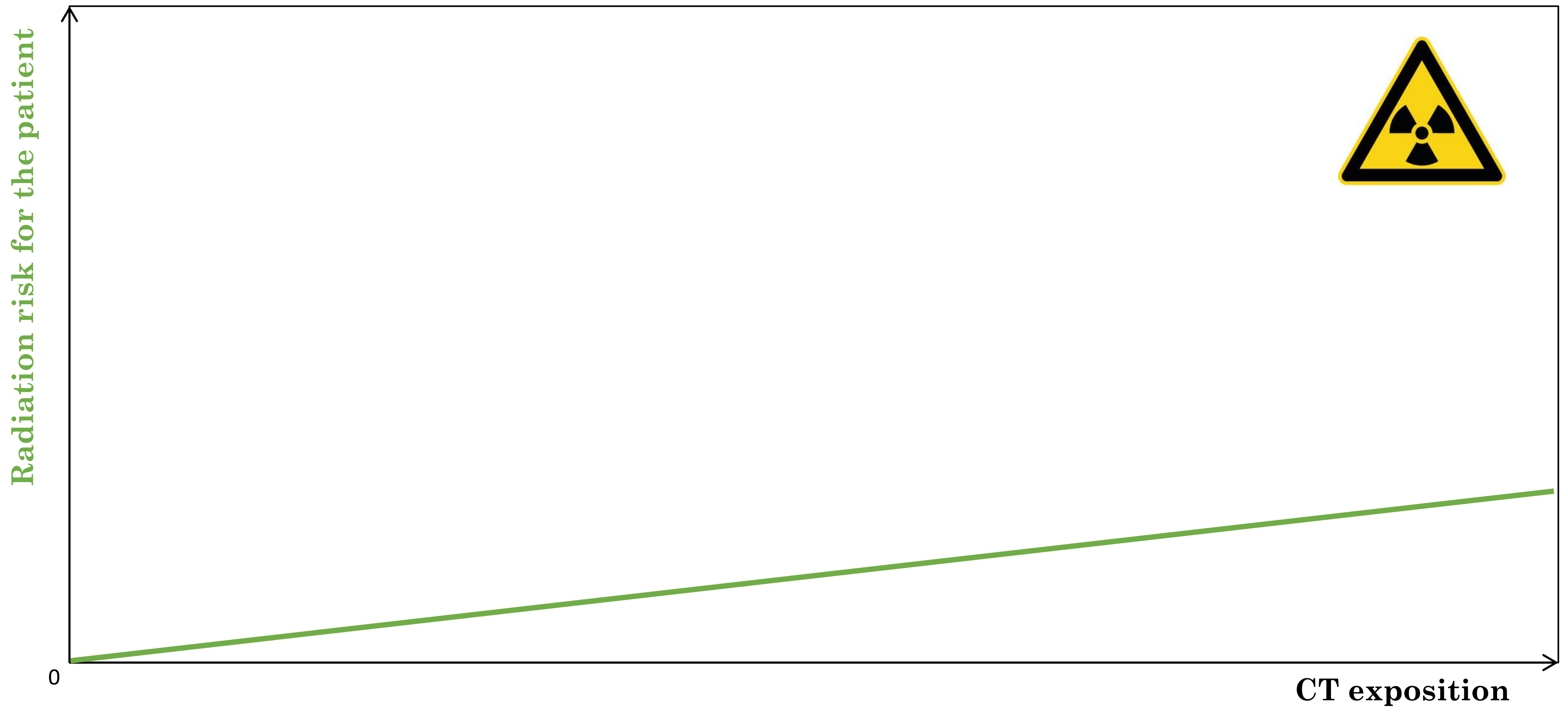


Image quality in CT – Advanced metrics

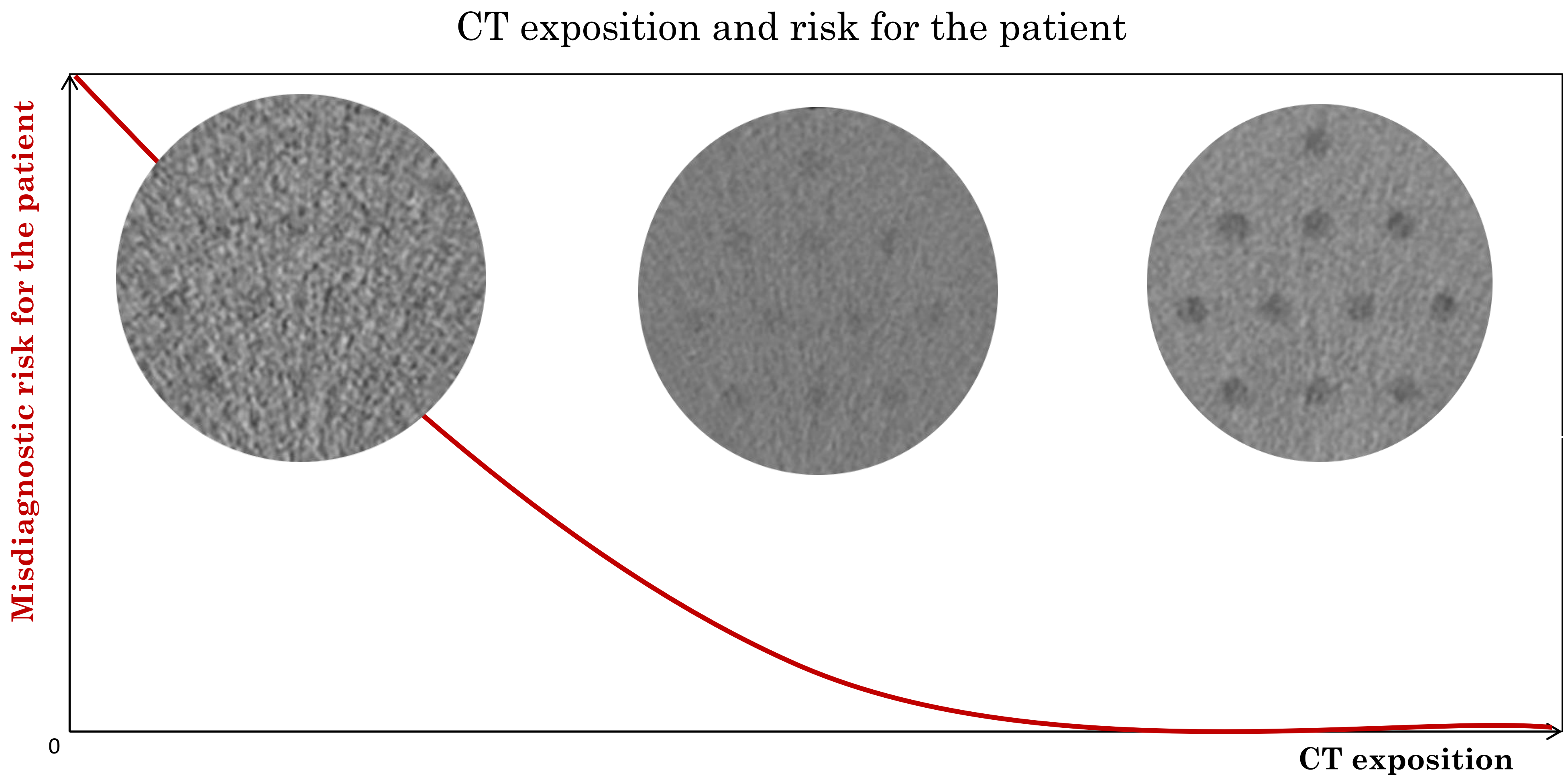
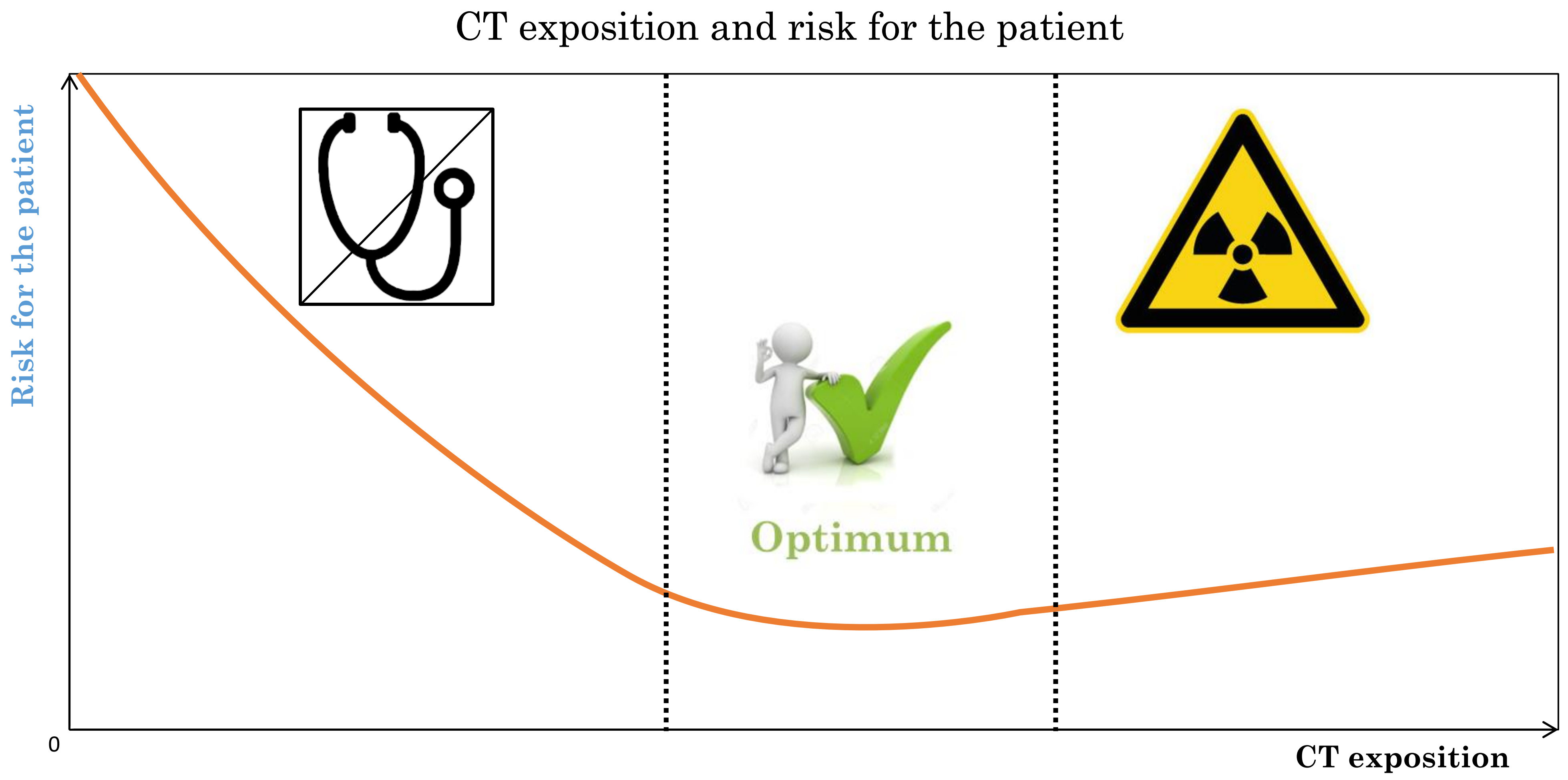
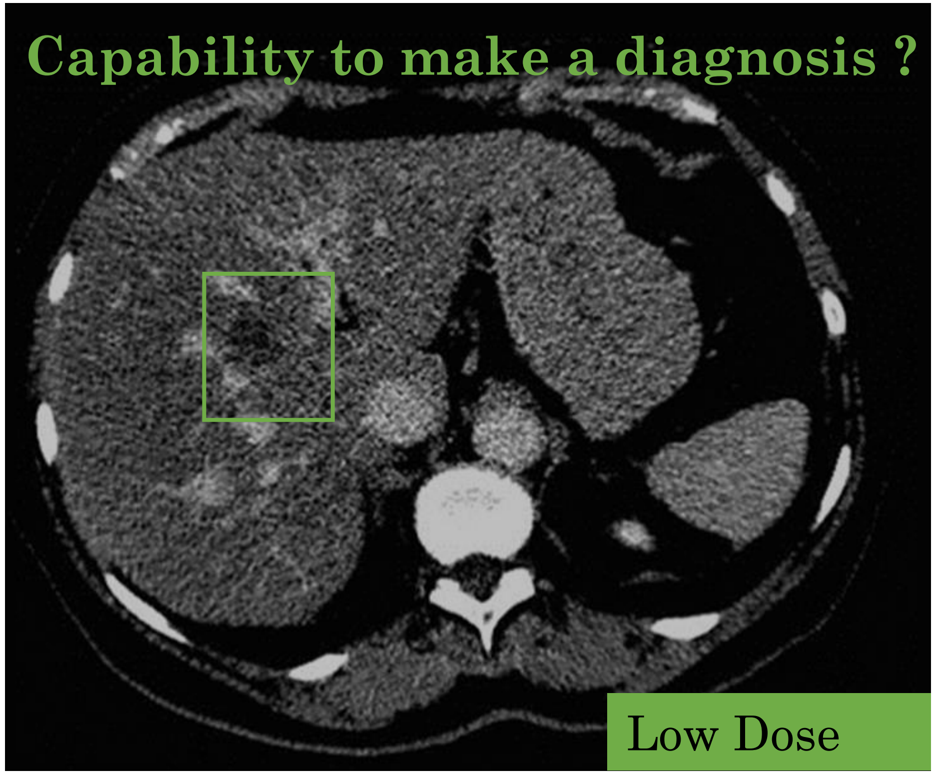


Image quality in CT – Advanced metrics



How to choose the «right dose» ?



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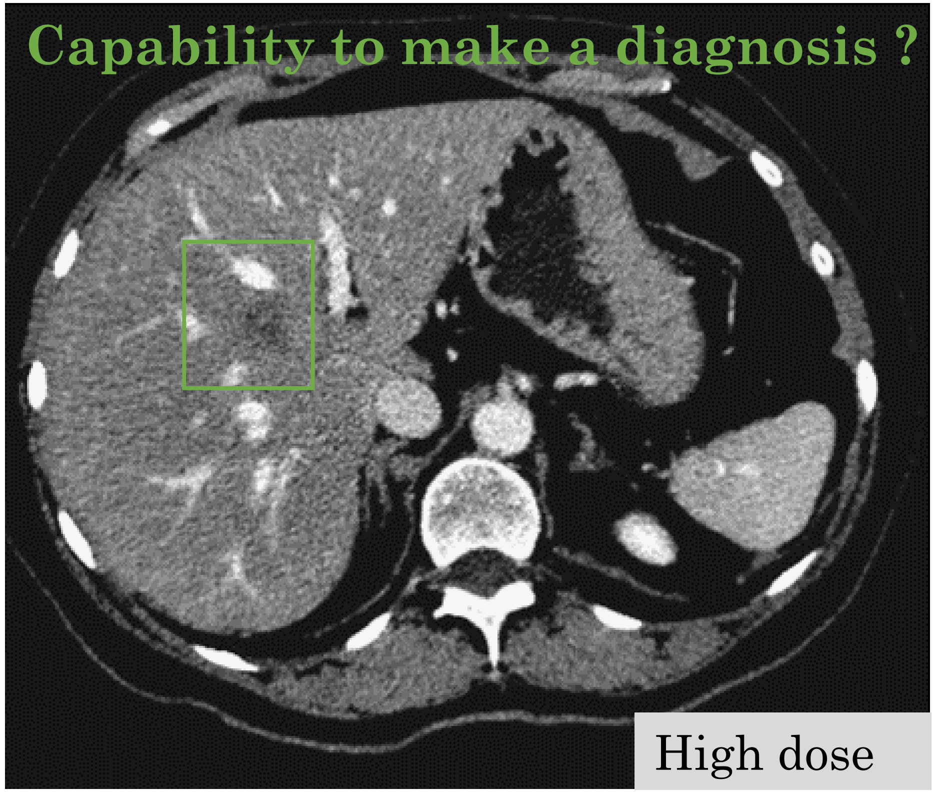

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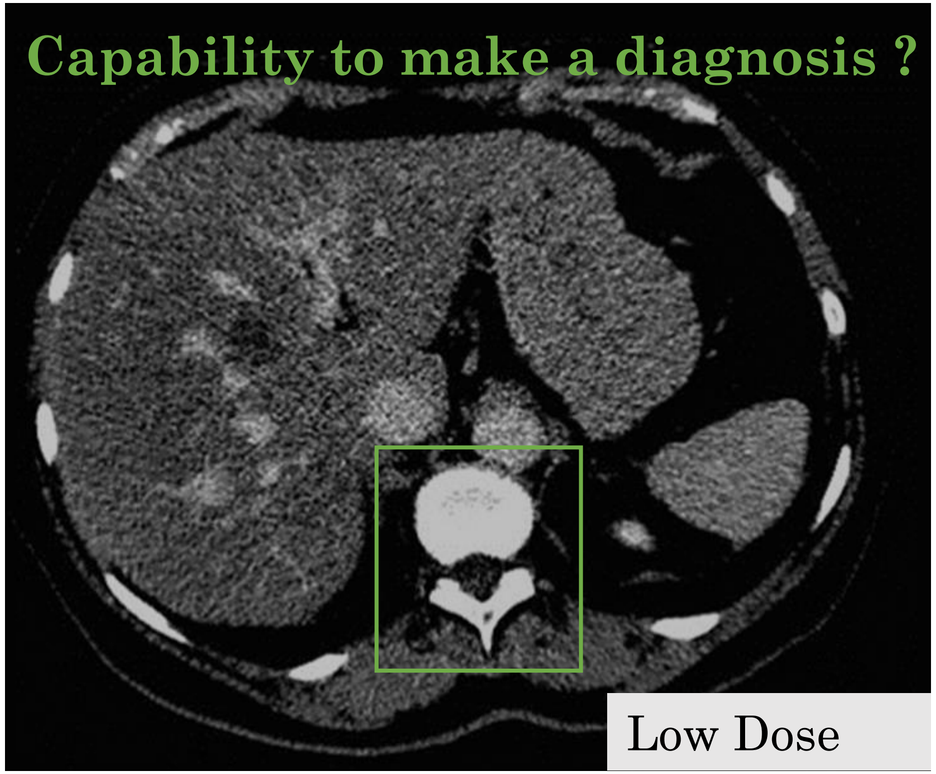

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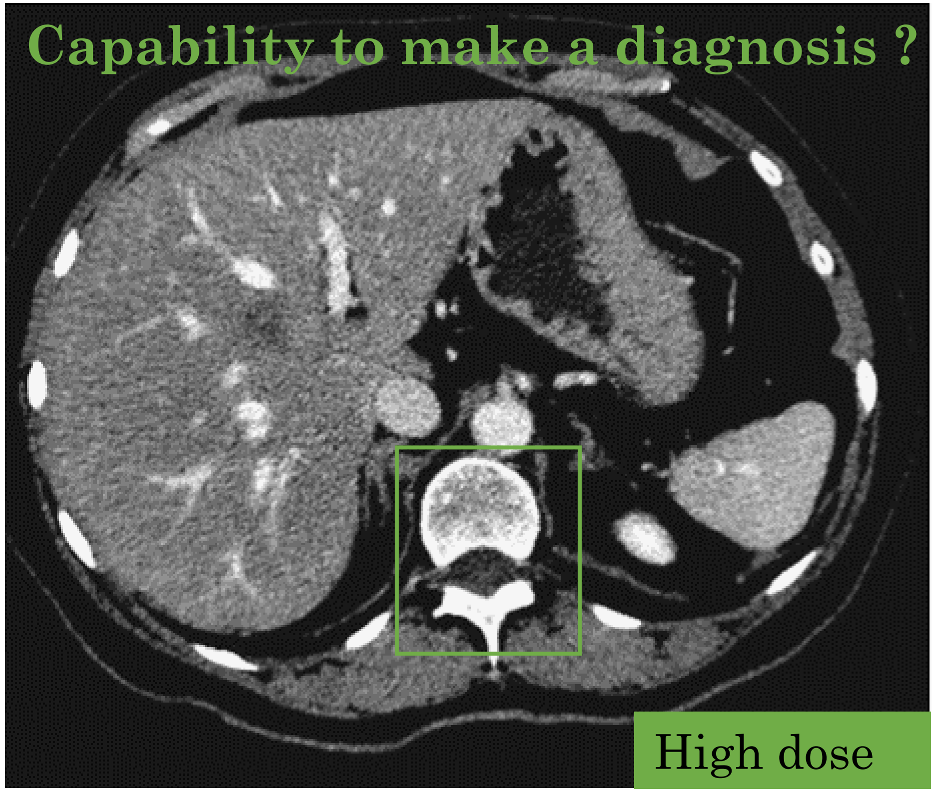
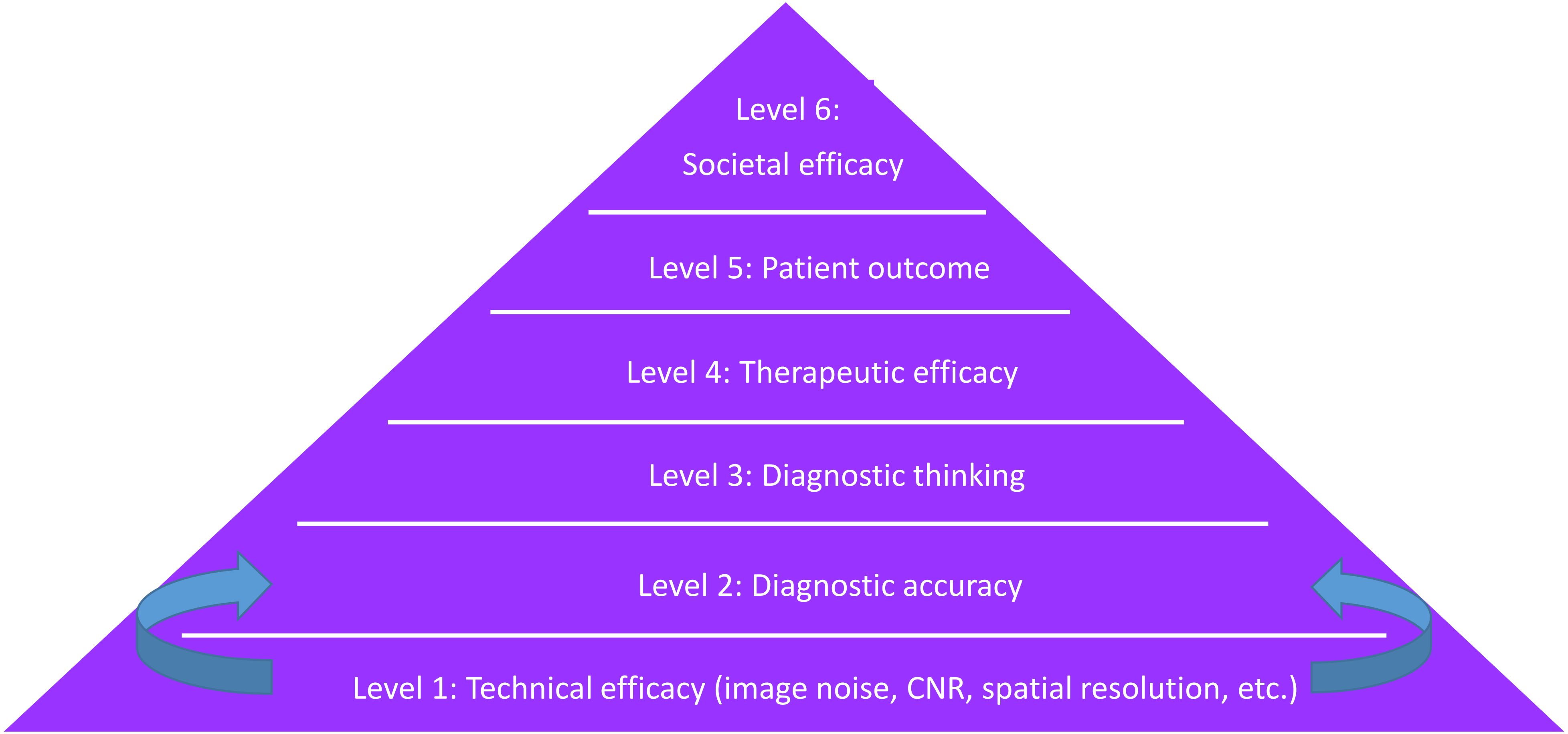


Link between Image quality and diagnostic

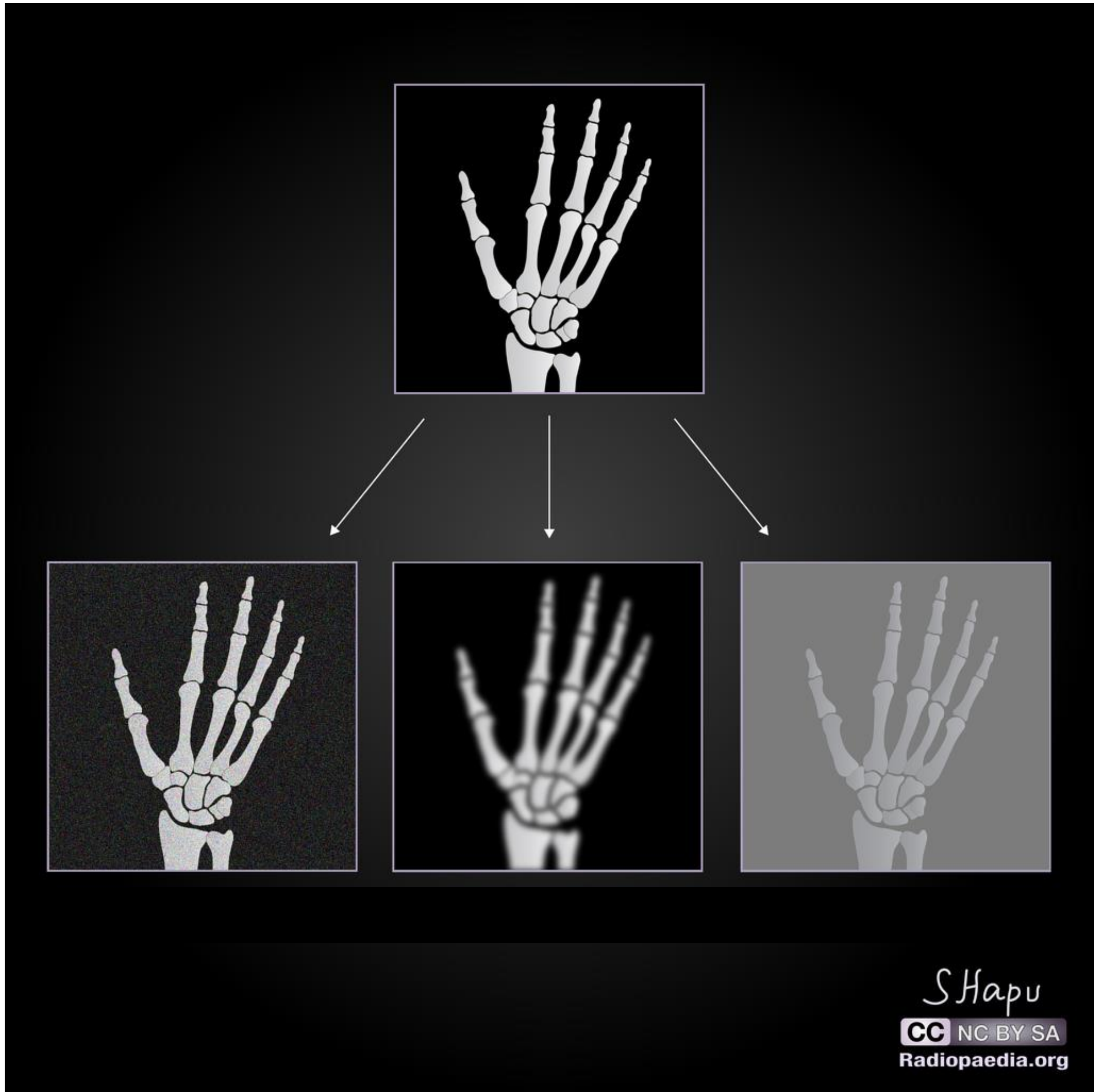
Hierachical model for assessing the efficacy in diagnostic imaging



Fryback DG et al. *Med Decis Making* 1991; 11:88-94

Reminder : Image Quality in medical imaging

What are the three parameters to define image quality ?



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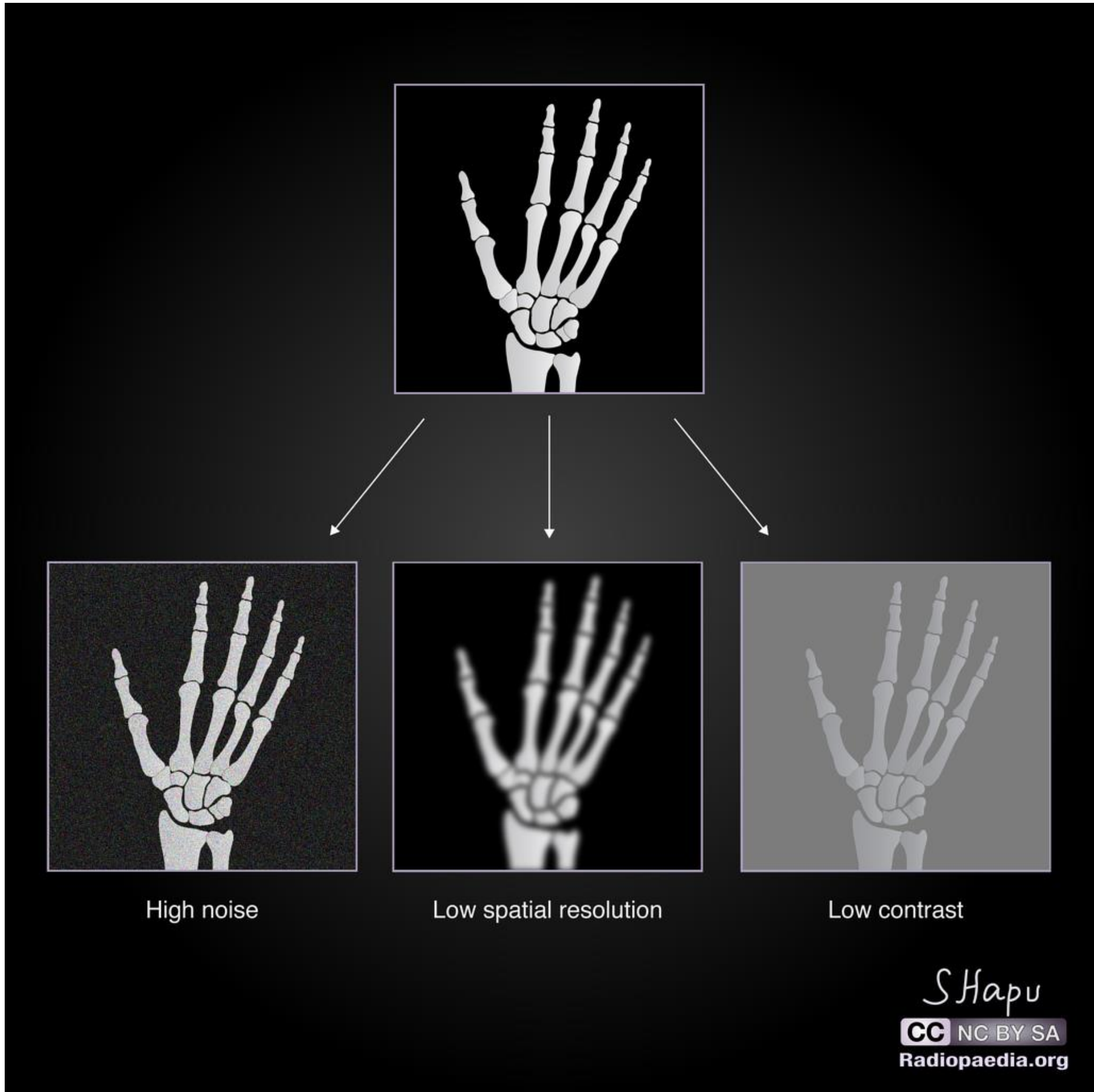
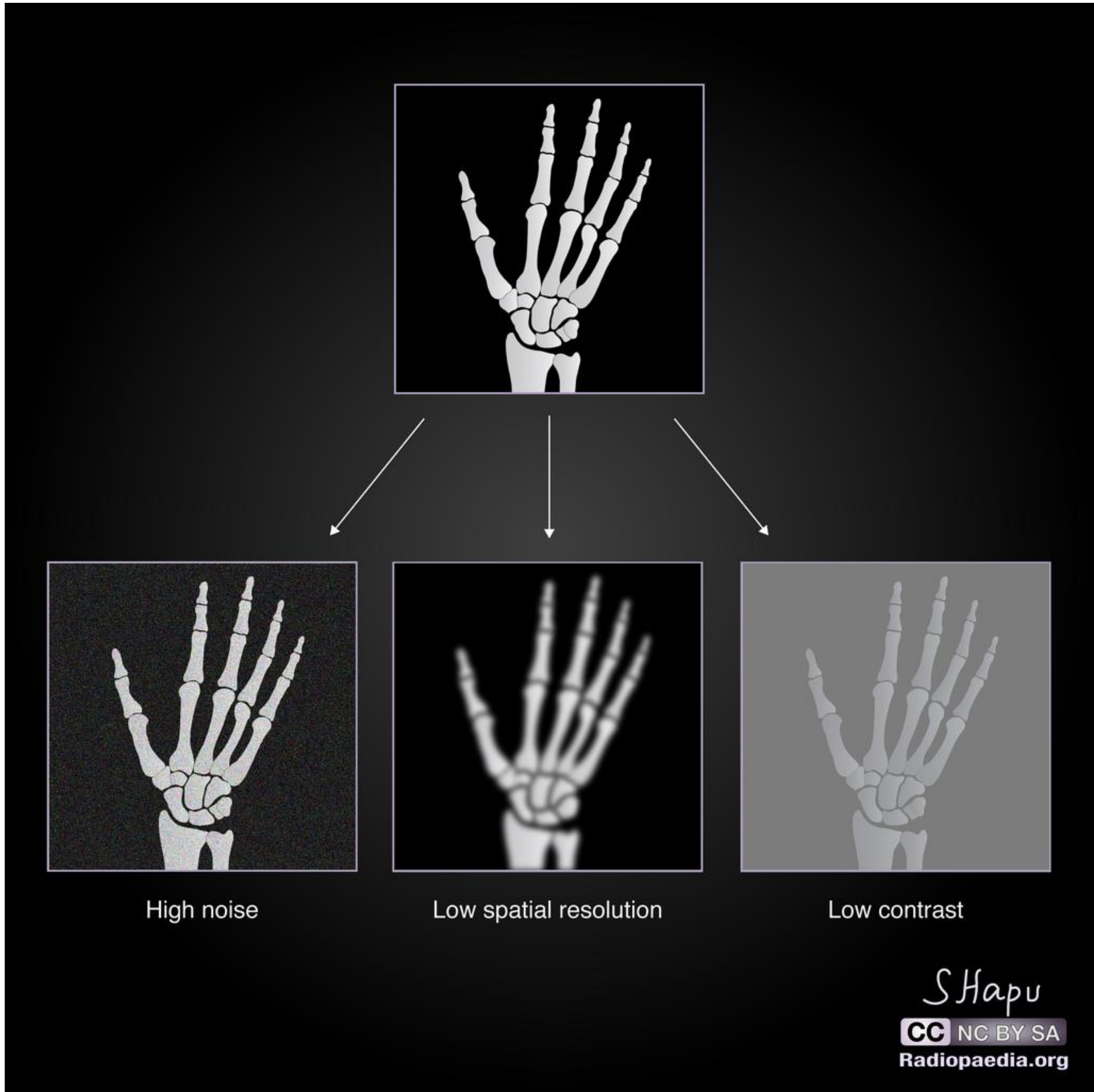


Reminder : First course – Image Quality

What are the three parameters to define image quality ?

ICRU REPORT No. 87

RADIATION DOSE AND IMAGE-QUALITY ASSESSMENT IN COMPUTED TOMOGRAPHY

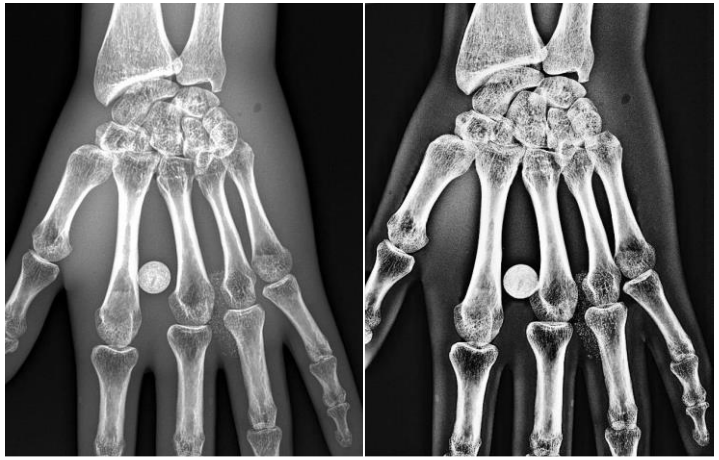


Reminder : The spatial resolution

Spatial resolution refers to the ability of an image to convey detail; **medical imaging systems produce images that are usually degraded in detail compared with the actual object being imaged.**

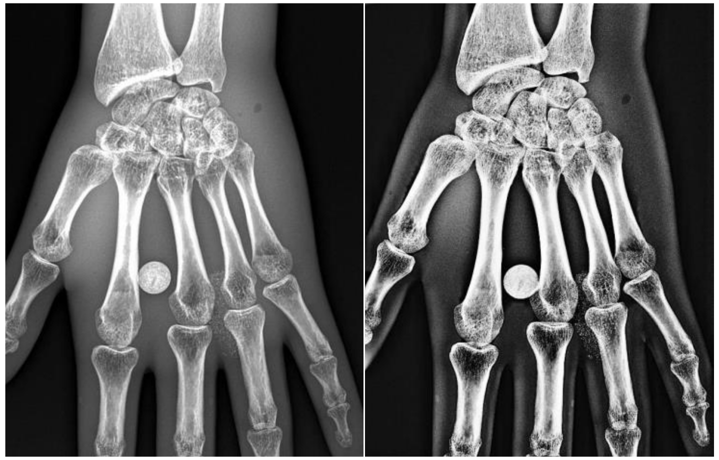
Which metric characterize the spatial resolution ?

1. MTF
2. NPS
3. FFT
4. DQE



Which metric characterize the spatial resolution ?

1. MTF : Modulation transfer function
2. NPS
3. FFT
4. DQE



How to measure MTF in CT ?

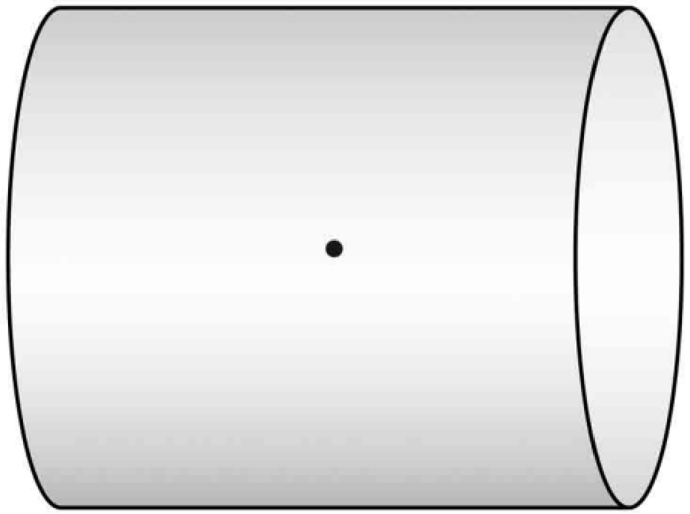
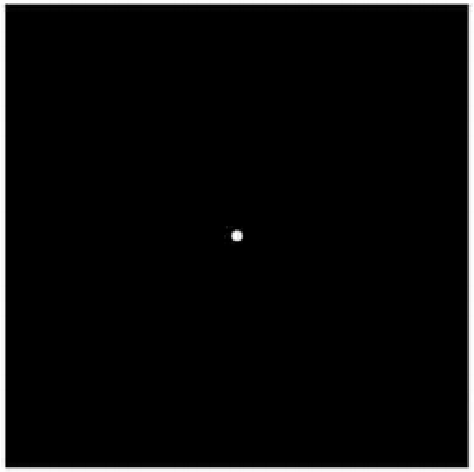
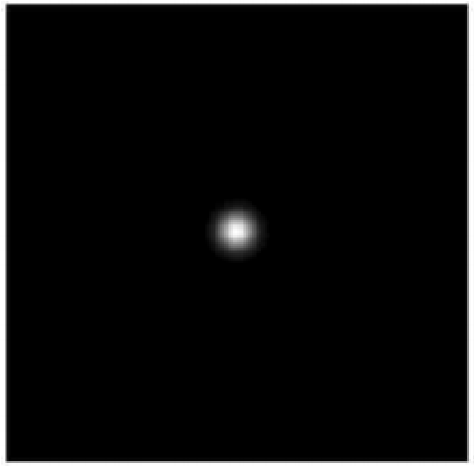


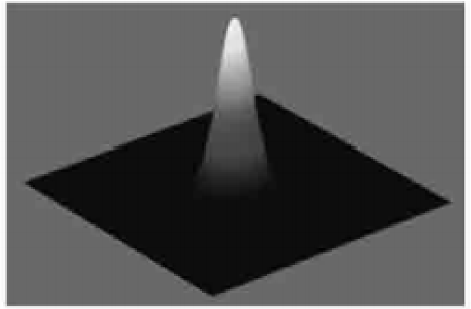
Figure 10.1. Measurement of the 3D *MTF*. A small high-contrast sphere placed in the center of a homogeneous phantom provides a 3D delta function, $\delta(x, y, z)$, as a stimulus to a CT system for characterization of the $PSF_{3D}(x, y, z)$.



Input signal

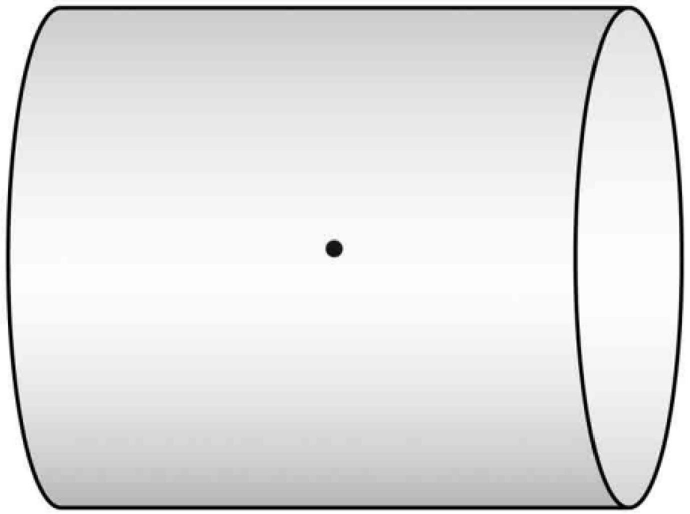


Output signal



PSF_{3D} (x,y,z)

How to measure MTF in CT ?



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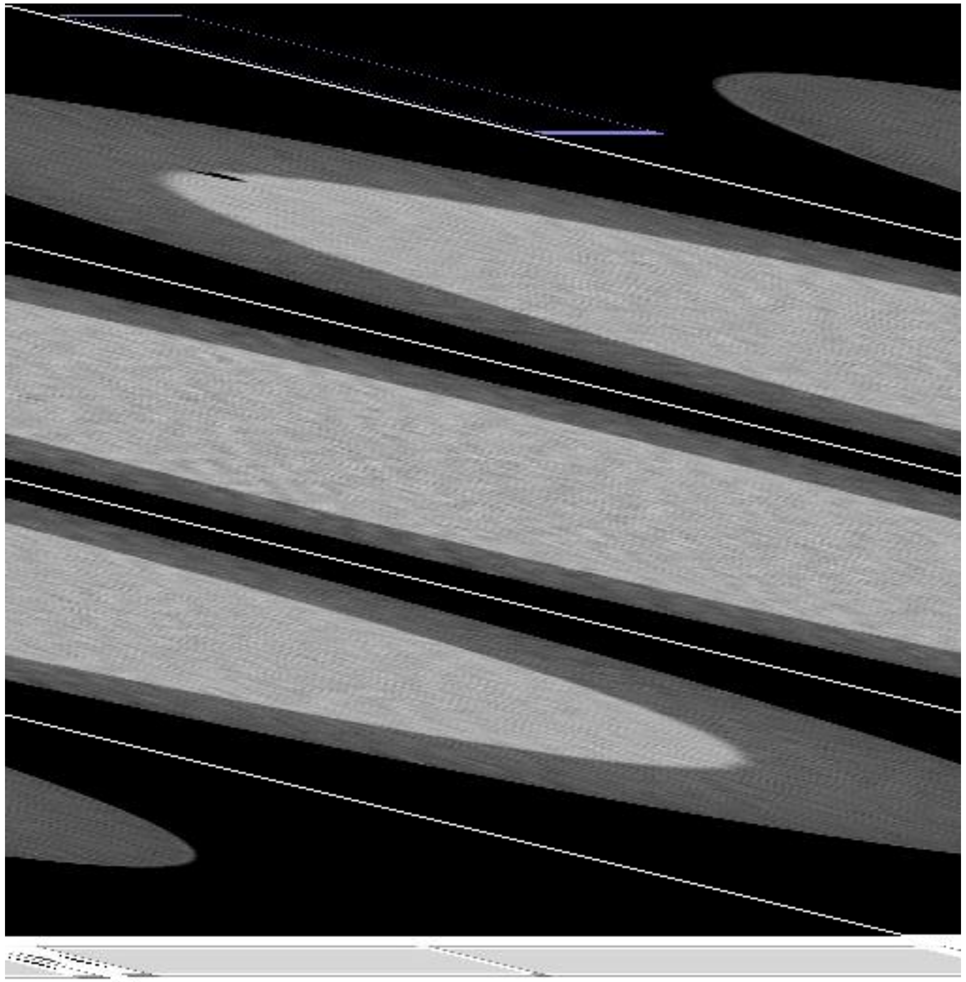

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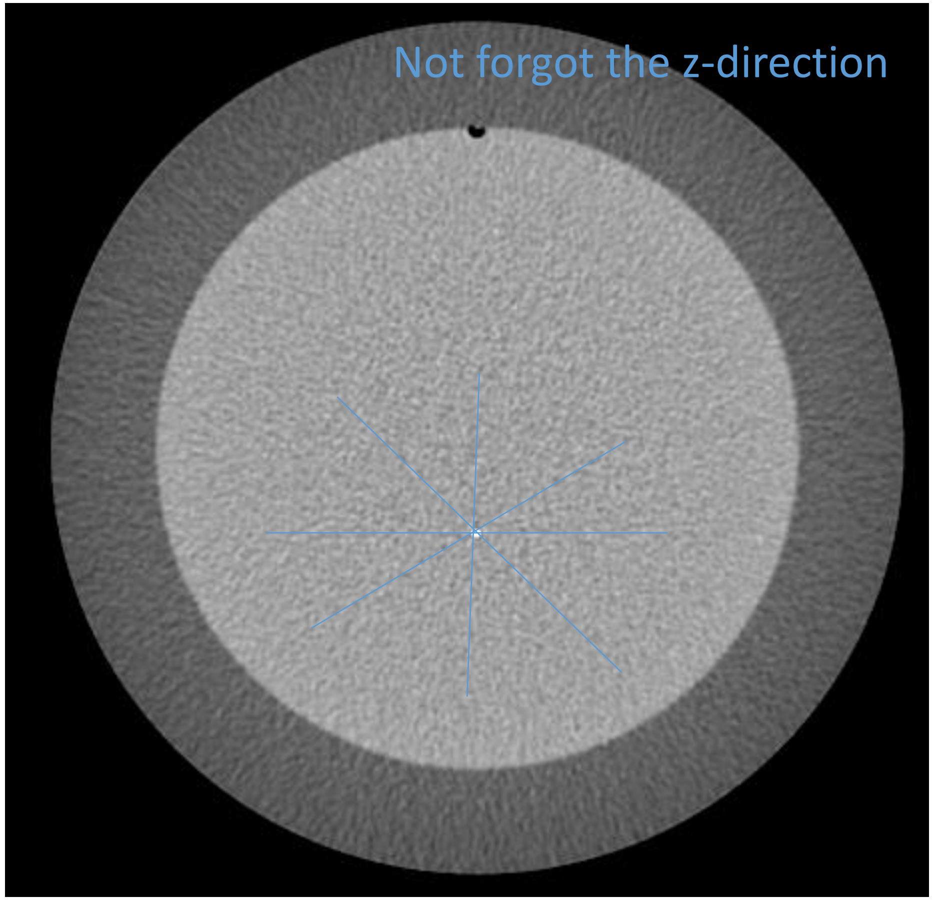
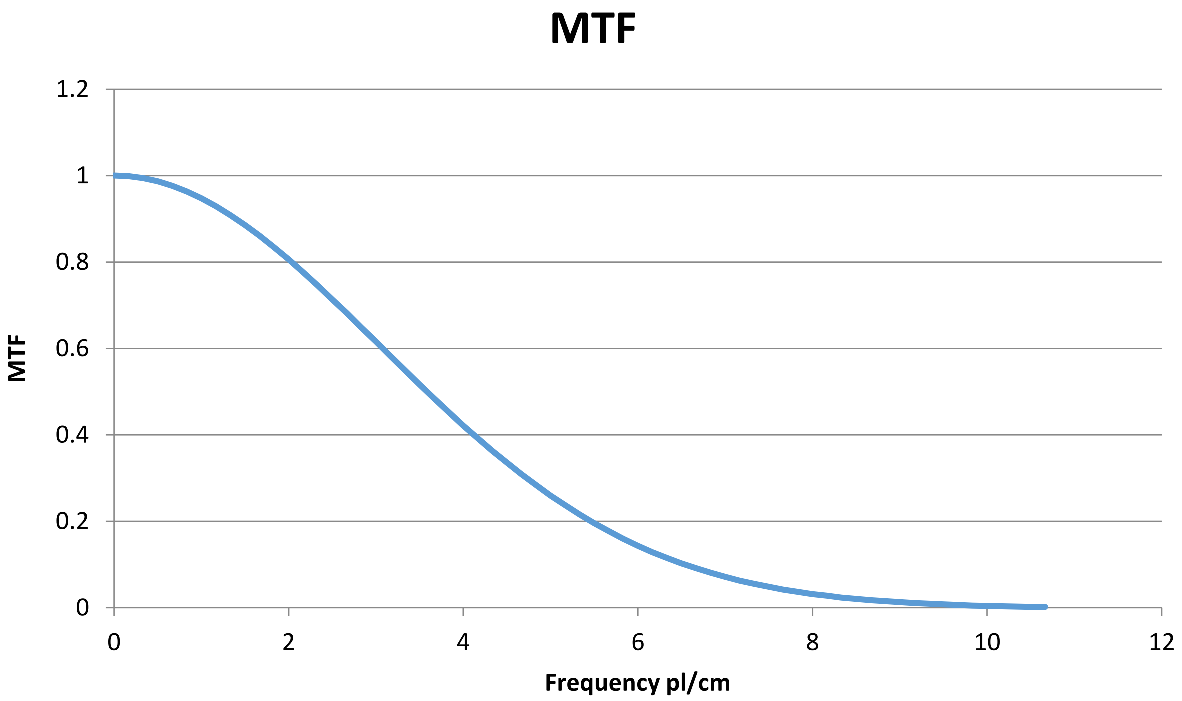


$$LSF_{\mathrm{axial}}(x) = \int_{z=-\infty}^{\infty} \int_{y=-\infty}^{\infty} PSF_{\mathrm{3D}}(x, y, z)\mathrm{d}y\mathrm{d}z.$$

Fourier Transform

$$MTF(f_{\mathrm{x}}) = \frac{\left| \int_{-\infty}^{\infty} LSF(x) \mathrm{e}^{-2\pi \mathrm{i} f_{\mathrm{x}} x} \, \mathrm{d}x \right|}{\int_{-\infty}^{\infty} LSF(x) \, \mathrm{d}x},$$

How to measure MTF in CT ?



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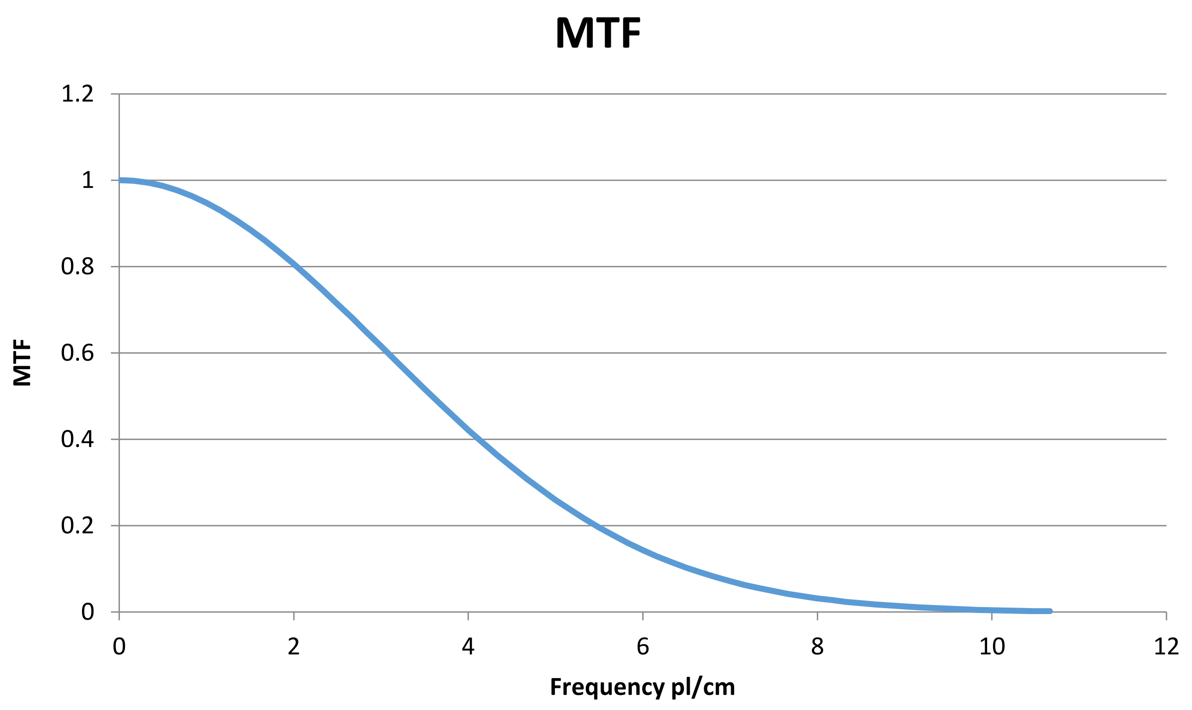
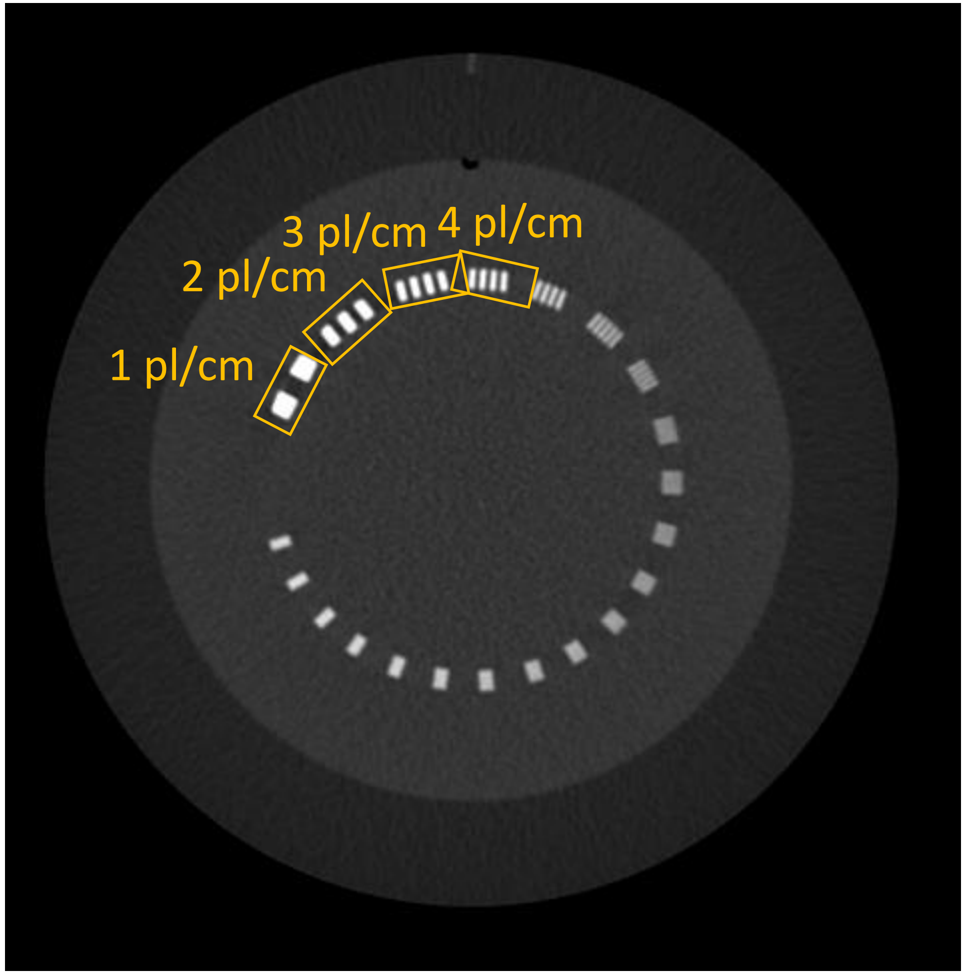
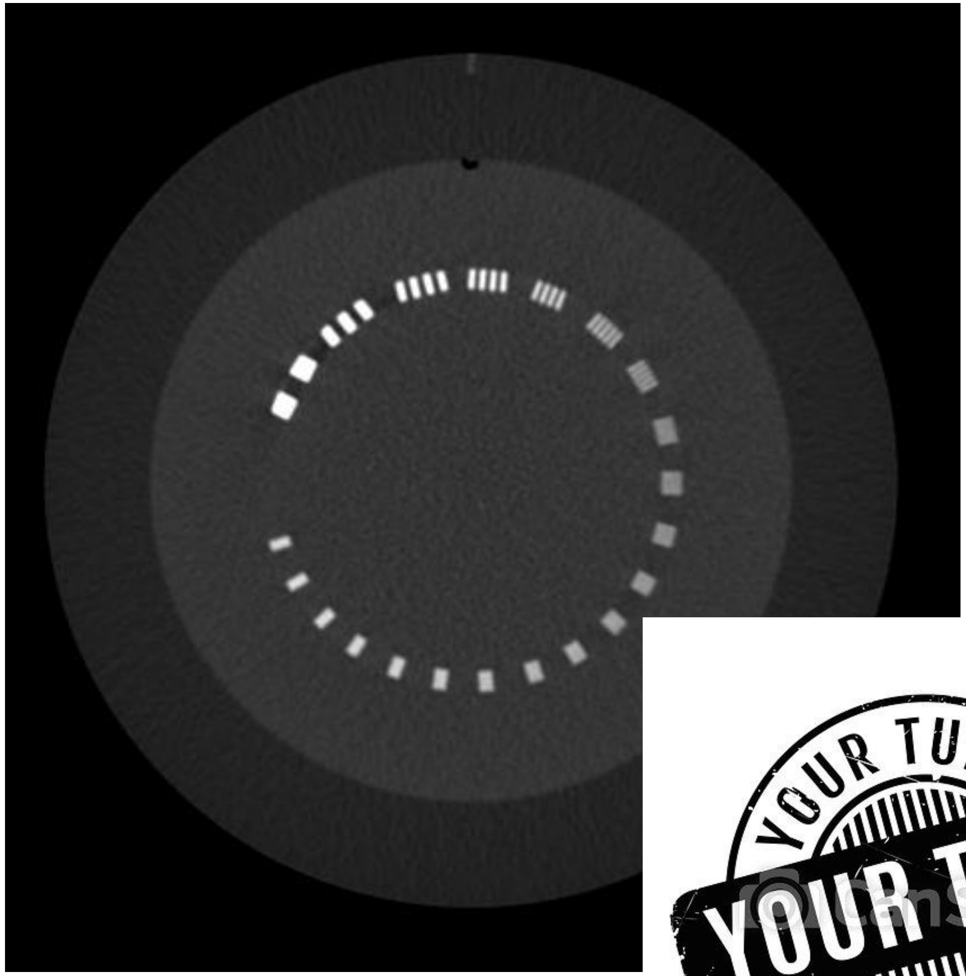




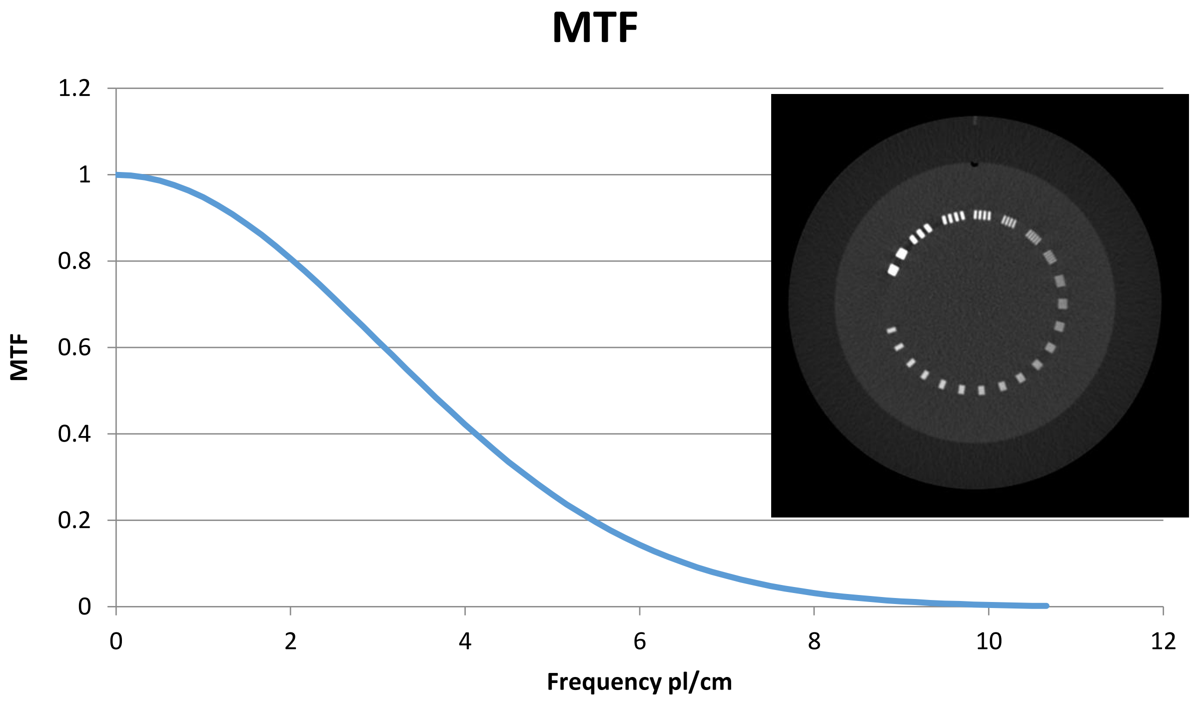
What is the limit of spatial resolution in this image ?

1. 4 pl/cm
2. 7 pl/cm
3. 10 pl/cm
4. 15 pl/cm



What is the limit of spatial resolution of the human eye (in terms of MTF)?

1. MTF 90%
2. MTF 50%
3. MTF 25%
4. MTF 10%



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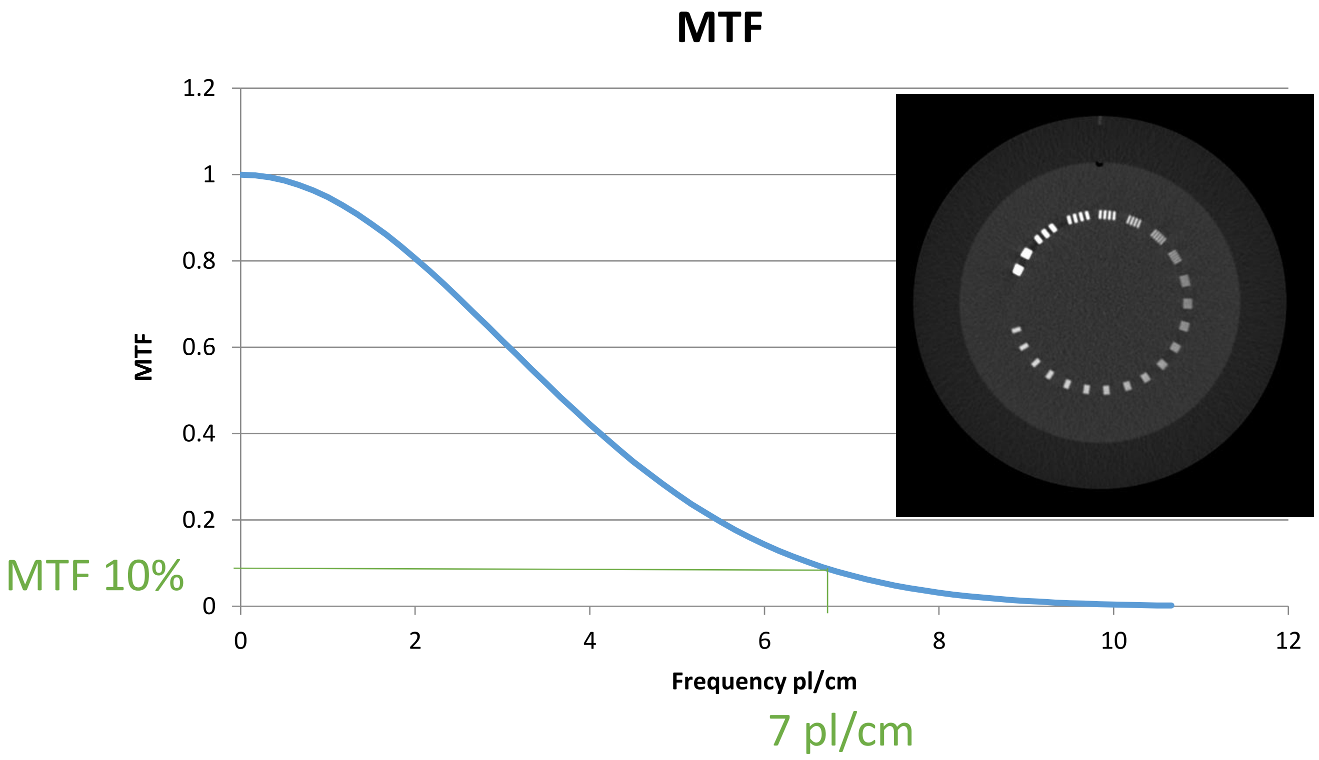
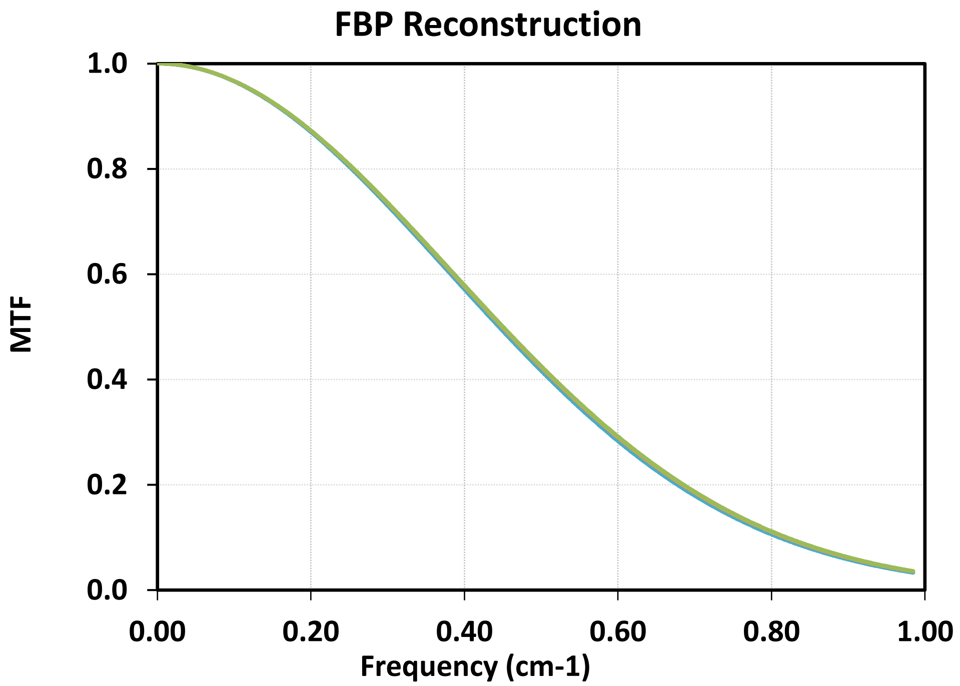
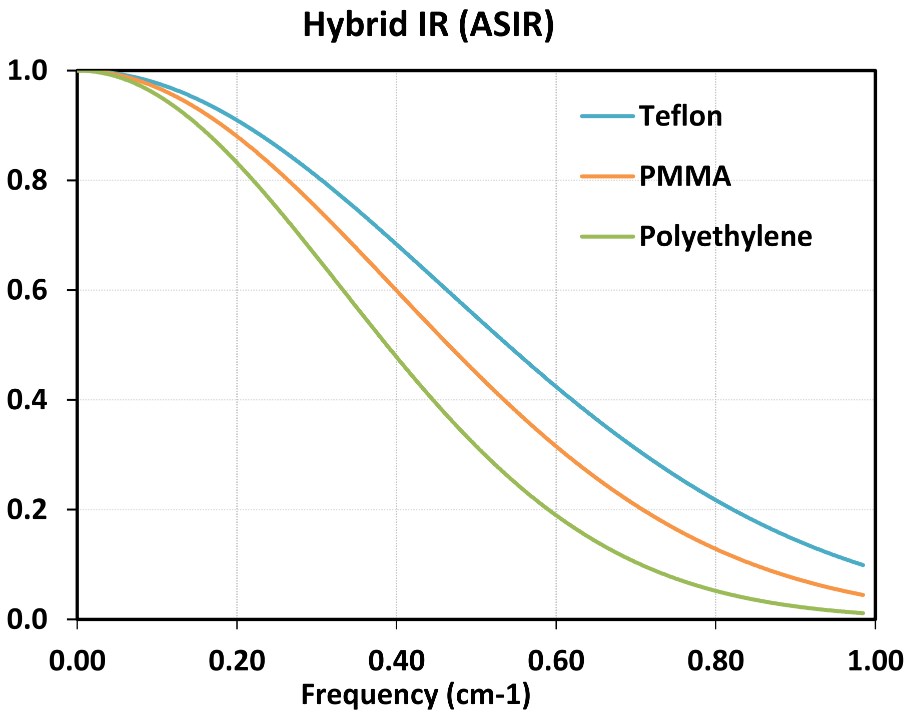


Limitation of MTF = Development of TTF (Target Transfer Function)

IR algorithms are known to be **highly non-linear** and to introduce a **dependency of the image contrast and noise on** the spatial resolution properties of the reconstructed images.

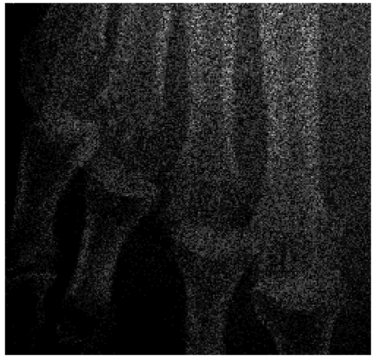




Reminder : The noise

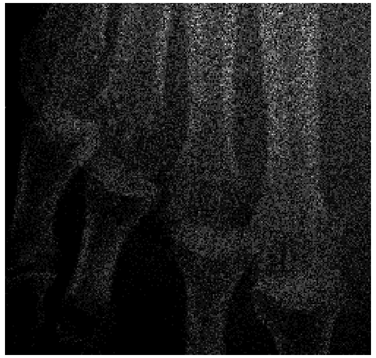
The various source of noise :

- **Quantum noise** decreases as the x-ray fluence increase
- **Structured noise** (slight pixel-to-pixel response variations in electronic-detector systems)
- **Electronic noise** (all electronic components)



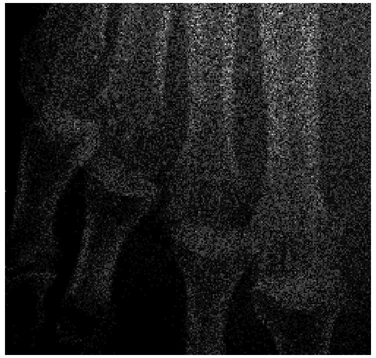
Which advanced metric characterize the noise ?

1. MTF
2. NPS
3. FFT
4. DQE

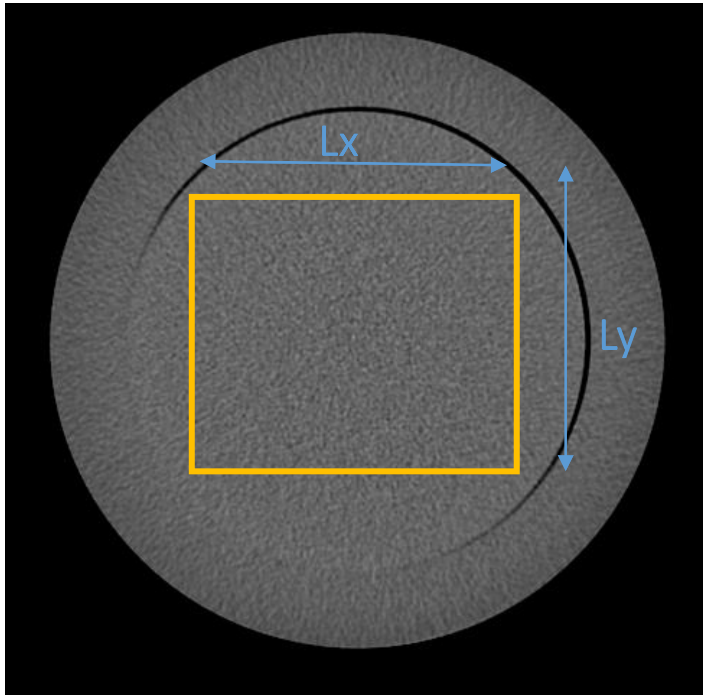


Which metric characterize the noise ?

1. MTF : Modulation transfer function
2. NPS : Noise Power Spectrum
3. FFT : Fast Fourier Transform
4. DQE : Detective Quantum efficiency



How to measure NPS in CT ?



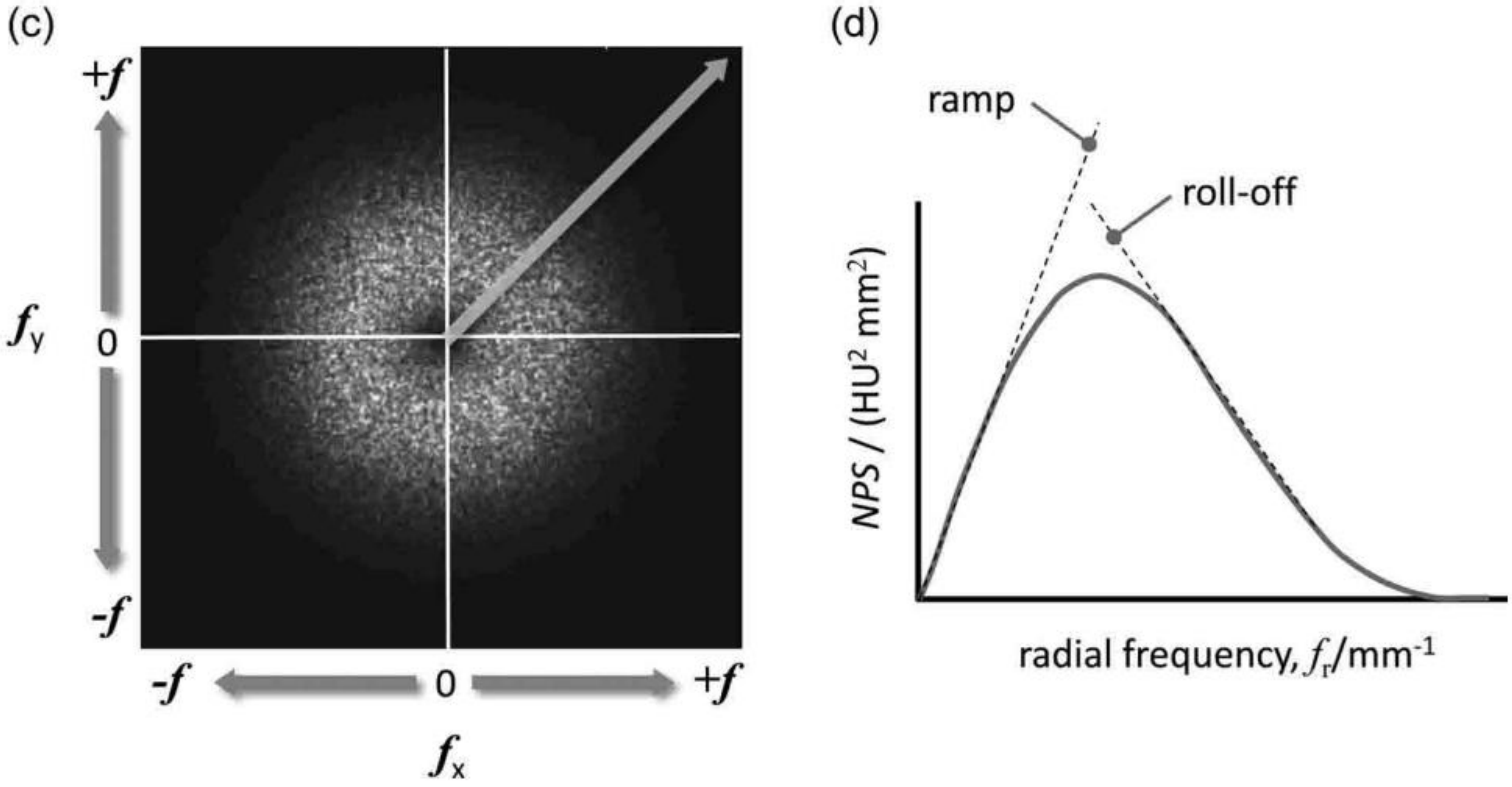
Pixel Size

mean pixel values of the ith ROI

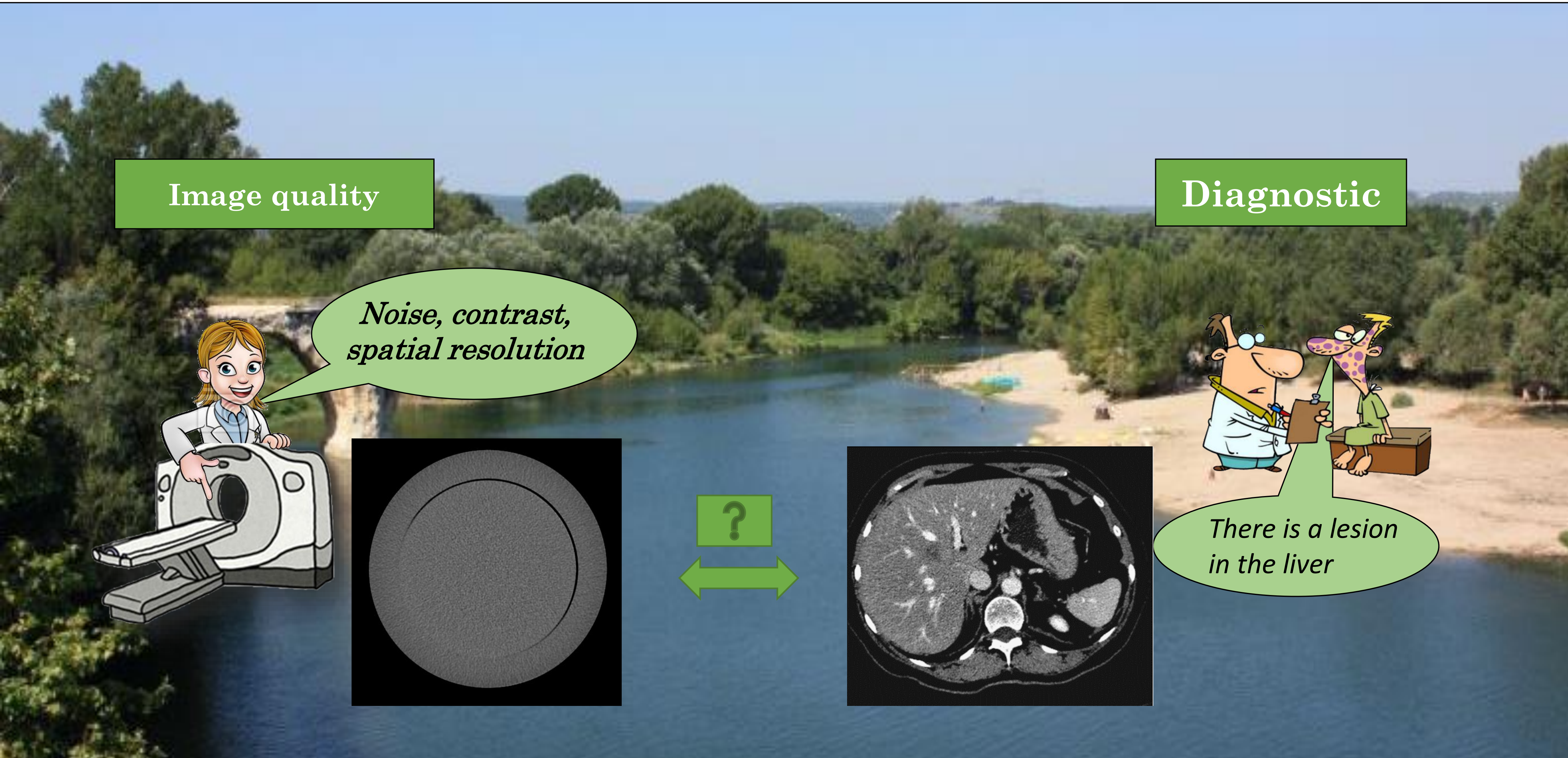
$$NPS_{2D}(f_x, f_y) = \frac{\Delta_x \Delta_y}{L_x L_y} \frac{1}{N_{ROI}} \sum_{i=1}^{N_{ROI}} |FT_{2D}\{ROI_i(x,y) - \overline{ROI_i}\}|^2$$

Number of ROIs

How to measure NPS in CT ?



Link between Image quality and detectability

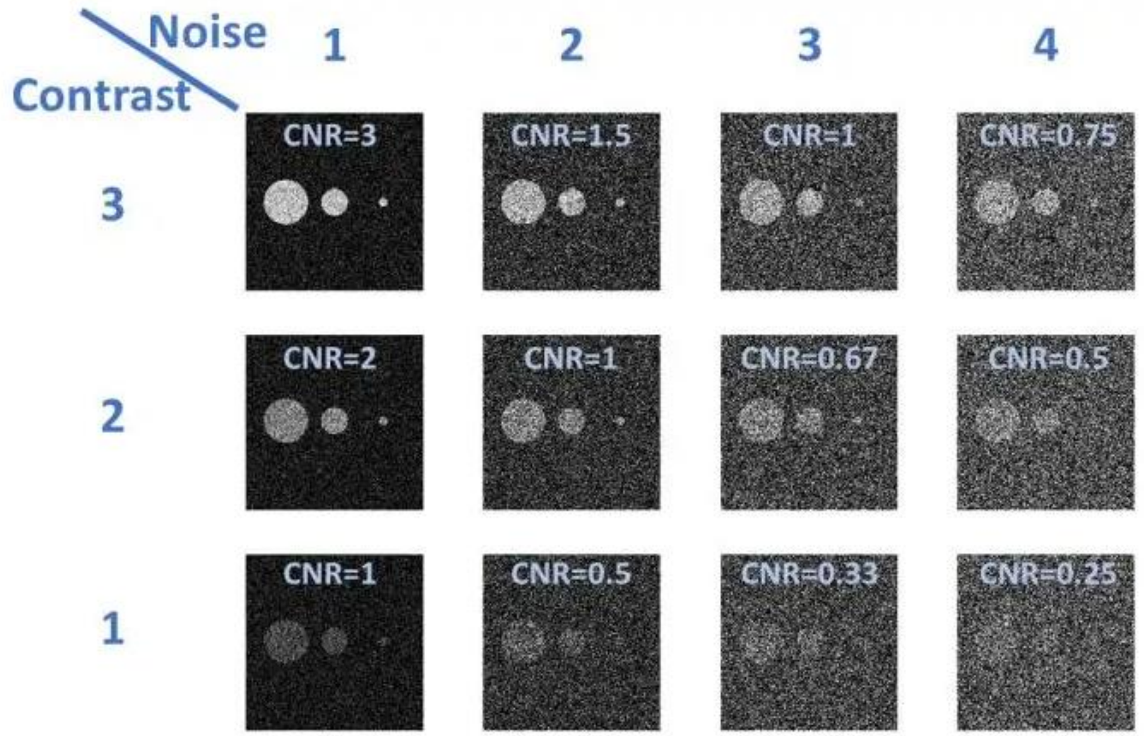


Link between Image quality and detectability

Before, lower was the contrast to noise ratio, harder was the detectability

$$C = |\overline{x_{ROI1}} - \overline{x_{ROI2}}|$$

$$CNR = \frac{|\overline{x_{ROI1}} - \overline{x_{ROI2}}|}{\sqrt{\frac{\sigma_{ROI1}^2 + \sigma_{ROI2}^2}{2}}}$$

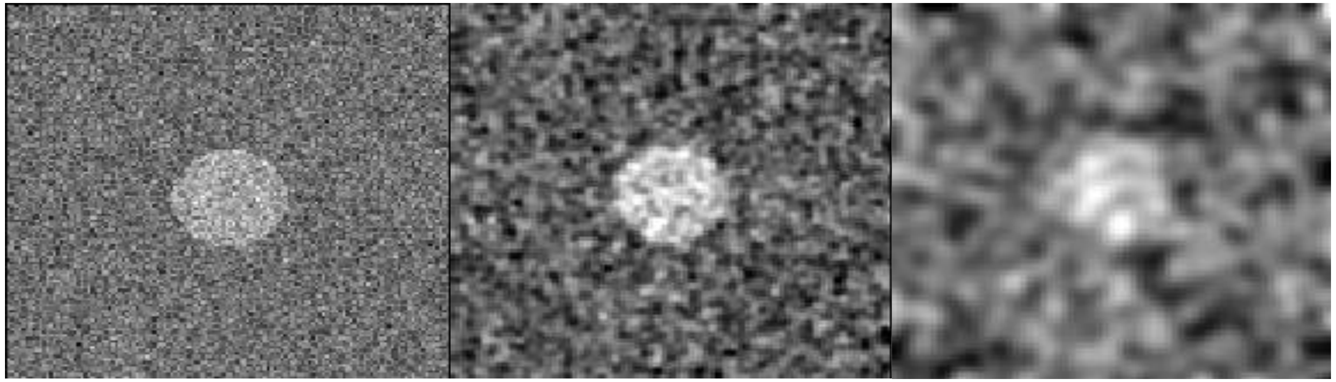


Link between Image quality and detectability

Before, lower was the contrast to noise ratio, harder was the detectability

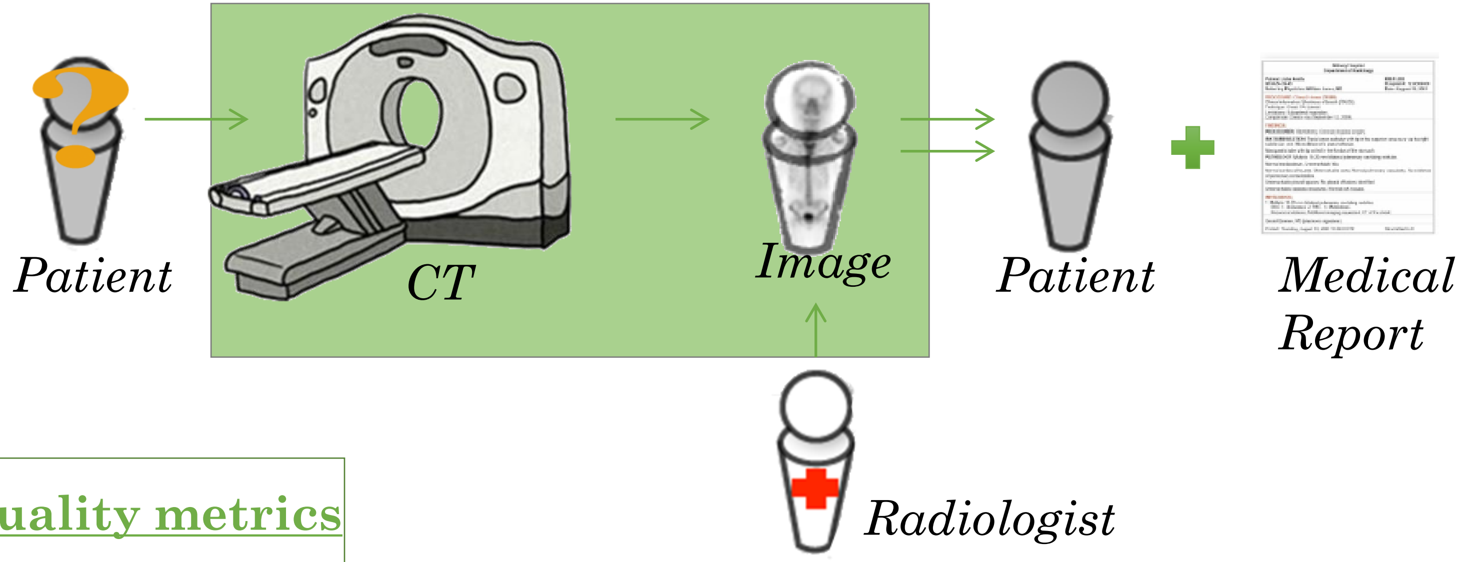
Condition : Sytem is linear and spatially invariant

Not the case in CT



Same CNR, different detectablity (various kernel)

Link between Image quality and detectability



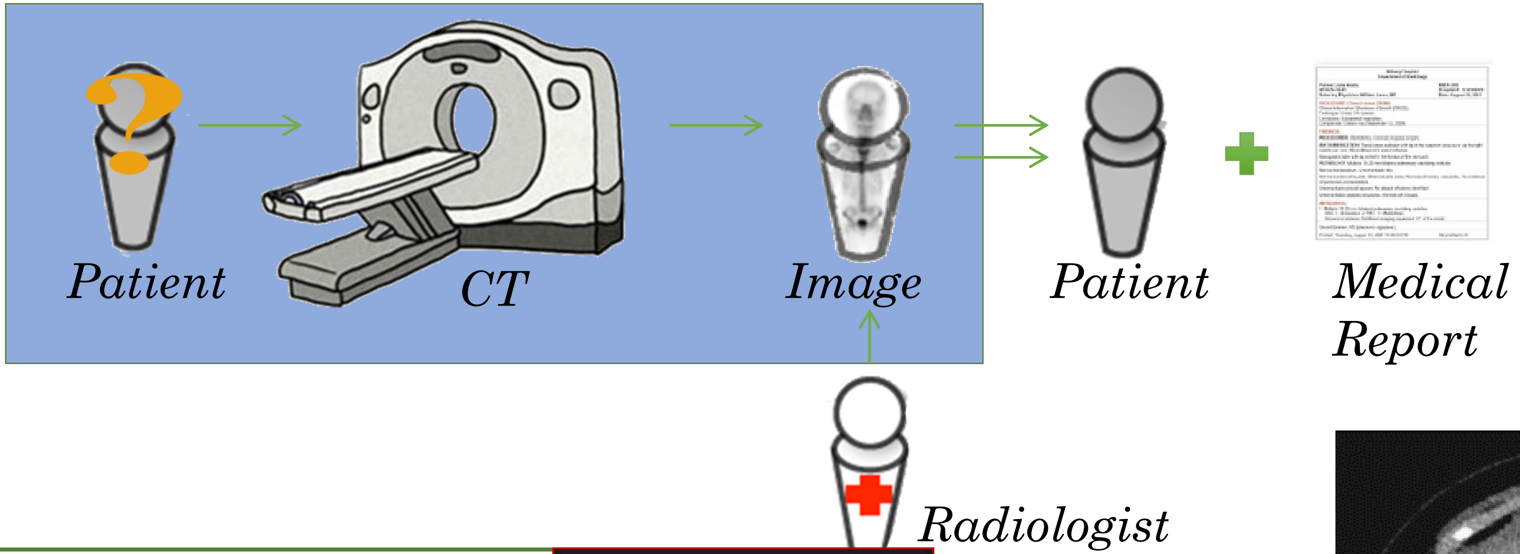
Standard Image quality metrics

Noise

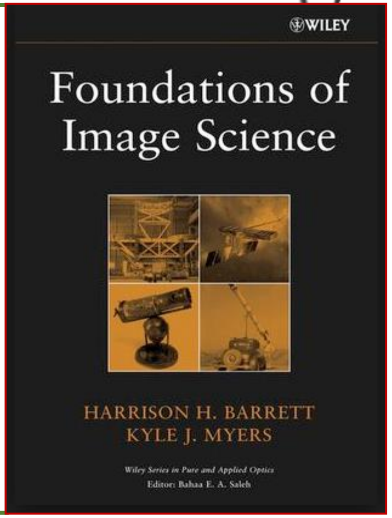
Spatial resolution

Contrast

Link between Image quality and detectability



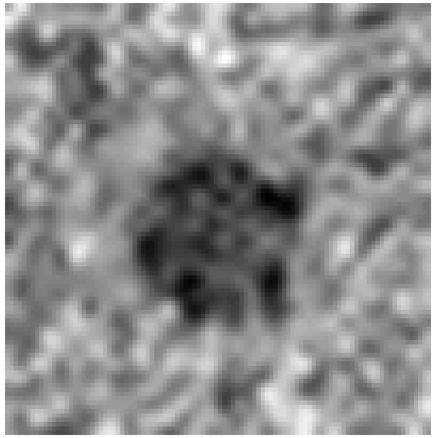
1. Define the **clinical question**
2. Translate to **clinical task**
3. Find **observers** to quantify the task: humans or mathematics

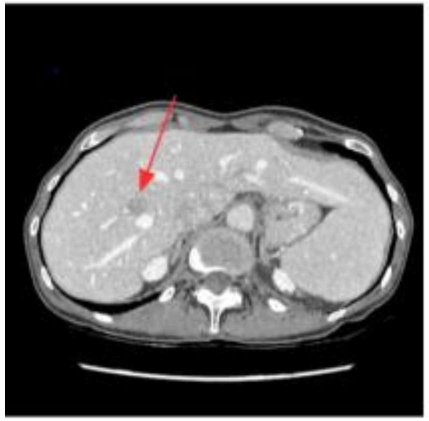


Link between Image quality and detectability

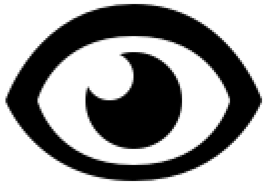
2. Find the clinical zask

Detection of low contrast signal in a noisy environement





Link between Image quality and detectability

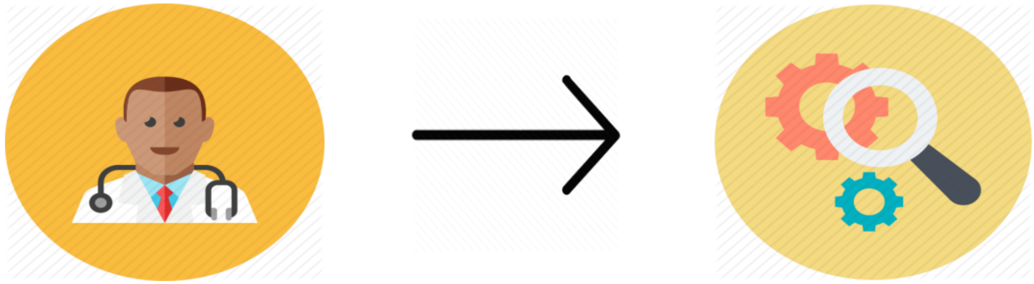


3. Find observers to quantify the task

The reference is obtained from **human observers clinical studies**

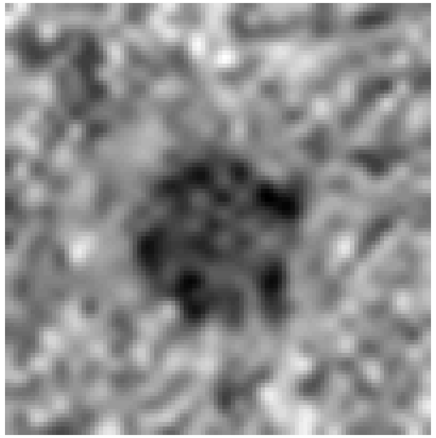
Time consuming
Subjective
Difficult to generalize

The use of mathematical observer is an alternative



What is a mathematical model observer ?

To account for and quantify the **combined effects of contrast, noise, and spatial resolution** for a specific clinical task (generally simple, **signal-known-exactly/background-known-exactly**)



What is a mathematical model observer ?

There is **two types** of mathematical observer :

The ideal observer : A model observer that **extracts as much** statistical **information as possible** from the images

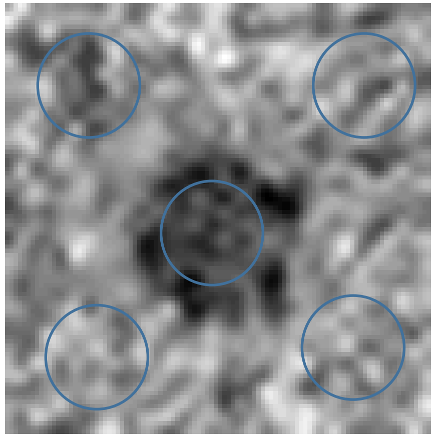
The anthropomorphic observer : A model that **mimics human-observer** performance

What is a mathematical model observer ?

The ideal observer (PW) : Computation of the detectability (d') of simaulated lesions

$$d'_{PW} = \sqrt{2\pi}\Delta HU \sqrt{\int_0^{f_{ny}} \frac{S^2(f)TTF^2(f)}{NPS(f)} f df}$$

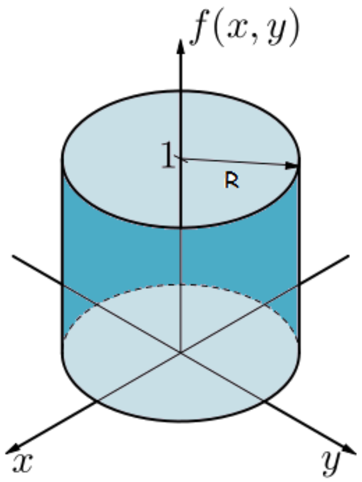
ΔHU = Contrast of the lesion (can be a theoretical value or measured value on phantom images)



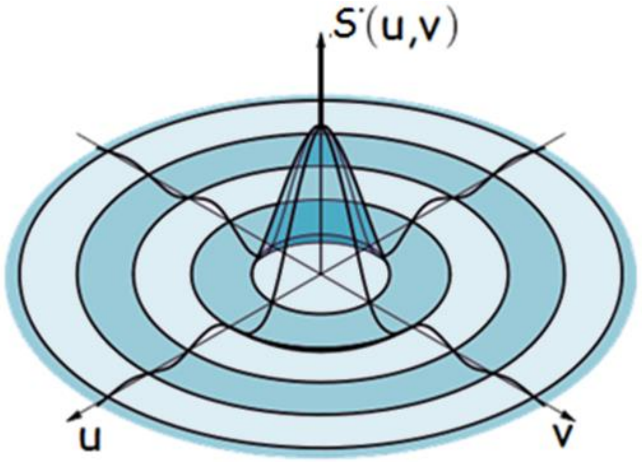
What is a mathematical model observer ?

The ideal observer

$$d'_{PW} = \sqrt{2\pi}\Delta HU \sqrt{\int_0^{f_{ny}} \frac{S^2(f)TTF^2(f)}{NPS(f)} f df}$$



Fourier Transform



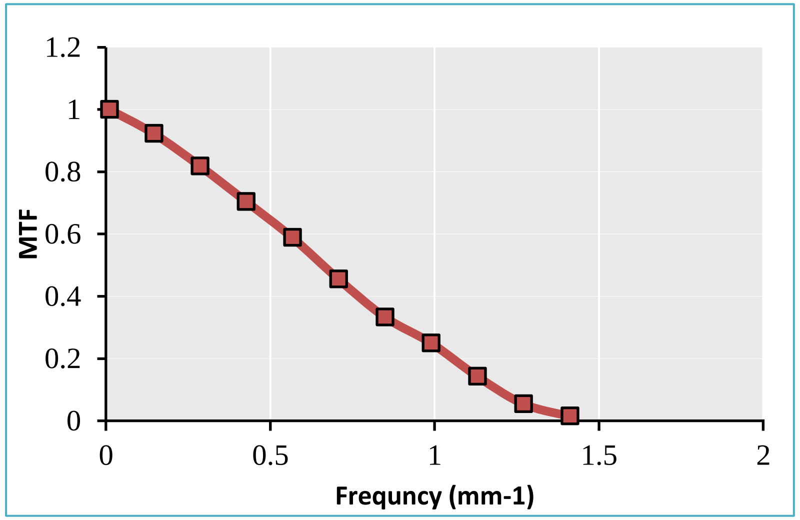
Simulated lesion (the task):
cylinder, radius R

What is a mathematical model observer ?

The ideal observer

$$d'_{PW} = \sqrt{2\pi}\Delta HU \sqrt{\int_0^{f_{ny}} \frac{S^2(f)\boldsymbol{TTF^2(f)}}{NPS(f)} f df}$$

MTF= Spatial resolution of the CT under investigation (for a specific protocol)

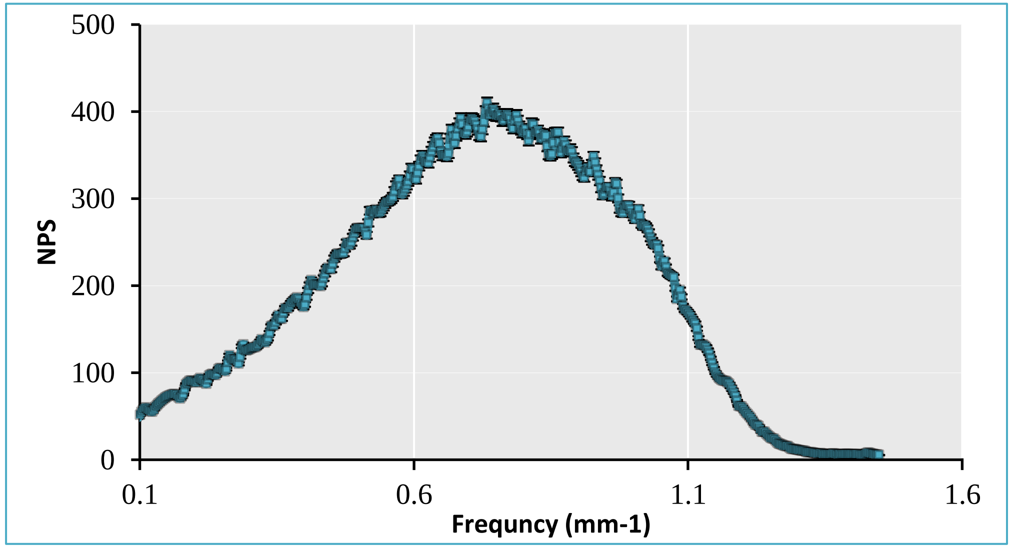


What is a mathematical model observer ?

The ideal observer

$$d'_{PW} = \sqrt{2\pi}\Delta HU \sqrt{\int_0^{f_{ny}} \frac{S^2(f)MTF^2(f)}{\boldsymbol{NPS(f)}} f df}$$

NPS= Noise of the CT under inverstigation (for a specific protocol, dose, slice thickness, kernel)

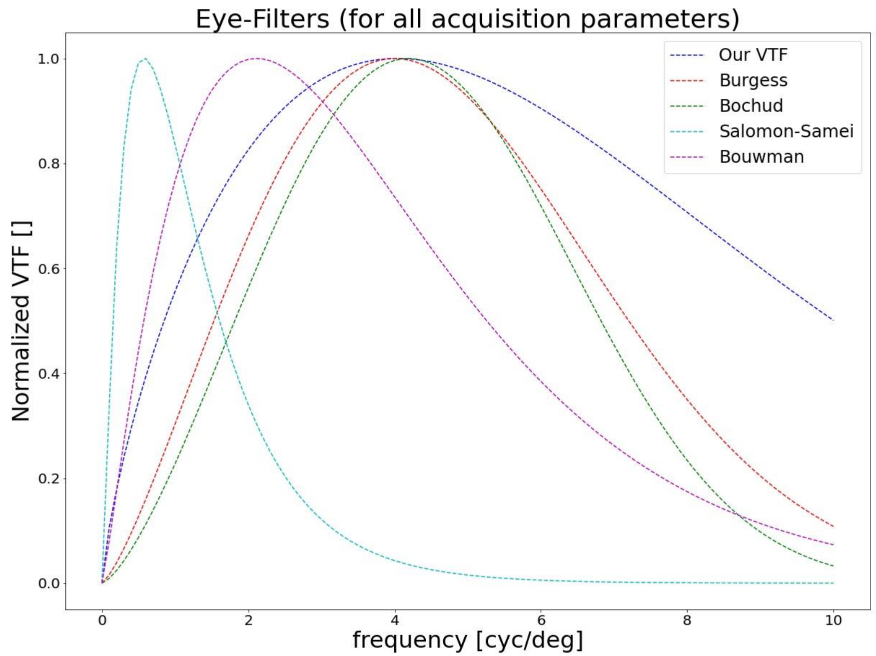


What is a mathematical model observer ?

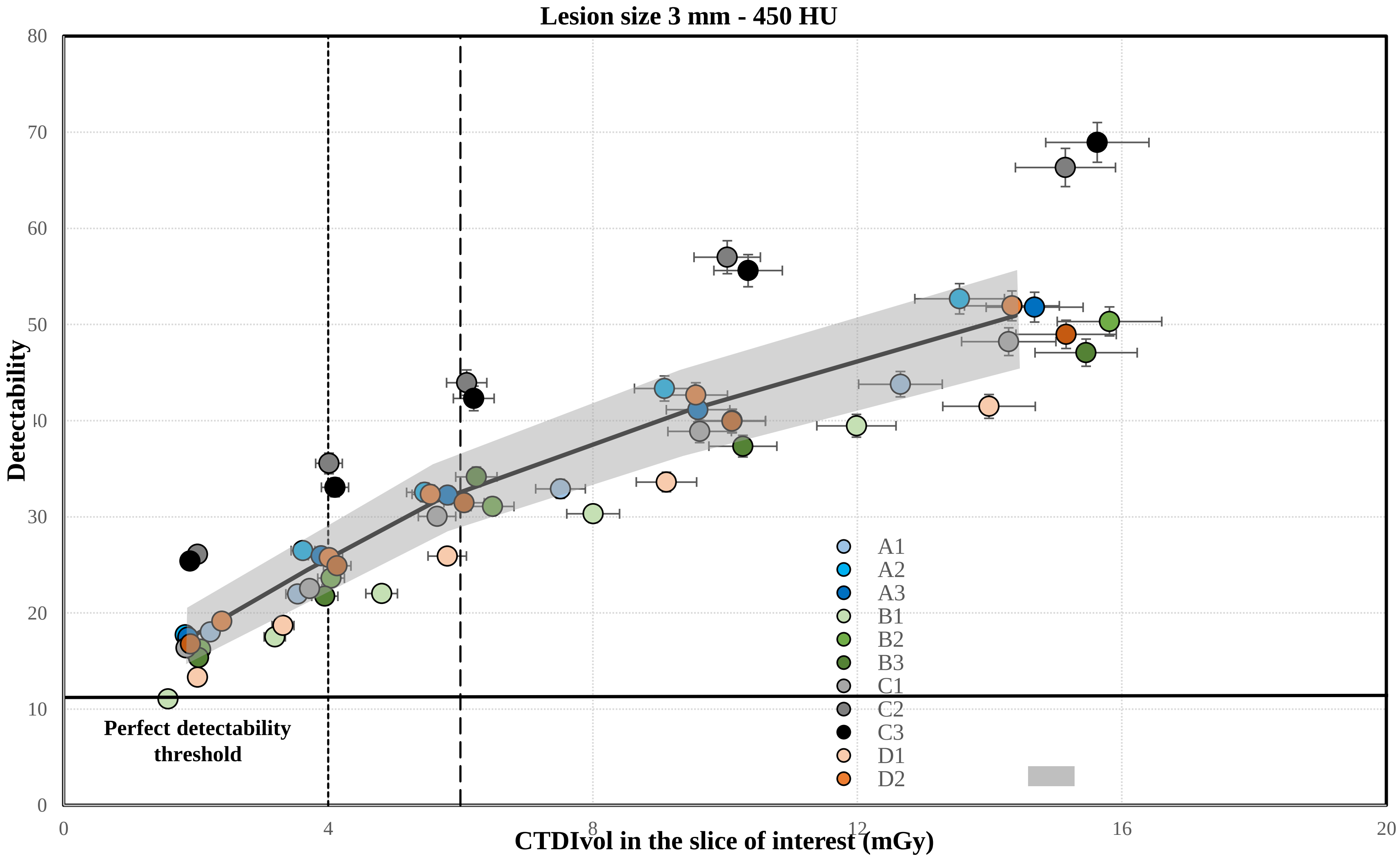
The anthropomorphic observer

$$d'_{NPWE} = \frac{\sqrt{2\pi}\,|\Delta HU|\int_0^{t_{Ny}} S(t)^2 \cdot TTF(t)^2 \boxed{E(t)}^2 t dt}{\sqrt{\int_0^{t_{Ny}} S(r)^2 \cdot TTF(t)^2 \cdot NPS(t)E(t)^4 t dt}}$$

E is an eye-filter to emulate the spatial frequency capabilities of the human eye.



Example : Lesion detectability for 12 CTs as a function of dose level



Exercice

A new CT system was installed in your hospital (to replace the old one), the engineer of the CT company performs all the quality control tests to ensure that the CT is ready to use.

After 15 days of clinical use, the radiologist calls you and explains that the old CT was clearly better, liver images are really bad and he can’t see anything.

What do you do ?

BREAK – 15 min

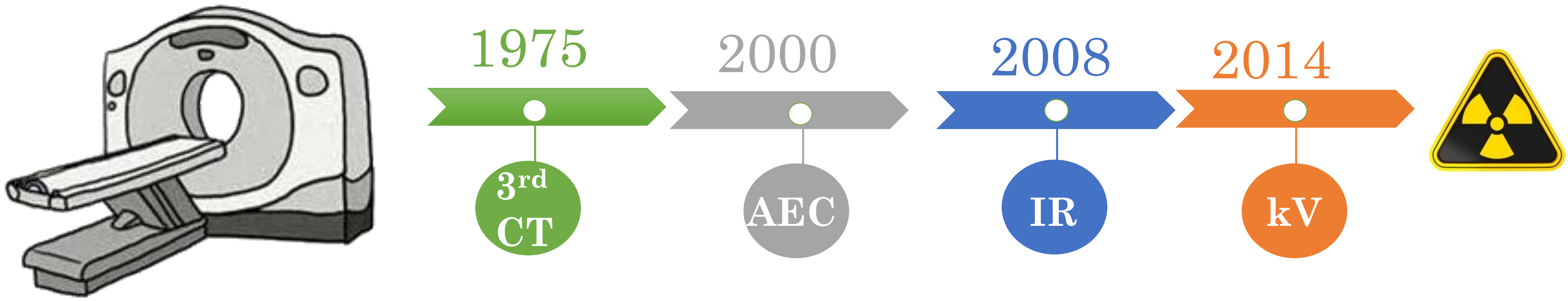
Content of the lecture today

- Image quality in CT – Advanced metrics (1h)
  - Link between human observers behaviour and physical image quality metrics

- **The last technologies in CT nowadays (1h15) :**
  - **Dual-Energy CT**
    - **Motivations for dual-energy CT**
    - **Dual-energy CT techniques**

  - Photon-Counting CT
    - Motivations for photon-counting CT
    - New detectors

The last technologies in CT

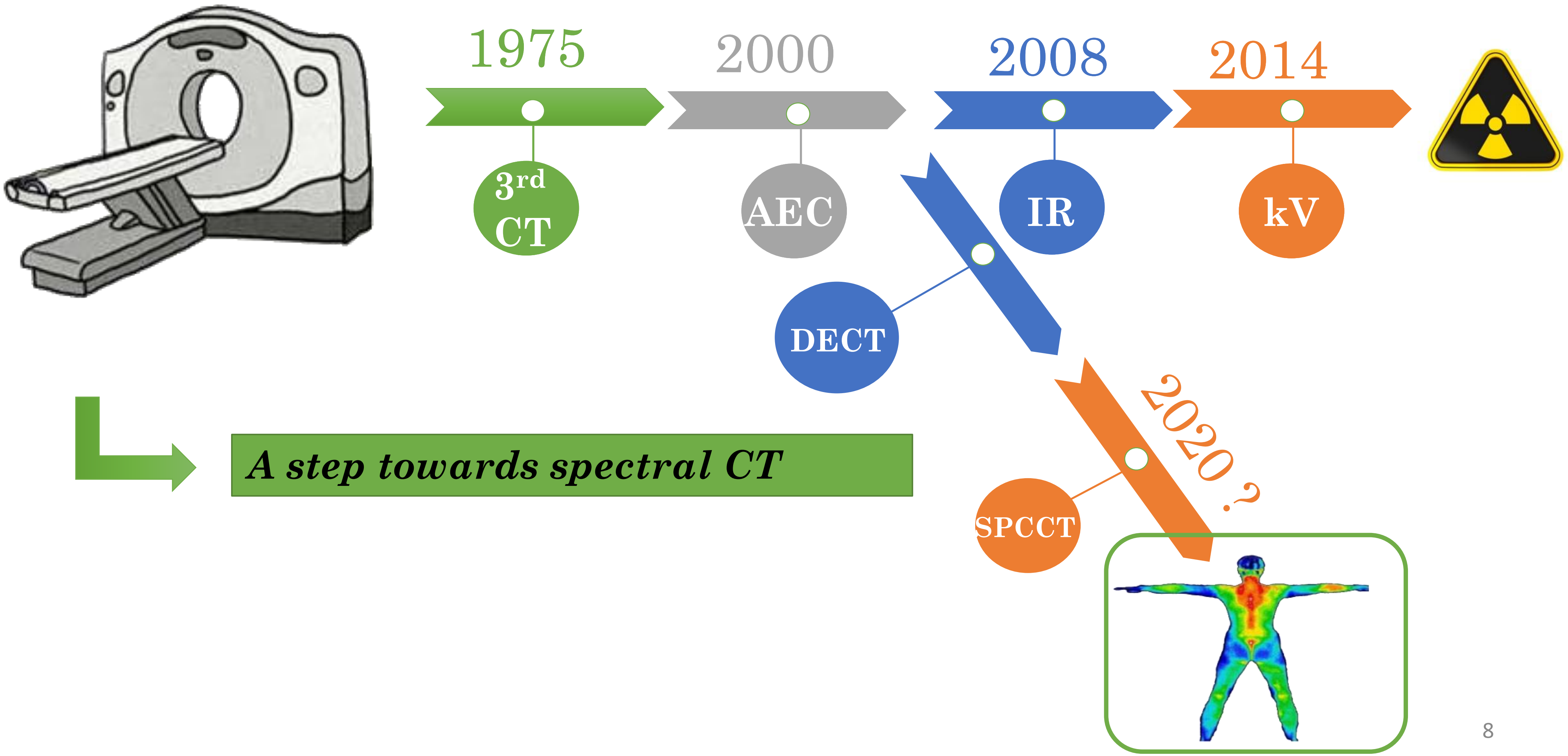


A technical race to reduce the dose level

Reminder : AEC what is it ?

1. A system ensuring that every patient receive the same dose
2. A system controlling that the same current is set for every patient
3. A system adapting the current as a function of patient size
4. A system adapting the current as a function of CT localization

The last technologies in CT



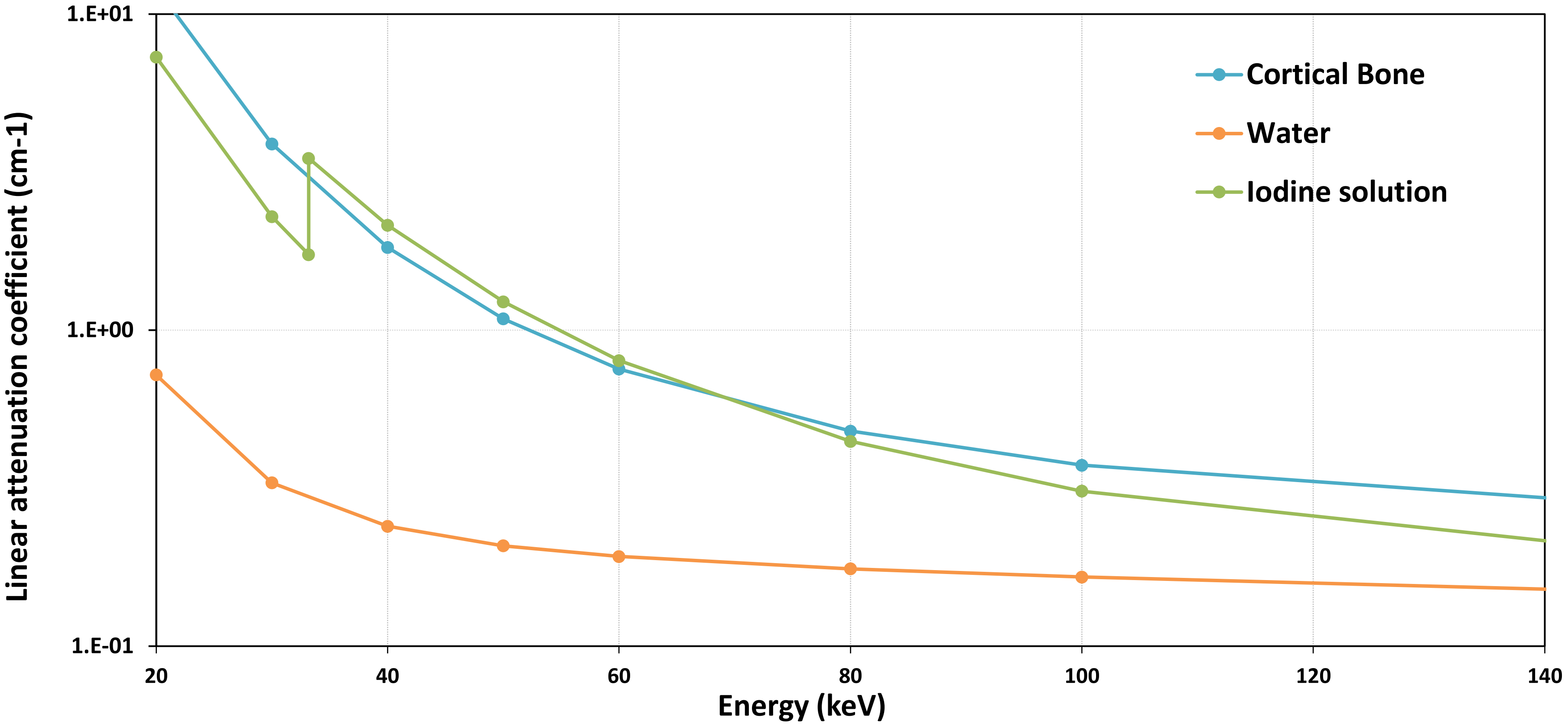
Motivations for spectral CT

1. X-ray tissue attenuation (HU number) in CT depends on :
    1. ..
    2. ..
    3. ..

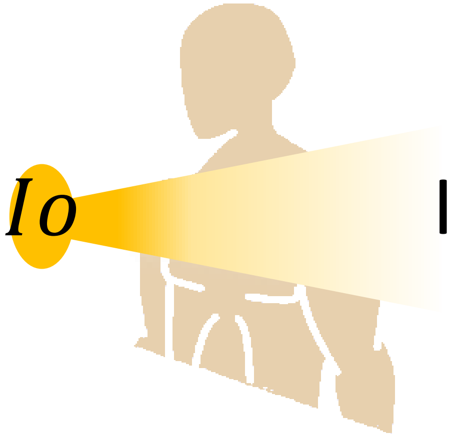
Motivations for spectral CT

1. X-ray tissue attenuation (HU number) depends on

- **Effective energy** of the polychromatic X-ray beam (keV)
- **Material density** (ρ, g/cm^3)
- Material composition (Effective Z, **Zeff**)

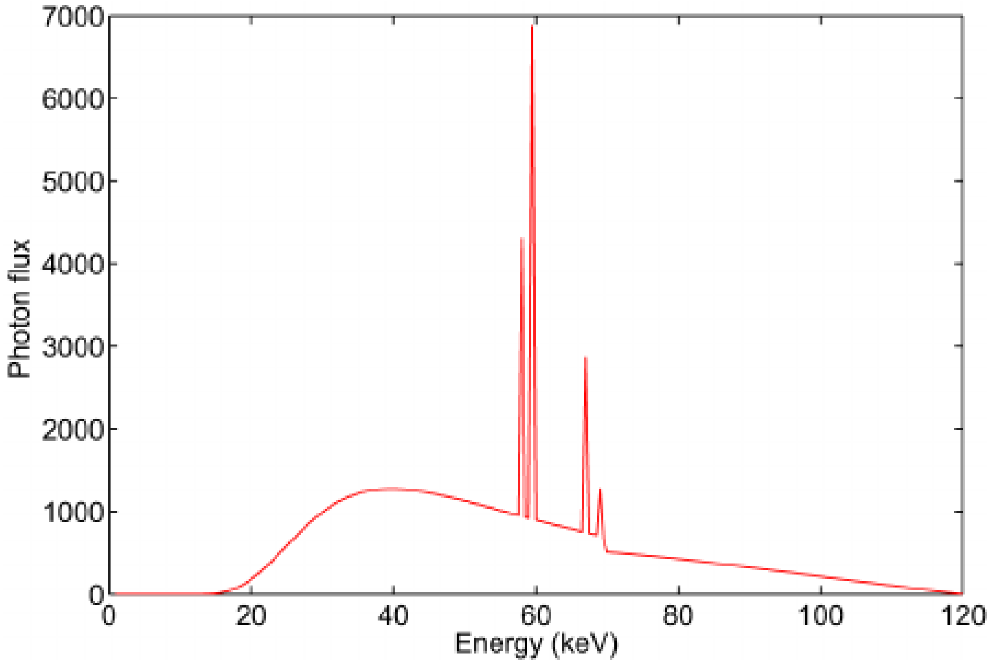


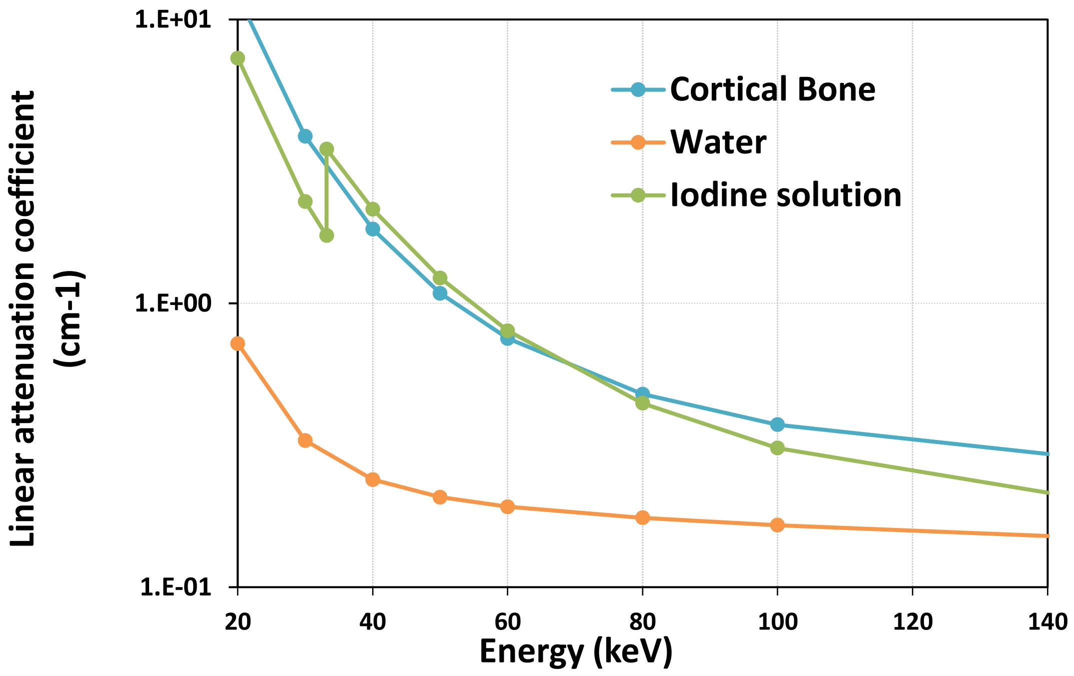
The main principal behind spectral CT



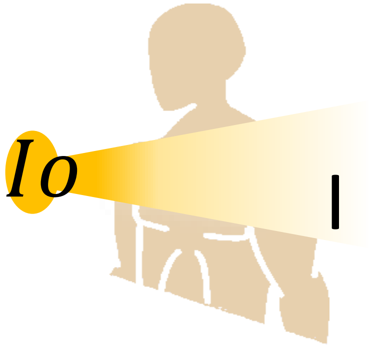
$$I = \int_E Io(E)e^{-\int_l \mu(E,l)dl} dE$$

Attenuation of X-ray beam after a length l of tissue

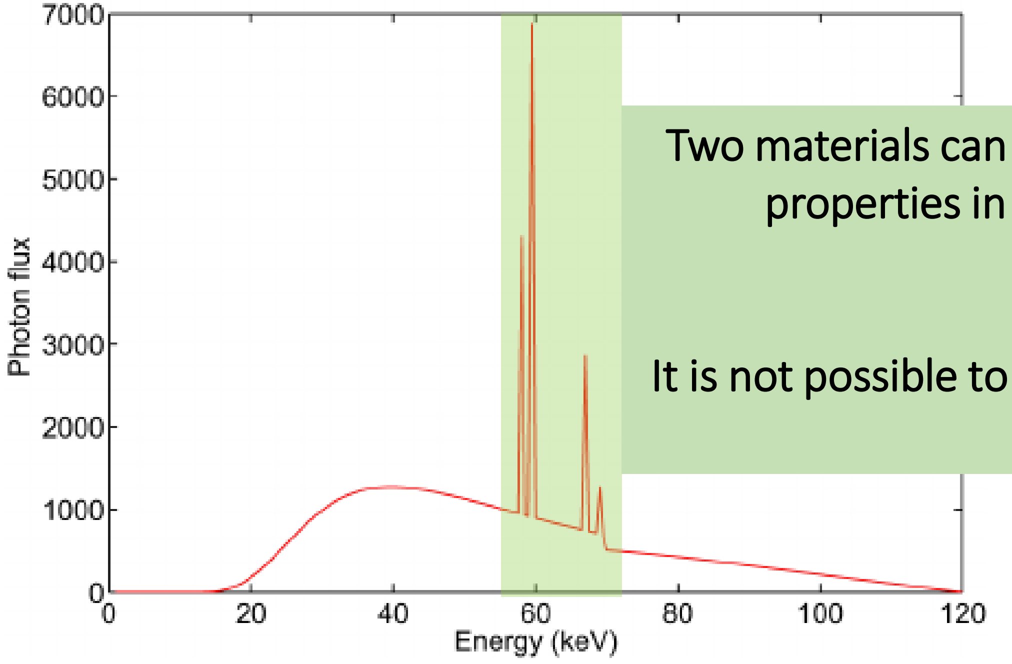




The main principal behind spectral CT

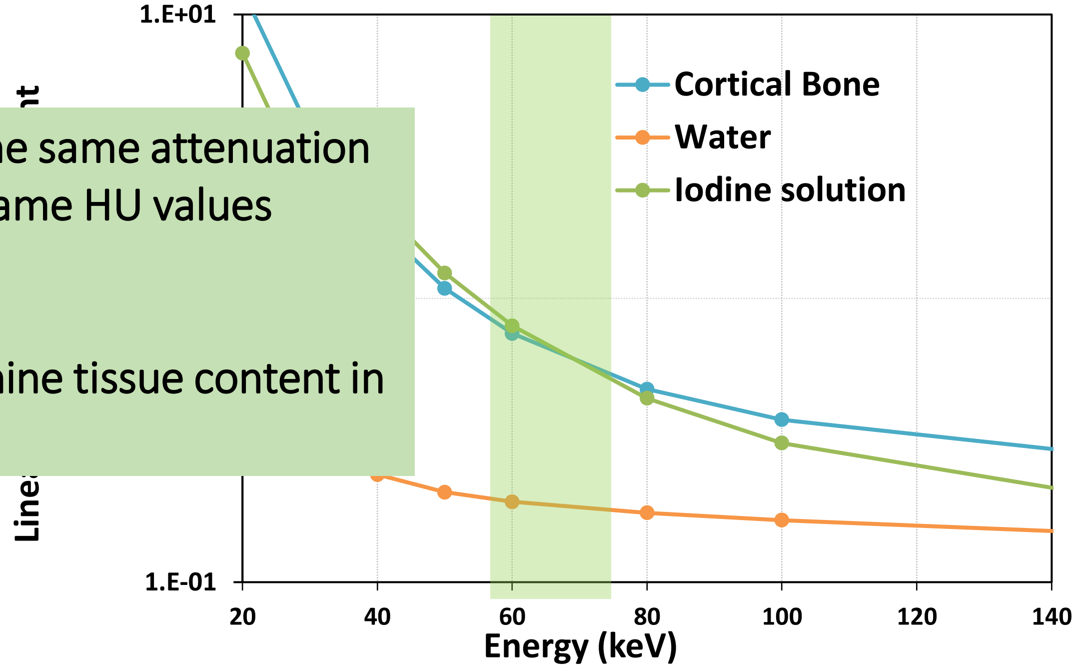


$$I = \int_E Io(E)e^{-\int_l \mu(E,l)dl}dE$$

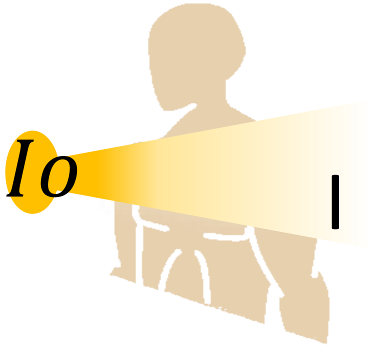


Two materials can have the same attenuation properties in CT -> same HU values

It is not possible to determine tissue content in CT

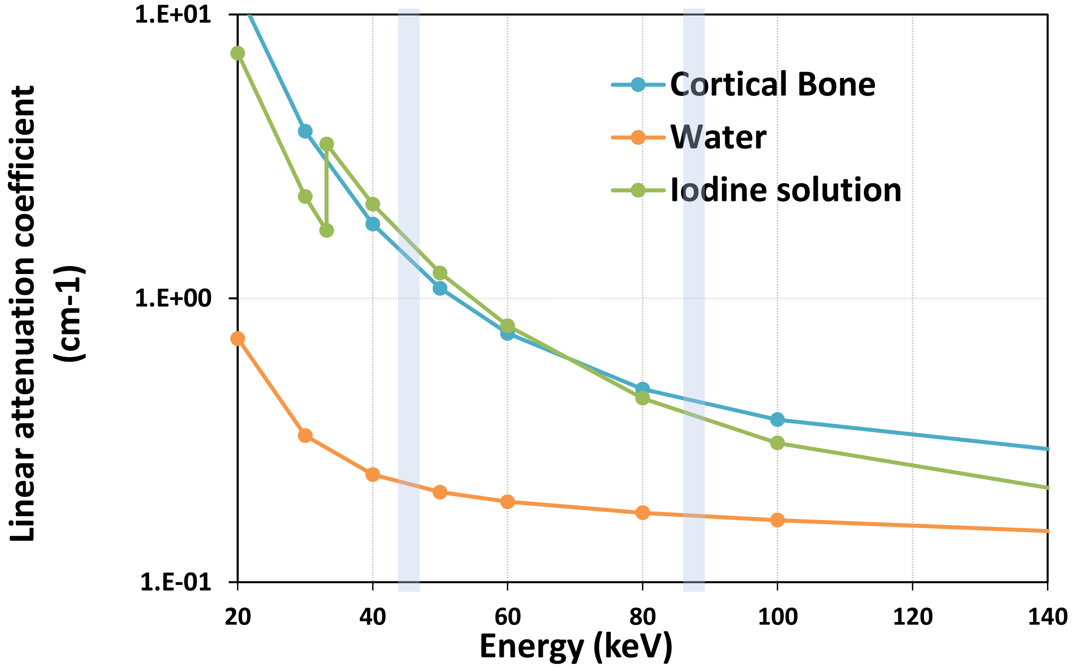


The main principal behind spectral CT

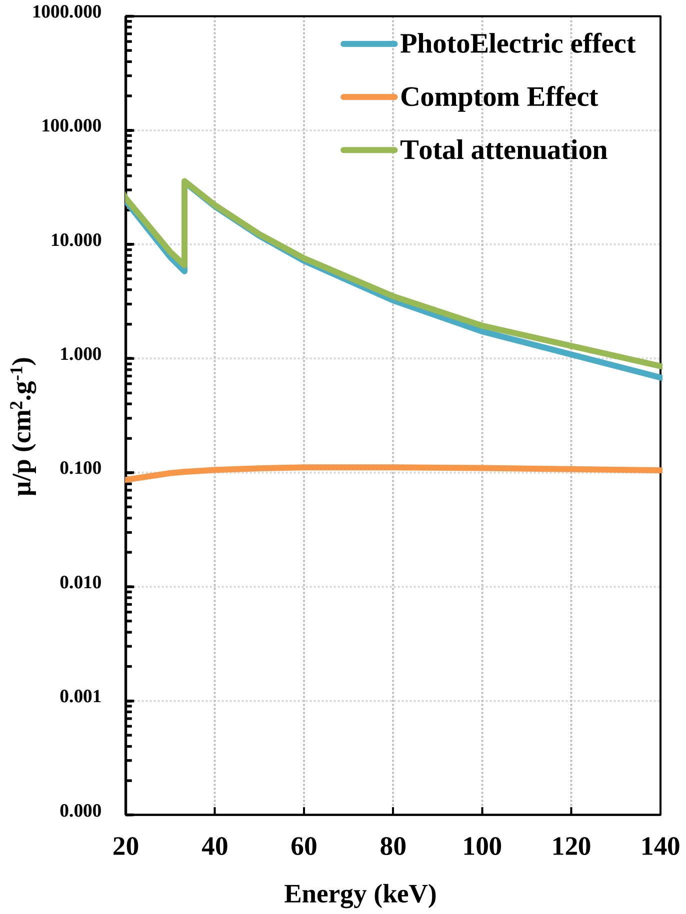


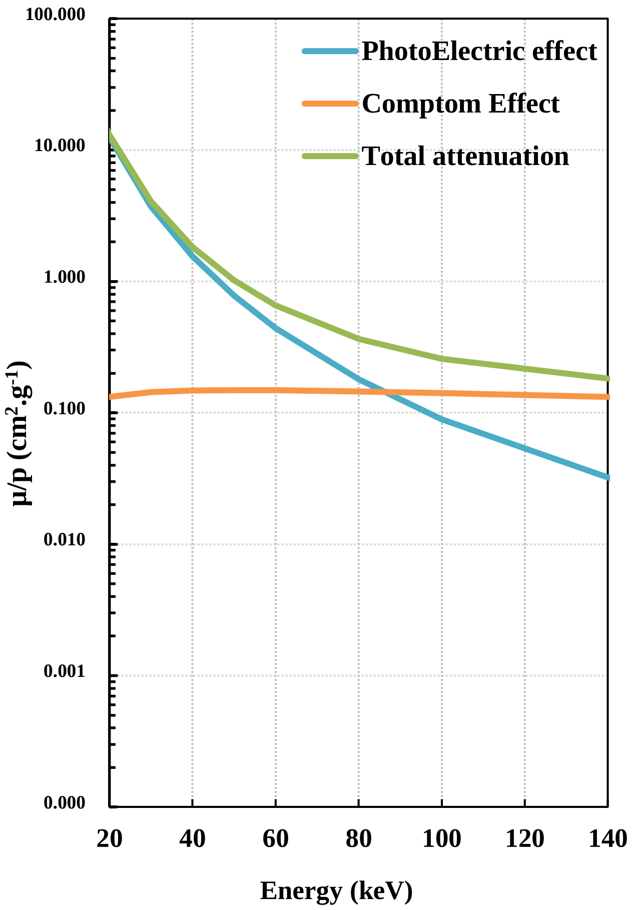
$$I = \int_E Io(E) e^{-\int_l \mu(E,l)dl} dE$$

Solution : use two energy levels to discriminate materials



Which figure corresponds to Iodine (Z=53) ? and Calcium (Z=20) ?

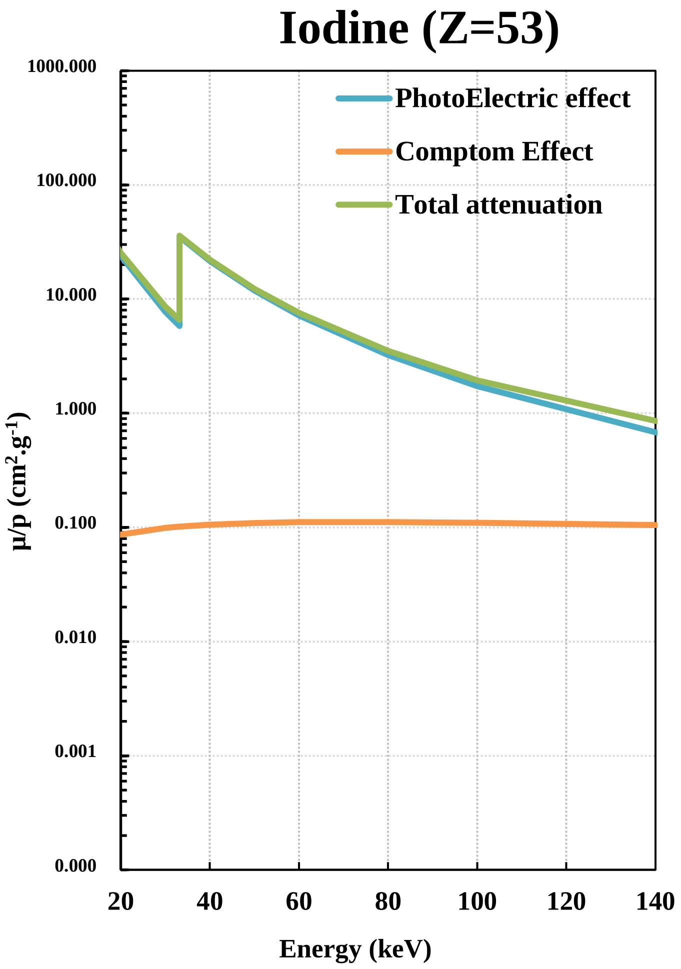


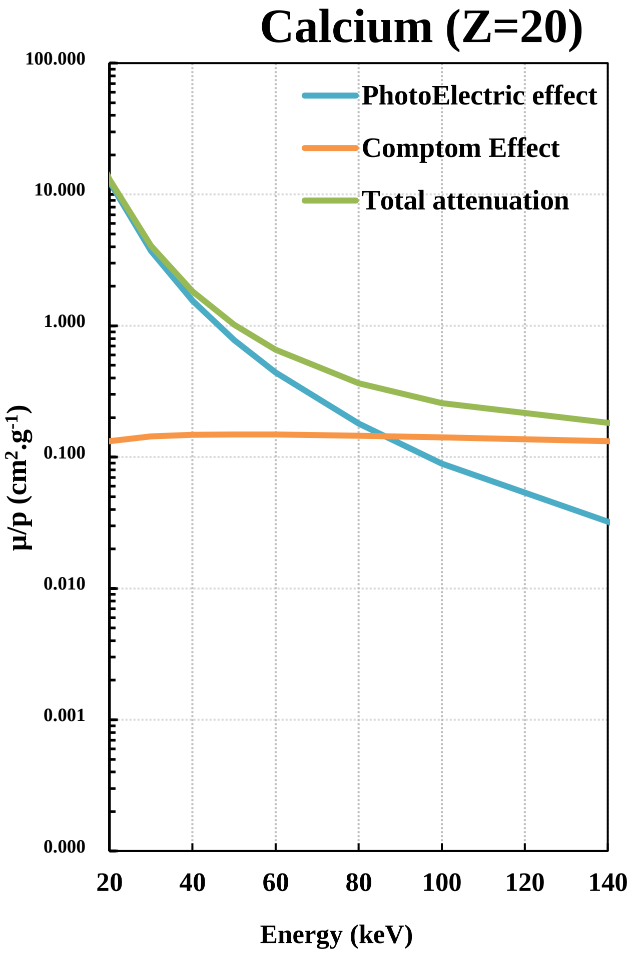


X-ray tissue attenuation primarily due to:

- **Compton effect** : for low Zeff compounds (non dependent on energy)
- **Photoelectric effect** : for high Zeff compounds (depends on effective energy ~Z^4/E^3

The main principal spectral CT





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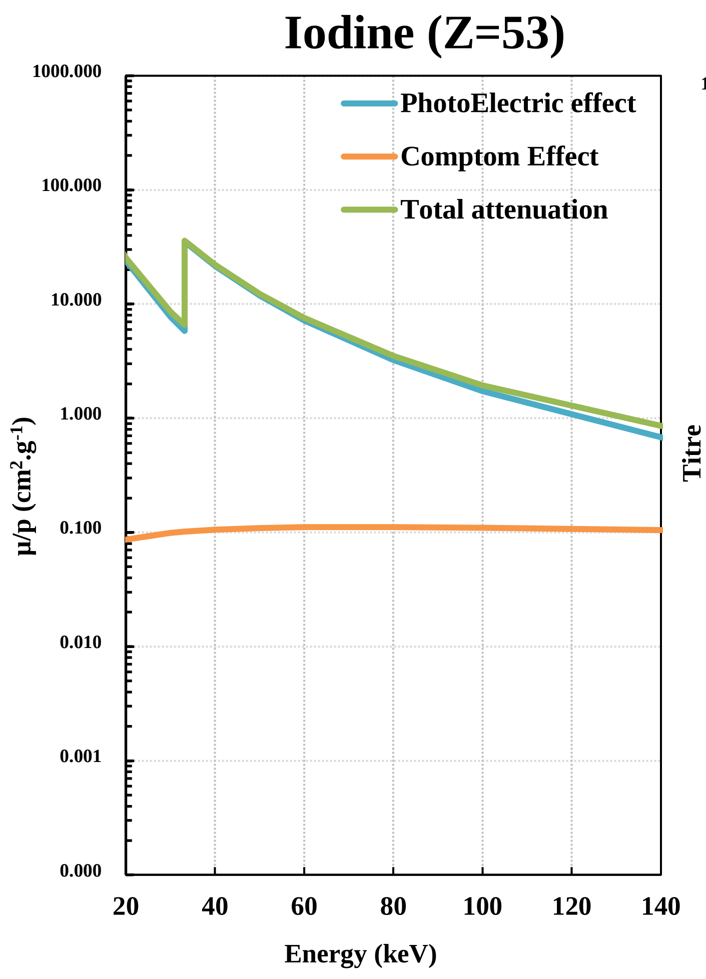
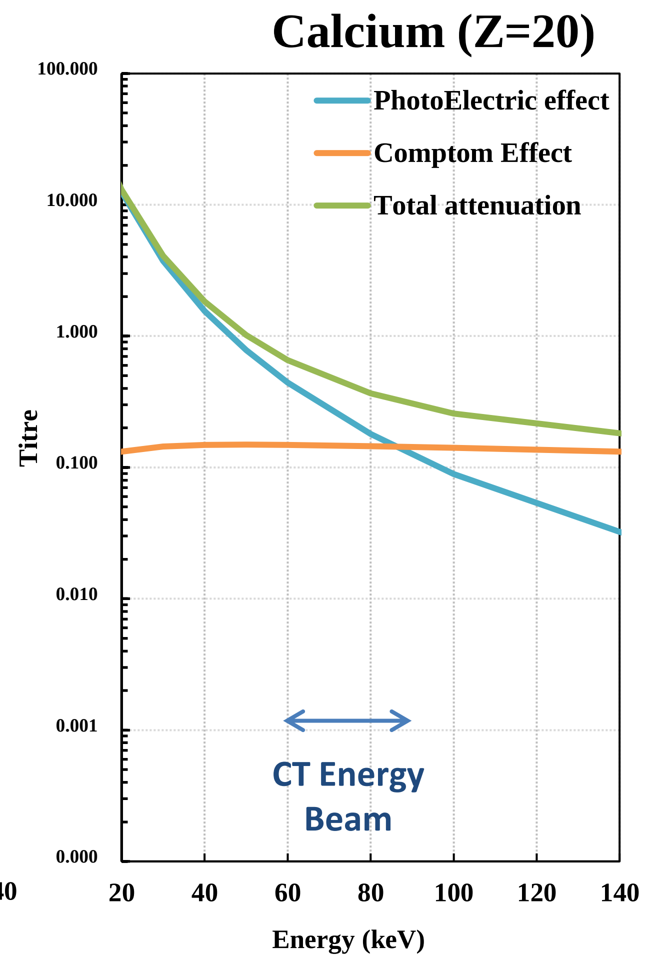
The main principal spectral CT





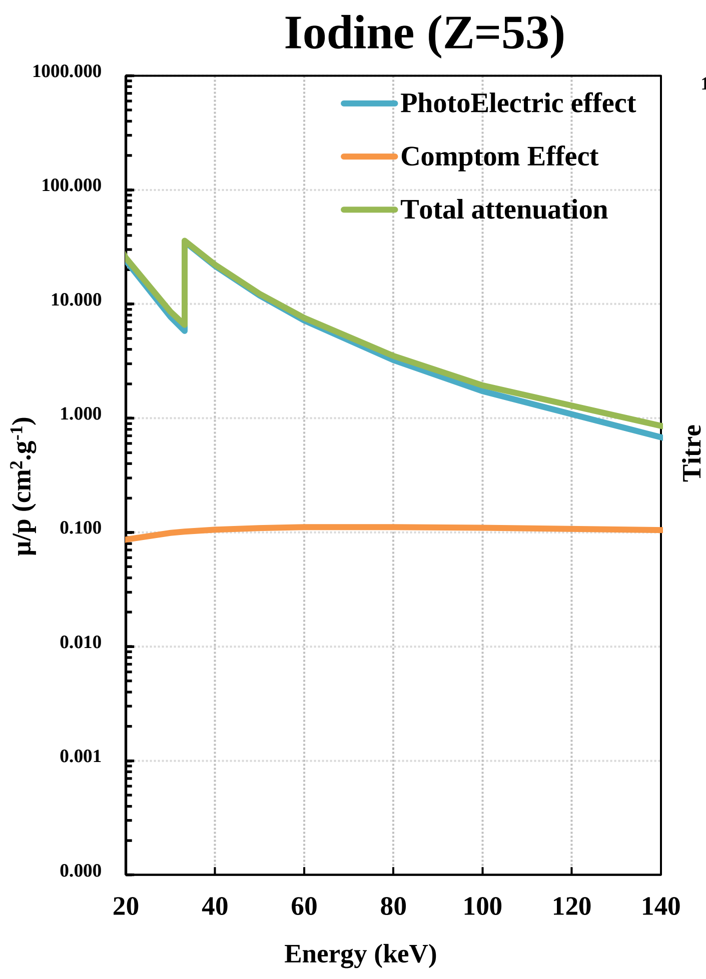
$$I = \int_E Io(E)e^{-\int_l \mu(E)dl}dE$$

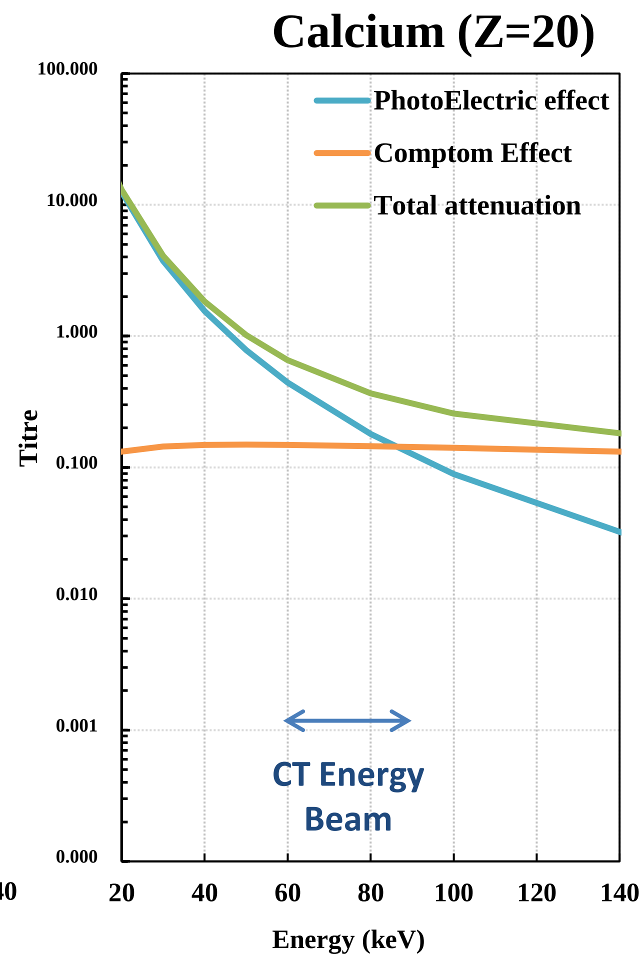
$$\mu(E) = \mu_{PH}(E) + \mu_{SC}(l,E)$$

For a tissue, with a density p and atomical number Z

$$\mu(E,l) \sim \frac{1}{E^3} K_1 \frac{\rho}{A} Z^4 + f_{SC}(E) K_1 \frac{\rho}{A} Z$$

The main principal spectral CT





$$I = \int_E Io(E) e^{-\int_l \mu(E,l) dl} dE$$

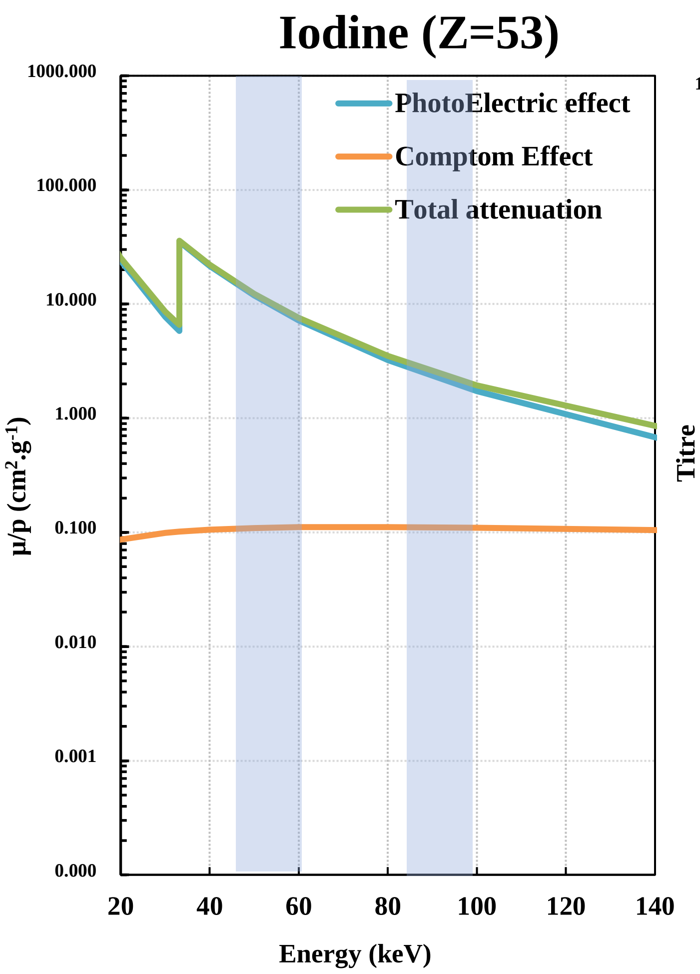
$$\mu(E,l) = \mu_{PH}(l,E) + \mu_{SC}(l,E)$$

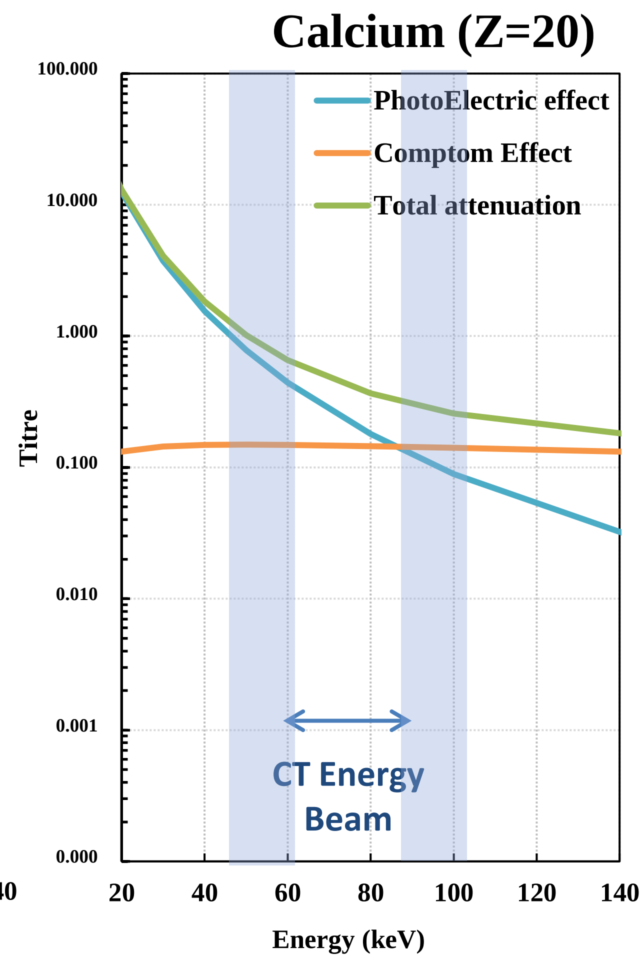
For a tissue, with a density p and atomical number Z

$$\boxed{\mu(E) \sim \frac{1}{E^3} K_1 \frac{\rho}{A} Z^4 + f_{SC}(E) K_1 \frac{\rho}{A} Z}$$

One equation, two unknowms

The main principal behind spectral CT

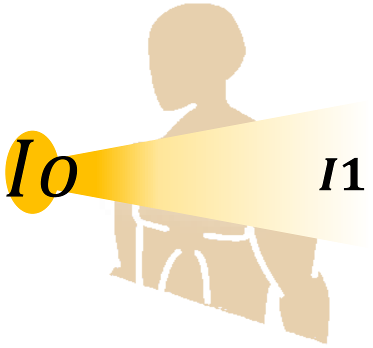


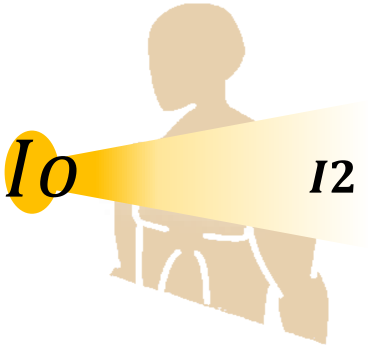


<u>One equation, two unknowms</u>

- Measure the attenuation with **two energies**
- Determine ρ and Z for the material (or compound, Zeff, ρeff)

The main principal behind spectral CT

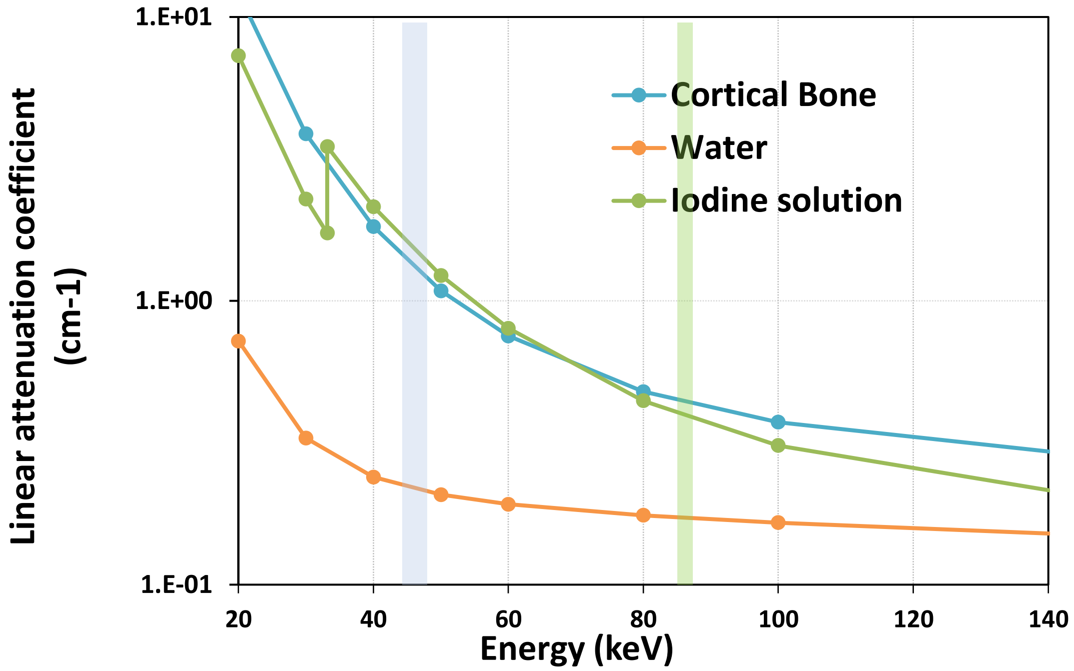




$$I1 = \int_{E1} Io(E1)e^{-\int_l \mu(E1,l)dl} dE$$

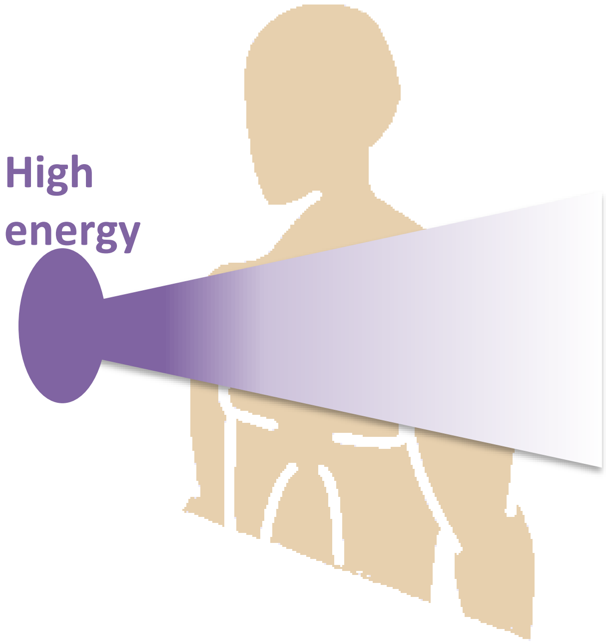
$$I2 = \int_{E2} Io(E2)e^{-\int_l \mu(E2,l)dl} dE$$

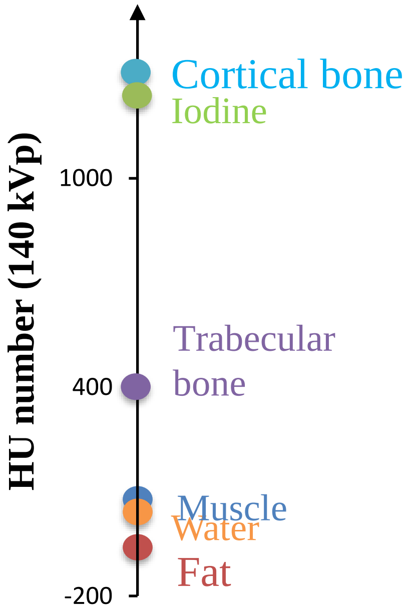
Solution : use two energy levels to discriminate materials



The main principal behind spectral CT

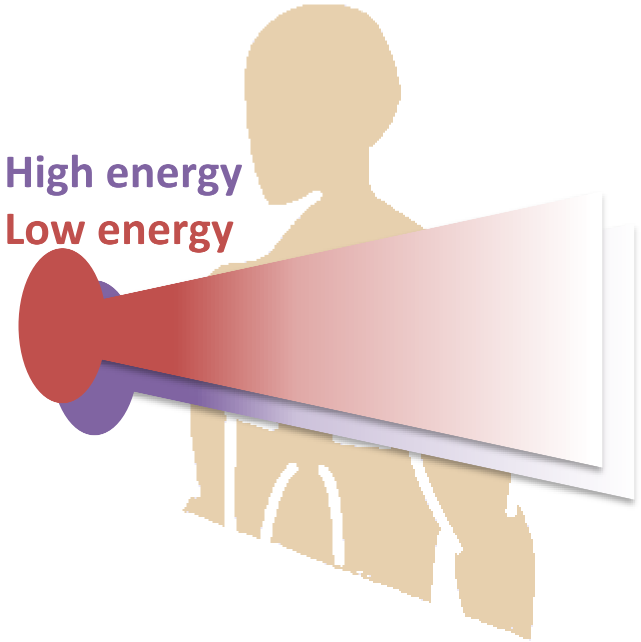
How to do ? Patient exposition with two «energies»

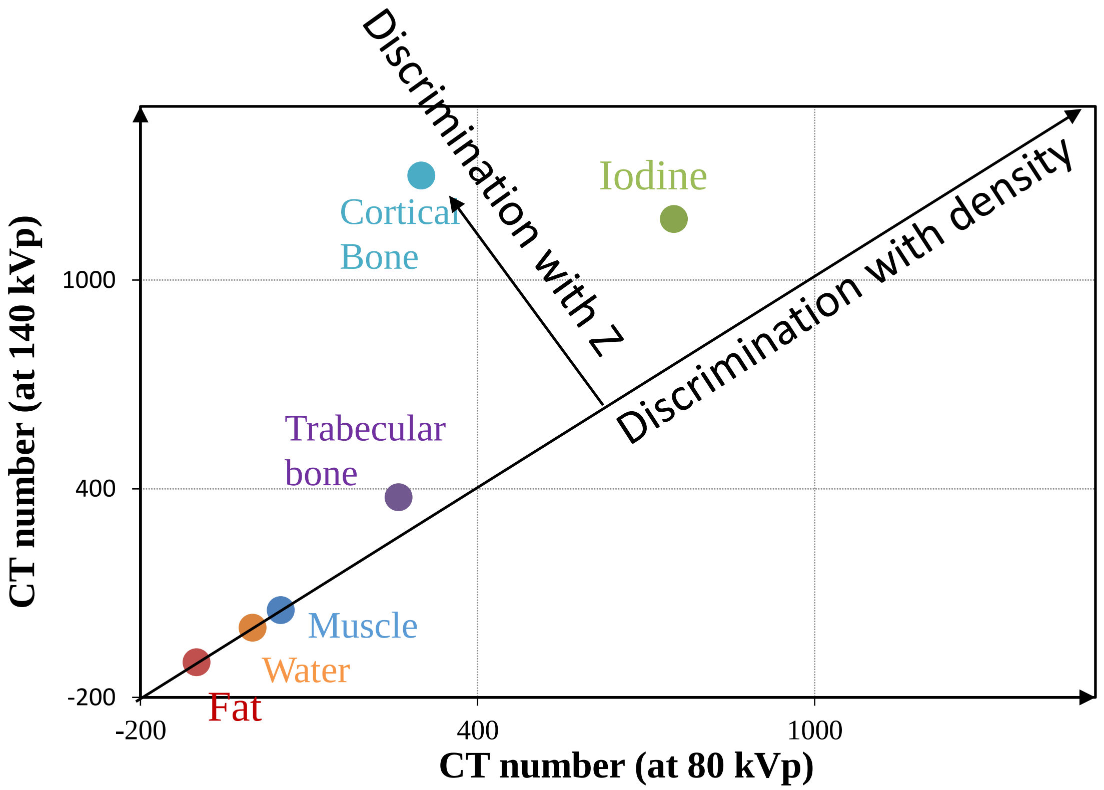




The main principal behind spectral CT

How to do ? Patient exposition with two beams at different voltage (kV)





Goal : identify, discriminate and quantify human tissues in CT

The three CT acquisition techniques

CT
single-energy

CT
dual energy

Photon counting CT

The three CT acquisition techniques

Scanner single-energy

Scanner double énergie

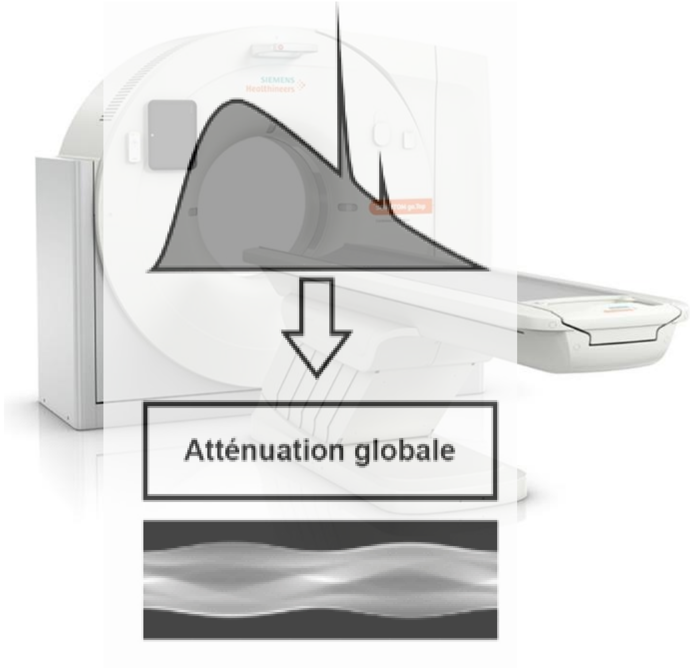
Scanner à comptage photonique

Scanners spectraux

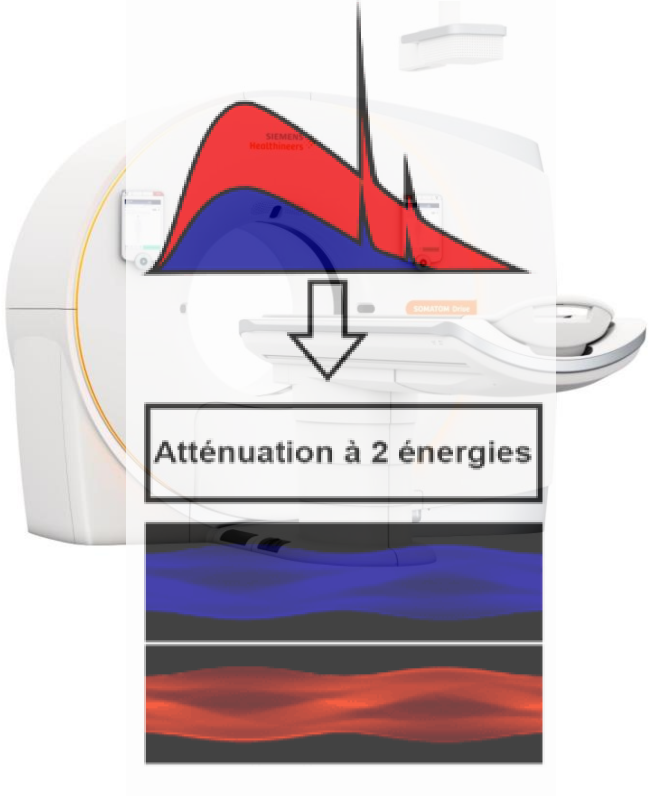
Avant de commencer, quelques définitions

Détecteurs à intégration d'énergie

Scanner single-energy



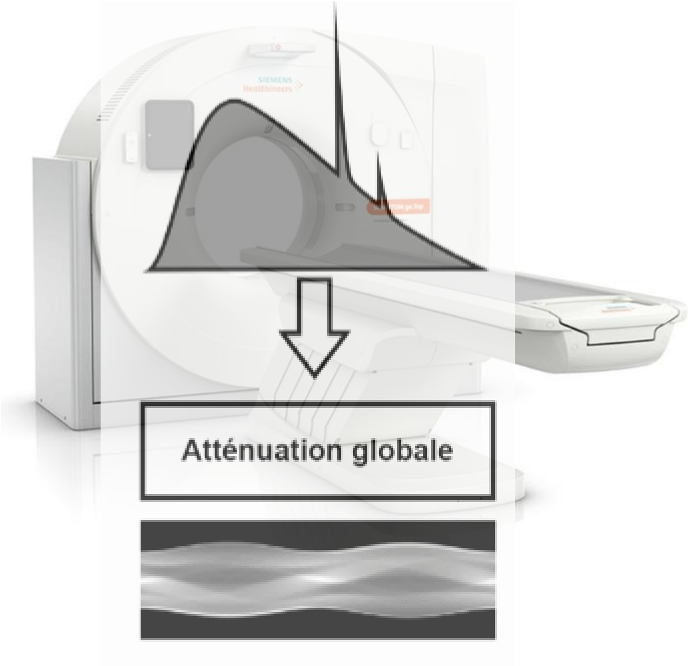
Scanner double énergie



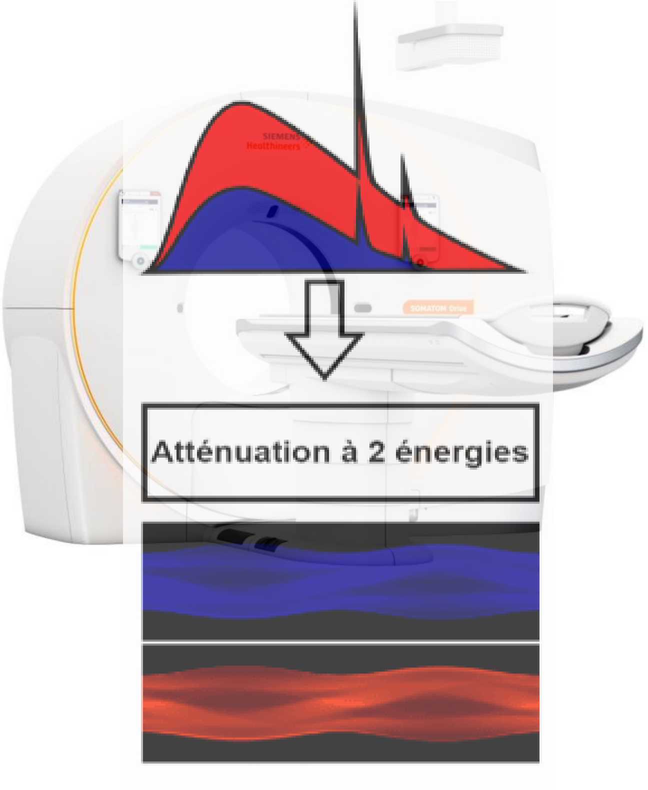
Avant de commencer, quelques définitions

Détecteurs à intégration d'énergie

Scanner single-energy

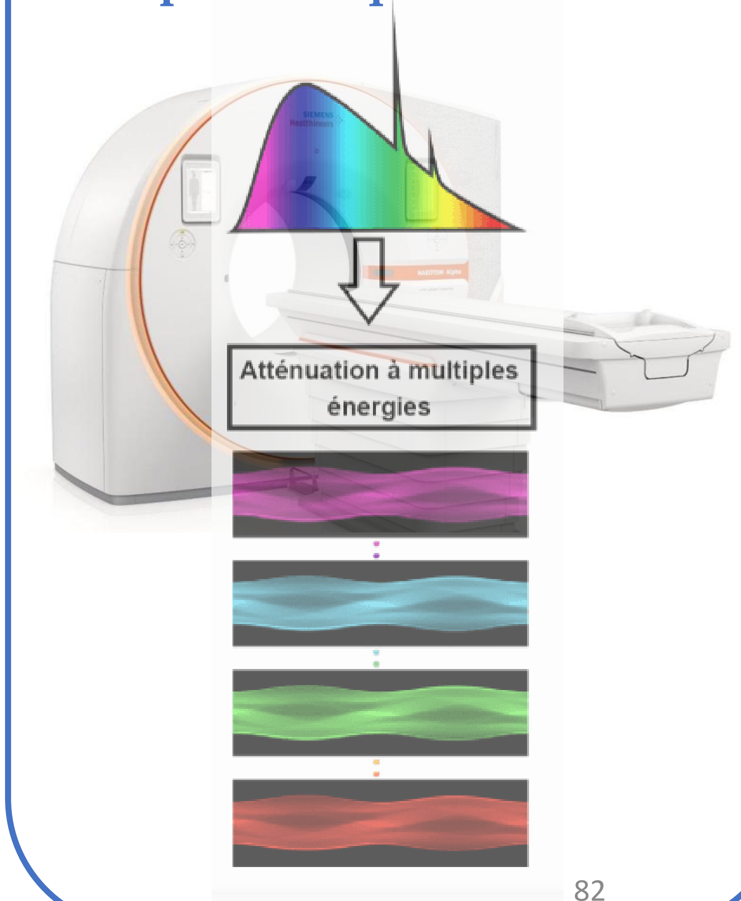


Scanner double énergie



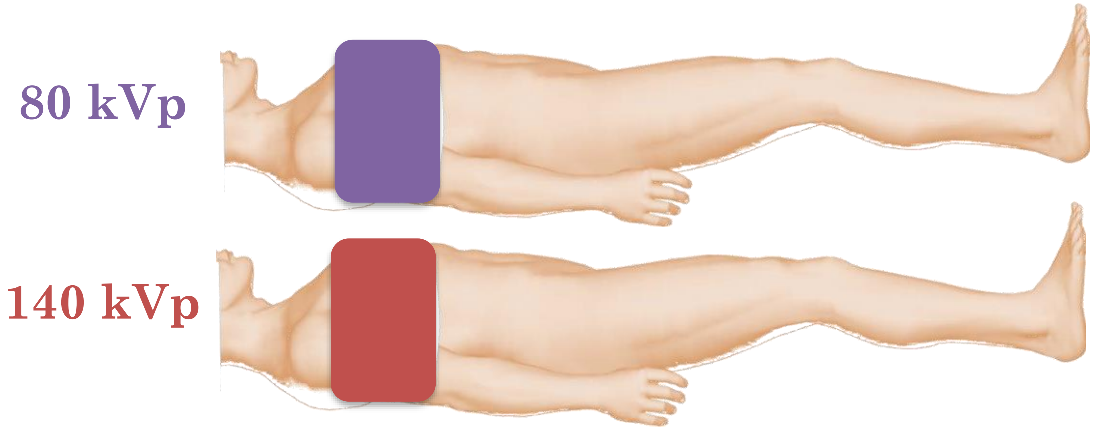
Détecteurs à comptage photonique

Scanner à comptage photonique



Dual-energy CT techniques

Initial choice : Two sequential acquisitions (rotate-rotate)

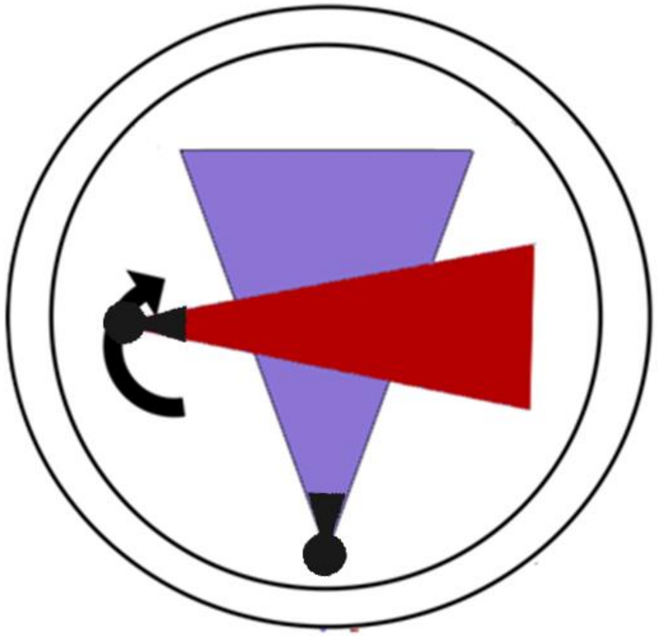


Filtration and tube voltage optimization to maximize the difference between the two spectra

Projection not paired
Patient movement between the two acquisitions
No contrast material

Dual-energy CT techniques

Choice n°2 : Two X-ray tubes - detector



Filtration and tube voltage optimization to maximize the difference between the two spectra

- Projection not paired
- Cross-talk of scattered radiation between both tube-detector couples
- Limited field of view (33cm)

Dual-energy CT techniques

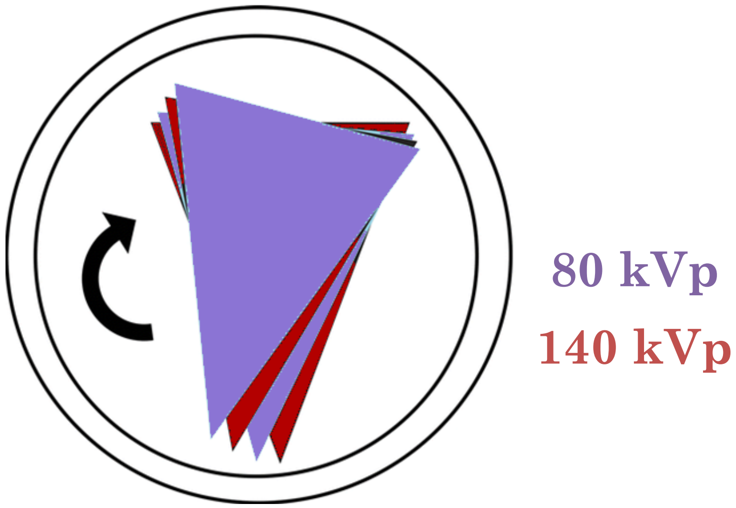
Choice n°3 : Split X-ray filter

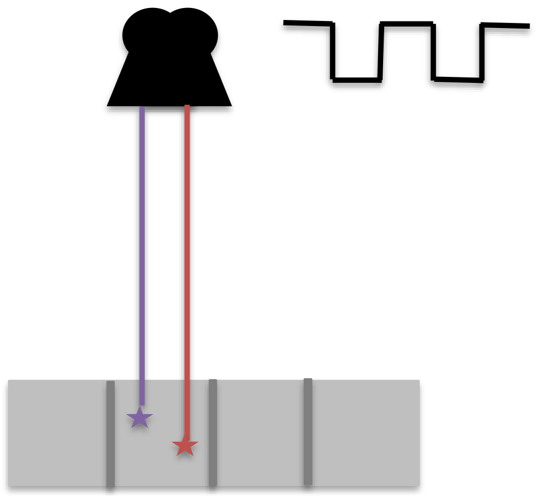
Projection data paired
Easy upgrade from a single source CT

Not possible to optimize tube voltage and filtration (reduced spectral separation)

Dual-energy CT techniques

Choice n°4 : Fast kVp switching



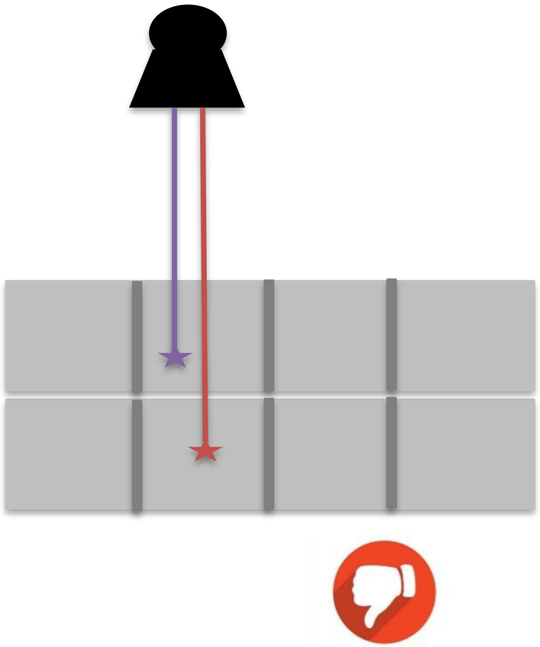


- Projection data paired

- Not possible to optimize tube voltage and filtration (reduced spectral separation)

Dual-energy CT techniques

Choice n°4 : Dual layer technique



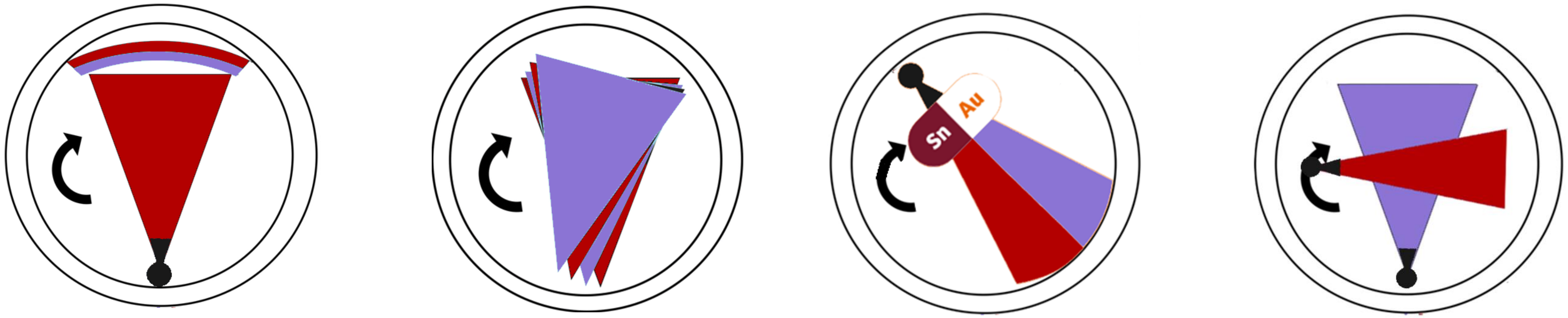
- Material-specific imaging can be generated from all image data acquisitions regardless of the scanning protocol

- Projection data paired

- Higher overlap of the energy spectra

Dual-energy CT techniques

Dual-energy CT : More or less exposed ?



Technology dependent

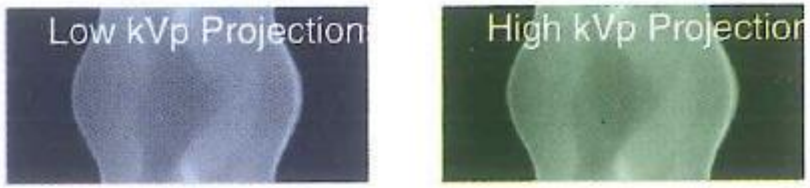
<u>Only few studies on the subject</u> :

- technology dependent
- dependent on the anatomical region
- dependent on patient size (we can't scan large patients with dual-source CT) …

Dual-energy CT techniques

Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

Raw Data DECT



Material selective image
(material decomposition)

Energy selective images
Or density map

- Iodine (material) quantification / Material characterisation
- Iodine (material) suppression : Virtual-non-contrast images / bone removal

- Mono-energetic images
- Density map
- Effective Z images

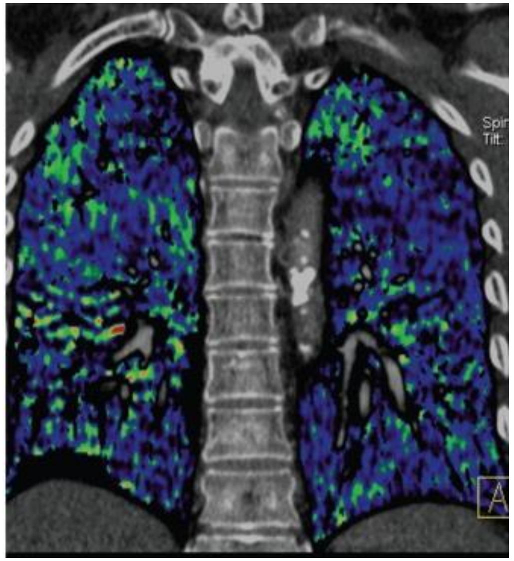
Dual-energy CT techniques

Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

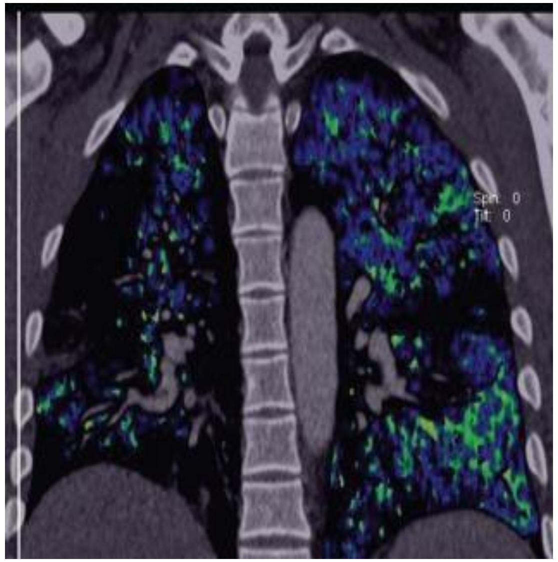
Material selective image
(material decomposition)

- Iodine (material) quantification / Material characterisation

- Pulmonary embolism (iodine perfusion)



"Normal perfusion"



Pulmonary embolism

Dual-energy CT techniques

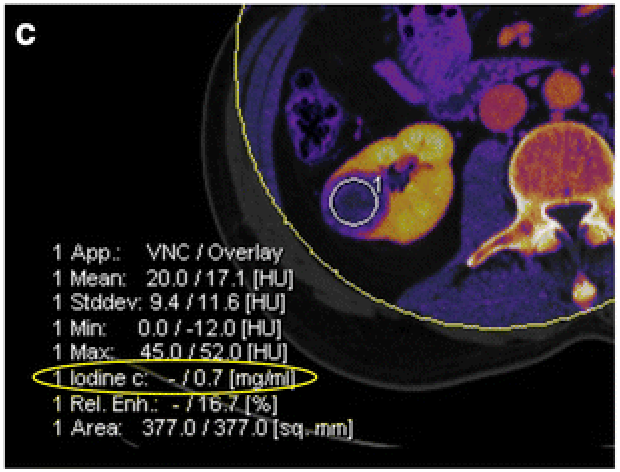
Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

Material selective image
(material decomposition)

- Iodine (material) quantification / Material characterisation

- *Iodine quantification (threshold 0.5 mg/mL – malignant renal tumour)*

DECT reconstruction (weighted) + carte iode



Dual-energy CT techniques

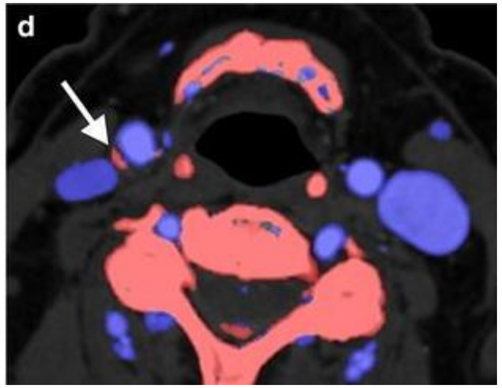
Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

Material selective image
(material decomposition)

- Iodine (material) quantification / Material characterisation

Artherosclerosis

Conventional CT image



Map iodine (blue) vs bone (red)

Dual-energy CT techniques

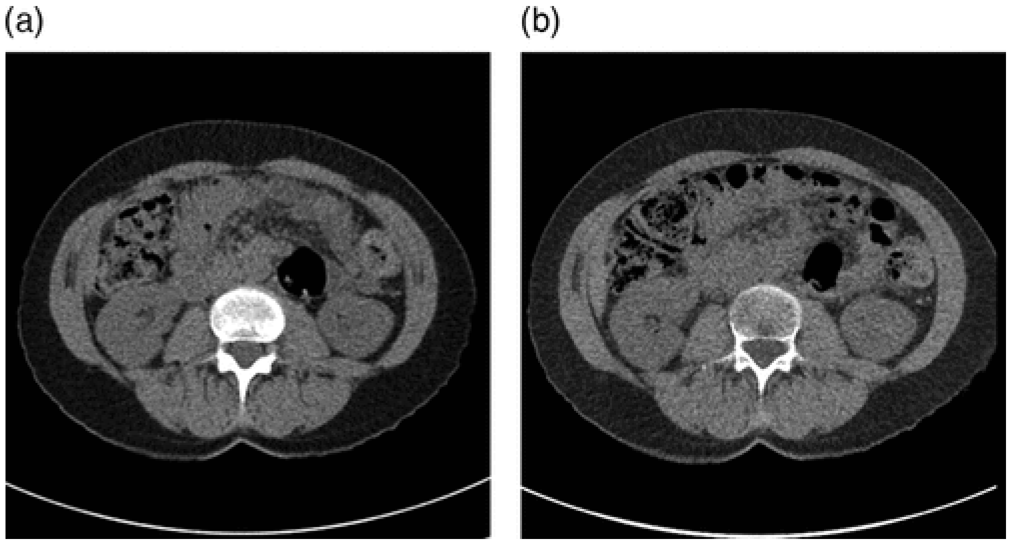
Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

Material selective image
(material decomposition)

- Iodine (material) quantification / Material characterisation
- Iodine (material) suppression : Virtual-non-contrast images

Native conventional CT image
(without iodine injection)

Virtual non contrast CT
(Iodine was suppressed from DECT iodine CT)



Dual-energy CT techniques

Post-processing is an important part for DECT techniques and includes many possibilities to qualitatively **visualize** and quantitatively **analyse** images.

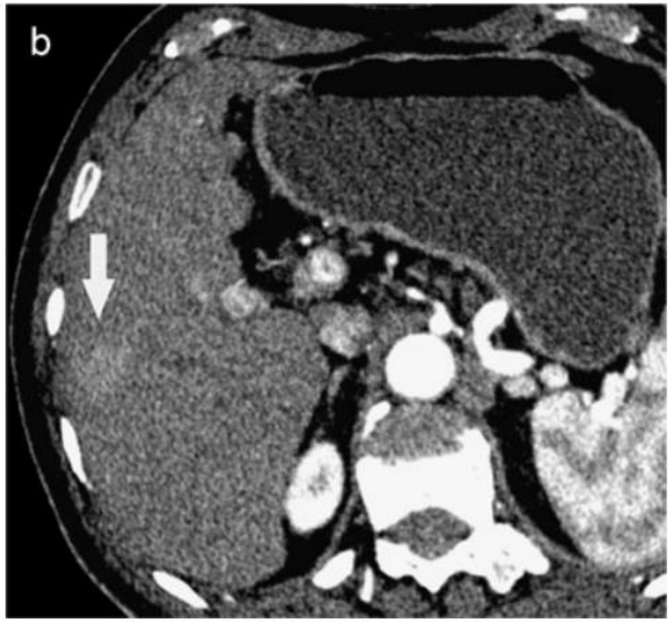
From ρ and Zeff tissue, reconstruction of mono-energetic map

Energy selective images
Or density map

- Mono-energetic images
- Density map
- Effective Z images

Conventional CT image

40 keV mono-energetic reconstruction



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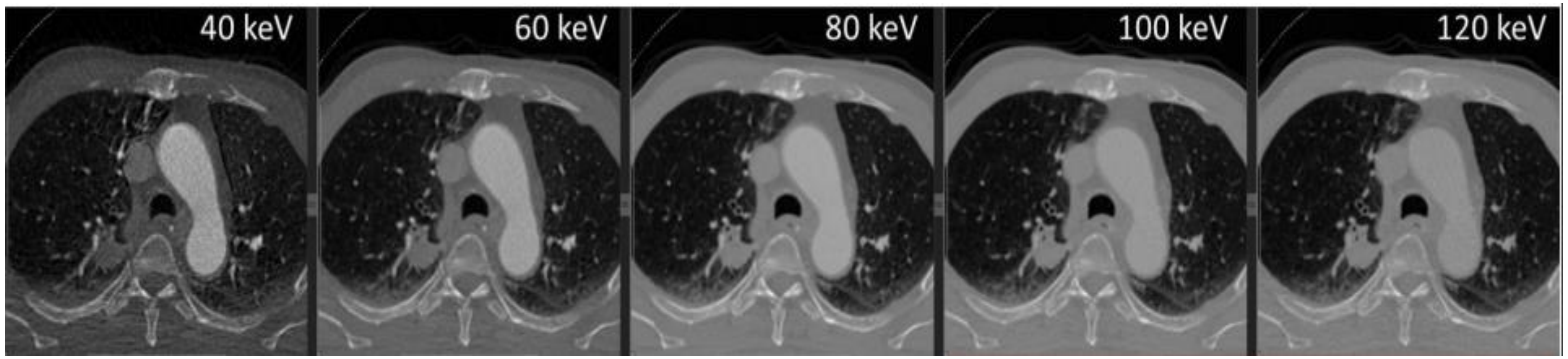

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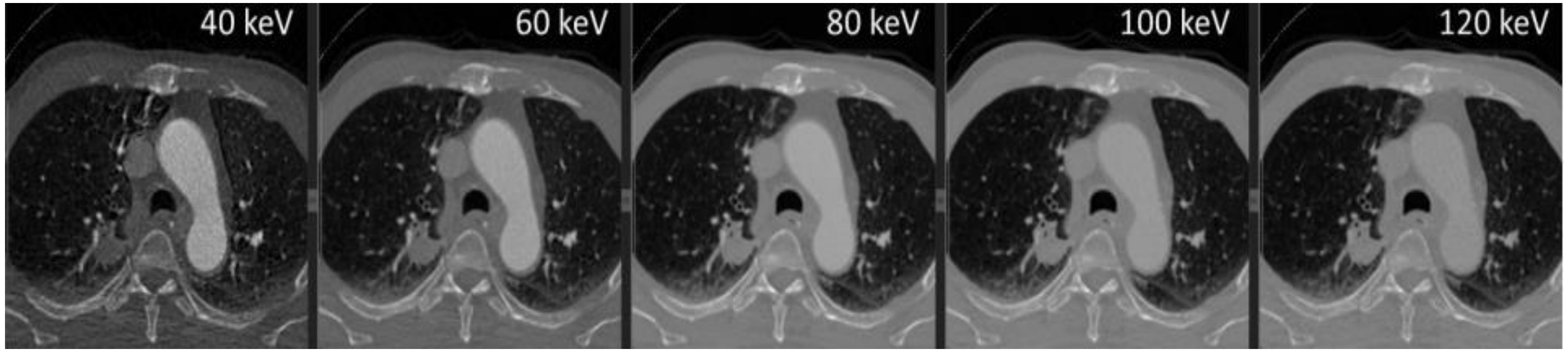
Dual-energy CT techniques

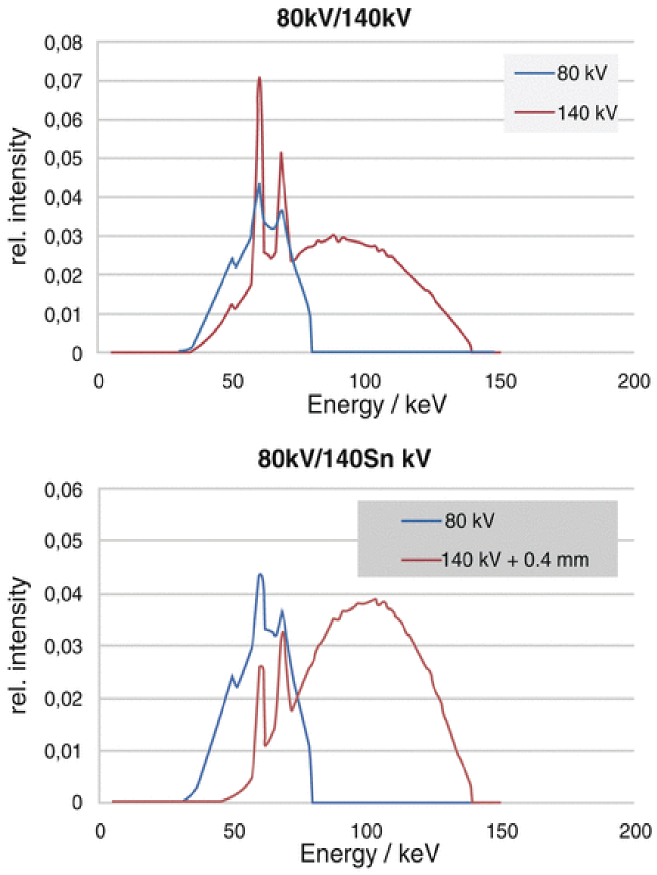


- Which image has the highest contrast ?

- Which image has the highest noise level ?

- Which image has a better image quality ?

Limitations of Dual-Energy CT



- The **separation between low and high kVp** beam pejorate the material discrimination

- Some material should **never been discriminate** (HU numbers too close for the energy levels of DECT)

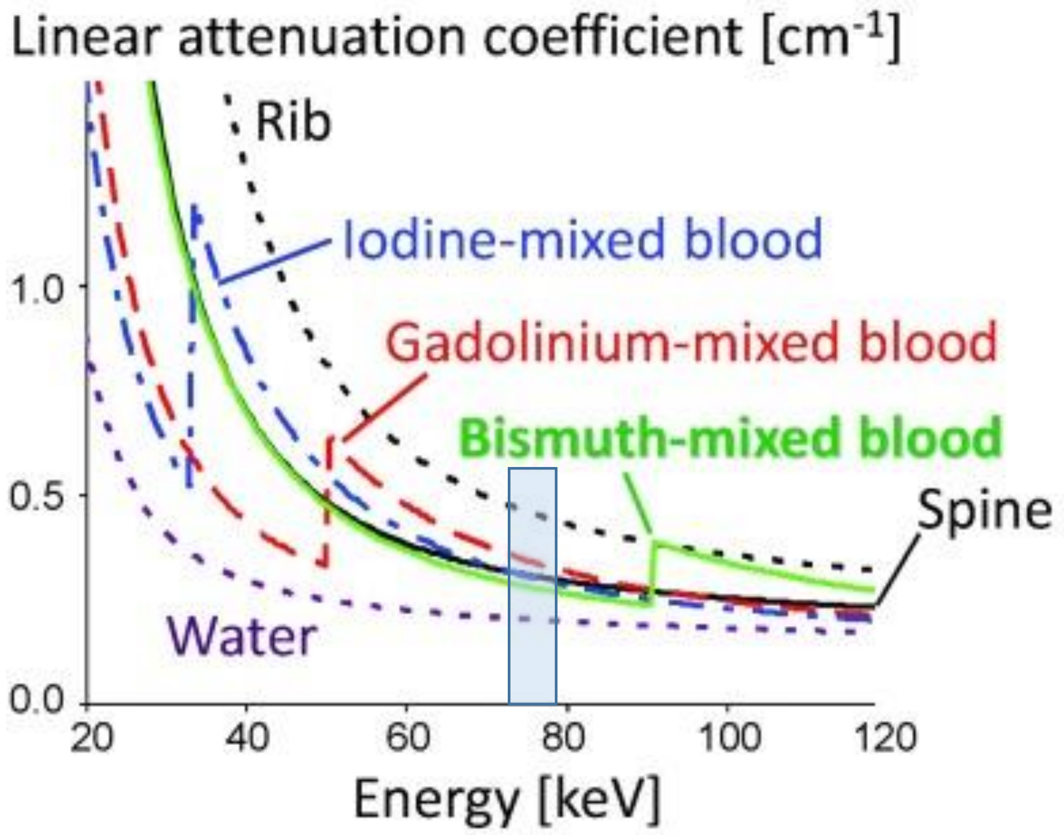
- The **spatial resolution of material decomposition map** is limited follwing the clinical applications

Content of the lecture today

- Image quality in CT – Advanced metrics (1h)
  - Link between human observers behaviour and physical image quality metrics

- The last technologies in CT nowadays (1h15) :
  - Dual-Energy CT
    - Motivations for dual-energy CT
    - Dual-energy CT techniques
  - **Photon-Counting CT**
    - **Motivations for photon-counting CT**
    - **New detectors**

Motivations for photon-counting CT



Equivalent HU numbers for conventional CT

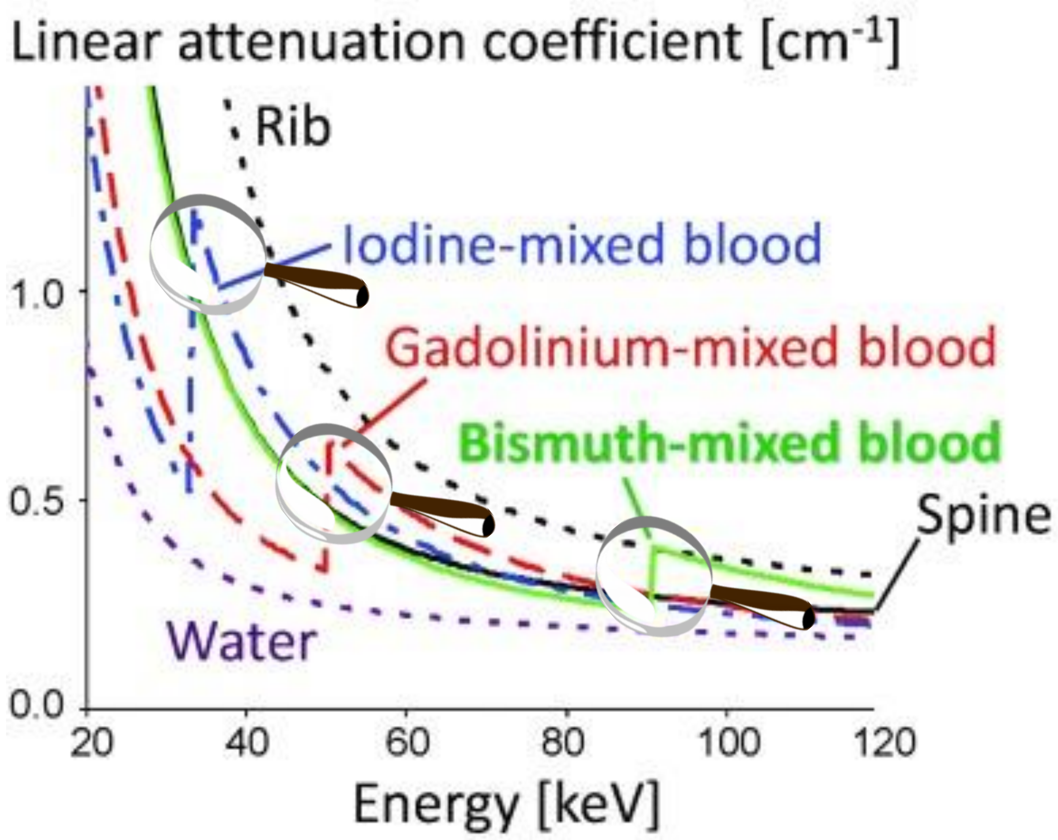
Vision 20/20: Single photon counting x-ray detectors in medical imaging

Katsuyuki Taguchi [1], Jan S Iwanczyk

Affiliations + expand

PMID: 24089889 PMCID: PMC3786515 DOI: 10.1118/1.4820371

Motivations for photon-counting CT



Possibility to discriminate these materials using various energy ranges (20-50 keV / 50-70 keV / 70-90 keV / 90-120 keV)

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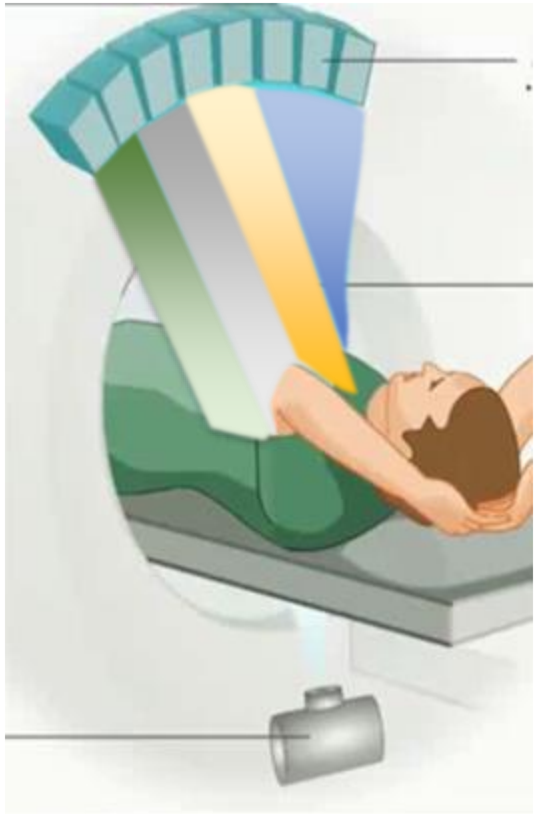
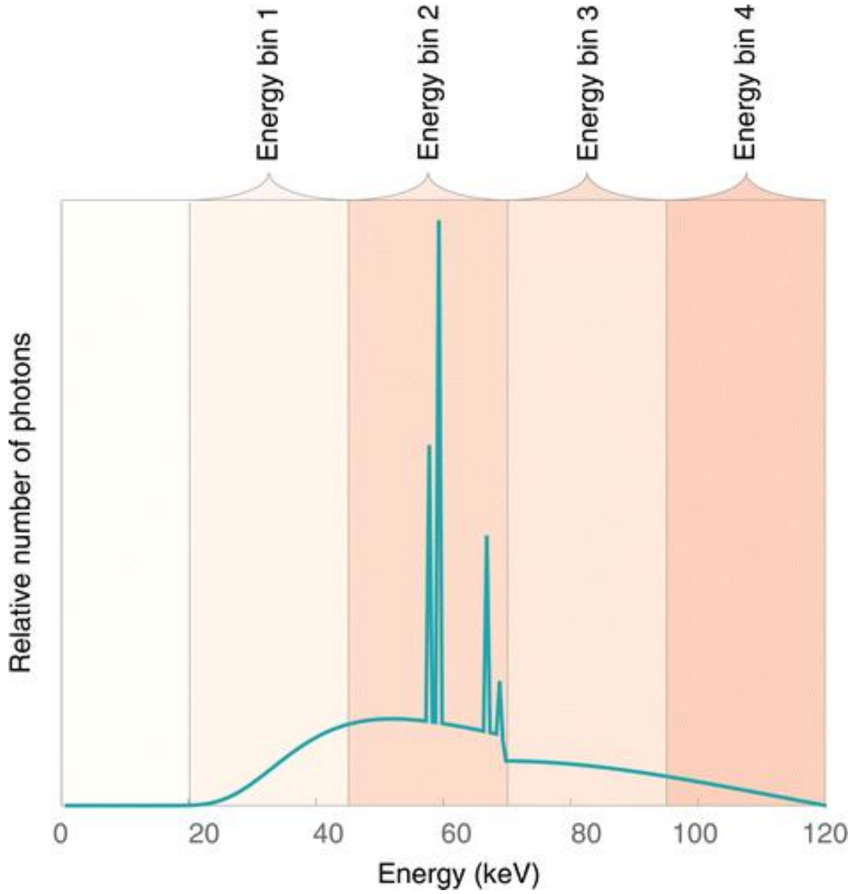
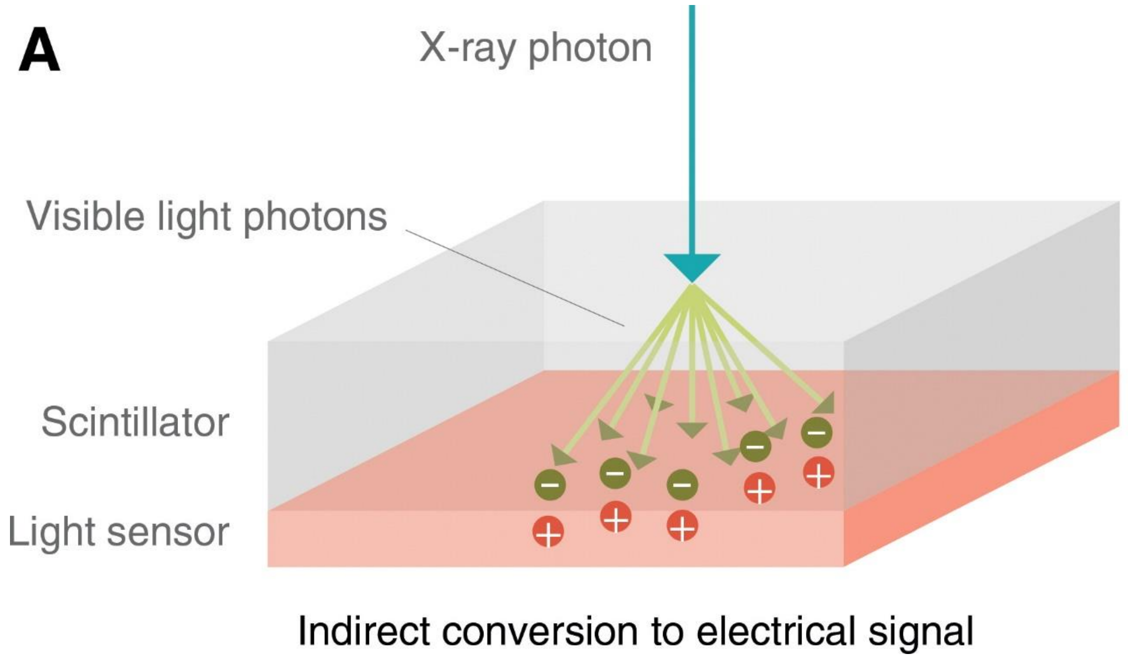
Motivations for photon-counting CT



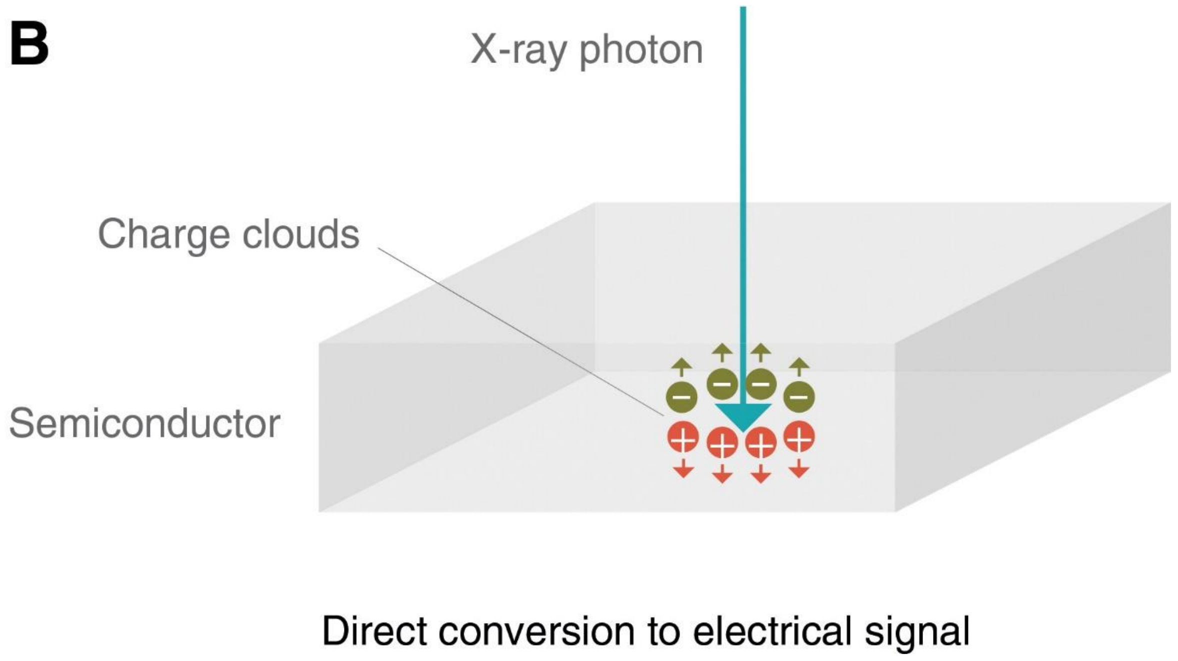


Discriminate photons with their energy instead using two different kV beams

Photon-counting CT technique = New detectors

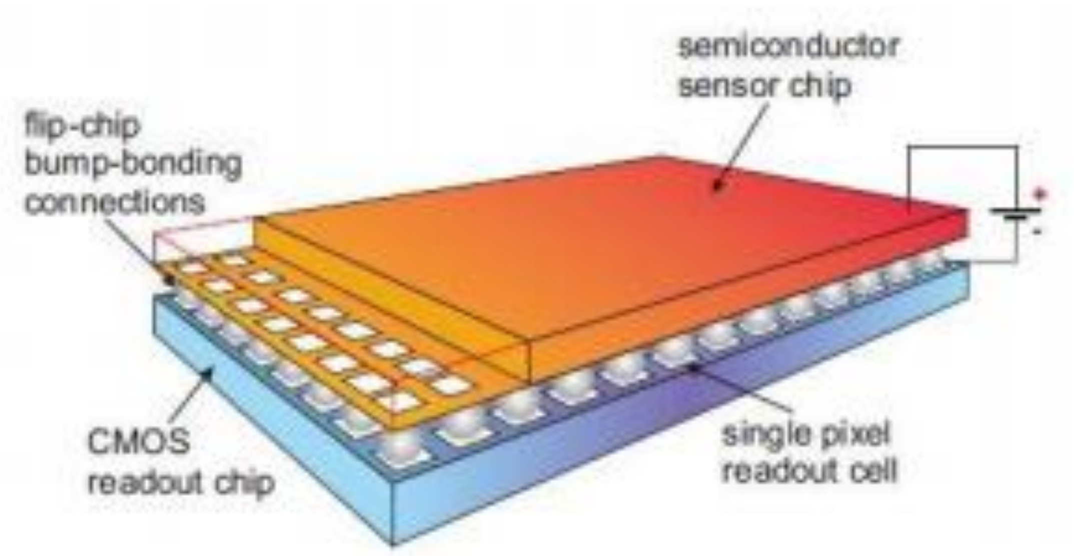


Conventional energy integrating detector



Photon-counting detector

Photon-counting CT technique = New detectors

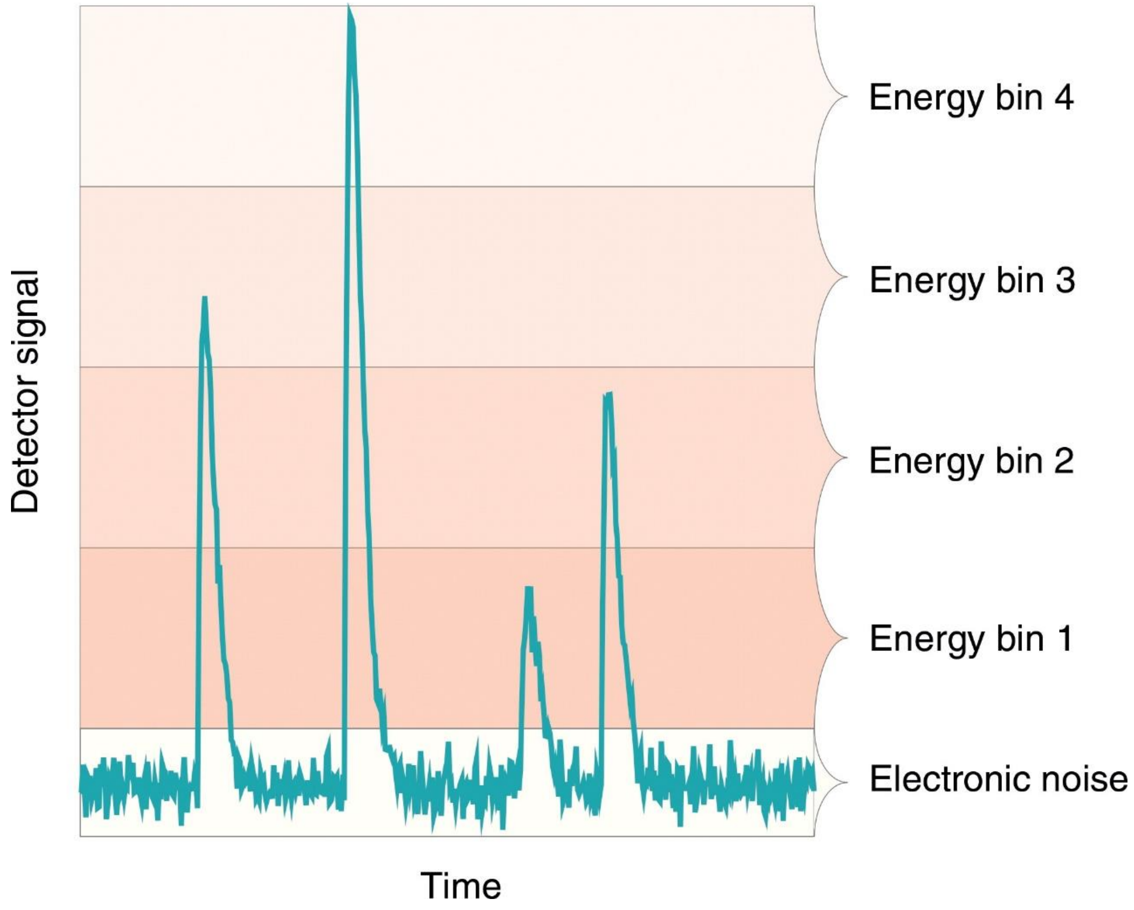


Photon-counting x-ray detectors for CT

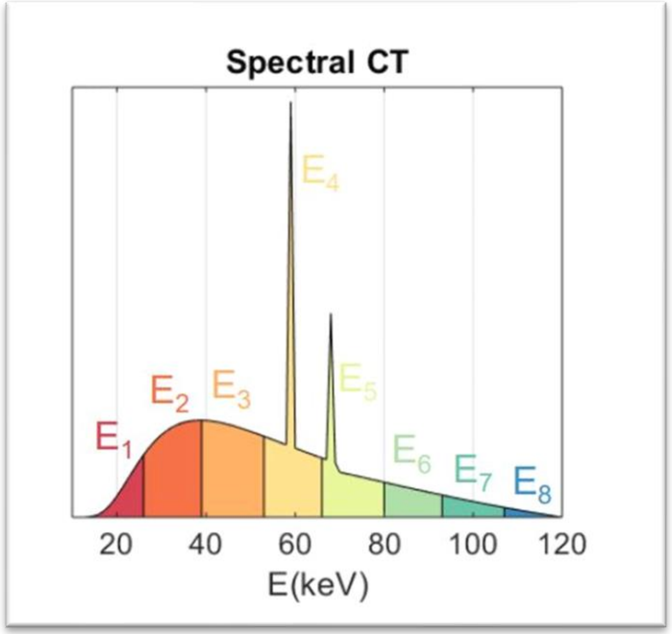
Mats Danielsson [1], Mats Persson, Martin Sjölin

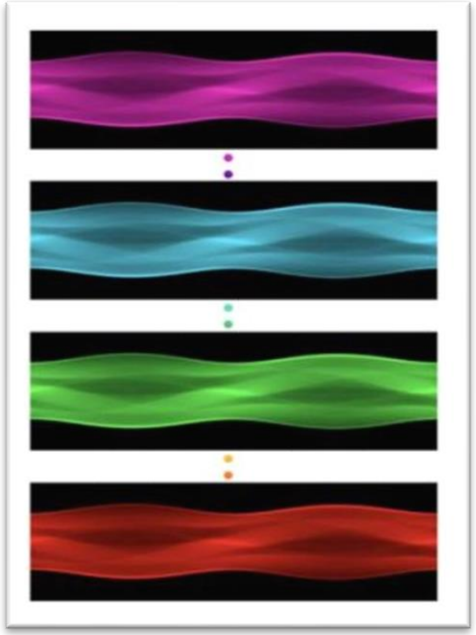
Affiliations + expand

PMID: 33113525 DOI: 10.1088/1361-6560/abc5a5

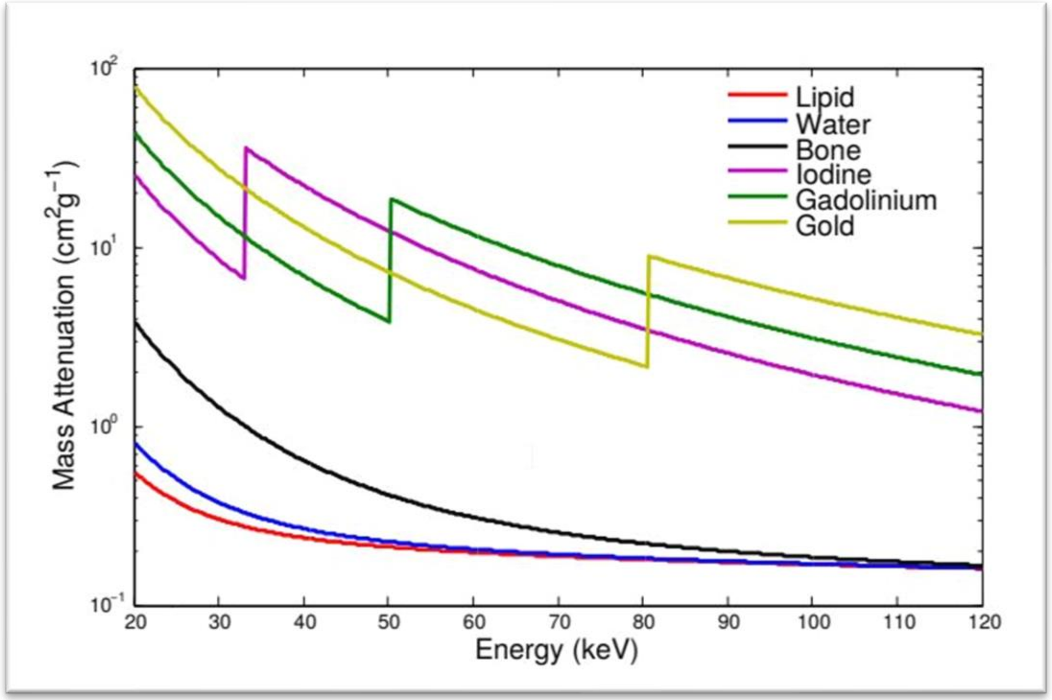


Motivations for photon-counting CT





Multiple spectral discrimination



Atténuation of photons in the tissues

Expected performances

Parameter	Feature Detection*	Material Quantification†
Higher geometric efficiency	1.5-fold improvement	1.5-fold improvement
Better spectral separation	Improved weighting (4,18,21,22); 1.3–2.5-fold improvement	Material decomposition (23,24); 2.0–3.1-fold improvement
No electronic noise	>1-fold improvement at very low count rate (25,26)	>1-fold improvement at very low count rate
Smaller detector elements	>1-fold improvement for high-spatial-resolution tasks	>1-fold improvement for high-spatial-resolution tasks
Total	2.0–3.8-fold improvement or more	3.0–4.6-fold improvement or more

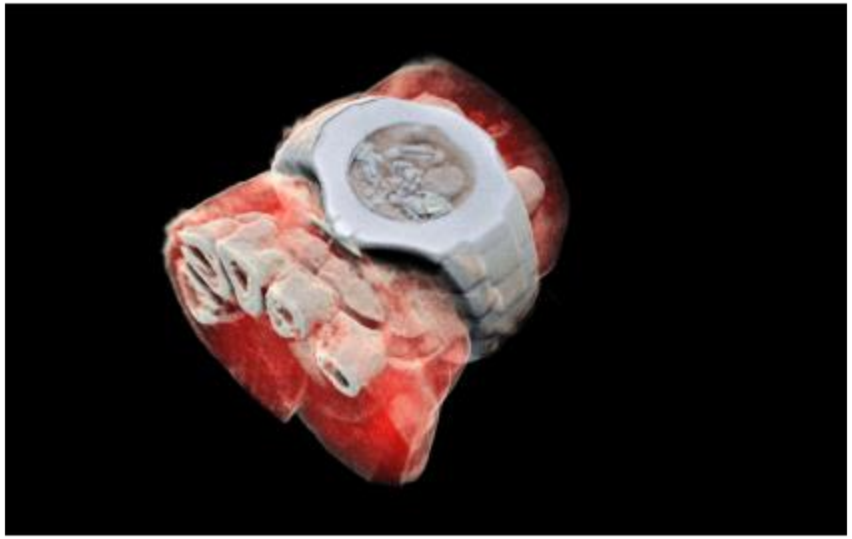
Photon-counting CT: Technical Principles and Clinical Prospects

Martin J. Willemink, Mats Persson, Amir Pourmorteza, Norbert J. Pelc, Dominik Fleischmann

Author Affiliations

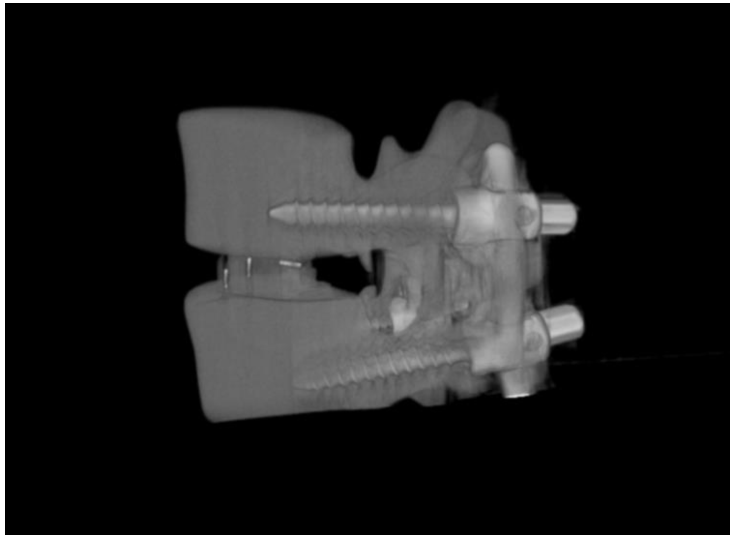
Published Online: Sep 4 2018 | https://doi.org/10.1148/radiol.2018172656

First images …

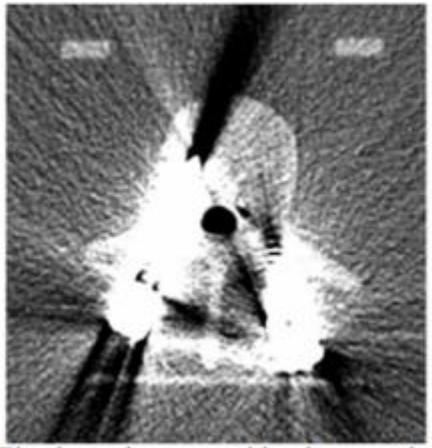


First human image (wrist)

Custom-made phantom
representig a brain aneuvrism



Vertebra phantom with screws
(with photon-counting CT)



Vertebra phantom with screws
(with conventional CT)

Any questions relative to medical physics ?

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SSRPM website : https://ssrpm.ch/