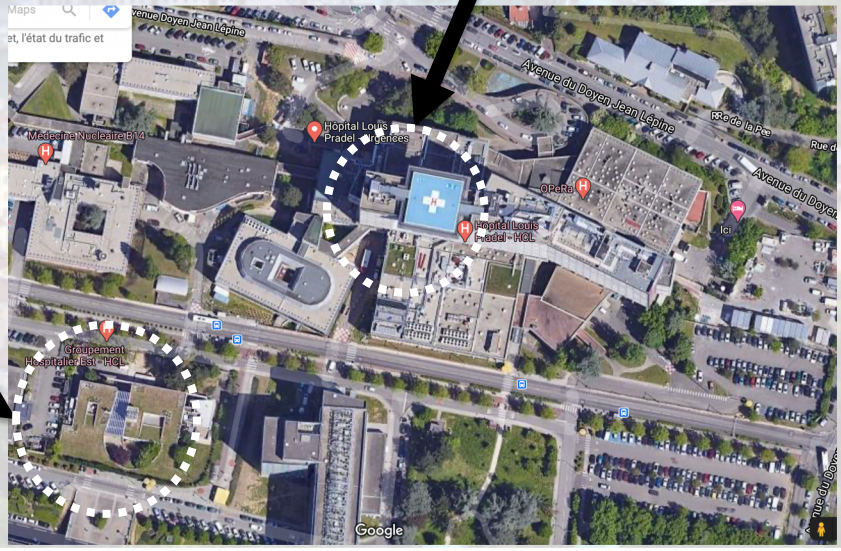
Principle, technology and cutting-edge applications of Spectral CT imaging

Speaker: Salim A. Si-Mohamed (MD, PhD), Associate Professor
salim.si-mohamed@chu-lyon.fr, https://www.spectralphotoncountingct.com/

Affiliations
[a] – Hôpital cardiothoracique et vasculaire, Louis Pradel, Lyon
[b] – University of Lyon : LabCREATIS, Team MYRIAD, CNRS – INSERM – Université Lyon 1 – INSA

Clinical and pre-clinical Spectral Photon-Counting CT platform (CERMEP)
(University of Lyon)

6 Clinical dual-layer dual-energy CT platform
(Universitary hospitals, Hospices Civils de Lyon)



Who wants to improve patient survival ?

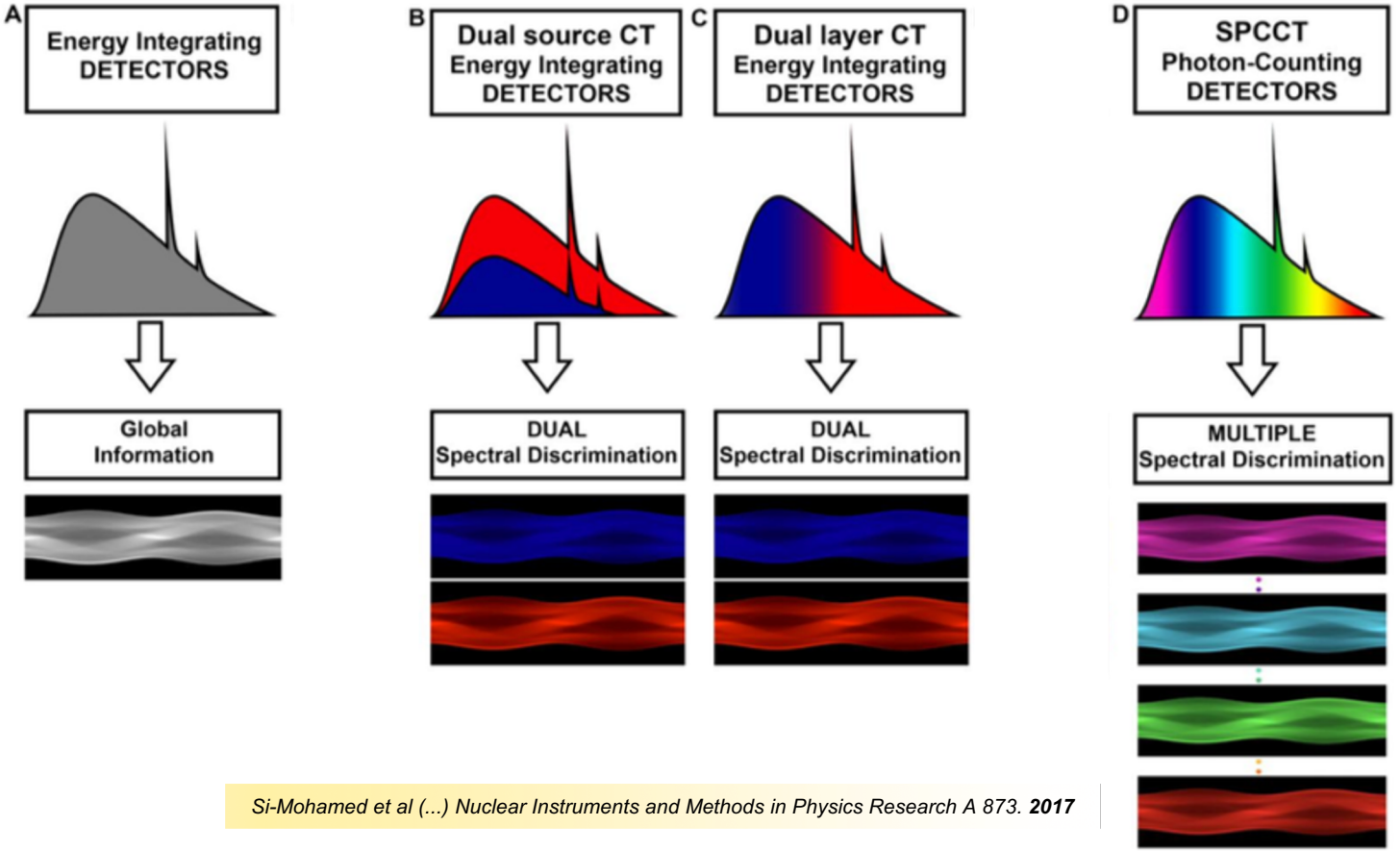
Teaching points

- Explain basic principles of Spectral CT imaging
- Differentiate the technology between dual and multi-energy CT
- Understand the clinical implications
- Be able to identify and discover new applications

Introduction

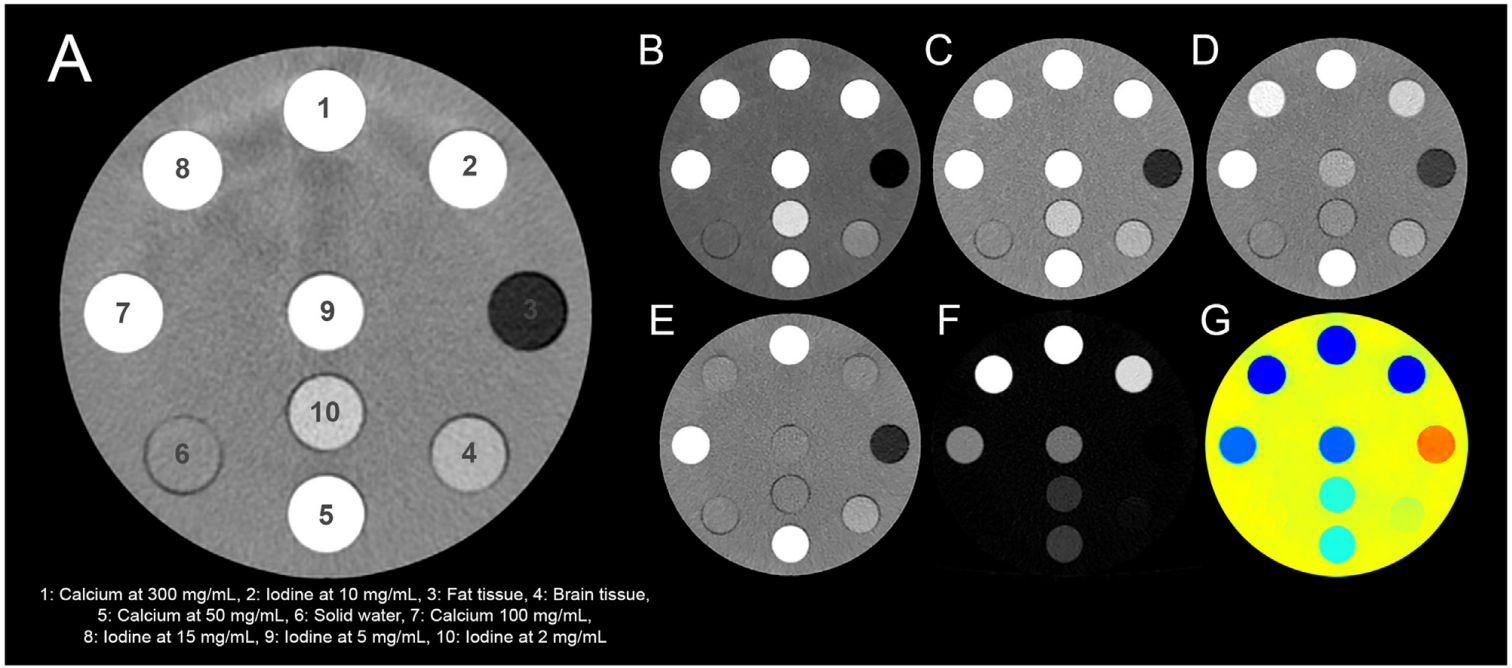
1895

Introduction



Si-Mohamed et al (...) Nuclear Instruments and Methods in Physics Research A 873. ***2017***

Introduction



« A must read » technical review on Spectral CT technology
Greffier J, Villani N, Defez D, Dabli D, Si-Mohamed S. DIII. ***2023***
French national working group SFR, G4, SFPM, CERF

I. Principles

Principle

$$\mu(E) = \mu_P(E) + \mu_C(E) = \alpha_P f_P(E) + \alpha_C f_C(E)$$

(α_P , α_C , $\alpha_{K\text{-}edge}$): *tissue-type specific*

$\alpha_P = d\, Z_{eff}^3$

$\alpha_C = d\, k$

D : *tissue density*, **et** Z_{eff} **:** *atomic number*

(f_P , f_C) : *depend only on the energy*

$f_P = 1/E^3$

$f_C = 1/E^{0.3}$ = *Klein and nishina fonction*

E : *photon energy*

PHYS. MED. BIOL., 1976, VOL. 21, NO. 5, 733–744. © 1976

Principle

$$\mu(E) = \mu_P(E) + \mu_C(E) = \alpha_P f_P(E) + \alpha_C f_C(E)$$

$$\begin{cases} \mu(E_L) = \alpha_P f_P(E_L) + \alpha_C f_C(E_L) \\ \mu(E_H) = \alpha_P f_P(E_H) + \alpha_C f_C(E_H) \end{cases}$$

Pros

- Generate tissue attenuation at different energies
- Generate specific images of tissue and contrast agent
- Generate specific image of chemical and physical composition of tissue

PHYS. MED. BIOL., 1976, VOL. 21, NO. 5, 733–744. © 1976

Material decomposition images

- Material decomposition in 2 basis based on their specific attenuation

$$\begin{cases} \mu(E_B) = \alpha_P f_P(E_B) + \alpha_C f_C(E_B) \\ \mu(E_H) = \alpha_P f_P(E_H) + \alpha_C f_C(E_H) \end{cases}$$

$$\downarrow$$

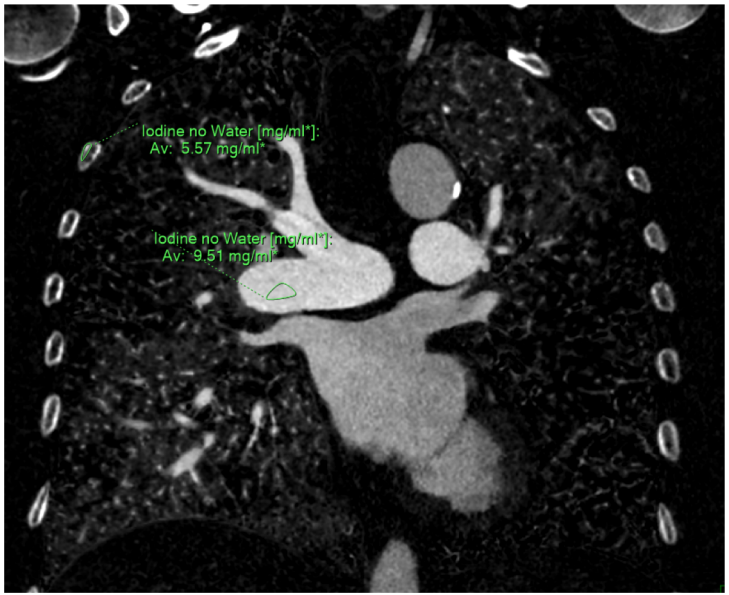
$$\begin{cases} \mu(E_B) = [C^\circ]_{iode}\,\mu_{iode}(E_B) + [C^\circ]_{eau}\,\mu_{eau}(E_B) \\ \mu(E_H) = [C^\circ]_{iode}\,\mu_{iode}(E_H) + [C^\circ]_{eau}\,\mu_{eau}(E_H) \end{cases}$$

➢ Measurement of tissue/agents concentrations based on specific attenuation

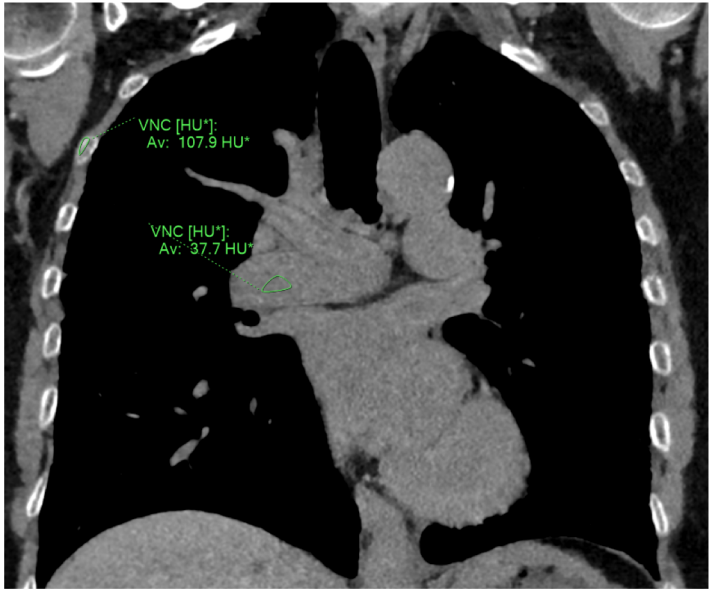
Material decomposition images

- Material decomposition in 2 basis based on their specific attenuation

Iodine-type image

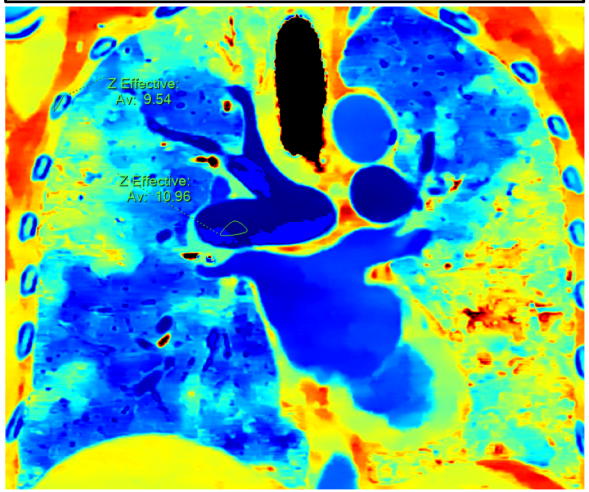


Water-type image



Material decomposition images

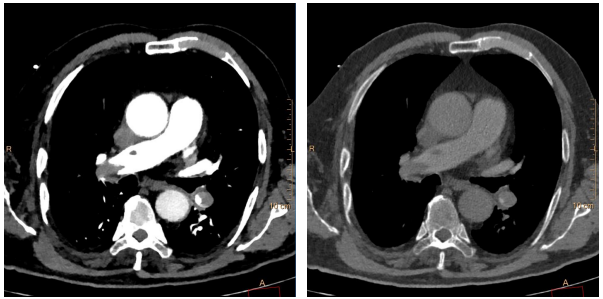
Z effectif



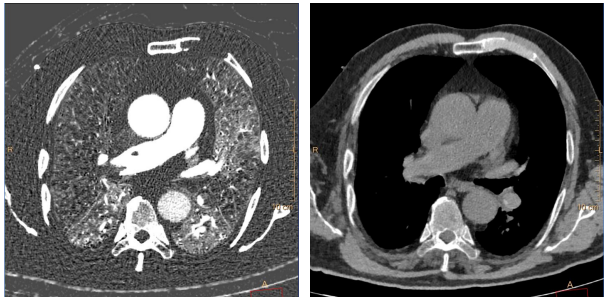
Electronic density

➢ But it offers many different solutions to be explored & validated

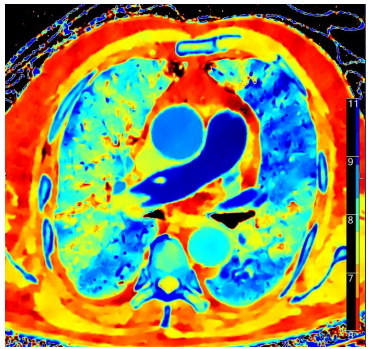
Spectral CT imaging = Multiparametric imaging modality



Mono E 40 – 200 keV

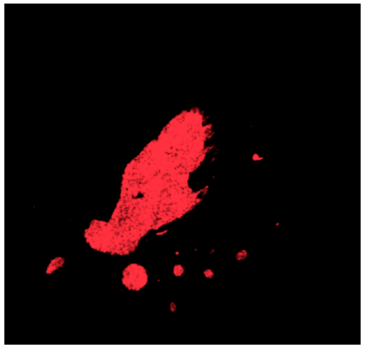


Two basis MD



Z-effectif

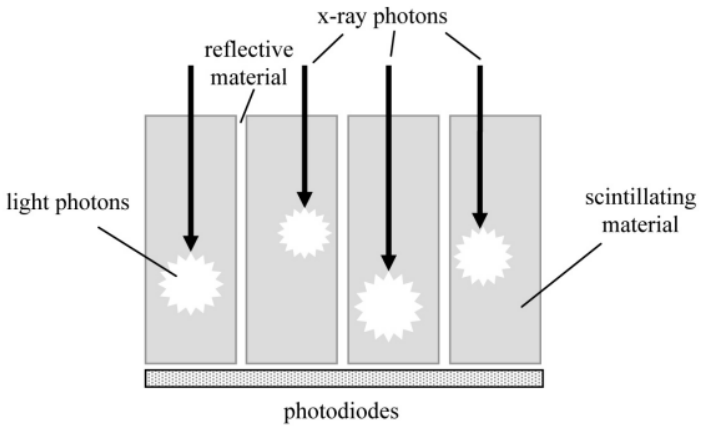
Electronic density

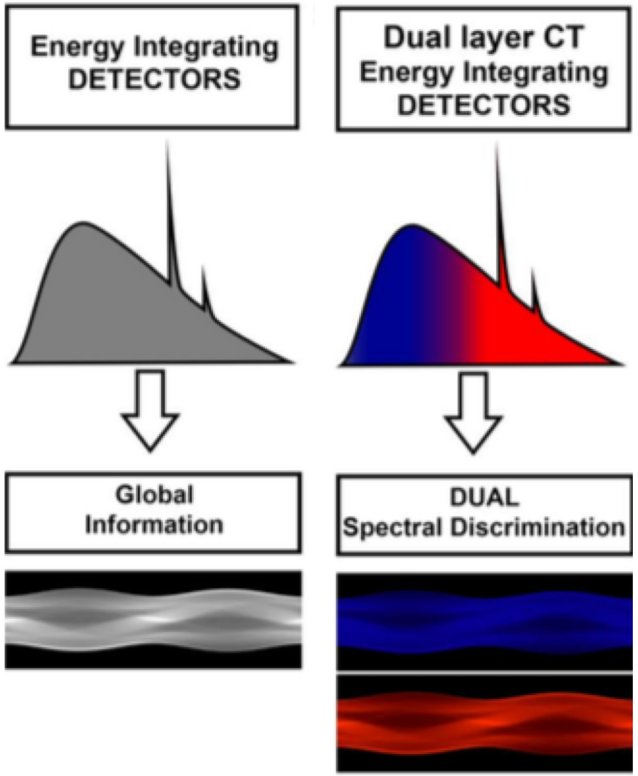


Color K-edge imaging

II. Technology

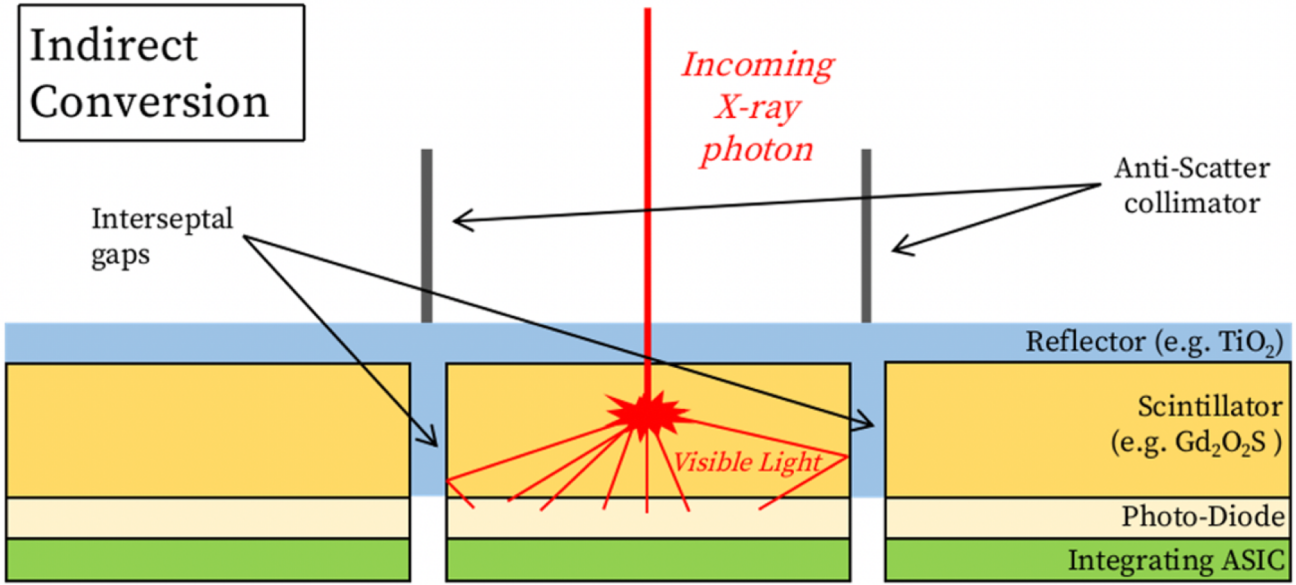
Technology





Energy integrating detectors (EIDs)

Technology



Energy integrating detectors (EIDs)

Si-Mohamed et al. Review: Spectral Photon-Counting CT technology in Chest Imaging. JCM ***2021***

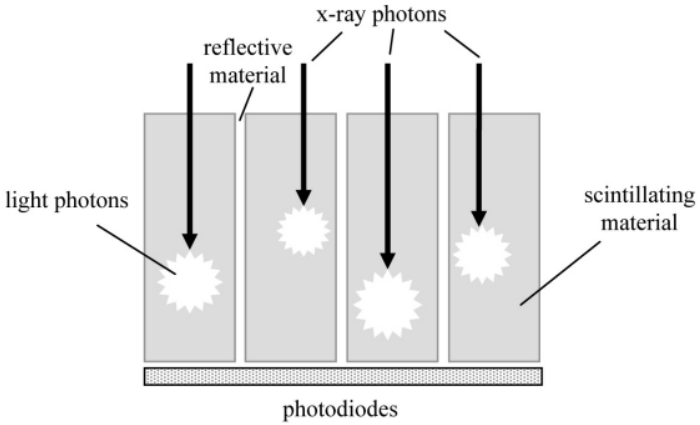
Advantages & Limitations of dual-energy CT technology

1. Perform a material decomposition of the Photoelectric and Compton effects

BUT

1. Perform a limited sampling of the transmitted spectrum in 2 energy windows
2. Limitations of EIDs:
    1. Limited spatial resolution
    2. Limited dose efficiency
    3. Absence of energy-resolving capabilites

Technology



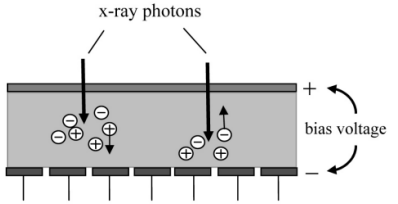
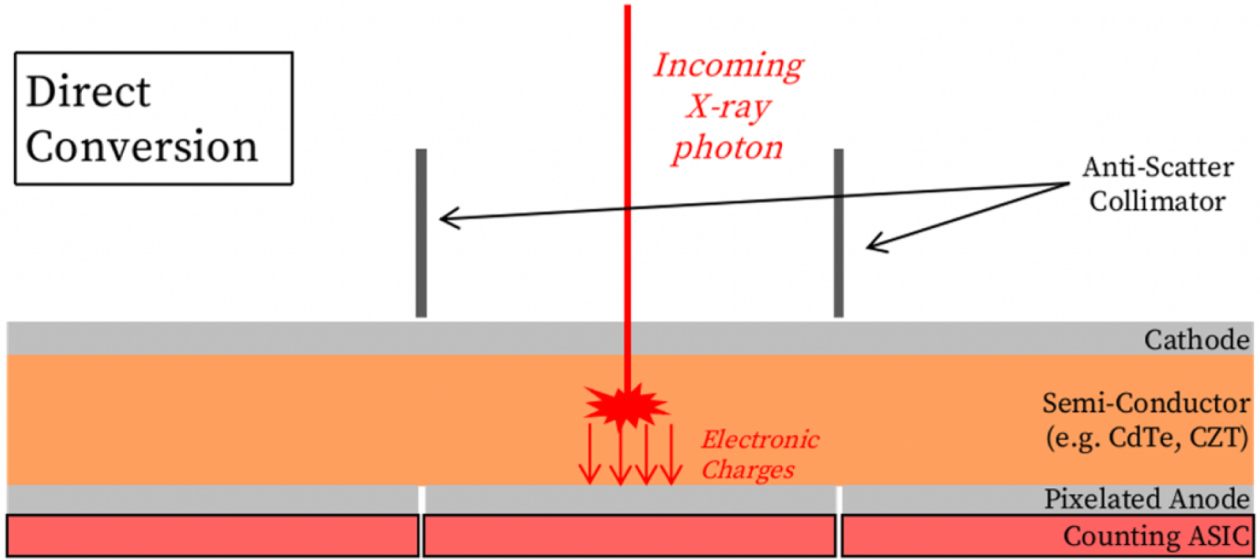


Figure 6.14 Schematic diagram of a semiconductor direct-conversion detector.

Energy integrating detectors (EIDs)

Photon-counting detectors (PCDs)

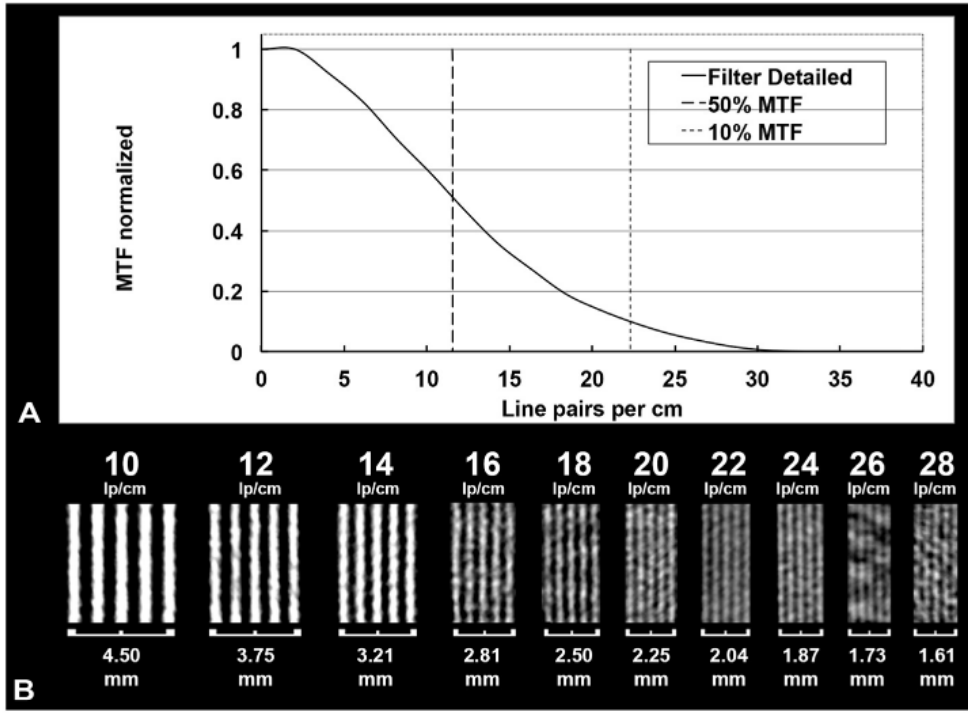
Technology



Photon-counting detectors (PCDs)

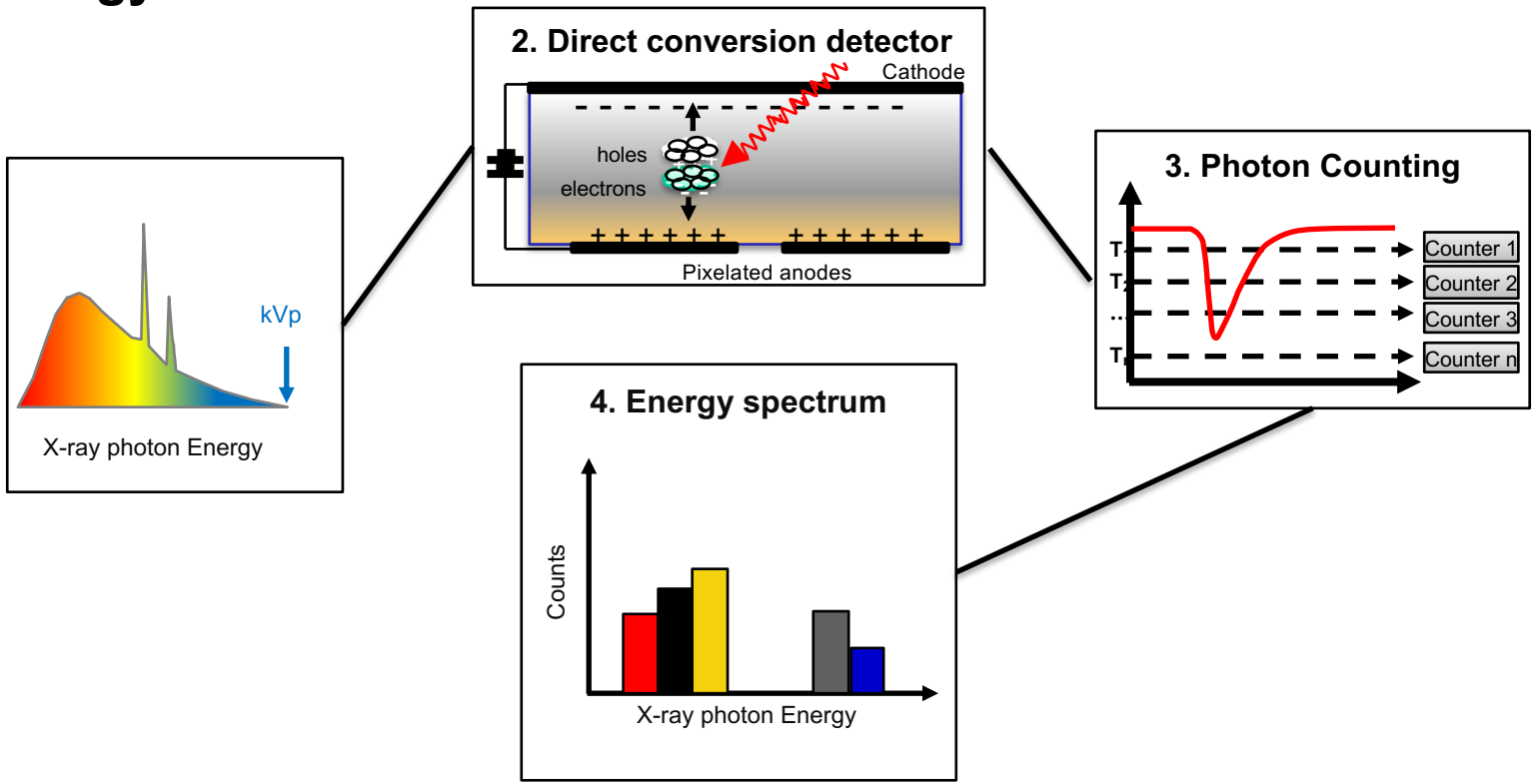
Si-Mohamed et al. Review: Spectral Photon-Counting CT technology in Chest Imaging. JCM ***2021***

Impact on spatial resolution



Si-Mohamed et al. DIII. ***2021***

Technology



Si-Mohamed et al. DIII. ***2021***

Technology

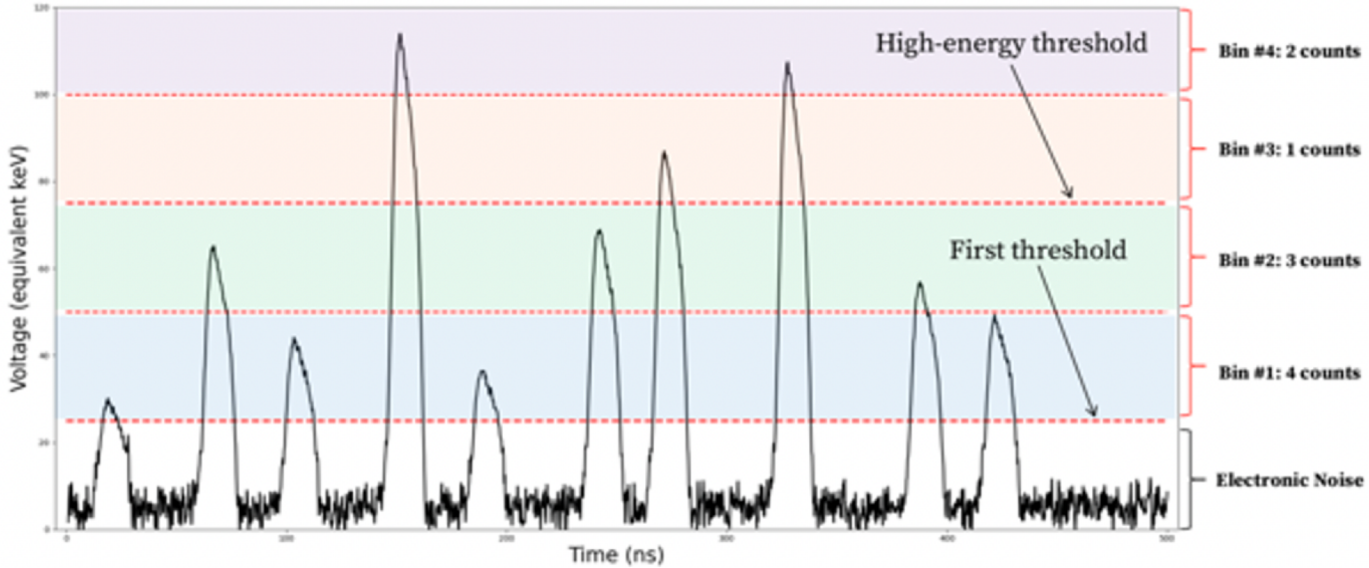
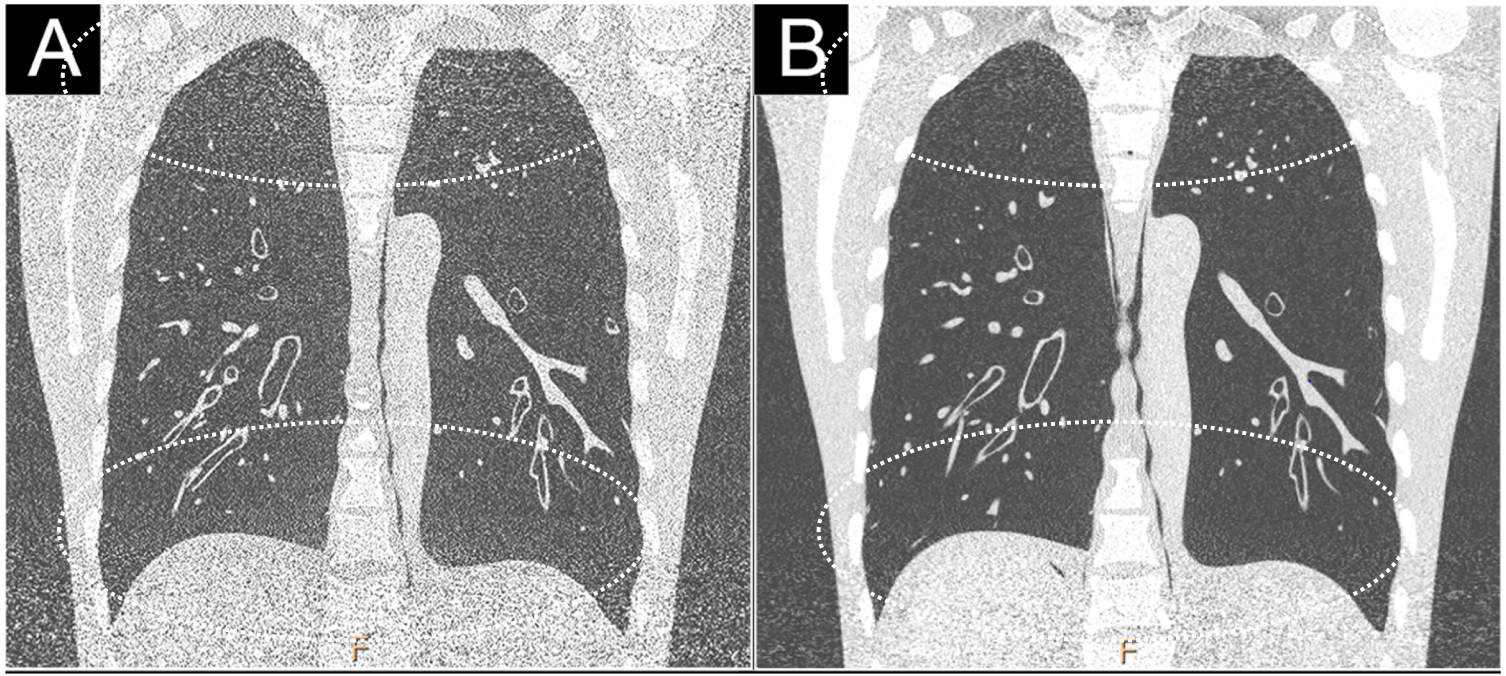


Figure 2. Example of a 500ns signal output of a PCD pixel.

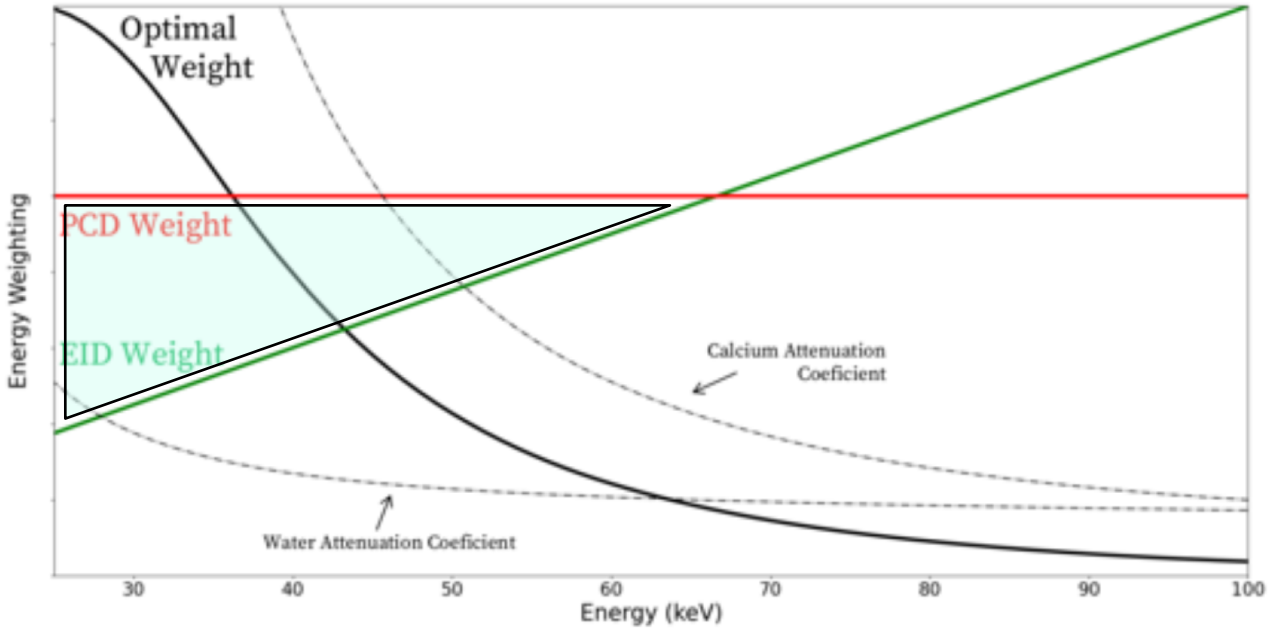
Si-Mohamed et al. Review: Spectral Photon-Counting CT technology in Chest Imaging. JCM ***2021***

Impact on the noise



Si-Mohamed et al. Review: Spectral Photon-Counting CT technology in Chest Imaging. JCM ***2021***

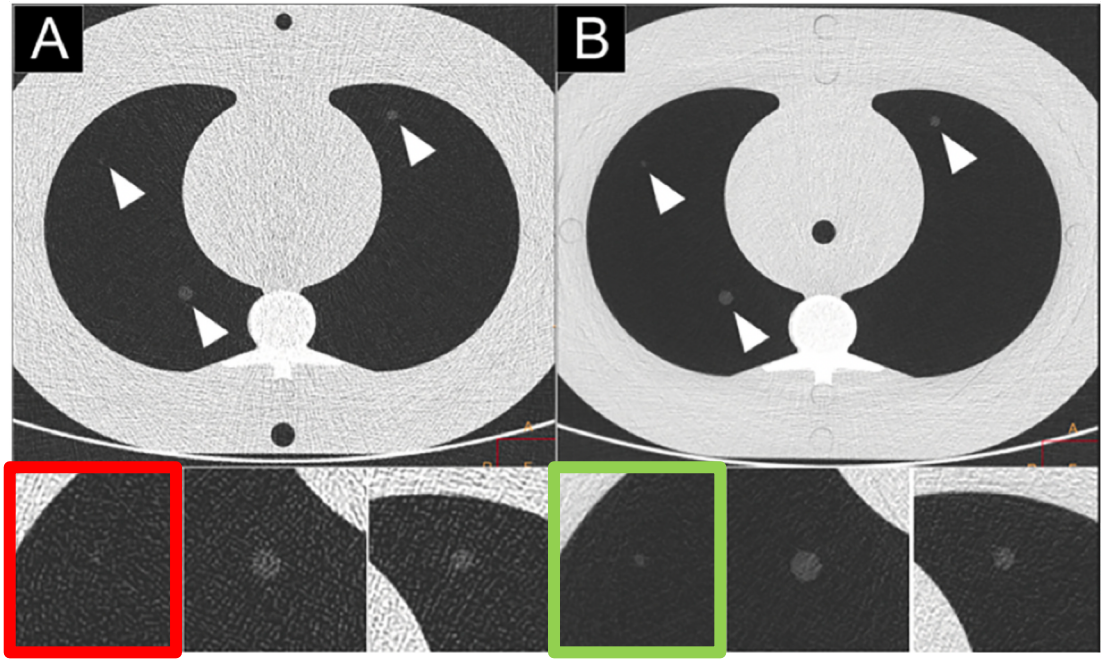
Technology



Si-Mohamed et al. Review: Spectral Photon-Counting CT technology in Chest Imaging. JCM ***2021***

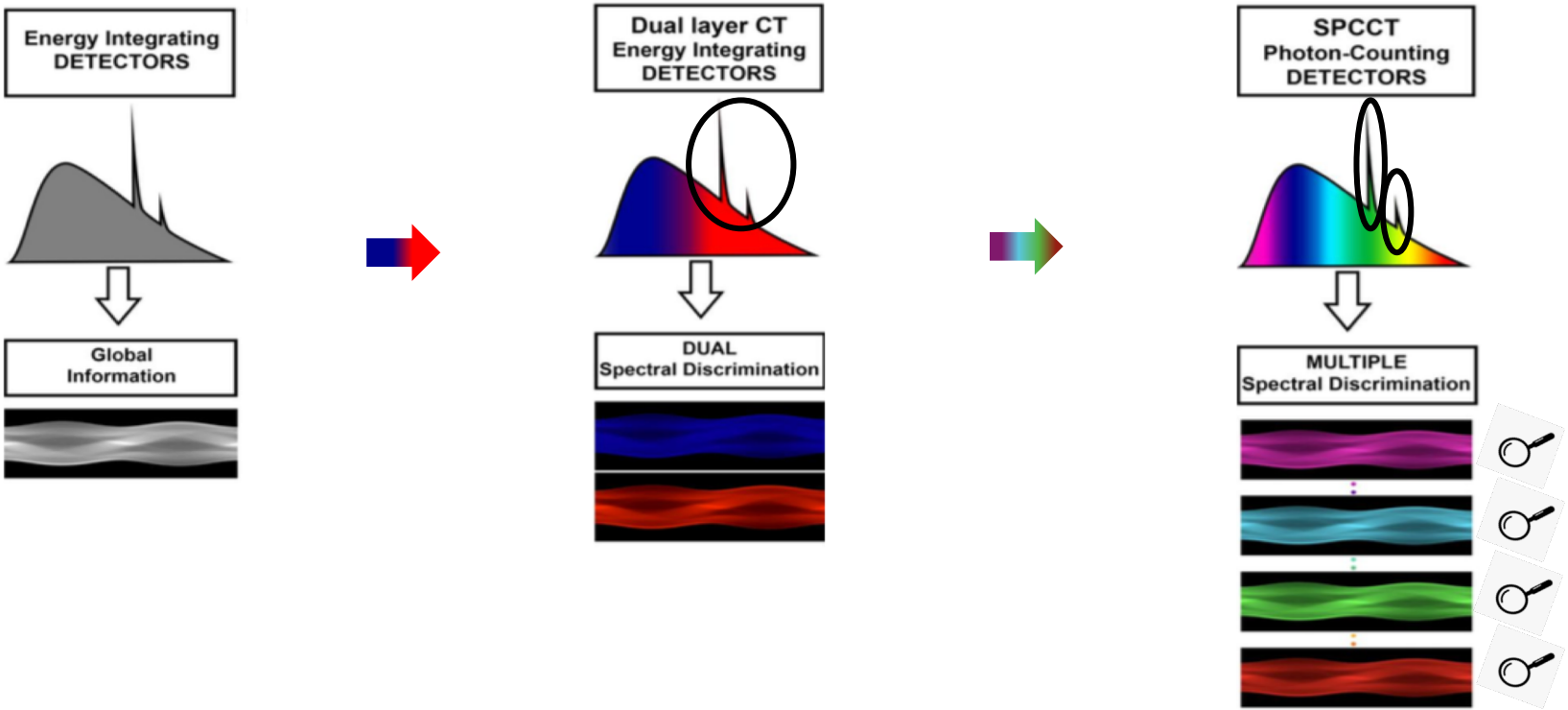
Impact on detectability

EIDs PCDs



Si-Mohamed et al. Eur Radiol. ***2021***

Technology



Si-Mohamed et al (...) Nuclear Instruments and Methods in Physics Research A 873. ***2017***

Technology

2 basis model

$$\mu(E) = \mu_P(E) + \mu_C(E) = \alpha_P f_P(E) + \alpha_C f_C(E)$$

$$\begin{cases} \mu(E_B) = \alpha_P f_P(E_B) + \alpha_C f_C(E_B) \\ \mu(E_H) = \alpha_P f_P(E_H) + \alpha_C f_C(E_H) \end{cases}$$

$(\alpha_P, \alpha_C, \alpha_{K\text{-}edge})$: tissu-)type specific

$\alpha_P = d\, Z_{eff}^3$

$\alpha_C = d\, k$

D : tissue density, et Z_{eff} : atomic number

(f_P, f_C) : energy dependant

$f_P = 1/E^3$

$f_C = 1/E^{0.3}$ = ***Klein and Nishina*** fonction

E : photon energy

3 basis model

$$\mu(E) = \mu_P(E) + \mu_C(E) + \mu_{K\text{-}edge}(E)$$

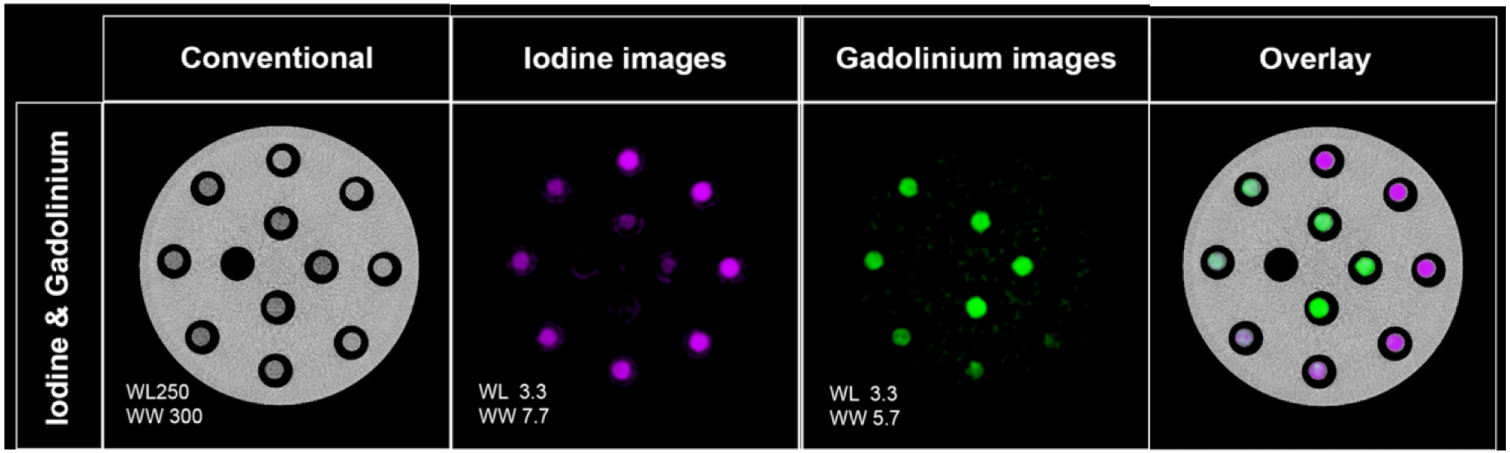
$$\mu(E_{bin\ 1}) = \alpha_P f_P(E_{bin\ 1}) + \alpha_C f_C(E_{bin\ 1}) + [C^\circ]_{K\text{-}edge}\, \mu_{K\text{-}edge}(E_{bin\ 1})$$

$$\mu(E_{bin\ 2}) = \alpha_P f_P(E_{bin\ 2}) + \alpha_C f_C(E_{bin\ 2}) + [C^\circ]_{K\text{-}edge}\, \mu_{K\text{-}edge}(E_{bin\ 2})$$

$$\mu(E_{bin\ X}) = \alpha_P f_P(E_{bin\ X}) + \alpha_C f_C(E_{bin\ X}) + [C^\circ]_{K\text{-}edge}\, \mu_{K\text{-}edge}(E_{bin\ X})$$

PHYS. MED. BIOL., 1976, VOL. 21, NO. 5, 733–744.

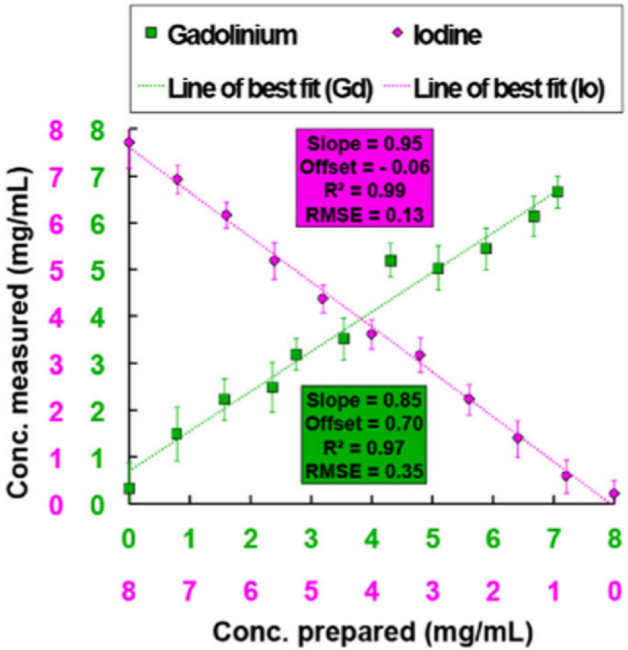
Color K-edge imaging

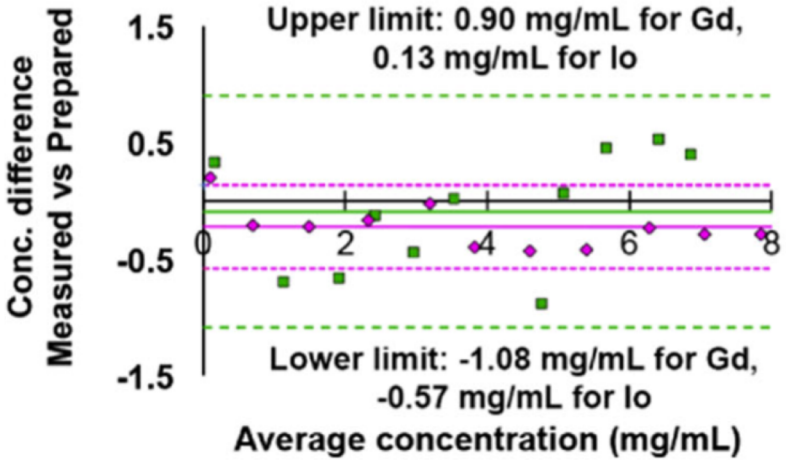


➢ Absolute quantification of multi-contrast agent imaging

Si-Mohamed et al. Eur Rad Exp. ***2018***

Color K-edge imaging





- Absolute quantification of multi-contrast agent imaging

Si-Mohamed et al. Eur Rad Exp. ***2018***

Advantages & Limitations of multi-energy SPCCT technology

1. Improve the intrinsic spatial resolution
2. Reduce the electronic noise
3. Improve the contrast
4. Perform a more accurate sampling of the transmitted spectrum
5. Identify the photoelectric effect of a contrast agent around its K-edge energy
6. Provide unprecedented specific and quantitative imaging of a contrast agent

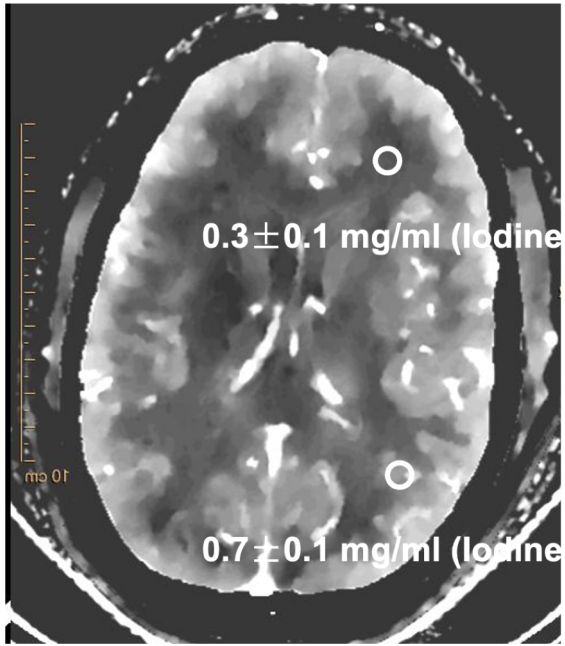
BUT

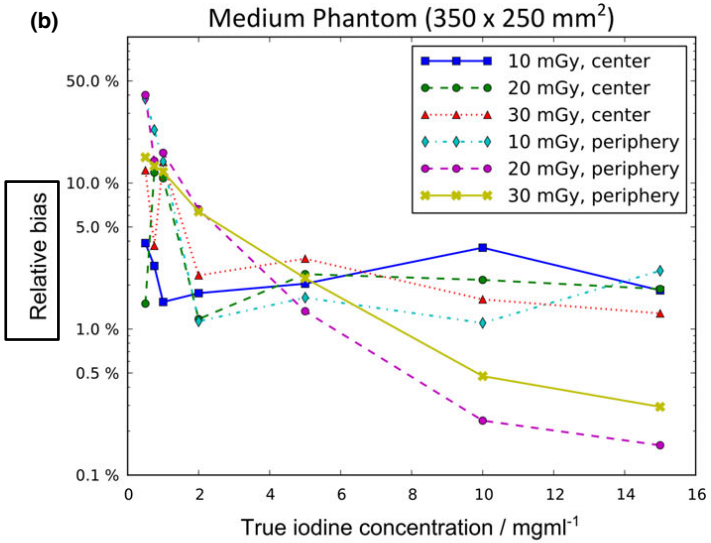
Emerging technology in need of development & validation

III. Current applications of Spectral CT imaging

Clinical applications in need of quantification

❖ Iodine and water images enables to quantify physiopathological process



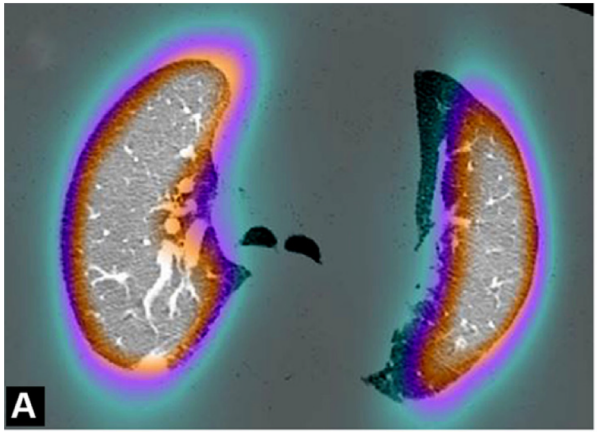


Ehn et al. JACMP. ***2017***

Clinical applications in need of functional imaging

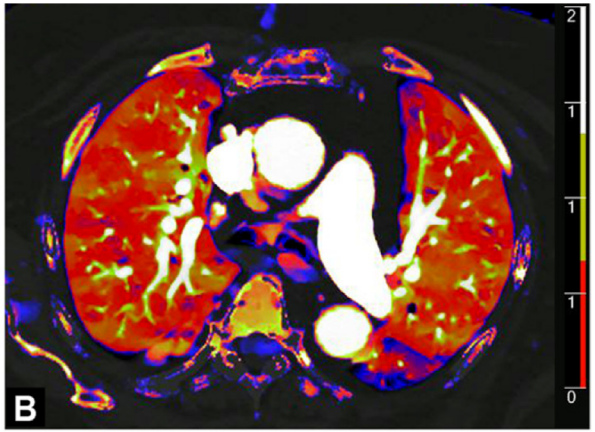
❖ **Iodine images provides a functional imaging of diseases**

Nuclear imaging (SPECT/CT)



Functional imaging

Iodine image



Functional imaging

Si-Mohamed et al. In vivo demonstration of pulmonary microvascular involvement in COVID-19 using dual-energy computed tomography. ERJ. ***2020***

Clinical applications in need of functional imaging

❖ **Iodine images provides a functional imaging of diseases**

- Sars-COV2
- First phase

Conventional image **PBV** Iodine image

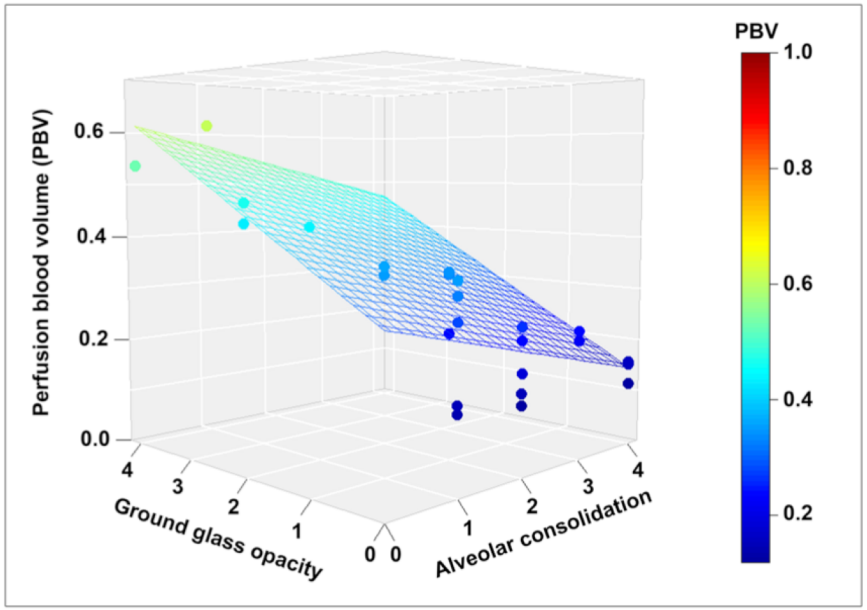
Morphology imaging Functional imaging

Si-Mohamed et al. In vivo demonstration of pulmonary microvascular involvement in COVID-19 using dual-energy computed tomography. ERJ. ***2020***

Clinical applications in need of functional imaging

❖ **Functional imaging provides a characterization of disease course**

- Sars-COV2
- Disease course

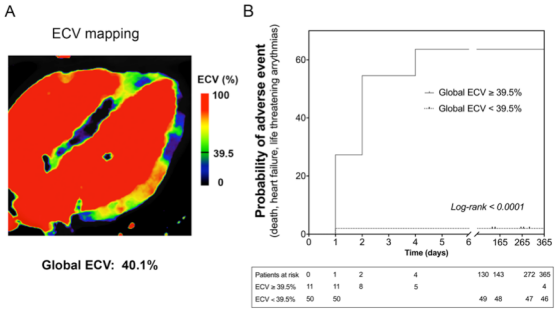


Si-Mohamed et al. In vivo demonstration of pulmonary microvascular involvement in COVID-19 using dual-energy computed tomography. ERJ. ***2020***

Clinical applications in need with multimodality imaging

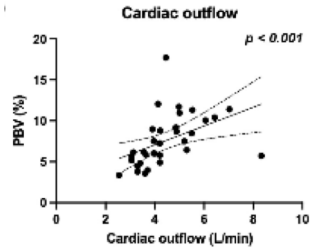
❖ Tissue characterization

MRI



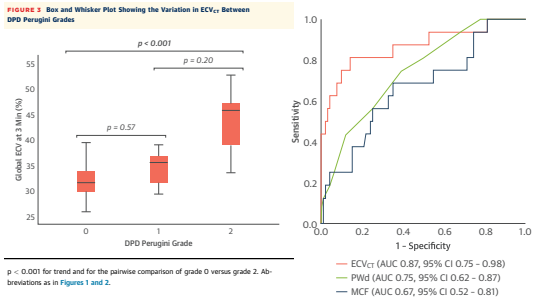
Si-Mohamed et al. JACC: CV imaging. ***2021***

Invasive right heart catheterization



Si-Mohamed et al. JCM. ***2023***

Nuclear imaging

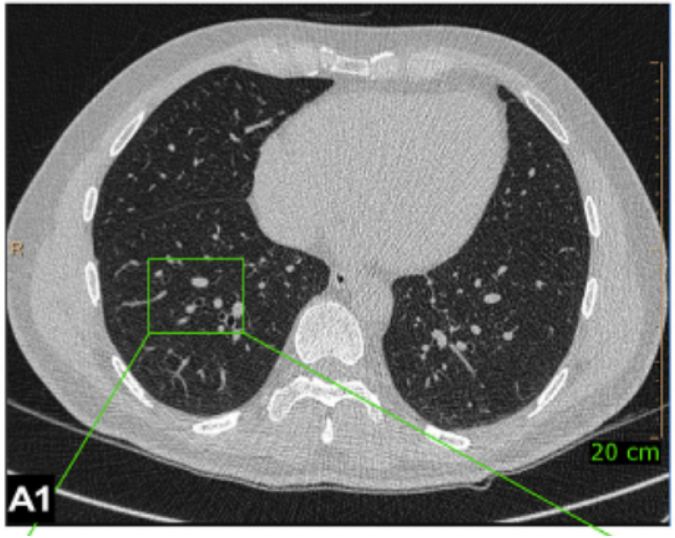


Scully P.R. et al. JACC: CV imaging. ***2020***

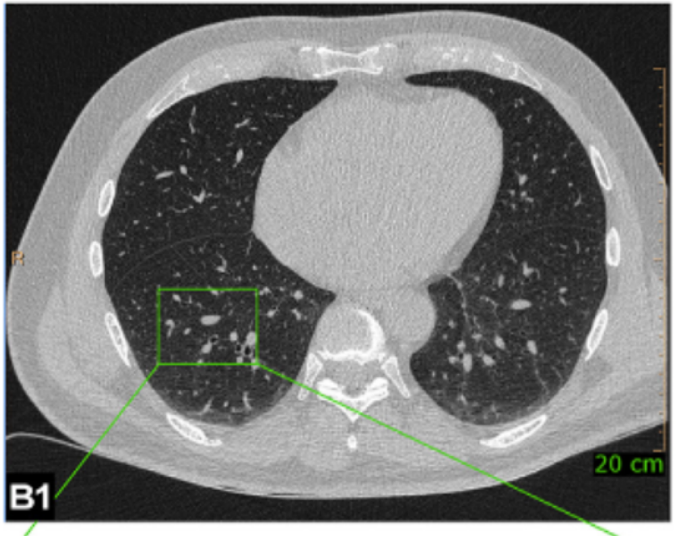
IV. Incremental applications of spectral photon–counting CT

Detection of elementary structures

Conventional CT
120 kVp/103 mAs
FBP/SW 0.800 mm

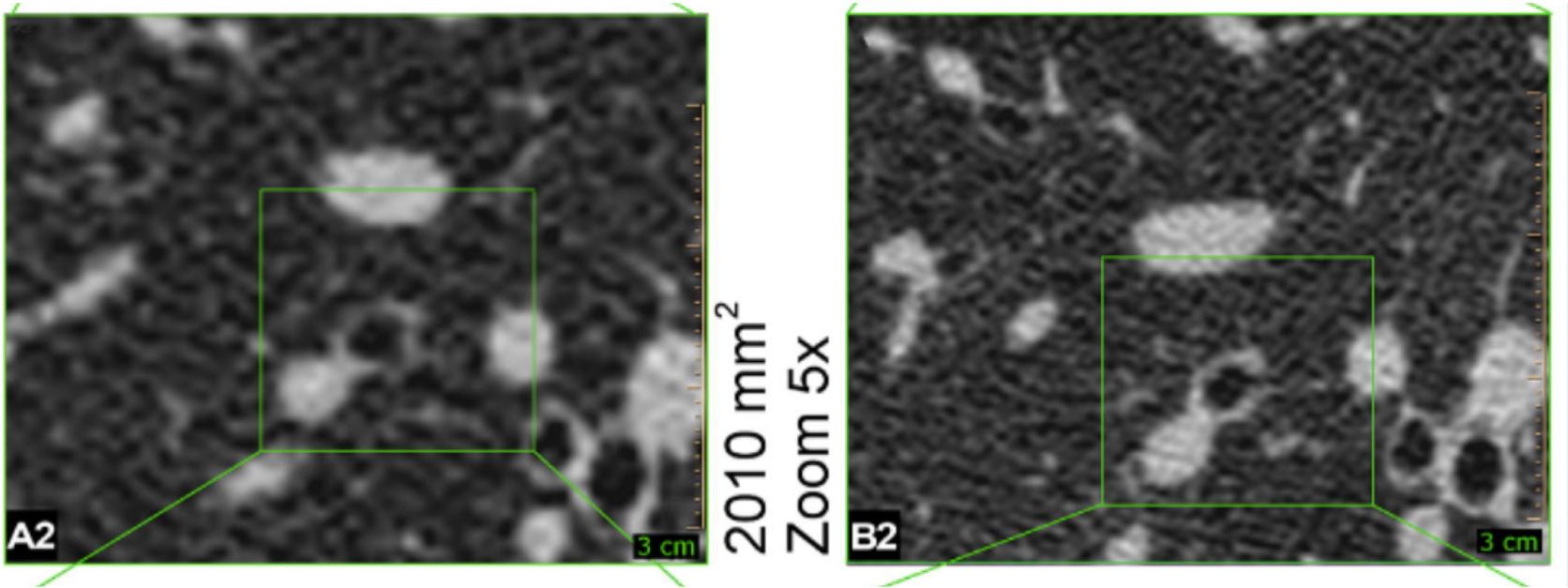


SPCCT
120 kVp/63 mAs
FBP/SW 0.250 mm



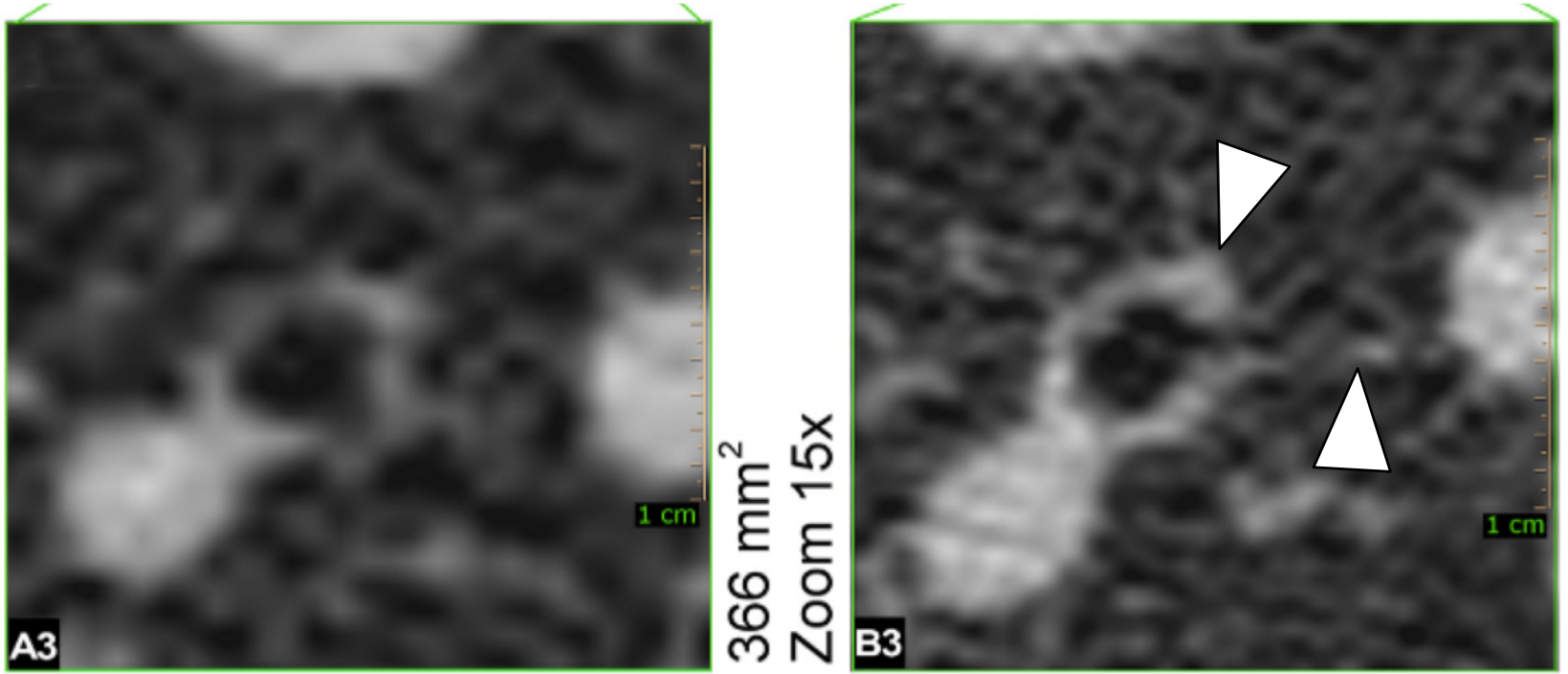
Si-Mohamed et al. DIII. ***2021***

Detection of elementary structures



Si-Mohamed et al. DIII. ***2021***

Detection of elementary structures

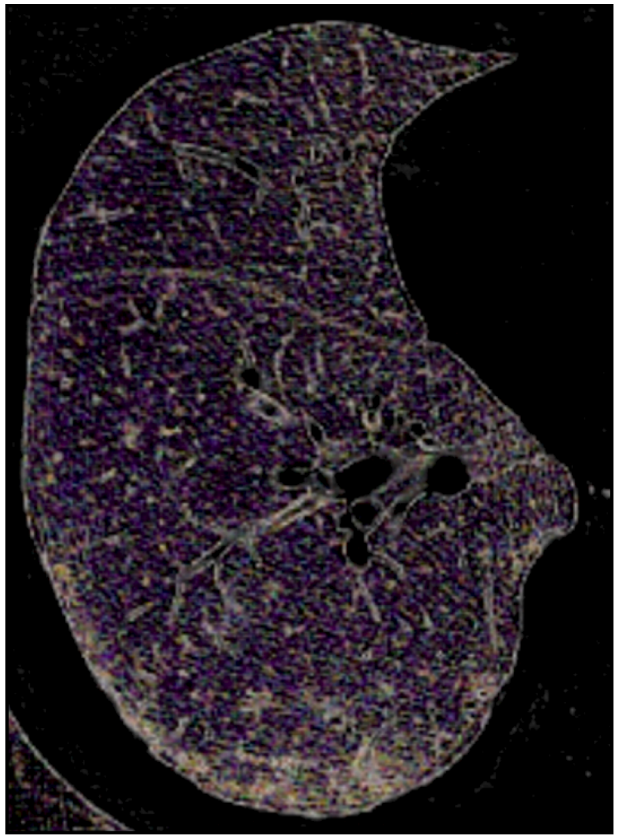


Si-Mohamed et al. DIII. ***2021***

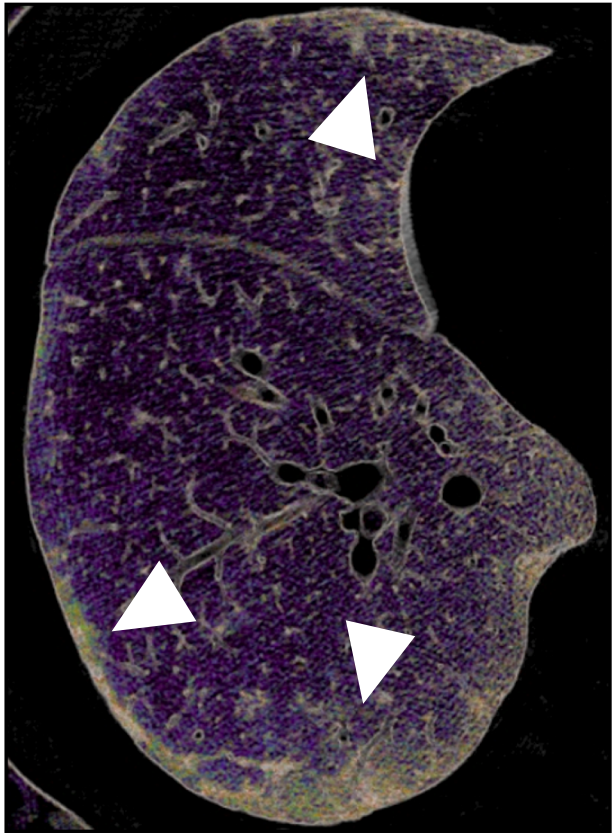
Quantification of elementary lesions

W, 39 yo
SSc

HRCT



SPCCT



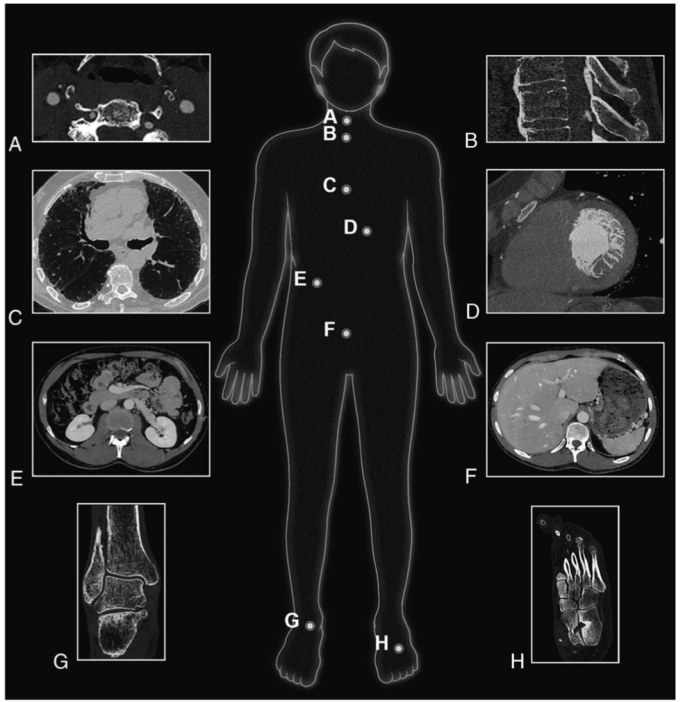
MD thesis of A. Bleunven. JFR. ***2023***

Clinical impact of Spectral CT imaging

1. Earlier detection of disease
2. More precise diagnosis
3. More reliable diagnosis
4. Substitutive of invasive imaging

BUT

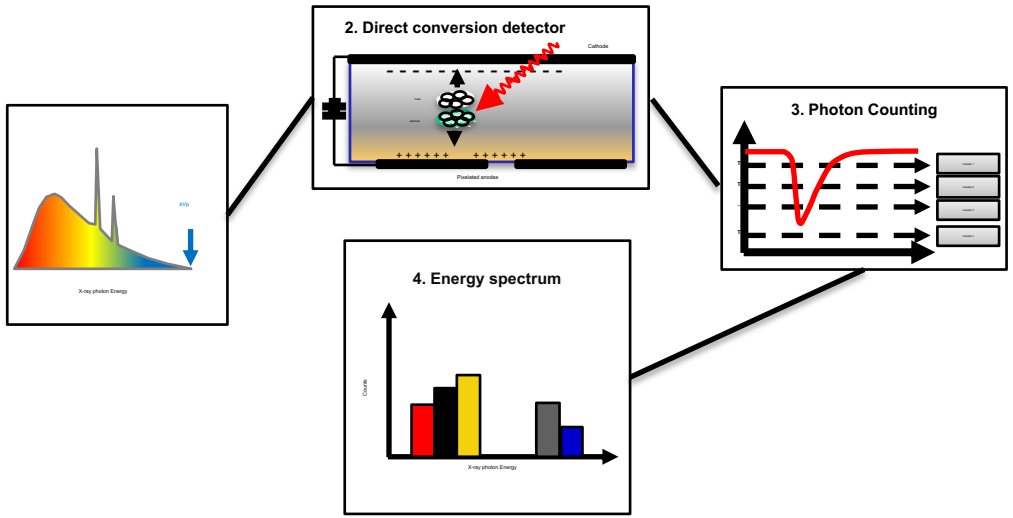
1. Need to adapt the work flow
2. Need to retrain the semiology

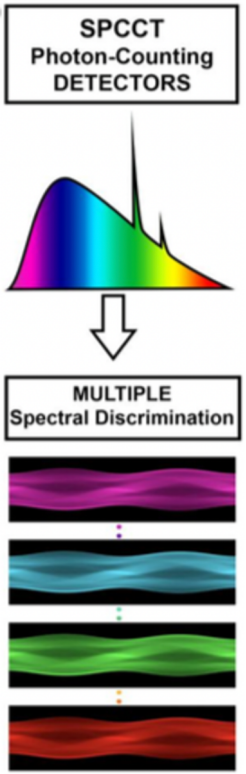


Si-Mohamed et al. Inv Radiol. ***2023***

V. Cutting edge applications

Color K-edge imaging



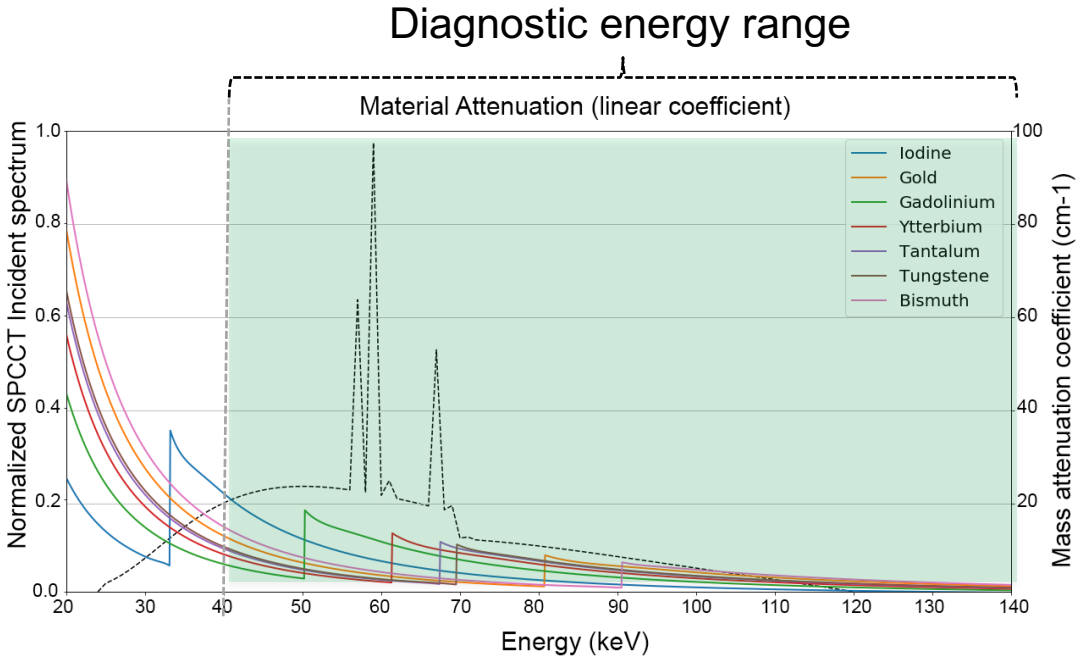


Multiple sampling of energy-dependent information to **detect** the K-edge energy-specific attenuation of a material and **quantify** its concentration

Si-Mohamed et al. Nuclear Instruments and Methods in Physics Research. ***2017***

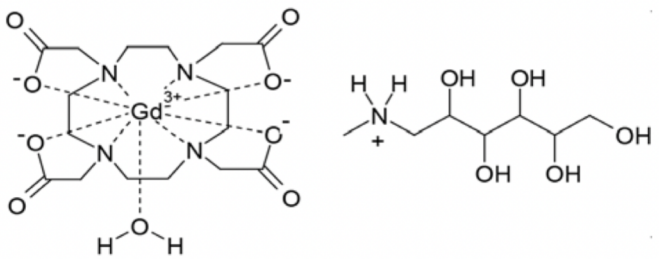
Color K-edge contrast agents

Iodine K-edge
33.3 keV

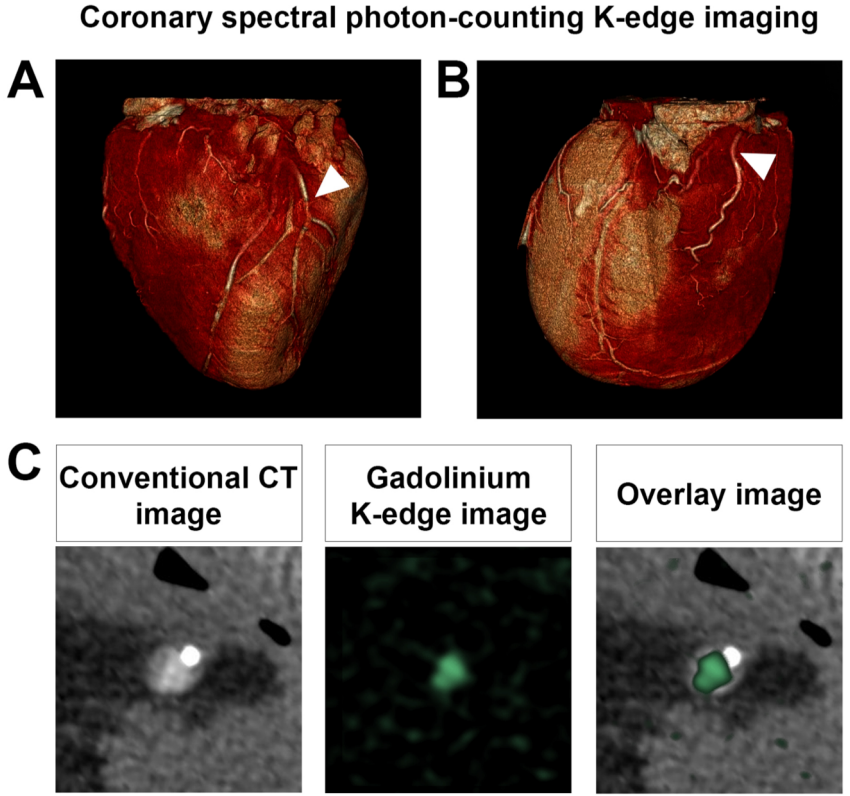


➢ Need to develop and validate dedicated K-edge contrast agents

Color K-edge coronary angiography



Acide gadotérique, 0.5 M (Dotarem)



Si-Mohamed et al. RSNA. Poster. ***2017***

Color K-edge aortic angiography

Hybrid Nano-GdF3 Contrast Media

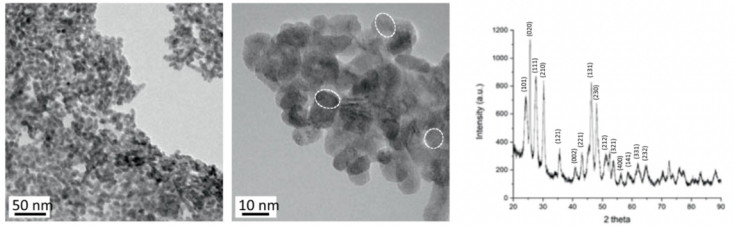


Figure 1. Transmission Electron Microscopy of GdF_3 nanoparticles (left); High resolution of the crystalline nanoparticles (middle) and powder X-Ray Diffraction pattern (right).

Conventional images

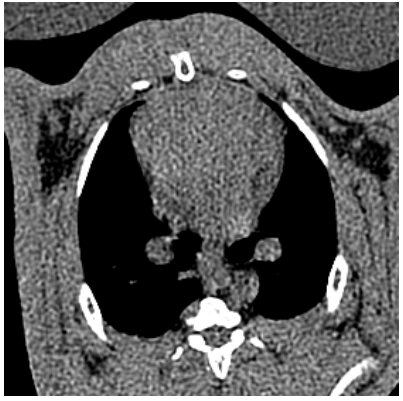
K-edge images

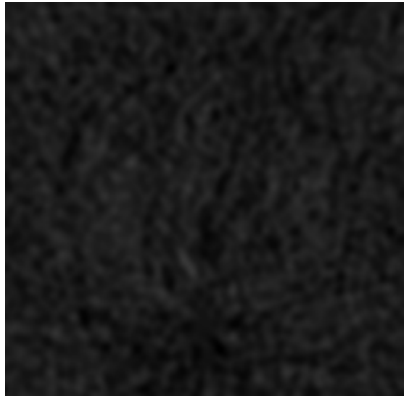
ENS DE LYON
LABORATOIRE DE CHIMIE ENS DE LYON

Halttunen, Niki et al. Scientific Reports, ***2019,*** *Boccalini et al. DIII.* ***2022***

Color K-edge myocardial perfusion

Development of a 1.25 M (700 mg/ml) of gadoteridol





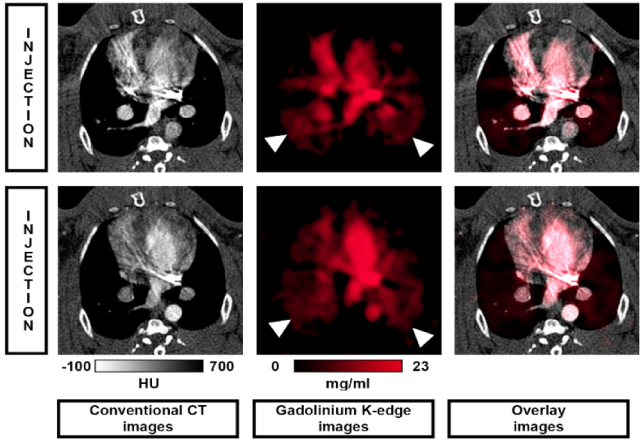
Giuseppe Digilio

Assistant Professor

Dipartimento di Scienze e Innovazione Tecnologica DISIT

Amedeo Avogadro University of Eastern Piedmont

Academic profile



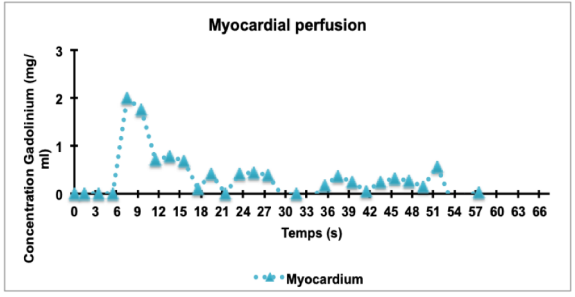
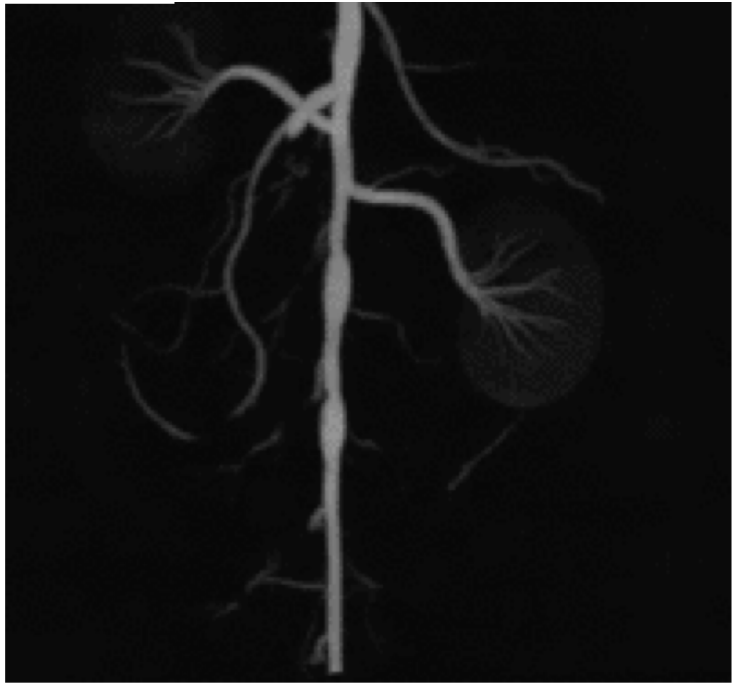


Figure. Dynamic K-edge SPCCT angiography with a high concentrated gadolinated contrast agent (Bracco, Milan, Italy) allowing for the vizualisation of the lung and myocardium enhancement. The Kedge images allow a quantitative analysis for myocardial perfusion as shown on the graph with a peak value found to be around 2 mg/mL

Si-Mohamed et al. Poster RSNA. ***2017***

Color K-edge atherosclerotic aortic angiography

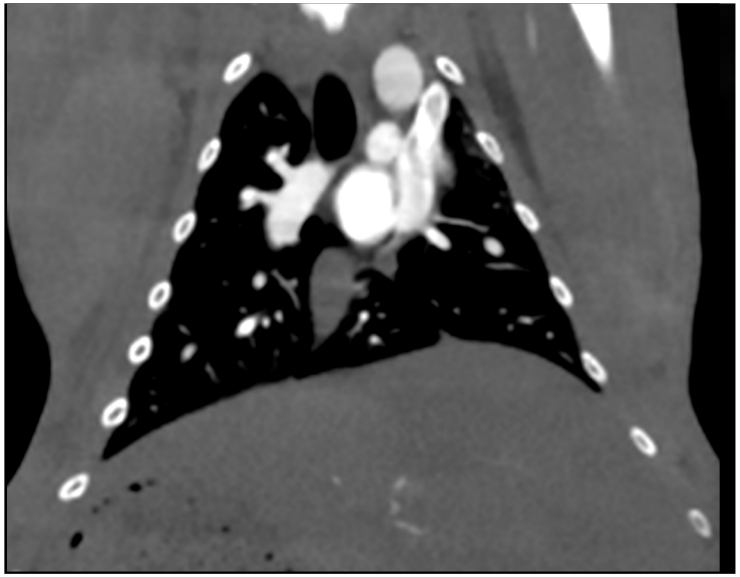


Patent N° 22306578.0

Color K-edge lung perfusion imaging

Conventional imaging

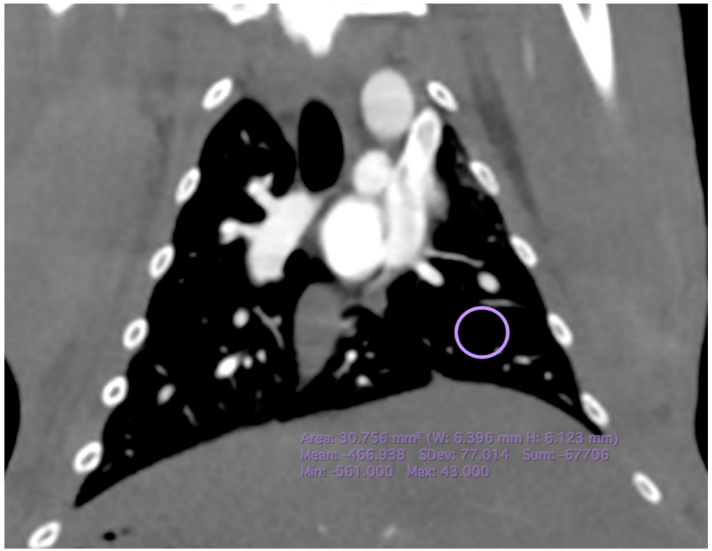
Functional Color K-edge imaging



Patent N° 22306578.0

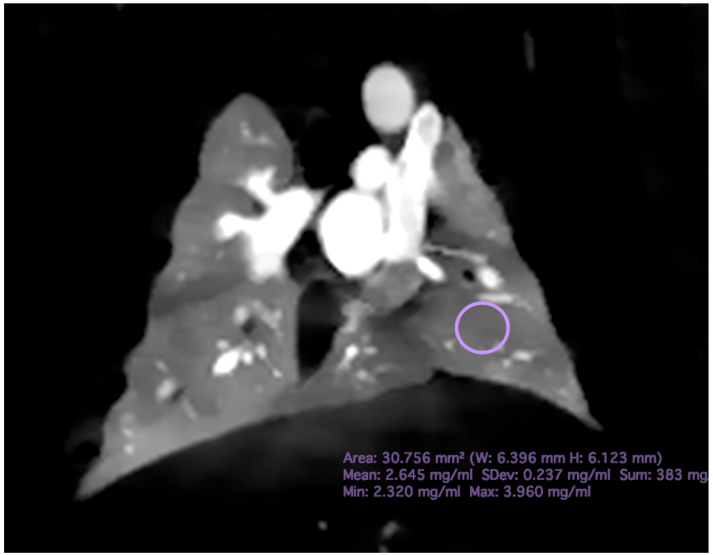
Color K-edge lung perfusion imaging

Conventional imaging



Only relative attenuation of -466 HU

Functional Color K-edge imaging

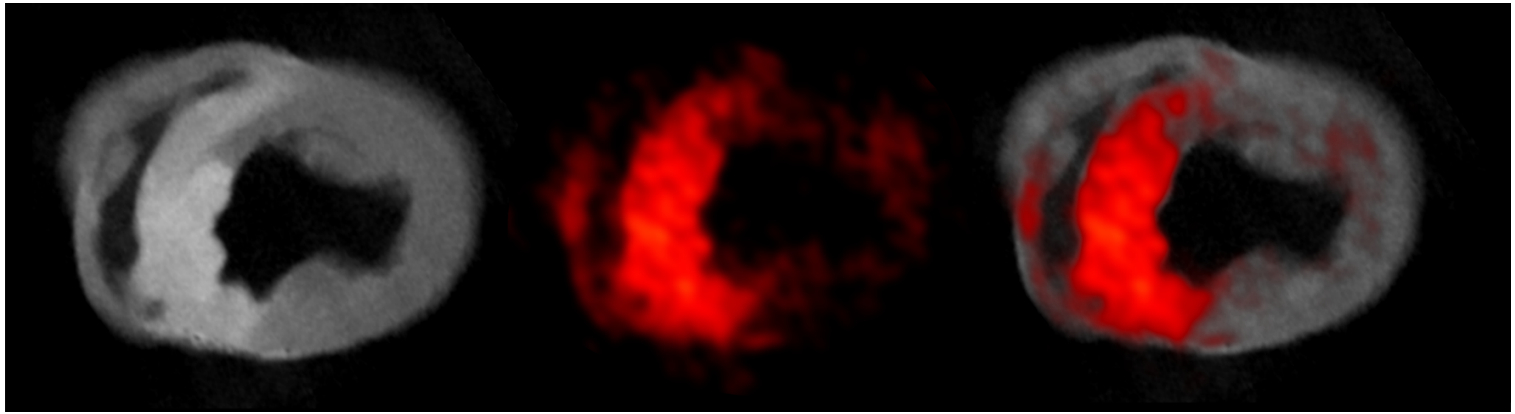


Absolute C° of 2.6 mg/mL

Patent N° 22306578.0

Color bi-modal K-edge myocardial infarction imaging

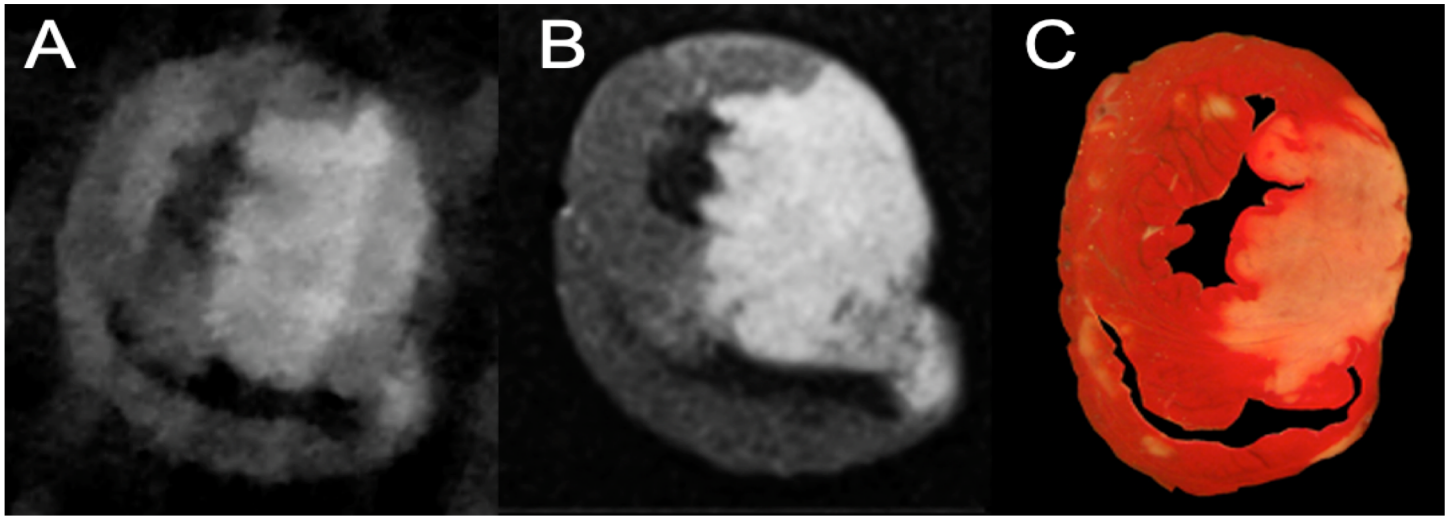
Conventional CT | Color K-edge | Fusion



Patent N° 22306578.0

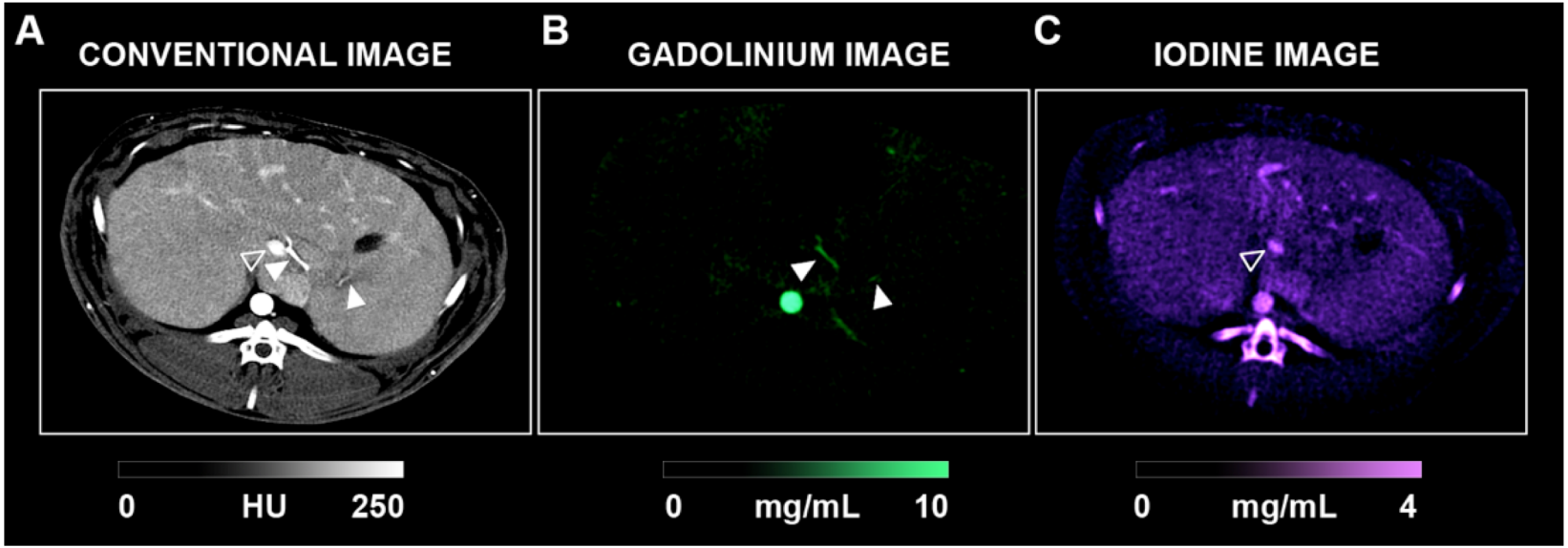
Color bi-modal K-edge myocardial infarction imaging

SPCCT | Cardiac MR | Staining TTC



Patent N° 22306578.0

Bi-Color functional K-edge imaging



➢ **Simultaneous imaging of 2 physiological processes**

Si-Mohamed et al. Sci Reports. ***2019***

Molecular functional color K-edge imaging

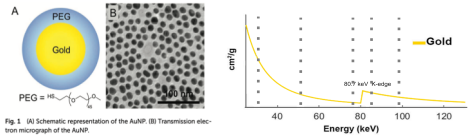
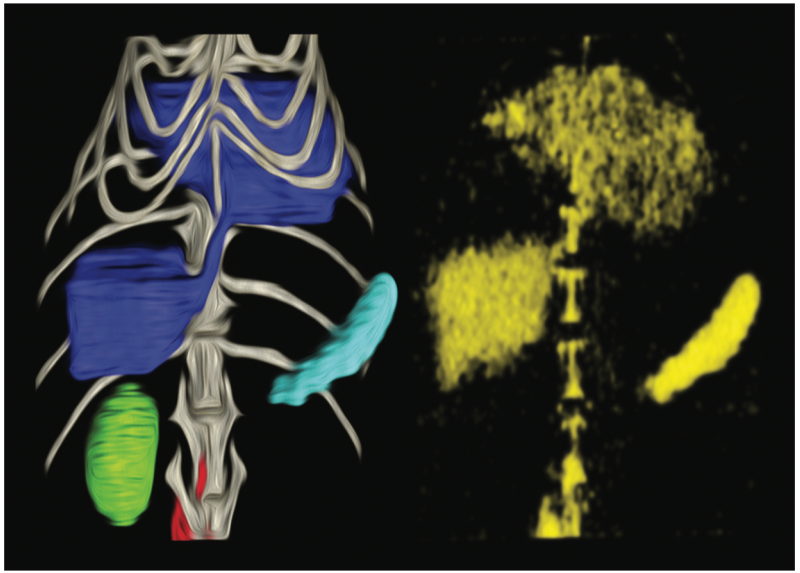
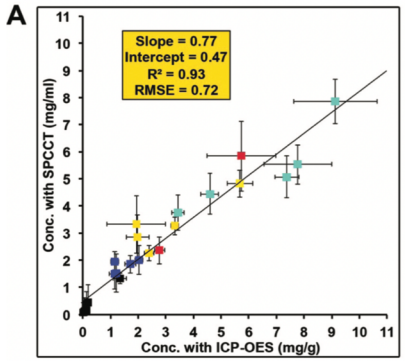
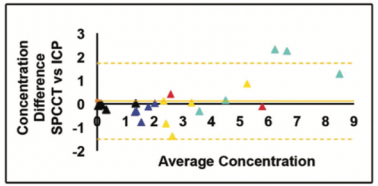
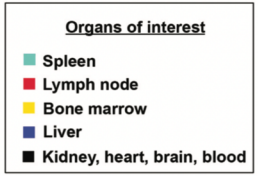


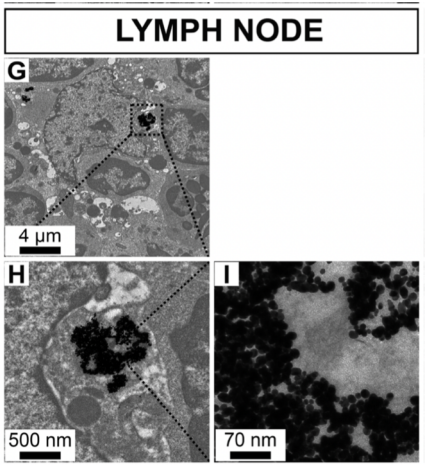
Fig. 1 (A) Schematic representation of the AuNP. (B) Transmission electron micrograph of the AuNP.





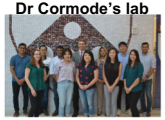






Si-Mohamed et al. Nanoscale. **2017**

Dr Cormode's lab



Nanomedicine and Molecular Imaging Lab

Molecular functional bi-color K-edge imaging

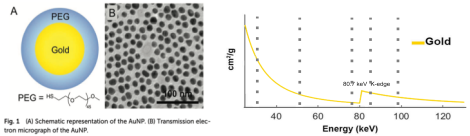
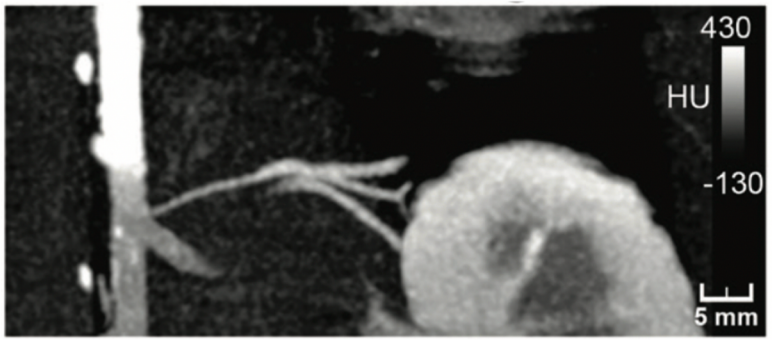
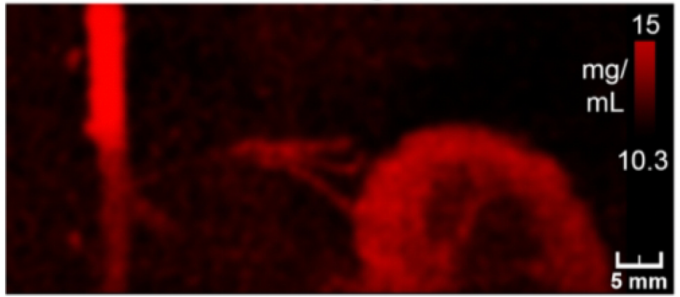


Fig. 1 (A) Schematic representation of the AuNP. (B) Transmission electron micrograph of the AuNP.

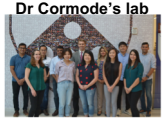


Gold K-edge image

Iodine image



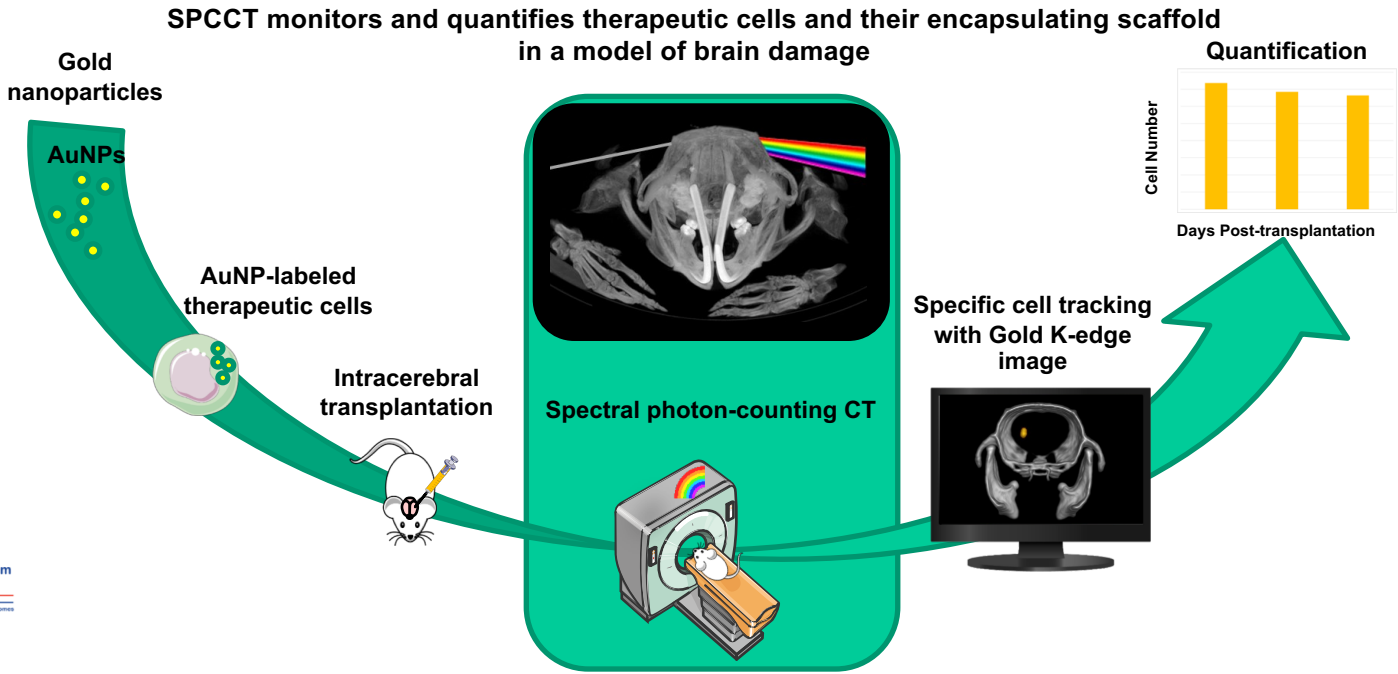
Dr Cormode's lab



Nanomedicine and Molecular Imaging Lab

Si-Mohamed et al. Radiology. **2021**

Bi-color K-edge imaging for cell tracking



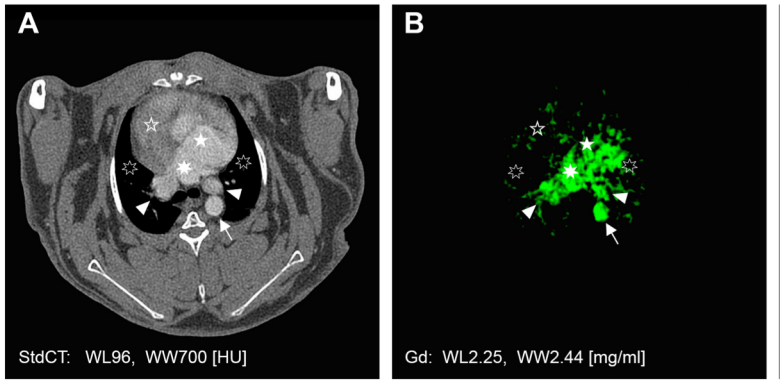
Cuccione et al. NanoTheranostics **2020**

Theranostic imaging

Conventional imaging

Color K-edge imaging with a radioluminescent contrast agent

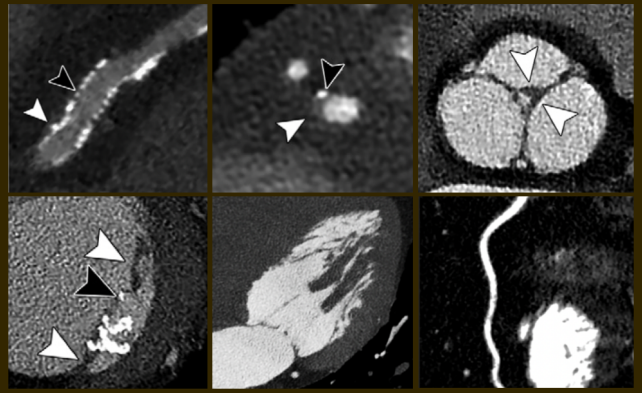
Luminescence induced by X-rays for dynamic phototherapy



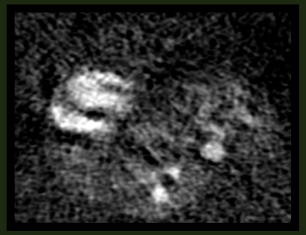
Halttunen et al. Sci Rep **2019**
Cuau et al. Nanoscale. **2024**

Versatility of Spectral CT imaging

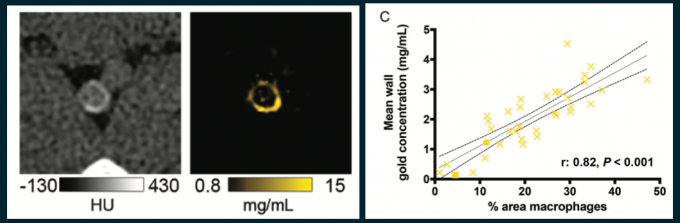
Spectral ultra-high resolution imaging with lower X-ray dose and higher contrast



Color functional imaging

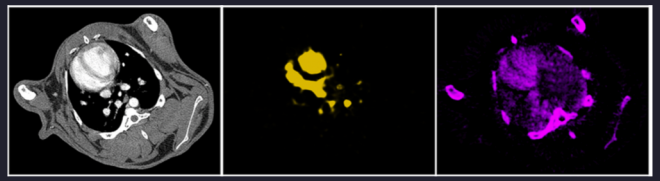


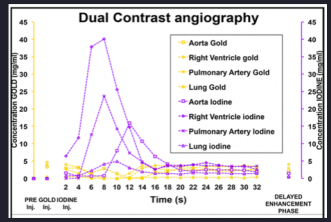
Color molecular imaging



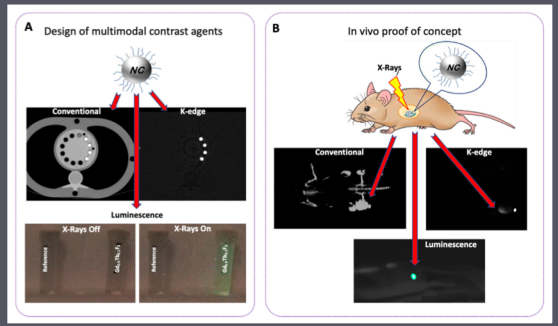
SPCCT
IMAGING ALL THE PHOTONS

Multi-color imaging

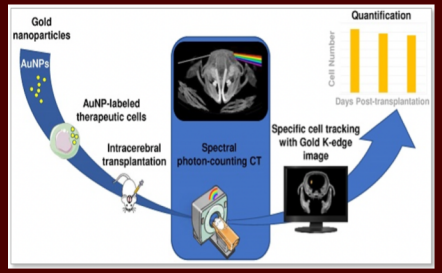




Luminescence Color imaging

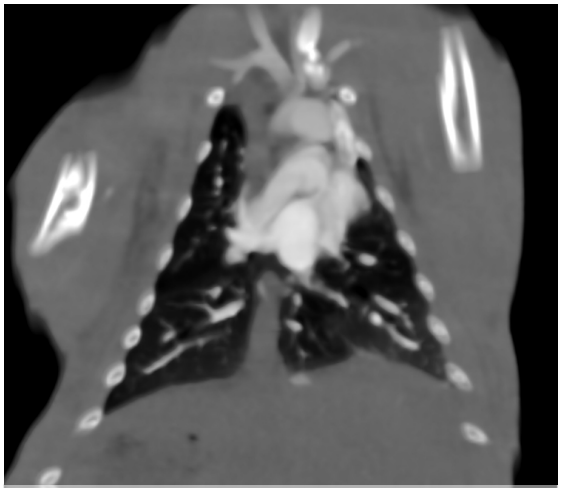


Multicolor Cell tracking

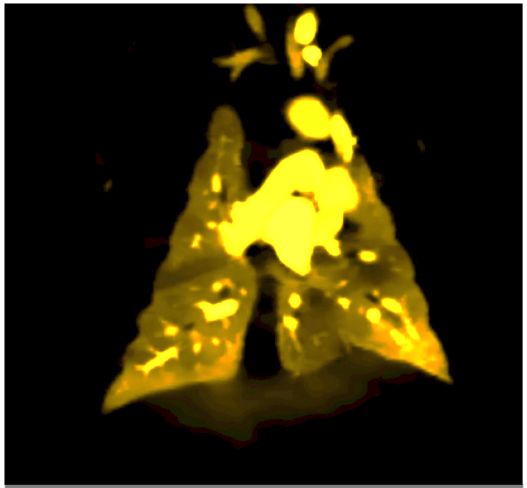


Starting Grant

« The time has come to color lung diseases »



KOLOR SPCCT
IMAGING



April 2024 for 5 years
Positions available !!
Post-doc, PhD, Eng, MSc

ERC starting grant : KOLOR SPCCT Imaging

However, patience is required

Table 6. Main characteristics of current spectral photon-counting CT systems suitable for clinical imaging. Note that 2 of them are designed with small bore gantry for head (Samsumg Healthcare) and for extremities (MARS Bioimaging limited system) imaging and that 2 of them have been FDA-cleared (Siemens Healthineers and Samsumg Healthcare).

Manufacturer	CT plateforms	PCD materials	Geometry	Detector size at isocenter	Field-of-view	Energy thresholds	Current status
Canon Healthcare	Aquilion ONE VISION	CdZT	Mono-source	0.342 mm	50 cm	6 available	Clinical prototype system; Not cleared or approved by the U.S. FDA or any other global regulator for commercial availability; Clinical trial pending
GE Healthcare	LightSpeed VCT CT Scanner	Silicon	Mono-source	0.250 mm	?? cm	8 available	CT performances evaluation on going; Not cleared or approved by the U.S. FDA or any other global regulator for commercial availability
MARS Bioimaging Limited (MBI)		CdZT	Mono-source	0.110 mm	11 cm	5 in "charge summing mode"	Not cleared or approved by the U.S. FDA or any other global regulator for commercial availability; Pre-clinical research; Clinical trail pending
Philips Healthcare	Philips iCT plateform	CdZT	Mono-source	0.274 mm	50 cm	5 in standard mode; 5 in HR modes	CT performances evaluation on going; Not cleared or approved by the U.S. FDA or any other global regulator for commercial availability; Clinical trial pending
Samsumg Healthcare	OmniTom Portable PCD Head CT	CdT	Mono-source	0.12 mm (UHR); 0.4 mm (HR); 0.7 mm (standard)	25 cm	3 available	Clinical research on Human; FDA-cleared in march 2022; Clinical trial pending
Siemens Healthineers	NAEOTOM Alpha	CdT	Dual-source	0.300 mm (standard); 0.150 mm (HR)	50 cm; 36 cm used for cardiac scans; 36 cm for high helical pitch scans	4 in standard mode; 2 in HR mode	FDA-cleared in september 2021; Pre-clinical and Clinical research on HumanFDA-cleared in september 2021; Commercially available

Footnote. Parameters listed are based on the current status of the manufacturer's development and are expected to evolve in a near future. Cd: Cadmium, Z: zinc, T: telluride.

Conclusion

Spectral CT imaging promises to push back the limits of conventional imaging by :

- Providing **incremental improvement** of current applications
- Providing **paradigm shift** for current applications
- Offering new **high-resolution morpho-functional applications** at the forefront of biology, chemistry, medical imaging, bio-engineering

High potential for improving the current state-of-care

High potential for improving the patients's survival

Principle, technology and cutting-edge applications of Spectral CT imaging

Follow us

kolor spcct imaging

https://www.spectralphotoncountingct.com/

Speaker: Salim A. Si-Mohamed (MD, PhD), Associate Professor
salim.si-mohamed@chu-lyon.fr, https://www.spectralphotoncountingct.com/

Affiliations
[a] – Hôpital cardiothoracique et vasculaire, Louis Pradel, Lyon
[b] – University of Lyon : LabCREATIS, Team MYRIAD, CNRS – INSERM – Université Lyon 1 – INSA

esmi
european society for molecular imaging

Université Claude Bernard Lyon 1

Hospices Civils de Lyon
votre santé, notre engagement

CREATIS

SPECT
IMAGING ALL THE PHOTONS