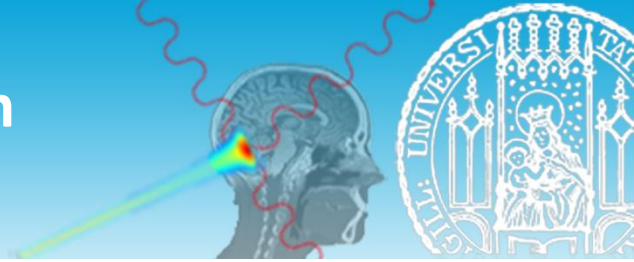
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

2nd Jagiellonian Symposium
June 8th 2017, Krakow



Next generation imaging for ion beam therapy treatment planning

Guillaume Landry, George Dedes, Katia Parodi

Department of Medical Physics, Faculty of Physics, Ludwig-Maximilians-Universität München, DE

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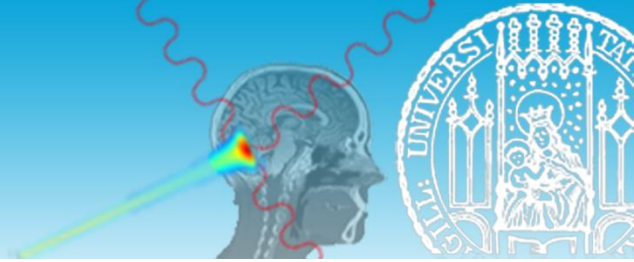
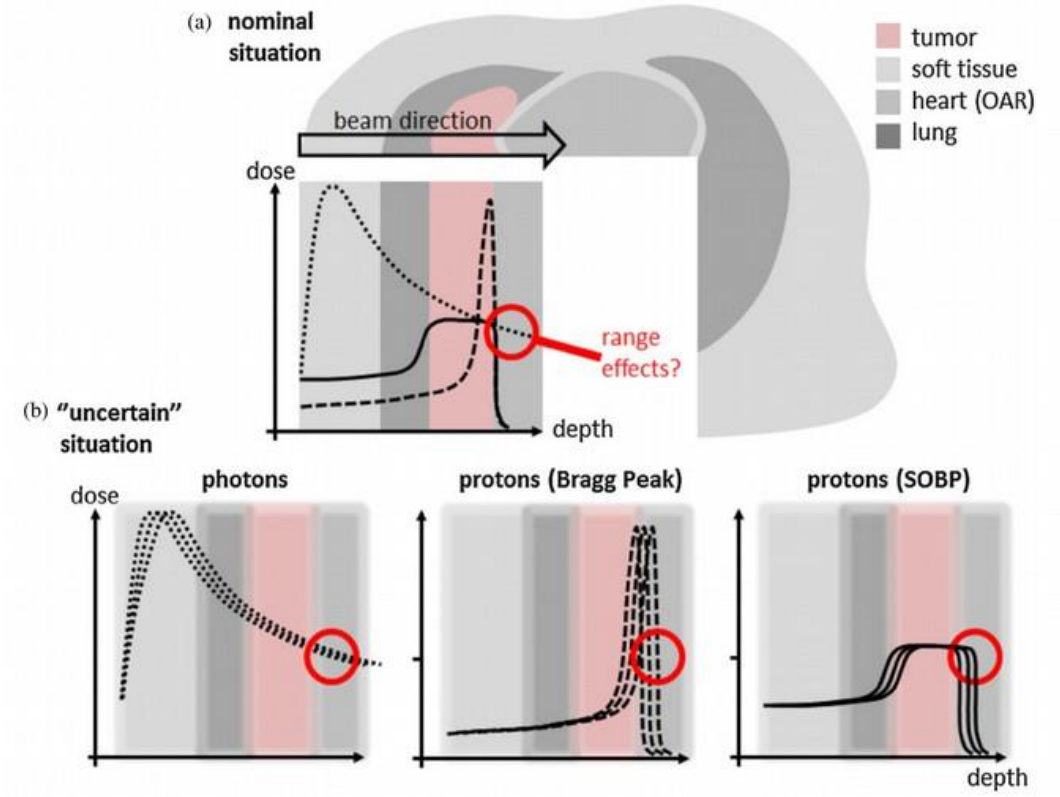
Outline



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

Motivation

- Protons and ions are **more conformal**
- However, they suffer from **different uncertainties** than photons
- **Robustness** is an issue



Knopf and Lomax Phys Med Biol **58** (2013) R131

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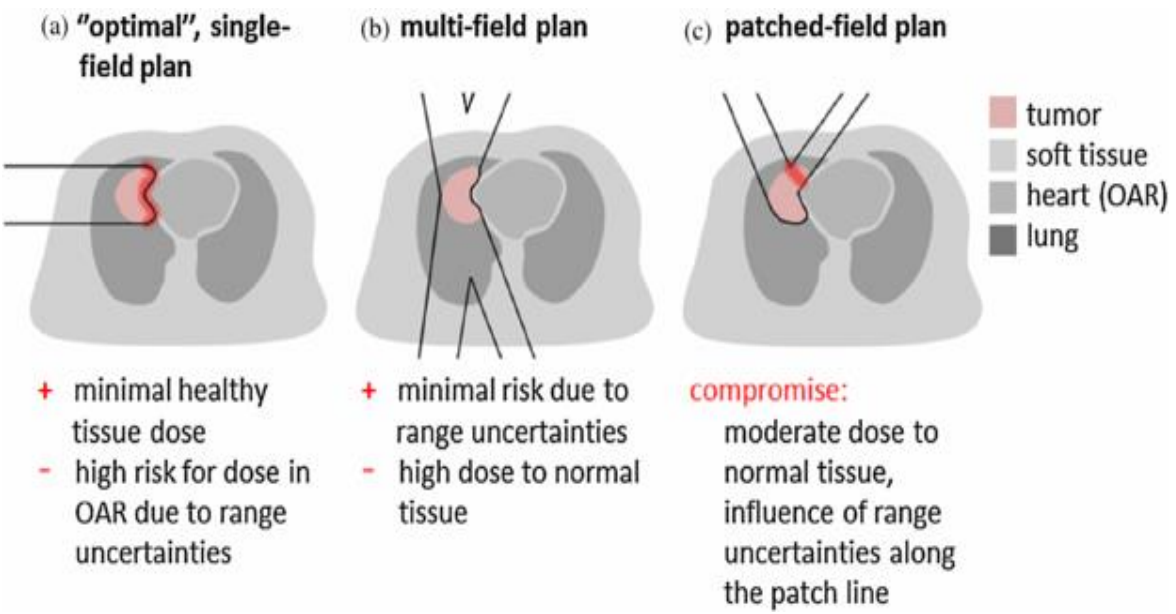
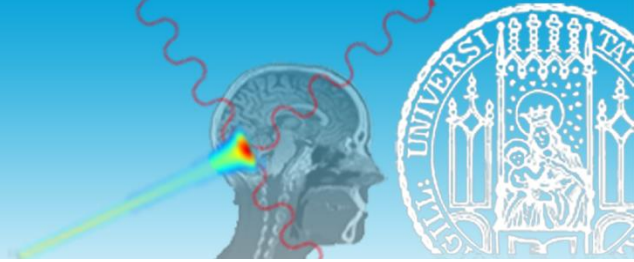


Knopf and Lomax Phys Med Biol **58** (2013) R131

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

Motivation



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

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

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

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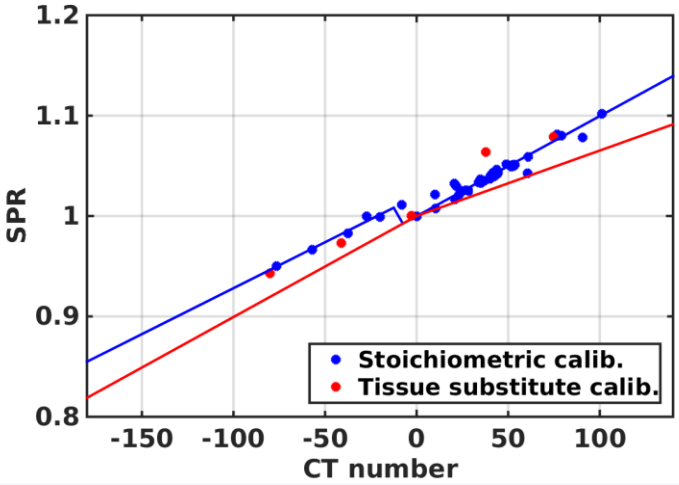
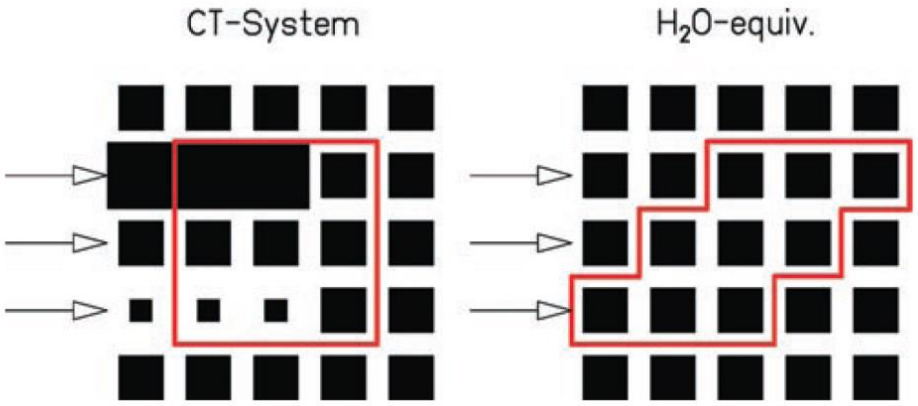
- Proton therapy treatment planning requires **stopping power ratio** to water

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





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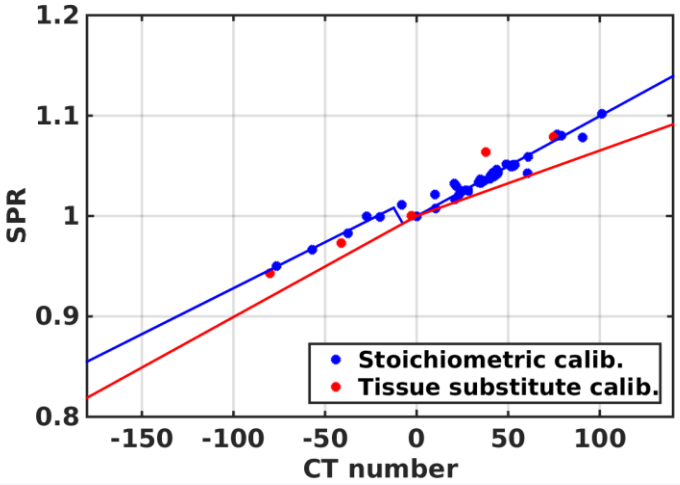

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SPR uncertainty from single energy CT (**SECT**) conversion is often stated as **3.5%** (95th percentile)

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

Motivation

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

2 equations, 2 unknowns

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

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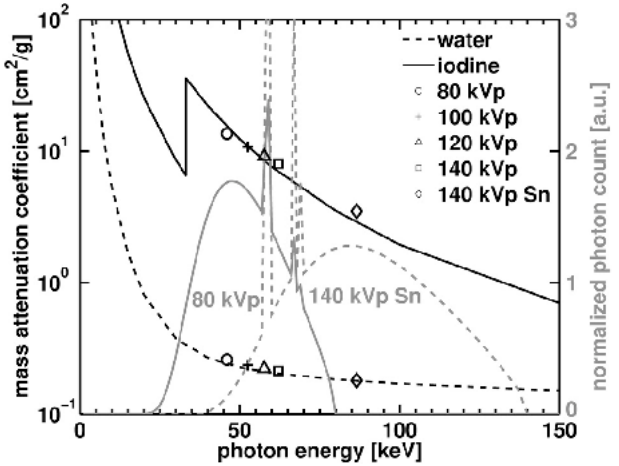
http://www.healthcare.siemens.com/computed-tomography/dual-source-ct/somatom-force/technical-specifications

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

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

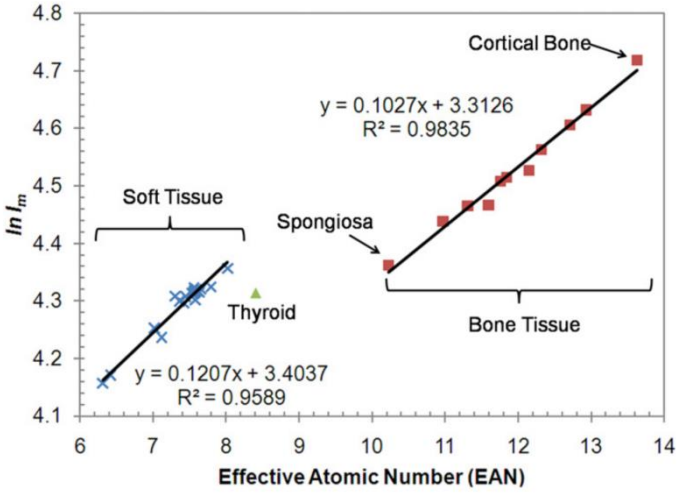


Van Elmpt, Landry et al. Radiother Oncol **119 (**2016) 137

Motivation

Theory

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



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

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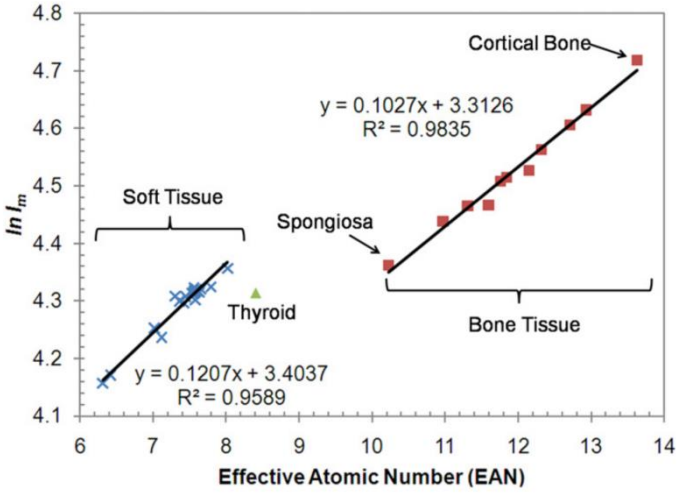
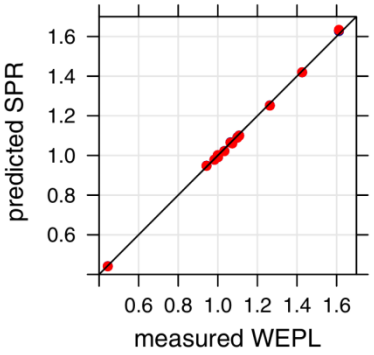
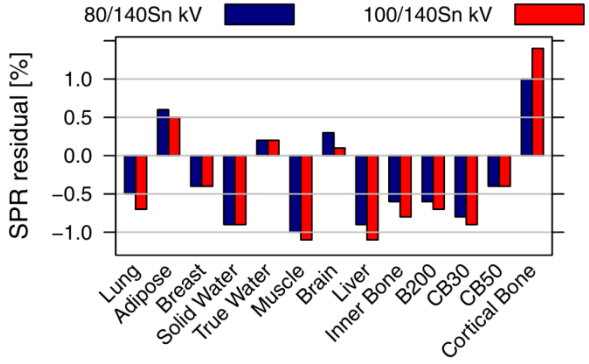


Yang et al. Phys Med Biol **55** (2010) 1343

Experiment





Hünemohr et al. Phys Med Biol **59** (2014) 83

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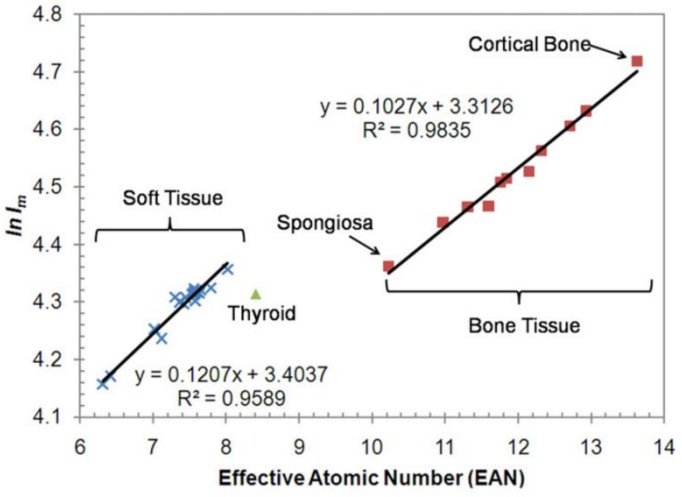

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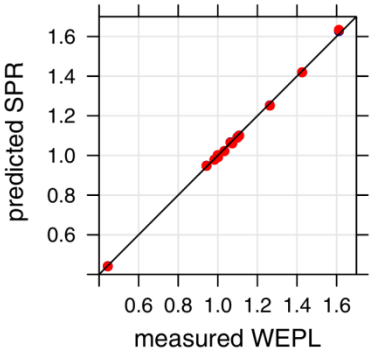
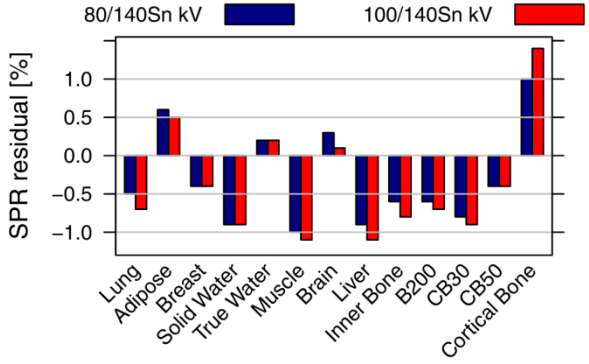
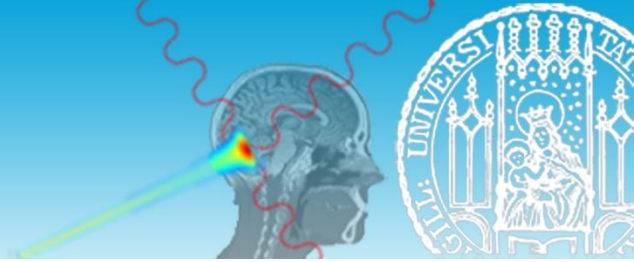




Mean SPR accuracy 0.6%

Hünemohr et al. Phys Med Biol **59** (2014) 83

Outline



- **Motivation for DECT in proton therapy**
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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**

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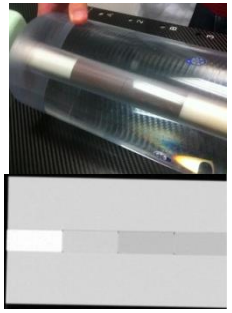
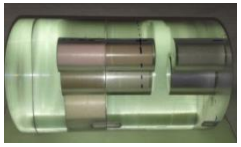
Phantoms

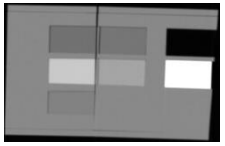
- **Calibration phantom**



17 Gammex inserts

- **Evaluation phantom**





7 CIRS inserts

Materials and methods

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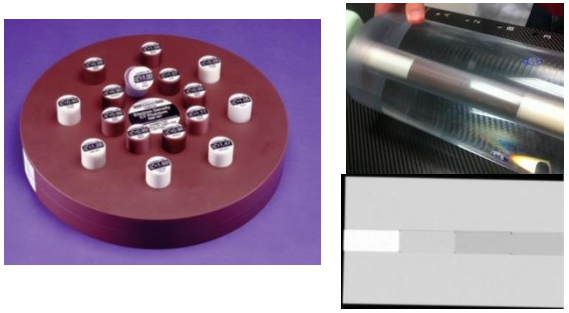

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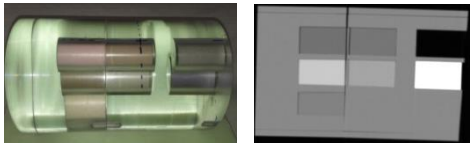
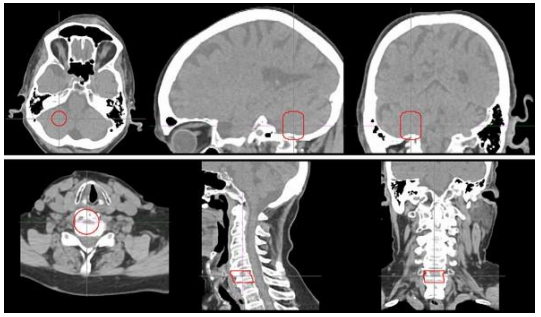


7 CIRS inserts

Patients

- **5 trauma patients**

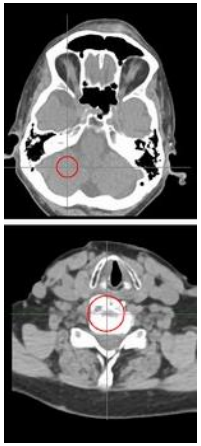


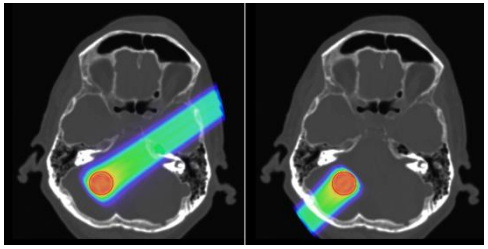
Head and neck scans

- **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

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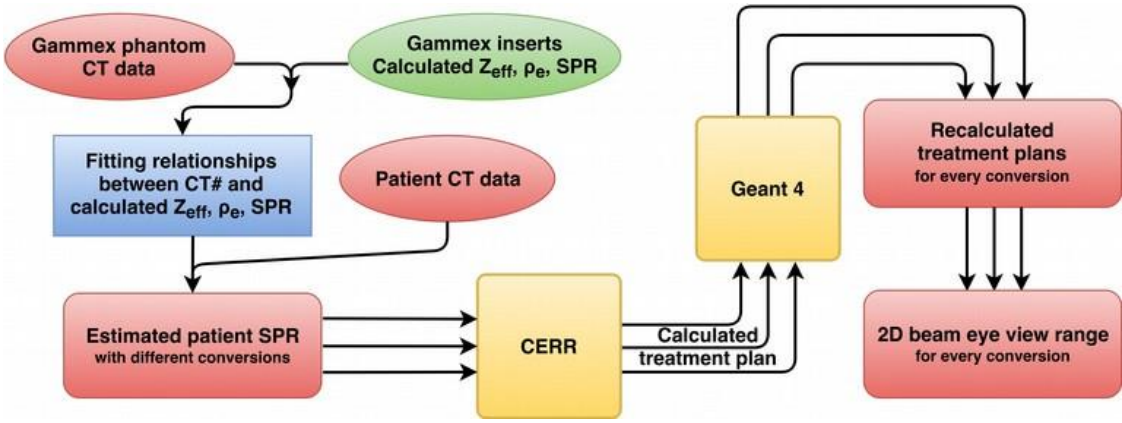

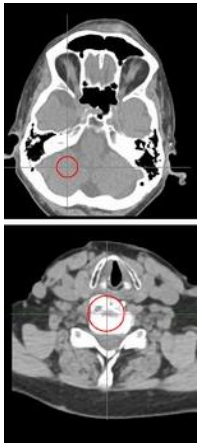

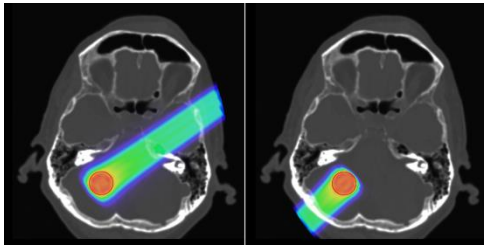

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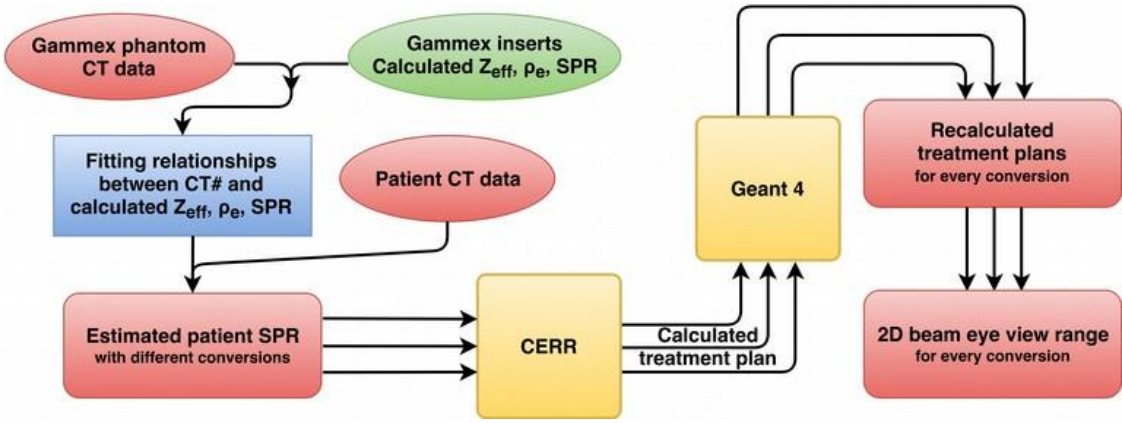
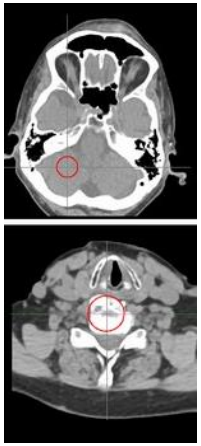
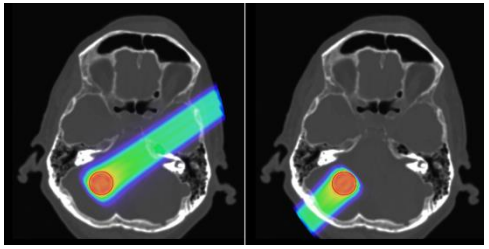






For brain tumors a **long** and **short range** plan was made

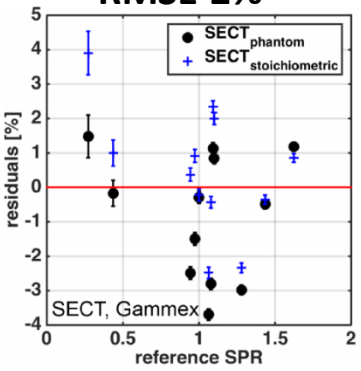
- **DECT** and **SECT** treatment plans were compared for **relative range differences**
- We used a **Monte Carlo recalculation** tool with a **single evaluation geometry** for all plans of a patient

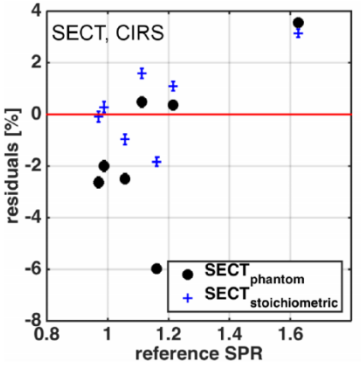
Results

Phantoms

SECT

RMSE 2%

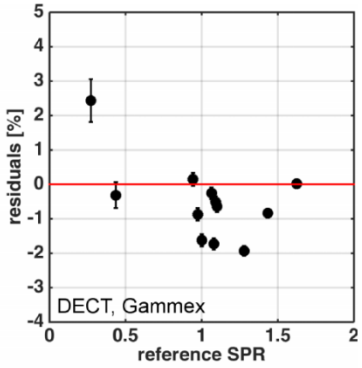


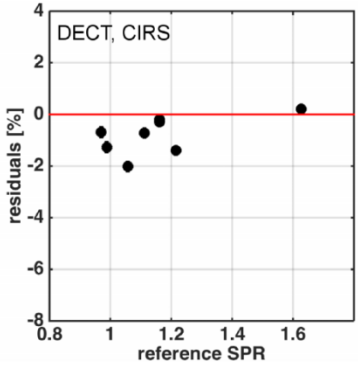


RMSE 3.6%

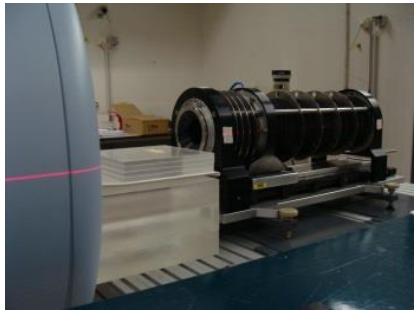
DECT

RMSE 1%





RMSE 0.8%



Reference SPR measured @ HIT

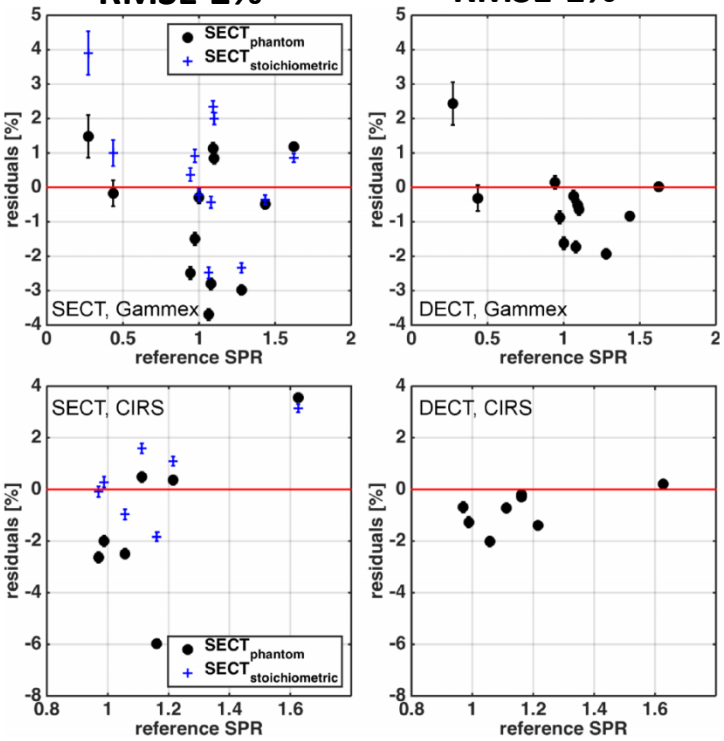
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

Phantoms

SECT

RMSE 2%



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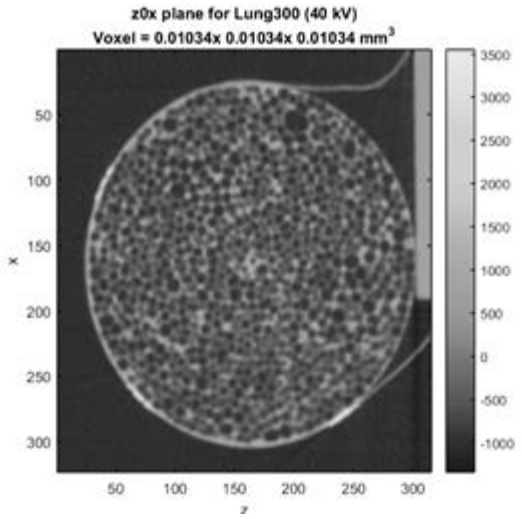
DECT

RMSE 1%

RMSE 0.8%

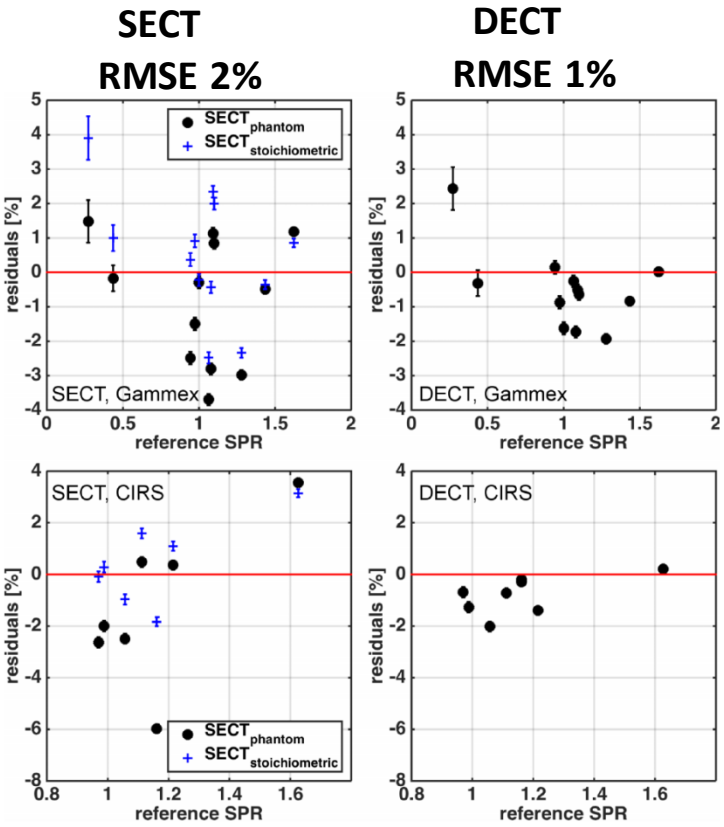


Lung insert @ small animal CBCT
Courtesy L. Schyns and I. Almeida, MAASTRO clinic

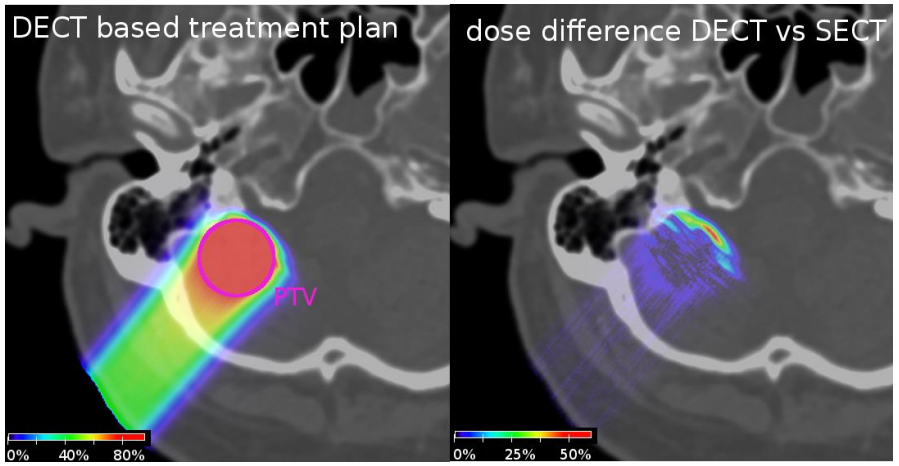
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

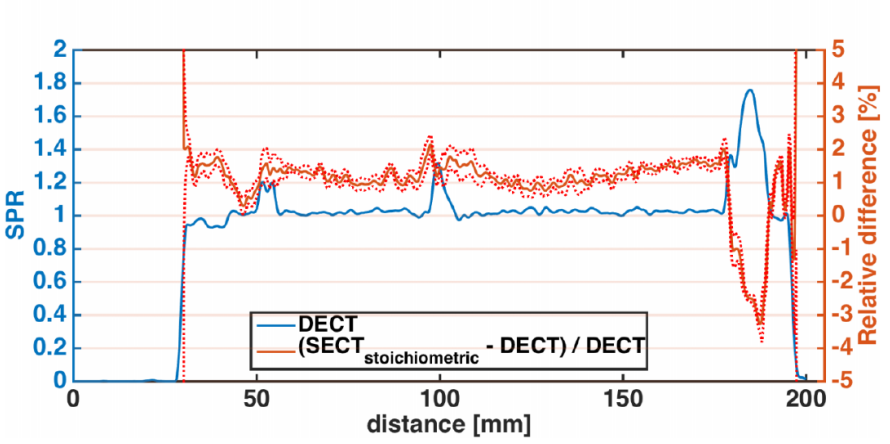
Phantoms



Patients



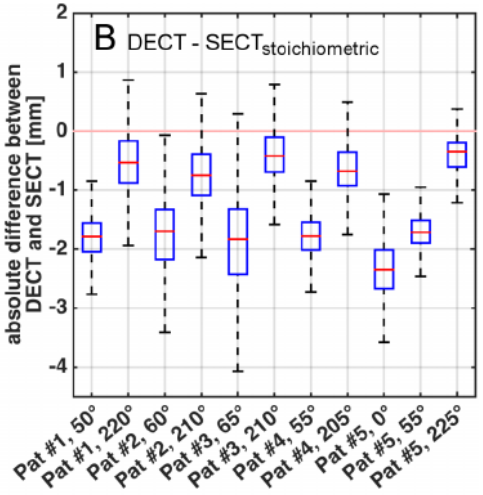
Van Elmpt, Landry et al. Radiother Oncol **119** 20016 137

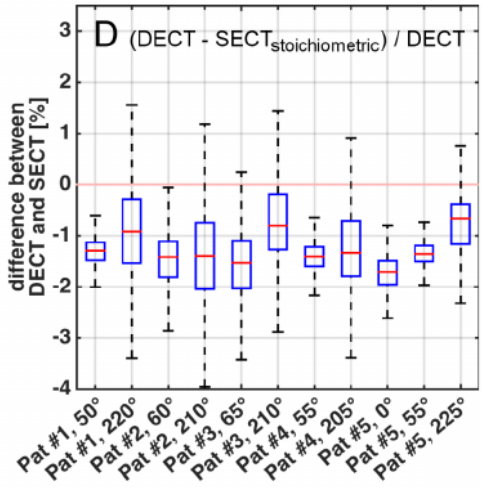


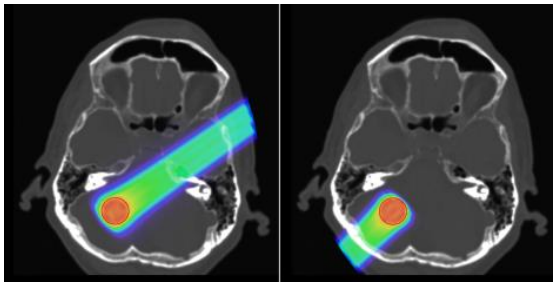
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

brain tumors
range differences







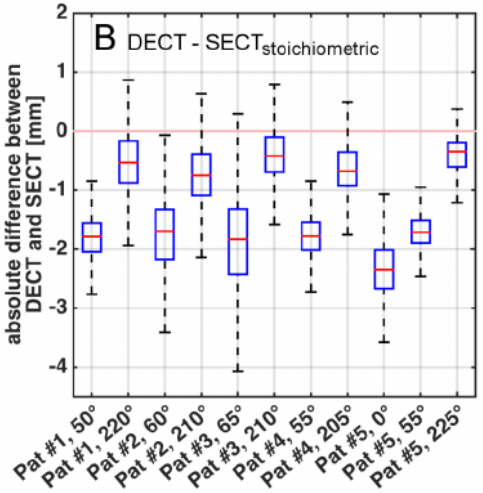
50° 220°

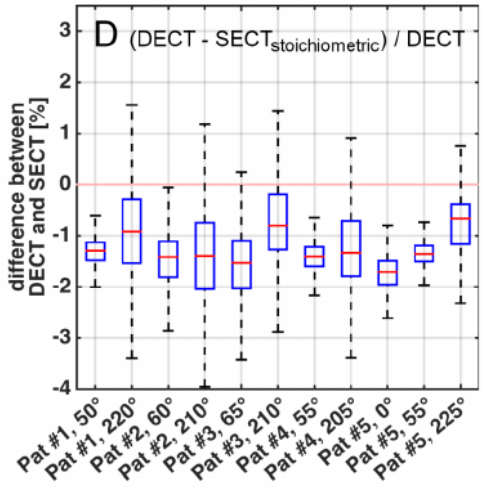
- Up to **2 mm** median shift

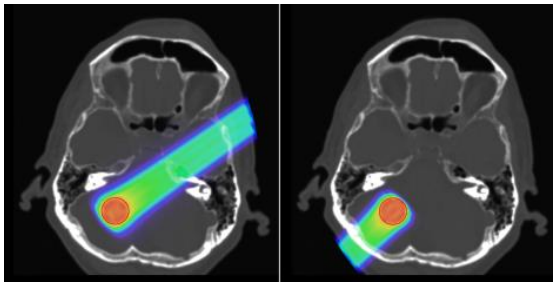
Hudobivnik,…,Landry. Med Phys **43** (2016) 495

Results

brain tumors range differences







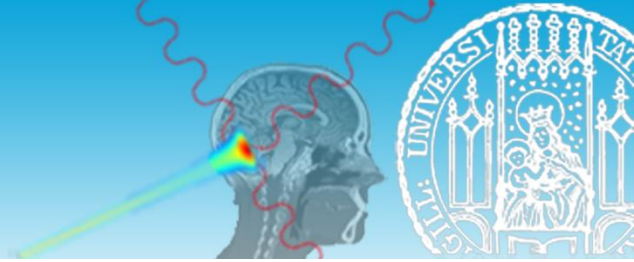
50° 220°

Range differences between **SECT and DECT of 1.5%** consistent with **RMSE error levels (2-3.5% vs 1%)**

- 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

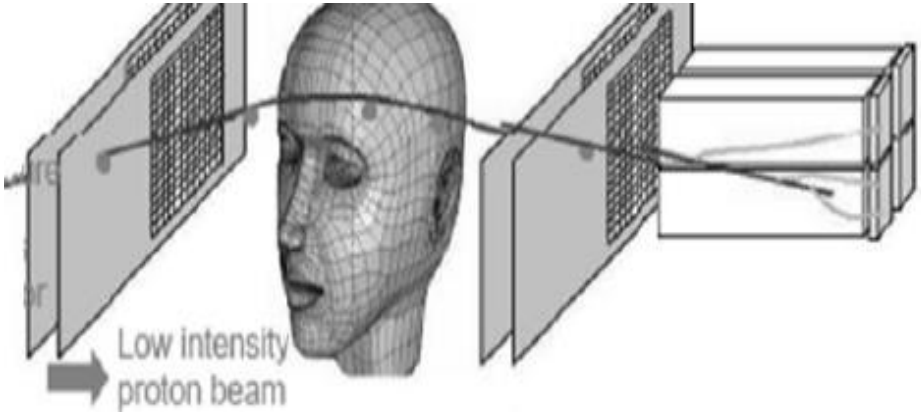
Outline



- **Motivation for DECT in proton therapy**
- **Is proton CT a superior alternative to DECT?**
- **Tissue determination in proton therapy**

Proton CT scanners

- Assuming that the initial energy is well known, we need:
  - **Position measurement at the entrance/exit**
  - **Direction measurement at the entrance/exit -> a second position measurement**
  - **Energy loss or residual energy or residual range measurement at the exit**



x1in,y1in
x2in,y2in

dE x1out,y1out | Eout
x2out,y2out

Proton CT scanners

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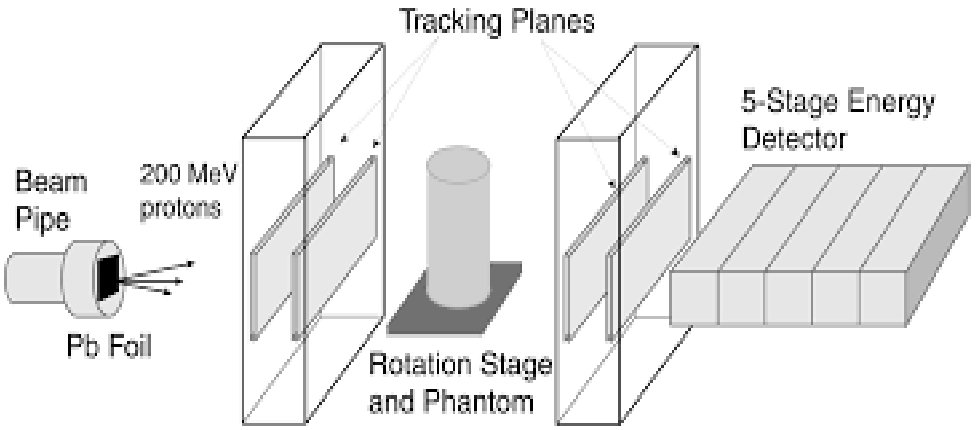

LLU pCT scanner prototype [**H.F.-W. Sadrozinski et al**. NIM A **831** 394-399 (2016)]

Proton CT scanners

- Assuming that the initial energy is well known, we need:
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  - **Single proton tracking!**

LLU pCT scanner prototype [**H.F.-W. Sadrozinski et al**. NIM A **831** 394-399 (2016)]

Proton CT scanners

- Assuming that the initial energy is well known, we need:
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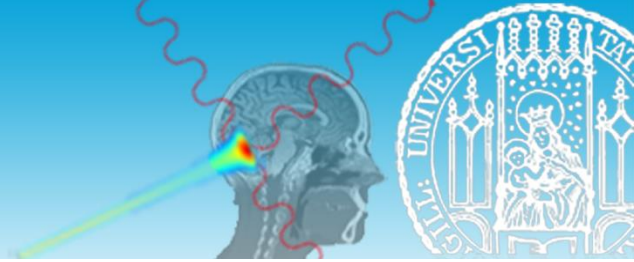
LLU pCT scanner prototype [**H.F.-W. Sadrozinski et al**. NIM A **831** 394-399 (2016)]

- The most advanced proton CT scanner prototype (Phase II preclinical prototype) built and operated by the pCT collaboration (USA).

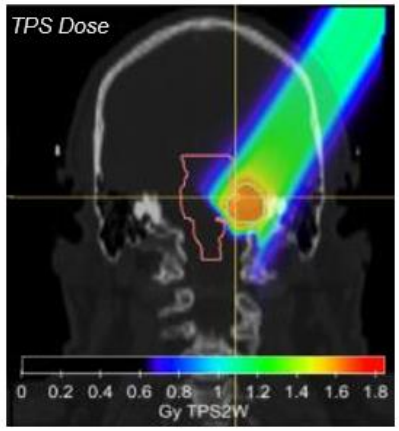
  LMU Dept Med Phys became a partner last year.

Outline



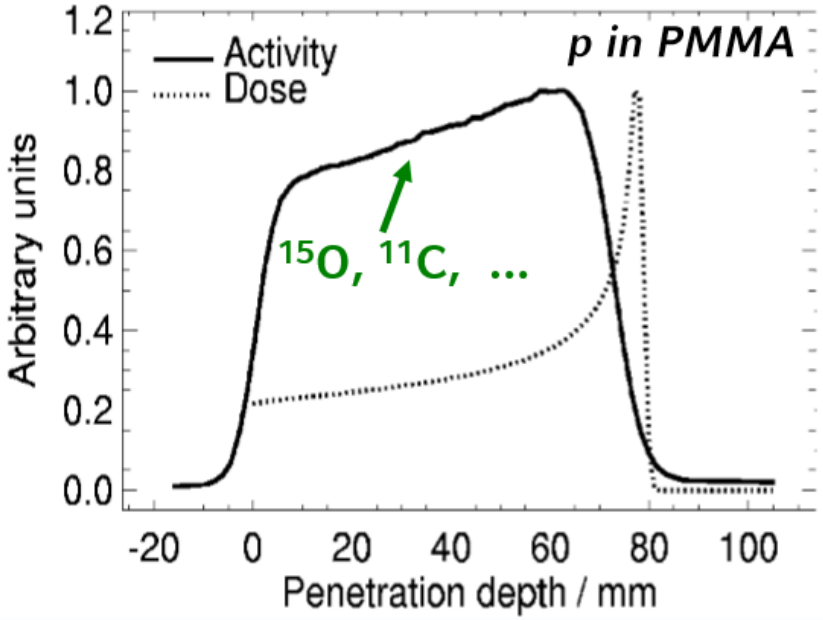
- **Motivation for DECT in proton therapy**
- **Stopping power and range in proton therapy treatment planning**
- **Tissue determination in proton therapy**

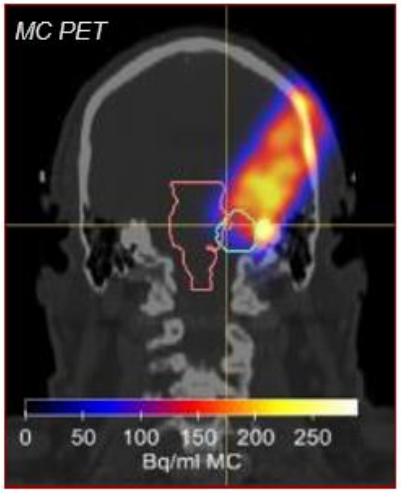
PET activity indicates proton dose delivery

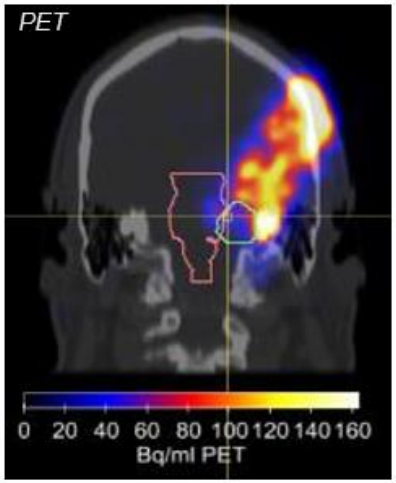


Proton dose distribution from TPS

- Activity profile for protons does not follow the Bragg peak as nicely as for Carbon ions (projectile fragmentation)
- Measured PET activity can be compared to MC prediction



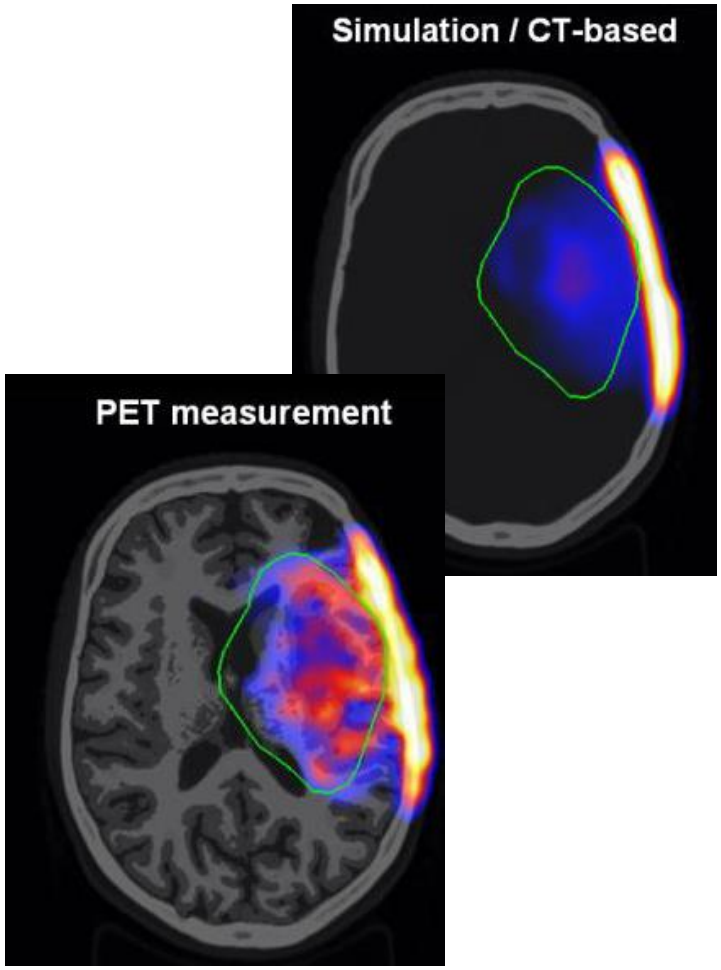




Courtesy of J. Bauer

Parodi et al. IEEE TNS 2005

Positron emission yield simulations



Courtesy of J. Bauer

Uncertainties in MC simulation and discrepancies to measurements due to underlying CT# to tissue composition conversion

Carbon fraction:
White matter: 19.4%
Grey matter: 9.5%
CSF: 0%

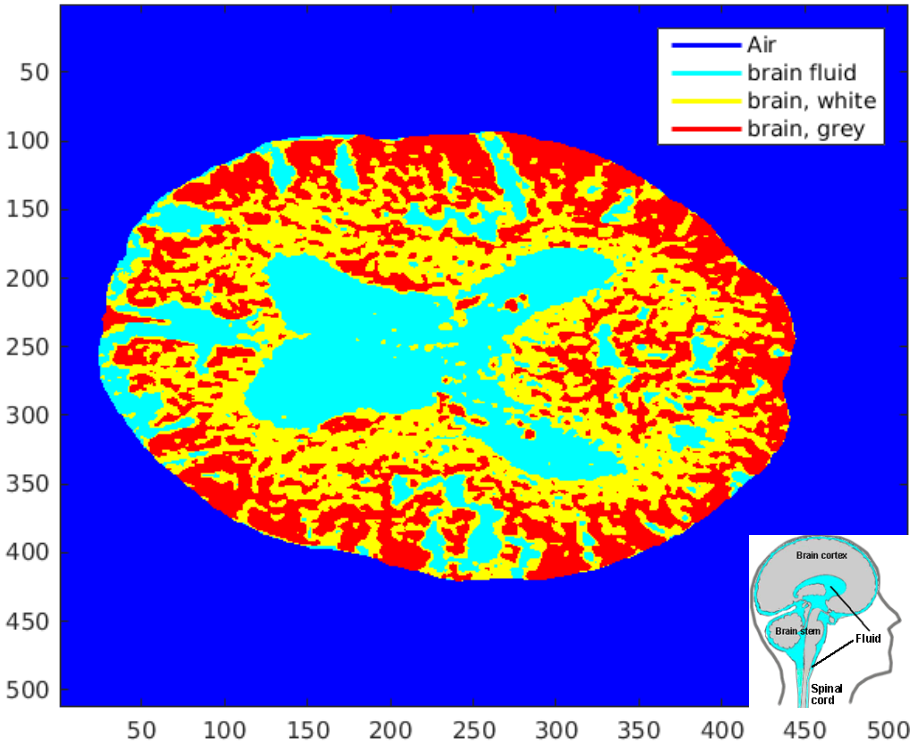
No accurate distinction between brain matter with currently available SECT decomposition method

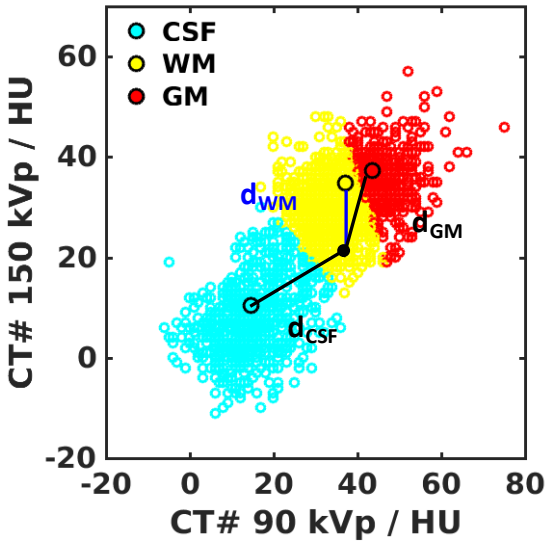
Use of **DECT data** for a different tissue segmentation approach

Euclidean distance approach for brain tissue segmentation

Tissue assignment:

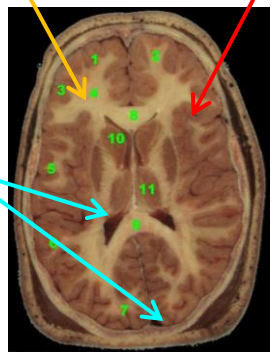
Minimal Euclidean distance between data points in DECT space and reference values





White matter Grey matter

Brain fluid



Selection rule

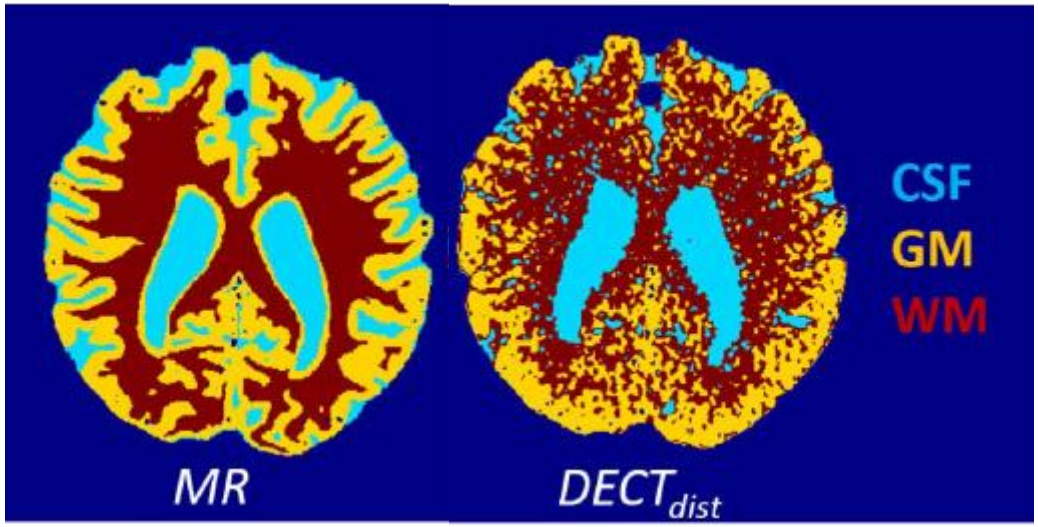
$d_{WM} < d_{GM} < d_{CSF}$

White matter

Berndt B, Landry G,…, Phys Med Biol 62 (2017) 2427

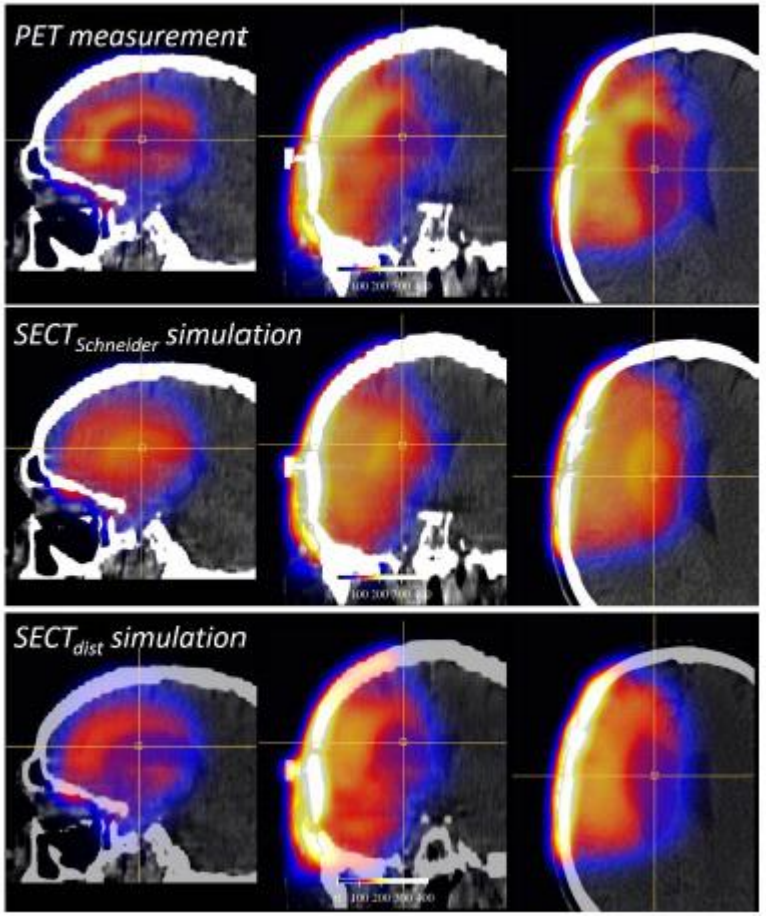
Validation of segmentation II - MR segmentation -

T1 MRI segmentation vs. DECT



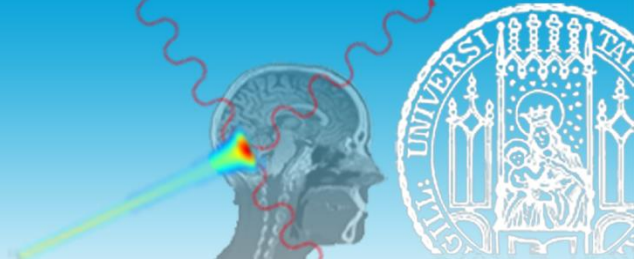
Largest impact is proper assignation of CSF

Impact on PET measurements



Berndt B, Landry G,…, Phys Med Biol 62 (2017) 2427

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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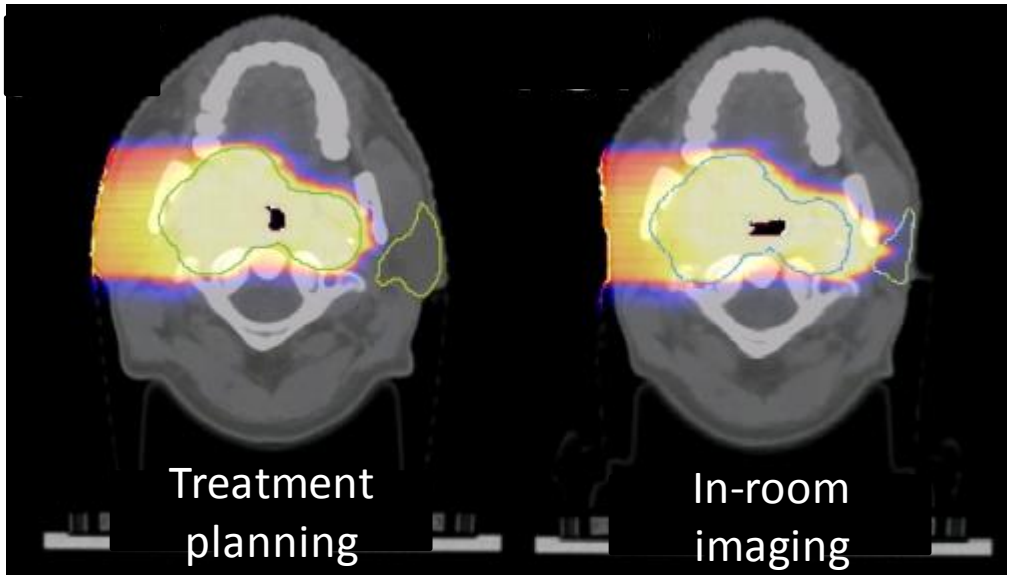
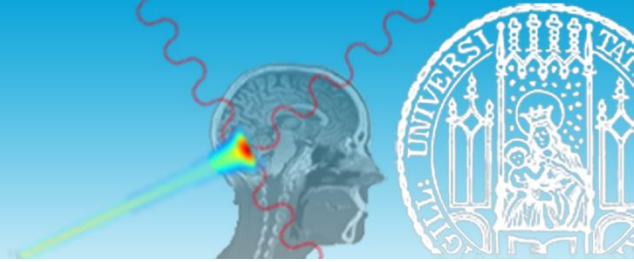
- **pCT:** in room imaging



G. Landry et al. Med Phys 42 (2015) 1354

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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  - Bianca Berndt
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