IGRT kV-imaging dose MC calculations validated in anthropomorphic phantoms using OSL

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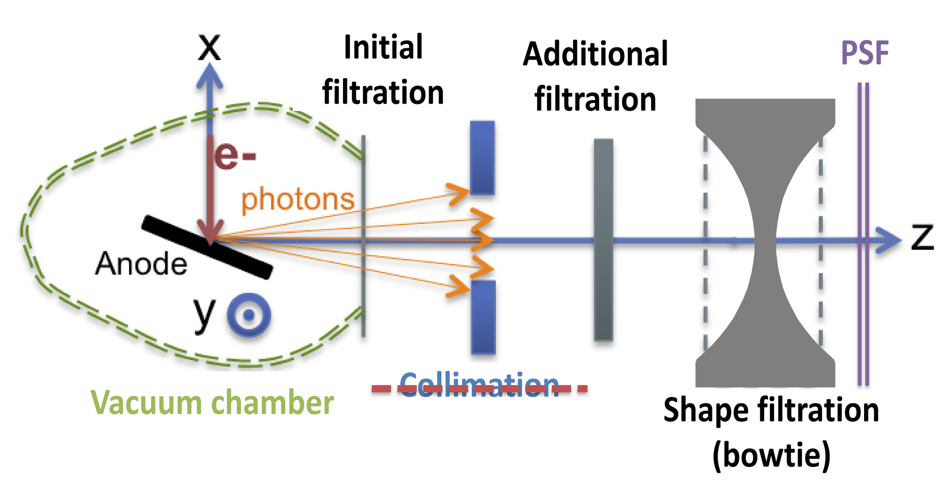
While in-room Magnetic Resonance Imaging starts becoming part of radiotherapy (RT) treatments, the use of X-ray imaging equipment in Image-Guided RT (IGRT) is still growing and with it, the need to evaluate the additional dose-to-organs it delivers. This study aims to verify the accuracy of Monte Carlo (MC) calculation of the patient's dose-to-organs delivered by four commercially available kV imaging systems: XVI CBCT (Elekta), OBI CBCT (Varian), ExacTrac 2D-kV system (Brainlab) and 2D-kV CyberKnife imaging system (Accuray). Simulations were validated against OSL measurements in the pediatric anthropomorphic phantom Grant (CIRS, ATOM) performed in three different clinical sites.

kV X-ray source description

All four systems kV X-ray source were described following the same principles :

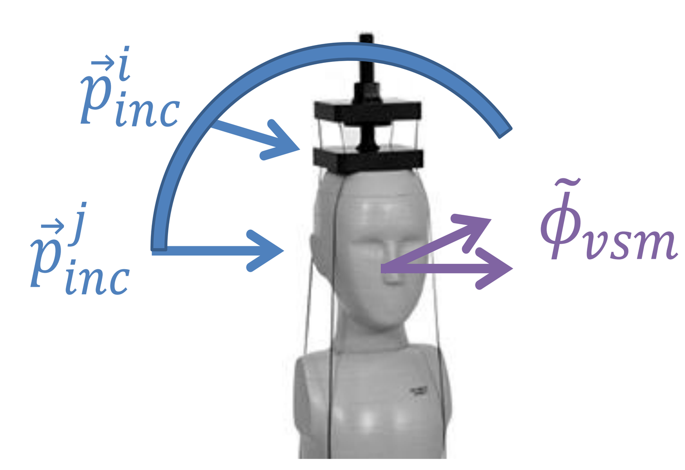
- Stage 1: **Geometry implementation and MC calculation (Penelope)**
  - ⇒ Electron incoming energy and direction
  - ⇒ Tungsten anode angle
  - ⇒ Initial filtration, additional filtration (bowtie filters)
  - ⇒ With no physical collimation
  - ⇒ The **photon energy fluence distribution** is finally stored in a **phase space file** further away from the origin



- Stage 2: **Photon energy fluence distribution simplification**
  - ⇒ Photons geometrically outside of the virtual selected collimation are removed from the distribution.
  - ⇒ The photon energy fluence distribution $\phi(x,y,E)$ is simplified as the product of two 1-D spatial functions $p_x(x)$ and $p_y(y)$ and a 2-D spatial-energetical function $p_{E|x \text{ or } y}(x \text{ or } y, E)$
  - ⇒ The three functions are smoothed using taking into account the MC noise

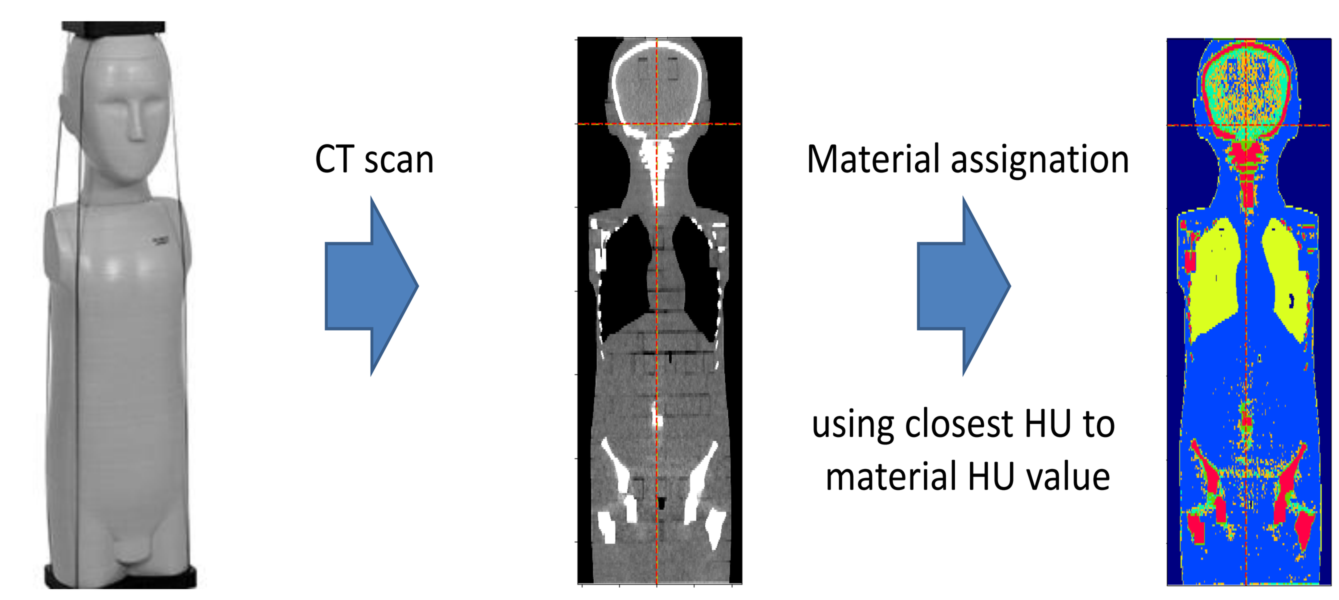
$$\phi(x,y,E) \approx \phi_0 \cdot p_x(x) \cdot p_y(y) \cdot p_{E|x \text{ or } y}(x \text{ or } y, E)$$

- Stage 3: **Generating new photons from the virtual source model**
  - ⇒ The cumulative functions of the three smoothed distributions are used to sample the position and energy of new photons.
  - ⇒ Obtained photons are translated and rotated according to **every** X-ray tube incidence used by the simulated imaging protocol.



Voxelized anthropomorphic phantom construction

The Pediatric anthropomorphic phantom: Grant (CIRS, ATOM) was scanned. The obtained 3D HU map was then converted into a 3D material map using the chemical composition found in the Grant documentation.



The in-house Penelope version (CEA-LIST) allowed us to simulate the dose deposition using the virtual source model in this Grant voxelized model.

OSL measurement

In this study the OSL nanodots detectors from Laundauer were used.

- Step 1: **OSL air-Kerma cross calibration**
  - ⇒ For every beam quality Q, OSL nanodots were calibrated with an air ionization chamber (with a 3% precision).
- Step 2: **From air-Kerma to dose in medium**
  - ⇒ For comparison purposes, air-Kerma OSL measurements were converted into dose-in-medium using the conversion factor $k_{air}^{med}(Q')$.
  - ⇒ As it is highly difficult to know the beam quality Q' at the measurement point, we assumed $Q' = Q$.
    The induced error $\varepsilon_{Q'}^{Q}$, was estimated, through MC calculation, as being inferior to 3% (1% in average).

$$k_{air}^{med}(Q') = \left[\frac{\left(\frac{\mu_{en}}{\rho}\right)_{med}}{\left(\frac{\mu_{en}}{\rho}\right)_{air}}\right]_{Q'}$$

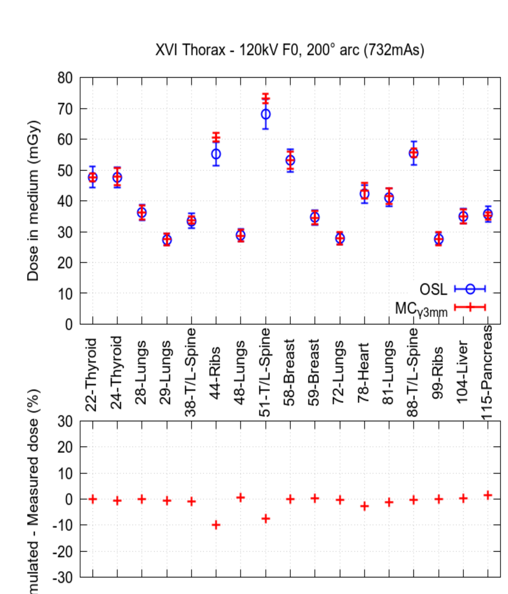
$$\varepsilon_{Q'}^{Q} = \frac{\left|k_{air}^{med}(Q') - k_{air}^{med}(Q)\right|}{k_{air}^{med}(Q')}$$

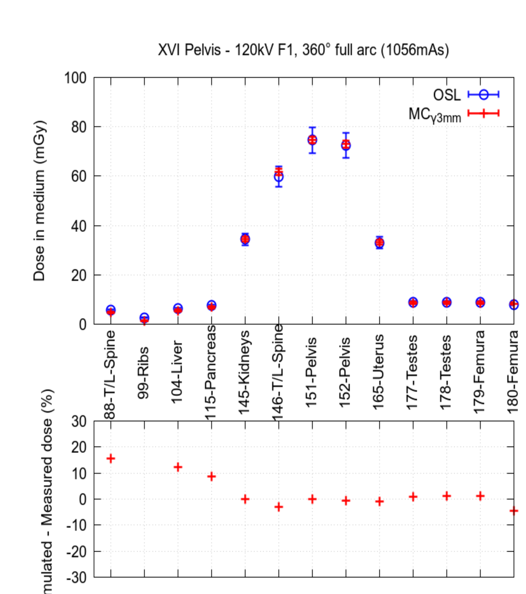
MC calculations comparison with OSL measurements

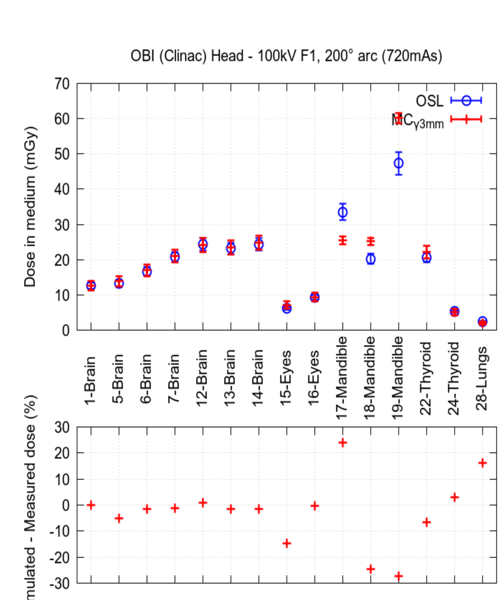
This study includes OSL measurements performed in radiotherapy centers with pediatric protocols* for the four IGRT. Three exam localizations were used : head (15 OSL), thorax (17 OSL) and pelvis (13 OSL). Monte Carlo dose maps were calculated in 2 hours on 40 CPU using an in-house parallelized version of Penelope.

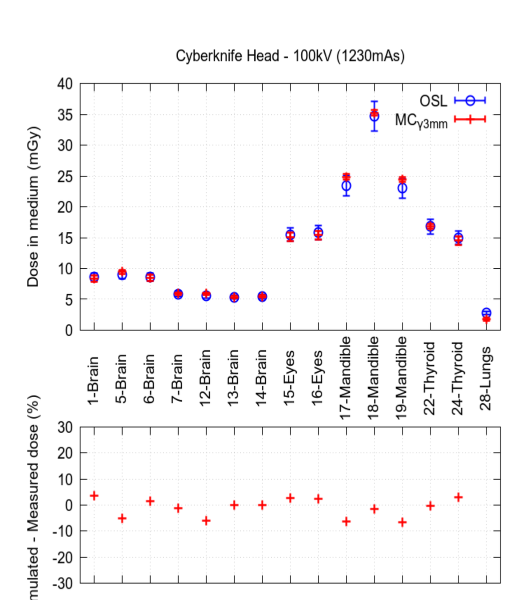
Taking in account measurements, calculations and positioning uncertainties, agreement between OSL measurements and MC calculations a 10%-3mm Gamma Index criteria was used.

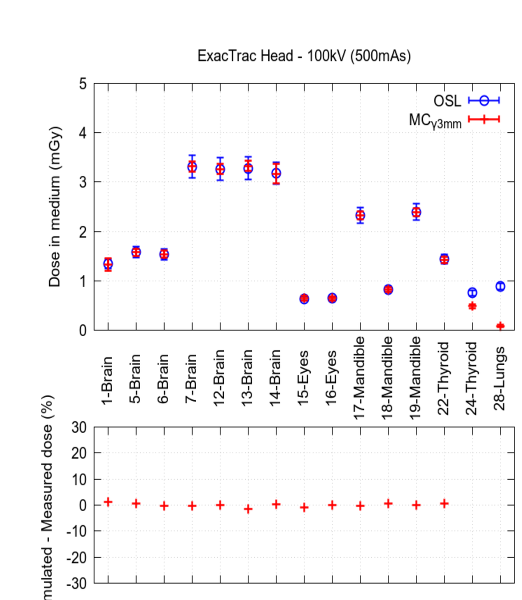
Over all the exams in the study, the Gamma index has a 87% success rate (94% if removing points localized outside of the geometrical collimation).





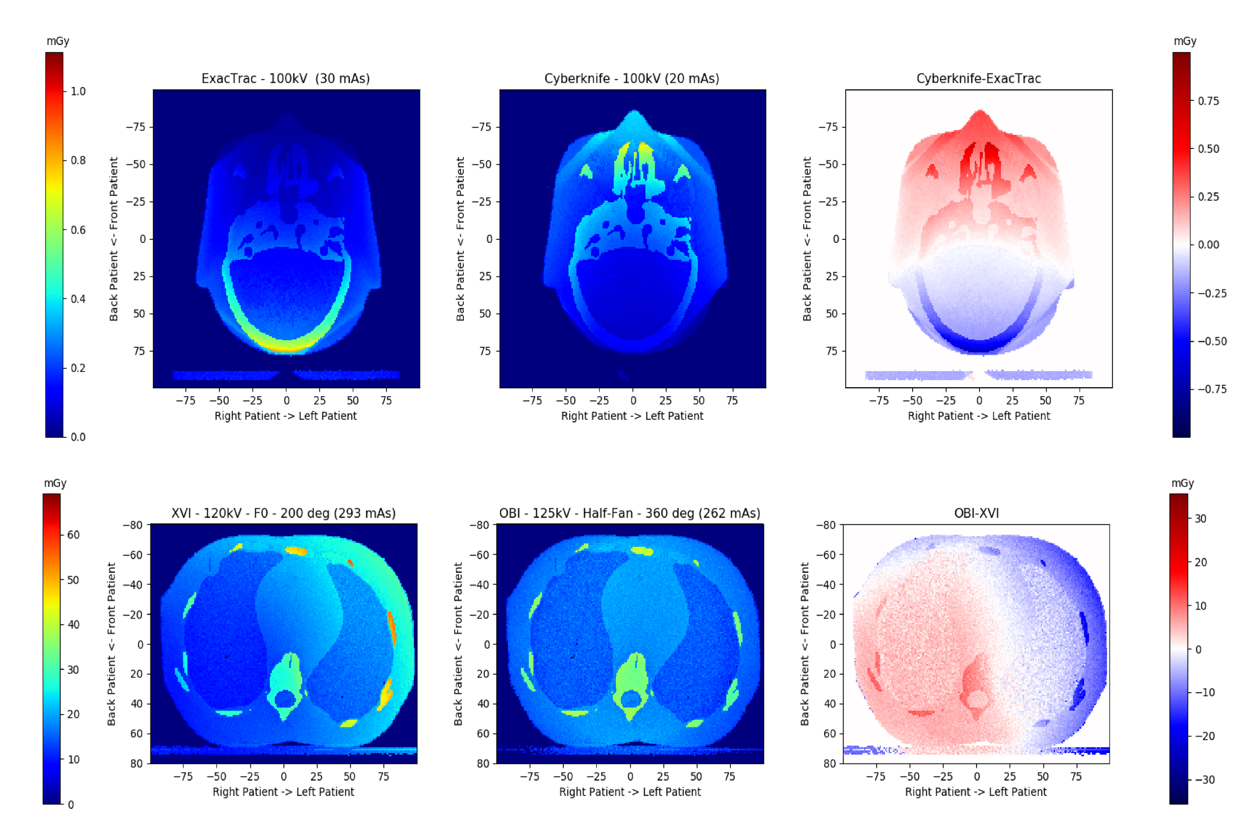






beam intensity (mAs) were increased compared to standard protocols in order to decrease OSL dose measurement uncertainties

Dose level comparisons between systems



Perspectives

As part of the AID-IGRT project, an in-house software was developed which allows to:

- Transform a CT image into a voxelized material map of the patient
- Select the imaging protocol (system, voltage, collimation, filtration, irradiation arc)
- Calculate the dose-in-tissue using the Penelope MC platform

In addition, a model of the Tomotherapy MV-CT was added to the software, thanks to developments done at CRG (Nantes).

This tool is currently being tested in clinical centers in order to evaluate the dose level currently added by the use of IGRT during the course of a radiotherapy treatment.

Summary

MC dose Calculation

- The photon distributions of four kV-IGRT systems were obtained using MC and converted into Virtual Source Model
- A voxelized material map of the anthropomorphic phantom was obtained by converting HU values from a CT scan into materials
- Photons from VSM are propagated into the voxelized geometry and the corresponding dose-in-medium are calculated using Penelope

Experimental validation

- In phantom, doses were measured using OSL detectors calibrated in air Kerma for the four kV-systems
- Measured doses were converted into dose-in-medium
- A 87% Gamma Index (10%, 3mm) success rate was obtained between measured and MC-calculated doses.

Overall, the method presented here seems suitable to reproduce doses with an accuracy better than 20% for various IGRT protocols and could be used to track the impact of the current IGRT practices on RT additional doses.

References

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