Decomposition of CT Contrast Agents: Single Spectral or Multiple CT Scans?

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Aim

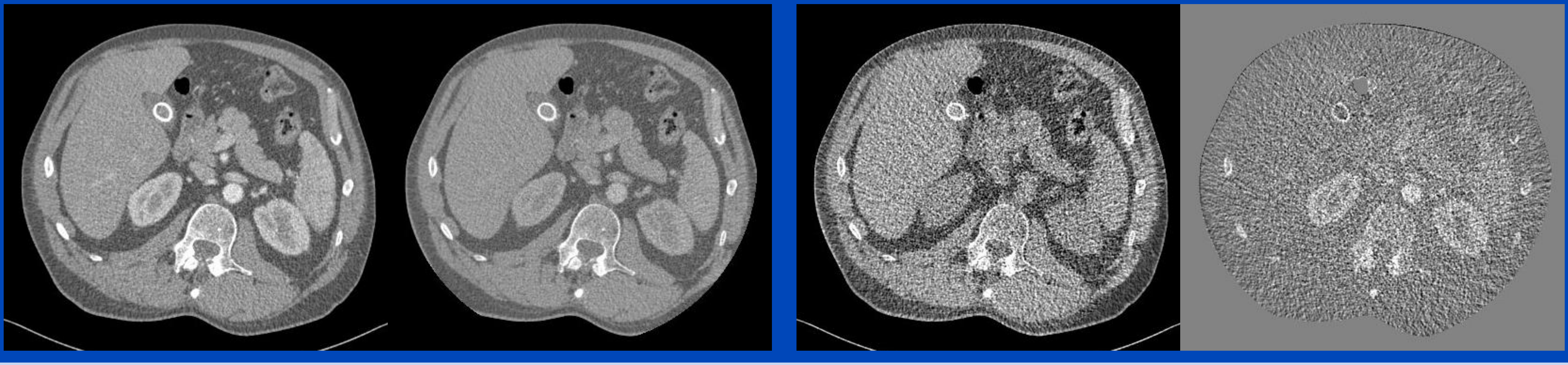
To find out whether a single PCCT acquisition should be preferred over multiple measurements.

Task: material decomposition.

Assumptions:

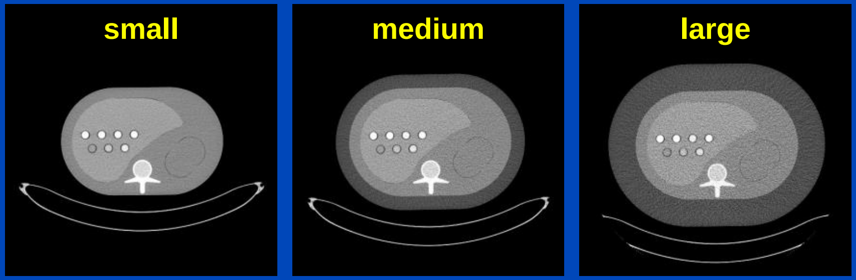
- **zero patient motion**
- **zero contrast agent motion**

low energy | high energy | VNC | Iodine map

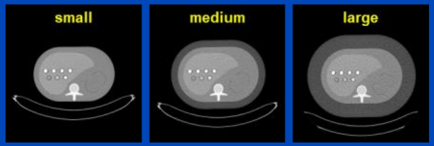


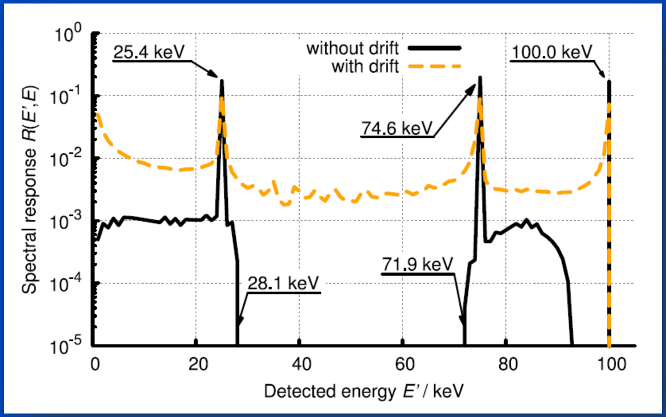
Problem Statement

- **Photon-counting CT (PCCT) can distinguish more than two materials.**
- **Using two contrast agents is often discussed. E.g.**
  - **iodine-gadolinium-enhanced (WXY)**
  - **…**
- **Is this the best way to go?**
  Why not do two or more scans? E.g.
  - **unenhanced, iodine-enhanced (W+WX)**
  - **unenhanced, iodine-enhanced, gadolinium-enhanced (W+WX+WY)**
  - **…**

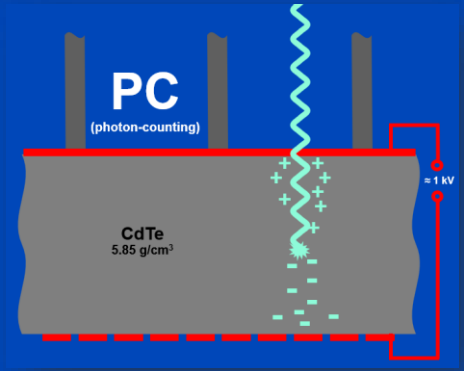


Materials





- **Simulations only**
- **Emitted spectra**
  - Tube current *I*, no TCM
  - Tube voltage *U*, from 70 kV to 150 kV
  - Cu prefilter[1] thickness *T* either 0, 1, 2 or 3 mm
  - Tucker spectrum filtered by 1 mm Al + 0.9 mm Ti



- **Detected spectra**
  - Photon-counting detector, 1.6 mm CdTe
  - Ideal (rectangular) and realistic[2] spectral response
  - Up to $B = 4$ energy bins
  - Thresholds positions {20, 33, 50, 61, 65, 70, 81, 91, 100, 120} keV

    I Gd Yb Hf W Au Bi
- **Dose = $\mathrm{CTDI}_{32\,\mathrm{cm}} = \kappa(U)\cdot I$**
- **Image domain material decomposition**
  - H_2O, I, Gd, Yb, Hf, W, Au, Bi

$$g(\boldsymbol{r}) = \boldsymbol{w}^{\mathrm{T}} \cdot \begin{pmatrix} f_1(\boldsymbol{r}) \\ \vdots \\ f_B(\boldsymbol{r}) \end{pmatrix}$$

[1]Using a 2 mm Cu prefilter approximately corresponds to 0.6 mm Sn or to 0.5 mm Ag.
[2]S. Faby, M. Kachelrieß et al. Med. Phys. 43(7):3945-3960, July 2016

Results

W+WX vs. WX+WX, Two Patient Sizes, *B* ≤ 3, for X = I, Gd, Hf, Bi

200 mm, real, rb	Iodine	Gadolinium	Hafnium	Bismuth	
W	48.8, 0.00, 48.8	48.8, 0.00, 48.8	48.8, 0.00, 48.8	48.8, 0.00, 48.8	
WX	14.7, 3.16, 3.39	12.4, 2.55, 2.74	10.1, 2.30, 2.47	8.39, 2.20, 2.35	
W+WX	34.9, 8.66, 9.29	34.5, 6.85, 7.35	34.7, 6.41, 6.88	34.9, 6.98, 7.49	2 scans
WX+WX	21.3, 6.08, 6.45	18.1, 3.88, 4.16	13.3, 2.85, 3.06	16.6, 4.03, 4.33	e.g. 1 DSCT scan
WX penalty	5.65, 7.51, 7.51	7.74, 7.18, 7.18	11.9, 7.76, 7.76	17.3, 10.1, 10.2	
WX+WX penalty	2.68, 2.03, 2.07	3.65, 3.11, 3.11	6.80, 5.05, 5.05	4.42, 3.00, 3.00	

400 mm, real, rb	Iodine	Gadolinium	Hafnium	Bismuth	
W	7.12, 7.12	7.12, 7.12	7.12, 7.12	7.12, 7.12	
WX	2.28, 0.38, 0.41	2.03, 0.36, 0.39	1.62, 0.29, 0.31	1.63, 0.31, 0.34	
W+WX	4.53, 0.91, 0.97	5.04, 0.90, 0.97	5.06, 0.94, 1.00	5.11, 0.73, 0.78	2 scans
WX+WX	3.23, 0.69, 0.74	3.05, 0.60, 0.64	2.06, 0.45, 0.48	1.95, 0.37, 0.40	e.g. 1 DSCT scan
WX penalty	3.95, 5.56, 5.56	6.19, 6.11, 6.11	9.72, 10.3, 10.3	9.78, 5.41, 5.41	
WX+WX penalty	1.97, 1.72, 1.72	2.73, 2.26, 2.26	6.00, 4.33, 4.33	6.85, 3.81, 3.81	

Values are SNRDs of W, X, tot. Penalty values are squared SNRD ratios given relative to W+WX.

Conclusions on W+WX vs. WX+WX

- The higher the atomic number the higher the penalties.
- Iodine (nearly) always has the best SNRD.
  - The reason could be that with iodine using very hard x-ray spectra (e.g. 150 kV plus thick PSP).
  - This makes WX look very similar as W, since the iodine contrast becomes very low. This is not the case for Gd, Hf or Bi.

X=Iodine Plus Another Contrast Agent Y

400 mm, real, rb	Y=Gadolinium	Y=Hafnium	Y=Bismuth
WXY	0.74, 0.25, 0.17, 0.20	1.40, 0.38, 0.27, 0.33	0.89, 0.25, 0.24, 0.26
W+WXY	2.25, 0.41, 0.33, 0.38	2.25, 0.47, 0.43, 0.47	2.37, 0.34, 0.39, 0.38
WXY+WXY	1.49, 0.41, 0.29, 0.35	1.56, 0.51, 0.30, 0.39	1.59, 0.46, 0.30, 0.37
WX+WXY	1.82, 0.49, 0.42, 0.5 [illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible], 0.72, 0.78	3.92, 0.75, 0.78, 0.81	3.99, 0.68, 0.61, 0.68
W+WXY+WXY	2.27, 0.41, 0.35, 0.39	3.20, 0.60, 0.58, 0.63	3.24, 0.47, 0.46, 0.49
WX+WXY+WY	3.34, 0.73, 0.78, 0.80	3.23, 0.74, 0.70, 0.77	3.31, 0.77, 0.69, 0.77
WX+WX+WXY	2.81, 0.62, 0.63, 0.67	2.81, 0.62, 0.69, 0.69	2.79, 0.58, 0.58, 0.62
WY+WY+WXY	2.45, 0.70, 0.52, 0.61	1.90, 0.66, 0.41, 0.51	1.73, 0.60, 0.34, 0.43
WXY penalty	$(0.80/0.20)^2 = 16.0$	$(0.82/0.33)^2 = 6.17$	$(0.77/0.26)^2 = 8.77$
WXY+WXY penalty	$(0.80/0.35)^2 = 5.22$	$(0.82/0.39)^2 = 4.42$	$(0.77/0.37)^2 = 4.33$

Y=Gadolinium	Scan	U	D	B	Thresholds	Dose
WXY	WXY	90 kV	0 mm	4	{20, 33, 50, 70} keV	$100\% \cdot 16.0$
WXY+WXY	WXY	70 kV	0 mm	3	{20, 33, 50} keV	$90\% \cdot 5.22$
	WXY	150 kV	3 mm	4	{20, 33, 50, 91} keV	$10\% \cdot 5.22$
WX+WXY+WY	WX	120 kV	3 mm	3	{20, 33, 81} keV	$30\% \cdot 1.00$
	WXY	70 kV	0 mm	3	{20, 33, 50} keV	$40\% \cdot 1.00$
	WY	70 kV	3 mm	3	{20, 33, 50} keV	$30\% \cdot 1.00$

Quadruples are SNRDs of W, X, Y, tot. Here, X=Iodine. Penalties are relative to the winning scan strategy.
The dose-wise 20% top scan strategies are highlighted.

dkfz.

Two Separate Scans with Motion

WX, WY				
400 mm, real, rb	Y=Iodine	Y=Gadolinium	Y=Hafnium	Y=Bismuth
X=Iodine	1.61, 0.27, 1.61, 0.27	1.57, 0.26, 1.47, 0.26	1.38, 0.23, 1.29, 0.23	1.45, 0.24, 1.27, 0.24
X=Gadolinium	1.47, 0.26, 1.57, 0.26	1.43, 0.26, 1.43, 0.26	1.26, 0.23, 1.27, 0.23	1.32, 0.24, 1.24, 0.24
X=Hafnium	1.29, 0.23, 1.38, 0.23	1.27, 0.23, 1.26, 0.23	1.15, 0.21, 1.15, 0.21	1.19, 0.21, 1.11, 0.21
X=Bismuth	1.27, 0.24, 1.45, 0.24	1.24, 0.24, 1.32, 0.24	1.11, 0.21, 1.19, 0.21	1.16, 0.22, 1.16, 0.22

WX+WX, WY+WY				
400 mm, real, rb	Y=Iodine	Y=Gadolinium	Y=Hafnium	Y=Bismuth
X=Iodine	2.28, 0.49, 2.28, 0.49	2.11, 0.45, 2.31, 0.45	1.76, 0.38, 1.73, 0.38	1.54, 0.33, 1.72, 0.33
X=Gadolinium	2.31, 0.45, 2.11, 0.45	2.16, 0.42, 2.16, 0.42	1.83, 0.36, 1.65, 0.36	1.62, 0.32, 1.66, 0.32
X=Hafnium	1.73, 0.38, 1.76, 0.38	1.65, 0.36, 1.83, 0.36	1.46, 0.32, 1.46, 0.32	1.32, 0.29, 1.50, 0.29
X=Bismuth	1.72, 0.33, 1.54, 0.33	1.66, 0.32, 1.62, 0.32	1.50, 0.29, 1.32, 0.29	1.38, 0.26, 1.38, 0.26

Quadruples are SNRDs of W_1, X, W_2, Y.

Two Separate Scans (with Motion) vs. One Simultaneous Single Scan

400 mm, real, rb	X	Y	SNRD of W, X, Y	CT	Comments
WX, WY	Iodine	Iodine	1.61, 0.27, 0.27	SSCT	Today's biphasic liver exams with PCCT with iodinated contrast agent (X=Y=Iodine)
WX+WX, WY+WY	Iodine	Iodine	2.28, 0.49, 0.49	DSCT	
WXY	Iodine	Gadolinium	0.74, 0.25, 0.17	SSCT	Proposed (future) biphasic liver exams with two contrast agents (X≠Y)
	Iodine	Hafnium	1.40, 0.38, 0.27		
WXY+WXY	Iodine	Gadolinium	1.49, 0.41, 0.29	DSCT	
	Iodine	Hafnium	1.56, 0.51, 0.30		
Gadolinium penalty for SSCT			5.73, 1.17, 2.52	SSCT	WXY vs. WX, WY
Gadolinium penalty for DSCT			2.34, 1.43, 2.85	DSCT	WXY+WXY vs. WX+WX, WY+WY

Triples are SNRDs of W, X, Y.
With the exception of gadolinium only the winning configurations are shown.

Conclusions

- **Iodine seems to be a very good agent.**
- **Investing into motion correction would be beneficial due to the very high penalties.**
- **Dual source PCCT is superior to single source PCCT.**
- **Biphasic liver exams are best done as two independent dual source PCCT scans with iodinated contrast agent.**

- **Limitations:**
  - **Simulation study only**
  - **No CT reconstruction involved. CT values and noise were estimated in projection domain.**

Thank You!

The 8th International Conference on

Image Formation in X-Ray Computed Tomography

Conference Chair

Marc Kachelrieß, German Cancer Research Center (DKFZ), Heidelberg, Germany

Job opportunities through marc.kachelriess@dkfz.de.

Parts of the reconstruction software were provided by RayConStruct® GmbH, Nürnberg, Germany.