ACCURATE MONTE CARLO INPUTS FOR DOSE CALCULATION USING MULTI-ENERGY CT

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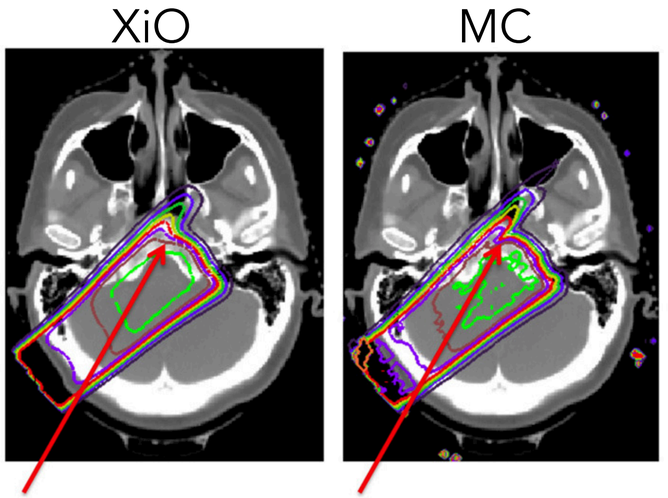
THE IMPORTANCE OF MC IN PROTON THERAPY

- For proton therapy applications, **Monte Carlo** (MC) techniques have many **advantages** over commercial algorithms:
  - Enhanced sensitivity to **complex geometries** and in–beam **density variations**,
  - Ability to report **dose** to **medium**,
  - Calculation of **LET distributions**,
  - Estimation of **neutron dose** levels,
  - Prediction of post-radiation **PET activity** for *in-vivo* **range verification.**



Paganetti *et al.* 2008 *Phys. Med. Biol.*

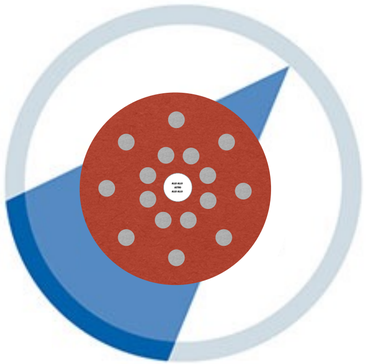
PATIENT GEOMETRY TO MC INPUTS

- One of the **key steps** in the preparation of a MC simulation is the creation of the patient **geometry**, including the assignation of **material composition** in each voxel.
  - Complete **elemental composition** and **mass density** is **necessary** to calculate the exact **cross sections** for all interactions considered.

- Great **attention** must be paid to this step as it influences **all results** generated by the simulation: « *Rubbish in, Rubbish out* ».

THE SCHNEIDER METHOD

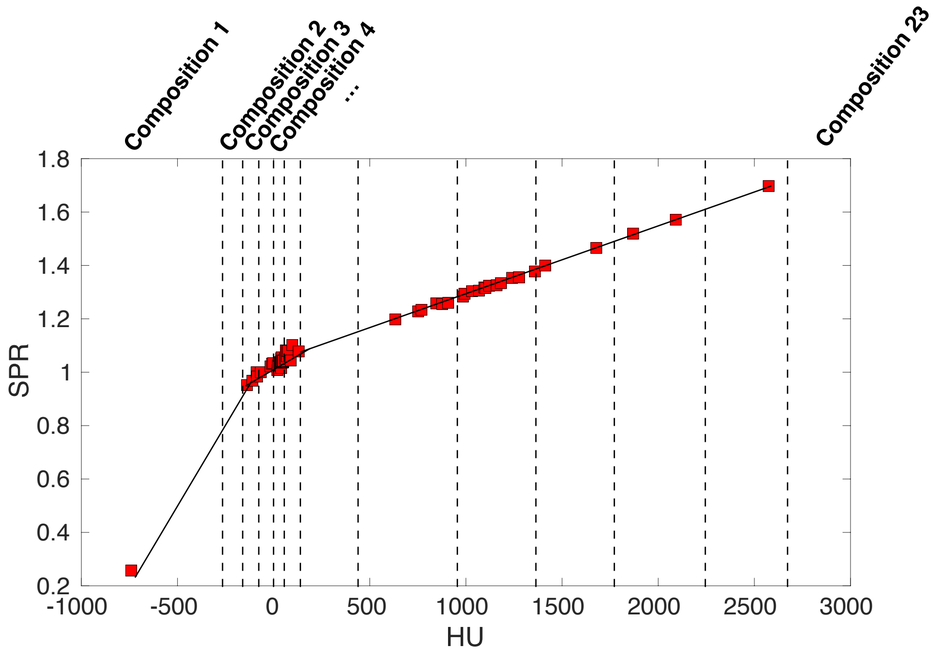
To extract MC **inputs** from single energy CT (**SECT**) data, the gold standard is the method of Schneider et al. (2000). The CT is **calibrated** to construct a segmented **look-up table** (LUT) that links every possible **HU** to a certain set of MC inputs.



Reference dataset

TABLE III
THE ELEMENTAL COMPOSITIONS OF THE BODY TISSUES

Body tissue	Elemental composition (% by mass)					Densities		
						Mass	Electron	
	H	C	N	O	Elements with $Z > 8$	kg m^{-3}	el. kg^{-1} $\times 10^{26}$	el. m^{-3} $\times 10^{26}$
Adipose tissue 1	11.2	51.7	1.3	35.8	Na(0.1), S(0.1), Cl(0.1)	970	3.342	3241
Adipose tissue 2	11.4	59.8	0.7	27.8	Na(0.1), S(0.1), Cl(0.1)	950	3.347	3180
Adipose tissue 3	11.6	68.1	0.2	19.8	Na(0.1), S(0.1), Cl(0.1)	930	3.353	3118
Adrenal gland	10.6	28.4	2.6	57.8	P(0.1), S(0.2), Cl(0.2), K(0.1)	1030	3.324	3424
Aorta	9.9	14.7	4.2	69.1	Na(0.1), P(0.1), S(0.2), Cl(0.2), K(0.4)	1050	3.304	3469
Blood—erythrocytes	9.5	19.0	5.9	64.6	Na(0.1), P(0.1), S(0.2), Cl(0.2), Fe(0.1)	1090	3.291	3588
Blood—plasma	10.8	4.1	1.1	83.2	Na(0.3), S(0.1), Cl(0.4)	1026	3.330	3417
Blood—whole	10.2	11.0	3.3	74.5	Na(0.1), P(0.1), S(0.2), Cl(0.3), K(0.2), Fe(0.1)	1060	3.312	3511
Brain—cerebrospinal fluid	11.1	—	—	88.0	Na(0.5), Cl(0.4)	1010	3.339	3373
Brain—grey matter	10.7	9.5	1.8	76.7	Na(0.2), P(0.3), S(0.2), Cl(0.3), K(0.3)	1040	3.327	3460
Brain—white matter	10.6	19.4	2.5	66.1	Na(0.2), P(0.4), S(0.2), Cl(0.3), K(0.3)	1040	3.324	3457
Connective tissue	9.4	20.7	6.2	62.2	Na(0.6), S(0.6), Cl(0.3)	1120	3.288	3683
Eye lens	9.6	19.5	5.7	64.6	Na(0.1), P(0.1), S(0.3), Cl(0.1)	1070	3.295	3525
Gallbladder—bile	10.8	6.1	0.1	82.2	Na(0.4), Cl(0.4)	1030	3.330	3430
Gastrointestinal tract—small intestine (wall)	10.6	11.5	2.2	75.1	Na(0.1), P(0.1), S(0.1), Cl(0.2), K(0.1)	1030	3.325	3424
Gastrointestinal tract—stomach	10.4	13.9	2.9	72.1	Na(0.1), P(0.1), S(0.2), Cl(0.1), K(0.2)	1050	3.319	3485
Heart	10.3	12.5	3.1	68.1	Na(0.1), P(0.2), S(0.2), Cl(0.2), K(0.3)	1050	3.315	3481



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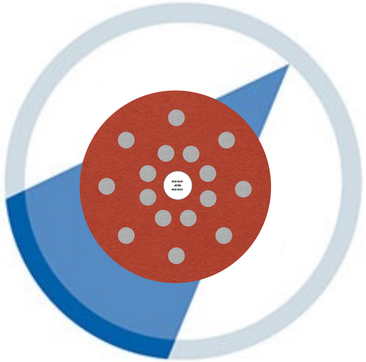

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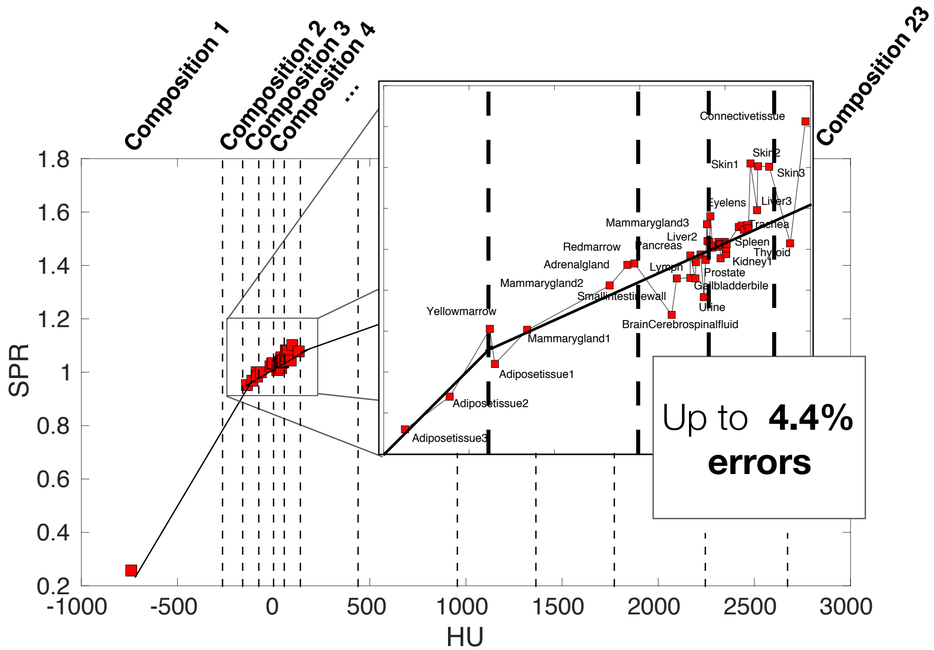
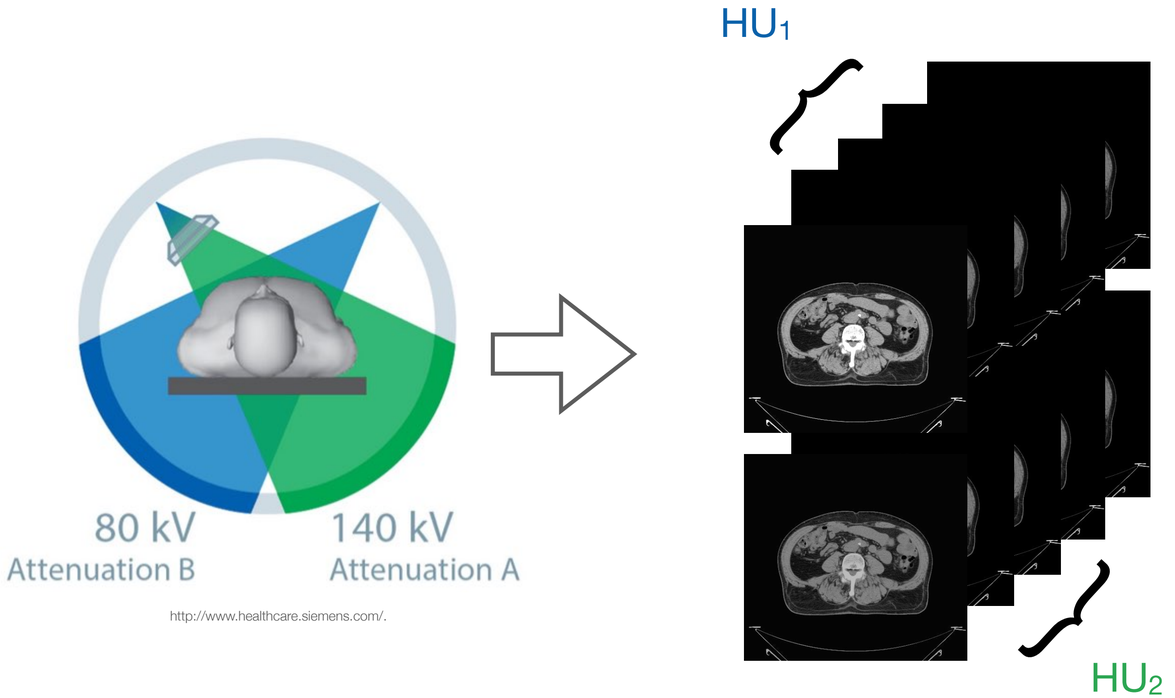


DUAL AND MULTI-ENERGY CT

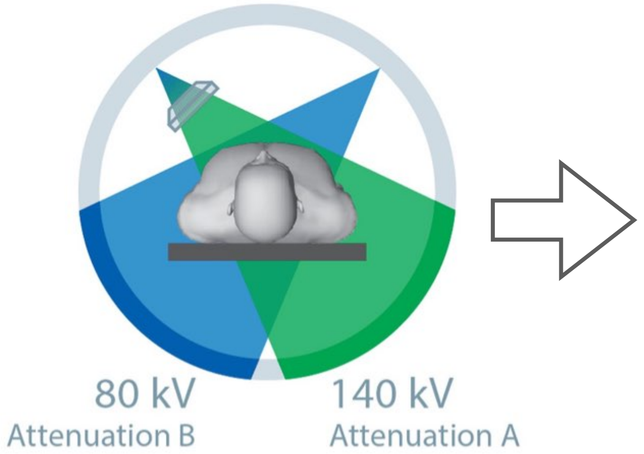
- With **dual-** or **multi-**energy CT, empirical LUT are **obsolete**, as more information can be extracted directly from MECT data



http://www.healthcare.siemens.com/.

DUAL AND MULTI-ENERGY CT

- With **dual-** or **multi-**energy CT, empirical LUT are **obsolete**, as more information can be extracted directly from MECT data
  - Still not enough information to **derive** directly MC inputs
- How can we use **optimally** the **added information** to **improve** the quality of MC inputs?



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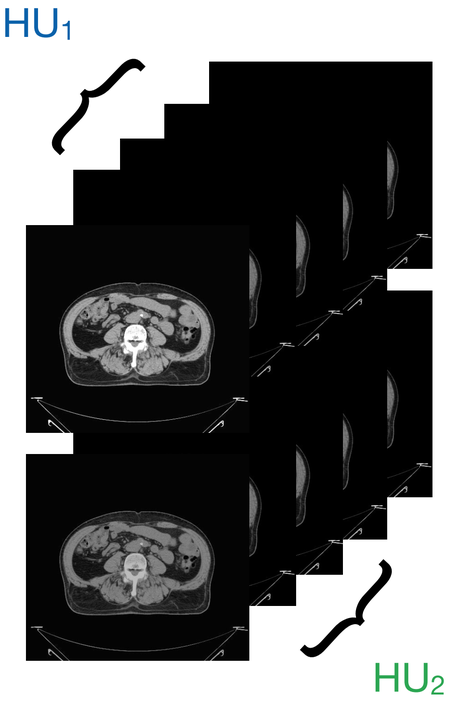

CT DATA TO MONTE CARLO INPUTS

- We want to extract **full atomic composition** and **mass density**, but we have only **limited** information (# of energies) per voxel.
  - Tissue characterization for Monte Carlo dose calculation from CT data is an **underdetermined** problem

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- We want to extract **full atomic composition** and **mass density**, but we have only **limited** information (# of energies) per voxel.
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- We propose to use **principal component analysis** (PCA) on reference dataset to extract a new basis of variables that can describe human tissues composition more **efficiently** by **reducing the dimensionality** of the problem.
  - We call these variables **Eigentissues** (ET)

EIGENTISSUE REPRESENTATION OF HUMAN BODY

- All **information** relevant for dose calculation can be **stocked** in a **vector** of partial electron densities:

Density of electrons

Fraction of electrons of element *M* in the tissue

$$\mathbf{x} = \rho_e \left[\lambda_1 \ \lambda_2 \ \dots \ \lambda_M\right]$$

$$= \left[x_1 \ x_2 \ \dots \ x_M\right]$$

- The **ET** representation consists of a **linear transformation** of **x**:

$$\mathbf{x} = y_1 \cdot \mathbf{ET}_1 + y_2 \cdot \mathbf{ET}_2 + \dots + y_M \cdot \mathbf{ET}_M$$

Vector of the partial densities in the *M th* eigentissue

EIGENTISSUE REPRESENTATION OF HUMAN BODY

- The ET are **orthogonal** vectors directed in the direction where there is the **highest variance** within the dataset.

- They are sorted in a way that the **variance** of their respective y_i **decreases** rapidly as *i* **increases**.
  - A given tissue can be **accurately** characterized using only **few** y_i :

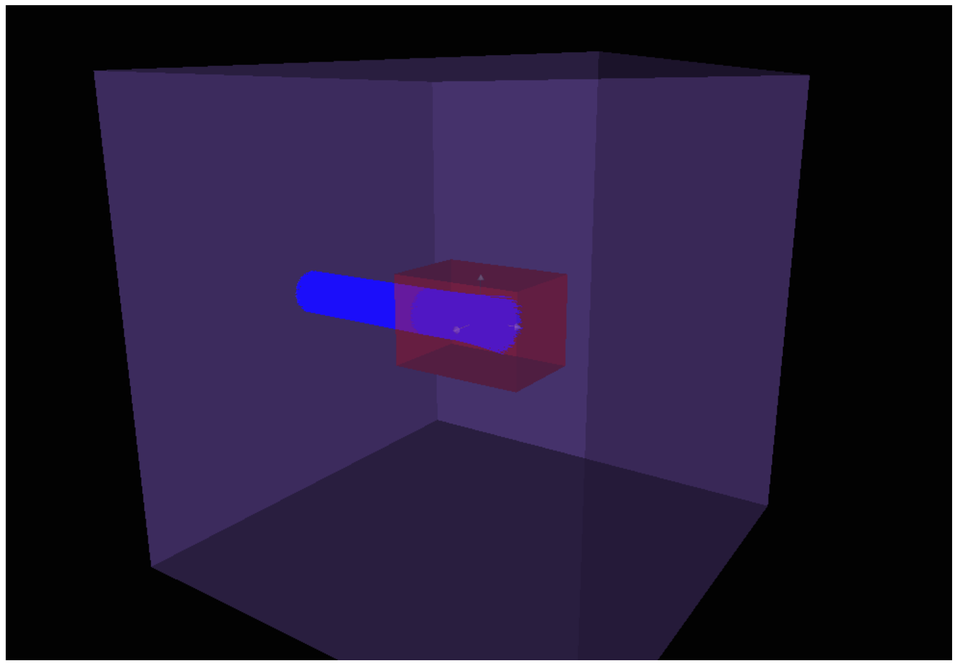
$$\mathbf{x} \simeq y_1 \cdot \mathbf{ET}_1 + y_2 \cdot \mathbf{ET}_2 + \overline{y_3} \cdot \mathbf{ET}_3 ... + \overline{y_M} \cdot \mathbf{ET}_M$$

APPLYING PCA TO HUMAN TISSUES

- Human tissues are composed of a **limited number** of elements. Including trace elements, only **13** different chemical components are reported in the literature.
- Also, the weight fraction of these elements is often strongly **correlated** (ex: P & Ca) or **anticorrelated** (ex: C & O).
- The eigentissues allow to characterize human tissues with **less** than 13 variables **without** losing much **accuracy**.

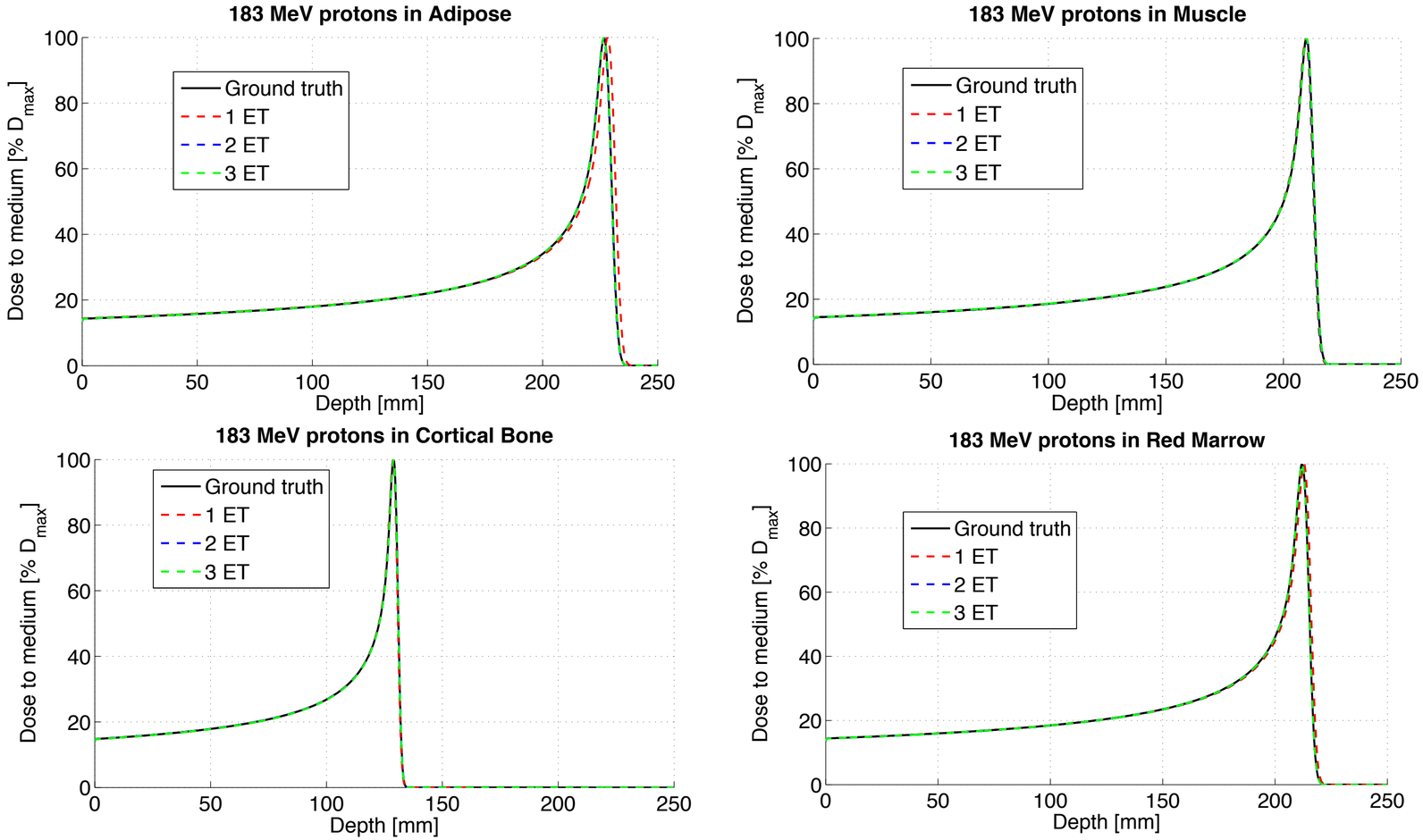
SELF-CONSISTENCY OF THE METHOD

- We tested the method in the context of Monte Carlo simulations using TOPAS to determine **how many** ETs are necessary to allow **accurate range** prediction
  - Mono-energetic proton beam of 183 MeV/u
  - Dose to medium scored in 0.1 mm slices
  - 250 000 histories per run



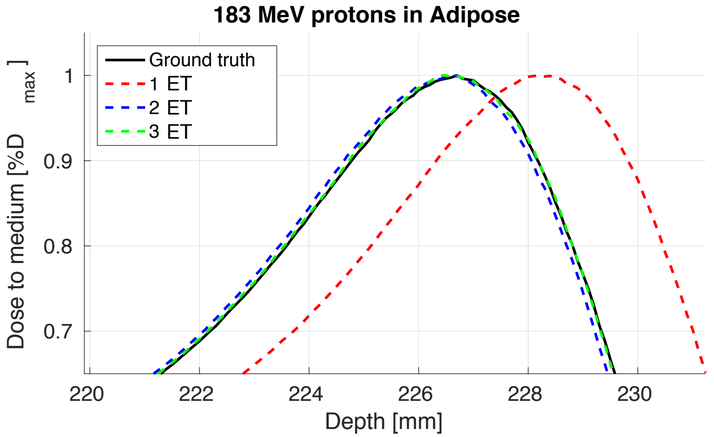
SELF-CONSISTENCY OF THE METHOD

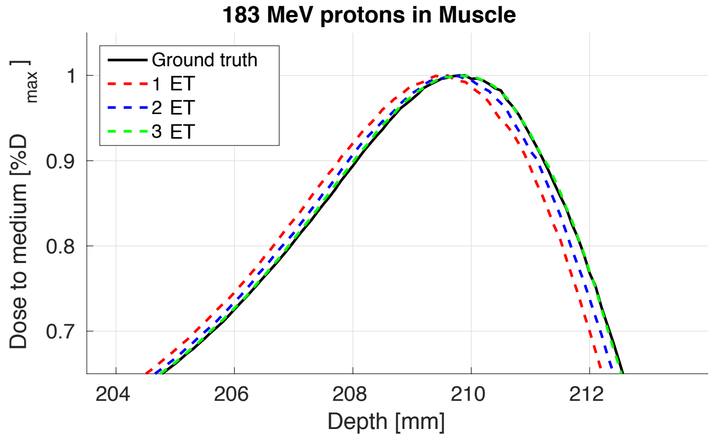
- Monte Carlo simulations using TOPAS for four reference tissues

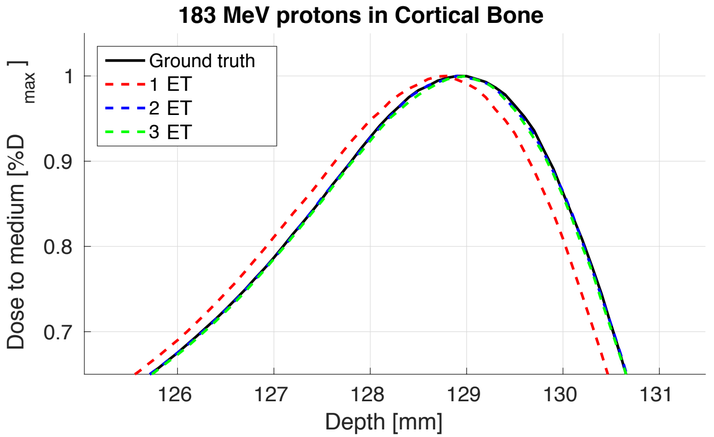


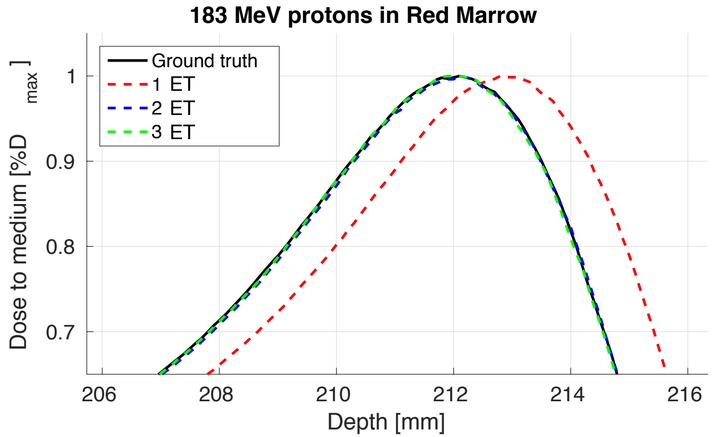
SELF-CONSISTENCY OF THE METHOD

- Monte Carlo simulations using TOPAS for four reference tissues
- **Only two ET** are enough to get a **submillimetric** precision on **proton range prediction**.









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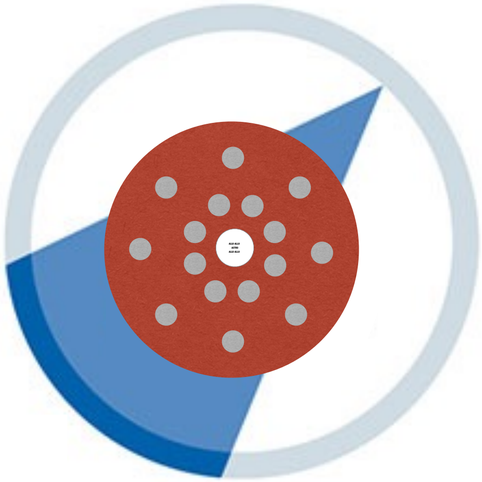
ADAPTATION TO CT DATA

- Using a suitable **stoichiometric calibration**, the photon **attenuation** of each ET can be estimated for **any spectrum** or imaging **protocol**.



$$\longrightarrow \mu(E_i, \mathbf{x}) \approx f\left(k_1^{(i)}, k_2^{(i)}, \ldots\right) \longrightarrow \begin{matrix} \hat{\mu}(E_i, \mathbf{ET}_1) \\ \hat{\mu}(E_i, \mathbf{ET}_2) \\ \vdots \\ \hat{\mu}(E_i, \mathbf{ET}_M) \end{matrix}$$

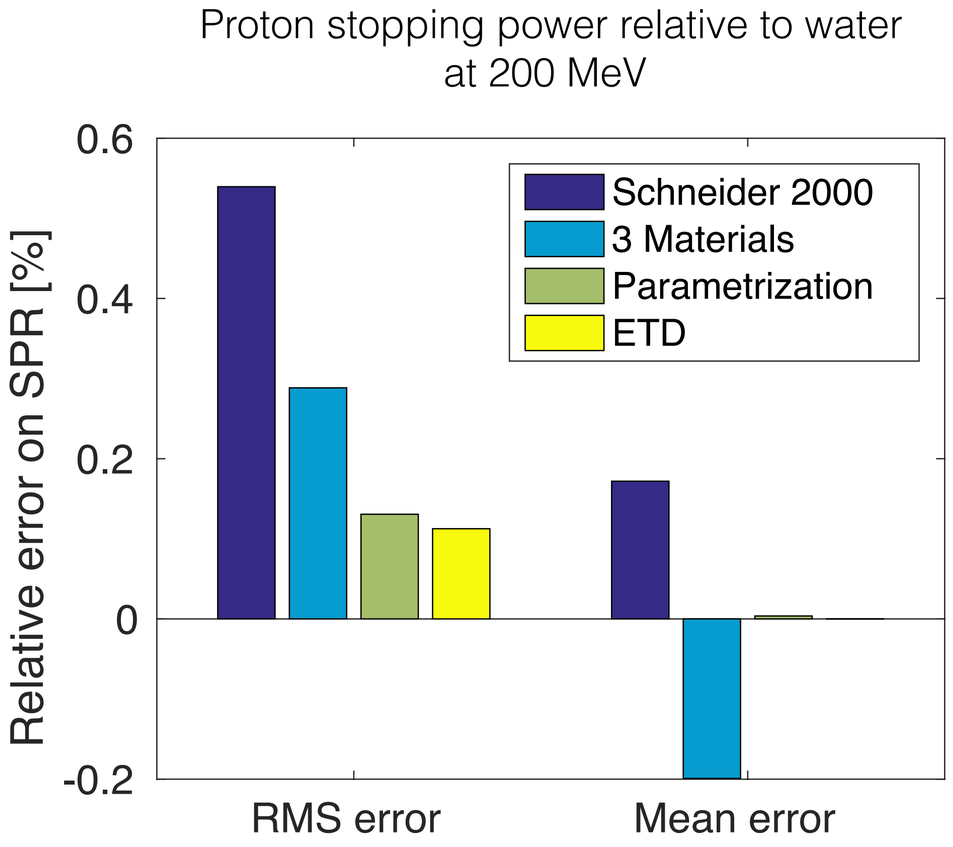
ADAPTATION TO CT DATA

- Once their attenuation coefficient is estimated, the ETs are treated as **virtual materials.**
- If *K* information is available (i.e. *K* energies), **decomposition** is performed to extract the **fraction** of the *K* more meaningful ETs in each voxel.

$$\begin{pmatrix} \hat{y}_1 \\ \vdots \\ \hat{y}_k \end{pmatrix} \equiv \begin{pmatrix} \hat{\mu}(E_1, \mathbf{ET}_1) & \dots & \hat{\mu}(E_K, \mathbf{ET}_1) \\ \vdots & \ddots & \vdots \\ \hat{\mu}(E_1, \mathbf{ET}_K) & \dots & \hat{\mu}(E_K, \mathbf{ET}_K) \end{pmatrix}^{-1} \begin{pmatrix} \mu(E_1) \\ \vdots \\ \mu(E_K) \end{pmatrix}$$

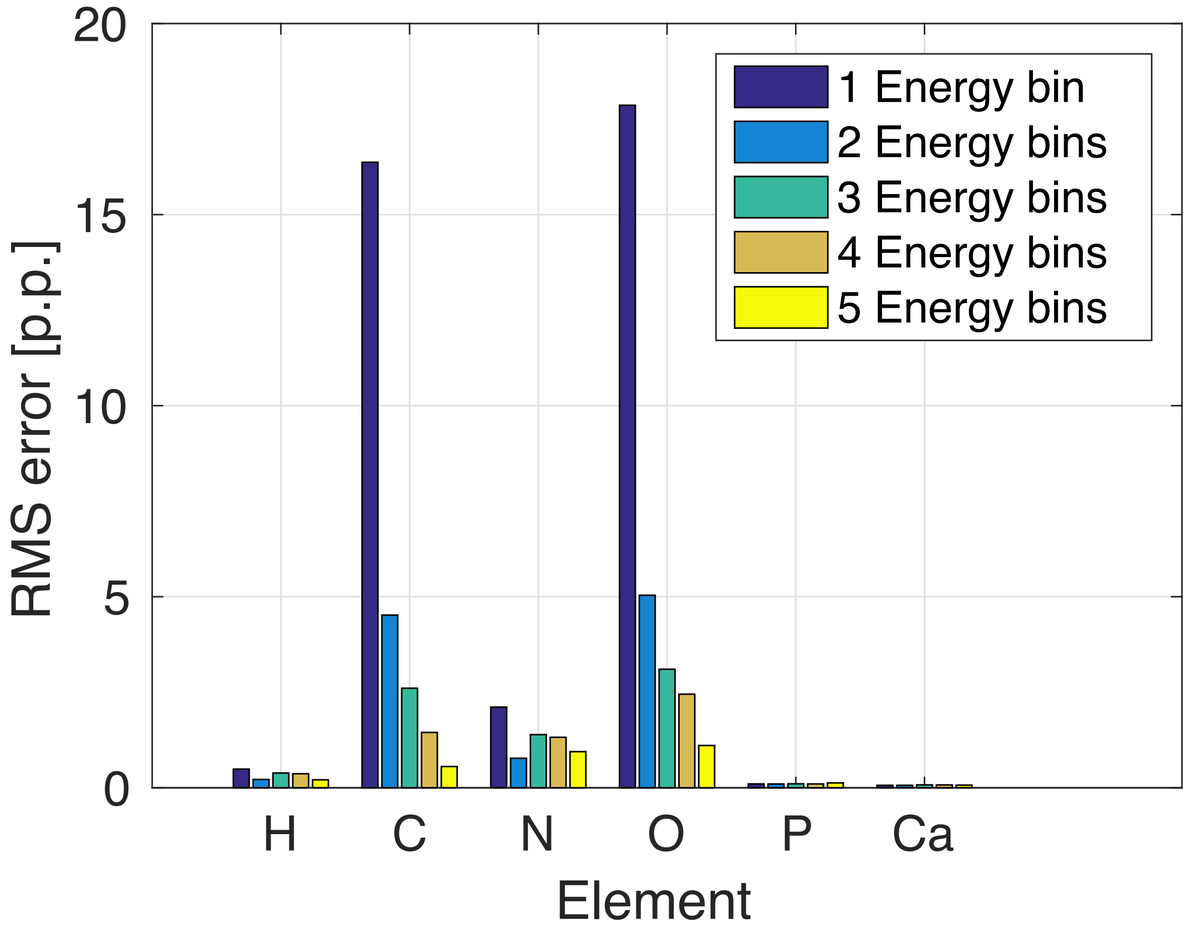
APPLICATION TO DECT: BENCHMARKING WITH OTHER METHODS

- **Comparison** with two recently published methods for the characterization of 43 reference soft tissues using DECT:
  - **Water-Lipid-Protein** (WLP) decomposition (Malusek *et al*. 2013)
  - **Parameterization** (Hünemohr *et al*. 2014)
- **Simulated HU** for 80 kVp and 140/Sn kVp spectra of the SOMATOM Definition Flash DSCT (noise is neglected)



POTENTIAL EXTENSION TO MECT

- Separating a 140 kVp spectrum in **five** energy bins, the method shows **improvement** in extracting elemental weights with **more** than **two information**.



CONCLUSION

- **Eigentissues** representation of human body composition **minimizes** the number of **parameters** needed for **accurate characterization**
- Adapting this representation to **material decomposition** of CT data allows extracting high quality **Monte Carlo inputs** from only **few** measurements
- The method is **accurate** and **versatile**:
  - Not limited to only **two** parameters (EAN and ED)
  - Valid through the **whole range** of X-ray energies (e.g. kV and MV)
  - RMS **errors** of **0.11%** on **SPR** for 43 reference tissues
- **Future work**: test the method in realistic conditions including noise
- **Recent publication**: A. Lalonde and H. Bouchard, *A general method to derive tissue parameters for Monte Carlo dose calculation with dual- and multi-energy CT*, Phys. Med. Biol.

ACKNOWLEDGEMENTS

- UK National Physical Laboratory
- Ministère de la santé et des services sociaux (MSSS) du Québec
- Université de Montréal
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