

Update of the CLRP eye plaque brachytherapy database for photon-emitting sources

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Purpose: To update and extend the Carleton Laboratory for Radiotherapy Physics (CLRP) Eye Plaque (EP) dosimetry database for low-energy photon-emitting brachytherapy sources using *egs_brachy*, an open-source EGSnrc application. The previous database, CLRP_EPv1, contained datasets for the Collaborative Ocular Melanoma Study (COMS) plaques (10–22 mm diameter) with ^{103}Pd or ^{125}I seeds (BrachyDose-computed, 2008). The new database, CLRP_EPv2, consists of newly calculated three-dimensional (3D) dose distributions for 17 plaques [eight COMS, five Eckert & Ziegler BEBIG, and four others representative of models used worldwide] for ^{103}Pd , ^{125}I , and ^{131}Cs seeds.

Acquisition and validation methods: Plaque models are developed with *egs_brachy*, based on published/manufacture dimensions and material data. The BEBIG plaques (modeled for the first time) are identical in dimensions to COMS plaques but differ in elemental composition and/or density. Previously benchmarked seed models are used. Eye plaques and seeds are simulated at the center of full-scatter water phantoms, scoring in $(0.05\text{ cm})^3$ voxels spanning the eye for scenarios: (a) “HOMO”: simulated TG43 conditions; (b) “HETERO”: eye plaques and seeds fully modeled; (c) “HETsi” (BEBIG only): one seed is active at a time with other seed geometries present but not emitting photons (inactive); summation over all i seeds in a plaque then yields “HETsum” (includes interseed effects). For validation, doses are compared to those from CLRP_EPv1 and published data.

Data format and access: Data are available at https://physics.carleton.ca/clrp/eye_plaque_v2, <http://doi.org/10.22215/clrp/EPv2>. The data consist of 3D dose distributions (text-based EGSnrc “3ddose” file format) and graphical presentations of the comparisons to previously published data.

Potential applications: The CLRP_EPv2 database provides accurate reference 3D dose distributions to advance ocular brachytherapy dose evaluations. The fully-benchmarked eye plaque models will be freely distributed with *egs_brachy*, supporting adoption of model-based dose evaluations as recommended by TG-129, TG-186, and TG-221. © 2021 American Association of Physicists in Medicine [<https://doi.org/10.1002/mp.14844>]

Key words: brachytherapy, CLRP, dose calculation, eye plaque, *egs_brachy*

1. INTRODUCTION

Eye plaque (EP) brachytherapy plays an important role in the treatment of intraocular cancers offering delivery of conformal doses to the tumor, with steep dose gradients sparing critical organs at risk.^{1–3} Survival rates with plaque therapy have been reported to be comparable to enucleation but with eye preservation and the possibility of retaining some visual function.^{4,5} Recent work suggests inferior clinical outcomes with proton therapy compared with eye plaque brachytherapy.⁶

The small size of the eye combined with considerable dose gradients for eye plaque brachytherapy means that dosimetry is critical.^{1,2} Traditionally, dose calculations for plaques containing photon-emitting sources follow the water-based approach of Task Group (TG) 43.⁷ Model-based dose calculation algorithms (MBDCAs), including Monte Carlo (MC) simulations, promise more accurate dose evaluations by accounting for non-water treatment components (applicator, sources), and patient non-water tissues. Various MC studies have demonstrated considerable errors incurred with the TG-43 approach for eye plaque brachytherapy dose evaluation.¹ For example, MC studies modeling plaque backing/insert

materials (in water phantom) report dose decreases relative to TG-43 of 11–40% in the tumor, and as large as 90% for organs at risk, focusing on the standardized plaques of the Collaborative Ocular Melanoma Study (COMS) containing ^{125}I or ^{103}Pd seeds.^{8–11} Considerable differences with TG-43 have been demonstrated for other photon-emitting plaque models as well as when modeling non-water patient/ocular anatomy.^{10,12–14} These discrepancies with TG-43 doses motivated both TG-129 and TG-221 to recommend that dose evaluations accounting for the effects of the plaque backing and insert be carried out in parallel with traditional TG-43 calculations,^{1,2} in accord with the general recommendations of TG-186 on adoption of MBDCAs in brachytherapy.¹⁵

The present work supports widespread adoption of MC dose evaluations for photon-emitting eye plaques. We use *egs_brachy*, a freely distributed and open-source EGSnrc application,^{16,17} to develop 17 eye plaque models: 10–24 mm diameter COMS, 12–20 mm BEBIG (manufactured by Eckert & Ziegler BEBIG, Berlin, Germany), and four 16 mm diameter plaques representative of various models in use worldwide.¹⁴ Employing benchmarked *egs_brachy* ^{125}I , ^{103}Pd , and ^{131}Cs seed models,¹⁸ we simulate the eye plaques

in a water phantom to generate 3D dose distributions scored in $(0.05 \text{ cm})^3$ voxels in the eye region.

These 3D dose distributions are used to completely update and extend the Carleton Laboratory for Radiotherapy Physics (CLRP) Eye Plaque Brachytherapy database that was originally published in 2008 (version 1, "CLRP_EPV1": contained BrachyDose-calculated dose distributions for 10–22 mm COMS plaques with ^{103}Pd or ^{125}I seeds¹⁰). The present article describes the CLRP_EPV2 database https://physics.carleton.ca/clrp/eye_plaque_v2 (<http://doi.org/10.22215/clrp/EPV2>) that contains 3D dose distributions for diverse photon-emitting eye plaques, and the egs_brachy plaque models that will be freely distributed with the egs_brachy distribution (https://physics.carleton.ca/clrp/egs_brachy/).

2. ACQUISITION AND VALIDATION METHODS

2.A. Monte Carlo simulations of eye plaques

All MC calculations are performed with EGSnrc application egs_brachy¹⁶ (GitHub commit hash 8166234, 2020, available at https://github.com/clrp-code/egs_brachy/tree/egs_brachy_2020). The benchmarking of egs_brachy is documented in previous publications.^{16–18} Transport parameters are generally EGSnrc defaults,¹⁹ using the low-energy default specifications distributed with egs_brachy. Electron transport is not modeled. The photon energy transport cutoff is set to 1 keV. Photoelectric absorption, Rayleigh scattering, Compton scattering, and fluorescent emission of characteristic x rays are simulated. Photon cross sections are from the XCOM database.²⁰ Dose is approximated as collision kerma, scored with a tracklength estimator in voxels with mass energy absorption coefficients (distributed with egs_brachy; previously calculated with EGSnrc application g²¹). The "unrenormalized" photoelectric cross sections are used, consistent with EGSnrc default¹⁹ (note that there is ambiguity in whether renormalized or unrenormalized Scofield photoelectric cross sections are in better agreement with experimental data²²).

The egs++ class library geometry module is used to develop the eye plaque models: COMS plaques with diameters (D) from 10 to 24 mm (in 2 mm increments),^{2,23} BEBIG

plaques with diameters from 12 to 20 mm (in 2 mm increments; simulated for the first time), and four different 16 mm diameter "representative" plaque models.^{1,14} These representative plaque models were previously developed by Lespérance et al.¹⁴ to approximate different plaque models in use worldwide (for which exact dimensions and material specifications are not widely available and/or accurately known), and include "Short lip-acrylic" (Sla),²⁴ "COMS-thin acrylic" (Cta),²⁵ "No lip-Silastic" (NIS),²⁶ and "Stainless steel-acrylic" (Ssa).²⁷ The plaque models and associated parameters are summarized in Table I with parameters/dimensions defined in Fig. 1; the online CLRP_EPV2 database contains diagrams of each plaque model.

Each eye plaque model has a backing (with or without collimating lips), and contains either a full insert (that conforms to the outer sclera) or a thin layer of fixative that holds seeds in place. The COMS plaques have a Modulay backing (elemental composition by mass: 77% Au, 14% Ag, 8% Cu, and 1% Pd; mass density, $\rho = 15.8 \text{ g/cm}^3$) with collimating lips and a full Silastic insert seed carrier (39.9% Si, 28.9% O, 24.9% C, 6.3% H, 0.005% Pt; $\rho = 1.12 \text{ g/cm}^3$).² Compared to the COMS plaques, the BEBIG plaques have identical geometry but with a different gold alloy comprising the backing, "Bio PontoStar" (87% Au, 10.6% Pt, 1.5% Zn, 0.2% Rh, 0.2% In, 0.2% Ta, and 0.02% Mn, $\rho = 18.8 \text{ g/cm}^3$), and the Silastic insert has a different mass density of ($\rho = 1.09 \text{ g/cm}^3$ [Personal communication, Michael Andrassy (Eckert & Ziegler BEBIG), June 18, 2019]). The representative plaque models (Cta, Sla, NIS) have Modulay backings, with the exception of the plaque model with the stainless steel backing (Ssa; 99.05% Fe, 0.005% Mn, 0.003% Si, and 0.0015%, $\rho = 7.9 \text{ g/cm}^3$); their inserts are either Silastic or acrylic (32% O, 60.1% C, 8.06% H, $\rho = 1.19 \text{ g/cm}^3$). All representative plaques have collimating lips (but of varying lengths, h_{lip} — see Table I) with the exception of "No lip-Silastic" (NIS).

All plaques models are based on fitting an idealized eye² assumed to be a sphere of radius 1.23 cm, *i.e.*, for the eye plaque models with a full insert (COMS, BEBIG, Sla, NIS, Ssa), the insert conforms to the eye's outer sclera (radius 1.23 cm). The "eye plaque" coordinate system is used^{2,10,14} and has its origin at the inner sclera on the plaque's central axis, taken to be 0.1 cm from the outer sclera (Fig. 1). The plaque's central

TABLE I. Summary of plaques modeled: reference notation; characteristics of the backing and insert; values for diameter (D ; does not include lip width if present), collimating lip height (h_{lip} , if lip present), plaque height (h), and radial distance from the center of the eye to seed centers (R_{seed}) — see Fig. 1.

Plaque model	Backing (thickness)	Insert	Radionuclides	Dimensions (mm)				Ref.
				D	h	h_{lip}	R_{seed}	
COMS	Modulay (0.5 mm)	Full, Silastic	^{125}I , ^{103}Pd , ^{131}Cs	10 – 24	2.75	2.7	13.7	[2,10,23]
BEBIG	BioPontoStar (0.5 mm)	Full, Silastic	^{125}I	12 – 20	2.75	2.7	13.7	^a
COMS - thin acrylic (Cta)	Modulay (0.5 mm)	Thin 0.85 mm, acrylic	^{125}I , ^{103}Pd , ^{131}Cs	16	—	2.7	13.7	[14,25]
Short lip - acrylic (Sla)	Modulay (0.5 mm)	Full, acrylic	^{125}I , ^{103}Pd , ^{131}Cs	16	1.8	1.5	12.95	[14,24]
No lip - Silastic (NIS)	Modulay (0.5 mm)	Full, Silastic	^{125}I , ^{103}Pd , ^{131}Cs	16	1.8	—	12.95	[14,26]
Stainless steel - acrylic (Ssa)	Stainless steel (1 mm)	Full, acrylic	^{125}I , ^{103}Pd , ^{131}Cs	16	2.75	2.1	13.45	[14,27]

^aPersonal communication, Michael Andrassy (Eckert & Ziegler BEBIG) June 18, 2019.

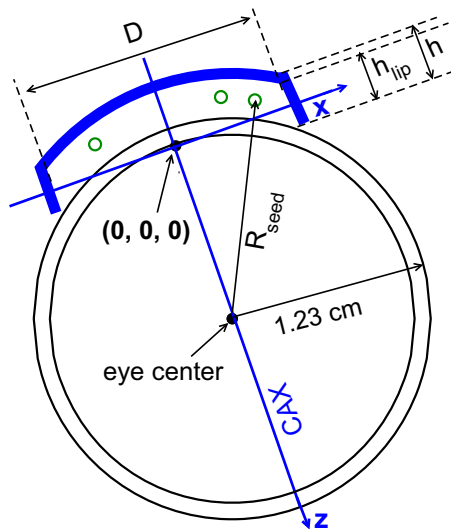


FIG. 1. Schematic diagram depicting the eye plaque. Indicated are parameters describing the eye plaque (D : diameter; h : height; h_{lip} : collimating lip height) and showing R_{seed} as the distance from seed center to the eye center, as well as the coordinate system (origin at the inner sclera, 0.1 cm from idealized eye's outer surface; CAX: central axis). [Color figure can be viewed at wileyonlinelibrary.com]

axis (CAX) defines the z -axis, with x and y coordinates transverse to the plaque. Plaques contain between 5 and 33 seeds, with positions and orientations provided in the online CLRP_EPV2 database based on earlier publications: TG-129 report² (COMS 10–22 mm; BEBIG), Cutsinger et al.²³ (COMS 24 mm), and Lépérance et al.¹⁴ (representative plaques: Cta, Sla, NIS, Ssa).

Three different seeds are used for COMS and representative plaque simulations: the ^{103}Pd Theragenics TheraSeed model 200,^{18,28} ^{125}I Amersham OncoSeed model 6711,^{18,29} and ^{131}Cs Isoray model CS-1 Rev2.^{18,30} For BEBIG plaques, the ophthalmic ^{125}I BEBIG IsoSeed I-125 (I25.S16) is used which is geometrically identical to the I25.S06 but has higher activity for use in ophthalmologic oncology.^{18,31} The egs_brachy models of these seeds were recently developed and benchmarked as part of updated 2020 CLRP TG-43v2 database.¹⁸ Photons are initialized within the seeds according to the NNDC spectra³² for ^{103}Pd and ^{131}Cs seeds, and for ^{125}I from the NCRP report 58,³³ all consistent with CLRP TG43v2 database.¹⁸ The phase space source and particle recycling features of egs_brachy (that enhance simulation efficiency) are not used. The mean energy of photons emitted from the seeds calculated by egs_brachy is 20.51 keV (^{103}Pd model 200), 27.34 keV (^{125}I model 6711), 30.29 keV (^{131}Cs model CS-1), and 28.16 keV (I25.S16).¹⁸

Plaques and seeds are modeled at the center of a full-scatter water phantom ($\rho = 0.998 \text{ g/cm}^3$) which extends from $-15 \text{ cm} \leq x, y, z \leq 15 \text{ cm}$. Dose is scored in a $51 \times 51 \times 51$ array of $(0.05 \text{ cm})^3$ voxels spanning the eye region, extending from $-1.275 \text{ cm} \leq x, y \leq 1.275 \text{ cm}$, and from $-0.075 \text{ cm} \leq z \leq 2.475 \text{ cm}$ (voxels centered along the plaque's central axis). For voxels that overlap with the plaque, dose is scored only in the portion of the voxel not occupied by

the plaque, necessitating application of egs_brachy's voxel volume correction for which 10^9 random points/cm³ are used.^{16,18}

Different scenarios are simulated, all with seeds fully modeled:

1. "HOMO": Simulated TG-43 conditions with the plaque backing/insert modeled as water and no interseed effects (egs_brachy in "superposition" run mode).
2. "HETERO": Eye plaques containing seeds are fully modeled in the water phantom.
3. "HETsi" (BEBIG plaques only): One seed is modeled at a time, with other seed geometries present but those seeds are inactive. This produces one 3D dose distribution for each seed position in a plaque. This is repeated for all seeds to enable superposition (accounting for seeds of possibly differing source strengths) to obtain "HETsum" which is the sum of all HETsi (includes interseed effects).

Each calculation involves simulation of 10^{11} photon histories to ensure type A statistical uncertainties $\leq 0.2\%$ (1 sigma) at $z = 2.26 \text{ cm}$ (along the central axis at the opposite side of the eye to the plaque). Doses are reported in terms of dose rate per unit seed air kerma strength ($\text{Gy h}^{-1} \text{ U}^{-1}$ where $1 \text{ U} = 1 \text{ cGy cm}^2 \text{ h}^{-1}$) by dividing the calculated MC dose per history by the seed air kerma strength per history (S_K^{hist}). The S_K^{hist} values were previously calculated for the NIST WAFAC detector geometry as part of the CLRP TG43v2 database as $6.4261(6) \times 10^{-14} \text{ Gy cm}^2/\text{hist}$ (^{103}Pd model 200), $3.7666(7) \times 10^{-14} \text{ Gy cm}^2/\text{hist}$ (^{125}I model 6711), $4.8312(5) \times 10^{-14} \text{ Gy cm}^2/\text{hist}$ (^{125}I I25.S16), and $3.7155(3) \times 10^{-14} \text{ Gy cm}^2/\text{hist}$ (^{131}Cs model CS-1) (https://physics.carleton.ca/clrp/egs_brachy/seed_database_v2)¹⁸ As an example of the calculation time for a clinical scenario: Simulation of a COMS 16 mm plaque fully loaded with 13 ^{125}I seeds (model 6711) requires 200 s to achieve 2% statistical uncertainty at the tumor apex ($z = 0.5 \text{ cm}$ on the plaque central axis) on a single Intel Xeon 3.0 GHz CPU; calculations can be completed in a few seconds running on multiple cores (in parallel).

For validation purposes, the results of the 3D MC dose calculations (.3ddose) are imported into a CLRP in-house software tool (https://physics.carleton.ca/clrp/3ddose_tools/3ddose-tools), for example, to extract doses along different axes (CAX: central axis, z ; transverse x, y for $z = 0.5, 1.0 \text{ cm}$).

2.B. CLRP_EPV2 data overview

Table II and Fig. 2 summarize CLRP_EPV2 data for all 17 plaques loaded with the different seeds, with additional data provided online. In general, considerable dose reductions for HETERO relative to HOMO doses are observed (e.g., Table II), due to the attenuation and scattering in the backing/insert material. Doses decrease considerably with position along the plaque central axis, with steeper fall-off for lower energy ^{103}Pd (20.51 keV) compared with higher energy ^{125}I [27.34 keV (6711), 28.16 keV (I25.S16)] or ^{131}Cs

TABLE II. Summary of CLRP_EPv2 HETERO/HOMO dose ratios at depths along the central axis for each plaque fully loaded with ^{125}I (model 6711 or I25.S16 for BEBIG), ^{103}Pd (model 200), or ^{131}Cs (CS-1 Rev2) seeds. The zero before the point is omitted (e.g., .889 = 0.889). Statistical uncertainties are <0.2%. Values of HOMO and HETERO dose rate per unit seed air kerma strength (Gy $\text{U}^{-1} \text{h}^{-1}$) are provided in the CLRP_EPv2 webpage.

Nuc	z (cm)	COMS (mm)									BEBIG (mm)				Representative			
		10	12	14	16	18	20	22	24	12	14	16	18	20	Cta	Sla	Ssa	NIS
¹²⁵ I	0.0	.889	.875	.867	.852	.853	.848	.854	.844	.879	.871	.857	.857	.852	1.00	1.02	.964	.922
	0.1	.897	.887	.880	.870	.866	.862	.863	.857	.885	.878	.869	.864	.861	.995	1.01	.963	.934
	0.2	.897	.890	.884	.878	.872	.870	.869	.864	.884	.879	.873	.867	.864	.988	1.00	.961	.938
	0.5	.883	.881	.880	.878	.874	.873	.872	.869	.871	.869	.868	.864	.862	.968	.978	.945	.935
	1.0	.854	.855	.857	.859	.858	.859	.859	.858	.843	.844	.846	.845	.844	.939	.949	.923	.919
	1.5	.832	.834	.835	.838	.838	.839	.839	.836	.824	.822	.825	.825	.824	.915	.927	.903	.904
¹⁰³ Pd	0.0	.780	.762	.753	.731	.737	.732	.741	.730						.989	1.01	.982	.850
	0.1	.803	.790	.781	.769	.767	.763	.766	.759						.984	.999	.982	.880
	0.2	.812	.803	.796	.788	.783	.781	.782	.776						.980	.992	.981	.893
	0.5	.814	.812	.809	.807	.804	.802	.802	.800						.967	.977	.973	.904
	1.0	.802	.803	.803	.804	.804	.803	.805	.803						.953	.962	.962	.901
	1.5	.793	.794	.793	.795	.794	.794	.795	.796						.943	.951	.953	.895
¹³¹ Cs	0.0	.919	.906	.896	.885	.881	.877	.882	.871						1.00	1.02	.948	.937
	0.1	.923	.912	.904	.897	.889	.886	.888	.879						.992	1.01	.945	.944
	0.2	.920	.913	.905	.900	.892	.889	.890	.882						.984	.996	.941	.945
	0.5	.897	.896	.893	.893	.887	.887	.887	.881						.961	.970	.925	.937
	1.0	.859	.861	.861	.865	.863	.864	.866	.861						.923	.935	.896	.916
	1.5	.830	.832	.833	.838	.836	.838	.839	.835						.895	.905	.874	.897

(30.29 keV) seeds. These general observations are consistent with earlier work.^{8–14} The lowest dose per unit seed air kerma strength along central and transverse axes is for 10 mm COMS which is the smallest diameter plaque; conversely, the highest values are for 24 mm COMS, the largest diameter plaque (Fig. 2). In general, HOMO and HETERO dose rates per unit seed air kerma strength for BEBIG plaques are greater than those for the corresponding COMS plaques.

All representative plaque models generated greater dose rates per unit seed air kerma strength compared to the 16 mm COMS or BEBIG plaques with the lowest dose rate for Cta and highest dose rate for Sla plaque. Also, the transverse dose profiles are relatively flat (near the central axis; 0–0.8 cm) for plaques with higher seed number capacity (22 and 24 mm) due to the seed distribution in the plaque.

2.C. Data validation

For validation, dose distributions (from 3ddose files: dose rates per unit seed air kerma strength, see Section 2.A) are compared to previously published doses computed with BrachyDose data from CLRP_EPv1 for 10–22 mm COMS with ^{125}I , ^{103}Pd ^{10,11} and 16 mm COMS with ^{131}Cs (Ref. [13]); MCNP data^{8,9} for 10–22 mm COMS plaques (^{125}I , ^{103}Pd , ^{131}Cs); BrachyDose data for representative plaques.¹⁴ It is not possible to directly compare results for BEBIG and 24 mm COMS plaques because the present study is the first published MC simulation of these plaques (but the results of these plaques are compared to the other plaque sizes/types). The following subsections summarize some of the

comparisons, including doses along central and transverse axes, as well as at points of interest in the eye (on the central axis: sclera, optic disk, posterior pole, fovea, eye center, lens, lacrimal gland for eight different plaque positions of the COMS 16 mm plaque, following the work of Rivard et al⁸). Doses are compared directly and also via the percent difference of doses for egs_brachy ($D_{\text{egs_brachy}}$) and another code (D_{code} , from BrachyDose or MCNP):

$$\% \Delta(\text{egs_brachy, code}) = \frac{D_{\text{egs_brachy}} - D_{\text{code}}}{D_{\text{egs_brachy}}} \times 100\%. \quad (1)$$

The following subsections provide a sample of the comparisons carried out, demonstrating overall that egs_brachy dose distributions are in excellent agreement with previously published results.

2.C.1. COMS plaques

Dose distributions generated with egs_brachy for COMS plaques compare well with published BrachyDose and MCNP data, as demonstrated by the overview of comparison results presented in this section.

Figure 3 presents data for some COMS plaques along the central and transverse (x) axis, focusing on HETERO results; Fig. 4 summarizes HETERO dose differences over all COMS plaque sizes, comparing egs_brachy with BrachyDose^{10,14} and MCNP.⁹ Across all plaque sizes, egs_brachy and BrachyDose central axis HETERO doses are within 1.2% (^{103}Pd), 1.3% (^{125}I), and 1.4% (^{131}Cs ; 16 mm COMS only), and

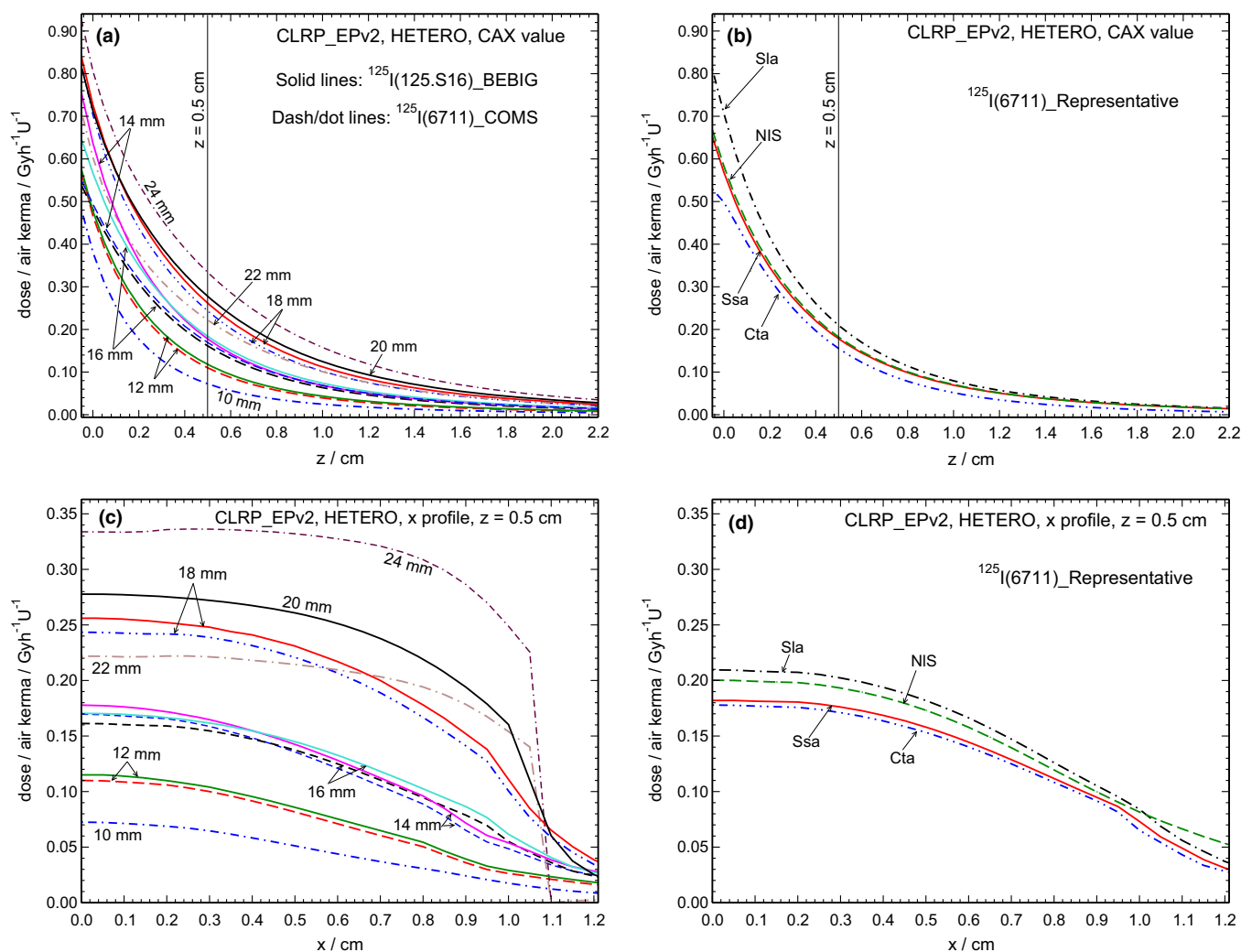


FIG. 2. Overview of CLRP_EPV2 HETERO results (for ^{125}I): doses along the (a) central axis (CAX; z -axis) for (a) COMS and BEBIG and (b) representative plaques; doses along the transverse axis (x , restricted to $x \geq 0$ for clarity) at $z = 0.5$ cm (indicated by the vertical line in (a,b)) for (c) COMS and BEBIG and (d) representative plaques. Statistical uncertainties are $\leq 0.2\%$ along the central axis at the opposite side of the sclera. [Color figure can be viewed at wileyonlinelibrary.com]

median discrepancies are much smaller (Fig. 4); agreement is comparable along transverse axes. Comparing *egs_brachy* and MCNP central axis HETERO doses, percent differences are at most 3.7% (^{103}Pd), 2.2% (^{125}I), and 1.8% (^{131}Cs) for HETERO.

In considering the results in Fig. 4, there are different trends for $\% \Delta$ with the different radionuclides and codes. For example, all median $\% \Delta$ values for *egs_brachy* and BrachyDose are very near zero for ^{103}Pd but slightly higher and positive (near 0.5%) for ^{125}I . The values of $\% \Delta$ are generally largest for MCNP and *egs_brachy*, with the largest and positive values for ^{103}Pd , followed by ^{131}Cs , whereas the values are more generally negative for ^{125}I . The fact that the $\% \Delta$ comparisons lie above and below zero for different radionuclides suggests good agreement in the plaque models.

Overall, doses along the central axis are in good agreement between *egs_brachy* and previously published BrachyDose and MCNP results, noting that 1σ statistical uncertainties are

$< 1\%$ on for BrachyDose^{10,13,14} and order of 2% for MCNP (exception: 7.6% for 22 mm plaque).⁹ Discrepancies between results between the different codes may be due to a combination of different factors including cross sections, transport parameters, code versions, source spectra, mass energy absorption coefficient values. Melhus and Rivard⁹ estimate that the total uncertainty on their results is 5% at a depth of 5 mm from the plaque (all three radionuclides and COMS plaque sizes, including nonstatistical sources of uncertainty).

Figure 5 provides further comparison of *egs_brachy* results with BrachyDose and MCNP for 16 mm COMS. Figure 5(a) presents the ratio of doses HETERO/HOMO along the central axis for *egs_brachy*, BrachyDose,^{10,13} and MCNP:⁸ comparing with *egs_brachy*, BrachyDose ratios are within 1.5% (^{103}Pd) and 0.5% (^{125}I), and those for MCNP are within 3.0% (^{103}Pd) and 3.5% (^{125}I). The fact that dose ratios are systematically higher for MCNP relative to *egs_brachy* (and BrachyDose) may be partially attributed to the fact that

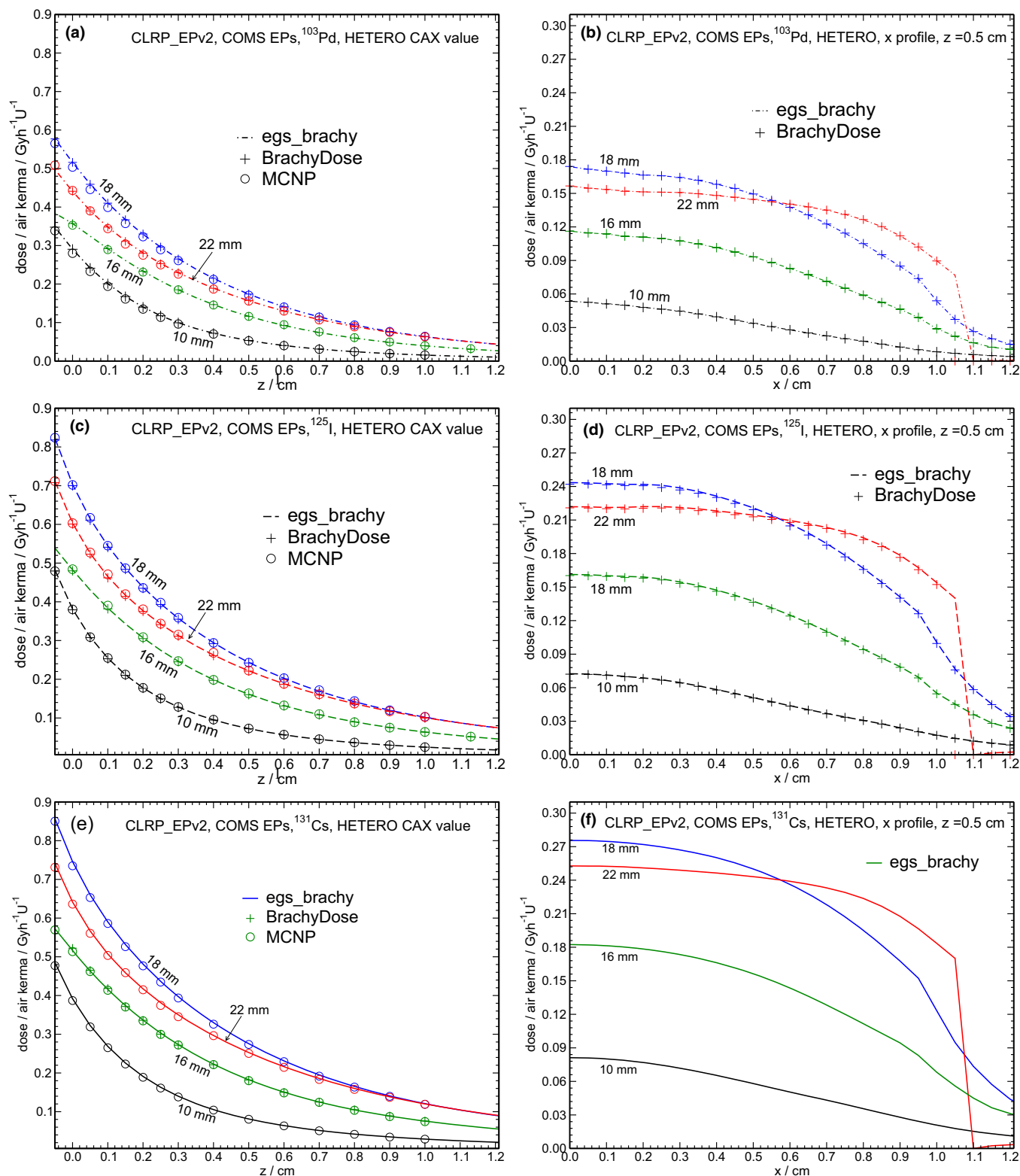


FIG. 3. COMS HETERO doses: (a, c, e) along the central axis; (b, d, f) transverse x axis (at 0.5 cm depth), for egs_brachy (lines), BrachyDose¹⁰ (“+” symbol) and MCNP⁹ (circle symbol) for nuclides: ^{103}Pd [model 200; panel (a, b)]; ^{125}I [model 6711; panel (c, d)]; ^{131}Cs [Cs-1 Rev 2; panel (e, f)]. The 10, 16, 18, and 22 mm EPs are shown in black, green, blue, and red colors, respectively. [Color figure can be viewed at wileyonlinelibrary.com]

HOMO MCNP simulations include interseed attenuation (those for egs_brachy and BrachyDose do not), thus lowering the dose in the denominator and increasing the HETERO/

HOMO ratio. Previous research assessed the magnitude of interseed effects, reporting that doses differed by less than 0.5% (HETERO) and by 1–2% for seeds in water (HOMO).¹⁰

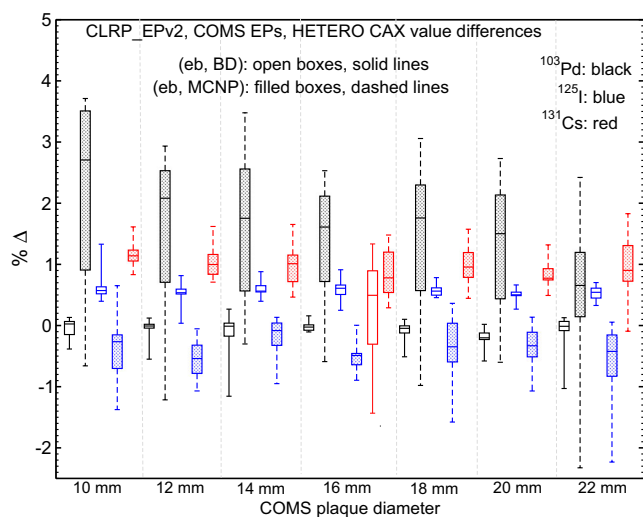


FIG. 4. Percent difference [% Δ ; Eq. (1)] for HETERO doses along the central axis of COMS plaques for eggs_brachy compared with published BrachyDose (BD)^{2,10} (open boxes, solid lines) and/or MCNP⁹ (filled boxes, dashed lines). Results are shown for all plaque diameters with ¹⁰³Pd (black), ¹²⁵I (blue), and ¹³¹Cs (red; BrachyDose only for 16 mm because data were not published for other sizes). Whiskers represent the total range of % Δ values, the boxes indicate the inner quartiles (extending between the first and third quartiles), and the horizontal line indicates the median. Statistical uncertainties are $\leq 0.2\%$ for eggs_brachy, $\leq 1\%$ for BrachyDose,¹⁰ and order of 2% (7.6% for 22 mm) for MCNP.⁹ [Color figure can be viewed at wileyonlinelibrary.com]

For all codes, the largest discrepancies are observed at the opposite side of the eye to the plaque where the statistical uncertainties are largest. Figure 5(b) summarizes comparisons of doses at organs at risk (positioned off the central axis), considering eight different plaque positions as done by Rivard et al.⁸ Differences are $\leq 2.3\%$ for eggs_brachy and BrachyDose and $\leq 4\%$ for eggs_brachy and MCNP with the exception of the lacrimal gland HETERO dose for two (of the eight) plaque positions considered. For those positions, the lacrimal gland HETERO doses are very low (3.5 Gy for ¹⁰³Pd and 6.6 Gy for ¹²⁵I, compared with 85 Gy as the prescription dose) and MCNP differs by 12.5% (¹⁰³Pd) and 17% (¹²⁵I) from eggs_brachy. This large discrepancy in the dose at the lacrimal gland for these plaque positions has been observed previously in comparing BrachyDose and MCNP doses⁸ and elsewhere in comparing eggs_brachy, BrachyDose, and MCNP results.^{8,17}

The results shown in this subsection demonstrate that there is generally closer agreement between the two EGSnrc-based codes, eggs_brachy and BrachyDose, than between eggs_brachy and MCNP, consistent with previous work.¹⁷ Overall, these comparisons validate the new eggs_brachy models and 3D dose distributions for COMS plaques.

2.C.2. BEBIG plaques

The present work offers the first MC simulations of the BEBIG model plaques, and so comparisons to previously

published results are not possible. However, the BEBIG plaques are of the same (geometric) dimensions to the COMS plaques, and thus, the validation of our eggs_brachy models for those plaques (Section 2.C.1) supports the new eggs_brachy BEBIG models. The dose distributions are expected to be different for BEBIG compared with COMS due to differences in plaque backing medium (elemental composition and density), insert density, and seed model (¹²⁵I: IsoSeed[®] I25.S16 for BEBIG, model 6711 for COMS) on the basis of earlier work investigating backing composition¹⁰ and seed type¹¹; this is confirmed by the results (e.g., Table II).

Figure 6 provides a subset of dose results for a few BEBIG plaque diameters, contrasted with corresponding COMS plaques. Figure 6(a) demonstrates that when the doses are normalized to the dose at $z = 0.5$ cm on the plaque central axis (as an example prescription point), doses on the plaque central axis within the tumor ($z < 0.5$ cm) are slightly lower for BEBIG than for the corresponding COMS plaque (by less than 2% on average), and at the inner sclera the doses for BEBIG plaques are lower by 3.5% (12 mm), 3.4% (14 mm), 2.5% (16 mm), 2.9% (18 mm), and 2.8% (20 mm).

Figure 6(b) presents the ratio of HETERO/HOMO doses for a subset of BEBIG and COMS plaque sizes (¹²⁵I seed models: I25.S16 for BEBIG, 6711 for COMS), characterizing the heterogeneity effect due to the plaque. Over all plaque sizes, the dose ratio HETERO/HOMO is larger for BEBIG relative to COMS very near the plaque, but further from the plaque, the dose decrease is more substantial for BEBIG than COMS. These differences between BEBIG and COMS dose distributions result from a combination of effects due to plaque backing materials of different elemental compositions and densities, different insert mass densities, and distinct seed models.

The lower mass density of Silastic combined with the slightly higher average energy of the BEBIG I25.S16 seeds results in a slightly higher HETERO/HOMO dose ratio very near the plaque. Further away, the higher atomic number of predominant plaque components (Au, Pt) for BEBIG plaques results in larger dose decreases compared with COMS plaques (no Pt; Ag with Au, among other elements), in accord with previous results comparing pure gold backings with Modulay.¹⁰ Overall, the differences between HETERO/HOMO dose ratios for BEBIG and COMS are 2% or less, consistent with previous comparisons of plaque backings¹⁰ and seed models.¹¹

In a separate set of simulations, interseed attenuation is investigated for the BEBIG plaques (containing I25.S16 seeds) by comparison of HETERO simulations with and without interseed effects (eggs_brachy “normal” and “superposition” run modes, respectively). Interseed attenuation reduces doses by 0.5% (12 mm), 0.4% (14 mm), 0.3% (16 mm), 1.0% (18 mm), and 1.6% (20 mm) at the inner sclera and by 0.3% (12 mm), 0.2% (14 mm), 0.2% (16 mm), 0.2% (18 mm), and 0.5% (20 mm) at $z = 1$ cm. These relatively small differences between HETERO simulations with

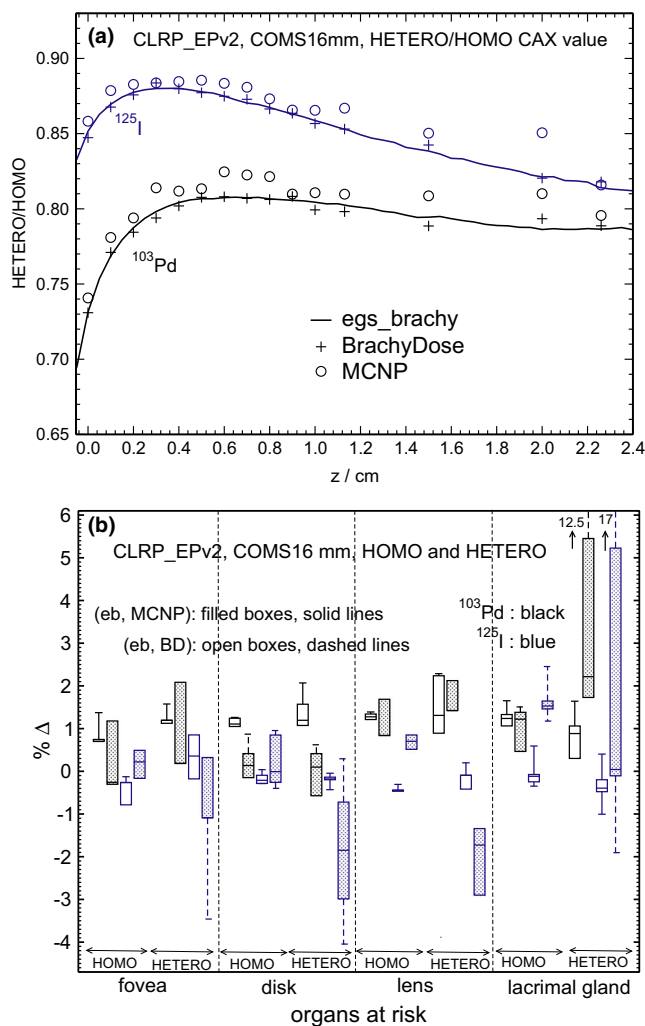


FIG. 5. Comparisons of results for 16 mm COMS plaques for (a) HETERO/HOMO ratio of doses along the central axis (for ^{103}Pd (200), ^{125}I (6711), ^{131}Cs (CS-1)) and (b) box-and-whisker summary of percent dose differences (egs_brachy (eb) compared with BrachyDose (BD) and MCNP) over eight different plaque positions considering four organs at risk and ^{103}Pd (200) and ^{125}I (6711) seeds.^{8,10} [Color figure can be viewed at wileyonlinelibrary.com]

and without interseed effects are in accord with previous work that considered other seed models.^{10,11}

Figure 7 summarizes the HETsi and HETsum results in comparison with HETERO and HOMO. The figures demonstrate that the HETsum dose distributions (obtained by superposition of HETsi results) are in excellent agreement with HETERO results (as expected).

2.C.3. Representative plaques

Figure 8 provides HETERO/HOMO dose ratios along the central axis for the representative plaques, comparing results to those from BrachyDose from previous work,^{1,14} as well as 16 mm COMS and BEBIG results for comparison. The egs_brachy and BrachyDose results are in good agreement, with percent differences of 0.1%–1.1% for $z \leq 0.5$ cm (assumed tumor apex) and between 0.1% and 4.5% beyond the tumor apex to the opposite side of sclera (where statistical

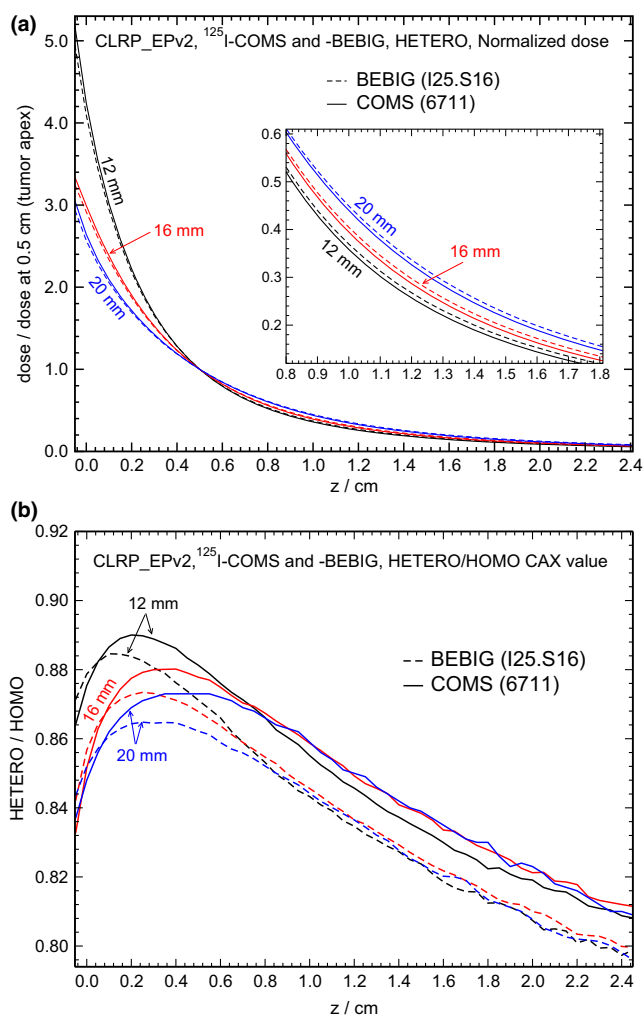


FIG. 6. Summary of results for BEBIG plaques with ^{125}I model I25.S16 seeds (dashed lines) compared with corresponding COMS plaques (containing ^{125}I model 6711 seeds) for 12, 16, and 20 mm plaque diameters for doses along the central axis (a) normalized to unity at $z = 0.5$ cm and (b) ratio HETERO/HOMO. Combined statistical uncertainties for HETERO/HOMO dose ratios are $\leq 0.2\%$. [Color figure can be viewed at wileyonlinelibrary.com]

uncertainties are larger). The smallest deviations overall are observed for the “Stainless steel – acrylic” (Ssa) plaque, with average deviations of 0.2% for $z \leq 0.5$ cm; conversely, the largest discrepancies are observed for “No-lip – Silastic” (NIS) with average deviations of 0.5% for $z \leq 0.5$ cm and 0.9% for larger z . The BrachyDose results for the HETERO/HOMO dose ratio are generally observed to fluctuate about the smoother lines presented by the egs_brachy results, in accord with the larger statistical uncertainties on the BrachyDose results (sub-1% for 1σ) in comparison with egs_brachy (sub-0.2%). Apart from differences in the number of histories used to generate results for egs_brachy and BrachyDose, there are also differences in the spectra of initialized particles, small differences in plaque dimensions (due to rounding in intermediate calculations to specify plaque geometries), and differences in the voxel scoring grid, as well as differences associated with the distinct codes as seen previously.^{8,17}

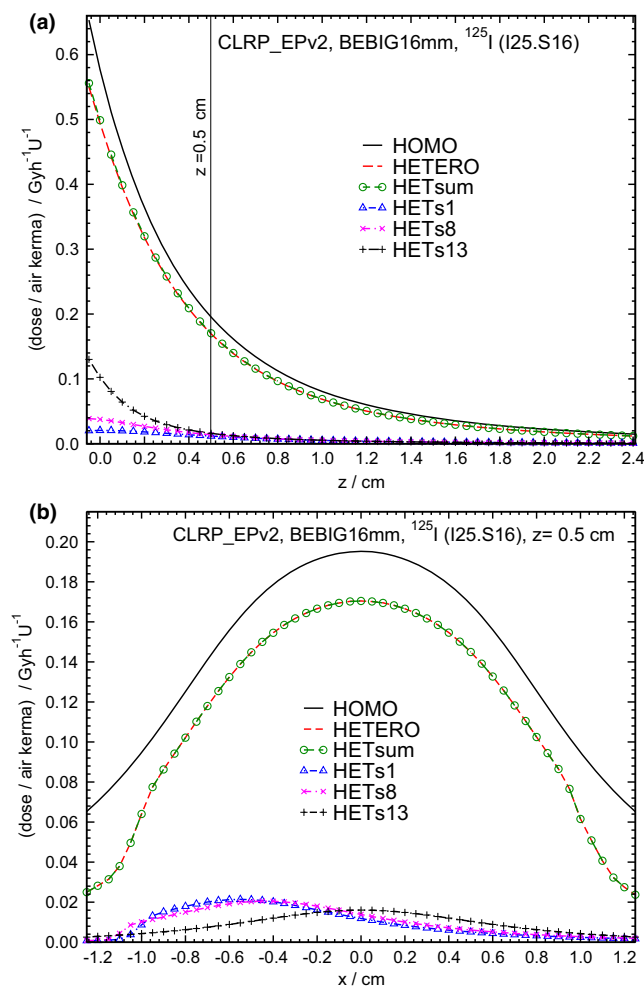


FIG. 7. Summary of 16 mm BEBIG (I25.S16) doses per unit seed air kerma strength for HOMO, HETERO, HETsum, and HETsi scenarios for (a) central axis and (b) transverse (x) axis at $z = 0.5$ cm. Note that central axis curves are identical for HETs1 to HETs7, HETs8 to HETs11, and HETs12 to HETs13, because the radial distance from the seed center to the z -axis is the same in each case. Statistical uncertainties are $\leq 0.2\%$ along the central axis. [Color figure can be viewed at wileyonlinelibrary.com]

Near the plaque (and sclera), the “Short lip – acrylic” plaque is observed to increase doses relative to HOMO doses, in accord with Lespérance et al.¹⁴ who attributed this to the combined effects of fluorescence photons from the plaque and less photon attenuation through the (short) acrylic insert (for HETERO simulations) in comparison with water (HOMO). For all other representative plaques, the HETERO/HOMO dose ratio is ≤ 1 near the plaque due to the lack of scatter and attenuation due to the plaque backing and insert. For all plaque models (and seed types), the dominant effect of the plaque is a reduction in backscattering from regions behind it. Scattered radiation accounts for more of the total dose in regions further from the plaque and so a reduction in the number of scattered photons when the plaque is present (in comparison with HOMO) causes decreasing HETERO/HOMO dose ratios with distance from the plaque.¹⁴

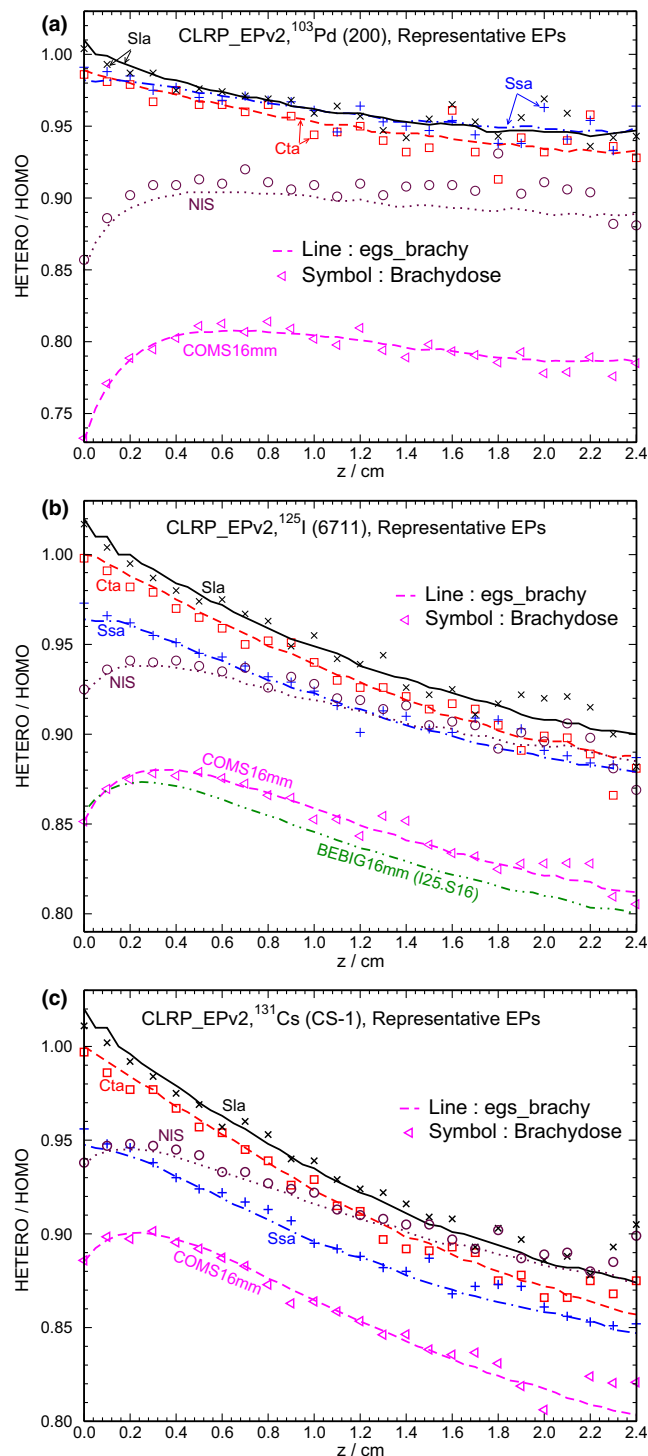


FIG. 8. Comparison of calculated HETERO/HOMO doses along the central axis for eggs_brachy (lines) and BrachyDose^{1,14} (symbols) for fully loaded representative plaques (Cta: COMS-thin acrylic; Sla: Short lip-acrylic; Ssa: Stainless steel-acrylic; NIS: No lip-Silastic) with 16 mm COMS and BEBIG results shown for comparison for (a) ^{103}Pd (model 200), (b) ^{125}I (model 6711; I25.S16 for BEBIG only), and (c) ^{131}Cs (CS-1 Rev2) seeds. Statistical uncertainties on the HETERO/HOMO dose ratio are at most 0.2% for eggs_brachy and 1% for BrachyDose.¹⁴ [Color figure can be viewed at wileyonlinelibrary.com]

3. DATA FORMAT AND ACCESS

The CLRP_EPV2 website is hosted at Carleton University, Ottawa, Ontario, Canada. The database is available online at https://physics.carleton.ca/clrp/eye_plaque_v2. The main page of the database lists the 17 plaques for which online datasets are available, as well as details about plaque and seed models, MC simulation scenarios and normalization, and a spreadsheet of HOMO and HETERO doses along the central axis with 0.05 cm resolutions. The CLRP_EPV2 database includes results from more than 100 independent *egs_brachy* simulations. For each plaque model, the following information is available on the CLRP_EPV2 database:

- An image showing the eye plaque cross section fully loaded with seeds in each of the Cartesian planes intersecting the origin, created using *egs_view* images of actual *egs++* model of the plaque and seeds.
- A description of the plaque model and seed coordinates according to publications and manufacturer information, as implemented in *egs++*. These models will be released for use with the open-source *egs_brachy* application.
- Files containing 3D dose distributions (*3ddose*) in a zipped format for HOMO and HETERO scenarios, as well as HETsi for BEBIG plaques. Doses are provided in units of dose rate per unit seed air kerma ($\text{Gy h}^{-1} \text{U}^{-1}$). The total dose (in Gy) in each voxel may be obtained by multiplying the data by the air kerma per seed (in units of U; $1 \text{ U} = 1 \text{ cGy cm}^2 \text{ h}^{-1}$), and integrated over the treatment time, taking the exponential decay of the sources into account. Statistical uncertainties (1 sigma) on the dose in each voxel are also included in the *3ddose* file (as fractions of the voxel's dose).
- A figure for the depth dose curve along the plaque central axis compared to the available BrachyDose^{1,2,10,11,14} and MCNP^{8,9} data for HOMO and HETERO scenarios in units of dose/air kerma ($\text{Gy h}^{-1} \text{U}^{-1}$) for different seeds (where data are available).
- A figure comparing *x, y* transverse dose profiles at different depths ($z = 0.5, 1 \text{ cm}$) for HOMO and HETERO doses with the available corresponding values from CLRP_EPV1 simulated with BrachyDose^{1,2,10,11,14} (where data are available). For BEBIG plaques, data for HETsi scenario are presented.
- For the 16 mm COMS plaque, a figure that summarizes percent dose differences of *egs_brachy* with BrachyDose¹⁰ or MCNP⁹ along the central axis and at some organs at risk (e.g., fovea, optic disk, lens, and lacrimal gland).⁸
- A figure comparing the ratio of HETERO/HOMO doses along the central axis with corresponding BrachyDose^{1,14} data for each representative plaque (Cta, Sla, Ssa, and NIS) and different nuclide (e.g., ¹⁰³Pd, ¹²⁵I, ¹³¹Cs).

4. POTENTIAL IMPACT

The most recent AAPM task group reports pertaining to eye plaque brachytherapy, namely TG-129² and TG-221,¹ recommend that HETERO doses be calculated (or estimated) and reported in parallel with the traditional water-based (HOMO) TG-43 doses. These recommendations are consistent with the recommendations of AAPM-ESTRO-ABG TG-186, namely adoption of model-based dose calculations where possible and reporting of their doses alongside TG-43. Thus, the publicly available 3D dose distributions and associated data provided in CLRP_EPV2 for each plaque and seed support TG-129, 221, and 186 recommendations, enabling HETERO dose estimations and MC dose evaluations. Furthermore, the plaque models developed herein will be distributed freely with *egs_brachy*, as will the seed models that are documented within the CLRP_TG43v2¹⁸ database (https://physics.carleton.ca/clrp/egs_brachy/seed_database_v2). The models may be used to carry out custom calculations within user-specified phantoms, including virtual patient models derived from patient (CT) datasets. In addition, the eye plaque models may then be modified by users to develop models representative of their own practice. Overall, the dose distributions and freely distributed *egs_brachy* plaque models support state-of-the-art dose evaluations for ocular brachytherapy.

5. CONCLUSION

The CLRP_EPV2 database offers accurate 3D dose distributions for more plaque models and radionuclides, plus lower statistical uncertainties than CLRP_EPV1. The CLRP_EPV2 database contains new datasets for 17 plaques (eight COMS, five BEBIG, and four representative plaques) and three radionuclides [¹⁰³Pd, ¹²⁵I (2 seed models), and ¹³¹Cs], including both HOMO and HETERO (also HETsi for BEBIG) scenarios. The CLRP_EPV2 data are validated by comparison with BrachyDose and MCNP published data, for the plaque models for which such data exist: COMS plaque data are in good accord with previous BrachyDose and MCNP results, and representative plaques agree with previous BrachyDose results. For example, on the plaque central axis HETERO doses agree within 2% for BrachyDose and 5% for MCNP for COMS plaques, while doses agree within 4.5% with BrachyDose for the representative plaques. The BEBIG plaques, modeled for the first time, differ only in media (elemental composition, density) from the COMS plaques, and differences in the relative HETERO/HOMO dose ratios may be understood on the basis of the higher atomic number content of the BEBIG plaque backings in comparison with COMS, the lower density of the seed-carrier insert, as well as the differences in emitted photon spectra [¹²⁵I : I125.S16 for BEBIG, 6711 for COMS]. The HETsi dose distributions offer the potential for users to tally dose distributions with different weights for custom-loading plaques with seeds of different activities. The CLRP_EPV2 database provides reference 3D

dose distributions that support the recommendations of AAPM TG-129 and TG-221. The reference 3D dose distributions and benchmarked egs_brachy (MC) models of plaques and seeds will be freely distributed at (https://physics.carleton.ca/clrp/eye_plaque_v2), enabling advances in ocular brachytherapy research, dosimetry, and clinical practice.

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CONFLICT OF INTEREST

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