Unlocking In-Vivo Dosimetry In HDR Brachytherapy with Plastic Scintillation Detectors through Experimentally Extracted and Validated Correction Factors

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INTRODUCTION

- Plastic Scintillation Detectors (PSDs) have been proved effective for dose measurement in High Dose Rate (HDR) brachytherapy[(1)].
- Still, accurate dosimetry remains challenging due to spectral changes as function of the Source to Detector Distances (SDDs)[(2)].
- Correction Factors (CFs) should be assessed to correct measurements, especially in low dose rate regions, where ionization quenching effect becomes important (electrons below 125 keV)[(2)].
- The solution is to adapt a complete formalism to PSD dosimetry in HDR brachytherapy.

Purpose: (1) extract and (2) validate CFs, to be applied to dose rates measured with a PSD for in-vivo dosimetry in HDR brachytherapy.

METHODS

- The PRB0109 PSD ($1{\times}3\ mm^3$, polystyrene) was calibrated[(3)] and coupled to the Hyperscint RP-200 from Medscint Inc., QC.
- Dose rates acquired at 1 and 10 Hz from an Ir-192 Flexisource ($\theta = 90°$) up to SDD=20 cm in the IBA Blue-Phantom² water tank.
- **TOPAS** v3.9 (G4 v10.7) was used to score photon energy fluence, dose to water, and to polystyrene, reproducing measurement conditions with the PSD and the Ir-192 Flexisource models. 10^{11} histories (u<0.2%).
- Measurements were compared to the MC dose rates in terms of Relative Difference (RD) over explored SDDs.

Formalism

Following the TG-51 report[(4,5)], dose rate to water at the Ir-192 quality Q ($\dot{\mathbf{D}}_{\mathbf{w,Q}}$), $SDD = r$, and $\theta = 90°$, is expressed as :

$$\dot{\mathbf{D}}_{\mathbf{w,Q}}(\boldsymbol{r},\boldsymbol{\theta}) = \boldsymbol{k}_{\boldsymbol{r,Q}} \cdot \boldsymbol{k}_{\boldsymbol{Q,Q_0}} \cdot \boldsymbol{k}_{\boldsymbol{RP}} \cdot \dot{\mathbf{D}}_{\mathbf{det},\boldsymbol{Q}}\,(\boldsymbol{r},\boldsymbol{\theta}).$$

Where,

- $\dot{\mathbf{D}}_{\mathbf{det},\boldsymbol{Q}}$ is the measured dose rate within the PSD volume.
- $\boldsymbol{k}_{\boldsymbol{RP}}$ corrects for the Hyperscint RP-200 dose rate dependency. Measured with a 6 MV beam ($10{\times}10\ cm^2; d_{max}$) as the dose ratio to a reference A12 chamber at dose rates of 15 to 600 MU/min : Out-of-field method.
- $\boldsymbol{k}_{\boldsymbol{Q,Q_0}}$ corrects the calibration to measurement energy dependence defined as : $\frac{[\mu_{en}/\rho]^{w}_{poly}|_{6MV}}{[\mu_{en}/\rho]^{w}_{poly}|_{Ir-192}}$. Mass energy-absorption coefficients were extracted at the mean photon energy, MC fluence spectra, from NIST database[(6)].
- $\boldsymbol{k}_{\boldsymbol{r,Q}}$ is the detector perturbation factor defined as :

$$\boldsymbol{k}_{\boldsymbol{r,Q}} = \boldsymbol{k}_{\boldsymbol{vol}} \cdot \boldsymbol{p}_{\boldsymbol{scint}} \cdot \boldsymbol{p}_{\boldsymbol{wall}} \cdot \boldsymbol{k}_{\boldsymbol{ioq}}\,(\boldsymbol{r},\boldsymbol{\theta}).$$

Where,

- k_{vol} corrects for volume averaging (Finite-volume analytical model): $k_{vol} = \frac{D_{eff}(r_0)}{\langle D\rangle_{Volume}}$.
- p_{scint} corrects medium non-equivalence as the D_w/D_{poly} ratio. Scored mean dose with no envelope/cladding.
- p_{wall} for envelope/cladding effects as the $D_{poly}/D_{PSD\ full\ geometry}$ ratio.
- k_{ioq} corrects for ionization quenching effect due to **secondary** low energy electrons. It has been extracted from the residual RDs after applying all other CFs to the measurement, and is defined as : $k_{ioq} = \dot{D}^{MC}_{w,Q}/\dot{D}^{CFs}_{w,Q}$.

RESULTS & DISCUSSION

TAB. 1 – MC mean photon energy $\langle \boldsymbol{E_\gamma} \rangle$, and electron deposited energy $\langle \boldsymbol{E_e} \rangle$ at $SDDs = r$ in the transverse plane of the Ir-192 source ($\theta = 90°$). MC statistical uncertainties on the mean energy were negligible ($\approx 10^{-8}$) compared with the reported mean values.

r (cm)	$\langle E_\gamma \rangle$ (keV)	$\langle E_e \rangle$ (keV)
1	321.77	60.17
5	214.79	47.49
10	169.66	39.78
15	146.21	34.98
20	132.84	31.15

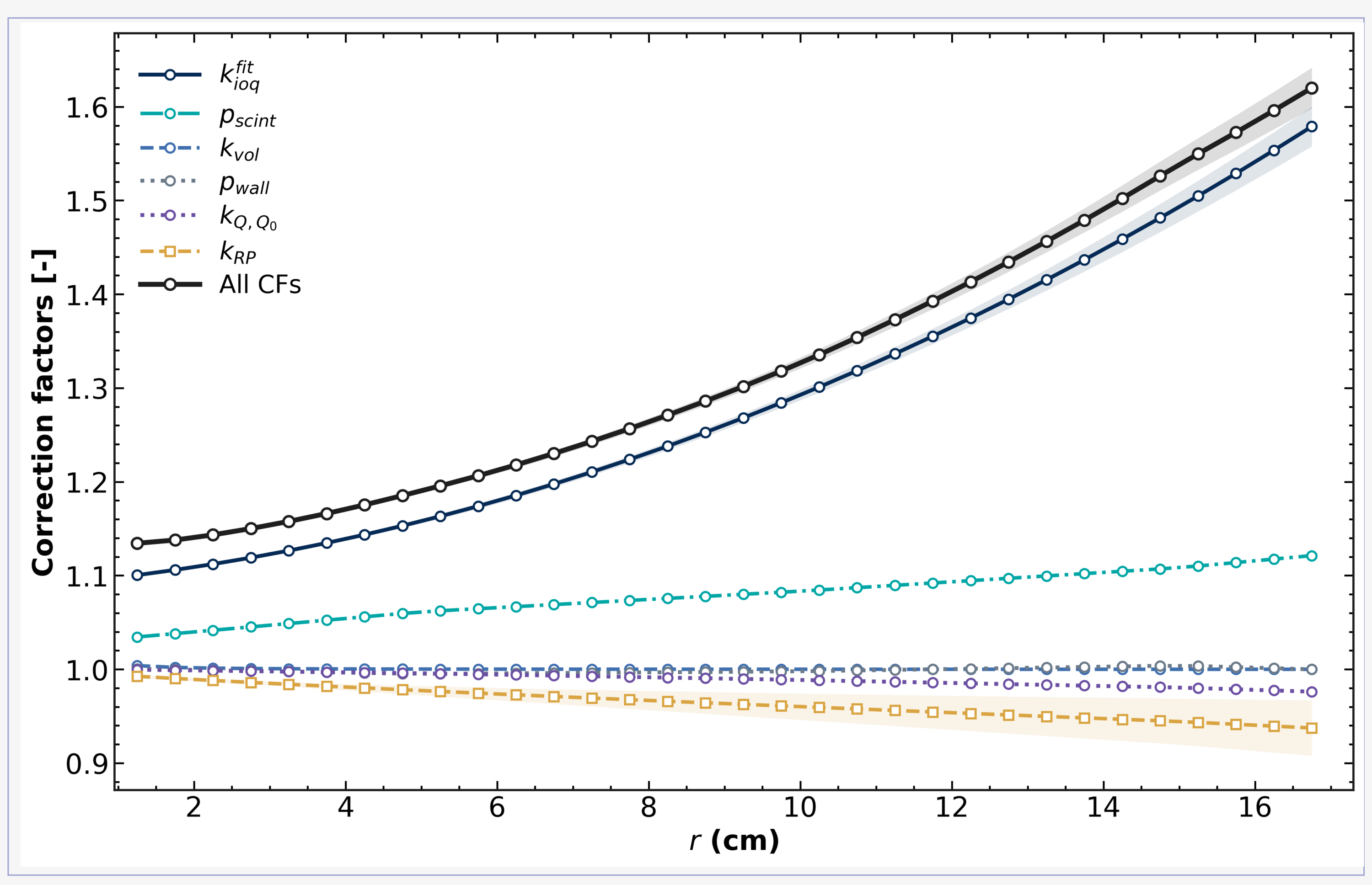

FIG. 1 – Extracted and calculated correction factors as function of the SDD at $\theta = 90°$. The experimental k_{ioq} values, extracted from residual RDs, fitted a quadratic function (red line). Extraction measurement were performed at 1 Hz, $\theta = 90°$, and $S_k = 32431\ U$.

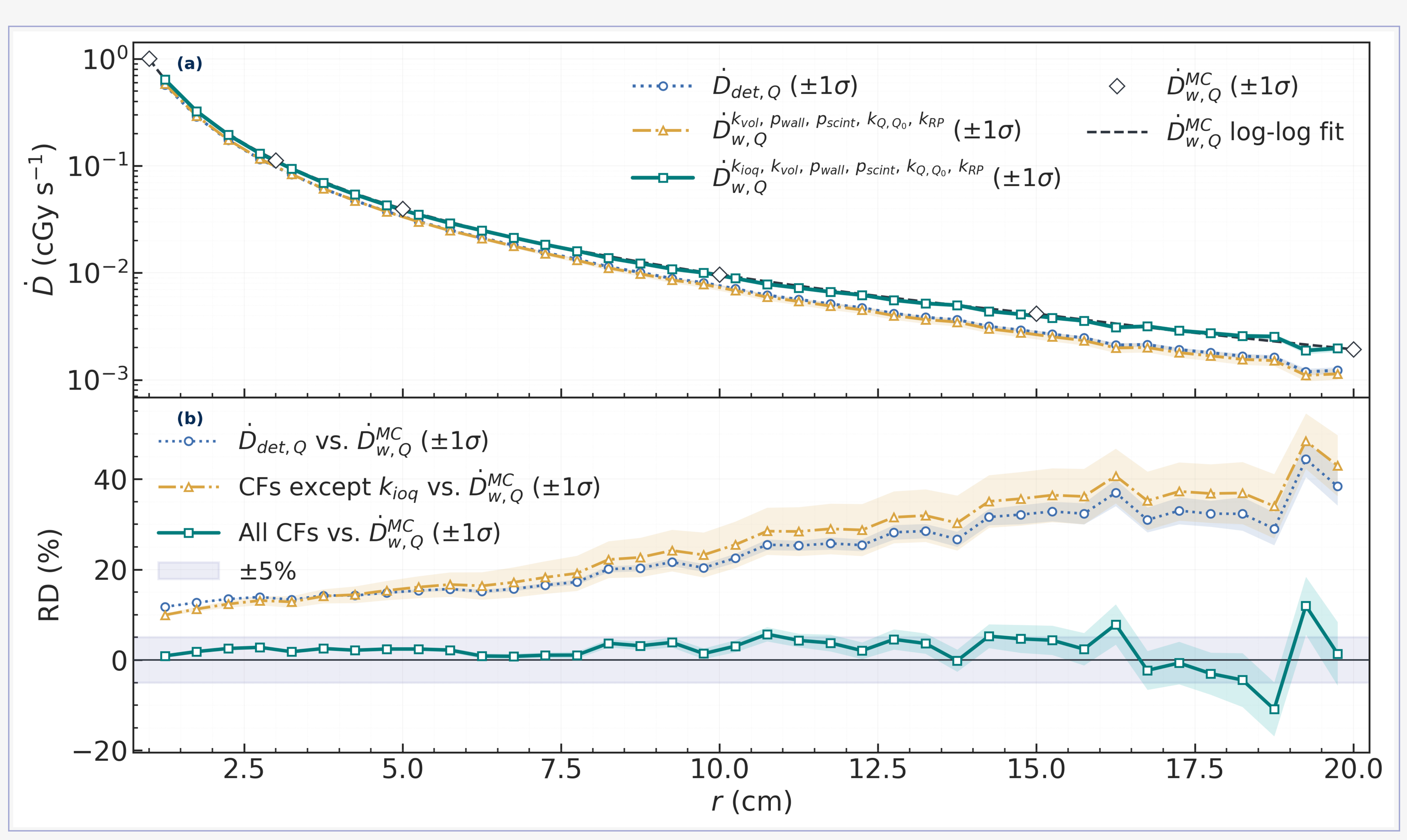

FIG. 2 – (a) Dose rates at 10 Hz; measured (blue), corrected for both CFs except k_{ioq} (yellow) and all CFs (green), and MC values (white diamonds + log-log fit in dotted black line). y-axis in logarithmic scale. **(b)** Relative differences, before and after correction, with and without the extracted k_{ioq}. The ±5 % agreement region in grey. Both measurement and MC simulations were performed at $\theta = 90°$ with $S_k = 32426\ U$.

- The correction factors k_{vol}, p_{scint}, p_{wall}, and k_{Q,Q_0} ranged between [1.006–1.00002], [1.0327–1.145], [1.0008 – 0.992], and [0.999 – 0.968], respectively, over distances from 1 to 20 cm.
- The Hyperscint RP200 dose rate CF (k_{RP}) ranged from 0.9938 to 0.9245 at 1 to 20 cm from the source for dose rates of 10.12 cGy/s and 0.019 cGy/s, respectively ($S_k = 32431U$). This corresponds to increased low-dose rate over-response up to 7.55% at 0.019 cGy/s from the reference (A12).
- After applying CFs except quenching effect, residual RDs reached up to $33.7 \pm 2.1\%$ at r=15 cm for a k_{ioq} value of $1.5 \pm 0.05\%$. Experimental data followed a quadratic fit to tabulate k_{ioq}^{fit} as function of SDDs being : $k_{ioq}(r) = 1.3e^{-3} \cdot r^2 + 7.12e^{-3} \cdot r + 1.09$.

✓ All CFs were calculated and extracted (Fig.1).

- CFs were applied on measured dose rates at 10 Hz with $S_k = 32426\ U$. RDs were $< 2.5\%$ for SDDs up to 7.5 cm and reached up to 5% for greater distances. Above 15 cm, at dose rates of 0.004 to 0.002 cGy/s, RDs reached a maximum of $\approx 12\%$.
- We mainly associate this fluctuations in RDs to a decrease in Signal to Noise Ratio (SNR) in low dose gradient regions.

✓ The validation measurement showed a mean signed RD of $2.14 \pm 0.74\%$ and a mean absolute RD of 3.27% over 1.25– 19.75 cm.

CONCLUSIONS

- A complete dose-to-water measurement formalism with PSDs for HDR brachytherapy is experimentally extracted and validated.
- The extracted k_{ioq} increased with SDD, reaching approximately 1.30 ± 0.03 at 15 cm and 1.51 ± 0.04 at 20 cm, consistent with an increasing contribution of low-energy secondary electrons (reduced light-yield when the linear energy transfer increases).

Future work:

- Cross validation of the experimental ionization quenching correction factor with MC simulations : extraction of the Birks parameter k_B.
- Extend the quenching analysis to different scintillator compositions, including plastic and inorganic detectors.

REFERENCES

[1] F. Therriault-Proulx *et al.*, "A phantom study of an *in vivo* dosimetry system using plastic scintillation detectors for real-time verification of ¹⁹²Ir HDR brachytherapy," *Med. Phys.*, vol. 38, pp. 2542–2551, 2011. doi: 10.1118/1.3572229.
[2] J. F. Williamson *et al.*, "Plastic scintillator response to low-energy photons," *Phys. Med. Biol.*, vol. 44, pp. 857–868, 1999. doi: 10.1088/0031-9155/44/4/004.
[3] C. Ghannoudi, M. C. Lavallée, B. Côté, and L. Beaulieu, "Robust external-beam calibration of plastic scintillation detectors and uncertainty analysis for in vivo dosimetry in HDR brachytherapy," Phys. Med. Biol., vol. 71, no. 7, 2026. doi: 10.1088/1361-6560/ae556d.
[4] Almond PR, Biggs PJ, Coursey BM, et al. AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon and electron beams. Med Phys. 1999;26:1847-1870.
[5] L. Gingras, Y. Cervantes, F. Beaulieu *et al.*, "Field output correction factors using a scintillation detector," *Med. Phys.*, vol. 52, no. 6, pp. 4844–4861, 2025.
[6] National Institute of Standards and Technology, "X-ray mass attenuation coefficients – Table 4," 2026. Accessed: Jan. 20, 2026. [Online]. Available: https://physics.nist.gov/PhysRefData/XrayMassCoef/tab4.html