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JOINT AAPM | COMP MEETING

Development of a Monte Carlo–Based Framework for Real-Time Operator Dose Estimation In Interventional X-Ray Procedures

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ABSTRACT

Medical staff in interventional radiology are exposed mainly to patient-scattered X-rays. Because the scatter field is highly non-uniform and depends on beam quality, geometry, patient position, and staff location, point-based dosemeters may not fully represent organ-specific exposure. This study developed a Monte Carlo–based framework for fast organ dose reconstruction using a scatter fluence database and an organ dose conversion coefficient (DCC) database.
Patient-scattered radiation was simulated in MCNP under PA projection using a BOMAB phantom. Angular and energy-dependent fluence was recorded on a scatter sphere centered at the isocenter. The ICRP 145 Adult MRCP was divided into six anterior panels, and panel-specific organ DCCs were calculated using monoenergetic photon beams. Preliminary results showed strong angular and energy dependence in scatter fluence and clear panel dependence in organ DCCs. The proposed database-based approach provides a physically interpretable basis for fast occupational organ dose estimation in interventional radiology.

INTRODUCTION

Medical staff in interventional radiology are mainly exposed to patient-scattered X-rays. The scatter field is highly non-uniform and depends on C-arm geometry, beam quality, field size, patient size, and staff position.

Conventional personal dosemeters provide point-based measurements and may not fully represent organ-specific exposure, especially for radiosensitive or partially shielded organs such as the eye lens and thyroid.

Inspired by the PODIUM project[1], this study separates the dose reconstruction problem into two pre-calculated components: an environmental scatter field database and a human body dose response database.

METHODS AND MATERIALS

A database-based dose reconstruction framework was developed.The full Monte Carlo problem was separated into two offline databases:

- Scatter field database: photon fluence around the patient
- DCC database: organ dose response per unit incident fluence

Organ dose is estimated by combining scatter fluence, DCC, distance correction, angular mapping, and energy weighting. The complete database-based reconstruction workflow is shown in Figure 1.

Scatter Field Database
- Monte Carlo code: MCNP
- Projection: PA
- Tube voltage: 60–120 kVp
- Filtration: 1 mm Al + 0.4 mm Cu
- Field size: 30 × 30 cm²
- Patient phantom: 182 cm BOMAB phantom
- Scatter sphere: radius = 35 cm, centered at the isocenter (Figure 2)
- Tally: F5 point detector
- Angular resolution: 10°
- Energy binning: 10 keV

DCC Database
- Operator phantom: ICRP 145 Adult MRCP (Figure 3)
- Field panels: Top, Mid, Bottom × Left, Right
- Source: monoenergetic parallel photon beam
- Tally: F6 tally
- DCC definition: organ absorbed dose per unit incident fluence

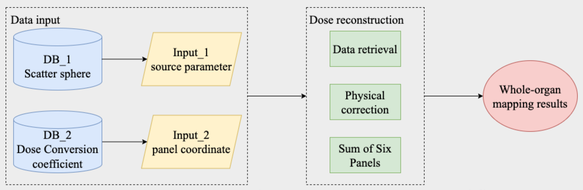

Figure 1. Database-Based Dose Reconstruction Workflow.

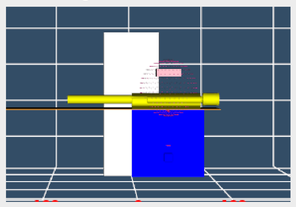

Figure 2. Simulation Setup for Patient-Scattered Radiation Field.

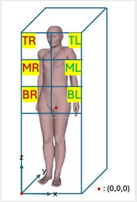

Figure 3. Six-Panel Field Definition on the ICRP 145 MRCP Phantom.

RESULTS

Scatter Field Distribution
The PA scatter sphere showed a non-uniform spatial fluence distribution, as shown in Figure 4. Higher scattered fluence appeared in specific angular regions, indicating that patient-scattered radiation has strong directional dependence.

The angular distribution of scatter fluence under different tube voltages is further shown in Chart 1. The log-scale presentation allows comparison of both high- and low-fluence regions and demonstrates that scatter fluence depends on both polar angle and tube voltage.

The polar-angle-bin comparison in Chart 2 shows that scatter fluence is not evenly distributed across all angular regions. This supports the need to include angular-bin information in the scatter fluence lookup table.

Panel-Dependent DCC Trends
The six-panel DCC comparison for representative organs is shown in Chart 3. The results demonstrate clear anatomical dependence of organ dose response.

These results indicate that organ DCC values depend on both the irradiated panel location and photon energy. Therefore, region-specific DCCs are necessary for organ dose reconstruction under non-uniform scattered radiation fields.

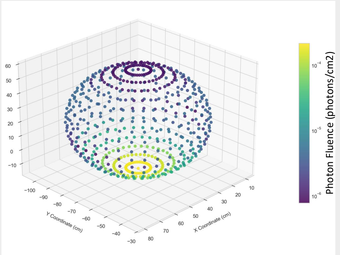

Figure 4. PA Scatter Fluence Distribution on the Scatter Sphere.

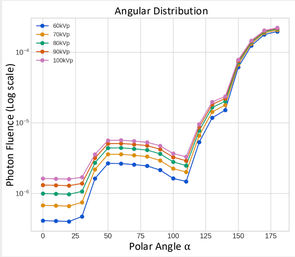

Chart 1. Log-Scale Angular Distribution of Scatter Fluence under Different Tube Voltages

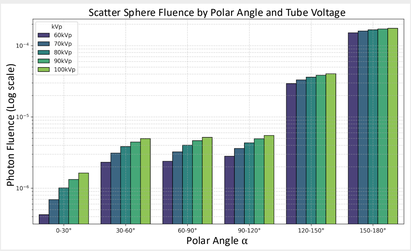

Chart 2. Angular-Bin Comparison of Scatter Fluence under PA Projection

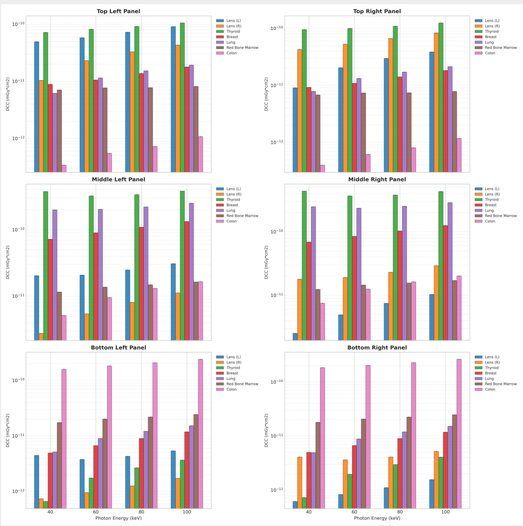

Chart 3. Six-Panel DCC Comparison for Representative Organs

DISCUSSION

The results indicate that staff dose estimation in interventional radiology should consider both the angular distribution of scattered radiation and the anatomical dependence of organ dose response. The PA scatter sphere showed a non-uniform fluence distribution, while the six-panel DCC results demonstrated that organ dose response varies with the irradiated body region.

The six-panel approach is important because organ dose cannot be accurately represented by a single whole-body conversion coefficient. When scattered photons enter the body from different regions or directions, internal organs may receive different dose contributions due to their anatomical locations, tissue depth, and organ self-shielding effects. For example, top panels contributed more strongly to the eye lenses and thyroid, middle panels to the breast and lung, and bottom panels to the colon and pelvic-region red bone marrow. These findings support the use of region-specific DCCs for organ dose reconstruction.

Since the scatter sphere was fixed at the isocenter, patient positioning becomes an important source of uncertainty. Changes in table height may shift the patient relative to the beam and the scatter sphere, leading to different patient-scattered fluence distributions. Therefore, future work should include table height variation or patient-to-isocenter correction in the scatter field database.

This database-based method provides a practical framework for fast organ dose reconstruction, but further validation is needed for different C-arm angles, patient positions, and clinical exposure conditions.

CONCLUSIONS

This study established a Monte Carlo–based framework for fast organ dose reconstruction in interventional radiology.

The preliminary results show that scattered photon fluence is strongly angle- and energy-dependent, and that organ dose responses vary with field panel location and photon energy.

The proposed database-based approach provides a physically interpretable foundation for future development of fast occupational organ dose estimation tools.

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