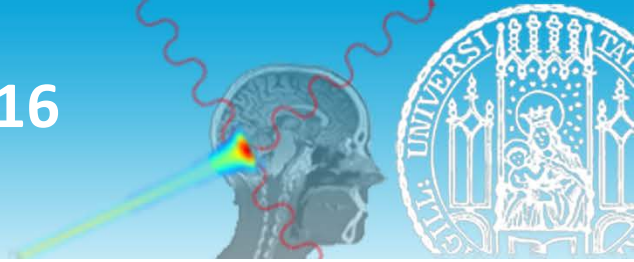
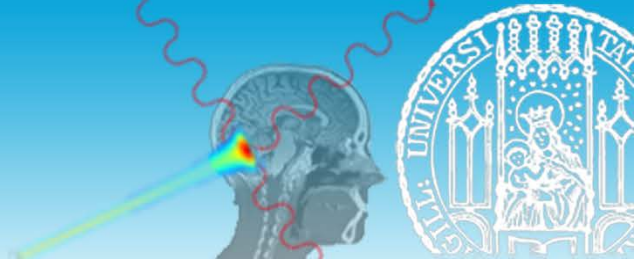


Dual energy CT for proton therapy

G. Landry[1], N. Hudobivnik[1], B. Berndt[1], F. Schwarz[2], G. Dedes[1], T. Tessonnier[1,3], J. Bauer[3], C. Thieke[4], I. Almeida[5], F. Verhaegen[5], W. H. Sommer[2], C. Belka[4], K. Parodi[1]

[1]Department of Medical Physics, Faculty of Physics, Ludwig-Maximilians-Universität München, DE
[2]Department of Radiology, Ludwig-Maximilians-Universität München, DE
[3]Department of Radiation Oncology, Heidelberg University Hospital, DE
[4]Department of Radiation Oncology, Ludwig-Maximilians-Universität München, DE
[5]Department of Radiation Oncology, MAASTRO clinic, NL

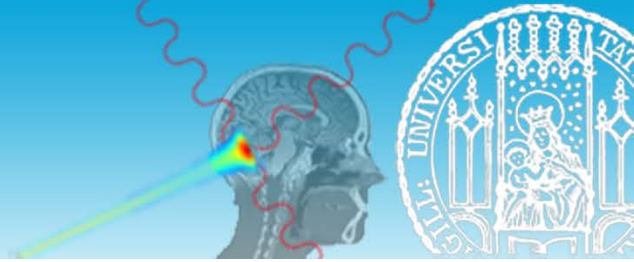
Outline



- **Motivation for DECT in proton therapy**
- **Stopping power and range in proton therapy treatment planning**
- **Tissue determination in proton therapy**

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Motivation



- X-ray CT measures **photon attenuation coefficient**

$$CT\ \# = \frac{\mu - \mu_{water}}{\mu_{water}} \cdot 1000$$

- $\mu \propto C_{\text{Compton}}(E)\boldsymbol{\rho_e} + C_{\text{PE}}(E)\boldsymbol{Z^3}$

Motivation

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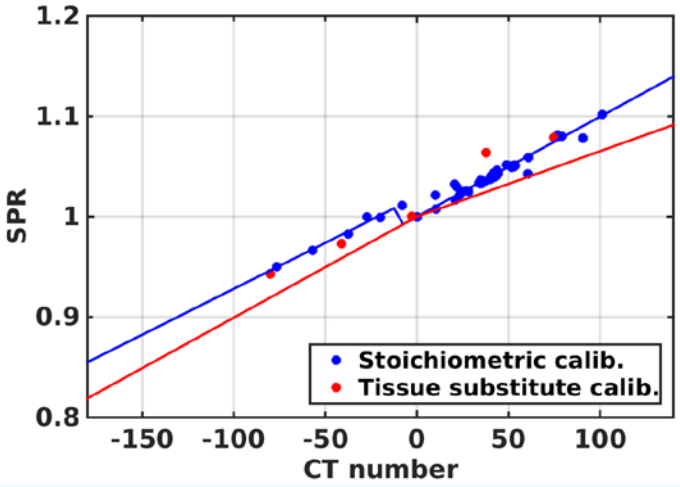

- Proton therapy treatment planning requires **stopping power ratio** to water

- $\mathrm{SPR} \propto \boldsymbol{\rho_e} \dfrac{\ln\left(\frac{2m_e c^2 \beta^2}{\boldsymbol{I}(1-\beta^2)}\right) - \beta^2}{\ln\left(\frac{2m_e c^2 \beta^2}{I_{water}(1-\beta^2)}\right) - \beta^2}$

Motivation

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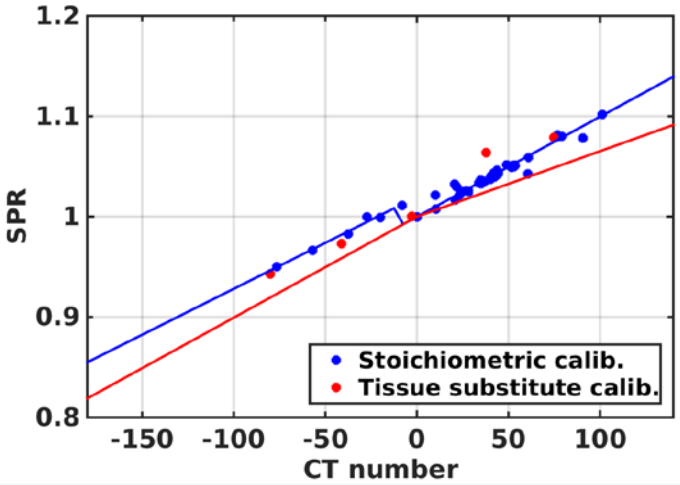

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SPR uncertainty from single energy CT (**SECT**) conversion is often stated as **3.5%** (95th percentile)

Yang et al. Med Phys **57** (2012) 4095

Motivation

$$\mu \propto C_{\text{Compton}}(E)\boldsymbol{\rho_e} + C_{\text{PE}}(E)\boldsymbol{Z^3}$$

2 equations, 2 unknowns

http://www.healthcare.siemens.com/computed-tomography/dual-source-ct/somatom-force/technical-specifications

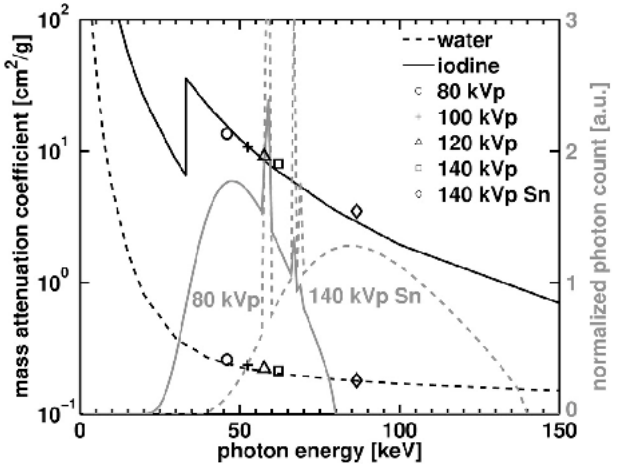
Motivation

$$\mu \propto C_{\mathrm{Compton}}(E)\boldsymbol{\rho_e} + C_{\mathrm{PE}}(E)\boldsymbol{Z^3}$$

2 equations, 2 unknowns

- Dual energy CT allows to solve for $\boldsymbol{\rho_e}$ and $\boldsymbol{Z_{\mathrm{eff}}}$

Bazalova et al. Phys Med Biol **53 (**2008) 2439



Van Elmpt, Landry et al. Radiother Oncol **119 (**2016) 137

http://www.healthcare.siemens.com/computed-tomography/dual-source-ct/somatom-force/technical-specifications

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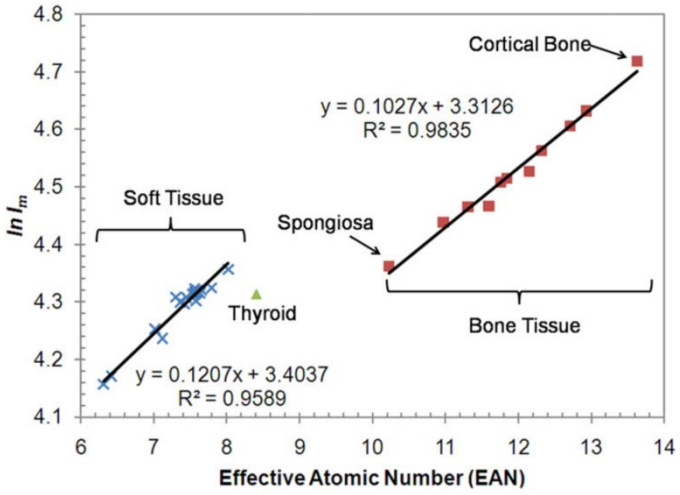
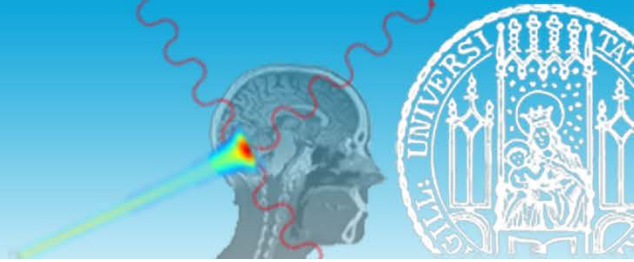


Yang et al. Phys Med Biol **55** (2010) 1343

http://www.healthcare.siemens.com/computed-tomography/dual-source-ct/somatom-force/technical-specifications

Outline



- **Motivation for DECT in proton therapy**
- **Stopping power and range in proton therapy treatment planning**
- **Tissue determination in proton therapy**

Materials and methods

Scanner

- **SOMATOM Force**
  Klinikum Grosshadern

- **90 kVp and 150 kVp/Sn**
  - **Including merged 120 kVp equivalent**
  - **ADMIRE recon**
  - **$CTDI_{vol}$ 20 mGy**

Materials and methods

Scanner

- **SOMATOM Force Klinikum Grosshadern**

- **90 kVp and 150 kVp/Sn**
  - **Including merged 120 kVp equivalent**
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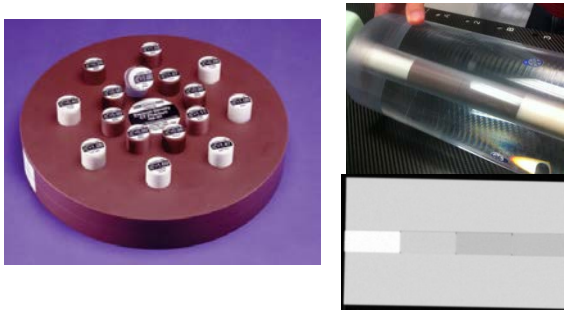
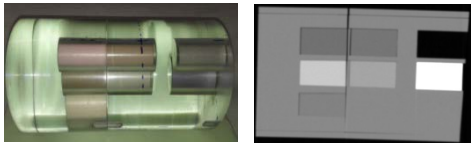
Phantoms

- **Calibration phantom**



17 Gammex inserts

- **Evaluation phantom**



7 CIRS inserts

Materials and methods

Scanner

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Phantoms

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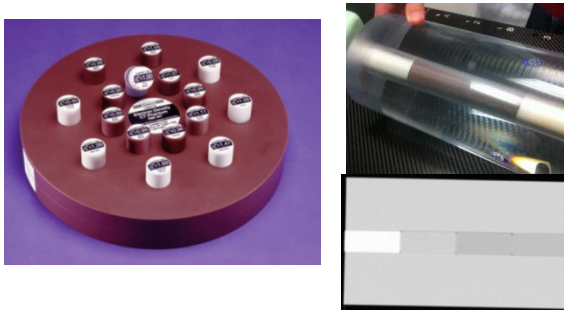

17 Gammex inserts

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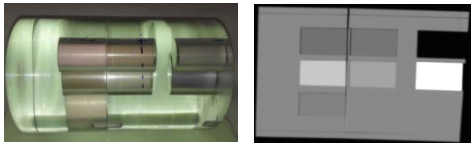
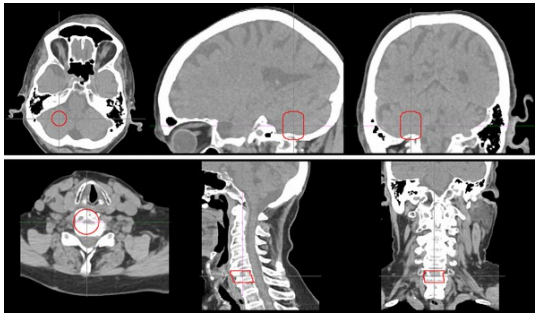


7 CIRS inserts

Patients

- **5 trauma patients**

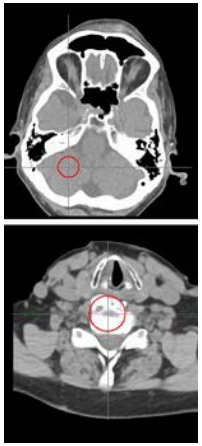


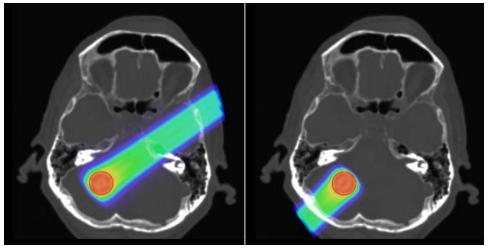
Head and neck scans

- **Merged image used for clinical routine**
- **Virtual tumors delineated by RO**

Materials and methods

- **DECT** based **treatment plans**
  - **Research TPS with pencil beam algorithm**
- Simulated **brain** tumors

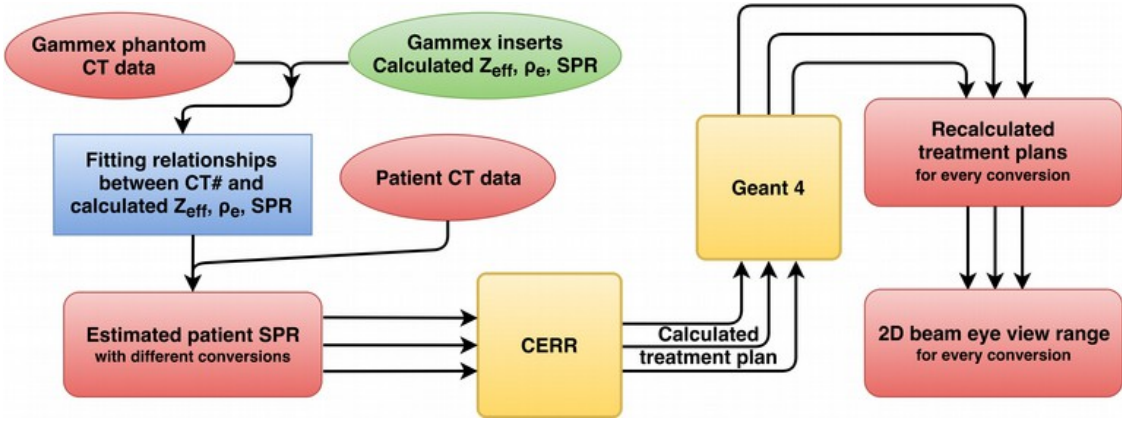


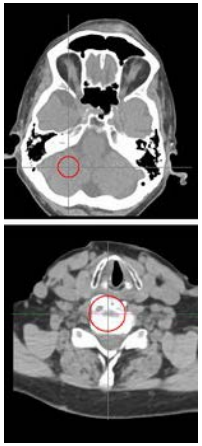


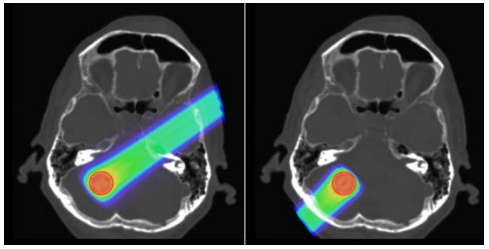
For brain tumors a **long** and **short range** plan was made

Materials and methods

- **DECT** based **treatment plans**
  - **Research TPS with pencil beam algorithm**
- Simulated **brain** tumors







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- **DECT** based **treatment plans**
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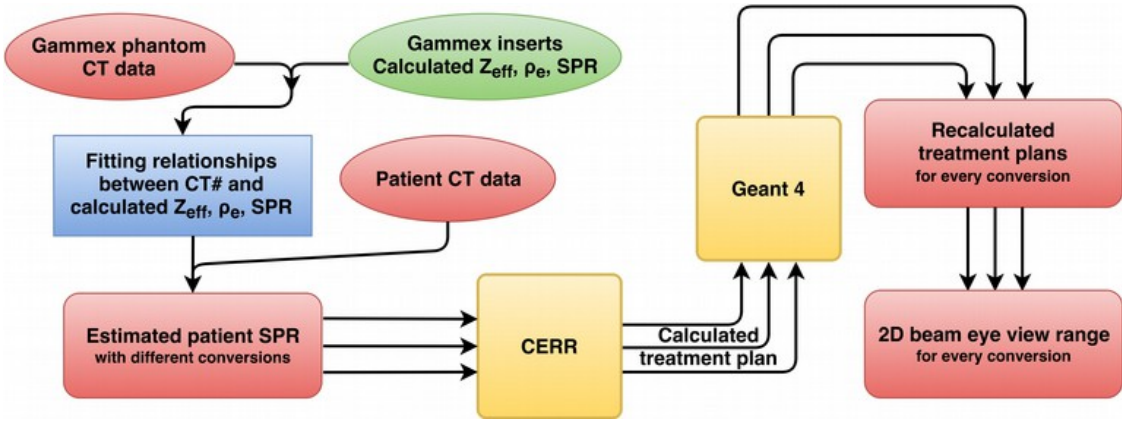
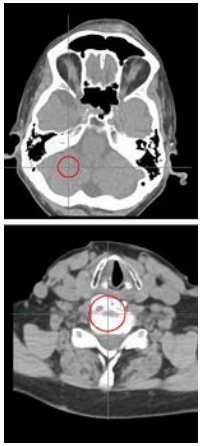
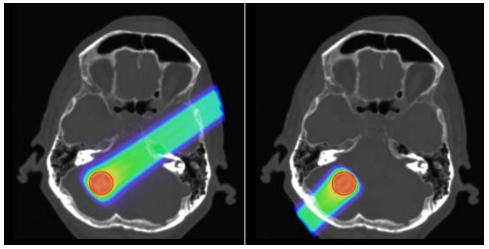






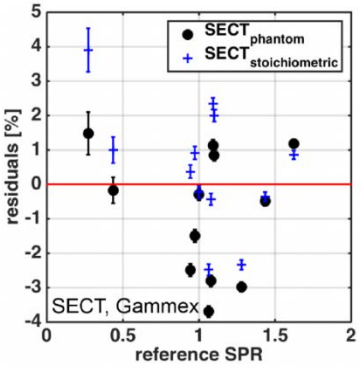
For brain tumors a **long** and **short range** plan was made

- **DECT** and **SECT** treatment plans were compared for **relative range differences**
- We used a **Monte Carlo recalculation** tool with a **single evaluation geometry** for all plans of a patient

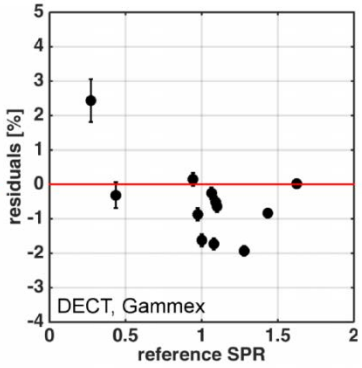
Results

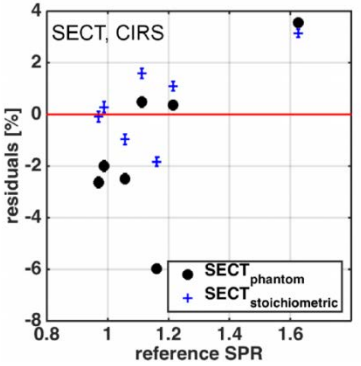
Phantoms

SECT
RMSE 2%

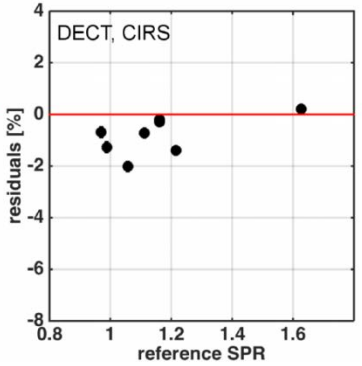


DECT
RMSE 1%

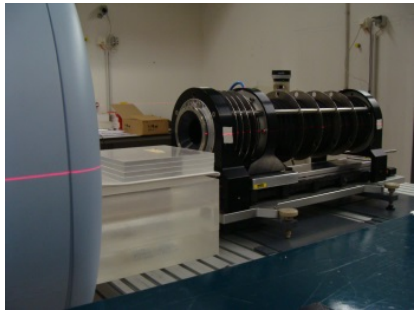




RMSE 3.6%



RMSE 0.8%



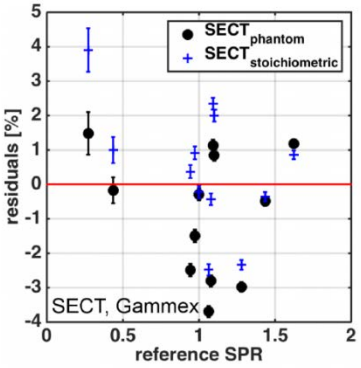
Reference SPR
measured @ HIT

Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

Phantoms

SECT
RMSE 2%



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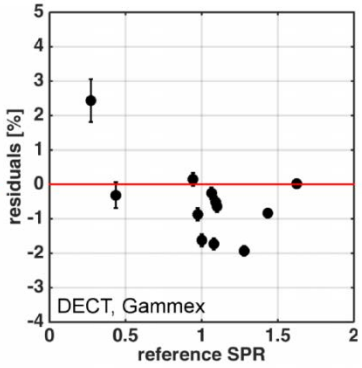

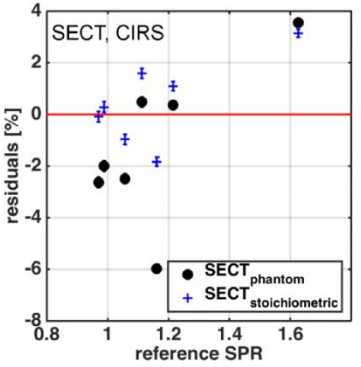

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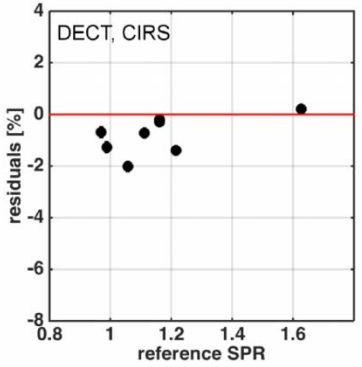

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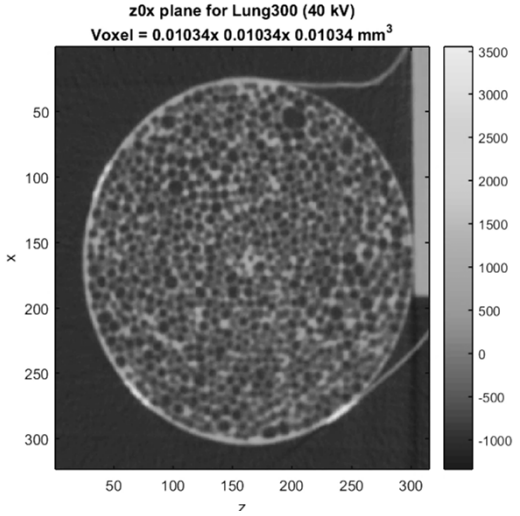


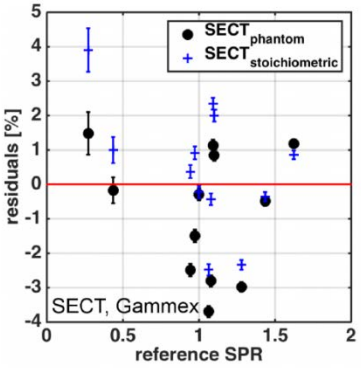
Lung insert @ small animal CBCT
Courtesy L. Schyns and I. Almeida, MAASTRO clinic

Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

Phantoms

SECT
RMSE 2%



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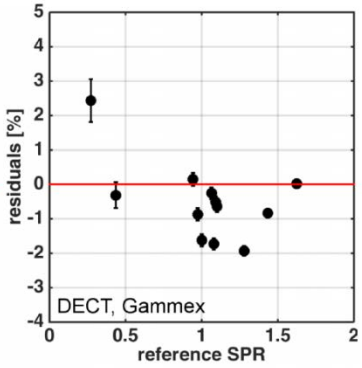
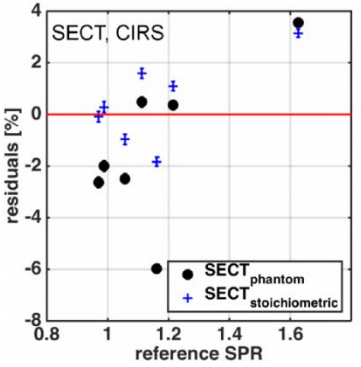
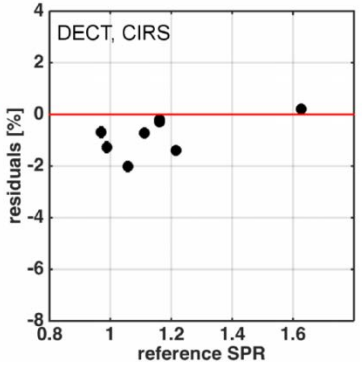


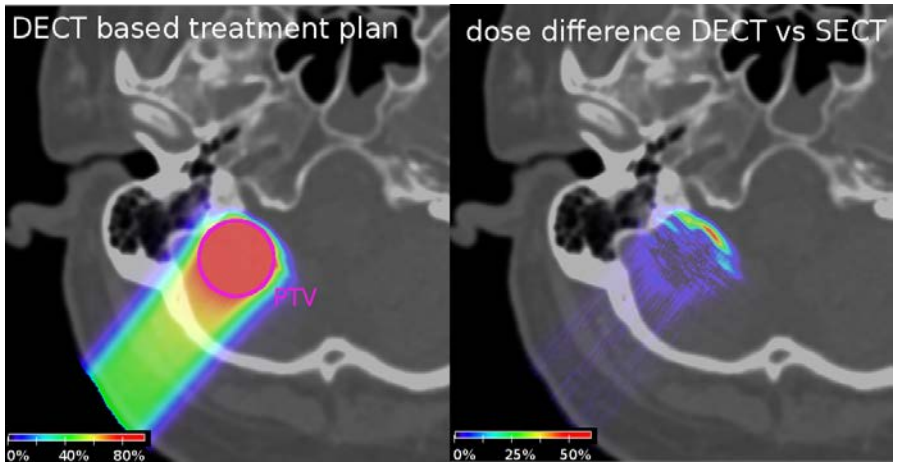




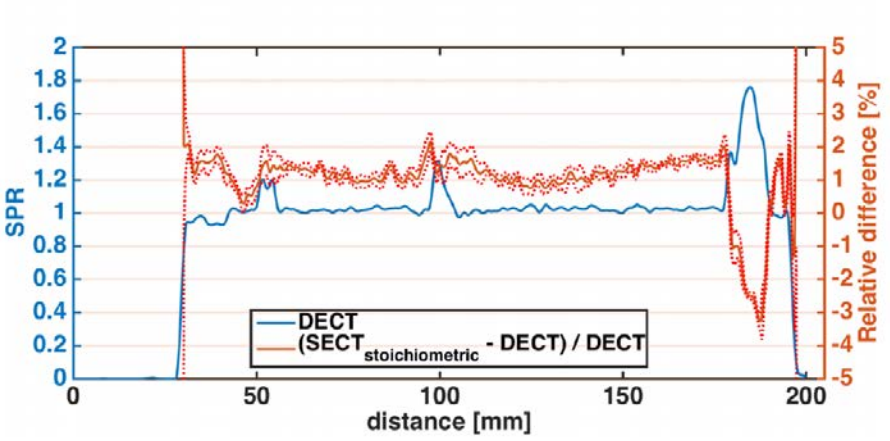
RMSE 3.6%

RMSE 0.8%

Patients



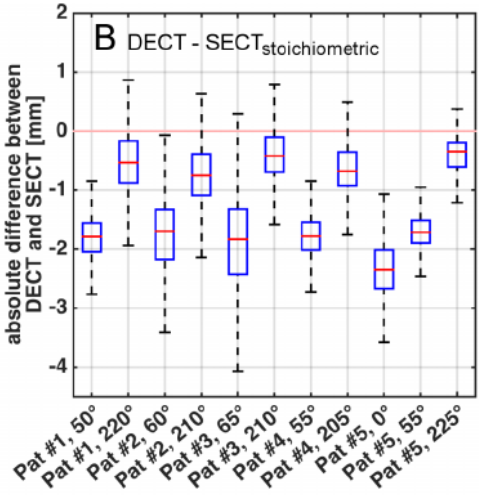
Van Elmpt, Landry et al. Radiother Oncol **119** 20016 137

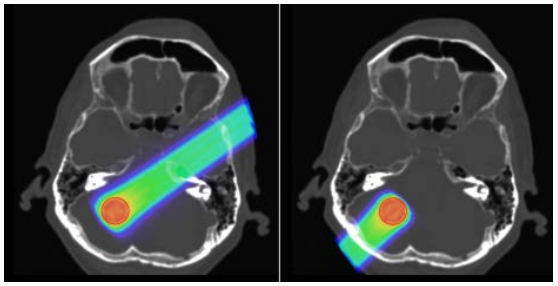


Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

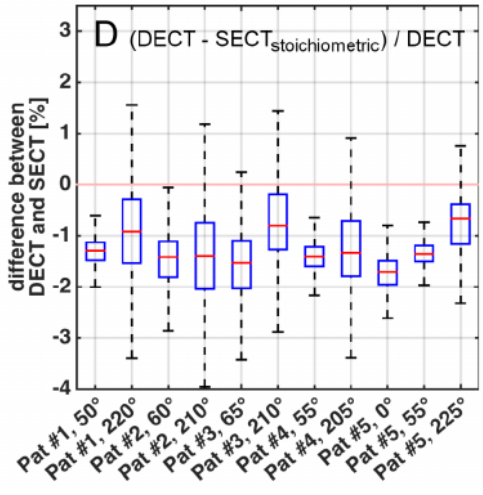
brain tumors
range differences





50° 220°

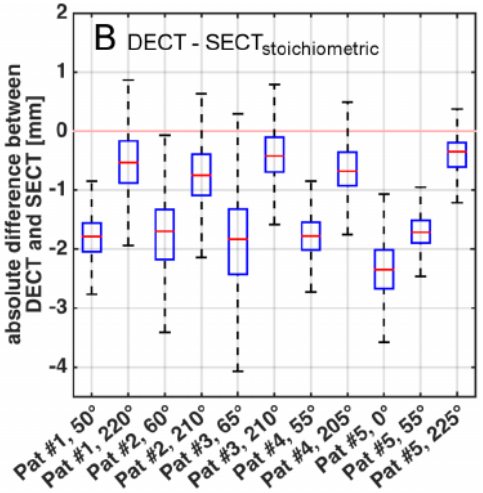
- Up to **2 mm** median shift

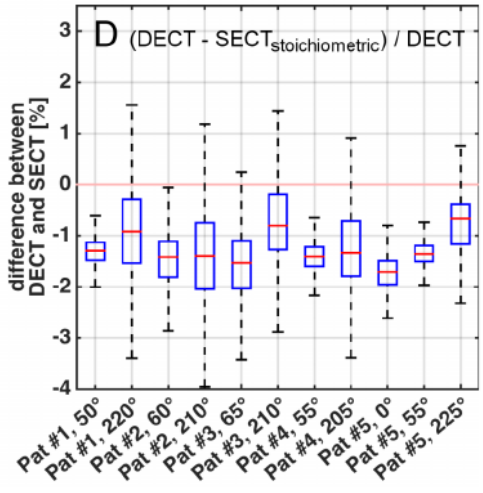


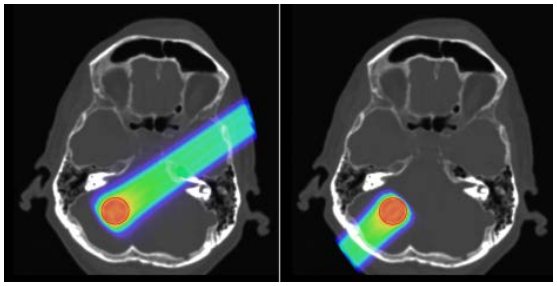
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

brain tumors
range differences







50° 220°

- Up to **2 mm** median shift
- Corresponds to about **1.5%** of the **range**
- CT image axial **pixels size 0.4 mm**

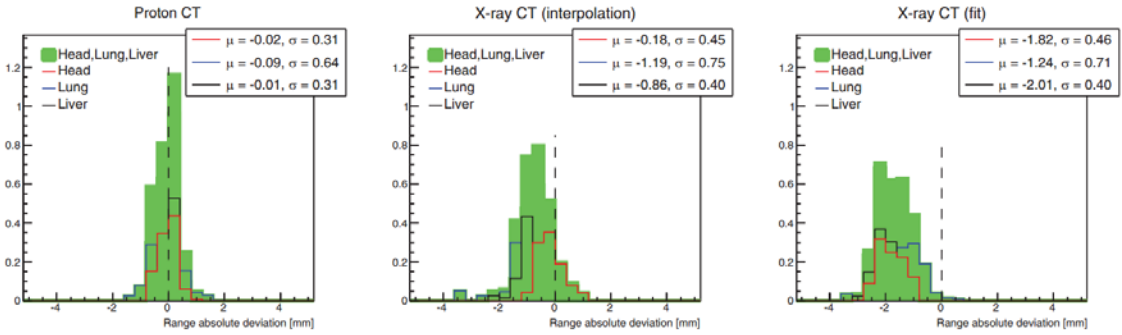
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Discussion and outlook

Discussion

- **Range differences** between **SECT and DECT of 1.5%** consistent with **RMSE error levels (2-3% vs 1%)**

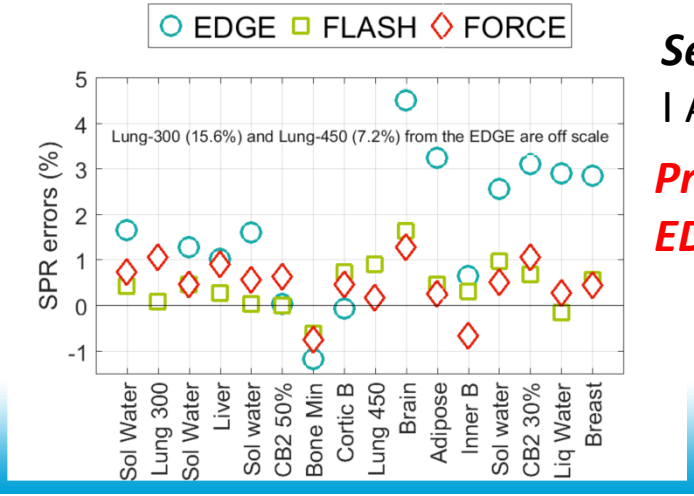
- **SECT** protocol using 150kVp/Sn is ideal for $\boldsymbol{\rho_e}$
  - High mean energy
  - Hard spectrum with little beam hardening



Arbor et al. Phys Med Biol **60** (2015) 7585

Outlook

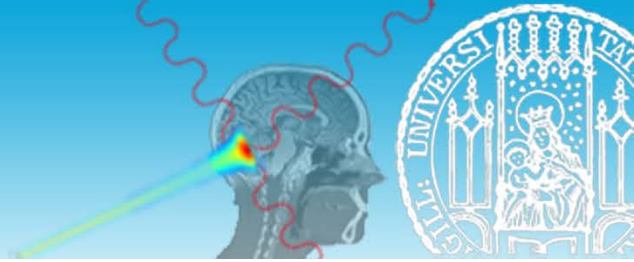
- Main issue Force FOV (~36 cm)
- Siemens EDGE has large FOV



See Poster:
I Almeida

Preliminary
EDGE: split beam

Outlook



Clinical implementation

Requirements

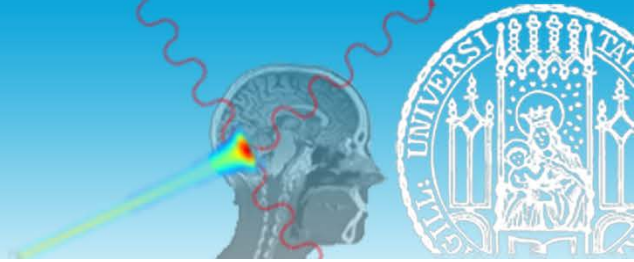
- DECT compatible **TPS**
- DECT **scanner in clinic**
- DECT scanner with sufficient **FOV** for all sites

Validation

- We suffer from **lack of ground truth** in biological tissues
- We need a **convincing test** showing improved range control with DECT

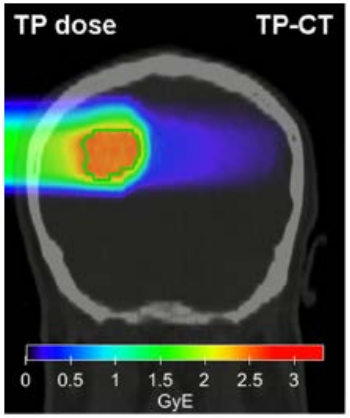
TU-FG-BRB-01, Xie, Y, …, Teo, B, Medical Physics, 43, 3756-3756 (2016)

Outline



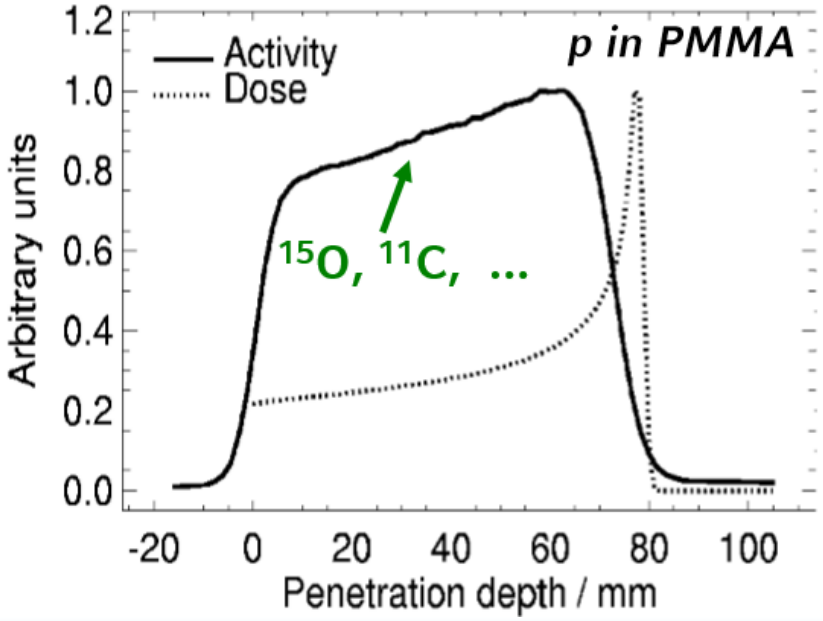
- **Motivation for DECT in proton therapy**
- **Stopping power and range in proton therapy treatment planning**
- **Tissue determination in proton therapy**

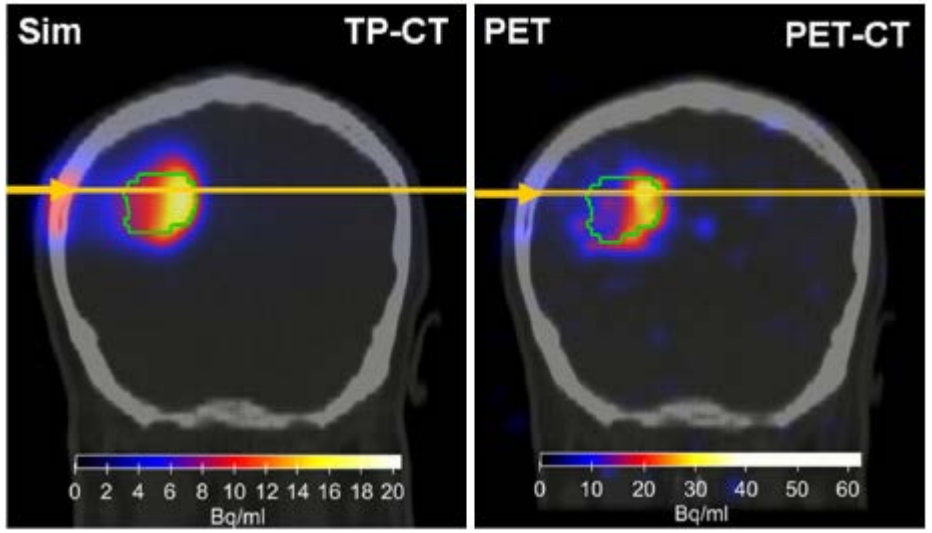
PET activity to verify dose delivery



Proton dose distribution from TPS

- Measured PET activity can be compared to MC prediction





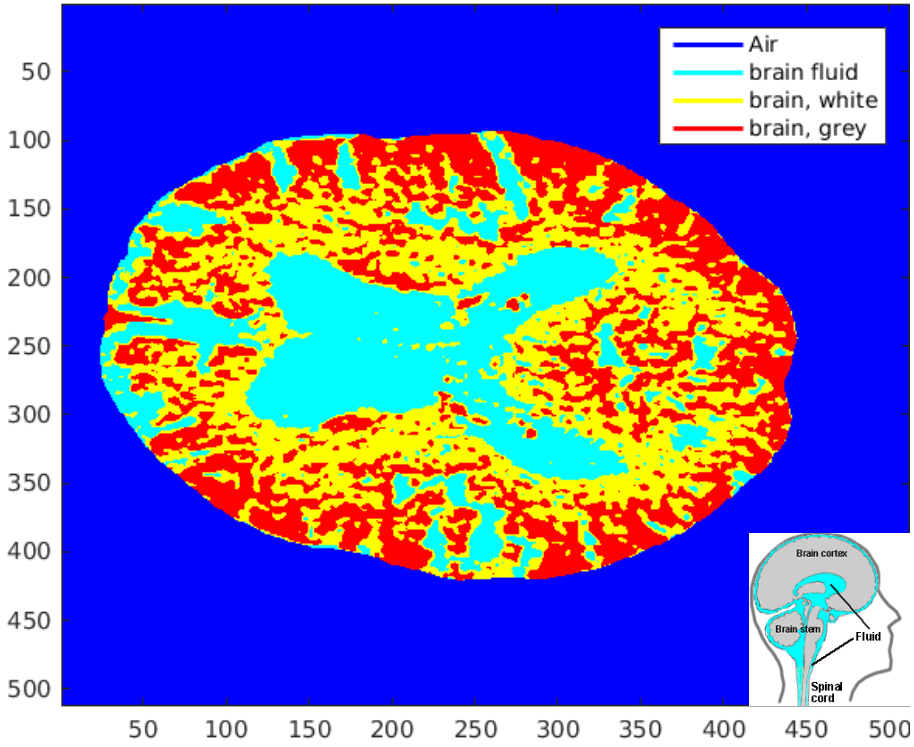
Julia Bauer, et al, Radiother and Oncol, 107 (2) 2013 pp 218-226

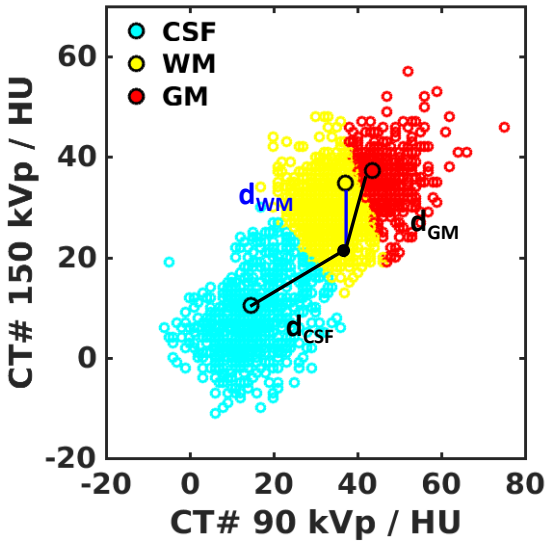
Parodi et al. IEEE TNS 2005

Euclidean distance approach for brain tissue segmentation

Tissue assignment:

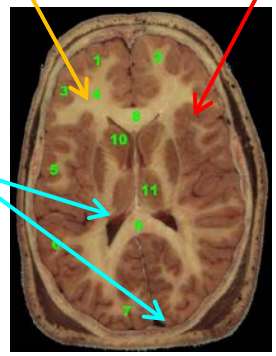
Minimal Euclidean distance between data points in DECT space and reference values





White matter Grey matter

Brain fluid



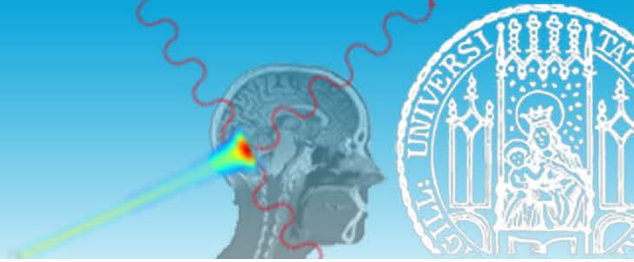
Selection rule

$d_{WM} < d_{GM} < d_{CSF}$

White matter

Berndt B, Landry G, et al. 2016 TH-CD-202-05: DECT Based Tissue Segmentation as Input to Monte Carlo Simulations for Proton Treatment Verification Using PET Imaging *Medical Physics* **43** 3877

Conclusion



Conclusion 1

- The **SPR accuracy** of **DECT** is **superior** to SECT
  - 1% vs 3.5%
- This **accuracy** is probably at the **level we need**
- This should be sufficient to **warrant clinical implementation**

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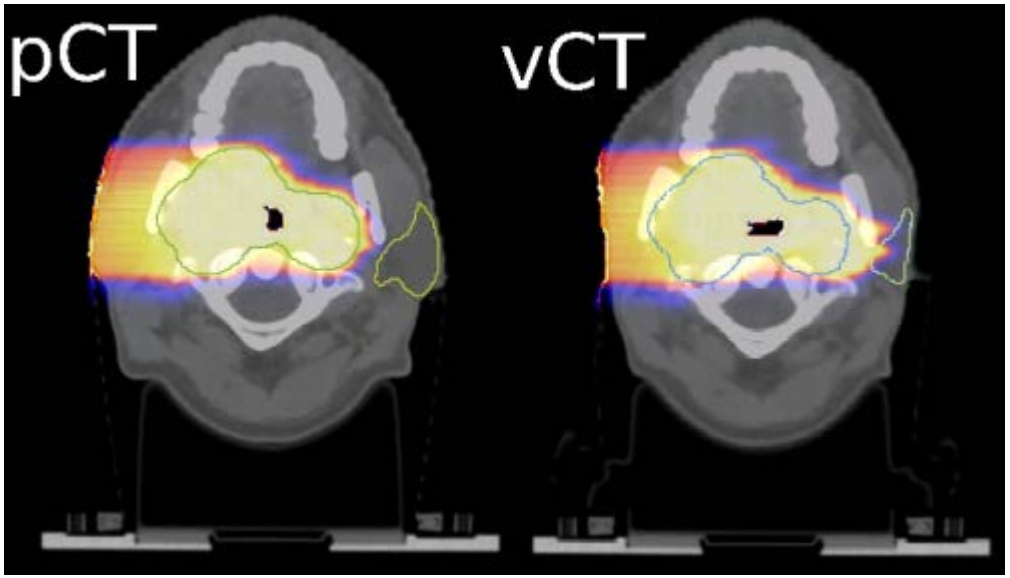
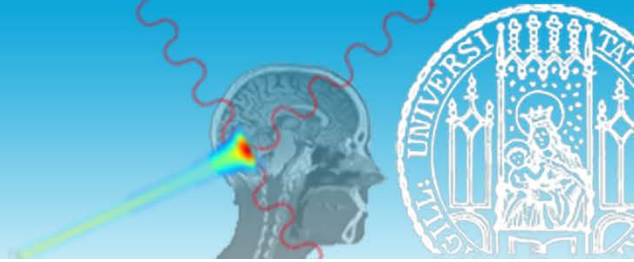


Landry et al. Med Phys 2015

Conclusion



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Conclusion 2

- For **specific applications DECT tissue segmentation** may be **beneficial**
- **PET** range verification example
- **Prompt gamma**?

Acknowledgement

- **Many thanks to**
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