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.

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.
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Still not enough information to derive directly MC inputs.

How can we use optimally the added information to improve the quality of MC inputs?
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 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:

\[
\mathbf{x} = \hat{\rho}_e \left[ \lambda_1 \; \lambda_2 \; \ldots \; \lambda_M \right] \\
= \left[ x_1 \; x_2 \; \ldots \; x_M \right]
\]

Density of electrons \quad Fraction of electrons of element \(M\) in the tissue

• The **ET** representation consists of a **linear transformation** of \(\mathbf{x}\):

\[
\mathbf{x} = y_1 \cdot \mathbf{ET}_1 + y_2 \cdot \mathbf{ET}_2 + \ldots + y_M \cdot \mathbf{ET}_M
\]

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** $y_i$:

$$\mathbf{x} \simeq y_1 \cdot \mathbf{ET}_1 + y_2 \cdot \mathbf{ET}_2 + y_3 \cdot \mathbf{ET}_3 \ldots + y_M \cdot \mathbf{ET}_M$$
• 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.
Using a suitable **stoichiometric calibration**, the photon **attenuation** of each ET can be estimated for **any spectrum** or imaging **protocol**.

\[
\mu(E_i, x) \approx f \left( k_{1}^{(i)}, k_{2}^{(i)}, \ldots \right) \quad \rightarrow \quad \hat{\mu}(E_i, \text{ET}_1) \quad \hat{\mu}(E_i, \text{ET}_2) \quad \vdots \quad \hat{\mu}(E_i, \text{ET}_M)
\]
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.

\[
\begin{pmatrix}
\hat{y}_1 \\
\vdots \\
\hat{y}_K
\end{pmatrix}
\equiv
\begin{pmatrix}
\hat{\mu}(E_1, \text{ET}_1) & \cdots & \hat{\mu}(E_K, \text{ET}_1) \\
\vdots & \ddots & \vdots \\
\hat{\mu}(E_1, \text{ET}_K) & \cdots & \hat{\mu}(E_K, \text{ET}_K)
\end{pmatrix}^{-1}
\begin{pmatrix}
\mu(E_1) \\
\vdots \\
\mu(E_K)
\end{pmatrix}
\]
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)
• 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.

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