MECT material quantification: Iodine and beyond

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Disclosures

- Research funding support:

Cancer Prevention & Research Institute of Texas

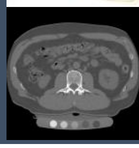
Outline

- Background: Material quantification in conventional CT
- Material quantification in dual- energy CT
  - Principles
  - Applications from CT vendors and in the literature
- Material quantification in photon-counting CT

Material quantification in conventional CT

- Bone mineral density (BMD) measurement using quantitative CT
  - 1970s – present: standard practice
  - Diagnosis of bone disease, osteopenia (low bone mass), or osteoporosis (low bone mass with possible frequent fracture).

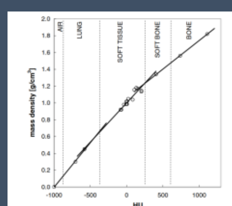
BMD calibration phantom



CT number → Calibration → BMD

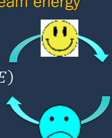
Material quantification in conventional CT

- Treatment planning in radiation therapy
  - Dose calculation using eletron density and tissue type (atomic number) from CT images
  - Stopping power ratio (f(Z)) for proton/heavy ion therapy



Magdalena et al, 2008

Limitations of material quantification in conventional CT

- Linear attenuation coefficient (CT number) is a function of mass density, material type (effective atomic number, Z) and beam energy
- (ρ, Z, E)  μ

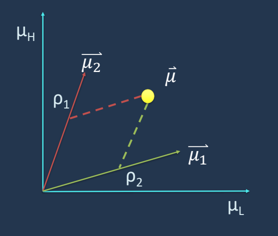
- Bone mineral density
  - Fat in the marrow lowers the CT number → appears lower bone density
- Radiation therapy
  - Inaccurate tissue assignment
  - Uncertainty in range calculation

Material quantification in dual-energy CT: Decomposition

- (ρ, Z) model
  - $\begin{cases} \mu_L = F(\rho, Z, E_L) \\ \mu_H = F(\rho, Z, E_H) \end{cases}$
  - E_L and E_H determined by calibration
  - prior knowledge of materials not needed
  - The empirical models simplify the F(ρ,Z,E) function.
- Basis material model
  - $\begin{cases} \mu_L = G_L(\rho_1, \rho_2) \\ \mu_H = G_H(\rho_1, \rho_2) \end{cases}$
  - ρ_1 and ρ_2 are density of two known (basis) materials, e.g., water and iodine
  - G(·) is a linear function, calibration matrix
  - *Need to determine the basis materials first*

Geometric explanation of material decomposition

- Two material decomposition
- $\vec{\mu} = \rho_1\overrightarrow{\mu_1} + \rho_2\overrightarrow{\mu_2}$,
- Each vector include low and high energy.
- Space (basis) change:
- $(\overrightarrow{\mu_L}, \overrightarrow{\mu_H}) \rightarrow (\overrightarrow{\mu_1}, \overrightarrow{\mu_2})$



Material quantification: Three unknowns

- Three material decomposition
- $\begin{cases} \mu_L = G_L(\rho_1, \rho_2, \rho_3) \\ \mu_H = G_H(\rho_1, \rho_2, \rho_3) \end{cases}$
- Underdetermined problem
  - Additional information (assumptions) required.
- Mass conservation
  - $\rho = \rho_1 + \rho_2 + \rho_3$
  - Exact, but difficult to solve the decomposition (ρ is unknown).
- Volume conservation
  - $1 = f_1 + f_2 + f_3$ (volume fraction)
  - Approximate, but good accuracy for human tissues and easy to solve decomposition.

Projection space decomposition

- Solving the equations using projection data
- For each projection data pair,
- $\begin{cases} p_L = P_L(\rho_1, \rho_2) \\ p_H = P_H(\rho_1, \rho_2) \end{cases}$

$$P(\cdot) = \int \underbrace{S_L(E)}_{\text{Spectrum}} \underbrace{exp\left[-\int (\rho_1 A_1 + \rho_2 A_2) ds\right]}_{\text{Projection}} dE$$

- Pros
  - More accurate model than image space decomposition
- Cons
  - Computation (much) more complicated
    - No exact analytical solutions
  - Noise/error sensitive
    - Artifact prone

Applications of material quantification in DECT

1. Contrast material quantification
   - Clinical use: Iodine
   - In research:
     - Xenon, Bismuth, gold
     - ....
2. Tissue and element quantification
   - Fat
   - Soft tissue (bone)
   - Iron
3. ρ and Z maps

- Scanners in this presentation:
  - GE – fast-kV switching
  - Siemens – dual-source
  - Philips –dual-layer detector

Iodine map in DECT

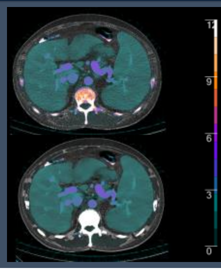
- Iodine map is a standard feature for all commercial DECTs.
  - Siemens DECT:
    - Image space decomposition
    - *Virtual unenhanced*
      - Two material decomposition: iodine and water (0 HU)
    - *Liver VNC*
      - Three material decomposition: iodine, tissue (~60 HU) and fat (~-110 HU)
    - Unit: HU and mg/ml

Virtual unenhanced:
Iodine: 7.8 mg/ml

Liver VNC:
Iodine: 8.1 mg/ml
Fat fraction: 12.3%

Iodine map in DECT

- Projection space decomposition (two materials)
  - GE:
    - Iodine (water) and Iodine (Calcium)
  - Philips:
    - Iodine no water and iodine density
    - Unit: mg/ml

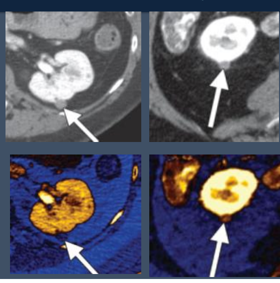


Philips

Iodine no water

Iodine density

Examples: renal cyst vs. carcinoma



Conventional image

a complicated cyst (benign) or an enhancing mass (malignant)?

Iodine map (overlay)

Renal cyst: hemorrhagic (hyperdense)

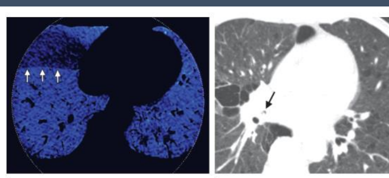
Iodine map (overlay)

Existence of vascularity (iodine)
Renal cell carcinoma

Silva, et al, 2011

Contrast material quantification

- Other contrast materials
  - Xenon (Z=54)
  - Bismuth (83)
  - Barium (56)
  - Gadolinium (64)
  - Gold (79)
  - Tungsten (74)
  - …



a. b.

Figure 17. Ventilation defect due to bronchial obstruction in a 55-year-old man. **(a)** Image from xenon ventilation CT shows a ventilation defect in the right middle lobe (arrows). **(b)** Axial CT image (lung window) shows partial obstruction of the right middle lobar bronchus (arrow) as a result of tumor invasion.

Using VNC with modified parameters (CT number threshold and iodine ratio)
Kang, et al, *RadioGraphics*, 2010

Tissue quantification: Fat

- Fat fraction map
  - Hepatic steatosis (fatty liver)
  - Siemens
    - Liver VNC →fat map
  - GE
    - Multiple-material decomposition (not commercially available)
    - Mendonca, et al, *IEEE Medical Imaging*, 2014

Tissue quantification: Fat

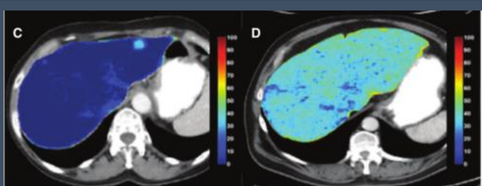


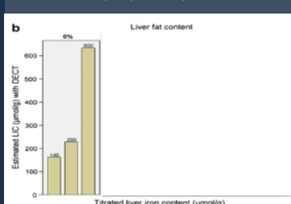
Figure 17. Liver fat quantification using material-specific fat images of two patients with different grades of fatty infiltration of the liver. *A*, *B*, Contrast-enhanced axial SE CT images. *C*, *D*, Color-overlay material-specific fat images created with an MMD algorithm provide a visual representation of the percentage of fat present in each voxel (color bar). Note the difference between a normal liver and fatty infiltration, on the basis of fat fraction.

Multiple-material decomposition
Patino et al, *RadioGraphics*, 2016

Trace element quantification: Iron

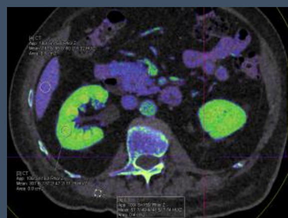
- Iron quantification in liver
  - Iron overload in liver (36 μmol/g, ~0.2%)
  - Non contrast scans
    - Three materials decomposition
    - Fat, iron and tissue
  - Iron estimation using liver VNC with modified parameters

Fischer, et al, *Eur Radiol*, 2011



ρ and Z map in DECT

- Siemens
  - Electron density: HU
  - Effective atomic number
- GE and Philips
  - Effective atomic number



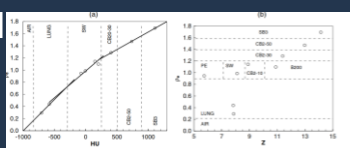
(effective Z overlay)

ρ, z calculation using CT numbers

- Material extraction for Monte Carlo dose calculations

$$\mu(E) = \rho_e'(Z^4 F(E,Z) + G(E,Z))$$

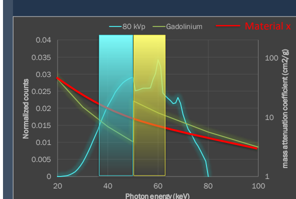
photoelectric   Compton + Rayleigh



Conventional CT   DECT

Bazalova, *Phys. Med. Biol*, 2007

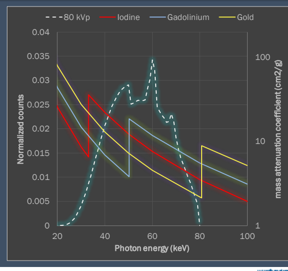
Photon counting: k edge imaging



- Conventional imaging
  - Energy integrating detector
  - Gadolinium and material x may have exact the same attenuation (CT number)
- Photon counting imaging
  - Two energy bins before and after k-edge
  - Gadolinium behaves very different from material x, which can be quantified.

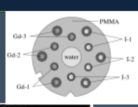
Photon counting: multiple contrasts

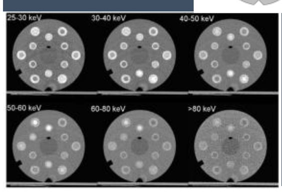
- In photon counting, for each bin
  - $\mu_i = G_i(\rho_1, \rho_2, \rho_{k-edge})$
  - At least three bins for k-edge imaging
  - Multiple contrast agents (k-edges) are possible

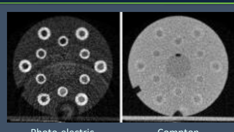


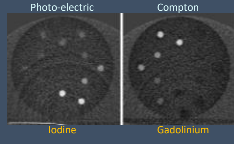
K-edge imaging: Example

- Schlomka et al, *Medical Physics*, 2008
- 8 cm diameter phantom
- 90 kVp









Four basis functions

Summary

- Commercial dual-energy CT scanners provide basic material quantification tools
  - Need to understand the physics behind them to correctly use the tools
  - Further extend the use of the tools, e.g., liver VNC for iron quantification.
  - Create your own material quantification from the images
- Active research is going on to look for
  - Creative ways to use MECT imaging
  - Best contrast agent to extend the function of MECT imaging

Thanks!