



UniversitätsKlinikum Heidelberg

## Experimentelle Dosimetrie & Simulation der Strahlenexposition in der Computertomographie Ansätze zur Dosisreduktion

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## **Overview**

## 1. Introduction

- Statement of the problem
- CT-specific dose descriptors
- Solution/approach

## 2. Measurement of radiation exposure in CT

- Radiation detectors results and evaluation
- Thermoluminiscence dosimetry methodogy

## 3. Monte Carlo simulation for dosimetry in CT

- Monte Carlo codes results and evaluation
- Geant4 modeling methodology

## 4. Conclusions & Outlook



## Introduction



## Statement of the problem

- CT is a widely available diagnostic tool
- CT examination is fast and comfortable for the patient
- ✓ User friendly
- High diagnostic accuracy
- New contrast media
- New combinations of imaging modalities
- Tendency to increase volume covered in a particular examination

# Increasing radiation exposure

Determination of dose and techniques for dose reduction in CT



## Parameters used to estimate dose in CT





## Solution/approach: 3D dosimetry





## Measurement of radiation exposure in CT



## Reports: Instrumentation used for dose measurement in CT

#### MOSFET

• Cumulative point doses: absorbed dose and effective dose in organs

#### SOLID STATE DETECTORS

- Dose profiles , CTDI
- z-axis geometric efficiency using real time dose profiles

#### TLD

- Point dose measurement along the z-axis: dose profiles
- z-axis geometric efficiency using dose profiles
- Effective dose in organs

#### OSL

• Dose profiles, CTDI



## **Reports: Detector response evaluation**

MOSFET

- Values available immediately
- ✓ Small size
- Isotropic
   response
- LLD = 1.40 mGy, limitation for low- dose applications



- 🗸 Small
- ✓ LiF approx. tissue equivalent (Z<sub>eff</sub>=8.14)
   With high quality processing (great care, precise repeatability and similarity), then:
   ✓ Linear response
- High accuracy and sensitivity

✓ High sensitivity

OSL

- ✓ Linear response
- ✓ Reproducibility
- × 15 cm active length
- No tissue equivalence (Z<sub>eff</sub>=11.28)

#### Solid state

- ✓ Higher sensitivity
- × 10 cm active length

#### Option selected: Thermoluminiscence dosimetry



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Experimental Dosimetry and Simulation of Computed Tomography Radiation Exposure

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## Thermoluminiscence dosimetry: Methodology





## Select TLD crystals

#### TLD- 100 LiF:Mg, Ti

- • $Z_{eff}$ =8.2
- •Relative sensitivity 1.0
- •Energy response: 1.25 Over-response to irradiation
- •Fading: 5%/yr at 20°

#### MCP-100D LiF:Mg,Cu,P

- • $Z_{eff}$ =8.2
- •Relative sensitivity 15
- •Energy response: 0.98 Under-response to radiation
- •Fading: negligible





Glow curves (signal intensity vs. time)





## **Time-temperature profiles for readout**

#### Time-temperature profile TLD-100



#### Time-temperature profile MCP-100D









### Data acquisition



Schematic of the experimental 3D thermoluminiscence dosimetry



Axial dose MC distribution Deak et al., Eur Radiol 2008(18)

Experimental Dosimetry and Simulation of Computed Tomography Radiation Exposure



## Monte Carlo simulation for dosimetry in CT



## **Reports: Aspects simulated**

#### **MNCP**

- 3D voxelized patient models (baby, adults)
- Point source, collimation
- Charged-particle equilibrium (CPE)
- X-Ray source movement
- Effect of ripple in electron energy
- Anode angle
- Distance from focal spot to isocenter

#### GEANT4 & GATE

- X-Ray source spectra and detector materials of Micro-CT scanners
- X-Ray source (64 monochromatic energies (17 to 80 keV))
- Detector rotation in CT
- Cone beam CT with a monochromatic spheric source

### ImpactMC

- TCM in MSCT scanners
- Homogeneous and heterogeneous phantoms

#### EGS

- CBCT of linear accelerator
- Target and filtration (manufacturer data)

#### PCXMC

- Mathematical hermaphroditic phantoms
- X-ray tube projection angles



## **Reports: Simulation results**

MNCP	
<ul> <li>CTDI</li> <li>Whole body effective dose for helical scans (various pitch values)</li> <li>Normalized dose values for radiosensitive organs</li> </ul>	<ul> <li>Quantitative CT Dose Index (CTDI)</li> <li>Axial dose distribution</li> <li>CTDI for long cone beam collimation in CT head and CT body phantoms</li> </ul>
<ul> <li>Breast dose (with/without TCM) in chest CT</li> <li>Absorbed radiation dose on surface</li> </ul>	EGS
GEANT4 & GATE	<ul><li>Point dose</li><li>Depth dose profiles</li></ul>
<ul> <li>Contrast different tissue types in Micro-CT</li> <li>Radiation dose absorbed by organs</li> </ul>	PCXMC • Absorbed doses



## Characteristics of the ideal software



Accurate modeling of low-energy processes Ideally suited for diagnostic imaging

Tools for modeling geometries

## Option selected: Geant4

C++ language Contacts to CERN and to the Geant4 collaboration



## Monte Carlo CT Model



detector array















## X-ray output

#### **Measurements of CT X-Ray spectra**

using a Compton spectrometer

# Schematic of the experimental arrangement:

# Experimental setup of the Compton spectrometer:







### X-ray output

#### **Measurements of CT X-Ray spectra**

using a Compton spectrometer

# Schematic of the experimental arrangement:

#### Compton spectrometer "Spectro-X AB":





### X-ray output

#### Reconstruction of primary X-ray spectra by deconvolution:



# 1. Calculation of primary photon energy:

$$E = \frac{E'}{1 - \frac{E'}{m_e c^2}}$$

#### 2. Deconvolution of characteristic X-ray peaks:

$$\overline{S(E) = S_0(E) - \frac{T}{3m_e C^2} \left(\frac{E}{E^*}\right)^2 \left[\frac{d^2 S_0(E)}{d(E)^2} \left[(E)^2 - (E^*)^2\right] + 2E\frac{d S_0(E)}{d(E)}\right]}$$







## Energy spectra: G4PrimaryGenerator

#### **≭**G4ParticleGun

Monoenergetic

#### ✓ G4GeneralParticleSource

Energy distribution histogram with different interpolation options

0,07 Normalized number of photons [a.u.] 0,06 -0° -2° 0,05 4° 6° 0,04 -8° -10° 0,03 -12° -14° -16° 0,02 18° 20° 0,01 0,00 20 40 60 80 100 0 120 Energy [keV]

X-ray Spectra Measured at Different Fan Angle





## Energy spectra: G4PrimaryGenerator

#### **≭**G4ParticleGun

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Energy distribution histogram with different interpolation options



#### X-ray Spectrum Input Histogram









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## **Bowtie filter profile**

Idea: Use measurements of attenuated spectra across the fan beam:

Principle of fan-angle dependent spectral measurement:

# X-ray spectra reconstructed as functions of fan angle:





### Simulation of Bowtie filter

#### Properties of Bowtie filter

Decreasing transmission for increasing fan angle
Deflection of transmitted beam toward smaller angles at large fan angle, e.g. 16°



#### Video Geant4 simulation



## **Empirical Filter Geometry: Simulated Spectra**



Comparison of measured & simulated spectra -**Results:** 

- Good qualitative agreement
- Difference below ±1% above 20 keV
- Larger deviations at energies below 20 keV









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## 3D rendering of simulated detector array





# Conclusion & Outlook



## Conclusions

- TLD is the most appropriate method to determine
   3D dose maps in CT
- A detailed model of an MDCT scanner is possible using Geant4, using spectral measurements as an input

Increased numbers of examinations, if correctly justified, must be viewed as resulting in a net benefit to patient management. However, the emphasis must be on dose optimization, and it requires accurate 3D dose maps to know the dose delivered to each radiosensitive organ.



## Outlook

## Future work:

- Model extension to "hybrid" filter materials/geometries
- Determination of Bowtie filter properties for different tube voltages

### **Perspectives:**

- Study influence & contribution of different parameters in the absorbed dose.
- Simulation & analysis of new scanner designs or new scanner components





## Outlook

## Validation of MC simulation models









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## Thank you for your attention !

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