Monte Carlo end-to-end validace dozimetrie v radionuklidové terapii

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Dosimetry in clinical practice

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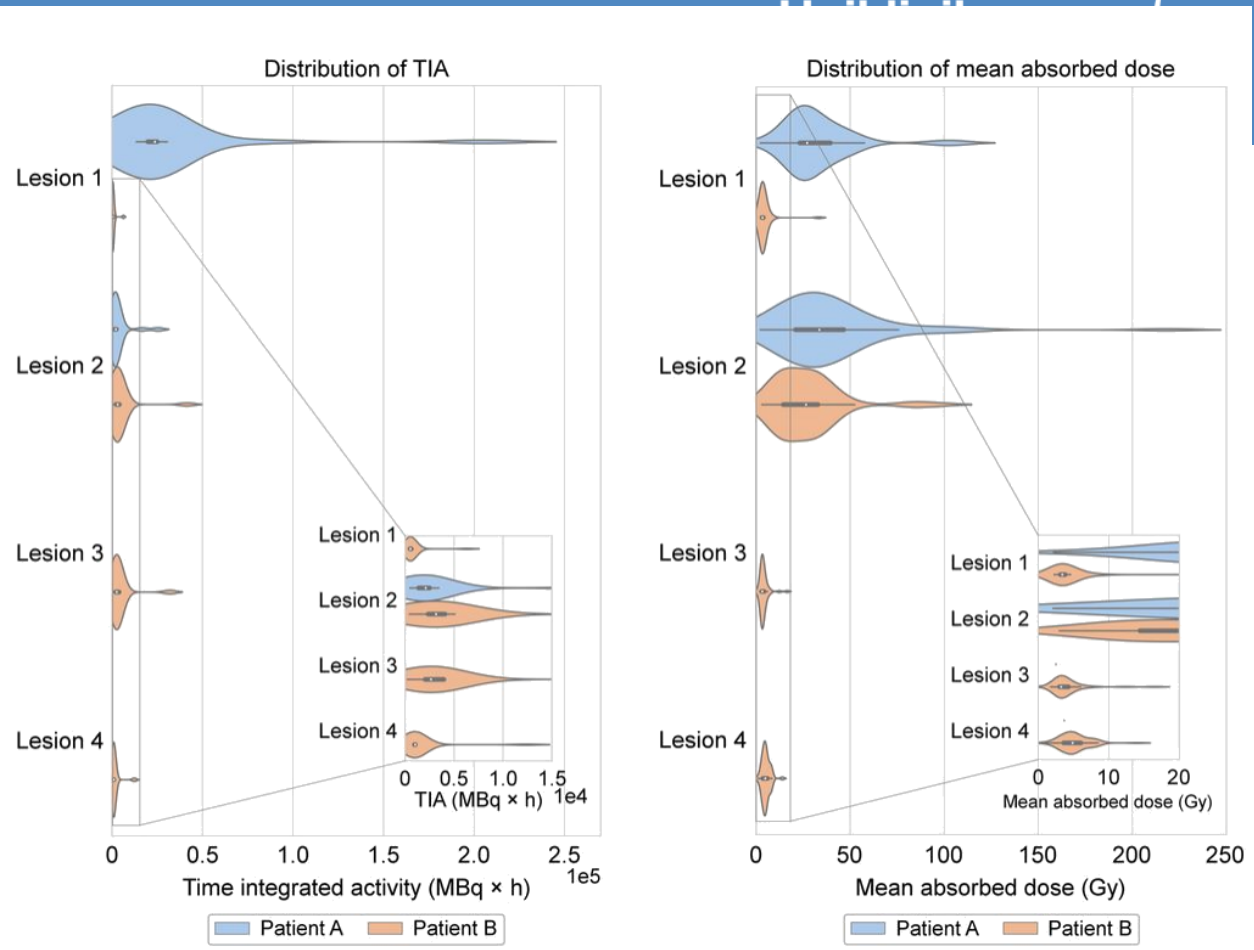
- Potential of dosimetry
  - Individualization of treatment
  - Adjustment of administered activity for subsequent treatment cycles
  - Possibility of early termination when dose thresholds are reached
- Current practice
  - not a standard part of clinical decision-making
  - Main reasons:
    - Low demand from physicians
    - **Lack of standardization**

Variability in dosimetry

- Varying approaches
  - Quantitative SPECT calibration
  - Absorbed dose calculation
  - Tumor/organ segmentation
  - Partial volume correction
  - Time-activity integration
- Concerns for dosimetry accuracy and reproducibilty
- **Need for dosimetry validation**



[1] Uribe et al., J. Nucl Med 2021; 62(Suppl 3)

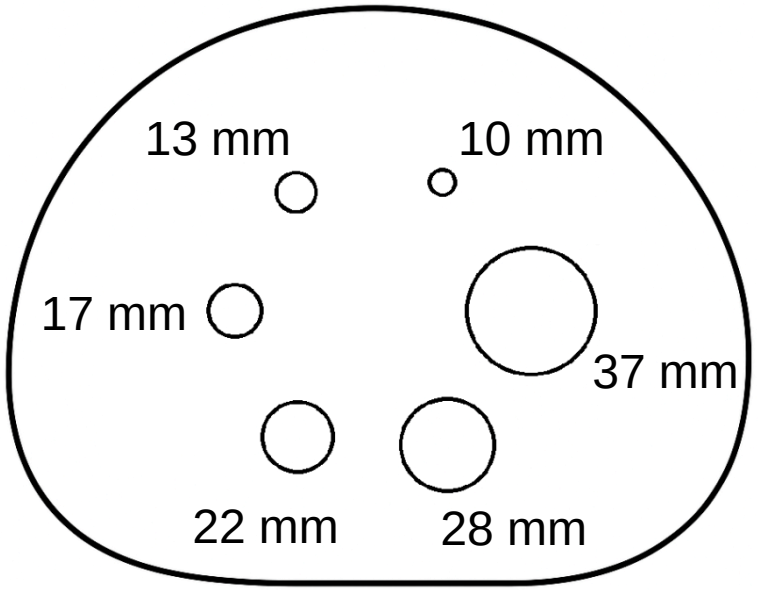
[1]

Aim

- Development of standardized reference method for end-to-end validation of clinical dosimetry
  - Use of widely available imaging phantom
  - Providing reference dosimetry data
  - Range of therapeutical radionuclides
  - Simple methodology
  - Enabling any filling activity concentration and any lesion-to-background ratio

Validation protocol

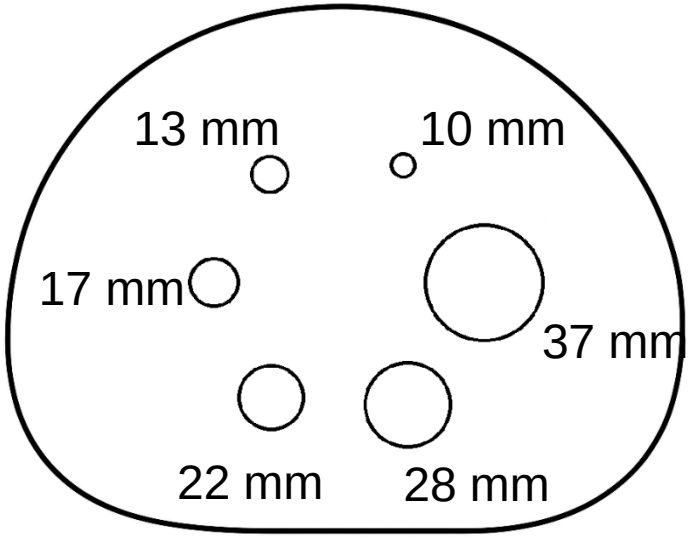
- NEMA IEC Body phantom
  - No lung insert
  - Standard set of spheres
- Radionuclides:
  - ^{177}Lu, ^{131}I, ^{90}Y, ^{67}Cu, ^{186}Re, ^{153}Sm, ^{161}Tb

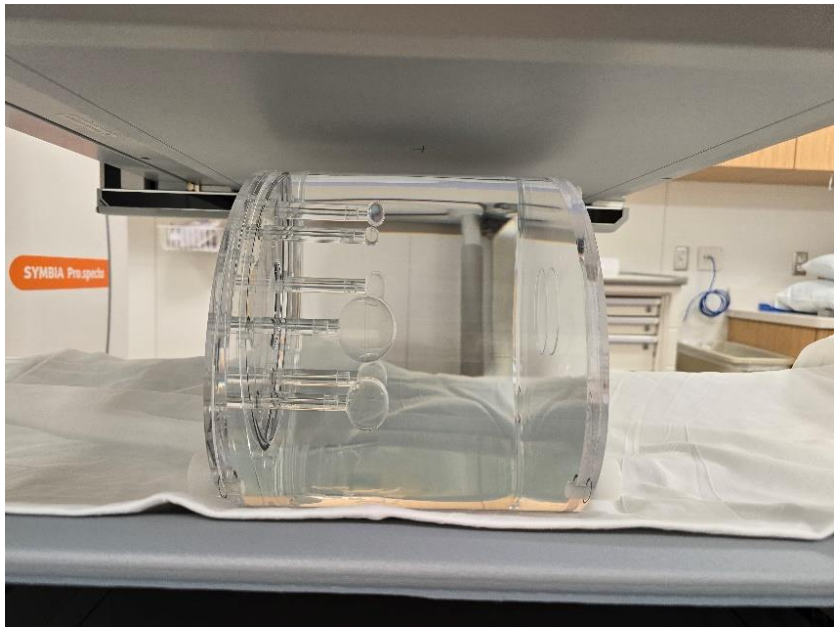


- Procedure:
  1. Fill NEMA phantom
     - Activity lesion-to-background ratio representative for patient population
  2. Acquire scans
     - Use clinical protocol + reconstruction
     - At least 3 scans over 2 half-lives
  3. Calculate absorbed dose
     - Use clinical dosimetry method
  4. Calculate reference absorbed dose
     - Scale reference data by activity concentrations used
  5. Compare

Reference dosimetry

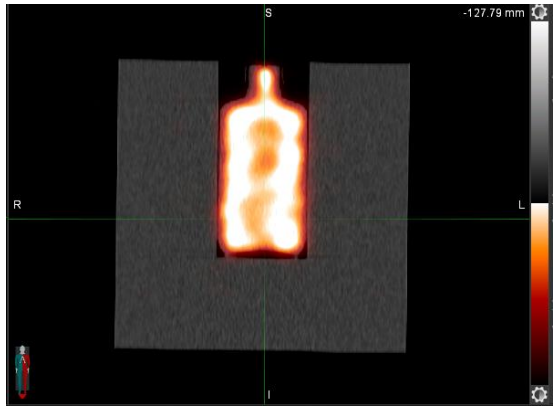
- MCNP 6.2
- *F8 tally in all inserts and background
- 10^9 source particles per emmission mode (photons, discrete energy electrons and beta particles)
- sampling efficiency 0.1%
- 2 scenarios:
  - Activity in inserts only
  - Activity in background only
- Apply branching ratios and compartment mass to get mGy/MBq*h





Experimental dosimetry

- Phantom filling
  - ^{177}Lu-PSMA (no ^{117m}Lu)
  - Capintec CRC-55tR traceable to NIST
  - 2,0 MBq/ml in inserts → 6 scans
  - Add background (8:1) → 7 scans
- SPECT/CT imaging
  - Siemens Pro.specta + BroadQuant calibration
  - Siemens Symbia Intevo + calibration with water-equivalent solid phantom



Acquisition parameter	Siemens Pro.Specta	Siemens Symbia Intevo
Energy window	208 keV ± 10%	208 keV ± 10%
Scatter window	10% upper and lower	10% upper and lower
Collimator	MELP	MELP
Number of projections	60 per detector head	60 per detector head
Time per projection	15 s	15 s
Orbit	Noncircular, 360°	Noncircular, 360°
Gantry rotation	Continuous	Continuous
Matrix size	128x128 (projection) 256x256 (reconstructed)	256x256
Zoom	1.00	1.23
Reconstruction	OSCGMM: 8i6s, 3 mm Gaussian filter	Flash3D: 12i8s, 3 mm Gaussian filter
Attenuation correction	CT-based	CT-based
Scatter correction	TEW	TEW
Resolution recovery	Enabled	Enabled
CT protocol	Sn 130kV, 0.80 pitch, 0.8 s/rotation, FAST kV IQ level 5, Qr40 3 mm slice, 512x512	130 kV, 0.75 pitch, 0.8 s/rotation, CareDose4D quality ref. 60 mAs, B31s medium smooth+, 3 mm slice, 512x512

Absorbed dose calculation – no background

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- S-value dosimetry
  - IDAC v2.1 and OLINDA v2.2 (sphere module), MIRD Calc v1.1 (tumor source tissue)
  - Assuming 1MBq/ml, nominal sphere volume
  - Absorbed dose calculated to:
    - IDAC and OLINDA: to water
    - MIRD Calc: to soft tissue (1,03 g/ml) and corrected for density
  - Calculated absorbed doses scaled by TIAC measured in MIM
- MIM SurePlan MRT v7.3.2 (next slide)

Absorbed dose calculation – 8:1

- MIM SurePlan MRT v7.3.2
  - SPECT-to-SPECT alignment
  - Segmentation on reference CT
  - Organ level fitting, function selected based on AIC (one or two exponentials)
  - Integrating from 0 to infinity
  - TIA convolution with VSV kernel to get dose map
  - CT-based density correction
  - Partial volume correction
    - Expanded VOI for no background scenario
    - Recovery curve for 8:1 scenario

Results – MC reference dosimetry

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Absorbed dose to target VOI per activity concentration in the source compartment [Gy/(MBq/ml)]								
Source	**Target VOI**	**^{177}Lu**	**^{131}I**	**^{90}Y**	**^{67}Cu**	**^{186}Re**	**^{153}Sm**	**^{161}Tb**
Spheres	10 mm	18,77	30,09	31,06	7,76	21,96	10,22	26,40
	37 mm	19,43	33,34	44,21	8,15	24,31	10,85	27,45
	Bkgd	2,82E-03	3,95E-02	9,33E-03	3,63E-03	1,39E-03	2,17E-03	5,05E-03
Background	10 mm	1,53	21,9	13,1	1,96	1,08	1,17	2,76
	13 mm	1,53	21,8	10,9	1,96	0,99	1,17	2,81
	17 mm	1,59	22,6	8,46	2,05	0,92	1,22	2,87
	22 mm	1,55	21,8	6,69	1,99	0,81	1,18	2,78
	28 mm	1,52	21,5	5,33	1,96	0,76	1,17	2,71
	37 mm	1,51	21,0	4,04	1,94	0,71	1,17	2,68
	Bkgd	20,2	41,8	48,0	8,97	25,1	11,4	28,8

Example: ^{177}Lu, 8:1, 0,46 MBq/ml in spheres

Dose to 37 mm sphere:

Spheres contribution + Background contribution

D = [0,46 MBq/ml * 19,43 Gy/(MBq/ml)] + [0,06 MBq/ml * 1,51 Gy/(MBq/ml)] = 9,03 Gy

Results – MC reference dosimetry

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Absorbed dose to target VOI per activity concentration in the source compartment [Gy/(MBq/ml)]								
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Spheres	10 mm	18,77	30,09	31,06	7,76	21,96	10,22	26,40
	13 mm	18,94	30,64	34,89	7,84	22,68	10,39	26,64
	17 mm	19,09	31,27	38,15	7,92	23,26	10,53	26,87
	22 mm	19,22	31,92	40,67	8,00	23,69	10,65	27,08
	28 mm	19,33	32,60	42,54	8,07	24,02	10,75	27,26
	37 mm	19,43	33,34	44,21	8,15	24,31	10,85	27,45
	Bkgd	2,82E-03	3,95E-02	9,33E-03	3,63E-03	1,39E-03	2,17E-03	5,05E-03
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Results – MC reference dosimetry

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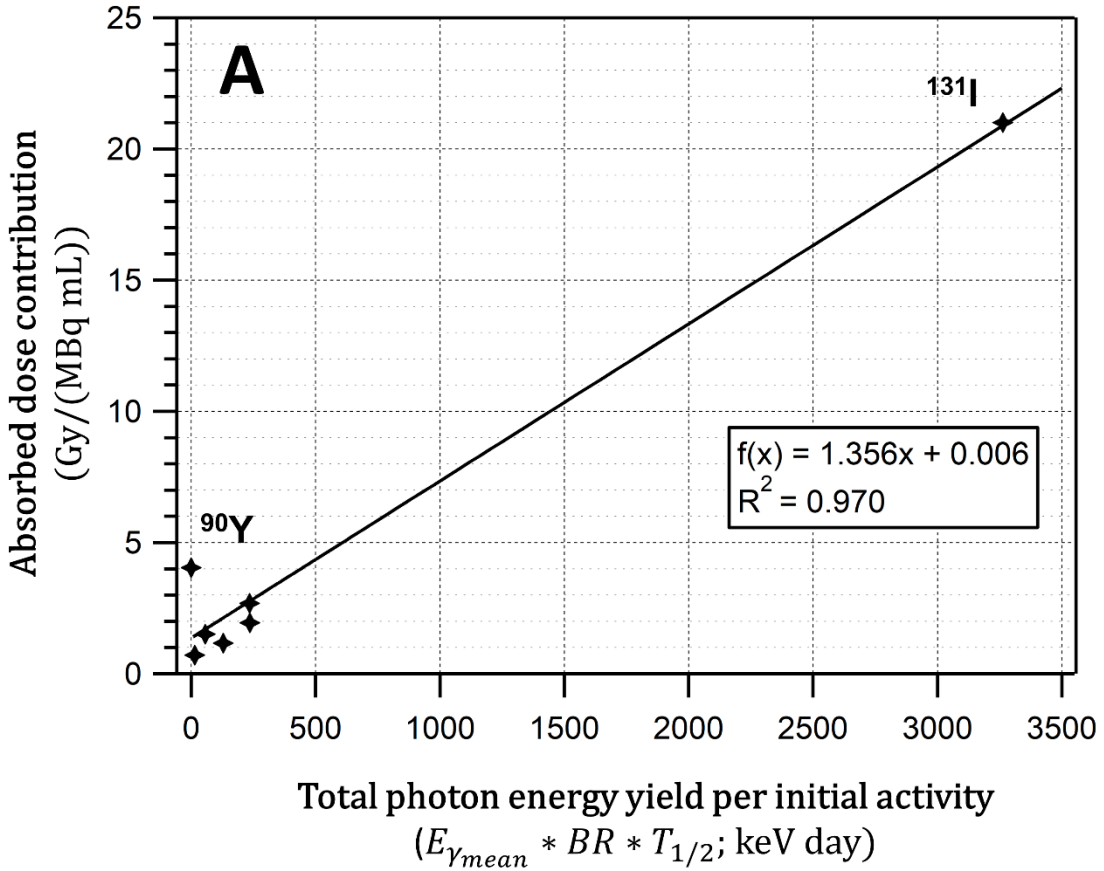
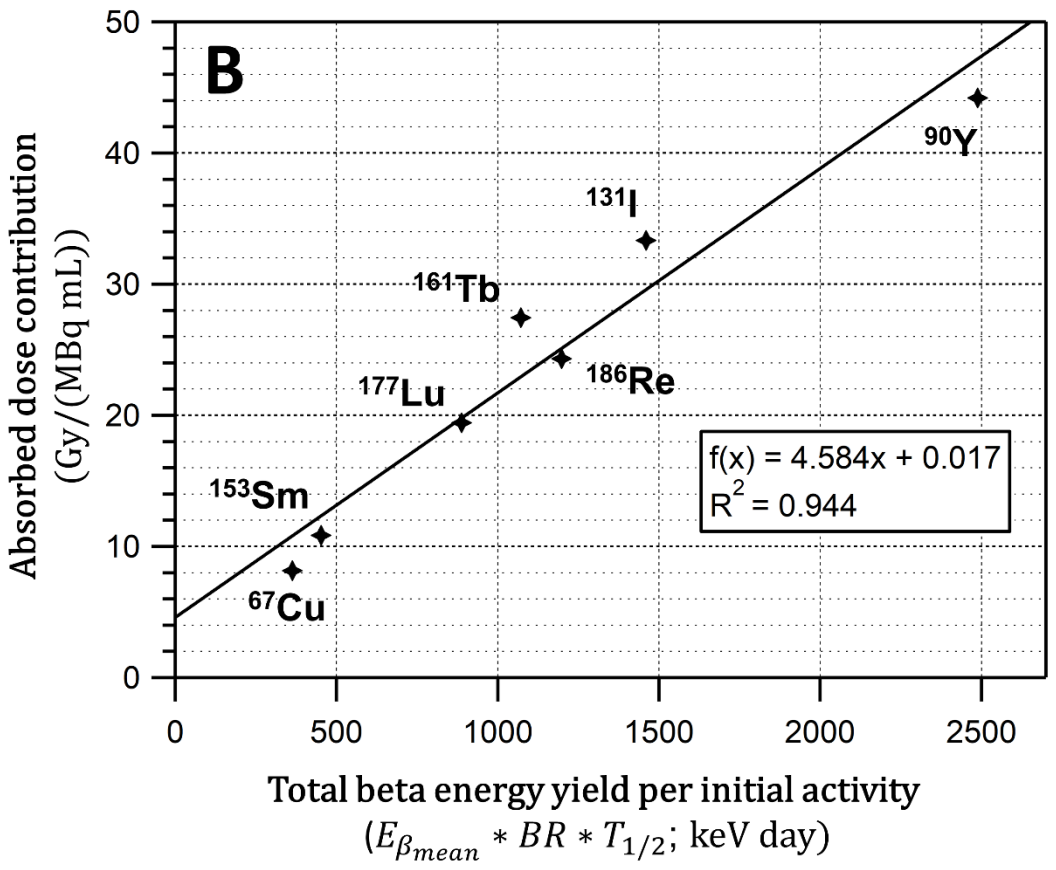
Activity in background



Activity in spheres



Results – Experimental dosimetry

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- MC dosimetry vs. S-value dosimetry

Relative deviations (%) – All radionuclides						
	10 mm	**13 mm**	**17 mm**	**22 mm**	**28 mm**	**37 mm**
OLINDA	3.24	3.07	2.13	1.56	1.06	0.86
MIRD Calc	0.06	-0.08	0.07	-0.04	-0.09	0.02
IDAC	-0.42	0.82	1.25	-0.32	1.83	1.44

Relative deviations (%) – 177Lu						
	10 mm	**13 mm**	**17 mm**	**22 mm**	**28 mm**	**37 mm**
OLINDA	2.38	2.65	2.13	1.81	1.70	1.55
MIRD Calc	1.52	1.70	1.96	1.82	1.79	1.77
IDAC	1.18	2.40	2.81	1.13	3.36	2.89

Results – Experimental dosimetry

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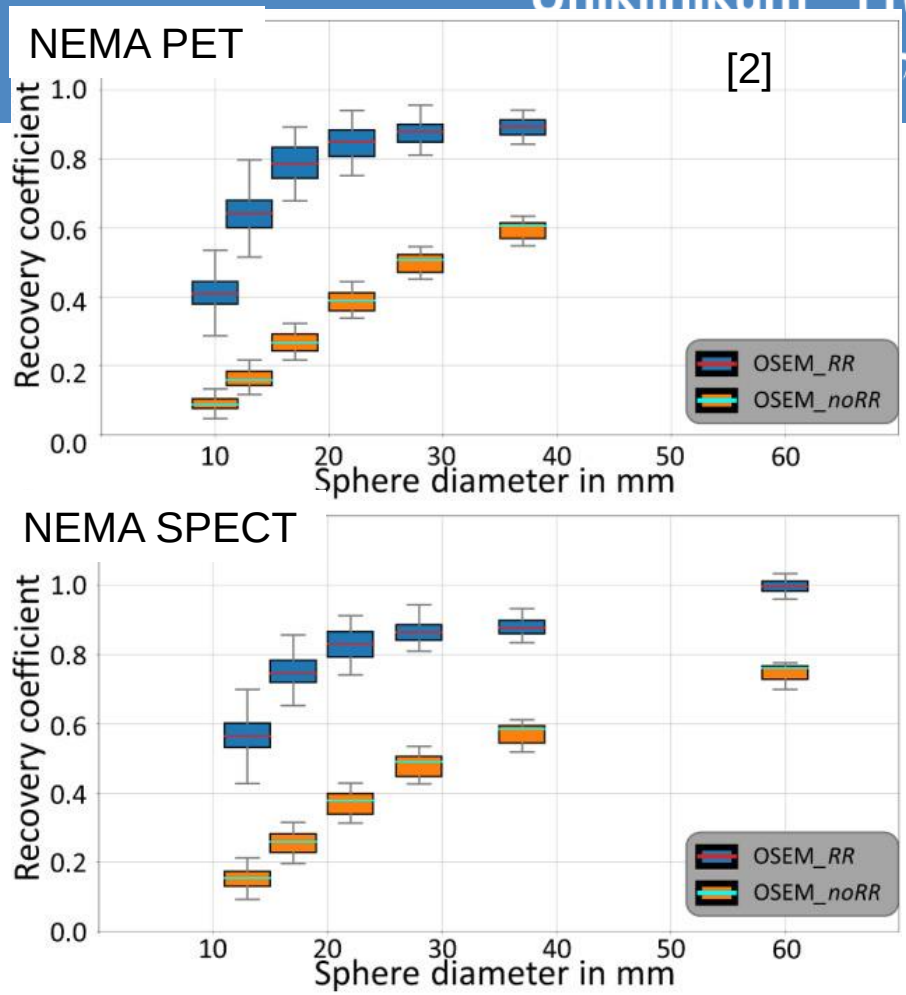
- MC dosimetry vs. MIM

Relative deviations (%) – 177Lu								
		10 mm	**13 mm**	**17 mm**	**22 mm**	**28 mm**	**37 mm**	**Bkgd**
Intevo	No bkgd	-30.4	-22.1	-13.3	-8.1	1.4	4.4	
	8:1	-36.6	-27.6	-38.6	-24.4	-15.3	-19.3	-4.3
Pro.Specta	No bkgd	-5.4	-6.4	4.7	8.1	14.1	14.8	
	8:1	-6.5	-4.4	21.9	-0.4	6.7	4.0	-11.2

Limitations

- Physical decay only
- Spherical lesions only
- Sigle-timepoint dosimetry preferred clinically
  - Acquire more scans for validation anyway:
    - enables testing the remaining aspects + easier investigation of discrepancies
    - Single-timepoint approach can be tested in parallel
- Be aware: sphere order matters for reconstruction [2]



[2]

[2] Leube et al., EJNMMI Phys 2024; 11(1)

Conclusions

- Presented simple methodology for end-to-end validation of clinical dosimetry using IEC NEMA Body Phantom
  - Monte Carlo reference dosimetry data provided
- Highlighted variability among dosimetry software tools
- Harmonization of practices is necessary to improve accuracy and reproducibility of dosimetry

Results – MC reference dosimetry

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