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## Research Article

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# Performance Characterization of a Thin-Walled Well Ionization Chamber for Yttrium-90 Resin Microspheres

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## Abstract

An in-house thin-walled well ionization chamber and low-current readout system were characterized by Monte Carlo simulation and experiment to assess their direct beta response to yttrium-90 resin microspheres. Beta-related transport accounted for 99.161% of simulated energy deposition. Absolute leakage current was below 30 fA, and short-term relative standard deviations were below 1%. The response decreased markedly with added wall thickness, consistent with beta-dominated detection. The measured thickness-response curve provides a basis for investigating corrections under specified material and geometric conditions; correction accuracy and activity calibration remain to be established.

## Article Highlights

- Thin electrodes allow electrons from yttrium-90 resin microspheres to enter the sensitive gas directly.
- Simulations and added-wall tests indicate that beta-related transport dominates the chamber signal.
- Good short-term repeatability and a thickness-dependent response support further study of relative corrections.

**Keywords:** Yttrium-90 resin microspheres; Beta radiation; Well ionization chamber; Monte Carlo; Performance testing

# 1 Introduction

Reliable activity measurements are required during preparation and administration of yttrium-90 ( $^{90}\text{Y}$ ) resin microspheres for hepatic radioembolization [1, 2]. Measurements of the pre-administration activity and post-administration residual activity help estimate the activity delivered to the patient and support absorbed-dose assessment [3, 4]. Measurement procedures and calibration relationships should correspond to the source container, filling volume, and sample position within the detector [5].

Yttrium-90 is an almost pure beta emitter with a maximum beta energy of approximately 2.28 MeV and a negligible prompt gamma-ray contribution for routine activity measurement [6]. In commonly used pressurized re-entrant ionization chambers, the source vial, holder, and inner chamber wall attenuate emitted electrons. The  $^{90}\text{Y}$  signal is therefore generated mainly by bremsstrahlung photons and the secondary electrons they produce; the relative electron and photon contributions depend on the chamber design and measurement configuration [7, 8]. Studies of resin microspheres have reported effects of vial differences, filling volume, and source distribution on the response [9–11]. These effects are not equally pronounced in all configurations. For example, studies of  $^{90}\text{Y}$  solutions in specific syringe and radionuclide-calibrator combinations found small volume effects or no need for a separate volume correction over the ranges examined [12, 13]. A correction established for one configuration cannot therefore be applied directly to another.

Conventional radionuclide calibrators can be used for routine  $^{90}\text{Y}$  measurements after calibration under specified geometric conditions, but the applicability of generic calibration settings still requires verification. An international multicenter study reported that approximately 61% of  $^{90}\text{Y}$  activity readings differed from the reference value by more than  $\pm 5\%$ , and approximately 25% differed by more than  $\pm 10\%$  [14]. For resin microspheres, activity standardization and standard transfer have been used to determine calibration factors for specific products, vial types, and measurement conditions [9, 10, 15, 16]. These findings indicate that the evaluation of a dedicated detector should address both the response mechanism and the effects of practical measurement geometry.

The well ionization chamber investigated here uses thin, low-atomic-number electrodes to increase the electron contribution to the signal. The inner high-voltage electrode and collecting electrode are both made of 0.15 mm aluminized polyimide, with an air-sensitive volume on each side of the collecting electrode. This arrangement is intended to reduce attenuation along the electron path, allowing beta particles and their charged secondary particles that emerge from the source vial to deposit energy directly in the sensitive gas. Placing the collecting electrode between the inner and outer high-voltage electrodes was also intended to reduce its exposure to air disturbances during

sample insertion. Because electrons must still pass through the vial and liquid before reaching the sensitive volumes, wall thickness and filling conditions remain relevant to detector performance.

This study combines Geant4 simulations and experimental measurements to characterize the thin-walled well ionization chamber and its low-current readout system. The simulations distinguish beta-related transport from bremsstrahlung contributions to the ionization signal. Experiments examine leakage current, electronic measurement ranges, repeatability, saturation behavior, and geometric response. The measured wall-thickness response is then used to discuss the potential for relative response corrections under specified material and measurement conditions.

## **2 Materials and methods**

### **2.1 Ionization chamber and readout system**

The chamber contains two concentric air-sensitive volumes surrounding a central well (Fig. 1). A bias voltage is applied to the inner and outer electrodes, while the intermediate electrode collects charge from both sensitive volumes. The inner high-voltage electrode and collecting electrode are made of 0.15 mm aluminized polyimide. A guard electrode at the signal feedthrough diverts surface leakage current away from the collecting electrode. The collecting electrode is connected to the low-current meter through polyether ether ketone (PEEK) insulators and a triaxial cable. The three conductors carry the signal, guard potential, and grounded shield, respectively. The measured current is the sum of the responses of the two sensitive volumes.

The nominal diameters of the inner high-voltage electrode, collecting electrode, and outer high-voltage electrode are 40, 117, and 200 mm, respectively, and their heights are 338, 377, and 417 mm. The outer high-voltage electrode is made of 2 mm aluminum. The combined sensitive volume is approximately 12670 cm<sup>3</sup>. The enclosure has a diameter of 252 mm and a height of 456 mm. Shielding comprises 15 mm polyoxymethylene and a composite layer of 2 mm stainless steel, 5 mm lead, and 2 mm stainless steel.

The three-range readout system uses an ADA4530 electrometer amplifier with feedback resistances of 100 G $\Omega$ , 100 M $\Omega$ , and 100 k $\Omega$ . After differential conditioning by an AD8421 and buffering by an ADA4898, the signal is digitized by a 24-bit AD7172 analog-to-digital converter, with digital isolation provided by an ADUM3151. An STM32L431VCT6 microcontroller handles data acquisition, range switching, and high-voltage control. An RK3568-based Linux host provides display, zero adjustment, calibration, background subtraction, charge integration, and data storage.

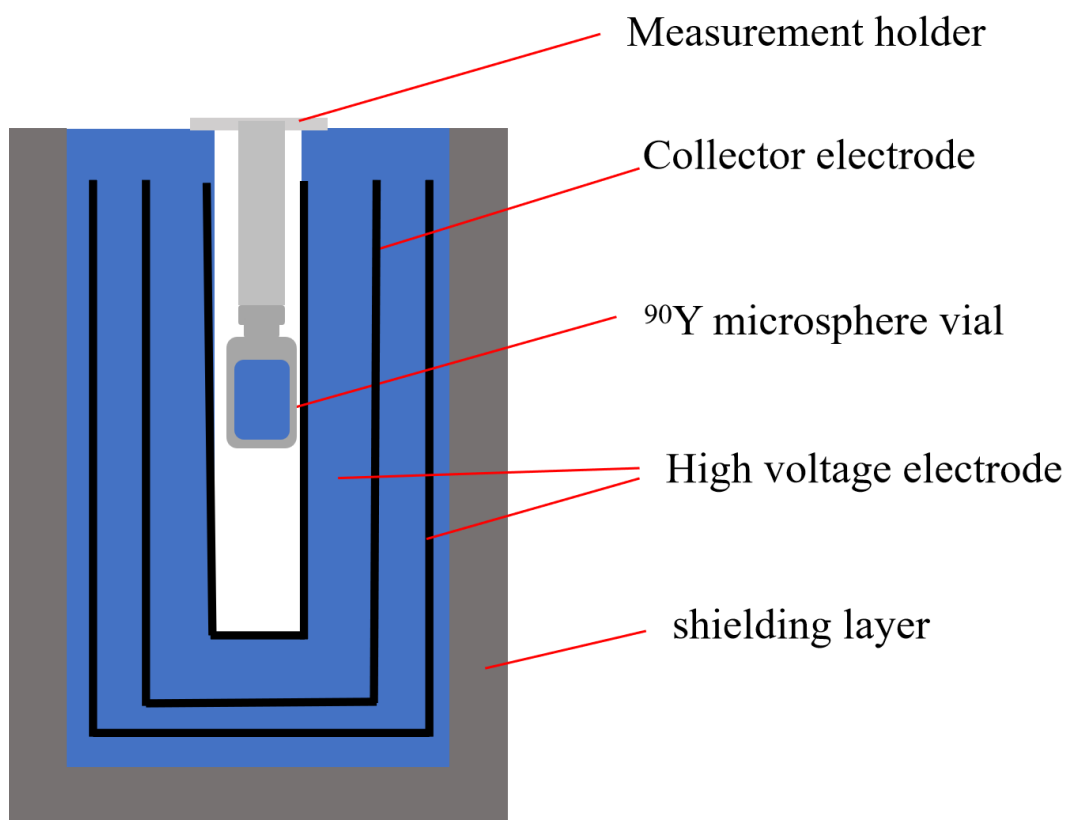


**Fig. 1** Cross-sectional schematic of the thin-walled well ionization chamber

## 2.2 Radioactive source and measurement geometry

The activity of the  $^{90}\text{Y}$  resin microsphere source was approximately 1 GBq at the start of the source measurements. The source was measured in the original vial supplied by the manufacturer. Each repeatability series was completed over a short interval; mean readings obtained on different dates were not used to assess long-term stability. Three-dimensional-printed polylactic acid (PLA) sleeves increased the material thickness around the vial in 1 mm increments. The PLA density was approximately  $1.2 \text{ g cm}^{-3}$ . In the liquid-height experiment, diluent was added to change the liquid column height while keeping the total  $^{90}\text{Y}$  activity constant.

## 2.3 Monte Carlo model

The chamber was modeled using Geant4 11.4.2 patch-02 [17, 18]. The model included the central well, thin electrodes, two air-sensitive volumes, a 0.5 mm aluminum base plate, and external aluminum, polymer, and lead shielding. Mechanical assembly details with minor effects on particle transport were simplified. Vial dimensions were obtained by computed tomography (CT). The glass wall and liquid region were imported as separate tessellated solids using CADMesh [19]. Yttrium-90 was distributed uniformly in water. Individual microspheres were not modeled, and sedimentation, aggregation, and microscopic self-absorption were not represented.

Radioactive decay and electromagnetic transport processes were enabled, including multiple scattering, fluorescence, and Auger processes. The high-statistics calculation used  $10^8$   $^{90}\text{Y}$  decays. Energy deposition was scored separately in the inner and outer air-sensitive volumes and converted to equivalent charge using the mean energy required to form an ion pair in air [20]. Complete charge collection was assumed, without accounting for electric-field nonuniformity, recombination, or attachment. The calculated charge therefore represents the detector response under idealized model conditions.

## 2.4 Scoring beta and bremsstrahlung contributions

Energy deposition was classified according to particle production processes and ancestry. When an electron emitted a bremsstrahlung photon, that photon initiated a bremsstrahlung branch. The photon and all its descendants retained this classification, including electrons produced by the photoelectric effect, Compton scattering, or pair production. Subsequent energy deposition by the electron that emitted the photon remained assigned to the beta contribution. If that electron emitted another bremsstrahlung photon, the new photon initiated a separate photon branch. Energy deposition outside the bremsstrahlung branches was assigned to the beta contribution. This definition includes

primary beta particles and their charged secondary particles, rather than only the original decay electrons. Throughout this paper, the photon contribution refers to bremsstrahlung photons and their descendants.

## **2.5 Electrical tests and radioactive-source measurements**

After a 30 min warm-up, leakage current was measured by charge integration at  $-400$  V. A Keithley 6430B current source was used to test the readout response from 30 fA to 50  $\mu$ A and to examine response compression in each of the three ranges. The lowest input was comparable in magnitude to the leakage current and was treated only as an electronic test point, not as a detection limit.

Before source measurements, the system was warmed up for 30 min, with the holder and readout settings fixed. Four repeatability series were acquired, each comprising ten consecutive readings. Saturation curves were measured from 50 to 500 V in 50 V increments with the vial center positioned 7.85, 12.85, 17.85, 22.85, 27.85, and 32.85 cm below the chamber top. An axial scan was performed at 400 V using the first five of these positions. Added PLA thickness ranged from 0 to 3 mm, and liquid height was increased in 1 mm increments. Only one geometric parameter was varied in each experiment.

## **2.6 Data analysis**

Repeatability was expressed as the relative standard deviation (RSD), calculated by dividing the sample standard deviation by the mean indicated current and expressing the result as a percentage ( $n = 10$  per series). Electronic range coverage was assessed from the onset of response compression in the input–output curves. An exponential function was fitted to the four added-wall-thickness measurements. This fit describes only the response of the vial and PLA-sleeve configuration tested; the fitted attenuation parameter was not treated as a universal material attenuation coefficient.

# **3 Results**

## **3.1 Beta and bremsstrahlung contributions**

Beta-related transport accounted for 99.296% of the signal in the inner sensitive volume and 99.030% in the outer volume (Table 1). For the combined response, the beta and bremsstrahlung contributions were 99.161% and 0.839%, respectively. Energy deposition in both sensitive volumes was thus dominated by beta-related transport in the modeled geometry.

**Table 1** Beta-related and bremsstrahlung contributions to the simulated ionization signal

| Sensitive volume | Beta (%) | Bremsstrahlung (%) |
|------------------|----------|--------------------|
| Inner            | 99.296   | 0.704              |
| Outer            | 99.030   | 0.970              |
| Combined         | 99.161   | 0.839              |

The bremsstrahlung contribution includes photons and all their descendants. The beta contribution includes primary electrons and charged secondary particles outside those photon branches. These fractions apply to the geometry modeled in this study.

### 3.2 Leakage current and electronic measurement ranges

Leakage current was measured to assess its effect on radioactive-source measurements. After the connectors were cleaned and the cable configuration was established, ten readings at  $-400$  V ranged from  $-26.8$  to  $-5.0$  fA (Fig. 2), all below 30 fA in absolute value. Leakage current was small compared with the currents of several hundred picoamperes measured in the source experiments, although its contribution remained relevant near the lowest electronic test input.

Known input currents were applied to assess the operating ranges of the readout electronics. The low-range output increased up to an input of approximately 50 pA and then approached saturation (Fig. 3). The medium- and high-range channels exhibited response compression above approximately 40 nA and 40  $\mu$ A, respectively (Figs. 4 and 5). The three tested ranges, 30 fA–50 pA, 1 pA–40 nA, and 1 nA–40  $\mu$ A, overlapped and covered approximately nine orders of magnitude. A factor-of-two voltage division between the buffer stage and the analog-to-digital converter affected the uncalibrated readings. These curves therefore characterize electronic range coverage and do not establish calibrated accuracy over the full range.

### 3.3 Repeatability and saturation behavior

Repeatability was measured at 400 V with the vial center fixed 22.85 cm below the chamber top. The means and standard deviations of four series of ten measurements were  $1264.2 \pm 6.8$ ,  $471.0 \pm 0.9$ ,  $445.3 \pm 1.1$ , and  $272.5 \pm 2.5$  pA (Fig. 6). The corresponding RSDs were 0.54%, 0.18%, 0.25%, and 0.92%, all below 1%. These results describe short-term repeatability within each series. Because the series were acquired at different times and activities, differences between their means were not used to assess long-term drift.

Current–voltage curves were used to select the operating voltage (Fig. 7). At all six axial positions, the current increased with bias voltage and reached a relatively flat region above approxi-

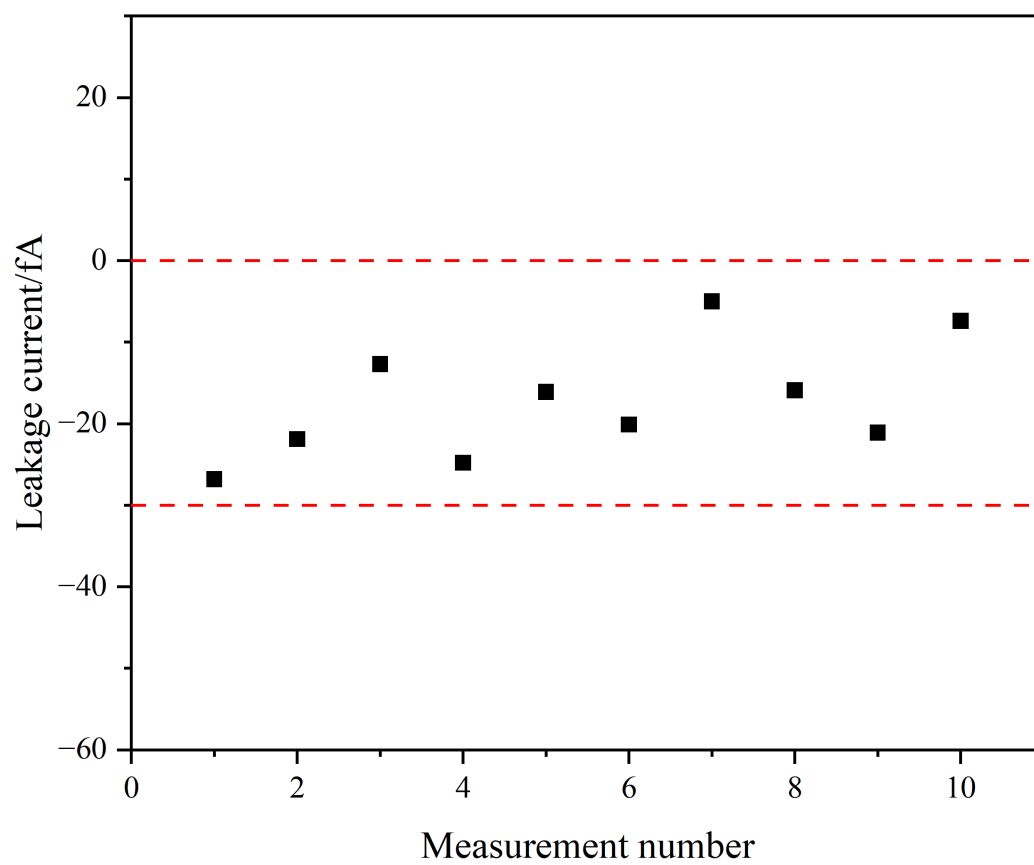


**Fig. 2** Leakage current at  $-400$  V after a 30 min warm-up

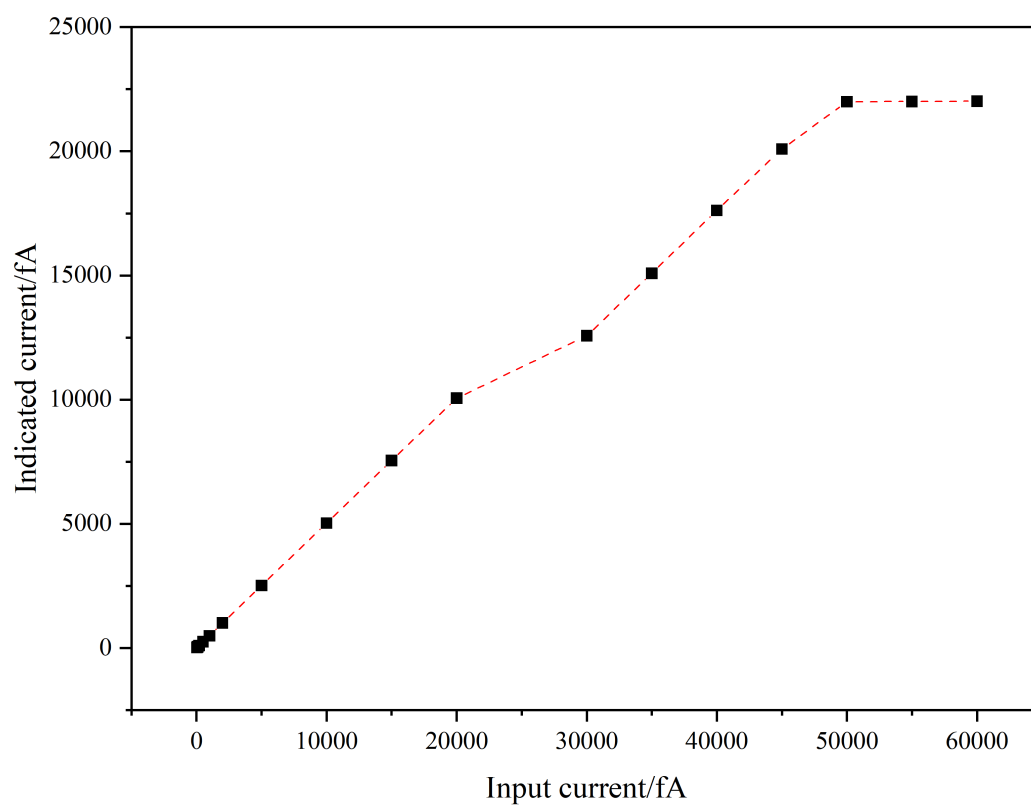


**Fig. 3** Input–output response of the low-range channel

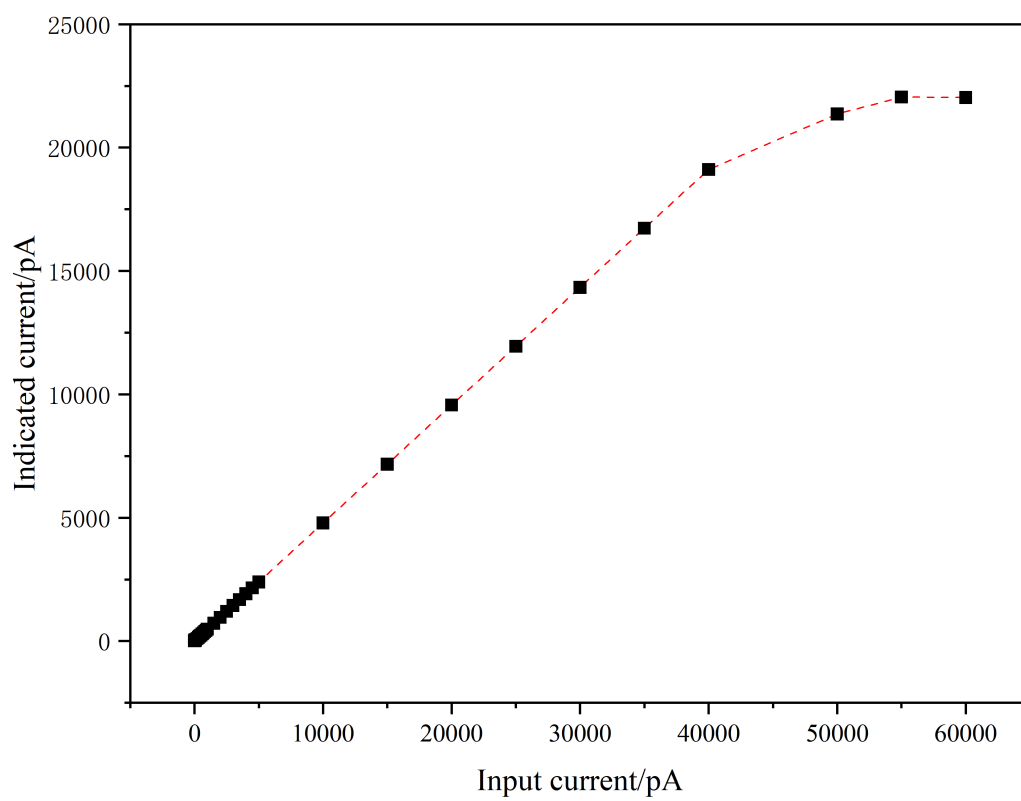


**Fig. 4** Input–output response of the medium-range channel

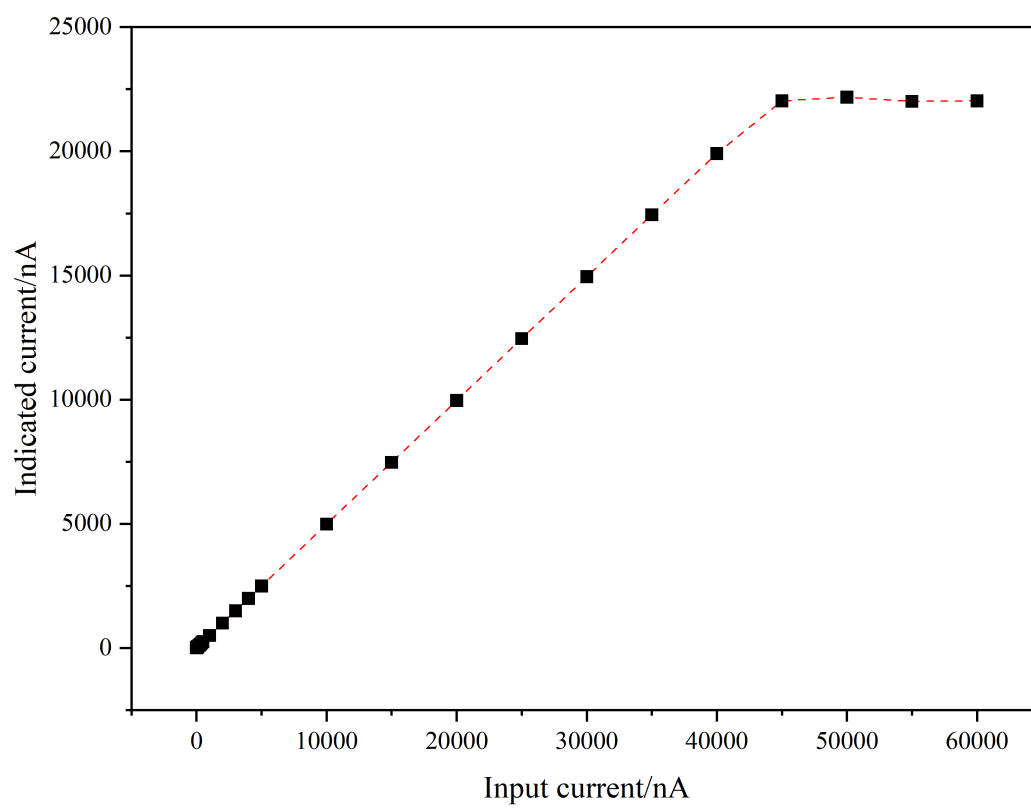


**Fig. 5** Input–output response of the high-range channel

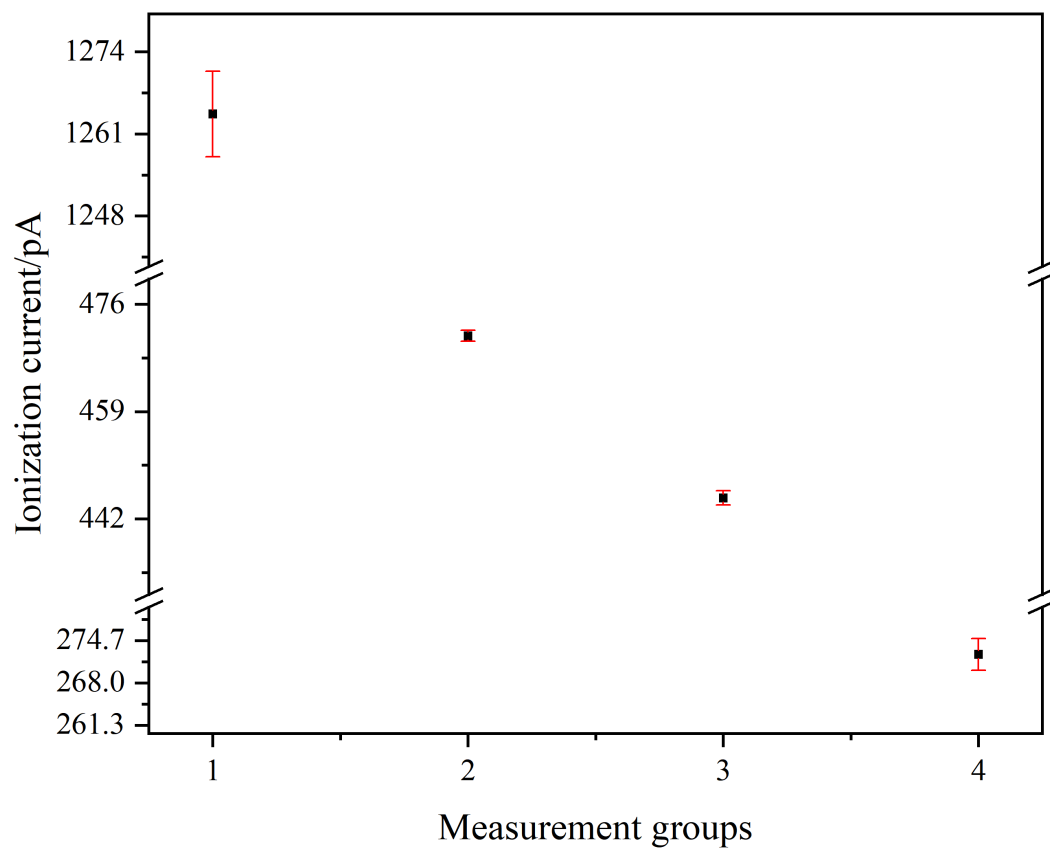


**Fig. 6** Mean current and one standard deviation for four series of ten measurements at fixed geometry; each series corresponds to a different activity

mately 350 V. Differences between positions persisted over 350–500 V. On this basis, 400 V within the plateau region was selected for subsequent radioactive-source measurements.

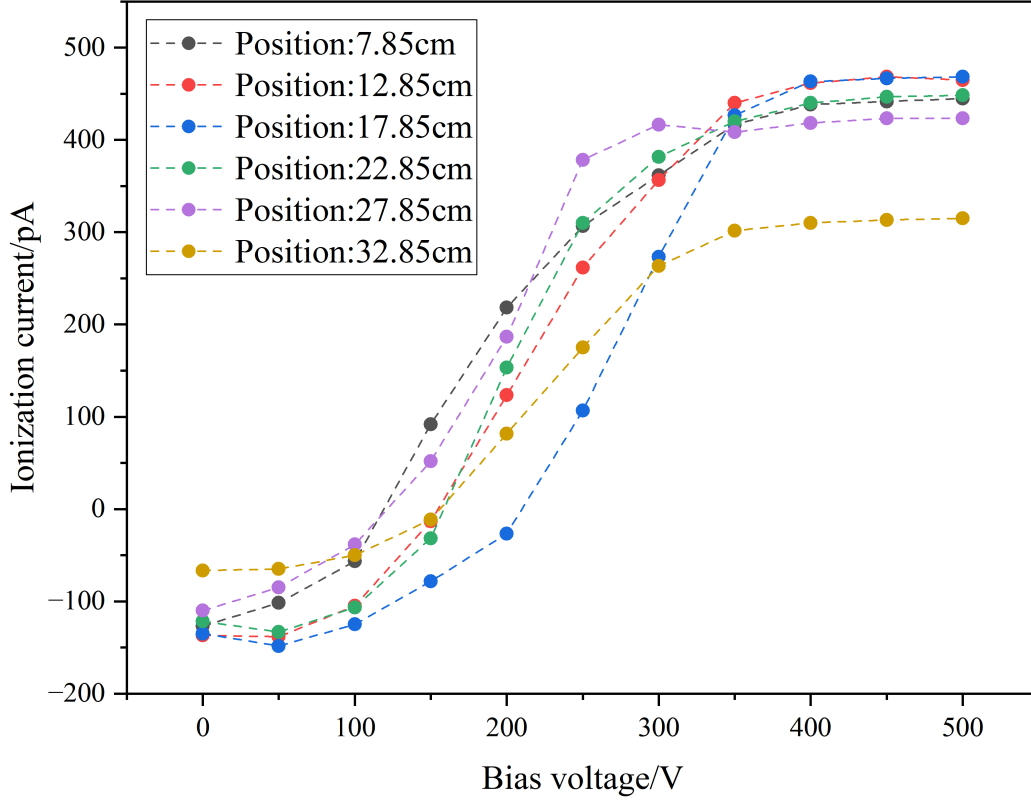


**Fig. 7** Saturation curves at six axial positions

### 3.4 Axial response

The vial was moved along the well axis at 400 V to examine the effect of source position. The current initially increased with insertion depth, reached a maximum 17.85 cm below the chamber top, and then decreased toward the well bottom (Fig. 8). This single-peaked profile is consistent with changes in solid-angle coverage and end effects. Insertion depth should therefore be fixed when comparing measurements.

### 3.5 Response to added wall thickness

Adding 3 mm of PLA around the original vial reduced the current from approximately 330 to 10 pA, a decrease of approximately 97% (Fig. 9). The four-point fit was  $f(t) = -17.99 + 351.7 \exp(-0.85t)$ , with  $R^2 = 0.999$ , where  $t$  is the added PLA thickness in millimeters and  $f(t)$  is the current in

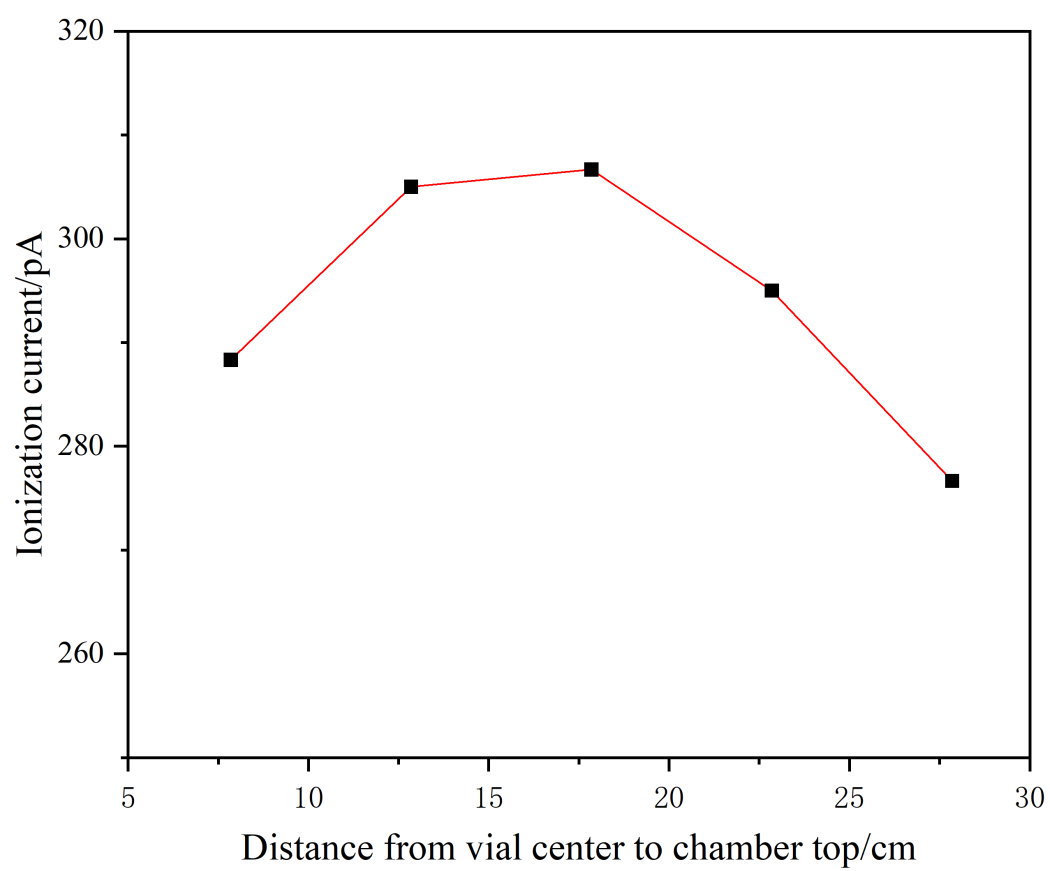


**Fig. 8** Axial current response at 400 V

picoamperes. This relationship describes the tested vial and sleeve configuration over 0–3 mm. The constant term is an empirical fitting parameter and does not represent a separate radiation component.

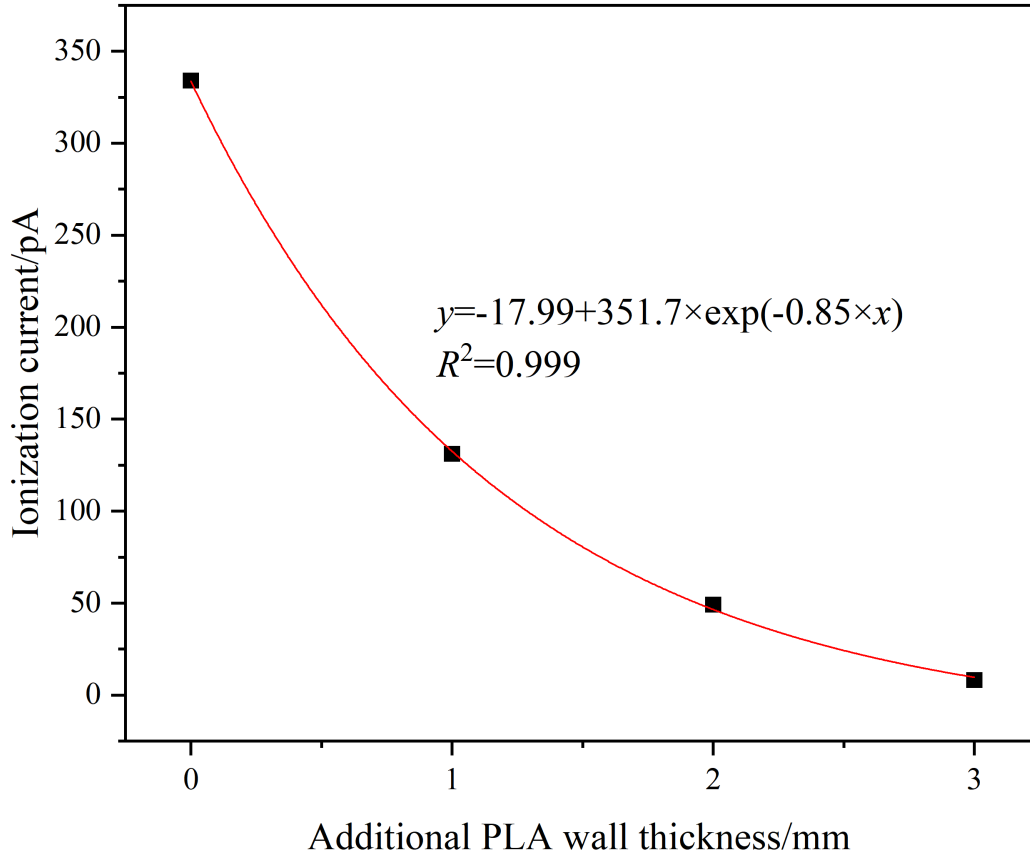


**Fig. 9** Effect of added PLA thickness on the response

The current decreased with increasing PLA thickness, as expected from electron attenuation before the particles reached the sensitive gas. This observation is also consistent with the beta-dominated response predicted by the simulation. The thickness dependence provides an experimental basis for investigating relative response corrections, but any correction must be established for the relevant material composition, density, and geometry.

### 3.6 Response to liquid height

The effect of liquid height was examined at constant total activity. Most of the current decrease occurred as the height increased from 1 to 3 mm, with smaller changes over 3–5 mm (Fig. 10). Adding diluent changes both the axial source distribution and beta self-absorption in the liquid. A filling-volume correction should therefore be established for a specified vial geometry.

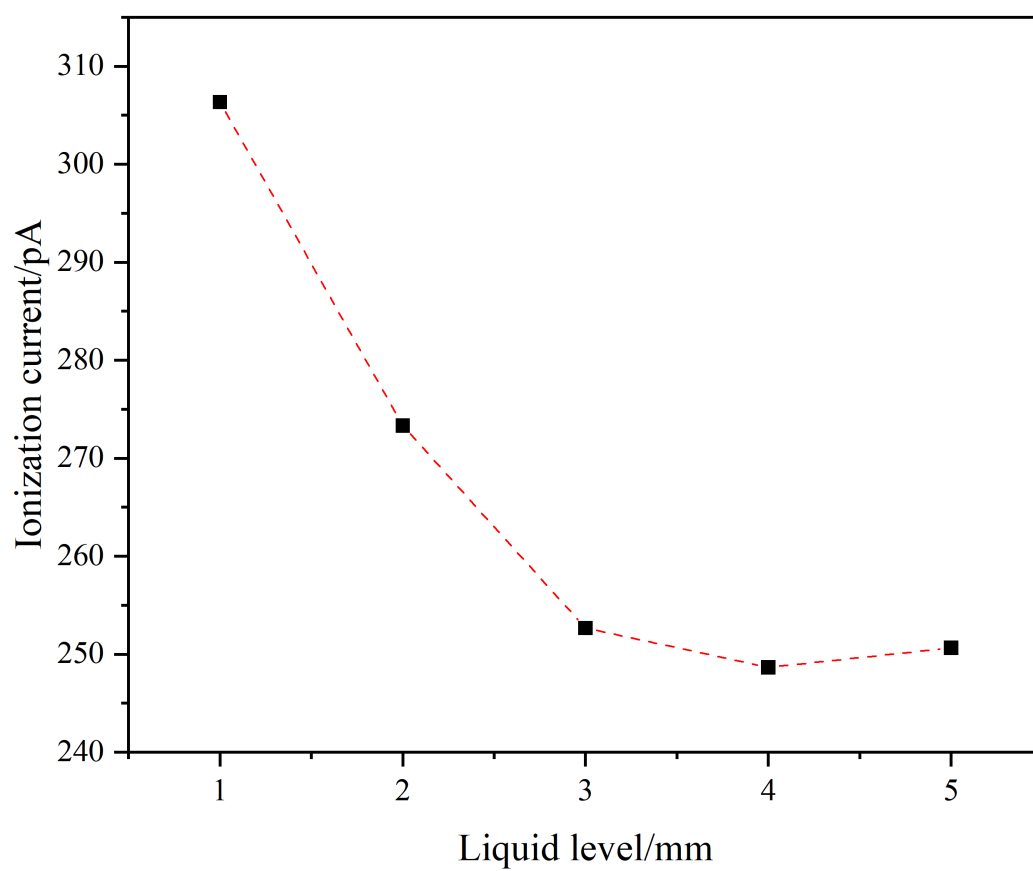


**Fig. 10** Current as a function of liquid height at fixed total  $^{90}\text{Y}$  activity

## 4 Discussion

### 4.1 Direct beta response

The main feature of the thin-walled design is that it preserves a path for electrons to enter the sensitive gas and generate an ionization signal directly. In the commercial radionuclide-calibrator model studied by Laedermann et al., energy deposition from radionuclides with maximum beta energies below approximately 2.5 MeV arose mainly from bremsstrahlung [7]. This finding depends on the wall and chamber geometry and should not be interpreted as a universal energy threshold for all ionization chambers. Yamada and Ishii also reported a substantial influence of well-wall thickness on the response to high-energy beta emitters [6]. These studies support the use of thin electrodes to increase the electron contribution, while emphasizing that the  $^{90}\text{Y}$  response of a conventional calibrator must be considered in relation to its specific design.

In the present model, 99.161% of energy deposition was assigned to beta-related branches. The simulated ionization signal therefore arose mainly from electrons and their charged secondary particles outside the bremsstrahlung-photon branches. Direct beta response here refers to energy deposition by these particles after they enter the sensitive gas; it does not imply collection of all emitted beta particles, nor is 99.161% a particle detection efficiency. The marked decrease in current after adding PLA is consistent with this mechanism, but the experiment alone cannot independently determine the beta and photon fractions.

### 4.2 Applicability of wall-thickness response corrections

When material composition and density are known, and vial geometry, source distribution, filling volume, and insertion depth are controlled, thickness-response curves could be investigated as a means of converting measurements at different added thicknesses to a reference configuration. Previous  $^{90}\text{Y}$  studies show that container and volume effects must be evaluated for specific calibrator and sample configurations [6, 9–13]. The direct beta response of the present chamber makes thickness changes apparent in the ionization current and thus provides a basis for developing an empirical correction. Converting the corrected current to activity would still require a calibration factor established with a traceable reference source.

The available experiment used 0–3 mm PLA sleeves around the original source vial. It supports discussion of relative thickness corrections for this configuration, not a general calibration applicable to different materials or vial types. Changes in actual container wall thickness may also alter internal dimensions, bottom thickness, and electron path lengths. The four fitted points do not provide an independent test of correction accuracy. Any future application should therefore be restricted to

validated materials, geometric conditions, and thickness ranges. As the transmitted signal decreases, the effects of thickness deviations and background on correction uncertainty must also be evaluated.

### **4.3 Measurement geometry and readout performance**

The wall-thickness and liquid-height experiments show that reproducible measurements require control of vial type, added material, filling volume, and insertion depth. Filling volume can be controlled gravimetrically or volumetrically; conversion from mass to volume should account for suspension density. Microsphere sedimentation may alter the axial activity distribution, so the mixing procedure and the interval between mixing and reading should also be kept consistent [11]. These conditions should match those used to establish the calibration or correction relationship.

Both simulated sensitive volumes provided beta-dominated responses, while the prototype combined their charges through a common collecting electrode. The present measurements did not establish the gain of the dual-sensitive-volume arrangement relative to a single sensitive volume. Such an evaluation would require a reference chamber or separate readout of the two volumes.

Absolute leakage currents below 30 fA and RSDs below 1% in each series indicate low leakage and good short-term repeatability under the fixed geometric conditions tested. The 30 fA input was close to the leakage-current level and cannot be used to establish the minimum measurable activity. That quantity requires repeated background measurements together with an assessment of integration time and zero drift.

### **4.4 Calibration and limitations**

The simulated contribution fractions apply to the uniform source and geometric conditions used in the model. Microsphere distribution and microscopic self-absorption were not represented, and charge collection was idealized. The fractions also depend on the particle-ancestry classification. Independent checks of the scoring implementation and sensitivity studies of the transport settings are needed to determine their uncertainty.

The experiments involved one microsphere product and vial type, a limited activity range, and short measurement periods. The current-to-activity calibration relationship remains to be established using traceable  $^{90}\text{Y}$  standards. Further evaluation should address activity-response linearity, long-term stability, and the effects of vial differences, filling volume, and positioning errors. These components should be included in a measurement uncertainty budget together with reference-activity uncertainty, decay correction, leakage current, and repeatability.

## 5 Conclusions

The thin-walled well ionization chamber and its low-current readout system demonstrated basic performance for current measurements of  $^{90}\text{Y}$  resin microspheres. In the model, beta-related transport and bremsstrahlung contributed 99.161% and 0.839% of the ionization signal, respectively. The response decrease observed with added wall thickness was consistent with direct beta detection. Experiments confirmed low leakage current and short-term RSDs below 1%, and the saturation curves supported selection of a 400 V operating bias. Unlike conventional configurations that rely mainly on bremsstrahlung response, this chamber preserves a direct electron contribution to the ionization signal, while requiring careful control of vial and filling geometry. The measured PLA response curve provides a basis for studying relative wall-thickness corrections in a specified configuration, but does not replace validation of correction accuracy or traceable activity calibration.

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**Author contributions:** Lixia Tian: study conception and experimental planning. Zhongbin Hang: data processing and manuscript review. Hongpeng Dong: experimental testing. Yan Zhang: manuscript drafting. Hai Hu: Monte Carlo simulations.

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**Data availability:** The data supporting the findings of this study are available from the corresponding author upon reasonable request.

**Conflict of interest:** The authors declare no conflicts of interest.

## References

- [1] Busse NC, Al-Ghazi MSAL, Abi-Jaoudeh N et al (2024) AAPM Medical Physics Practice Guideline 14.a: Yttrium-90 microsphere radioembolization. J Appl Clin Med Phys 25:e14157. <https://doi.org/10.1002/acm2.14157>
- [2] Dezarn WA, Cessna JT, DeWerd LA et al (2011) Recommendations of the American Association of Physicists in Medicine on dosimetry, imaging, and quality assurance procedures for  $^{90}\text{Y}$  microsphere brachytherapy in the treatment of hepatic malignancies. Med Phys 38:4824-4845. <https://doi.org/10.1118/1.3608909>

- [3] Chiesa C, Sjogreen-Gleisner K, Walrand S et al (2021) EANM dosimetry committee series on standard operational procedures: a unified methodology for  $^{99m}\text{Tc}$ -MAA pre- and  $^{90}\text{Y}$  perit-therapy dosimetry in liver radioembolization with  $^{90}\text{Y}$  microspheres. *EJNMMI Phys* 8:77. <https://doi.org/10.1186/s40658-021-00394-3>
- [4] Hang ZB, Hu H, Liang ZW et al (2026) Dosimetric development of yttrium-90 resin microspheres for selective internal radiation therapy: current status and perspectives. *J Labelled Compd Radiopharm* 69:e70022. <https://doi.org/10.1002/jlcr.70022>
- [5] Carey JE, Byrne P, DeWerd L, Lieto R, Petry N (2012) The selection, use, calibration, and quality assurance of radionuclide calibrators used in nuclear medicine. AAPM Report No. 181. American Association of Physicists in Medicine, Alexandria. <https://doi.org/10.37206/137>
- [6] Yamada T, Ishii T (2012) Precise practical measurements of  $^{90}\text{Y}$  used in radiopharmaceuticals using re-entrant ionization chambers. *Appl Radiat Isot* 70:2246-2250. <https://doi.org/10.1016/j.apradiso.2012.02.096>
- [7] Laedermann JP, Valley JF, Bulling S, Bochud FO (2004) Monte Carlo calculation of the sensitivity of a commercial dose calibrator to gamma and beta radiation. *Med Phys* 31:1614-1622. <https://doi.org/10.1118/1.1755181>
- [8] Valley JF, Bulling S, Leresche M, Wastiel C (2003) Determination of the efficiency of commercially available dose calibrators for beta-emitters. *J Nucl Med Technol* 31:27-32. <https://tech.snmjournals.org/content/31/1/27>
- [9] Ferreira KM, Fenwick AJ, Arinc A, Johansson LC (2016) Standardisation of  $^{90}\text{Y}$  and determination of calibration factors for  $^{90}\text{Y}$  microspheres (resin) for the NPL secondary ionisation chamber and a Capintec CRC-25R. *Appl Radiat Isot* 109:226-230. <https://doi.org/10.1016/j.apradiso.2015.11.074>
- [10] Thiam C, Bobin C, Lourenço V et al (2016) Investigation of the response variability of ionization chambers for the standard transfer of SIR-Spheres®. *Appl Radiat Isot* 109:231-235. <https://doi.org/10.1016/j.apradiso.2015.11.056>
- [11] Forwood N, Willowson KP, Tapner M, Bailey DL (2017) Assessment of the relative contribution of volume and concentration changes in Yttrium-90 labelled resin microspheres on ionization chamber measurements. *Australas Phys Eng Sci Med* 40:943-948. <https://doi.org/10.1007/s13246-017-0601-z>

- [12] Zimmerman BE, Cessna JT, Millican MA (2004) Experimental determination of calibration settings for plastic syringes containing solutions of  $^{90}\text{Y}$  using commercial radionuclide calibrators. *Appl Radiat Isot* 60:511-517. <https://doi.org/10.1016/j.apradiso.2003.11.068>
- [13] Siegel JA, Zimmerman BE, Kodimer K, Dell MA, Simon WE (2004) Accurate dose calibrator activity measurement of  $^{90}\text{Y}$ -ibritumomab tiuxetan. *J Nucl Med* 45:450-454. <https://jnm.snmjournals.org/content/45/3/450>
- [14] Saldarriaga Vargas C, Bauwens M, Pooters INA et al (2020) An international multi-center investigation on the accuracy of radionuclide calibrators in nuclear medicine theragnostics. *EJNMMI Phys* 7:69. <https://doi.org/10.1186/s40658-020-00338-3>
- [15] Mo L, Avci B, James D et al (2005) Development of activity standard for  $^{90}\text{Y}$  microspheres. *Appl Radiat Isot* 63:193-199. <https://doi.org/10.1016/j.apradiso.2005.02.002>
- [16] Lourenço V, Bobin C, Chisté V et al (2015) Primary standardization of SIR-Spheres based on the dissolution of the  $^{90}\text{Y}$ -labeled resin microspheres. *Appl Radiat Isot* 97:170-176. <https://doi.org/10.1016/j.apradiso.2014.12.024>
- [17] Agostinelli S, Allison J, Amako K et al (2003) Geant4—a simulation toolkit. *Nucl Instrum Methods Phys Res A* 506:250-303. [https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8)
- [18] Allison J, Amako K, Apostolakis J et al (2016) Recent developments in Geant4. *Nucl Instrum Methods Phys Res A* 835:186-225. <https://doi.org/10.1016/j.nima.2016.06.125>
- [19] Poole CM, Cornelius I, Trapp JV, Langton CM (2012) A CAD interface for GEANT4. *Australas Phys Eng Sci Med* 35:329-334. <https://doi.org/10.1007/s13246-012-0159-8>
- [20] International Commission on Radiation Units and Measurements (2016) Key data for ionizing-radiation dosimetry: measurement standards and applications. ICRU Report 90. *J ICRU* 14(1). <https://doi.org/10.1093/jicru/ndw043>