Simulation and validation of scatter radiation measurements in Ultra-High Dose Rate (UHDR) irradiations

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Situation

Recent preclinical studies suggest that **UHDR-RT**, which delivers radiation at dose rates greater than 30–40 Gy/s, may **reduce damage to healthy tissue** while maintaining effective tumor control, a phenomenon known as the **FLASH effect**. The FLASH effect is shown in figure 1. Despite its promise, the underlying mechanisms, optimal dose thresholds, and response to treatment interruptions remain unclear. Figure 2 shows the linear accelaretor (**ElectronFLASH**) at the university hospital Antwerp. The ElectronFLASH is being used to study these effects, though challenges such as **radiation protection** and limitations of conventional detectors persist. Further research is needed to ensure safe implementation of UHDR-RT [1].

Figure 2: ElectronFlash [3]

Figure 1: Histological lung tissue comparison showing reduced fibrosis with FLASH RT [2]

Problem statement

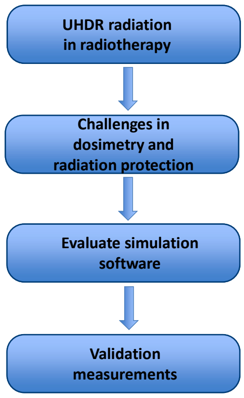

Figure 3: Problem statement flowchart

The introduction of Ultra-High Dose Rate radiation in radiotherapy presents major **challenges in dosimetry and radiation protection**. A critical concern is the quantification of scatter radiation, particularly **bremsstrahlung photons** produced when accelerated electrons interact with materials (e.g., phantoms). These high-energy photons contribute to **occupational exposure**, making accurate dose assessment essential.

Monte Carlo simulations are widely used for modeling scattered radiation, but many different codes exist, each with unique strengths and limitations in **UHDR contexts**. Choosing the most suitable simulation software and validating its results through **experimental measurements** is vital. However, standard detectors often become saturated at high dose rates, making detector selection and setup another key challenge. Figure 3 shows an overview of the problem statement

Research question

Which **simulation software** is most suitable for **radiation protection** calculations in **UHDR radiotherapy**, and how can these calculations be **experimentally validated**?

Methodology

Figure 4 shows the **benchmark case**, which was created and calculated by means of three different software programs. The evaluated software programs are:

- MicroShield (deterministic approach),
- RayXpert (Monte Carlo method),
- PHITS (Monte Carlo method).

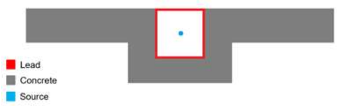

Figure 4: Benchmark (Radionuclide transfer line in a hospital)

The goal was to determine which simulation tool is **most practical** and accurate for **UHDR radiation protection** scenarios. The benchmark simulation of each software is shown in figures 5-8. The most promising tool was then used to **simulate the bunker** containing the ElectronFLASH (ELF) accelerator.

Figure 5: Benchmark in MicroShield

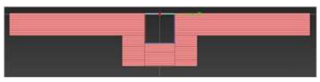

Figure 6: Benchmark in RayXpert

Finally, **experimental dose measurements** were performed at selected points in the bunker to validate the simulation results.

Figure 7: Benchmark in PHITS (with weight windows)

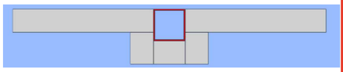

Figure 8: Benchmark in PHITS (without weight windows)

Results & Conclusion

Figure 9 shows that **MicroShield** produced the highest dose rate estimate at **9.45 µSv/h**, but as a deterministic tool, it lacks the accuracy of Monte Carlo-based methods. **RayXpert**, using Monte Carlo calculations and weight windows, yielded a dose rate of **3.11 µSv/h**. **PHITS**, when weight windows were disabled, produced a dose rate of **2.77 µSv/h**. When weight windows were enabled, PHITS computed a dose rate of **2.65 µSv/h.**

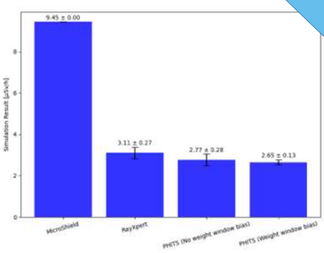

Figure 9: Calculated dose rate with different software

Figure 10 presents the two-dimensional **dose rate distribution** in the ElectronFLASH bunker, calculated by PHITS. Although absolute values are displayed, the results should be **interpreted as relative** as the **ElectronFLASH** settings can **vary** between irradiations

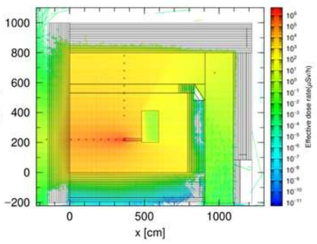

Figure 10: Dose rate distribution of the ElectronFLASH bunker

After comparing the simulation results with the validation measurements, it can be concluded that **the simulation is not yet fully optimized**. This discrepancy may be attributed to the **time-dependent nature** of the ElectronFLASH source, which **was not accounted for** in the current simulation model.

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[1] C. Garibaldi e.a., 'Minimum and optimal requirements for a safe clinical implementation of ultra-high dose rate radiotherapy: A focus on patient's safety and radiation protection', *Radiotherapy and Oncology*, vol. 196, jul. 2024, doi: 10.1016/j.radonc.2024.110291.

[2] V. Favaudon et al., "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice," *Science Translational Medicine*, vol. 6, no. 245, pp. 245ra93, Jul. 2014, doi: 10.1126/scitranslmed.3008973.

[3] S.I.T. - Sordina IORT Technologies S.p.A., ElectronFlash – Description and Radiation Protection Elements, Aprilia, Italy, internal technical document, 2023.

De opleiding industrieel ingenieur is een gezamenlijke opleiding van UHasselt en KU Leuven