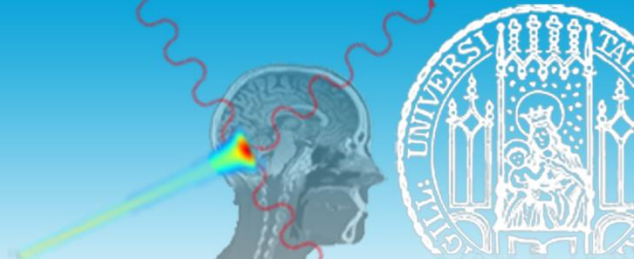


Investigating the physics of a CBCT projection shading correction based on a prior CT

Guillaume Landry (1), Christoph Zoellner (1), Christopher Kurz (1,2), Gloria Vilches-Freixas (3), George Dedes (1), Florian Kamp (2), Claus Belka (2), Simon Rit (3) and Katia Parodi (1)

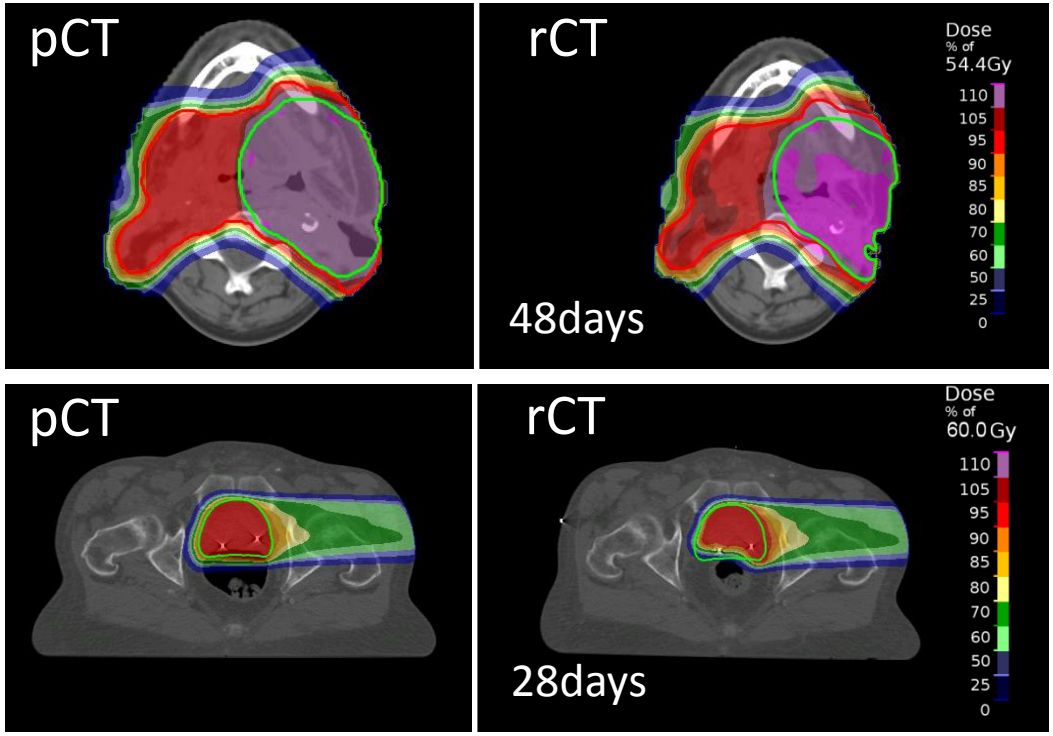
(1) Ludwig-Maximilians-Universität München (LMU Munich), Department of Medical Physics, Faculty of Physics, Munich, Germany

(2) LMU Munich, Department of Radiation Oncology, Munich, Germany

(3) Universite de Lyon, CREATIS, Lyon, France

Introduction

- **IMPT plan quality** might be compromised due to **anatomical changes**



Head and neck:
Timescale: days/weeks

Prostate:
Timescale: hours/days

- May be restored by **plan adaptation**
- Requires **frequent** imaging and accurate **up to date 3D dose** calculation

CBCT imaging

- **CBCT imaging** entering clinical routine for patient **positioning** in IMPT

- **CBCT** imaging provides:
  - **Bony anatomy** position
  - Gross **volume changes**
  - **Treatment** position

- **CBCT** imaging **does not** provide:
  - Soft tissue contrast for delineation
  - Reliable **electron densities**

→ **Utilization of CBCT images in IMPT requires intensity correction**

→ **Recently published methods have relied on prior CT**

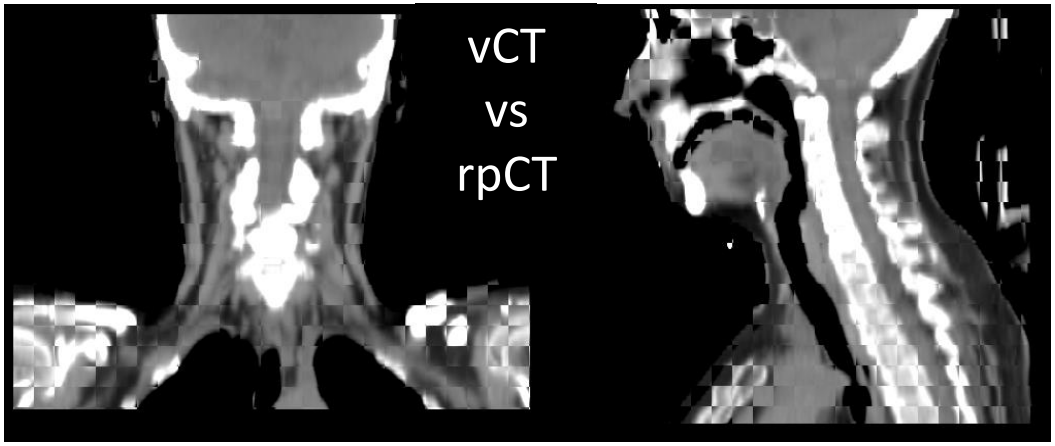
→ **Aim at reproducing equivalent SFUD proton range and delineation accuracy**

pCT vs rpCT CBCT vs rpCT

Virtual CT

Virtual CT (vCT)

- **Deformable** image registration of **pCT** to daily **CBCT → vCT**
- Use **Morphons algorithm** (REGGUI package*)
- Yields **up-to-date contours**
- **Validated** and found **accurate** for **H&N** [1],



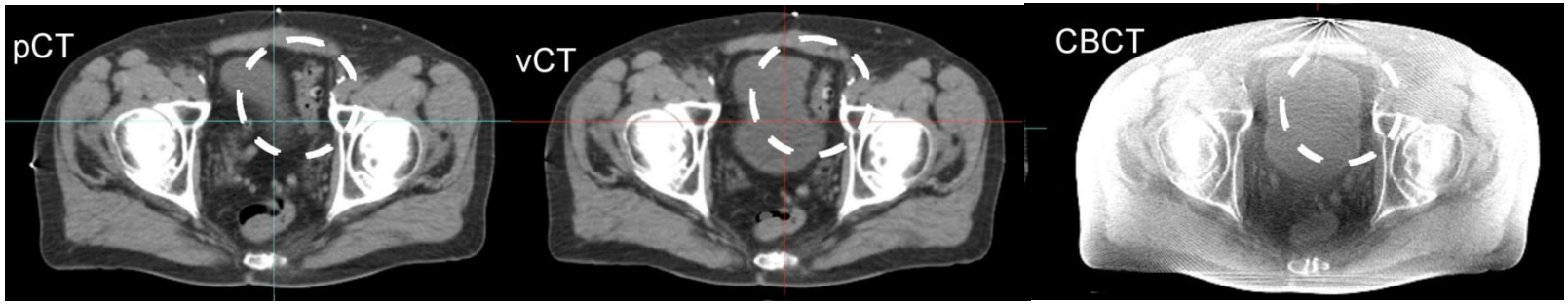
*REGGUI kindly shared and developed at ICTEAM/UCL, Belgium

[1] G Landry et al, 2015. Investigating CT to CBCT image registration for head and neck proton therapy as tool for daily dose recalculation. Med. Phys. **42**(3)

Virtual CT

Virtual CT (vCT)

- **Deformable** image registration of **pCT** to daily **CBCT** → **vCT**
- Use **Morphons algorithm** (REGGUI package*)
- Yields **up-to-date contours**
- **Validated** and found **accurate** for **H&N** [1], **extension** to **prostate** showed limitations



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[1] G Landry et al, 2015. Investigating CT to CBCT image registration for head and neck proton therapy as tool for daily dose recalculation. Med. Phys. **42**(3)

$CBCT_{cor}$

Scatter corrected CBCT ($CBCT_{cor}$)

- **vCT** as **prior**: **Forward projection** of **vCT** according to CBCT geometry

  I_{vCT}

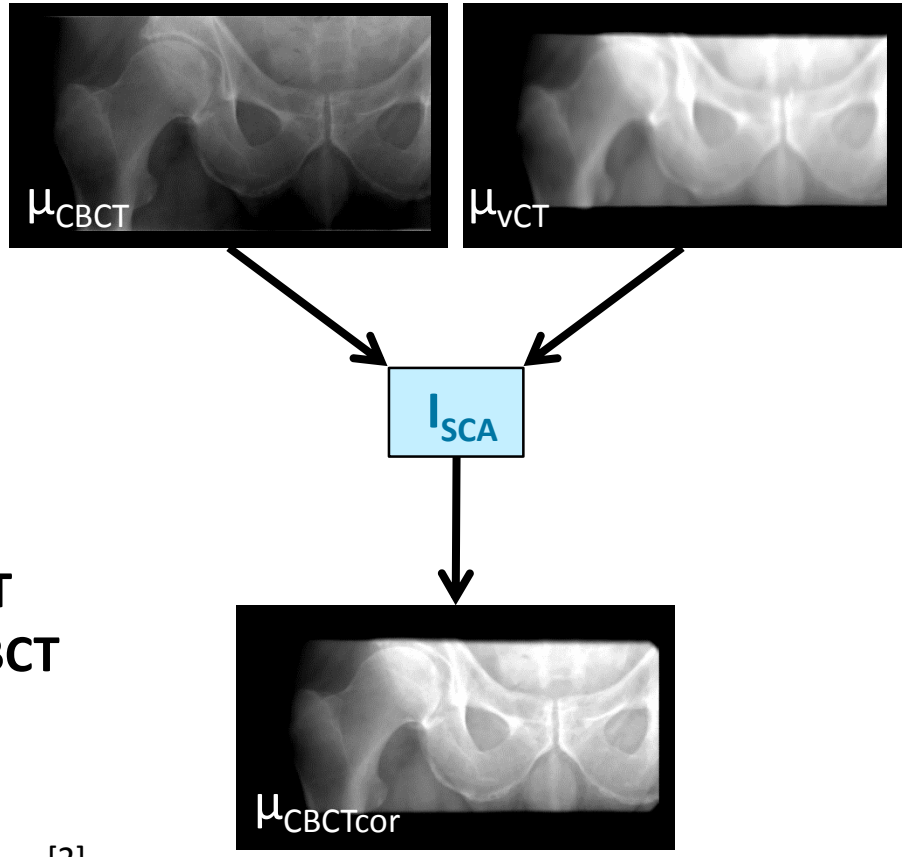
- **Scatter estimate by subtracting I_{vCT}** from scaled **daily CBCT projections I_{CBCT}** and smoothing

  $I_{SCA}=f(CF \times I_{CBCT} - I_{vCT})$

- **Subtract scatter map** from **daily CBCT** projections, **reconstruct** corrected **CBCT**

  $CBCT_{cor}=FBP(CF \times I_{CBCT} - I_{SCA})$

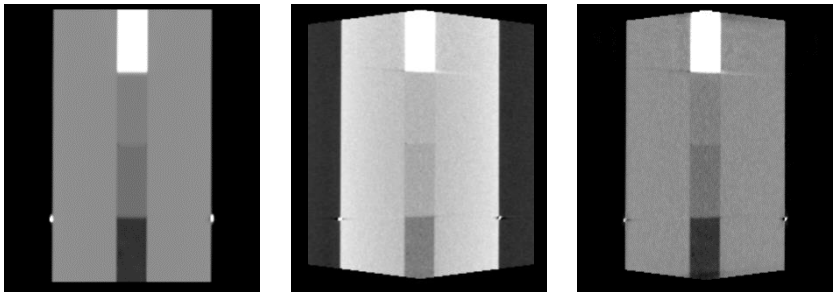
- **Validated** for **H&N** and **abdominal** sites[2]



[2] Y K Park et al, 2015. Proton dose calculation on scatter-corrected CBCT image: Feasibility study for adaptive proton therapy. Med. Phys. **42**(8)

$CBCT_{cor}$ validation

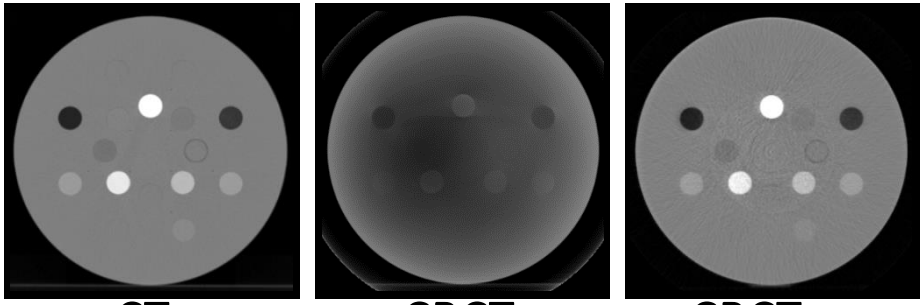
- **$CBCT_{cor}$ validated** for **LMU** on-board CBCT using **phantom data**
- H&N gammex phantom



CT CBCT $CBCT_{COR}$

Insert	CT HU	$CBCT_{cor}$ HU
Lung	-588±18	-585±36
Adipose	-114±3	-104±31
Solide Water	4±3	15±32
Cort. Bone	1517±12	1481±94

- Gammex phantom

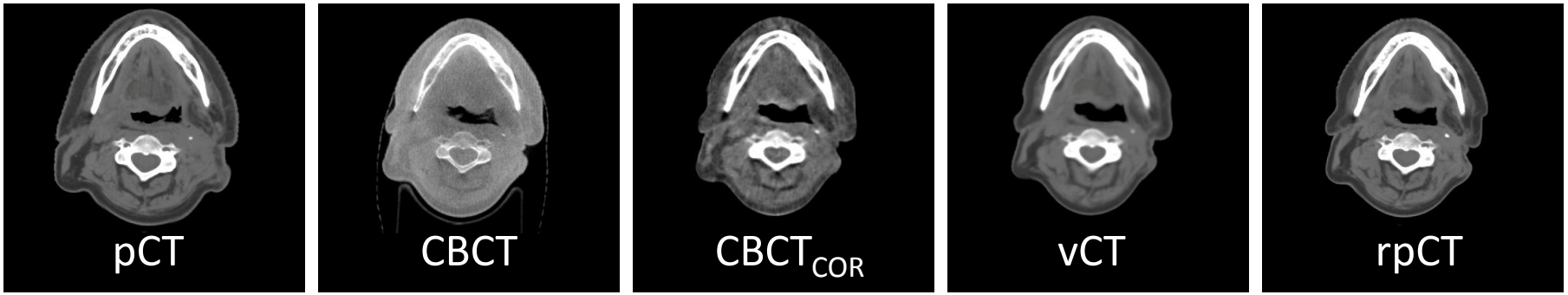


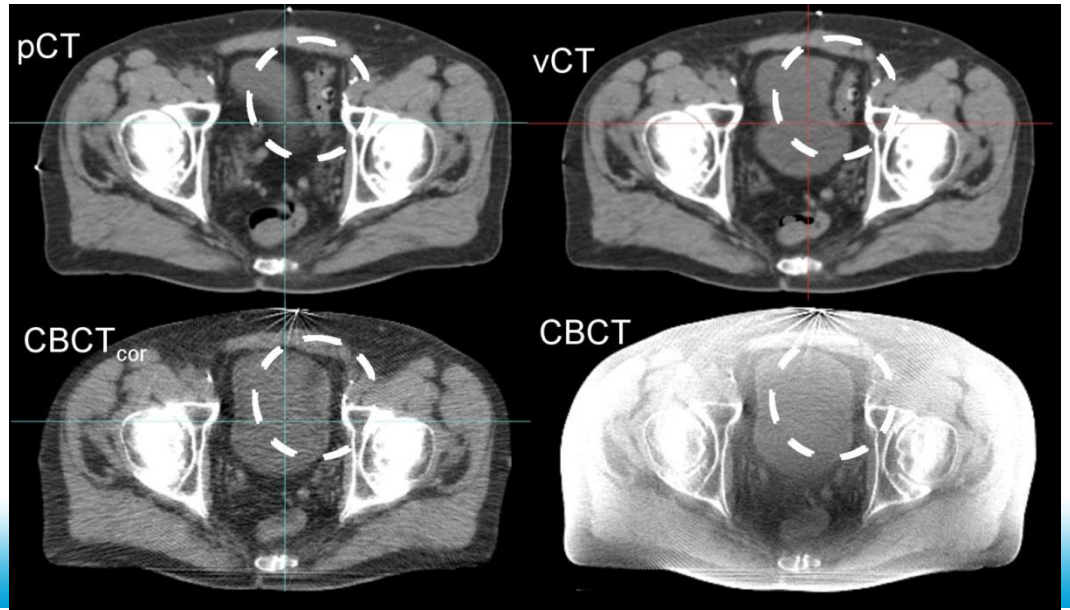
CT CBCT $CBCT_{COR}$

Insert	CT HU	$CBCT_{cor}$ HU
Lung	-562±19	-571±34
Adipose	-101±16	-93±50
Solide Water	-9±16	0±42
Cort. Bone	1249±17	1317±96

$CBCT_{cor}$ and vCT

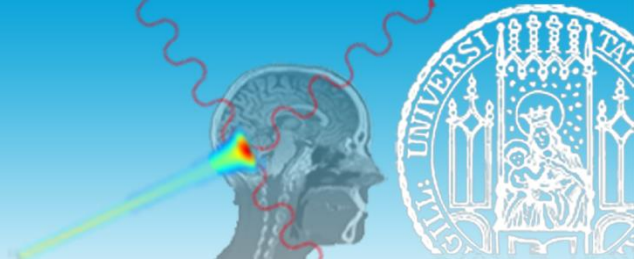
- **$CBCT_{cor}$** implementation for **prostate** and **H&N patient data**
- H&N





Kurz C, Kamp F, Park YK, Zöllner C, Rit S, Hansen D, Podesta M, Sharp GC, Li M, Reiner M, Hofmaier J. Medical physics. 2016 Oct 1;43(10):5635-46.

Physical basis



- **Does the scatter correction have a physical basis?**

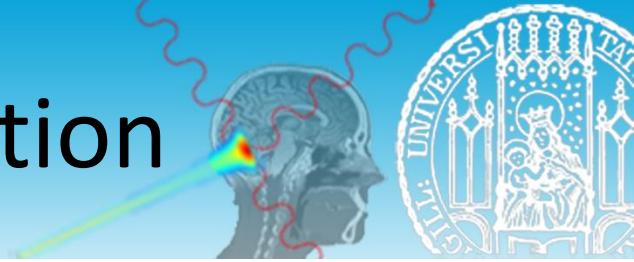
$I_{SCA}=f(CF \times I_{CBCT} - I_{vCT})$

$CBCT_{cor}=FBP(CF \times I_{CBCT} - I_{SCA})$

- **The SCA in fact performs scatter correction as well as beam hardening correction, in addition to other low frequency errors**

- **Perform Monte Carlo simulation of the scatter distribution to compare to the SCA's correction**

Monte Carlo simulation



XVI parameter optimization[1]

- SpelkCalc[2] source model vs ion chamber measurements
  - **mm Al**
  - **mm Cu**
  - **Anode angle**
- GATE detector model vs flat panel measurements[3]
  - **CsI length**

[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.
[2]Poludniowski G, Landry G, DeBlois F, Evans PM, Verhaegen F. SpekCalc: a program to calculate photon spectra from tungsten anode x-ray tubes. Physics in medicine and biology. 2009 Sep 1;54(19):N433.
[3]Granton PV, Podesta M, Landry G, Nijsten S, Bootsma G, Verhaegen F. Medical physics. 2012 Jul 1;39(7):4155-66.

Monte Carlo simulation

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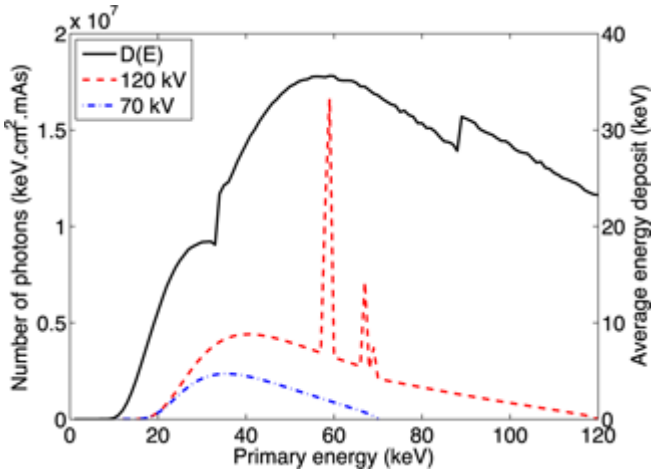

[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.

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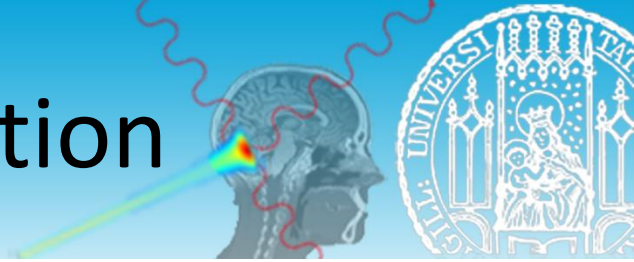
Monte Carlo simulation



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GATE MC simulation

- **Fixed forced detection actor**
  - **Deterministic primary using ray tracing**

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[3]Granton PV, Podesta M, Landry G, Nijsten S, Bootsma G, Verhaegen F. Medical physics. 2012 Jul 1;39(7):4155-66.

Monte Carlo simulation

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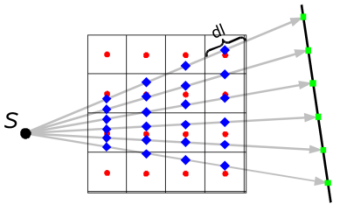
$$\Phi = \Phi_0 \exp\left(-\int_L \mu(\boldsymbol{x}, E)\,\mathrm{d}l\right)$$

applied for each pixel of the detector and each energy in the spectrum.

μ computed using Geant4 material definition and physics list



RTK

Ray casting using the Reconstruction Toolkit (www.openrtk.org)

[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.

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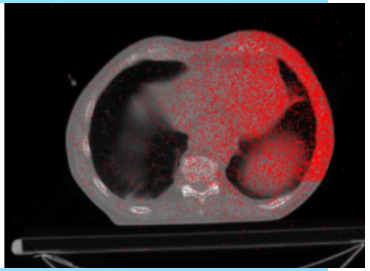
GATE MC simulation

- **Fixed forced detection actor**
  - **Fixed forced detection simulation of scatter events**

Retrieve at every interaction

- interaction type (Compton, Rayleigh or Fluorescence),
- position,
- direction,
- energy.



[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.

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Monte Carlo simulation

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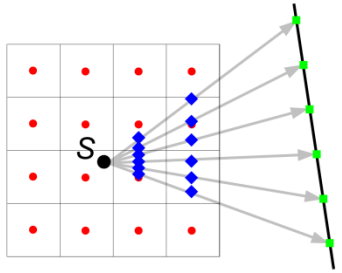

Probability of a photon to reach pixel after an interaction:

$$dp = \frac{1}{\sigma(E^b)} \frac{d\sigma(\theta, E^b)}{d\Omega} \exp\left(- \int_L \mu(\boldsymbol{x}, E^a)\, dl \right) d\Omega$$

[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.
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Monte Carlo simulation

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GATE MC simulation

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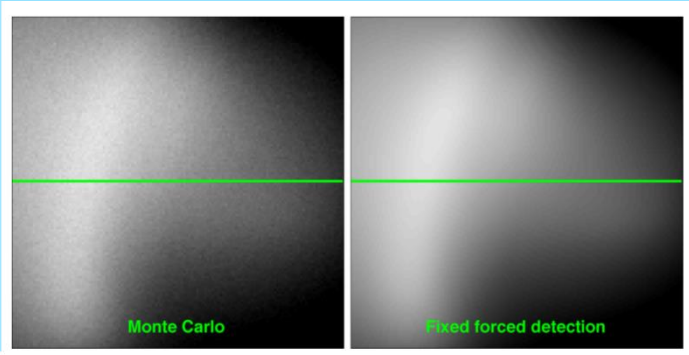

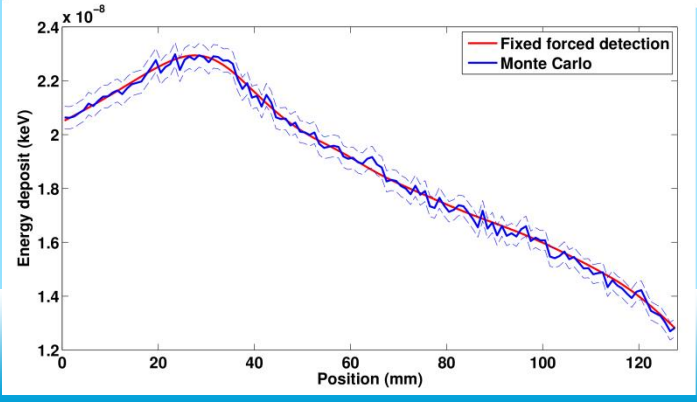

[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.
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[3]Granton PV, Podesta M, Landry G, Nijsten S, Bootsma G, Verhaegen F. Medical physics. 2012 Jul 1;39(7):4155-66.

Monte Carlo simulation

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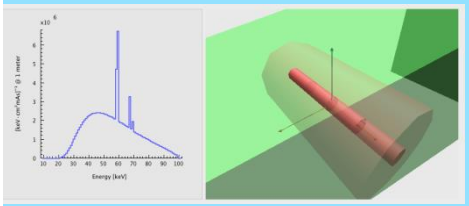
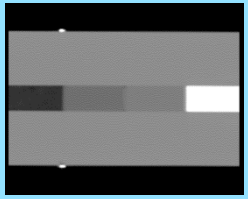
  - **mm Cu**
  - **Anode angle**
- GATE detector model vs flat panel measurements[3]
  - **CsI length**

GATE MC simulation

- **Fixed forced detection actor**
  - **Deterministic primary using ray tracing**
  - **Fixed forced detection simulation of scatter events**
- **15 cm diameter PMMA phantom with 4 inserts of known density and composition**





[1]Vilches-Freixas G, Létang JM, Brousmiche S, Romero E, Vila Oliva M, Kellner D, Deutschmann H, Keuschnigg P, Steininger P, Rit S. Medical physics. 2016 Sep 1;43(9):5199-204.

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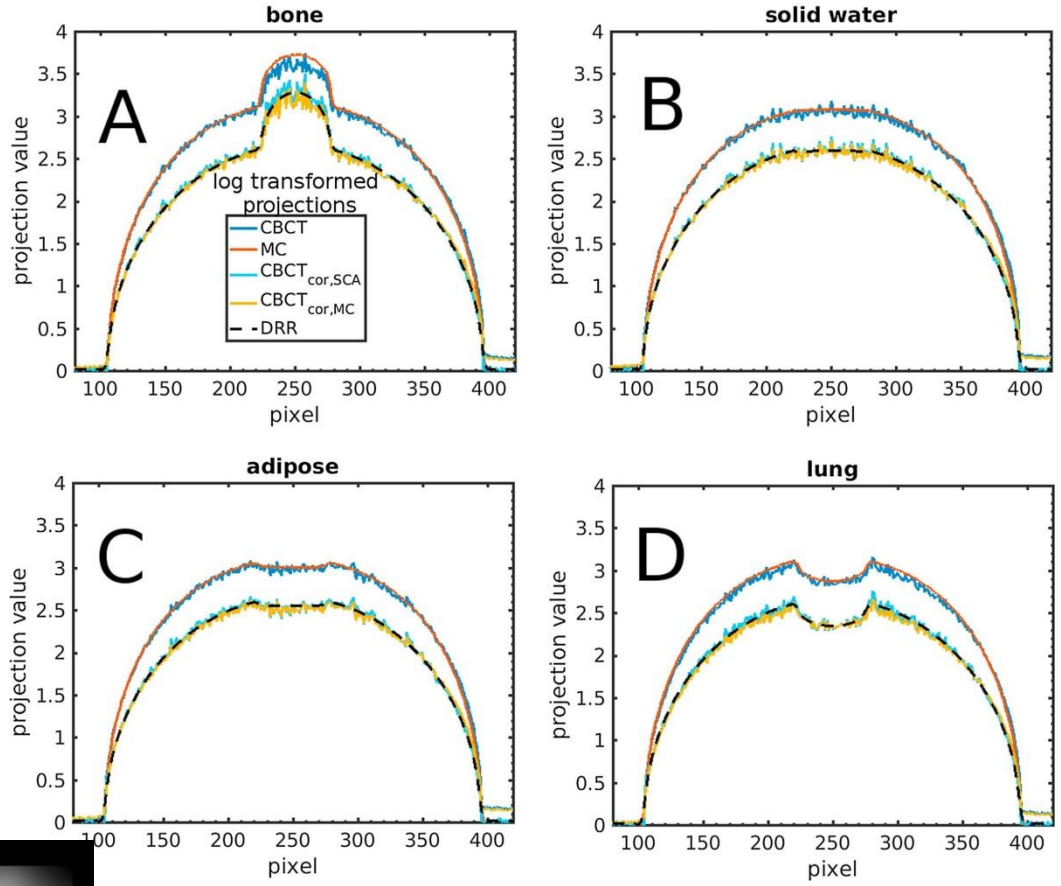
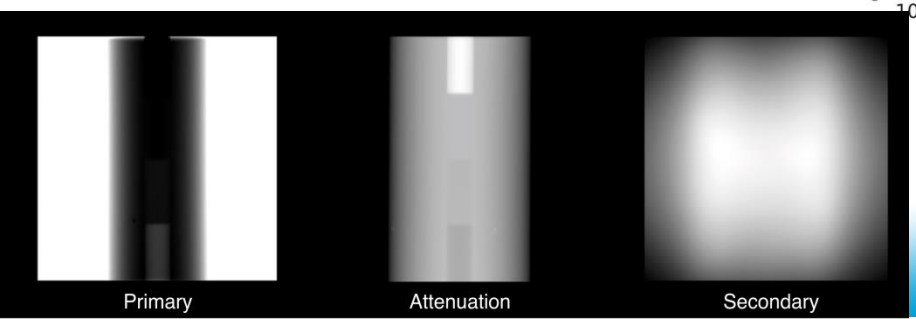
[3]Granton PV, Podesta M, Landry G, Nijsten S, Bootsma G, Verhaegen F. Medical physics. 2012 Jul 1;39(7):4155-66.

Monte Carlo simulation

Transverse projection profiles across each inserts

- Good agreement (<3%)
- Bone insert has largest error





Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Monte Carlo simulation

Transverse projection profiles across each inserts

- Good agreement (<3%)
- Bone insert has largest error

SCA correction vs MC correction

Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Monte Carlo simulation

Transverse projection profiles across each inserts

- Good agreement (<3%)
- Bone insert has largest error

SCA correction vs MC correction

- Remove MC scatter

Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

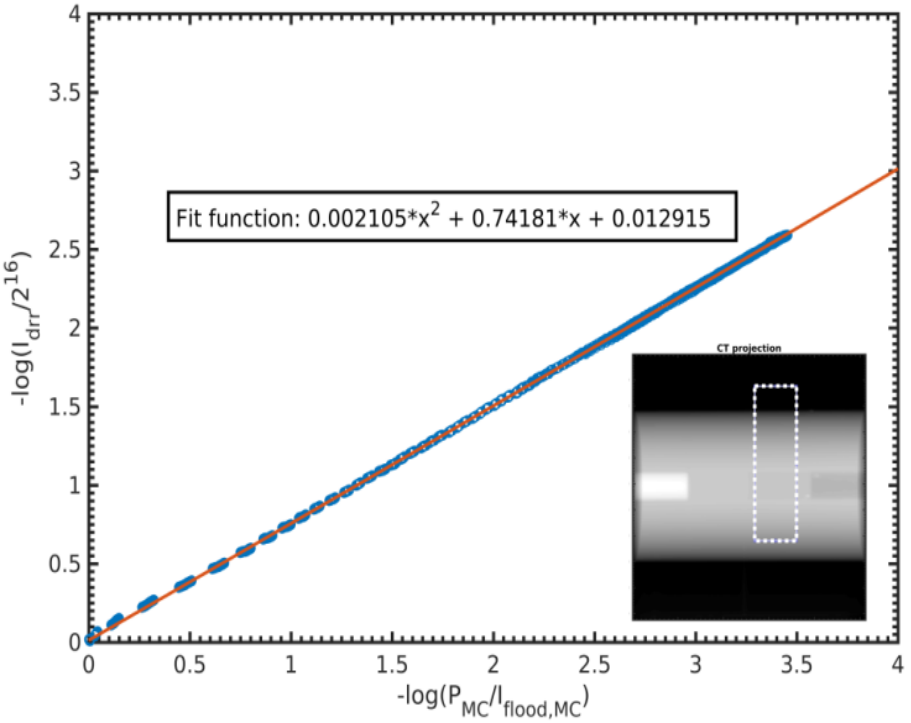
Monte Carlo simulation

Transverse projection profiles across each inserts

- Good agreement (<3%)
- Bone insert has largest error

SCA correction vs MC correction

- Remove MC scatter
- Apply beam hardening correction



Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Monte Carlo simulation

Transverse projection profiles across each inserts

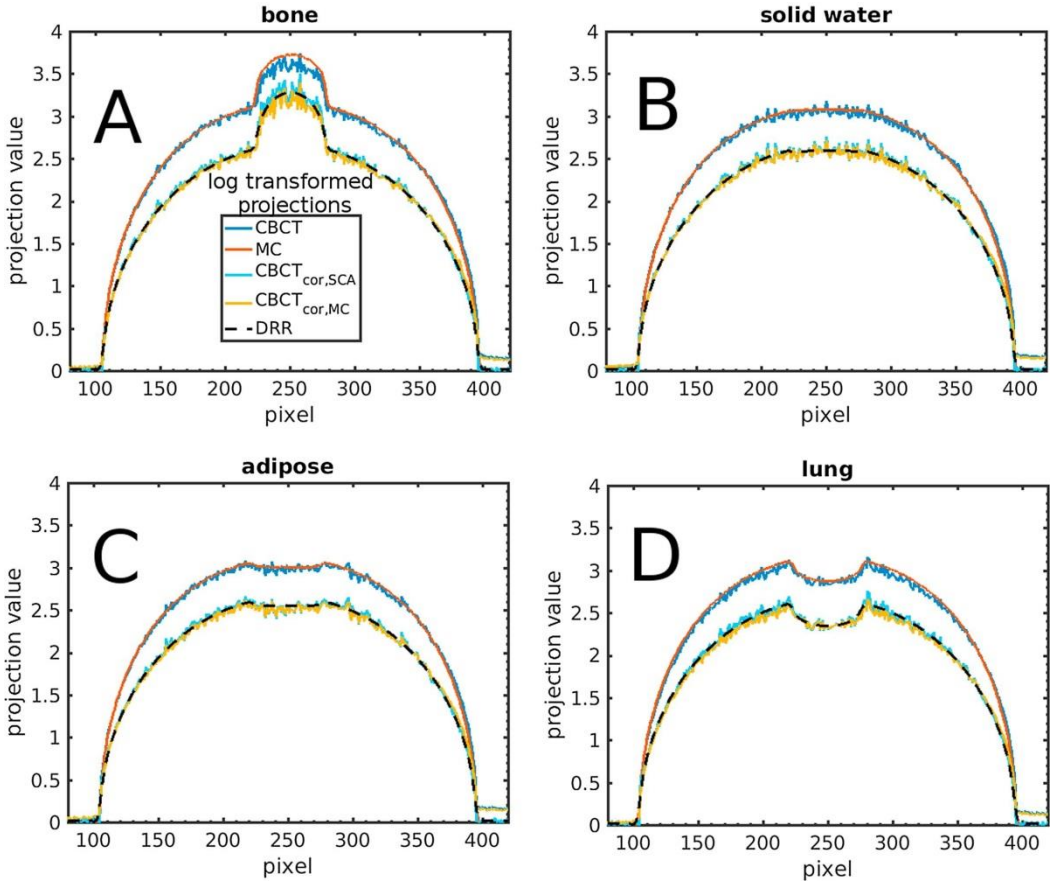
- Good agreement (<3%)
- Bone insert has largest error

SCR correction vs MC correction

- Remove MC scatter
- Apply beam hardening correction

Good agreement between:

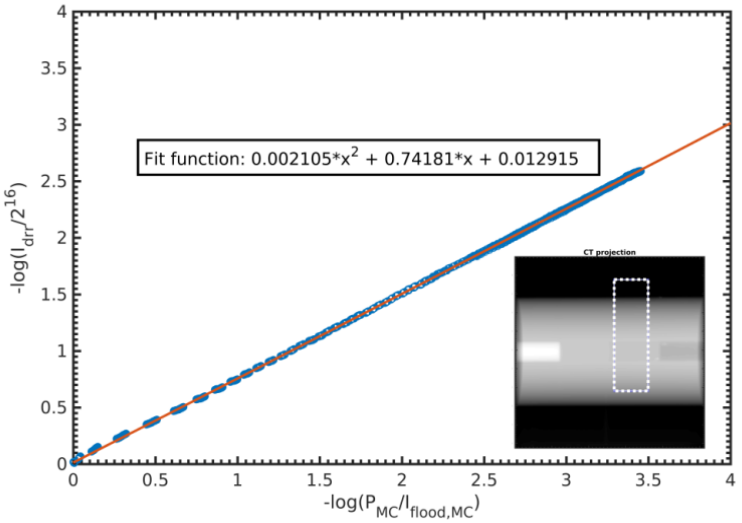
- CT DRR
- CBCT corrected by SCA
- CBCT corrected by MC



Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Scatter component

Undo the **beam hardening** component from I_{SCA} to **obtain** I_{SCA}' with eq 1



$$I_{SCA}=f(CF \times I_{CBCT} - I_{vCT})$$

$$CBCT_{cor}=FBP(CF \times I_{CBCT} - I_{SCA})$$

$$I_{SCA}' = [I_{SCA} - CF(F^{-1}_{BH}(I_{DRR})) + I_{DRR}]/CF$$

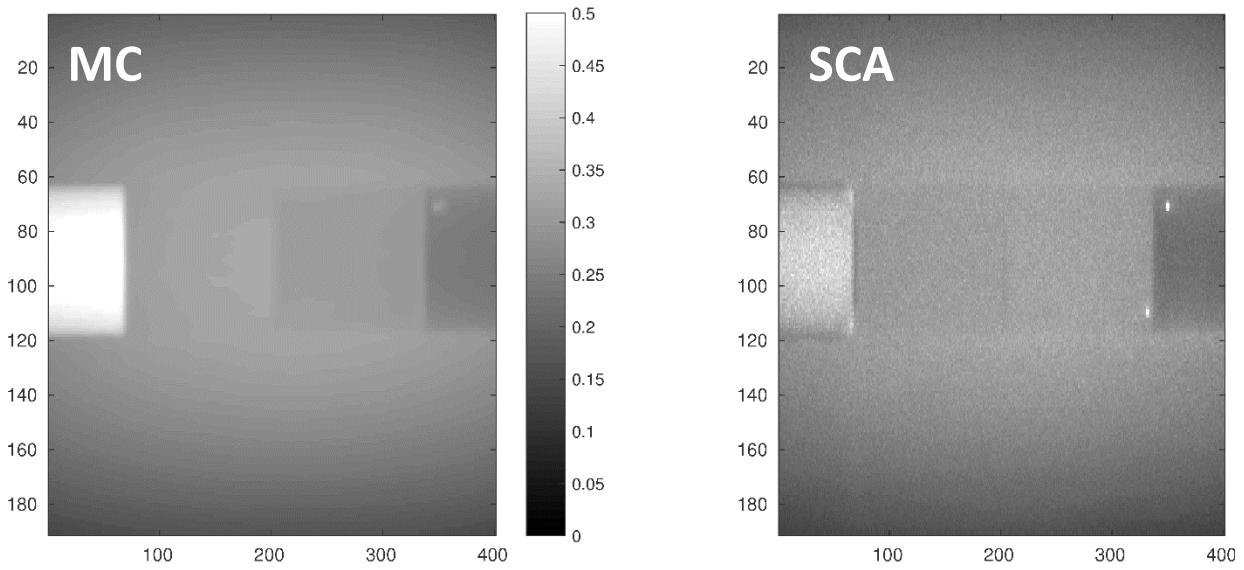
Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Scatter component

Undo the **beam hardening** component from I_{SCA} to **obtain** I_{SCA}' with eq 1

I_{SCA}' is the **SCA based** estimation of **scatter signal**

Scatter/total projection



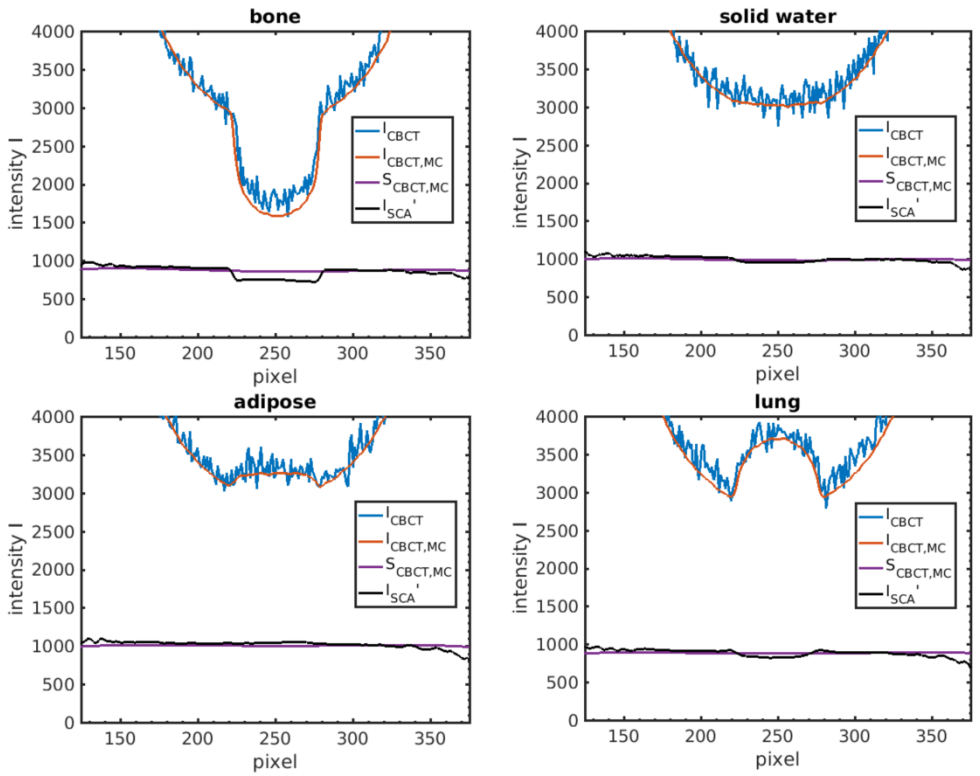
Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Scatter component

Undo the **beam hardening** component from I_{SCA} to **obtain** I_{SCA}' with eq 1

I_{SCA}' is the **SCA based** estimation of **scatter signal**

Transverse profiles through inserts



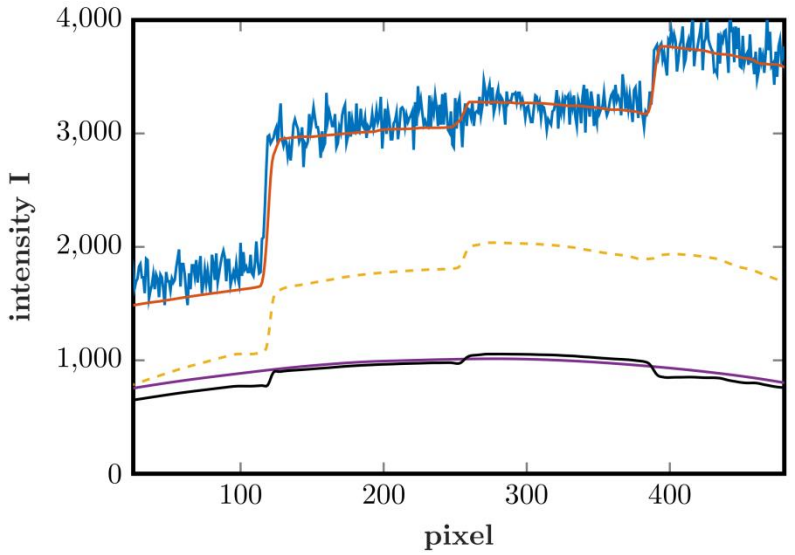
Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Scatter component

Undo the **beam hardening** component from I_{SCA} to **obtain** I_{SCA}' with eq 1

I_{SCA}' is the **SCA based** estimation of **scatter signal**

Longitudinal profile through inserts

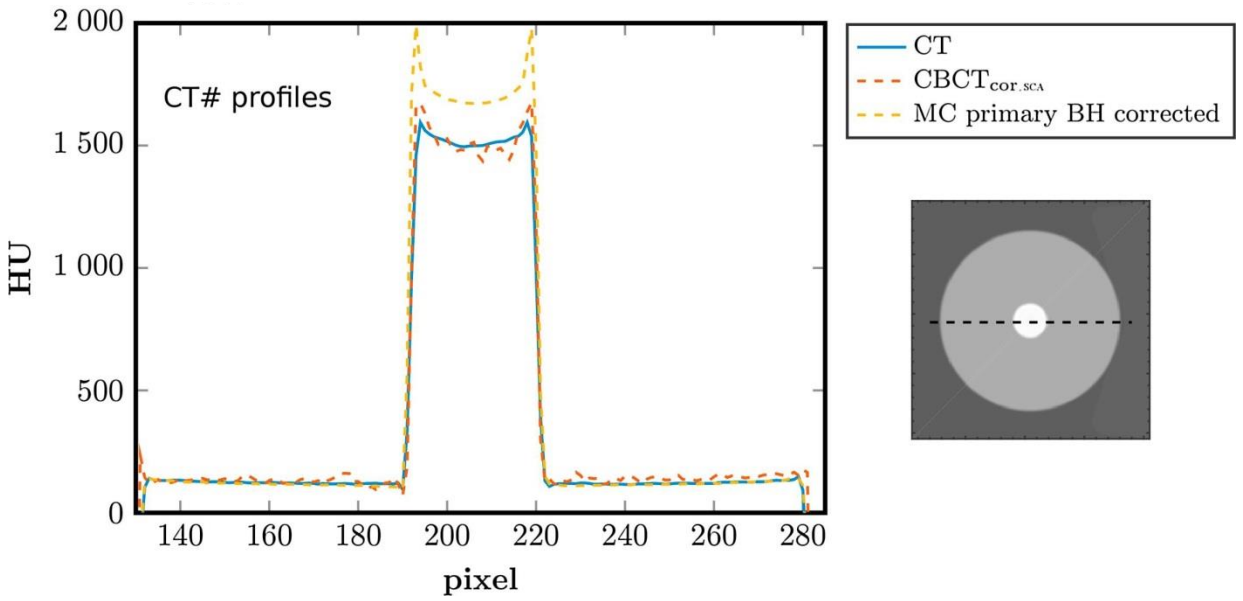


Zoellner C, Rit S, Kurz C, Vilches-Freixas G, Kamp F, Dedes G, Belka C, Parodi K, Landry G. 2017 Physics and Imaging in Radiation Oncology , Volume 3 , 49 - 52

Discussion

- Despite good agreement, **residual errors** in the **prior CT** image affect the $CBCT_{COR}$
- Especially for **beam hardening**

Incorrect beam hardening



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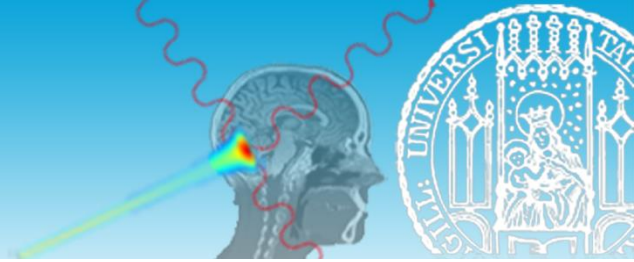
Conclusions



- **Monte Carlo simulations** of **CBCT projections** based on **source** and **detector** model **optimization** are **accurate**

- The **SCA corrected** CBCT **projections** are **equivalent** to those **corrected** with **MC simulation**

- The **SCA correction** can be **approximated** by separate **beam hardening** and **scatter corrections**

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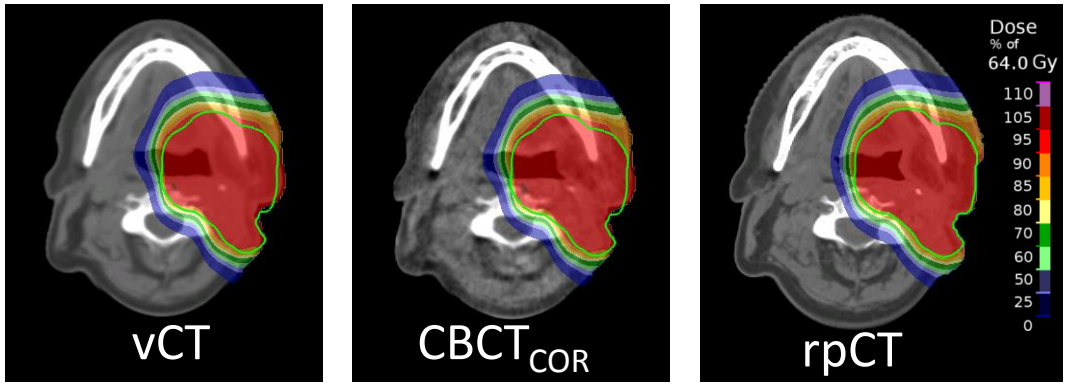
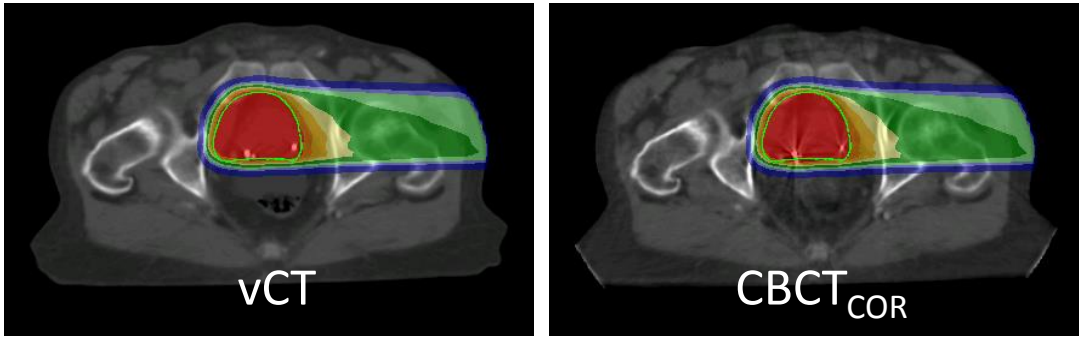
$CBCT_{cor}$ and vCT

- **$CBCT_{cor}$** and **vCT comparison** in terms of **proton SFUD range** difference
- H&N



Pat	RD<2mm	Med. RD
HN1	99%	**0.1mm**
HN2	91%	**0.1mm**
HN3	99%	**0.3mm**

- Prostate



Pat	RD<2mm	Med. RD
PR1	100%	0.2mm
PR2	100%	0.5mm
PR3	99%	0.1mm